Benthic Mat Study

Productivity estimates of local assessment units

ESSP-EN-14-TRPT-0029

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Eramurra Solar Salt Project

This report was prepared for:

Leichhardt Salt

Mark Coleman
Actis Consulting Pty Ltd
PO Box 176
Darlington
WA 6070
08 92521050

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Revisions

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13/11/2023	M Coleman	Draft
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1 Executive Summary

This report is to be read in conjunction with *Benthic Mat Study- Productivity Estimate of Proposed Eramurra Project.* June 2023 report and associated prepared for Leichhardt Salt Pty Ltd by Actis Environmental Services. The current report is by Actis Consulting Pty Ltd previously trading as Actis Environmental Services.

Leichhardt Salt is proposing to build a solar salt field east of Cape Preston in the Pilbara region of Western Australia. The disturbance area of the proposed salt field covers 12,174ha. Most of the area covers terrestrial landscapes but a significant proportion (ca 2,000ha) also covers an area variously described as mudflat, tidal flats and algae mats. 'Microbial mats' is a more accurate description, but this community is commonly known as an algal mat.

The scope of this report is to estimate the productivity of the microbial mat and relate this to the relative impact on mat productivity by the proposed development.

This report expands on previous reports by Actis Environmental Services titled:

- *Benthic Mat Study, Eramurra Solar Salt Project* June 2022; and
- *Benthic Mat Study- Productivity Estimate of Proposed Eramurra Project* June 2023.

The above studies were restricted to the pond disturbance area of the project and not the standard land units used elsewhere. In this report the productivity estimates have been standardised to the Local Assessment Units (LAU), and the Indicative Disturbance Area (IDA). The mat productivity model (Version 15) has been extended geographically to previously undescribed areas outside of the disturbance area to the limits of the LAU.

The most important aspect of a mat is its productivity, and its potential to support the nutrient requirements of the near shore environment by exporting biomass and its incorporated nutrient load. Productivity can only be measured *in situ* and the procedure limits the number of sites and times that it can be measured. Chl a is a factor of productivity but it cannot be used as a direct measure. There are several other factors that will influence the productivity. If these factors are considered across the study area then the relative productivity can be estimated from Chl a.

The productivity estimate can be further refined by estimating time that the mat is wet from tidal inundation, which gives the period of maximum productivity, and the time desiccated with zero nett productivity.

The resulting calculation using benchmark productivity values measured in other locations allowed for the generation of hypothetical productivity amounts for each chlorophyll band. These were incorporated into the spatial mat model described in *Benthic Mat Study- Productivity Estimate of Proposed Eramurra Project* June 2023; Model Version15 being functionally the same as that modelled using Version 14 but expanded to a greater region to generate a numeric of the productivity per unit area for the IDA as a proportion of the LAU. The proportional numeric for each mat type was expressed as a percentage of the total LAU (see Table 1). The total percentage of the LAU mat productivity taken up in the IDA was 13% and primarily in the LAU-3.

Table 1 Estimate of percent Nett Productivity in the IDA versus the LAU area

Classification	Chl a (mg.m^{-2})	LAU-1	LAU-2	LAU-3	LAU-4
Very active mat 301-400mg/m2	301 +	0.01%	0.82%	10.93%	1.17%
Active mat 151-300 mg/m2	151-300	0.01%	2.54%	8.63%	2.95%
Limited activity far 51-150 mg/m2	51-150	0.00%	3.01%	11.57%	2.98%
Limited activity near 51-150 mg/m2	51-150	0.01%	0.54%	0.64%	0.33%
Low far 0-50 mg/m2	0-50	0.00%	2.93%	22.5%	3.46%
Low near 0-50 mg/m2	0-50	0.05%	1.91%	0.00%	0.73%
Total		0.08%	11.75%	54.2%	11.6%

- The benthic mat productivity within the IDA is 12.9 percent or 188 t C yr^{-1} of that within the area of the LAU.
- The two more active bands of productivity (very active and active) contribute to 52% of the productivity within the LAU but only 34% of the IDA within the LAU.
- The four less active bands of productivity contribute to 48% of the productivity within the LAU but 66% of the IDA within the LAU.

2 Introduction

Leichhardt Salt is proposing to build a solar salt field east of Cape Preston in the Pilbara region of Western Australia (Figure 1).

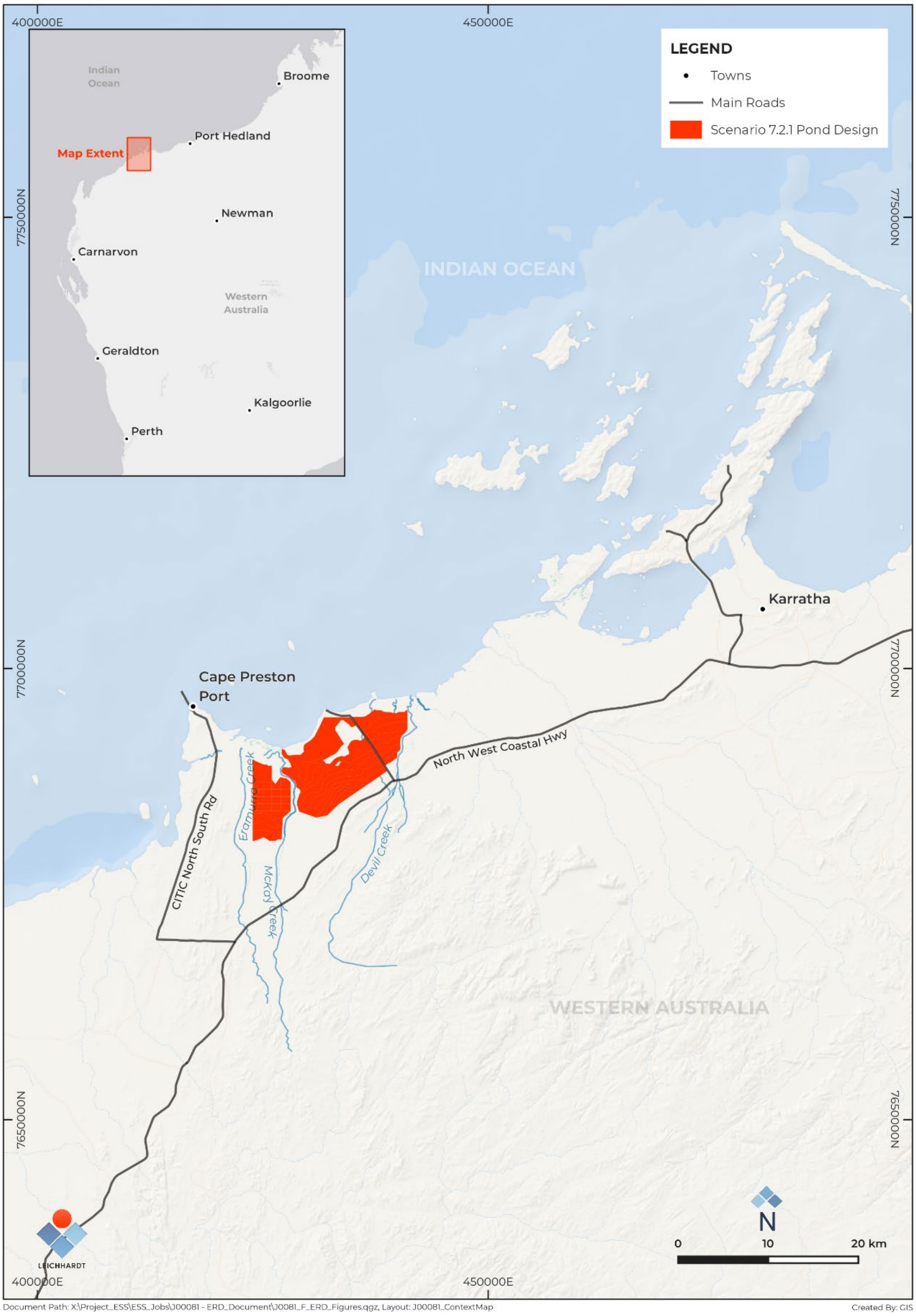

Figure 1 Location of proposed salt field

The disturbance area of the salt field as proposed covers 12,174ha (Figure 2). Most of the area covers terrestrial landscapes but a significant proportion (1,839ha) also covers an area variously described as mudflat, tidal flats and algae mats or benthic microbial mats.

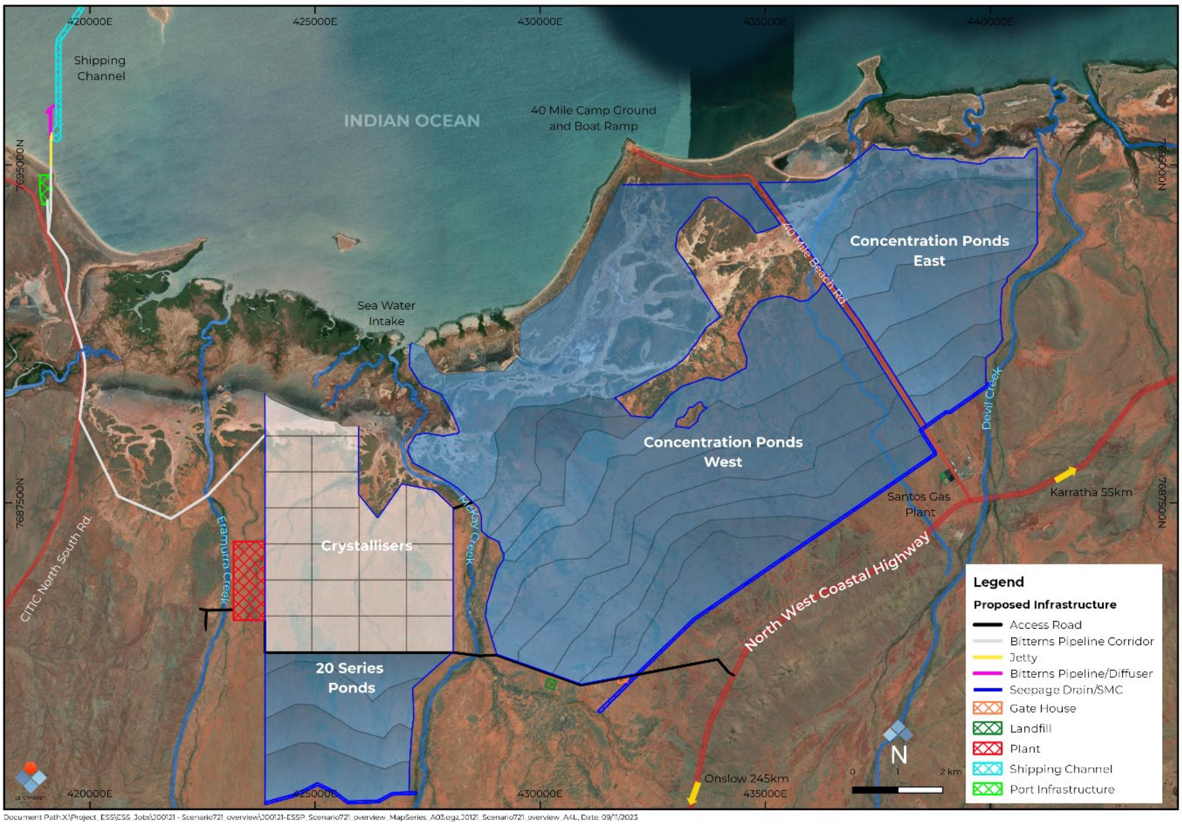

Figure 2 Layout of infrastructure (7.2.1)

The land units used in this report are Local Assessment Units 1-4 (LAU), and the Indicative Disturbance Area (IDA). These are illustrated in Figure 3.

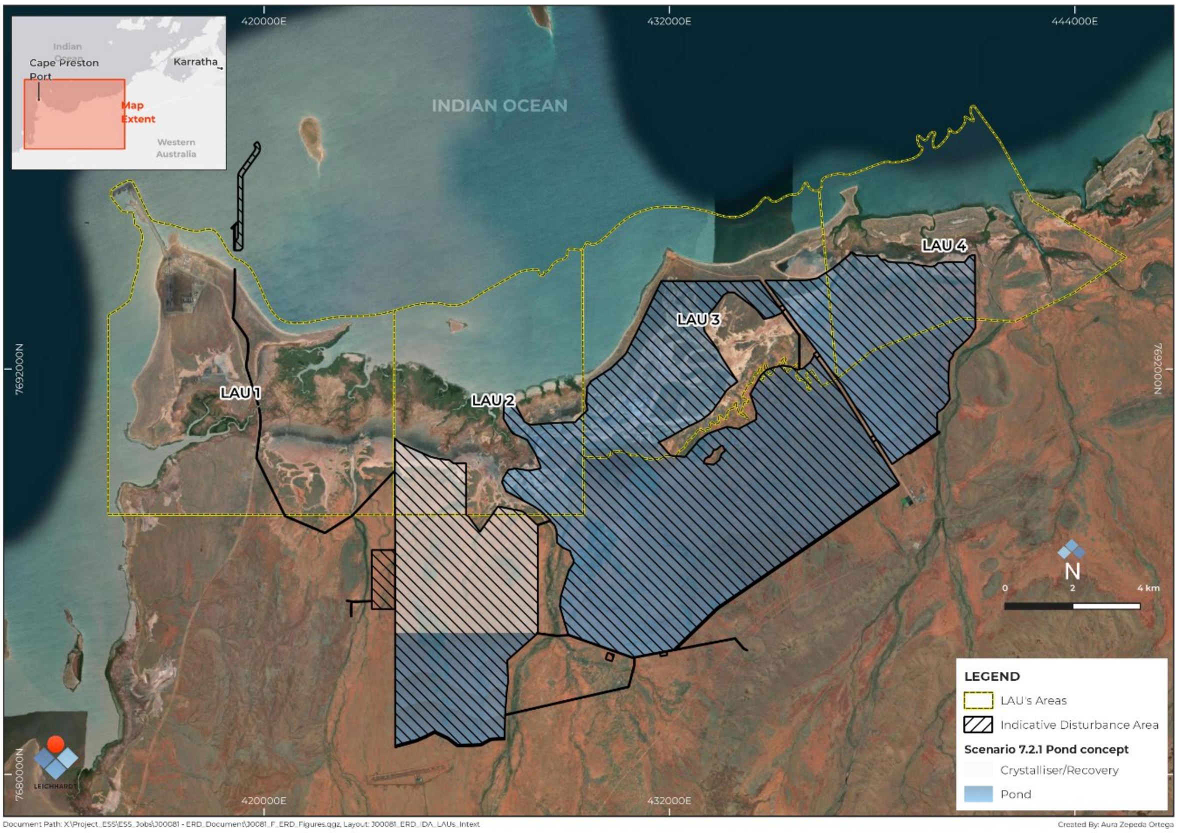

Figure 3 Eramurra Project LAUs and IDA

Benthic microbial mats, as defined in this report, refers to those areas under tidal influence and do not extend to the more ubiquitous 'biofilms' that can be found on the surface of the land in most undisturbed landscapes, including desert sands. The landforms of the study are shown in Figure 4.

Microbial mats are typically found in intertidal areas protected from the sea by either dunes or mangroves. The flats are usually made from alluvial soils formed by sea or terrestrial water flow, where material has become entrapped between the sea fringe and the land. They are typically flat and dry for most times, with occasional flooding from the tide or freshwater flow. The microbial mats are normally a darker colour due to an organic layer and can reach high temperatures (50 degrees Celsius plus) in summertime.

Figure 4 Benthic tidal mats in project site - tidal flats behind mangroves on left, mixed in middle and secondary dunes to the right

The project site has tidal mats behind both secondary dunes and mangroves. Both types are flooded periodically with tides and runoff from creeks or rivers.

Microbial mats have a similar composition to biofilms and are made up primarily of species from the Kingdoms of Bacteria and Archaea but with the occasional species from the Kingdom of Protista (algae, mostly diatoms). All these organisms can be collectively described as microbes. Algae are not the dominant group in biomass or function.

Microbial mats are areas of importance for several reasons. They serve as areas for wading birds to feed and rest (particularly at high tide and stormy weather), biomass storage, biodiversity conservation[1], nutrient transfer between the land and ocean and to stabilise what would be mobile alluvial material if it were not covered by a mat.

An important measure of the importance of an ecosystem to the environment is productivity. The report only considers primary (photosynthesis) productivity of the mat in terms of units of carbon converted to organic (carbon) material.

[1] There is little discussion in the public forum on microbial biodiversity, but it obviously has a role if only implicit.

3 Description of a Benthic Mat (Literature)

3.1 Tidal benthic microbial mat location

Lovelock et al. (2010) found that the microbial mats at Exmouth occupied a 40 cm range in the intertidal range (Figure 5). They also found that the microbial mats were an important source of the total carbon budget in the Exmouth Gulf.

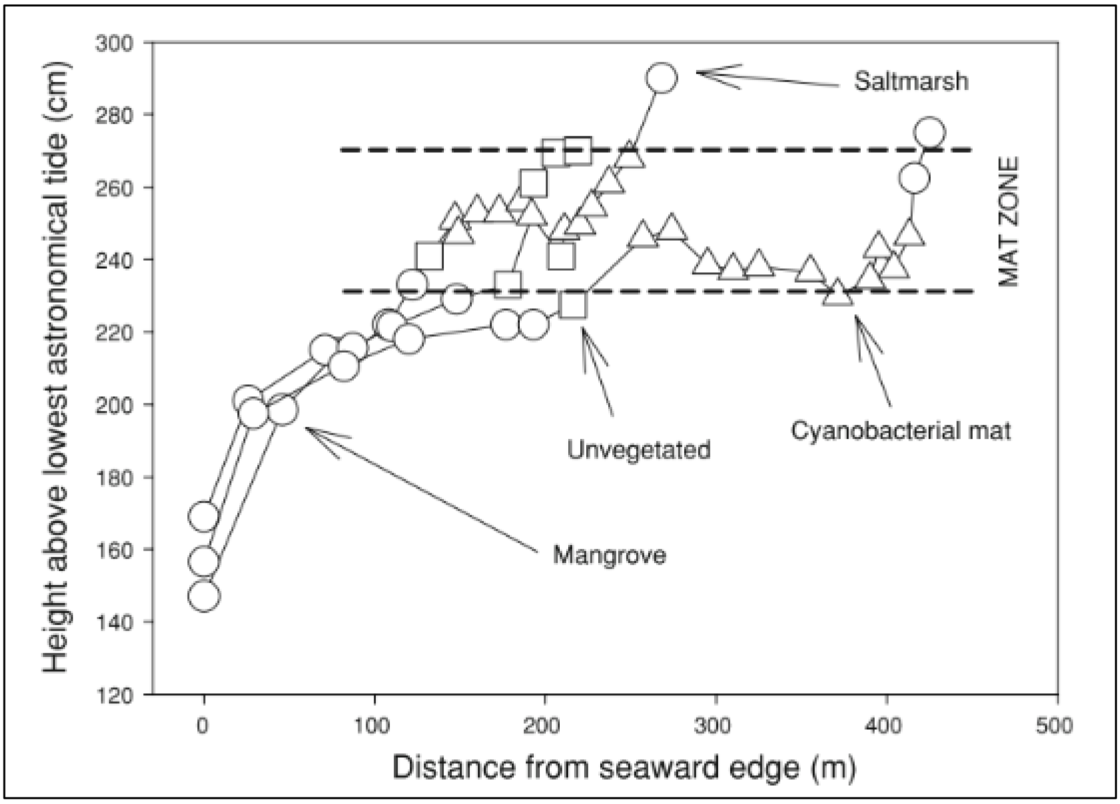

Figure 5 Transition of ecosystems across tidal range from Lovelock et al. (2010) p41 using three transects[2]

Biota Environmental Sciences Pty Ltd (2005) found that the microbial mat was found in a much smaller range between 1.366 and 1.44 m AHD in the Yannarie Salt Project for Strait's Resources. Biota's range was approximately 10 cm whereas Lovelock et al. (2010) was more like 40 cm.

The conclusion is that there is a narrow tidal range that suits microbial mats. This suggests that the range is determined by the frequency and duration of flooding enabling biological activity in what may be an extreme environment for temperature, desiccation and salinity.

The mat is unlikely to be active when it is desiccated, and the surface temperature raised by the sun. Flooding by tidal water would both reduce the temperature and hydrate the microbes. The period of wetting (hydroperiod) would be a major factor and would be determined by the speed (fall/tidal height) and distance from the source of tidal flooding. More specifically the factors are:

- Range of tidal movement. It follows that a 4-metre tidal range will have a greater effect as a 2-metre range in area covered and speed of covering the tidal flat.
- Measurements of tidal range will be impacted by geographical features, such as in a gulf as opposed to open ocean exposure.

[2] It is not clear from Lovelock et al. (2010) as to how the LAT was measured given the sampling site is at the end of an extensive gulf.

- Distance from the source of water to the mat will be a factor. Tidal creeks enable the rapid movement of seawater across the mat. It would be expected that mats at the upper tidal flood at a distance from a creek will be flooded for less time than a mat at the same height closer to a tidal creek. It takes time for flood water to move across a shallow flat when constricted by inflow from a narrow creek.
- Freshwater runoff will affect the wetted area, fanning out from creeks and maintaining saturation of the mat.
- Depressions will have the effect of forming temporary perched ponds and the mats will be more active in these areas. These can be formed artificially near structures such as roads and banks.

A point that can be made is that the tidal range for mats is likely to be different for different parts of the coast. The tidal range in the Exmouth Gulf will not be the same as at Eramurra. It is the flooding duration that is important.

3.1.1 Chlorophyll a

Cyanobacteria and Chlorophytes both use Chlorophyll a (Chl a) to convert light into energy. For the purposes of this work and the analysis used to determine Chl a, the analysis does not distinguish between the two photosynthesising groups. However, microscopic analysis of the mat did not find any Chlorophytes so for the purposes of the study all Chl a can be attributed to Cyanobacteria. No other primary chlorophyl peaks were identified in the scans.

Various trials were completed to determine the best method of measuring the Chl a in the mat and they are described in the report "Benthic Mat Study, Eramurra Solar Salt Project"[3]. Initial work on site showed that other photosynthesizing phyla were not present in enough numbers to be readily detected by acetone or ethanol extraction.

Chennu et al. (2015) found that the amount of Chl a in a desiccated mat from Exmouth, WA rapidly increased after flooding (2-5 times increase after 15 minutes of flooding) indicating that time of measurement is important. Lovelock et al. (2010) found that the Chl a ranged between 224-416 $mg.m^{-2}$ but this was after inundation with artificial seawater or what might be referred to a 'reactivated' mat.

The recovery of higher concentration of Chl a after wetting is recorded in the literature without cell growth. Abed et al. (2014) used isotopes of carbon (C13) to determine the rate of active chlorophyll after wetting desiccated mat. They found that the mat started recovering almost immediately and reached maximum activity after two hours and that Chl a from synthesis did not appear in any concentration until two days after wetting. Raanan et al. (2016) results supported the above. It is clear from these results that the timing of the sampling relative to the wetting event is important when quantifying the mat activity.

Pinckney et al. (1995) found that the Chl a in North Carolina microbial mats varied between 100-400 $mg.m^{-2}$. The only site that had a Chl a less than 50 $mg\ m^{-2}$ was a sandy site. There was seasonal variation.

In summary, it may be expected that a mat may have a 'resting' Chl a concentration of 200 $mg.m^{-2}$ but will reach much higher values after wetting or becoming 'active'.

3.1.2 Carbohydrates and Total Organic Carbon (TOC)

Lovelock et al. (2010) found that the microbial mats contributed significantly to the TOC and carbohydrates (see Table 2). The mangroves are by far the most productive part of the Exmouth ecosystem in respect to TOC. The evidence presented in the paper was that the microbial mats contributed less than the mangroves, but more than the plankton in the Gulf itself. It is not clear from the article if the primary productivity was calculated on the 'reactivated' mat (see Chlorophyll a note

[3] *Benthic Mat Study, Eramurra Solar Salt Project* June 2022 Actis Environmental Services

above) in which case the mat is only active on high tide and or after flooding from a rain event. If this is the case, then the primary productivity in the mat for annual budgets would be substantially smaller as the mat would only be ‘active’ when flooded and not be ‘active’ for the entire 24 hours of the day.

Table 2 Carbon statistics for Exmouth Gulf as derived from Lovelock et al. (2010)

		Total fixed C (tonne.year^{-1})		**Total fixed C (tonne.year^{-1}.ha^{-1})**	
	Area ha	Lower estimate	Higher estimate	Lower per ha	Higher per ha
Gulf	2,600	154,325	400,750	59	154
Mangrove	161	383,305	1,432,360	2,381	8,897
Mat	100	10,000	954,805	100	9,548

4 Distribution of Benthic Mat at Eramurra

The procedure for determining the Chl a of the mat and the determination of the estimated productivity is described in detailed elsewhere[4]. The benthic microbial mat at Eramurra has been surveyed by taking subsamples of the mat in structured transects and at relatively random sites of interest. Photos were taken of the mat environ and of the sample after a core had been extracted from the mat. An estimate of the thickness of the mat was made. Each sample was located with a GPS and the results entered a GIS database.

Previous work had determined that pigment analysis, specifically Chl a, was a useful technique in determining the biomass. Most if not all the Chl a can be attributed to Cyanobacteria. Non photosynthesising bacteria and Archaea do not have Chl a and would not be included but, assuming that the ratio of organisms with to those without Chl a remains the same from sample to sample, Chl a is a useful indicator of total biomass and productivity. There are limitations to using chlorophylls as an indication of biomass as described by Kruskopf and Flynn (2006) but there are limited alternative methods that can be readily applied.

4.1 Pigment analysis method

Samples were taken from the benthic mat using a corer with a 32 mm diameter and 50 mm depth. The samples were then freeze dried, weighed and homogenised before the Chl a extracted and calculated using standard methods.

4.1.1 Distribution of the benthic microbial mat

The tidal movement of seawater is the main wetting event. Hydroperiod or time that a site is flooded is a major factor for the abundance of a mat. The two most obvious factors that may influence the location of the more active mats are location within the tidal range (AHD) and distance that the tidal water needs to transverse or *de facto* delay effect. This view has been supported in the previous report, the two key parameters for defining where a mat may be found was tidal height (AHD in the current study) and distance from tidal creeks.

The elevation (AHD) was determined by LiDAR survey. The distance was determined by measuring the line-of-sight distance to the nearest mangrove group. The mangrove or mangal fringe was chosen because mangrove species are largely limited by tidal hydroperiod. The upper fringes of the mangal (*Avicenna marina*) represent a hydroperiod that is consistent along the coast and serves as a useful baseline. A more refined method of determining tidal flooding frequency would be more helpful but, until that time, the mangrove fringe serves as a useful analogue.

Mat with a high Chl a were found over a very small range of 40 cm (Figure 6) and this is comparable to other work in the area. The relationship between Chl a and AHD held, independent of wetting and desiccation, and only varied with magnitude of the amount of Chl a per area.

There were no significant microbial mats beyond 1,700 metres from the nearest tidal creek.

The typical concentration of Chl a was also very low at a distance less than 175 metres and greater than 2,000 metres from a tidal source (Figure 7). Anecdotally the low concentration of Chl a near the tidal

[4] *Benthic Mat Study, Eramurra Solar Salt Project* June 2022 Actis Environmental Services
Benthic Mat Study- Productivity Estimate of Proposed Eramurra Project. June 2023 Actis Environmental Services

creeks is due to velocity of tidal water and ploughing activity of animals (fish and invertebrates) close to the creeks.

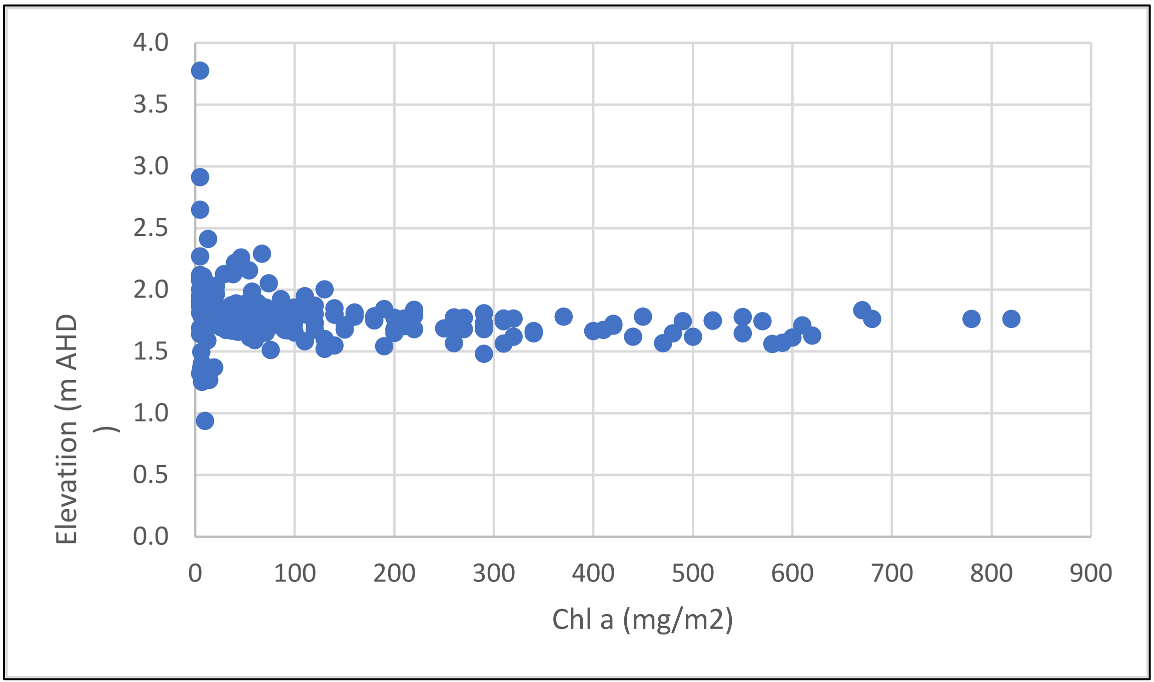

Figure 6 Elevation (AHD m) of sample versus chlorophyll content (all samples, wet mat)

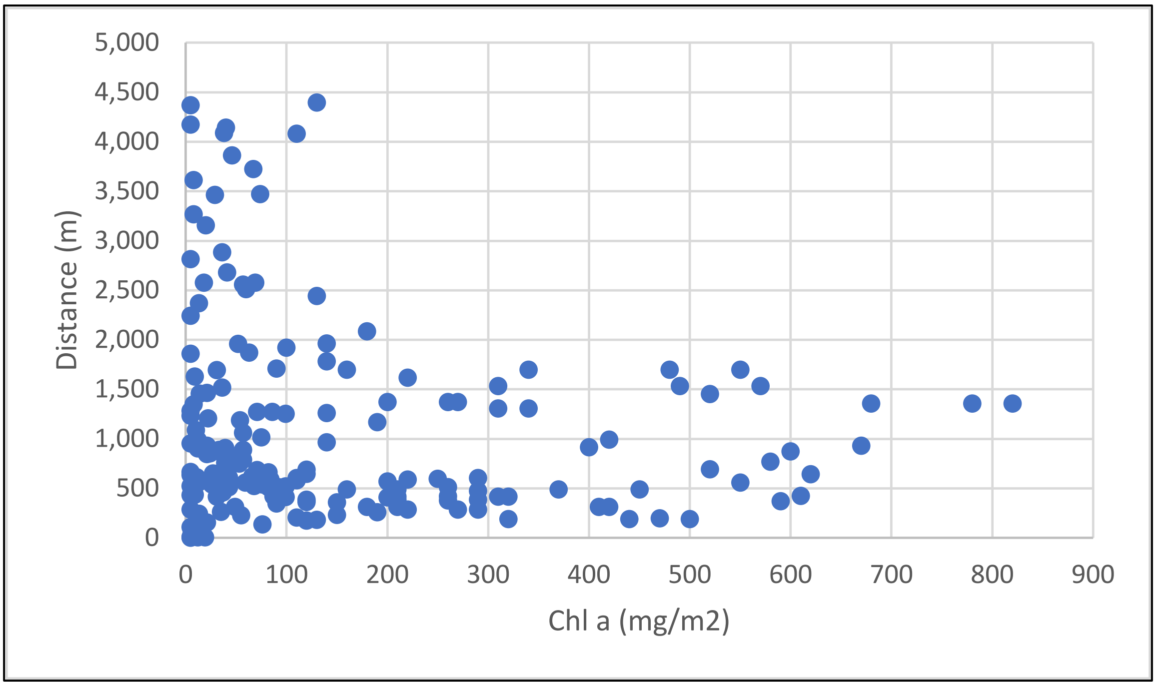

Figure 7 Chlorophyll a from wet mats as a function of distance from tidal source (all samples)

4.1.2 Modelling the distribution of the mat

A GIS model was developed to map the distribution of the mat using hydroperiod as defined by elevation and distance from the mangal. The numerical model used the selected data which was minus the samples in basins and freshwater flows. The current model (Version 15) is the same as model Version 14 used in previous reports but extended to the full expanse of the four LAU.

These criteria were used to predict ranges for the four main classifications of microbial mat found at the Eramurra site as defined by Chl a level.

The two lower ranges were split into two subgroups depending on their position in the tidal flat. The samples were in the same Chl a band, but the sample sites had radically different hydroperiods and flooding times. The mat close to a tidal influence was impacted by the activity of animals and speed of water flow (Figure 8) compared with the mat further from tidal influence (Figure 9).

Figure 8 Example of 'bio turbid' zone with low Chl a concentration close to the tidal creeks

Figure 9 Example of mat at a distance from tidal influence with low Chl a concentration

5 Productivity of the mat

Chl a is a useful measurement of biomass and indicator of potential productivity. However, Chl a concentration is not a direct measure of productivity. Productivity, defined as the conversion of inorganic carbon to organic carbon, varies with season, time of day and availability of nutrients.

Although there is no direct conversion from Chl a concentration to productivity, by assuming similar environmental conditions, it is possible to benchmark a Chl a concentration against a measured productivity.

Chen et al. (2021) found that the Chl a could be used as a measure of productivity if the chlorophyll fluorescence–induced dynamic curve was known. Their work provides a theoretical relationship between productivity and Chl a. They described the following formulae:

Equation 1 P=K × r × c ×(Chla) × DH

> where P represents primary productivity (mg C m^{-3} d^{-1}), r represents the assimilation coefficient (mg biomass $h^{-1}$$mg^{-1}$ Chlorophyll a), c (Chlorophyll a) represents the content of Chlorophyll a (mg.m^{-2}), DH represents sunshine time (h d–1) and K represents the experience constant.

This formula relies on determining the assimilation coefficient which is essentially the rate by which an ecosystem can convert light to organic matter. The formula supports the notion that within the same environment and ambient conditions, Chl a is being directly proportional to the Chl a concentration. Solving for simultaneous equation results in:

Equation 2 P_1/P_2 = Chlorophyll a_1/Chlorophyll a_2

Lovelock et al. (2010) found that the gross primary production on the flats around Exmouth Gulf peaked at approximately 18 mmol O_2 m^{-2} h^{-1}. The average gross primary production for permanently seawater flooded mats under laboratory conditions was Chl a 312 mg.m^{-2} and gross primary productivity 8.75 mmol O_2 m^{-2} h^{-1}. The dark cycle respiration was determined to be 3.35 mmole O_2 m^{-2} h^{-1} making the nett productivity 5.4 mmole O_2 m^{-2} h^{-1}. This converts to 0.065 g C m^{-2} hr^{-1} or 108 g C m^{-2} yr^{-1}. This forms a benchmark for the productivity for Eramurra.

However the mat is not active every hour of the year because it is not wet, and therefore this rate represents the maximum productivity potential. Lovelock et al. (2010) reported between 96.5 and 193 g C m^{-2} yr^{-1} for the Exmouth Gulf tidal mats. The reference noted that the productivity was limited by the times of wetting as it was reasoned that the times that the mat was dry it was not productive, and in maintenance mode. It was suggested that the mat remained productive for seven days after wetting, but there are no objective measurements to support the hypothesis.

Zedler (1980) found that in a southern Californian re-wet desiccated tidal mat, the nett primary productivity was 185 g C m^{-2} yr^{-1}. This is comparable to the Lovelock et al. (2010) estimate of nett productivity as per conversion in the paragraph above.

The modelling of the distribution of the mat in the Eramurra study uses AHD and distance as a *de facto* measure of wetting, so it can be assumed that the mat where the Chl a is higher, then the flooding is more frequent and therefore more productive. The analysis of data suggests that mats with a Chl a greater than 300 mg.m^{-2} will have a productivity of approximately 240 g C m^{-2} yr^{-1} for substantial periods of time. It may be argued that this productivity rate is valid for the entire year. The other areas with lower chlorophyll content can similarly be classified but mindful that mats with a chlorophyll lower than 50 mg.m^{-2} will be primarily in a maintenance phase and spend most of the year dry and not active. The line of logic can be extended to form a view on the relative magnitude of nett primary productivity that each mat zone contributes to the environment.

5.1 Productivity literature summary

Chl a is proportional to productivity under similar circumstances, so if a benchmark can be determined then a range of Chl a can be extrapolated for their productivity. A range of benchmark values would make the extrapolation more accurate. A single benchmark remains a powerful tool for comparing relative productivities from the Chl a concentration. A mat with twice the Chl a concentration of another would be expected to have twice the potential productivity within reasonable margins.

Studies in nearby regions provided estimates of the productivity per unit Chl a in a laboratory situation. This published work did provide a maximum value for a wet mat under a range of light intensities. Various publications indicated that once the base level of light intensity is reached, the bacteria can operate at a stable level for a broad range of light intensity. The light in the region (Karratha) is within the maximum productivity range for all seasons.

The high temperature (up to 50ºC) in the mat is not limiting for the species *Microcoleus* sp. but undoubtably is an environmental impediment for other species.

Desiccation is a principal factor in function of the mat. As the mat dries, *Microcoleus* sp. uses various processes to slow down photosynthesis and, more importantly, rapidly reduce Chl a in the cell. This process is also temperature related making the species ideally suited for the tidal mat environment. The Chl a is reactivated in a very short time and is at maximum capacity after 24 hours of wetting.

As a result of this work, it is possible to say that the mat Chl a after wetting is a measure of maximum productivity for that site. The dry mat Chl a is the minimum productivity for that site as the cell is in maintenance mode only with zero nett productivity.

The mat is sensitive to disturbance and where the lower elevations close to the sea water usually have some depth of water, is disturbed by various littoral animals such as crabs and fish. The mat activity in the upper elevations is determined by the almost constant desiccation, and rarely is flooded by seawater. There is obviously an optimum height between disturbance and desiccation.

6 Estimate of Productivity Refinement

The productivity of the mat has been estimated using the same system as in *Benthic Mat Study-Productivity Estimate of Proposed Eramurra Project June 2023* and expanded to cover the LAU for the Project.

In the first instance the area of different Chl a bands were generated using Model Version 15 (Table 3).

Table 3 Area within broad chlorophyll a zones

Area (ha) of Algal Mat Version 15 within LAU (1-4)						
Classification	Chl a (mg.m-^{2})	LAU-1	LAU-2	LAU-3	LAU-4	Sub Total
Very active mat	301 +	61.28	37.37	24.47	35.54	159
Active mat	151-300	225.27	227.43	53.45	116.44	623
Limited activity far	51-150	88.64	97.54	134.10	64.14	384
Limited activity near	51-150	91.57	78.43	10.18	57.49	238
Low far	0-50	331.63	207.65	703.46	227.35	1,470
Low near	0-50	557.51	289.72	24.24	295.22	1,167
Total		1,355.90	938.14	949.89	796.16	4,040
Area (ha) of Algal Mat Version 15 within IDA						
Classification	Chl a (mg.m-^{2})	LAU-1	LAU-2	LAU-3	LAU-4	Sub Total
Very active mat	301 +	0.03	1.93	12.20	2.08	16.2
Active mat	151-300	0.06	13.50	21.72	11.80	47
Limited activity far	51-150	0.05	42.93	78.06	31.96	153
Limited activity near	51-150	0.11	7.12	4.05	3.34	14.6
Low far	0-50	0.04	140.05	508.24	124.57	773
Low near	0-50	0.87	22.78	0.00	6.54	30.2
Total		1.15	228.31	624.27	180.28	1,034

The flooding times used to estimate productivity in the field as opposed to maximum productivity per unit area are shown in Table 4.

Table 4 Flood times for Chl a bands

Chl a mg.m-2	Flood times (%)	Description
301 +	90%	Very active mat 301-400 mg/m^2
151-300	80%	Active mat 151-300 mg/m^2
51-150 far	60%	Limited activity far 51-150 mg/m^2
51-150 near	90%	Limited activity near 51-150 mg/m^2
0-50 far	25%	Low far 0-50 mg/m^2
0-50 near	100%	Low near 0-50 mg/m^2

The nett productivities have been calculated for the indicative disturbance area (IDA) of this revised pond layout in Table 5 and the relative percentages in Table 6.

Table 5 Nett Productivity (t C yr^{-1})

Total LAU						
Classification	Chl a (mg.m^{-2})	LAU-1	LAU-2	LAU-3	LAU-4	Sub Total
Very active mat	301 +	105.6	64.4	42.2	61.3	273
Active mat	151-300	172.1	173.8	40.8	89.0	476
Limited activity far	51-150	25.3	27.8	38.2	18.3	110
Limited activity near	51-150	28.0	24.0	3.1	17.6	73
Low far	0-50	28.2	17.7	59.8	19.3	125
Low near	0-50	189.6	98.5	8.2	100.4	397
Total		548.8	406.1	192.4	305.8	1,453
IDA within LAU						
Classification	Chl a (mg.m^{-2})	LAU-1	LAU-2	LAU-3	LAU-4	Sub Total
Very active mat	301 +	0.043	3.33	21.03	3.59	28
Active mat	151-300	0.042	10.32	16.59	9.01	36
Limited activity far	51-150	0.014	12.23	22.25	9.11	44
Limited activity near	51-150	0.033	2.18	1.24	1.02	4
Low far	0-50	0.004	11.90	43.20	10.59	66
Low near	0-50	0.296	7.75	0.00	2.22	10
Total		0.432	47.7	104	35.5	188

Table 6 Percentage of Algal mat within LAU

Total LAU					
Classification	Chl a (mg.m-^{2})	LAU-1	LAU-2	LAU-3	LAU-4
Very active mat	301 +	19.2%	15.9%	21.9%	20.0%
Active mat	151-300	31.4%	42.8%	21.2%	29.1%
Limited activity far	51-150	4.60%	6.8%	19.9%	6.0%
Limited activity near	51-150	5.11%	5.9%	1.6%	5.8%
Low far	0-50	5.14%	4.3%	31.1%	6.3%
Low near	0-50	34.54%	24.3%	4.3%	32.8%
Total		100%	100.0%	100.0%	100.0%
IDA within LAU					
Classification	Chl a (mg.m-^{2})	LAU-1	LAU-2	LAU-3	LAU-4
Very active mat	301 +	0.01%	0.8%	10.9%	1.2%
Active mat	151-300	0.01%	2.5%	8.6%	2.9%
Limited activity far	51-150	0.00%	3.0%	11.6%	3.0%
Limited activity near	51-150	0.01%	0.5%	0.6%	0.3%
Low far	0-50	0.00%	2.9%	22.5%	3.5%
Low near	0-50	0.05%	1.9%	0.0%	0.7%
Total		0.08%	11.7%	54.2%	11.6%

The area of mat productivity as modelled (v.15) within the LAU is shown in Figure 10 to Figure 14.

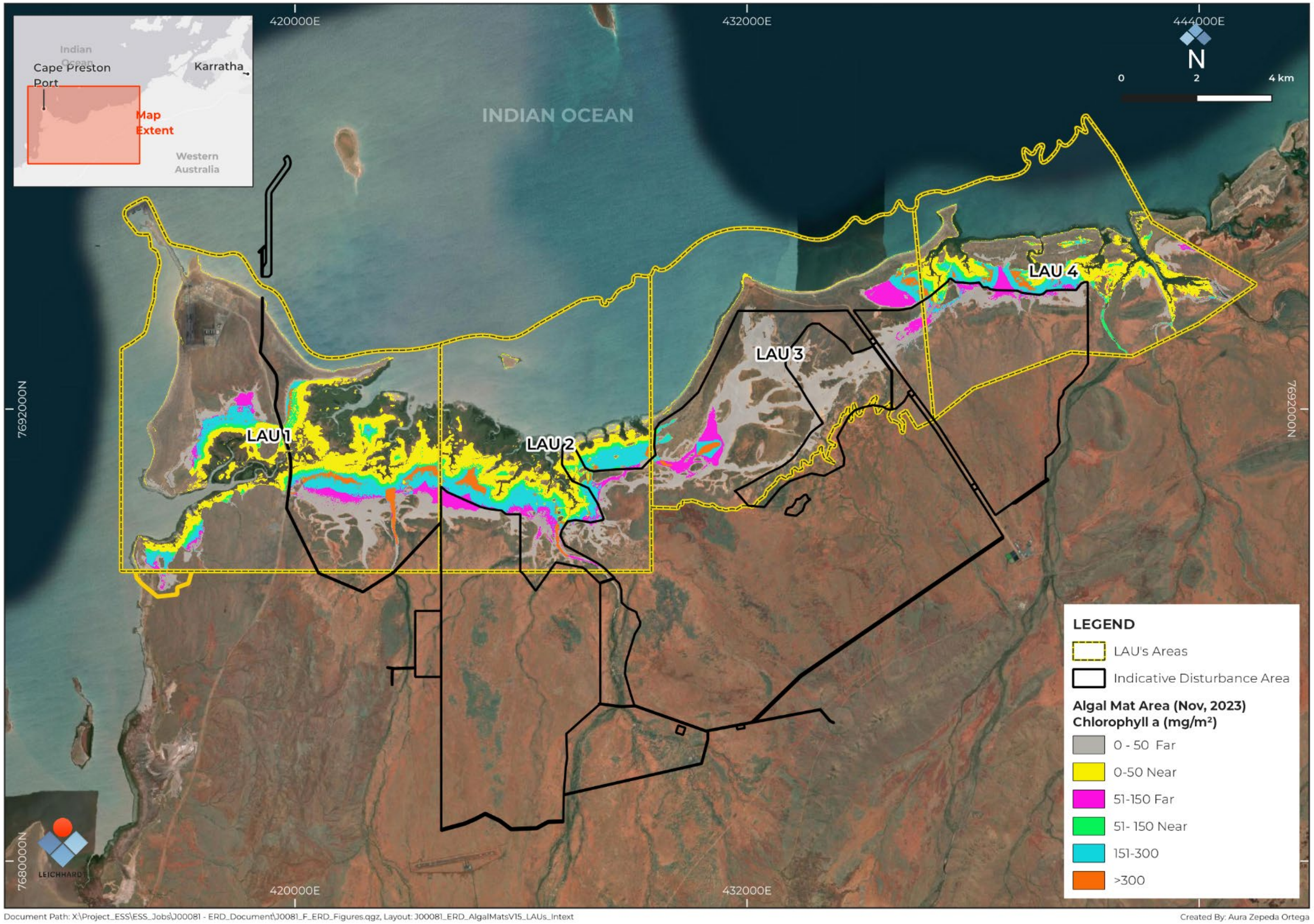

Figure 10 Extent of mat distribution within LAU

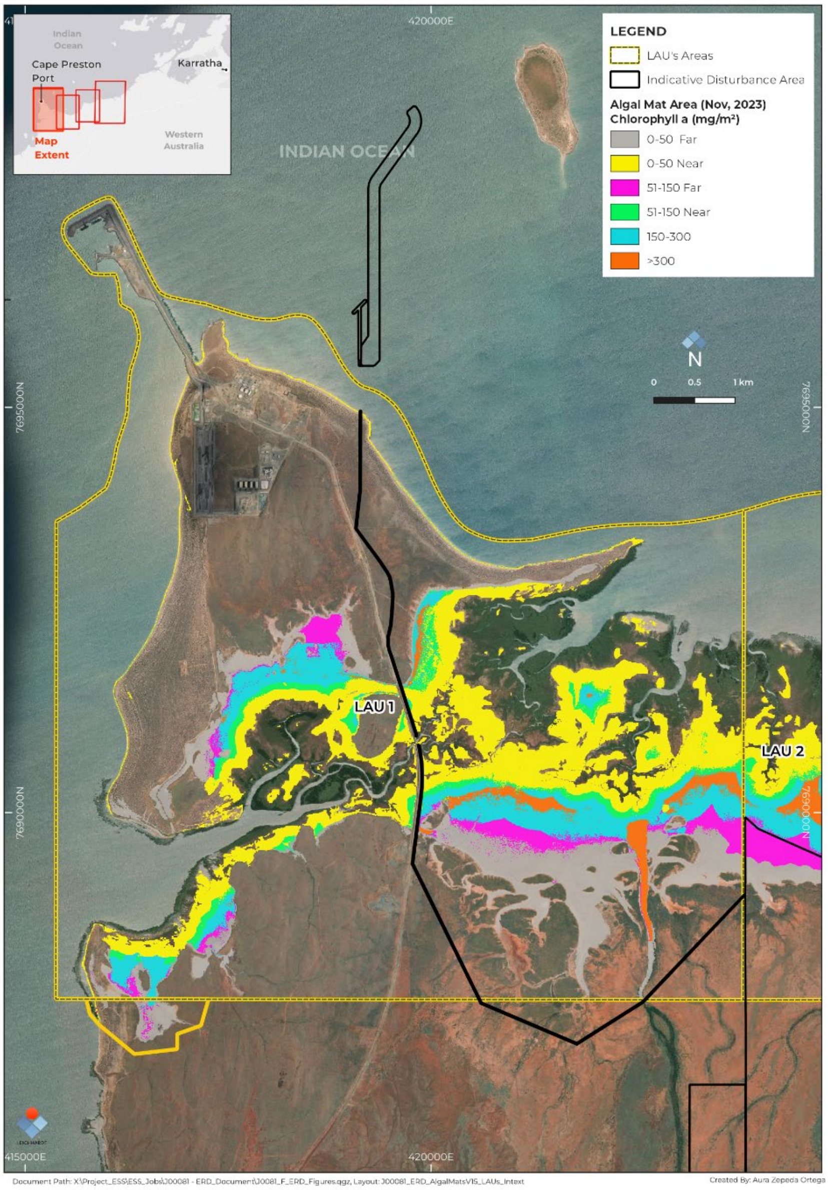

Figure 11 Map of Microbial Mat in the Eramurra study site with layout LAU 1

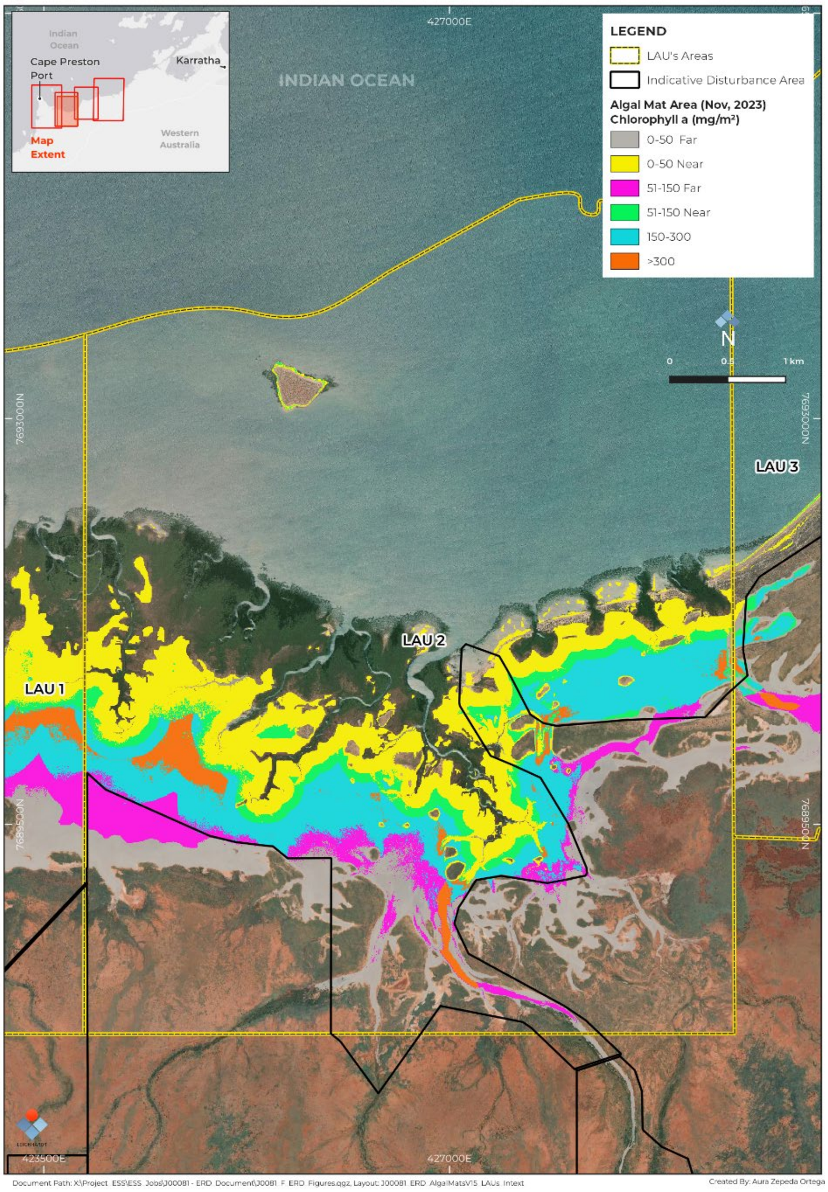

Figure 12 Map of Microbial Mat in the Eramurra study site LAU 2

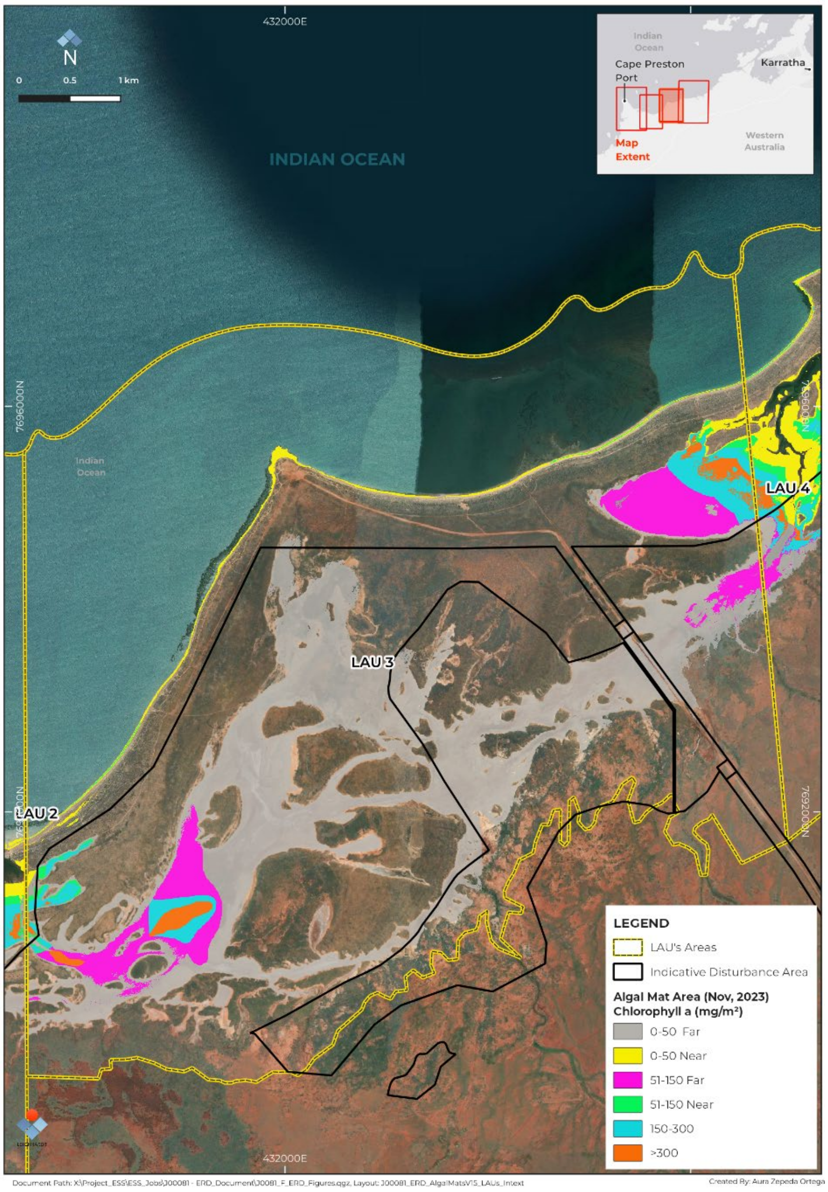

Figure 13 Map of Microbial Mat in the Eramurra study site LAU 3

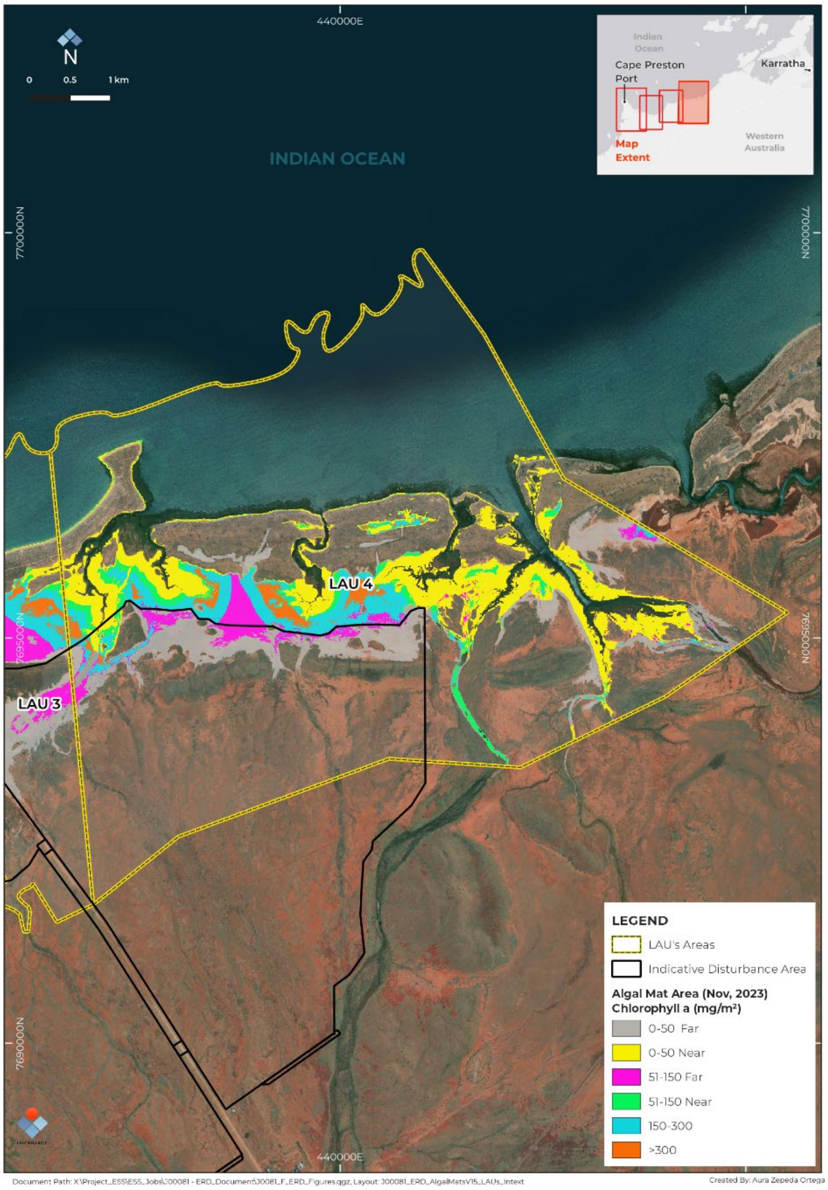

Figure 14 Map of Microbial Mat in the Eramurra study site LAU 4

7 Conclusion

The most important aspect of a mat is its productivity, and its potential to support the nutrient requirements of the near shore environment by exporting biomass. This report uses techniques developed in earlier reports by Actis Environmental Services to estimate and model productivity across the mud flats.

As a result, the following statistics have been estimated.

- The benthic mat productivity within the IDA is 12.9 percent or 188 t C yr^{-1} of that within the area of the LAU.
- The two more active bands of productivity (very active and active) contribute to 52% of the productivity within the LAU but only 34% of the IDA within the LAU.
- The four less active bands of productivity contribute to 48% of the productivity within the LAU but 66% of the IDA within the LAU.

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9 Glossary

Term	Definition
ºC	Degrees Celsius
AHD	Australian Height Datum
Chl a	Chlorophyll *a*
cm	Centimetre
Development area	The area in which project disturbance may occur
Disturbance area	The proposed project footprint
Eramurra	Eramurra Solar Salt Project
GIS	Geographic Information System
GPS	Global Positioning System
$g\ C\ m^{-2}\ yr^{-1}$	Gram of Carbon per metre square per year
h	Hour
ha	hectare
IDA	Indicative Disturbance Area
Leichhardt Salt	Leichhardt Salt Pty Ltd
LAU	Local Assessment Unit
LiDAR	Light Detection and Ranging remote sensing
m	Metres
mg	Milligram
mmol	Millimole
N	Nitrogen
O_2	Oxygen gas
s	Second
$t\ C\ yr^{-1}$	Tonne of Carbon per year
TOC	Total Organic Carbon
W	Watt
yr	Year

BENTHIC MAT STUDY
Productivity Estimate of Proposed Eramurra Project

ESSP-EN-14-TRPT-0024

June 2023

Eramurra Solar Salt Project

This report was prepared for:

Leichhardt

LEICHHARDT

Mark Coleman
actis Environmental Services
PO Box 176
Darlington
WA 6070
08 92521050

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Disclaimer

The information contained in this report is based on sources believed to be reliable and correct. While every care has been taken in the preparation of this report, *actis* Environmental Services gives no warranty that the said base sources are correct and accepts no responsibility for any resultant errors contained herein and any damage or loss, howsoever caused, suffered by any individual or corporation.

1 Executive Summary

Leichhardt Salt is proposing to build a solar salt field east of Cape Preston in the Pilbara region of Western Australia. The disturbance area of the proposed salt field covers 12,201 ha. Most of the area covers terrestrial landscapes but a significant proportion (ca 1,100 ha) also covers an area variously described as mudflat, tidal flats and algae mats. ‘Microbial mats’ is a more accurate description, but this community is commonly known as an algal mat.

The scope of this report is to estimate the productivity of the microbial mat in the proposed salt pond disturbance area and relate this to the relative impact on mat productivity. This process was used to minimise the impact of the pond disturbance on the mat productivity (Version 7.2.0).

Tidal microbial mats have a similar composition to biofilms and are made up primarily of species from the Kingdoms of Bacteria and Archaea, but with the occasional species from the Kingdom of Protista (algae, mostly diatoms). All these organisms can be collectively described as microbes. Algae are not the dominant group in biomass or function within the mats.

The mats are important as they serve as areas for wading birds to feed and rest (particularly at high tide and stormy weather), biomass storage, biodiversity conservation, nutrient transfer between the land and ocean, and they hydrologically stabilise what would otherwise be mobile alluvial material if it were not covered by a mat.

Various authors have found that mats are most active in a narrow range between low and high tide. The range is relatively narrow over 0.5 m of tidal range. The lower zone is defined by a disturbance zone from littoral animals and the upper by desiccation due to infrequent tidal flooding. This study has supported these findings.

In a previous report[1], Chl a concentration was found to be a repeatable measure of mat density. This method was used again in this study. Site variation was noticeable, but analysis of subsamples was consistent. Variation between samples was attributed to spatial and temporal variation in sampling, not the analytical technique. Previous investigations have shown that Chl a was the dominant photosynthesis pigment.

This report includes specific information on the Eramurra site. However, the mat composition did not vary from that reported elsewhere such as Exmouth, Dampier and Mardie. Filamentous cyanobacteria were the most dominant group in numbers and biomass. The common genera were *Oscillatoria*, *Coleofasciculus* and *Microcoleus*. Numerous other species were noted but in much lesser numbers. Algae in the form of diatoms were counted but only represented a minor component of the biomass. Undoubtably other bacteria are present as well but not found. Chlorophyta and other algae orders were poorly represented.

The nutrient flow from natural tidal benthic mats is also largely unknown but there are some estimates of Total Organic Carbon (TOC) that suggest that the mats are important contributors. Adame and Lovelock (2011), Adame et al. (2012) and others showed that mats can fix nitrogen but the flux is less known, with the mat being an absorber of biological nitrogen at times and others being an exporter. Methods using acetylene are not accurate measures of *in situ* flux as the method inactivates large parts of the mat biology (Fulweiler et al. (2015)).

The tidal range for the mat was well defined and, as described by other authors, in the range of 1.5 and 1.9 metres AHD. The mat biomass is also a function of distance with the mat being more active between 175 and 2,000 metres from the nearest tidal creek. There are obviously other factors affecting the

[1] *Benthic Mat Study- Eramurra Solar Salt Project* June 2022 Actis Environmental Services

distribution, not the least being physical disturbance, tidal restriction and ponding from surface runoff. Basically, the mat density and activity is a function of hydroperiod or period of wetting.

As reported elsewhere, the mat has an ability to desiccate and 'deactivate' the Chl a. The organisms go into a survival mode upon drying until the next suitable period. The chlorophyll as analysed for Chl a is rapidly activated after a very short time of being re-wet (fifteen minutes in some cases). This meant that the analysed Chl a was influenced by the time that elapsed before the last wetting. This short amount of time for activation precludes cell division or growth of biomass. To gain an accurate estimate of biomass or Chl a 'activity' all samples were wet for 24 hours before analysis.

A model of the likely mat biomass was constructed using the distance from the creeks and tidal height to enable the distribution of hydrated mat Chl a to be mapped across the flats. This was also discussed in the previous report[2]. The work determined that there were ranges of Chl a concentration across the mud flat. The bands are arbitrary/nominal, but some grouping is needed. The lower two bands, 0-50 and 51-150 $mg.m^{-2}$ were each further divided into two sub-bands representing the different flooding times.

The most important aspect of a mat is its productivity, and its potential to support the nutrient requirements of the near shore environment by exporting biomass and its incorporated nutrient load. Productivity can only be measured *in situ* and the procedure limits the number of sites and times that it can be measured. Chl a is a factor of productivity but it cannot be used as a direct measure. There are several other factors that will influence the productivity. These include available individual species conversion efficiencies, sunlight, nutrients and not being desiccated. It is reasoned that localised areas with similar environmental factors and biological composition would enable relative comparisons between potential productivity using only Chl a. These factors include the same incidental light across the mat and relative efficiencies of converting light energy to productivity in the relative monoculture.

The productivity estimate can be further refined by estimating time that the mat is wet from tidal inundation, which gives the period of maximum productivity, and the time desiccated with zero net productivity.

Whereas it is not proposed that the resulting productivity is accurate, as it does not consider all the temporal and spatial factors that influence productivity, it is proposed that it is a useful estimate of relative productivity between areas at the same location and time, plus a better than order of magnitude estimate of total productivity. That is, the relative environmental importance of each area to the near shore nutrient balance.

The resulting calculation using benchmark productivity values measured in other locations to generate productivity estimates for each chlorophyll band. These were incorporated into the spatial mat model to generate a productivity per unit area across the disturbance area and development area. The proportional numeric for each mat type was expressed as a percentage of the total development envelope (see Table 1). The part of the mat that is proposed to be taken out of the near shore ecosystem is shown for each mat band and in total.

[2] *Benthic Mat Study- Eramurra Solar Salt Project* June 2022 Actis Environmental Services

Table 1 Estimate of total Net Productivity

Chl a	Development Envelope	Scenario 7.2 Indicative Disturbance Area Mat V14	
$mg.m^{-2}$	Percent of productivity	Percent of productivity	Description
301-600	19%	3%	Very active mat 301-400 $mg.m^{-2}$
151-300	37%	4%	Active mat 151-300 $mg.m^{-2}$
51-150	10%	5%	Limited activity far 51-150 $mg.m^{-2}$
51-150	7%	1%	Limited activity near 51-150 $mg.m^{-2}$
0-50	11%	8%	Low far 0-50 $mg.m^{-2}$
0-50	16%	1%	Low near 0-50 $mg.m^{-2}$
Total %	**100%**	**23.4%**	

There is a further area (heritage) that contributes 1.8% of the productivity which, although outside of the pond laydown area, may be isolated from tidal flooding and therefore the mat productivity would be lost to the total contribution to the near shore environment. Therefore, the total productivity loss due to the construction of the salt field would be 25.2%.

2 Introduction

Leichhardt Salt is proposing to build a solar salt field east of Cape Preston in the Pilbara region of Western Australia (Figure 1).

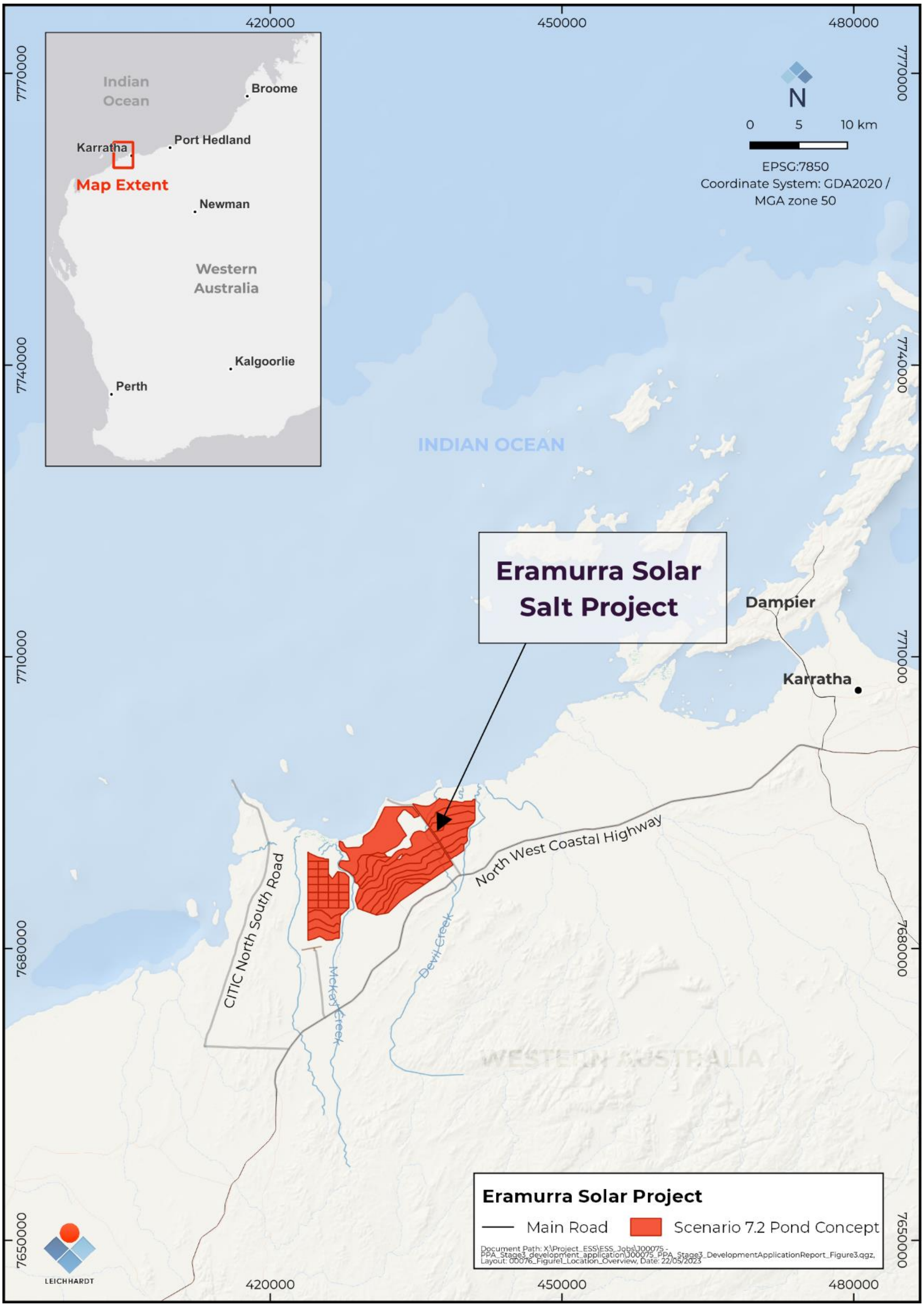

Figure 1 Location of proposed salt field

The development area of the salt field as proposed covers 17,800 ha of ponds. Most of the area covers terrestrial landscapes but a significant proportion (ca. 2,300 ha) also covers an area variously described as mudflat, tidal flats and algae mats. It is proposed to use the more accurate term benthic microbial mats.

Benthic microbial mats, as defined in this report, refers to those areas under tidal influence and do not extend to the more ubiquitous ‘biofilms’ that can be found on the surface of the land in most undisturbed landscapes, including desert sands. The landforms of the study are shown in Figure 2.

Microbial mats are typically found in intertidal areas protected from the sea by either dunes or mangroves. The flats are usually made from alluvial soils formed by sea or terrestrial water flow, where material has become entrapped between the sea fringe and the land. They are typically flat and dry for most times, with occasional flooding from the tide or freshwater flow. The microbial mats are normally a darker colour due to an organic layer and can reach high temperatures (50 ºC plus) in summertime.

Figure 2 Benthic tidal mats in project site - tidal flats behind mangroves on left, mixed in middle and secondary dunes to the right

The project site has tidal mats behind both secondary dunes and mangroves. Both types are flooded periodically with tides and runoff from creeks or rivers. The total area of ‘potential’ benthic microbial mat within the area of disturbance is approximately 1,000 ha.

Microbial mats have a similar composition to biofilms and are made up primarily of species from the Kingdoms of Bacteria and Archaea but with the occasional species from the Kingdom of Protista (algae, mostly diatoms). All these organisms can be collectively described as microbes. Algae are not the dominant group in biomass or function.

Microbial mats are areas of importance for several reasons. They serve as areas for wading birds to feed and rest (particularly at high tide and stormy weather), biomass storage, biodiversity conservation[3], nutrient transfer between the land and ocean and to stabilise what would be mobile alluvial material if it were not covered by a mat.

An important measure of the importance of an ecosystem to the environment is productivity. For the purposes of this report productivity is an estimate of total amount of organic material produced by living organisms in a particular area within a set period. The report only considers primary (photosynthesis) productivity of the mat in terms of units of carbon converted to organic (carbon) material.

[3] There is little discussion in the public forum on microbial biodiversity, but it obviously has a role if only implicit.

3 Description of a Benthic Mat (Literature)

3.1 Tidal benthic microbial mat location

Lovelock et al. (2010) found that the microbial mats at Exmouth occupied a 40 cm range in the intertidal range (Figure 3). They also found that the microbial mats were an important source of the total carbon budget in the Exmouth Gulf.

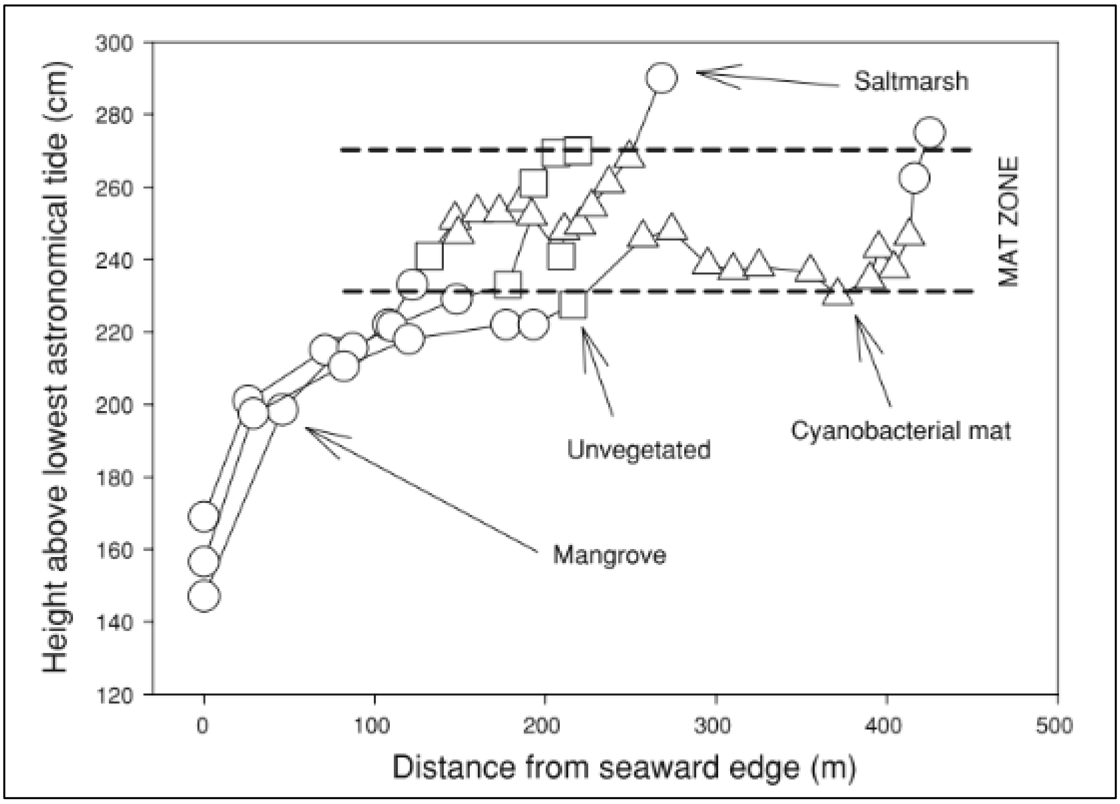

Figure 3 Transition of ecosystems across tidal range from Lovelock et al. (2010) p41 using three transects[4]

Biota Environmental Sciences Pty Ltd (2005) found that the microbial mat was found in a much smaller range between 1.366 and 1.44 m AHD in the Yannarie Salt Project for Straits Resources. Biota's range was approximately 10 cm whereas Lovelock et al. (2010) was more like 40 cm.

The conclusion is that there is a narrow tidal range that suits microbial mats. This suggests that the range is determined by the frequency and duration of flooding enabling biological activity in what may be an extreme environment for temperature, desiccation and salinity.

The mat is unlikely to be active when it is desiccated, and the surface temperature raised by the sun. Flooding by tidal water would both reduce the temperature and hydrate the microbes. The period of wetting (hydroperiod) would be a major factor and would be determined by the speed (fall/tidal height) and distance from the source of tidal flooding. More specifically the factors are:

- Range of tidal movement. It follows that a 4-metre tidal range will have a greater effect than a 2-metre tidal range in area covered and speed of covering the tidal flat.
- Measurements of tidal range will be impacted by geographical features, such as in a gulf as opposed to open ocean exposure.

[4] It is not clear from Lovelock *et al.* (2010) as to how the LAT was measured given the sampling site is at the end of an extensive gulf.

- Distance from the source of water to the mat will be a factor. Tidal creeks enable the rapid movement of seawater across the mat. It would be expected that mats at the upper tidal flood at a distance from a creek will be flooded for less time than a mat at the same height closer to a tidal creek. It takes time for flood water to move across a shallow flat when constricted by inflow from a narrow creek.
- Freshwater runoff will affect the wetted area, fanning out from creeks and maintaining saturation of the mat.
- Depressions or basins will have the effect of forming temporary perched ponds and the mats will be more active in these areas. These can be formed artificially near structures such as roads and banks.

A point that can be made is that the tidal range for mats is likely to change for different parts of the coast. The tidal range in the Exmouth Gulf will not be the same as at Eramurra. It is the flooding duration that is important.

3.2 Nutrient cycle

Generally, the microbial mats provide a backwater where material is transferred from overland flows (rare in arid zones) and tidal flux. The organisms in the mat accumulate biomass *in situ* and generate mass by fixing nitrogen and carbon dioxide. Of specific interest is the movement of nutrients from the microbial mats into the near shore environment. Carbon and phosphate are readily available from the air and river flows respectively. Although nitrogen makes up the bulk of air and is readily available as a gas (N_2), it is not readily available in a form useful for photosynthesising plants. Nitrogen needs to be 'fixed' into a more reactive form such as NH_4^+, NO_2^- or NO_3^-. Once fixed it can then be incorporated into organic material (TOC) such as proteins. A generic nitrogen cycle is shown in Figure 4.

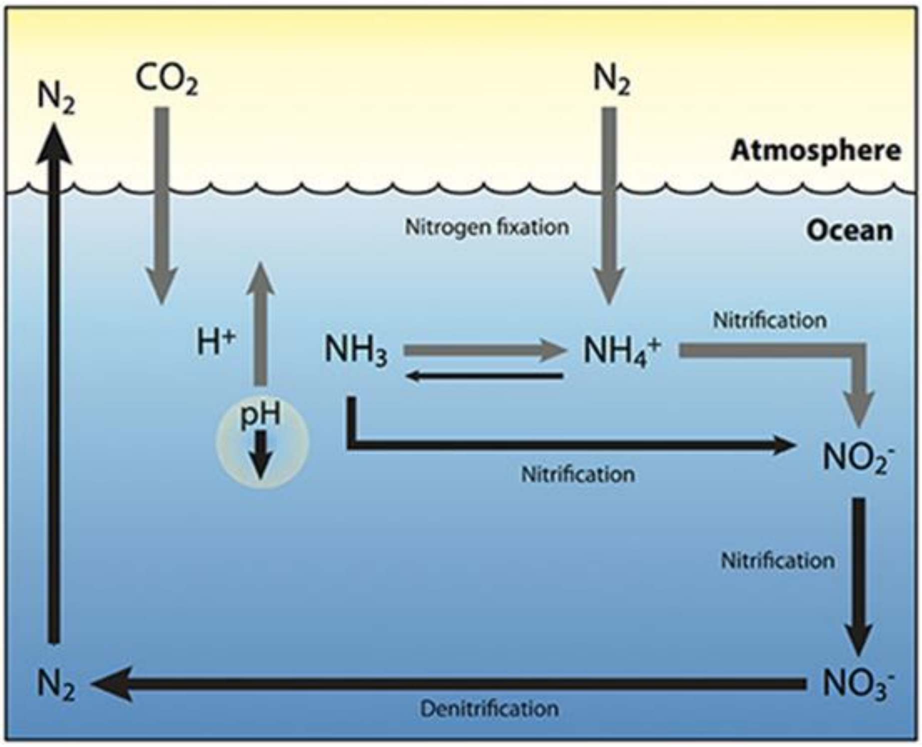

Figure 4 Stylized nitrogen cycle[5]

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[5]https://en.wikipedia.org/wiki/Nitrogen_cycle#:~:text=Ammonia%20and%20ammonium%20%2D%20two%20reduced,of%20their%20roots%20and%20shoots..

The 'fixing' is nearly always done by microbes that commonly inhabit anerobic environments. More recently it has been shown that unicellular microbes can fix nitrogen in apparent aerobic environments (Bandyopadhyay et al. (2011, Garlick et al. (1977)) but the opportunity and energy cycle restrictions suggest the more anaerobic layers would be more successful in fixing nitrogen.

Microbial mats are not the only marine environment that fixes nitrogen and others of note are deep oceans, sediments generally, but specifically seagrass meadows, and cyanobacteria plankton. Most marine sediments aerated by animals do not form a stable anerobic mud.

Paling (1986) speculated that loss of nutrients from the microbial mats to other environments may occur when desiccated mat portions are carried by wind and by leaching and showed loss of nitrate from mat sections exposed to freshwater, indicating that rainfall may be significant in contributing to nutrient loss.

Paling and McComb (1994) found that small scale trials (leaching) with excised mats exported nutrients. However, in the trials with large scale enclosures and mats *in situ*, the export of nutrients still occurred but the variation was greater than net export. The average for five tidal cycles was slightly less than 15 $mg.m^{-2}$. Most of the N was in the form of organic N. It Is not clear if it is water soluble organic nitrogen or insoluble organic nitrogen.

Joye and Paerl (1993) found that coastal intertidal mats had N_2 fixing rates of 3 mmol N $m^{-2}d^{-1}$ before runoff, using acetylene reduction to determine enzyme activity. After runoff occurred, they found that the N_2 fixing decreased and approached zero with denitrification increasing rapidly. Their model to explain the change was that organic carbon required for denitrification increased with runoff. There was no direct explanation of the decrease in nitrogen fixing other than there was a change in mat N cycling. The acetylene method for determining nitrogen fixing is a valuable tool but is known to have several artefacts (Fulweiler et al. (2015)).

Adame et al. (2012) provide data for *in situ* nitrogen exchange from a microbial mat in Exmouth Gulf. They focussed on exchange of soluble nitrogen species (not organic N) in tidal creeks and isolation chambers. The tidal experiment was from brine above the benthic microbial mat during a spring tide. They showed that the mats were net removers of soluble nitrogen. In addition to the soluble nitrogen species, the mats fixed nitrogen (acetylene) and the nitrogen fixing was a significate part of the nitrogen cycle. The N_2 fixing accounted for 1.7 nmol N $cm^{-2}h^{-1}$ and the mat absorbed 3.2 nmol N $cm^{-2}h^{-1}$.

The evidence from the literature is that benthic microbial mats actively accumulate nitrogen from soluble N in the flood water and fix N_2 within the mat. The mats do not generally release soluble N to the near shore environment. There is evidence that organic N is exported but the variation over time is significant. Preliminary work at the Eramurra site is consistent with these findings of low soluble nitrogen exports from the tidal flats.

3.2.1 Chlorophyll a

Cyanobacteria and Chlorophytes both use Chlorophyll a (Chl a) to convert light into energy. For the purposes of this work and the analysis used to determine Chl a, the analysis does not distinguish between the two photosynthesising groups. However, microscopic analysis of the mat did not find any Chlorophytes so for the purposes of the study all Chl a can be attributed to Cyanobacteria. No other primary chlorophyll peaks were identified in the scans.

Various trials were completed to determine the best method of measuring the Chl a in the mat and they are described in the report "Benthic Mat Study, Eramurra Solar Salt Project"[6]. Initial investigations

[6] *Benthic Mat Study, Eramurra Solar Salt Project* June 2022 Actis Environmental Services

showed that other photosynthesizing phyla were not present in enough numbers to be readily detected by acetone or ethanol extraction.

Chennu et al. (2015) found that the amount of Chl a in a desiccated mat from Exmouth WA rapidly increased after flooding (2-5 times increase after 15 minutes of flooding). Lovelock et al. (2010) found that the Chl a ranged between 224-416 $mg.m^{-2}$ but this was after inundation with artificial seawater or what might be referred to as a 'reactivated' mat.

The recovery of higher concentration of Chl a after wetting is recorded in the literature without cell growth. Abed et al. (2014) used isotopes of carbon (C13) to determine the rate of active chlorophyll after wetting desiccated mat. They found that the mat started recovering almost immediately, reaching maximum activity after two hours and that Chl a from synthesis did not appear in any concentration until two days after wetting. Raanan et al. (2016) results supported the above. It is clear from these results that the timing of the sampling relative to the wetting event is important when quantifying the mat activity.

Pinckney et al. (1995) found that the Chl a in North Carolina microbial mats varied between 100-400 $mg.m^{-2}$. The only site that had a Chl a less than 50 mg. m^{-2} was a sandy site. There was seasonal variation.

In summary, it may be expected that a mat may have a 'resting' Chl a concentration of 200 $mg.m^{-2}$ but will reach much higher values after wetting or becoming 'active'.

3.2.2 Carbohydrates and Total Organic Carbon (TOC)

Lovelock et al. (2010) found that the microbial mats contributed significantly to the TOC and carbohydrates (see Table 2). The mangroves are by far the most productive part of the Exmouth ecosystem in respect to TOC. The evidence presented in the paper was that the microbial mats contributed less than the mangroves, but more than the plankton in the Gulf itself. It is not clear from the article if the primary productivity was calculated on the 'reactivated' mat (see Chlorophyll a note above) in which case the mat is only active on high tide and or after flooding from a rain event. If this is the case, then the primary productivity in the mat for annual budgets would be substantially smaller as the mat would only be 'active' when flooded and not be 'active' for the entire 24 hours of the day.

Table 2 Carbon statistics for Exmouth Gulf as derived from Lovelock et al. (2010)

		Total fixed C (tonne. $year^{-1}$)		**Total fixed C (tonne. $year^{-1}.ha^{-1}$)**	
	Area ha	Lower estimate	Higher estimate	Lower per ha	Higher per ha
Gulf	2,600	154,325	400,750	59	154
Mangrove	161	383,305	1,432,360	2,381	8,897
Mat	100	10,000	954,805	100	9,548

4 Distribution of Benthic Mat at Eramurra

The benthic microbial mat at Eramurra has been surveyed by taking subsamples of the mat in structured transects and at relatively random sites of interest. Photos were taken of the mat environ and of the sample after a core had been extracted from the mat. An estimate of the thickness of the mat was made. Each sample was located with a GPS and the results entered into a GIS database.

Previous work had determined that pigment analysis, specifically Chl a, was a useful technique in determining the biomass. Most if not all the Chl a can be attributed to Cyanobacteria. Chl a is a useful indicator of total biomass and productivity. There are limitations to using chlorophylls as an indicator as described by Kruskopf and Flynn (2006) but there are limited alternative methods that can be readily applied.

4.1 Pigment analysis method

Samples were taken from the benthic mat using a corer with a 32 mm diameter. The samples, approximately 5 cm in depth, were then freeze dried, weighed and homogenised. The depth having been previously determined as not being critical if the profile included the mat (approx. 1 cm thick). A five gram subsample was analysed according to Baird et al. (2017). The total pigment per five-gram sample was used to calculate the total pigment in the sample and that value is divided by the unit area to be expressed as mg per square metre of benthic mat.

4.2 Chl a distribution across the intertidal mat

4.2.1 Wetting of sample prior to analysis

It is apparent from the literature (e.g. Chennu et al. (2015)) and field trials that the Chl a of a mat is dependent on recent wetting regime. Chennu et al. (2015) found that 15 minutes of flooding will rapidly reactivate Chl a in the mat, with some increase over the next twelve hours. This suggests that the timing of the analysis is important in the measuring of the Chl a in the mat.

The reactivation of the Chl a was tested by flooding the sample with deionised water for twenty-four hours after sampling, before drying and homogenising the sample in preparation of the analysis. Deionised water was used instead of artificial seawater because it was thought to approximate rainwater, and rain or runoff was one type of wetting that the mat would be exposed to in the natural environment. The residual salt in the sample would counter any osmotic shock, the logic being that a sample from a more saline situation would have more salt in the sample and those from a fresher environment would have less salt.

The results of wetting desiccated samples are shown below in Figure 5.

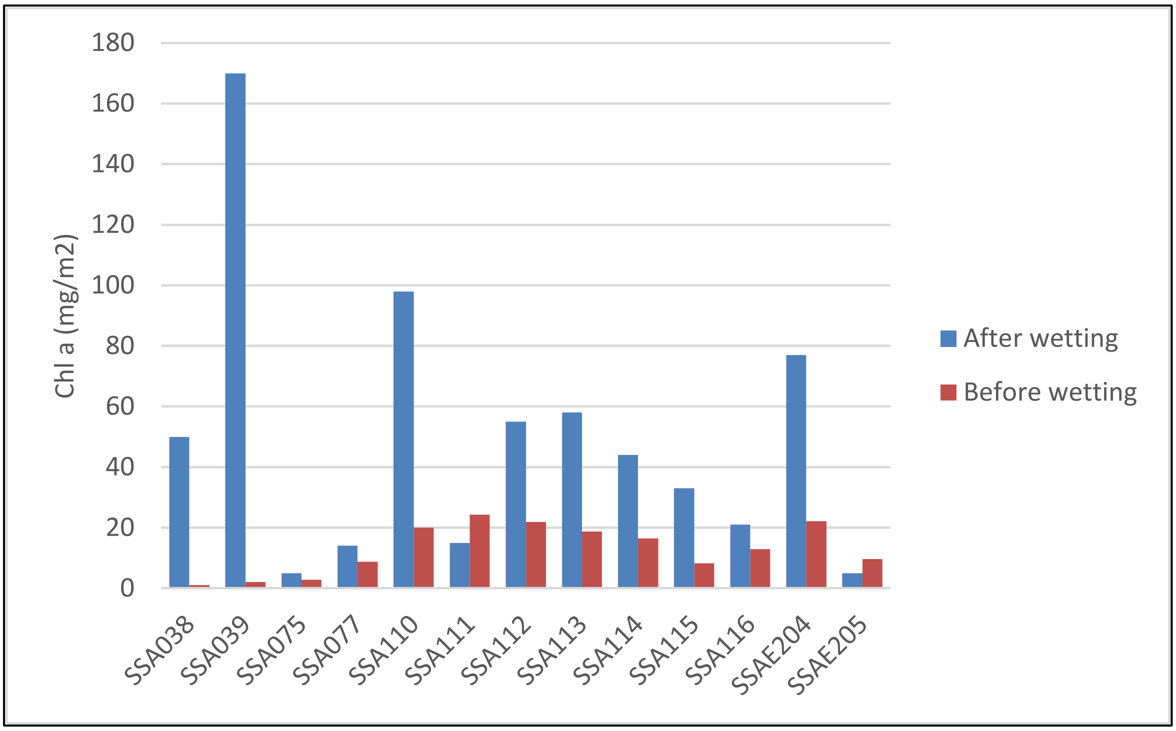

Figure 5 Chlorophyll a of mat before and after wetting

The before wetting set of samples was taken in August/September 2021. These samples were taken in a period where there had been very little rain. The second set of samples were taken in May/June 2022 just after an episodic rain event, plus the samples were wet with water for twenty-four hours prior to analysis. See Figure 6 for the difference in precipitation during this period.

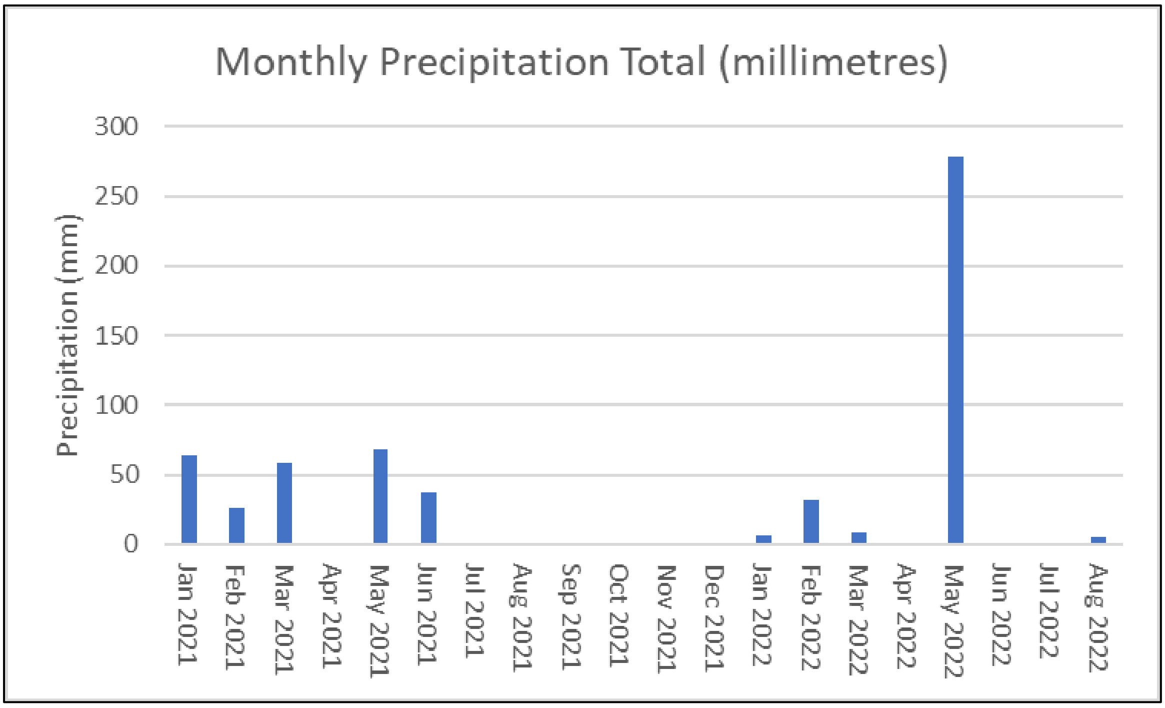

Figure 6 Recent precipitation in sampling period (Mardie BOM 5082)

As can be seen in Figure 7 most samples had a significant increase in Chl a after the samples were rehydrated for 24 hours. In most cases the dry Chl a content was about 50% of the wet Chl a content.

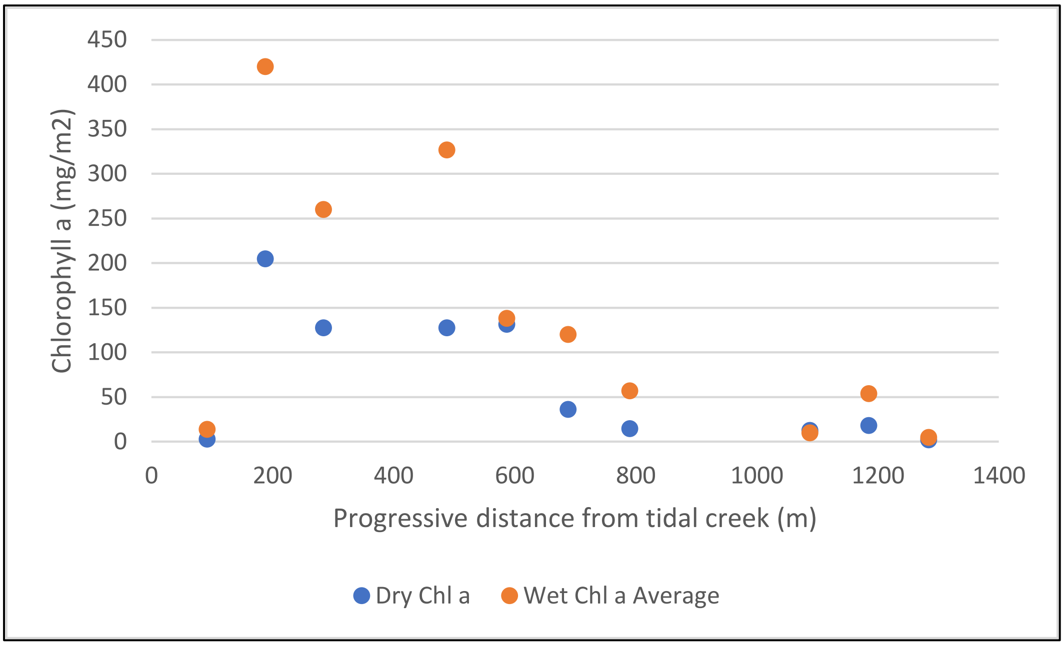

Figure 7 Comparison between wet and dry samples at same location in transect

Abed et al. (2014) described the mechanism whereby Chl a is synthesised rapidly from non-Chlorophyll components. They showed that photosynthetic activity increased concomitantly with the increase of Chl a reaching a maximum net rate of 92 μmol m^{-2} h^{-1} approximately two hours after wetting, and thus concluded that the recovery was due to the reassembly of pigments.

In terms of estimating the maximum photosynthesis and productivity, the dry Chl a content is not that useful. It does suggest that the dry Chl a estimate could approximate the maintenance/survival level of photosynthesis for the mat.

4.2.2 Sampling repeatability

The mat is not homogenous in any local area. Variability of results can be caused where the mat is folded on itself and disturbed (erosion, footprints and tracks). Samples taken four months apart at the same approximate location (± 10 metres to the accuracy of hand-held GPS) were similar in Chl a but not close in all cases (Figure 8).

Visual inspection showed that the benthic mat is patchy, particularly around the edges and in areas of high physical disturbance and this is supported by the analytical results.

Multiple samples were taken from several locations after rain and rehydrated in the laboratory before analysis.

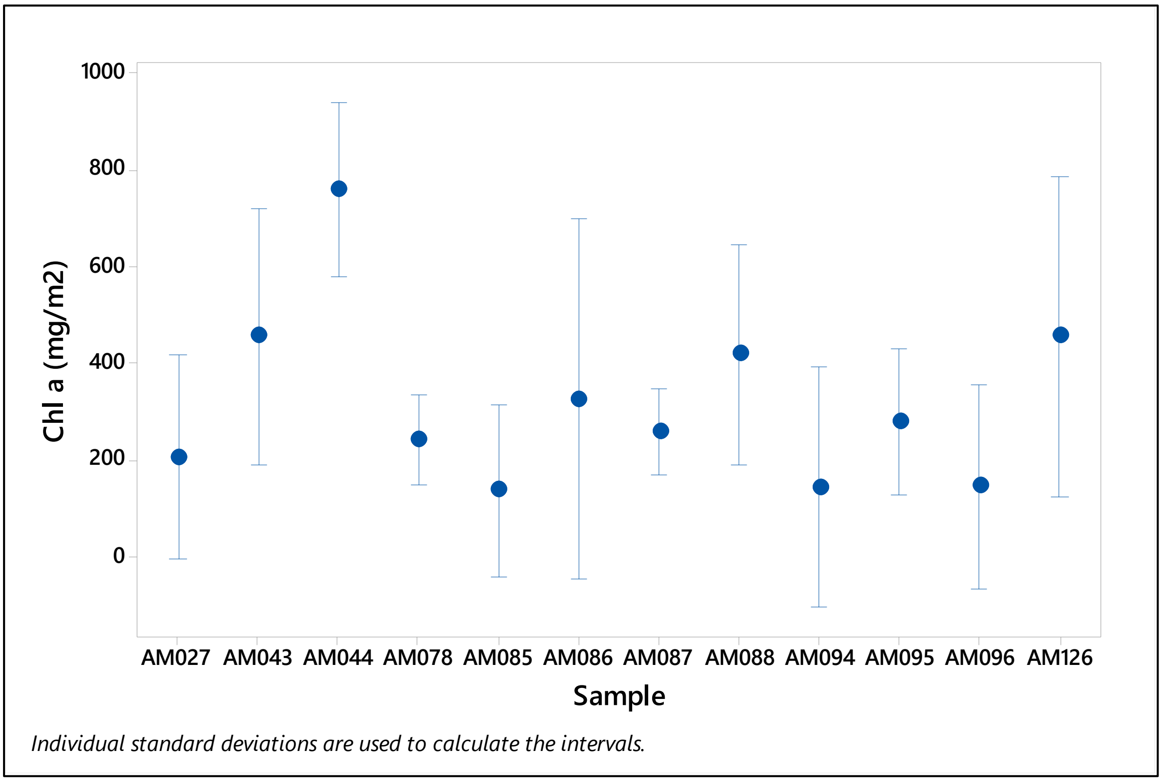

Figure 8 Variability of Chlorophyll a from various sites (3 repeats, 1 Standard Error)

A pooled standard deviation ANOVA test gave an F value of 11.58 and a P of 0.0 meaning that the sample means are different and therefore the method validly separates locations.

The conclusion is that even though the analysis is repeatable, the mat is very variable. However statistical analysis shows that the variability at a location does not negate the ability to map changes in mat Chl a across the landscape. In other words, the results support using the method to indicate the activity of the mat as it shows clear differences between sites.

4.3 Sample comparison between regions

Lovelock et al. (2010) found that the Chl a in the Exmouth region was on average 312 ± 22 $mg.m^{-2}$ with a range between 224-416 $mg.m^{-2}$. Paling (1986) found that the chlorophyll concentration varied between 'seasons and sites' near Karratha but generally the chlorophyll was 100 mg/m^2 or more. The findings are reproduced in part in Figure 9. Both regions are similar but separated by 250 to 50 km respectively.

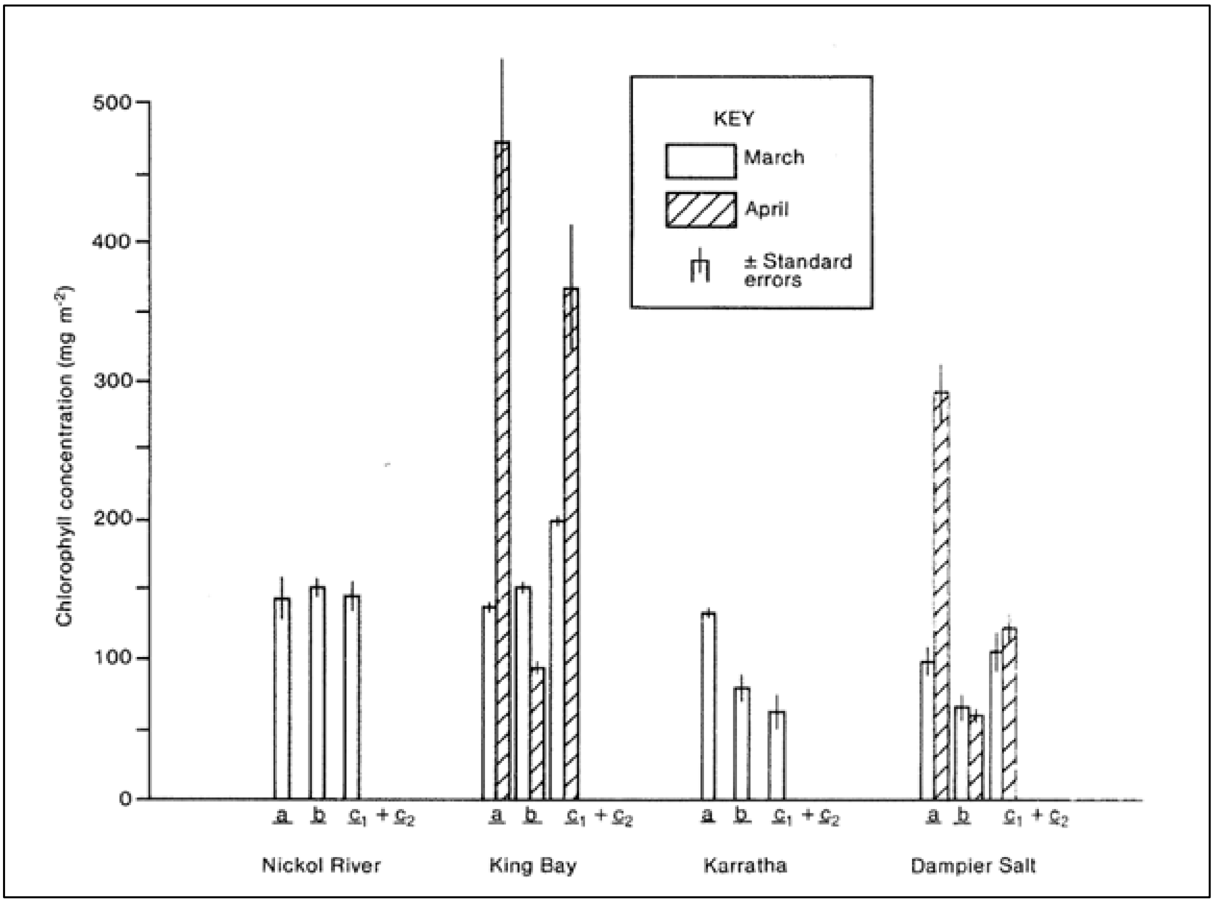

Figure 9 Survey results from Paling (1986) p55.

The base statistics for the various surveys using the wet analysis are shown in Table 3 and Figure 10. The samples analysed at Eramurra are on average lower than those found in other locations in the Pilbara. Refining the area defined as mat would increase the average but this brings into the discussion as to what is a mat and what is not. The analysis shows that some areas are high activity in Chl a but there are large tracts of land that have very little productivity potential.

Table 3 Statistics of samples at Eramurra

Variable	N	Mean	SE Mean	St Dev	Minimum	Median	Maximum
Chl a $mg.m^{-2}$	186	152.8	13.2	180.1	5	76	820

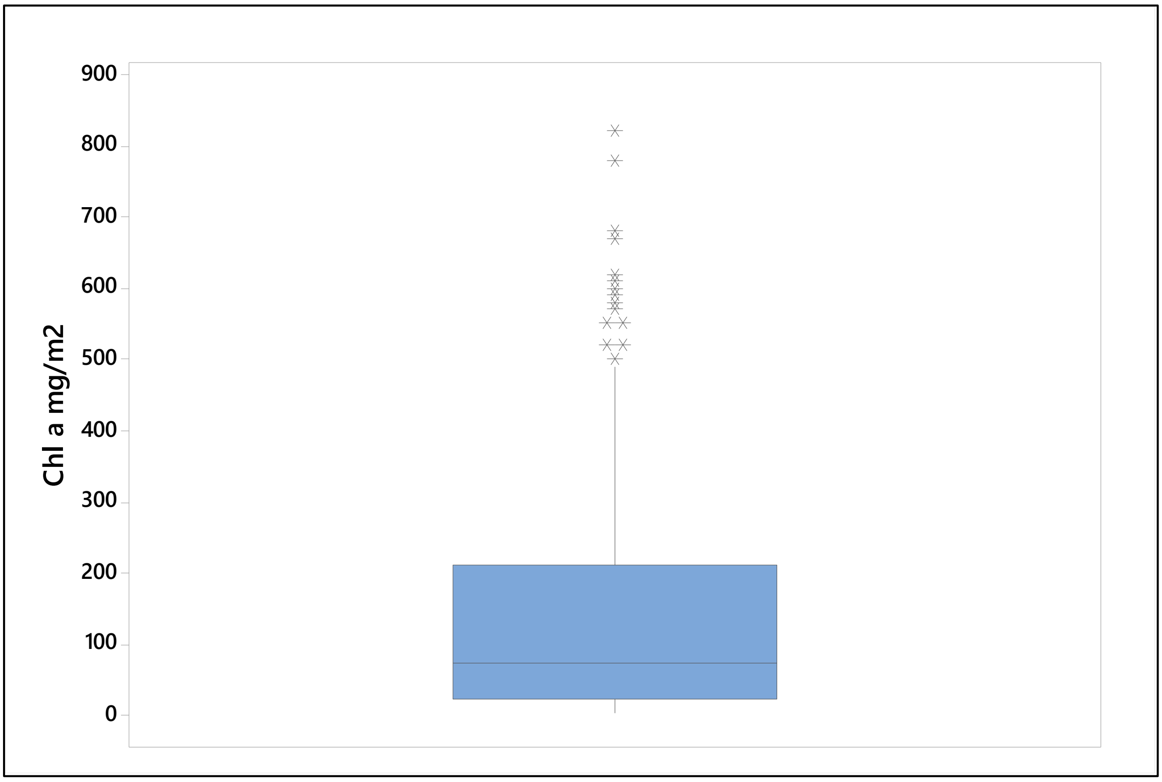

Figure 10 Graphical representation of Chlorophyll a variation in sample set

4.3.1 Distribution of the benthic microbial mat

The tidal movement of seawater is the main wetting event. Hydroperiod or time that a site is flooded is a major factor for the abundance of a mat. The two most obvious factors that may influence the location of the more active mats are location within the tidal range (AHD) and distance that the tidal water needs to transverse or *de facto* delay effect. This view has been supported in the previous report[7], the two key parameters for defining where a mat may be found was tidal height (AHD in the current study) and distance from tidal creeks.

The elevation (AHD) was determined by LiDAR survey. The distance was determined by measuring the line-of-sight distance to the nearest mangrove group. The mangrove or mangal fringe was chosen because mangrove species are largely limited by tidal hydroperiod. The landward fringe of the mangal (*Avicenna marina*) represents a hydroperiod that is consistent along the coast and serves as a useful baseline. An oceanographic model that generated terrestrial flood times would be more help but until then the mangrove fringe serves as a useful analogue. Such a model would be a complex undertaking and time consuming to get right.

Mats with a high Chl a were found over a very small range of 40 cm (Figure 11) and this is comparable to other work in the Pilbara region. The relationship between Chl a and AHD held, independent of wetting and desiccation, and only varied with magnitude of the amount of Chl a per area.

There were no significant microbial mats beyond 1,700 metres from the nearest tidal creek.

It is obvious from the data (see Figure 11and Figure 12) that there were other factors, as although distance and elevation described a large part of the variation, it did not account for all of the variation. It was determined that many of the high chlorophyll results were in shallow basins within the landscape,

[7] *Benthic Mat Study- Eramurra Solar Salt Project* June 2022 Actis Environmental Services

particularly what appeared to be scour areas from runoff events. If these areas were removed (‘selected’), then the data for the simple relationship of distance from mangroves and AHD was a better fit (Figure 13). These samples were captured at a later stage as manual corrections (basins) to the map.

The typical concentration of Chl a was also very low at a distance less than 175 m and greater than 2,000 metres from a tidal source. Anecdotally the low concentration of Chl a near the tidal creeks is due to velocity of tidal water and ploughing activity of animals (fish and invertebrates) close to the creeks (Figure 15).

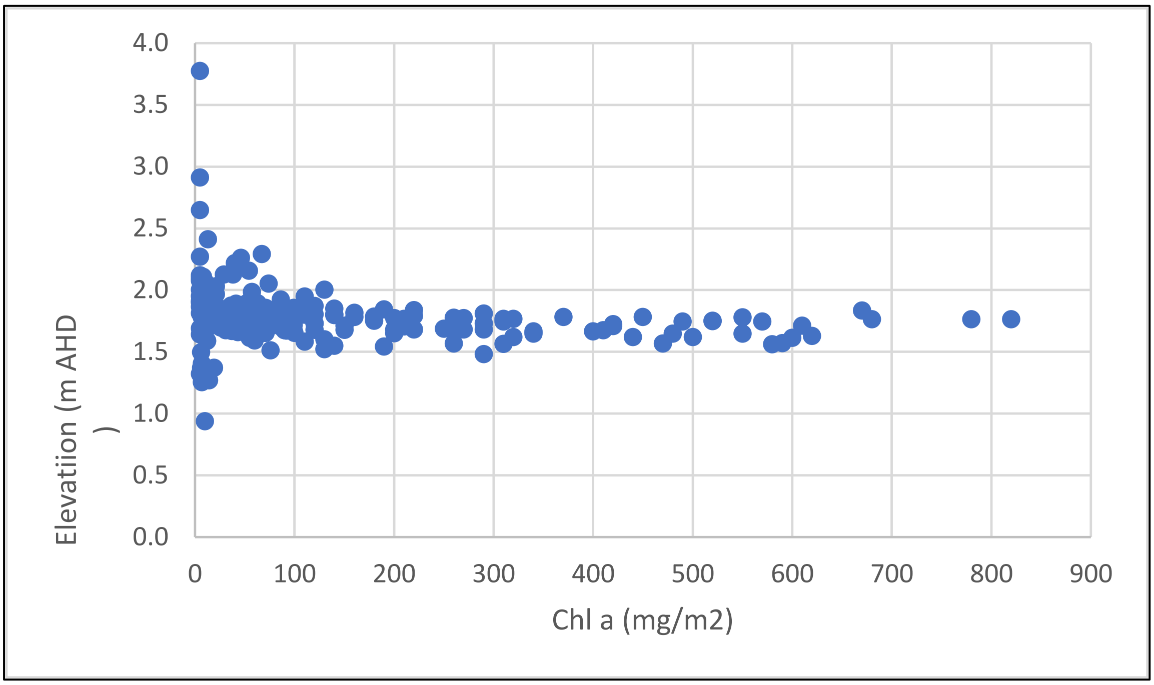

Figure 11 Elevation (AHD m) of sample versus chlorophyll content (all samples, wet mat)

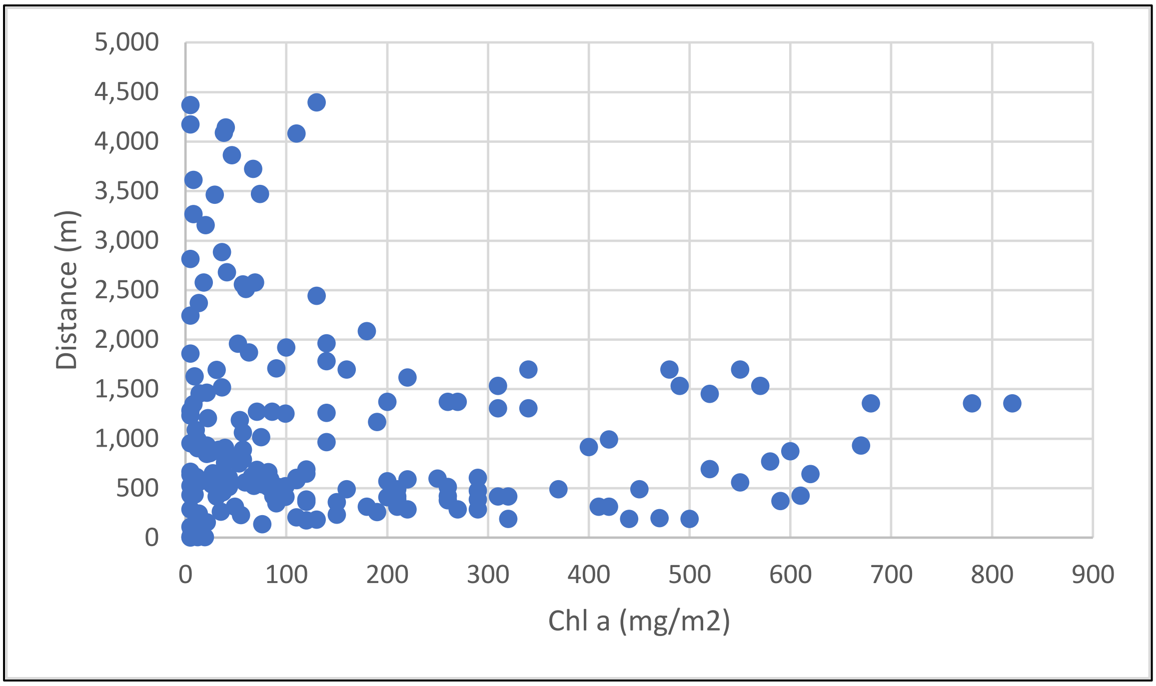

Figure 12 Chlorophyll a from wet mats as a function of distance from tidal source (all samples)

The other factors that influence the period of flooding are freshwater runoff and basins in the playa as determined by the GIS analysis of the LiDAR. Both have the effect of increasing the hydroperiod at any one location. Removing samples taken from sets that were part of a creek/river flow or in a localised basin reduced the set by 21% with 147 samples remaining. The accuracy of the Chl a distribution model across the playa increased radically with these samples removed (see Figure 13).

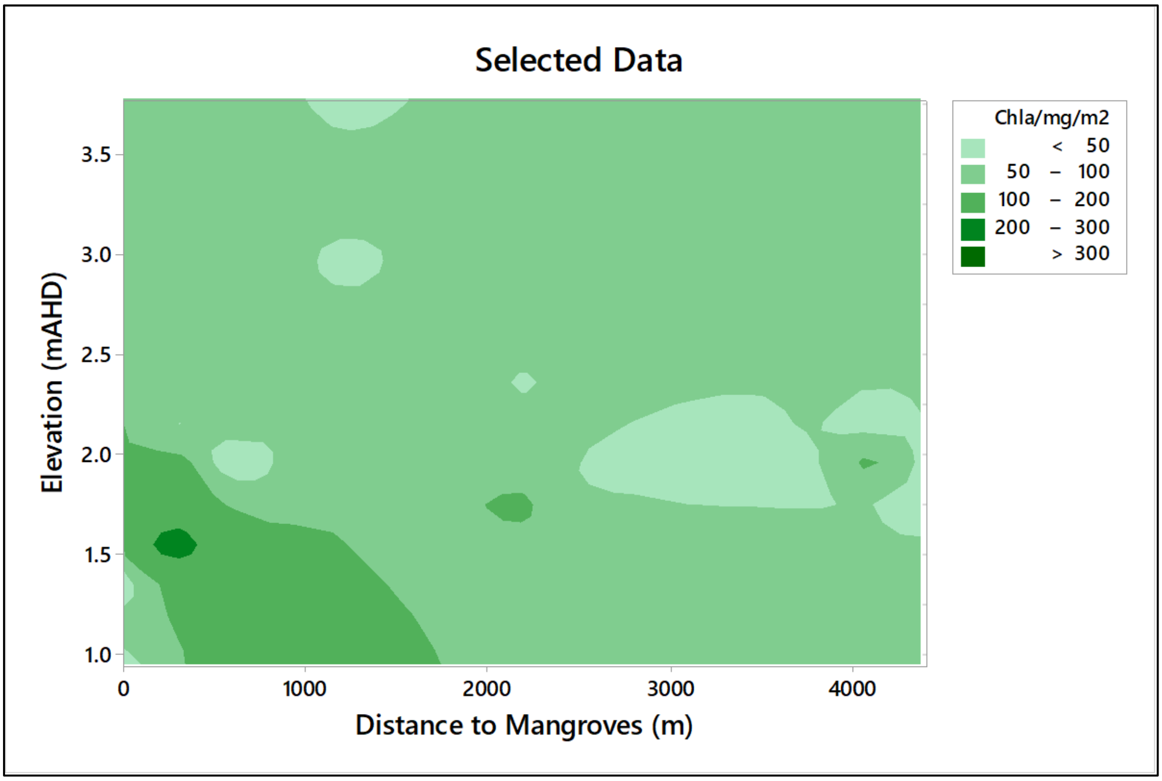

Figure 13 Selected samples (wet analysed) versus distance and height

4.3.2 Modelling the distribution of the mat

A GIS model was developed to map the distribution of the mat using hydroperiod as defined by elevation and distance from the mangal. The numerical model used the selected data which was minus the samples in basins and freshwater flows. The Chl a results from samples in basins were reintroduced manually to the map. To be clear all samples were used, just selected samples were used to map the base mat Chl a, and the map manually adjusted after to included areas of high Chl a. Therefore, all samples were accounted for in the final map (Figure 14).

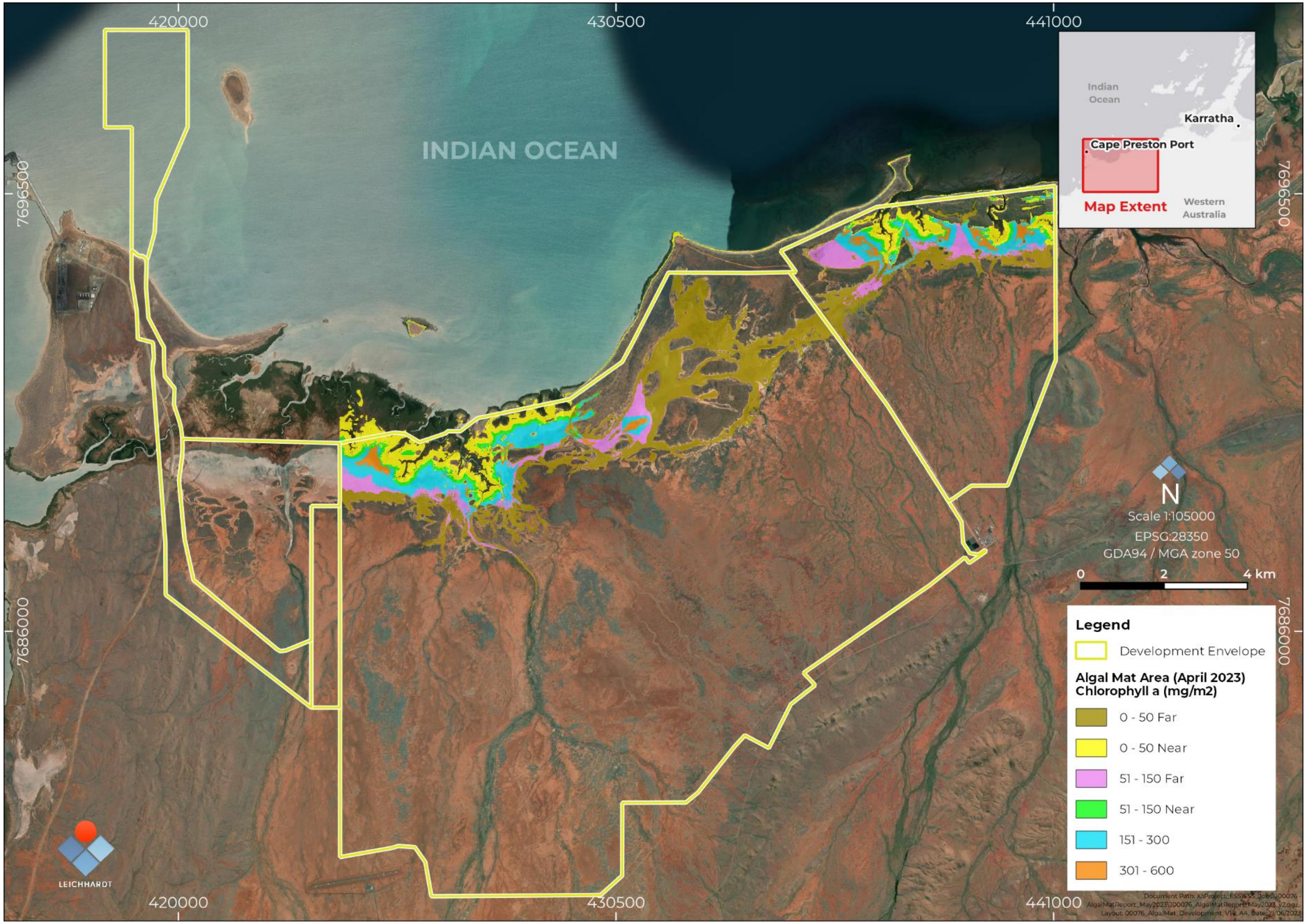

Figure 14 Extent of mat distribution within development envelope

The criteria for different mat types are provided in Table 4:

Table 4 Mat types based on chlorophyll a

Chl a (mg.m^{-2})	Lower	Higher
Very Active	301	300 plus
Active	151	300
Limited Activity	51	150
Low Activity	0	50

The criteria for the calculation to determine the area covered by each mat type (Table 4) for the numerical model were as follows in Table 5:

Table 5 Hydroperiod range for each wet sample type

Chl a band (mg.m^{-2})	0-50	50-150	151-300	301+
AHD (m)range				
Min	1	1.52	1.56	1.57
Max	2.5	1.875	1.82	1.675
Distance (m) range				
Min	0	120	200	300
Max	4500	1750	700	550

These criteria were used to predict ranges for the four main classifications of microbial mat found at the Eramurra site as defined by Chl a level. The two lower ranges were split into two subgroups depending on their position in the tidal flat (Figure 15 and Figure 16). It became obvious that although the samples were in the same Chl a band, the sample sites had radically different hydroperiods and flooding times. The mat close to a tidal influence was impacted by the activity of animals and speed of water flow.

Figure 15 Example of 'bio turbid' zone with low Chl a concentration close to the tidal creeks

Figure 16 Example of mat at a distance from tidal influence with low Chl a concentration

These criteria captured the results from the sample to a great extent. Difficulty in defining distance from the nearest tidal intake has reduced the accuracy of the work but this is being improved.

The type of mat was generated as a raster image and then converted to units of area (m^2) for each classification. These are shown in Table 6 and Figure 17.

Table 6 Land area for each benthic mat activity category (wet samples)

Chl a	**Development Envelope**	
$mg.m^{-2}$	Area (m^2)	Description
301-600	886,100	Very active mat 301-400 $mg.m^{-2}$
151-300	3,866,325	Active mat 151-300 $mg.m^{-2}$
51-150	2,922,475	Limited activity far 51-150 $mg.m^{-2}$
51-150	1,248,600	Limited activity near 51-150 $mg.m^{-2}$
0-50	10,531,100	Low far 0-50 $mg.m^{-2}$
0-50	3,729,875	Low near 0-50 $mg.m^{-2}$
Total	**23,188,200**	

5 Productivity of the mat

Productivity is normally determined by carbon isotope uptake or oxygen production in laboratory situations. Carbon isotope studies have limited use in the field, as does determining the exchange of gases such as oxygen between the mat and the ambient air (oxygen production being a direct measure of carbon fixing).

Productivity, defined as the conversion of inorganic carbon to organic carbon, varies with season, time of day and availability of nutrients. Productivity is divided into gross and net productivity.

Equation 1: Net Primary Productivity equals Gross Primary Productivity minus respiration by plants.

It was determined that a more suitable method was needed to characterise the extensive area under study. Chl a is a useful measurement of biomass and indicator of potential productivity. However, Chl a concentration is not a direct measure of productivity because, although photosynthesis is the mechanism whereby inorganic carbon is converted to organic carbon, there are many situations when photosynthesis is not effective.

Another factor which has been observed during the surveys is that the Chl a content depends on the wetting history. Microbial activity during a long dry spell will not be very productive and represents maintenance activity with no growth or net productivity.

Although there is no direct conversion from Chl a concentration to productivity, by assuming similar environmental conditions, it is possible to benchmark a Chl a concentration against a measured productivity. For instance, Exmouth Gulf mat studies are very close to the Eramurra site with similar species. Notwithstanding any questions as to the accuracy of the absolute value of an ecosystem's productivity, this method enables comparison between the relative productivity within similar ecosystems.

Chen et al. (2021) found that the Chl a could be used as a measure of productivity if the chlorophyll fluorescence–induced dynamic curve was known. Their work provides a theoretical relationship between productivity and Chl a. They described the following formulae:

Equation 2 $P = K \times r \times c \times (\text{Chl a}) \times DH$

> where P represents primary productivity (mg C m^{-3} d^{-1}), r represents the assimilation coefficient (mg biomass $h^{-1}mg^{-1}$ Chlorophyll a), c (Chlorophyll a) represents the content of Chlorophyll a (mg.m^{-2}), DH represents sunshine time (h d–1) and K represents the experience constant.

This formula relies on determining the assimilation coefficient which is essentially the rate by which an ecosystem can convert light to organic matter. The assimilation coefficient is known for several planktonic (Chlorophyte) systems. It is not known for saline mats which are composed of Cyanobacteria and, at times, overlaid by a substantial amount of inorganic sediment. Any estimate would be problematic, so it could not be used in this analysis. However, the formula does support the notion that the productivity in the same environment and ambient conditions is directly proportional to the Chl a concentration. If the ambient conditions and the other factors are the same, then the productivity of high Chl a mat and low Chl a mat becomes directly proportional to the Chl a concentration. Solving for simultaneous equation results in:

Equation 3 $P_1/P_2 = \text{Chlorophyll } a_1/\text{Chlorophyll } a_2$

It follows that:

Equation 4 $P_1 = P_2 \times \text{Chlorophyll } a_2/\text{Chlorophyll } a_1$

In other words, if all other conditions are the same and the productivity and Chl a is known for site, it should be possible to calculate the productivity of a second site if the Chl a is known.

Lovelock et al. (2010) found that the gross primary production on the flats around Exmouth Gulf peaked at approximately 18 mmol O_2 m^{-2} h^{-1}. The average gross primary production for permanently seawater flooded mats under laboratory conditions was Chl a 312 mg.m^{-2} and gross primary productivity 8.75 mmol O_2 m^{-2} h^{-1}. The dark cycle respiration was determined to be 3.35 mmol O_2 m^{-2} h^{-1} making the net productivity 5.4 mmol O_2 m^{-2} h^{-1}. This converts to 0.065 g C m^{-2} h^{-1} or 108 g C m^{-2} yr^{-1}. This forms a suitable benchmark for productivity for Eramurra.

However the mat is not always active because it is not wet, and therefore this rate represents the maximum productivity potential. Lovelock et al. (2010) reported between 96.5 and 193 g C m^{-2} yr^{-1} for the Exmouth Gulf tidal mats. The reference noted that the productivity was limited by the times of wetting as it was reasoned that the times that the mat was dry it was not productive, and in maintenance mode. It was suggested that the mat remained productive for seven days after wetting, but there are no objective measurements to support the hypothesis.

Zedler (1980) found that in a southern Californian re-wet desiccated tidal mat, the net primary productivity was 185 g C m^{-2} yr^{-1}. This is comparable to the Lovelock et al. (2010) estimate of net productivity as per conversion in the paragraph above.

As a comparison, the author has unpublished data from a cyanobacteria mat in a solar pond. Comparisons are questionable as the species are not the same and the mats in a salt field are covered by a stable saline brine 24 hours and all days. The salt fields had a much higher productivity at 890 g C m^{-2} yr^{-1}. The respiration rate was roughly half of the gross productivity rate. It would be expected that the productivity in a salt field mat would be more as they are consistently covered with a controlled salinity brine.

It can be concluded that Chl a is a useful indicator of productivity and can be used to compare different areas if the conditions are similar. The productivity can be quantified for survey purposes if a suitable benchmark is found, such as the Exmouth mats are for the Eramurra mats.

5.1 Seasonality

The light intensity at Karratha, a close location to the site, indicates that the available light or PAR will always be at or more than the range of maximum productivity of the mat. Lovelock et al. (2010) proposed that the maximum photosynthetic electron transport would be in the range of 500-1,000 μmol m^{-2} s^{-1}. Table 7 shows that the available PAR at Karratha is within or above this range for all months of the year. The higher PAR values inhibit the potential of the mat to use the energy but not significantly.

Cyanobacteria have evolved a suite of strategies to extend the optimum electron flow in the thylakoid membrane when the cells are exposed to high light, such as non-photochemical quenching and alternative electron flow pathways Mackey et al. (2013).

For this reason it is logical to assume the maximum rate that Lovelock et al. (2010) suggested at 18 mmol O_2 $m^{-2}h^{-1}$ for gross primary production. There is no reason to expect a large variation in seasonality based on light intensity.

Salinity is a factor, but it is not easily predicable as a seasonal factor. Salinity is a function of replenishment of water (rain, tide, run-off, initial start salinity, evaporation). The rainfall in the area is episodic and although the average rainfall statistics may suggest most of the rain is in the late summer or autumn months, it is not predictable with many years having little rainfall for the entire summer. Tidal flooding is lunar dominated but atypical tides are influenced by wind and storm surge. The Class A pan evaporation is seasonal, but the salinity of the brine is a function of historical rain/runoff, net evaporation (current rainfall and evaporation) and capillary wicking through the playa.

Table 7 Light Statistics[8] for Karratha (BOM site 5061)

	Mean daily solar exposure			**PAR**	
	(MJ/m^2)	(kWh/m^2)	kW/m^2	W sec/m^2	µmole photons m^{-2} s^{-1}
January	27.1	7.53	0.75	338.8	1,561
February	25.6	7.11	0.71	320.0	1,475
March	23.7	6.58	0.66	296.3	1,365
April	20.4	5.67	0.57	255.0	1,175
May	16.9	4.69	0.47	211.3	974
June	15.2	4.22	0.42	190.0	876
July	16.9	4.69	0.47	211.3	974
August	20.3	5.64	0.56	253.8	1,169
September	23.8	6.61	0.66	297.5	1,371
October	26.9	7.47	0.75	336.3	1,550
November	28.6	7.94	0.79	357.5	1,647
December	28.4	7.89	0.79	355.0	1,636
Annual	22.8	6.33	0.63	285.0	1,313

The optimum temperature may be more relevant to the ability of cyanobacteria to photosynthesise. Mackey et al. (2013) worked with *Synechococcus* species which are unicellular cyanobacteria and seawater, which is significantly different from the filamentous cyanobacteria (*Microcoleus* sp.). The paucity of unicellular cyanobacteria such as *Synechococcus* sp, which is ubiquitous in marine mats and plankton suggests that temperature may be a factor. The work by Mackey et al. (2013) showed that the photosynthesis by strains of *Synechococcus* sp. was inhibited at temperatures (27°C) much lower than would be expected on a hot day at Eramurra.

Lan et al. (2014) studying *Microcoleus vaginatus* found that the photosynthesis pathway was destroyed by high temperatures only, but with high temperatures (45°C) and desiccation, demonstrated rapid recovery of photosynthesis within twelve hours. The desiccation apparently initiated some protective mechanism that shields the Chl a to an undefined degree. Similar work by Ángeles (2020) supported the above using different intertidal species.

Microcoleus has mechanisms that allow them to 'hibernate' during dry periods. This environment with high temperatures and long periods of desiccation is not colonisable by many species and hence the relative monoculture. Only species that can resist desiccation and recover quickly when reflooded will be successful in this environment. The productivity is a function of wetting of the mat.

5.2 Productivity literature summary

It is clear that Chl a is not the same as productivity, as many different factors influence the pathway from converting light energy to organic matter (productivity). These include wetting, temperature and nutrients. A level of photosynthetic activity is used to maintain the cells, and it is only the surplus that is used to divide cells and export organic matter. The exportable productivity is the main interest for the study.

[8] Assuming ten hours of usable light per day and 45% of ambient light is available for photosynthesis (PAR).

Chl a is proportional to productivity under similar circumstances, so if a benchmark can be determined then a range of Chl a can be extrapolated for their productivity. A single benchmark is a powerful tool for comparing relative productivities from the Chl a concentration. A range of benchmark values would make the extrapolation more accurate. A mat with twice the Chl a concentration of another would be expected to have twice the potential productivity within reasonable margins.

Studies in nearby regions provided estimates of the productivity per unit Chl a in a laboratory situation. This published work did provide a maximum value for a wet mat under a range of light intensities. Various publications indicated that once the base level of light intensity is reached, the bacteria can operate at a stable level for a broad range of light intensity. The light in the region (Karratha) is within the maximum productivity range for all seasons.

The high temperature (up to 50°C) in the mat is not limiting for the species *Microcoleus* sp. but undoubtably is an environmental impediment for other species.

Desiccation is a principal factor in function of the mat. As the mat dries, *Microcoleus* sp. uses various processes to slow down photosynthesis and, more importantly, rapidly reduce Chl a in the cell. This process is also temperature related making the species ideally suited for the tidal mat environment. The Chl a is reactivated in a very short time and is at maximum capacity after 24 hours of wetting.

As a result of this work, it is possible to say that the mat Chl a after wetting is a measure of maximum productivity for that site. The dry mat Chl a is the minimum productivity for that site as the cell is in maintenance mode only with zero net productivity.

The mat is also sensitive to disturbance. The mats at lower elevations close to the mangroves are usually wet, but they are constantly disturbed by various littoral animals such as crabs and fish. The mat in the upper elevations have similar Chl a concentration to these close to the mangroves but are rarely wet and mostly undisturbed. There is obviously an optimum height between disturbance and desiccation.

5.3 Estimate of productivity at Eramurra

The main contribution to regional productivity is in the prime mat area between 200 and 550 metres, and in areas where the Chl a concentration is greater than 100 $mg.m^{-2}$. The low Chl a area close to the mangroves did not have marked variation between wet and dry samples.

As it has been mentioned before, an accurate estimate of productivity is not possible across the entire playa. However, a measure of relative productivity can be made with caveats. The literature has provided an estimate of productivity under laboratory conditions and some indication of field values.

Samples were taken from site and the Chl a content per unit area measured after 24 hours of wetting. The area for each Chl a type was modelled as a band and the area of the band estimated (GIS).

During the dormant dehydrated phase the cyanobacteria would be maintaining adequate metabolic activity to sustain life, and not contributing to the net productivity of the ecosystem. Lovelock et al. (2010) and the author have found the night cycle respiration was in the region of 50% (40 and 60% respectively) of the gross productivity. Therefore, it is proposed to convert the gross productivity to indicative net productivity by dividing gross productivity by two to give net productivity.

Lovelock et al. (2010) found that the mean gross primary productivity 8.75 mmol $O_2\ m^{-2}\ h^{-1}$ at a Chl a content of 312 $mg.m^{-2}$. The dark cycle respiration was determined to be 3.35 mmol $O_2\ m^{-2}\ h^{-1}$ making the net productivity 5.4 mmol $O_2\ m^{-2}\ h^{-1}$. The test was under conditions with suboptimum light intensity and optimum temperature. The much higher temperatures would reduce the efficiency of the Chl a.

For the above reasons, it was decided to approximate the field conditions in mats with 400 $mg.m^{-2}$ as having a gross productivity of 8.75 mmol O_2 m^{-2} h^{-1} and the net productivity being 50% of the gross productivity. Given that Chl a and productivity are directly proportional under the same conditions as per Equation 4 $P_1 = P_2$ x Chlorophyll a_2/Chlorophyll a_1 it is possible to generate relative productivities for all mat groups with the same Chl a.

Using the above relationships and assuming 10 hours of useful sunlight per day and 365 days in the year, a coarse estimate of the net productivity per year can be generated. It is emphasised the estimate should only be used as a relative tool for the local area. The main point is that, notwithstanding all the caveats, the relative contribution of the mat Chl a band remains the same. Table 8 approximates the net and gross productivity possible for the different areas of the mat if it was wet or rehydrated for the entire time.

Table 8 Estimate of maximum productivity based on Chlorophyll a

Chlorophyll a Range			**Maximum Productivity**	
Lower ($mg.m^{-2}$)	Higher ($mg.m^{-2}$)	Midrange ($mg.m^{-2}$)	Gross Productivity (g C m^{-2} yr^{-1})	Net Productivity (g C m^{-2} yr^{-1})
301	600	400	383	192
151	300	225	191	95
51	150	100	95	48
0	50	50[9]	68	34

The next consideration is that not all areas would be flooded all the time and for a large period, the mat would be merely maintaining respiration and have no net productivity. A measure of flooding time is needed to estimate the contribution of areas to the ecosystem productivity.

It should be emphasised that the estimates of wetting time are best guess based on field experience. The main reason for providing the flooding times is to demonstrate that the areas closer to the sea will have the higher productivity. The proportion of the total time spent wet is dependent on tides, storms surges and rainfall frequency. It is expected that the mat will remain wet for a time after an event. Lovelock et al. (2010) estimated seven days post a flood event.

The tide floods from the seaward side, so the area closer to the mangroves will have a higher productivity because it has a longer period of being wet and active. The flooding time will get progressively less the further away from the mangal fringe (Table 9).

Table 9 Tidal flooding time

Chl a $mg.m^{-2}$	**Flood**	**Description**
0-50	100%	Low near 0-50 $mg.m^{-2}$
301-600	90%	Very active mat 301-400 $mg.m^{-2}$
51-150	90%	Limited activity near 51-150 $mg.m^{-2}$
151-300	80%	Active mat 151-300 $mg.m^{-2}$
51-150	60%	Limited activity far 51-150 $mg.m^{-2}$
0-50	25%	Low far 0-50 $mg.m^{-2}$

[9] 50 $mg.m^{-2}$ is obviously not midrange but a conservative estimate of potential production. The area of low Chl a may have a higher productivity but is regularly harvested by grazers. For this reason, the area of low Chl a has exaggerated productivity.

The time of flooding is based on the mat being wet by tidal inundation on a weekly basis. It is known by experience that the mangal (*Avicenna marina*) fringe is approximately the upper elevation for the neap tide highs. On this basis the area of low Chl a close to the mangroves had 100% cover. The high Chl a areas closest to the mangroves would be wet most of the tidal cycle but are likely to be dry for a short period of neap tides. The flooding time would get progressively less for the parts of the playa further from the mangroves until the low Chl a area along terrestrial border. These areas were reasoned to be only covered by tidal inundation on the spring tides and in some cases only the king tides.

6 Productivity Estimate for Eramurra

The productivity estimate was applied to the areas to be disturbed by the construction of a salt field. This work was used to modify the layout of the ponds to minimise the potential impact on the productivity of the mat ecosystem. The process has several steps.

The presence of basins within the mat topography has been recognised as being important and was included in the analysis. The areas with increased productivity as per sampling and LiDAR determined basins (sinks) were used to increase the productivity as appropriate. These modifications were completed manually by comparing basins with sampling results and areas of high productivity not predicted by sampling, but represented basins were marked at the higher productivity. In other words, there was a degree of manual refinement in the model to represent the sampling results more accurately. The end result was a raster map of the area with estimated mat Chl a based on extensive sampling and modelled extrapolations, taking into account exceptions to the model where they were recognised.

Additionally, it was recognised that the flooding time of all categories and therefore maximum productivity should be adjusted to reflect different flooding periods and therefore net productivity. Calculations showed that the two highest bands of Chl a mat were only marginally changed by a more targeted flooding time and therefore only the two lower bands 0-50 and 51-150 $mg.m^2$ were split into far and near zones with near being closer to the mangal and far being much more terrestrial (Table 10).

The layout of the ponds was adjusted to minimise the impact of the ponds on the mat productivity. The new pond layout has the working notation of 7.2.0 and using the mat model V14. The maximum and net productivities have been determined for the indicative disturbance area (IDA) of this revised pond layout (Table 10 to
Table 13).

Table 10 Area within broad chlorophyll a zones

Chl a	**Development Envelope**	**Scenario 7.2 Indicative Disturbance Area Mat V14**	
$mg.m^{-2}$	Area (m^2)	Area (m^2)	Description
301-600	886,100	161,100	Very active mat 301-400 $mg.m^{-2}$
151-300	3,866,325	470,200	Active mat 151-300 $mg.m^{-2}$
51-150	2,922,475	1,517,000	Limited activity far 51-150 $mg.m^{-2}$
51-150	1,248,600	146,800	Limited activity near 51-150 $mg.m^{-2}$
0-50	10,531,100	7,675,259	Low far 0-50 $mg.m^{-2}$
0-50	3,729,875	308,450	Low near 0-50 $mg.m^{-2}$
Total	**23,188,200**	**10,289,450**	

Table 11 Maximum productivity contribution

Chl a	Development Envelope	Scenario 7.2 IDA	
$mg.m^{-2}$	Net Productivity ($t\ C\ yr^{-1}$)	Net Productivity ($t\ C\ yr^{-1}$)	Description
301-600	170	31	Very active mat 301-400 $mg.m^{-2}$
151-300	369	45	Active mat 151-300 $mg.m^{-2}$
51-150	139	72	Limited activity far 51-150 $mg.m^{-2}$
51-150	59	5	Limited activity near 51-150 $mg.m^{-2}$
0-50	358	261	Low far 0-50 $mg.m^{-2}$
0-50	127	10	Low near 0-50 $mg.m^{-2}$
Total	**1,222**	**424**	

Table 12 Net Productivity adjusted for flooding time

Chl a	Development Envelope	Scenario 7.2 IDA		
$mg.m^{-2}$	Net Productivity ($t\ C\ yr^{-1}$)		Flood	Description
301-600	153	28	90%	Very active mat 301-400 $mg.m^{-2}$
151-300	295	36	80%	Active mat 151-300 $mg.m^{-2}$
51-150	83	43	60%	Limited activity far 51-150 $mg.m^{-2}$
51-150	53	4	90%	Limited activity near 51-150 $mg.m^{-2}$
0-50	90	65	25%	Low far 0-50 $mg.m^{-2}$
0-50	127	10	100%	Low near 0-50 $mg.m^{-2}$
Total	**801**	**187**		

Table 13 Estimate of total Net Productivity

Chl a	Development Envelope	Scenario 7.2 Mat V14 IDA	
$mg.m^{-2}$	Percent of productivity	Percent of productivity	Description
301-600	19%	3%	Very active mat 301-400 $mg.m^{-2}$
151-300	37%	4%	Active mat 151-300 $mg.m^{-2}$
51-150	10%	5%	Limited activity far 51-150 $mg.m^{-2}$
51-150	7%	1%	Limited activity near 51-150 $mg.m^{-2}$
0-50	11%	8%	Low far 0-50 $mg.m^{-2}$
0-50	16%	1%	Low near 0-50 $mg.m^{-2}$
Total %	**100%**	**23.4%**	

The disturbance area for salt field layout 7.2 is 12,201 ha, of which 1,029 ha is benthic mat as defined by version 14 of the map (Figure 17). The detail of the site is shown for the west (Figure 18), middle (Figure 19) and eastern section (Figure 20) of the site for layout version 7.2.0.

There is a further area (heritage) that currently contributes 1.8% of the productivity that will be isolated from tidal flooding and therefore the mat productivity would not contribute to the near shore environment. This would make the total loss of productivity under the proposed layout of the ponds and infrastructure as 25.2%

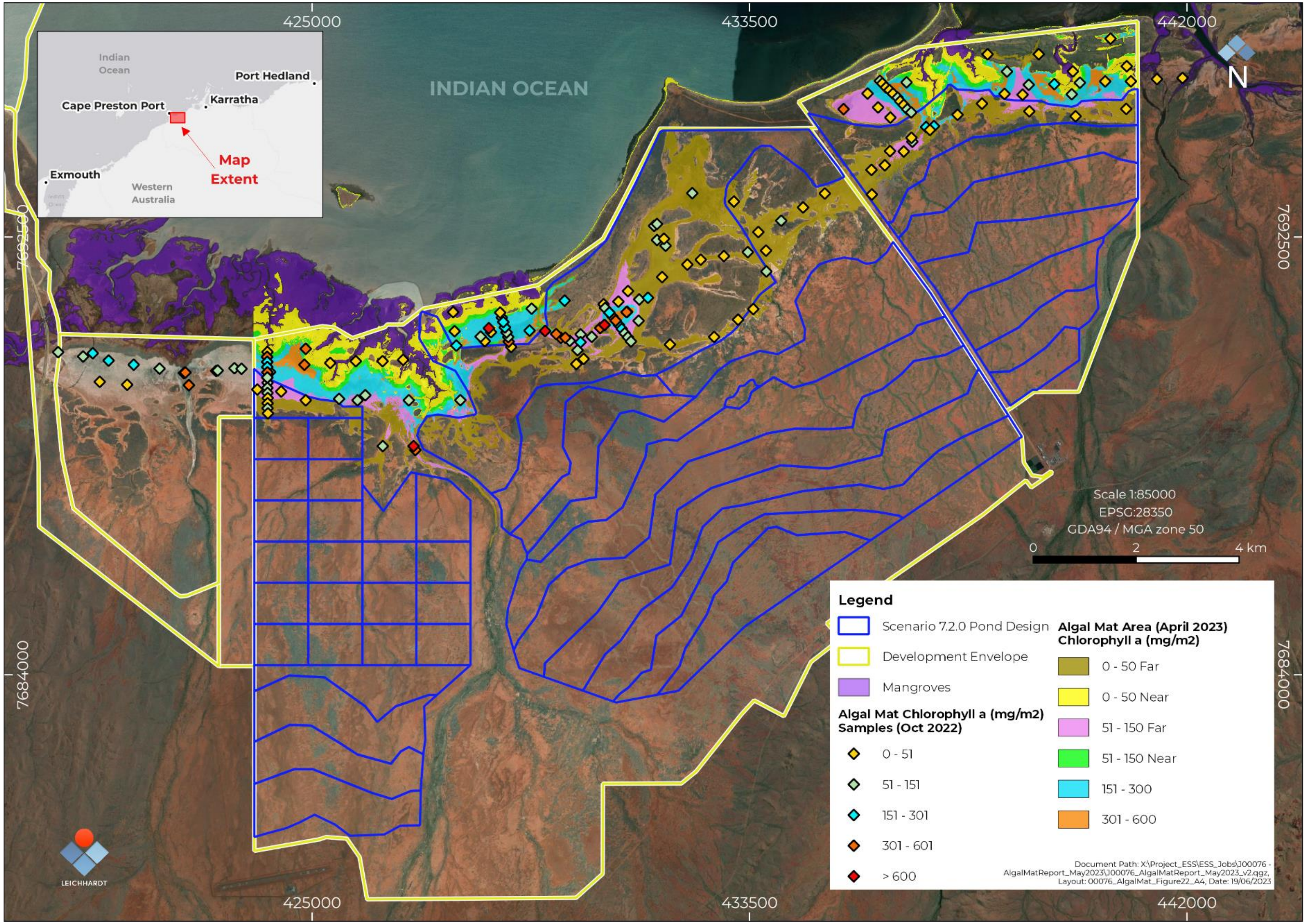

Figure 17 Map of Microbial Mat in the Eramurra study site with layout 7.2.0 (overview)

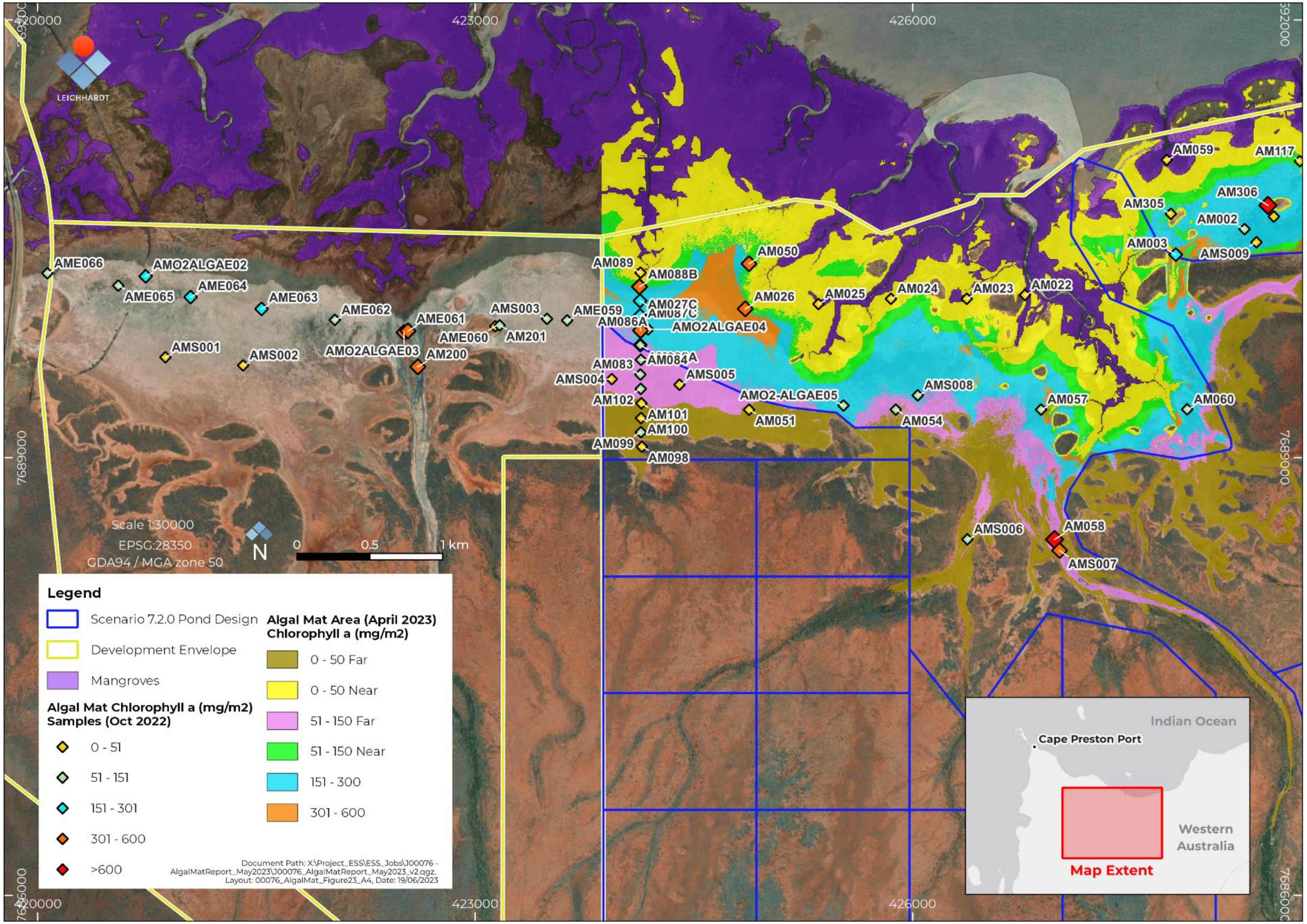

Figure 18 Map of Microbial Mat in the Eramurra study site with layout 7.2.0 (west)

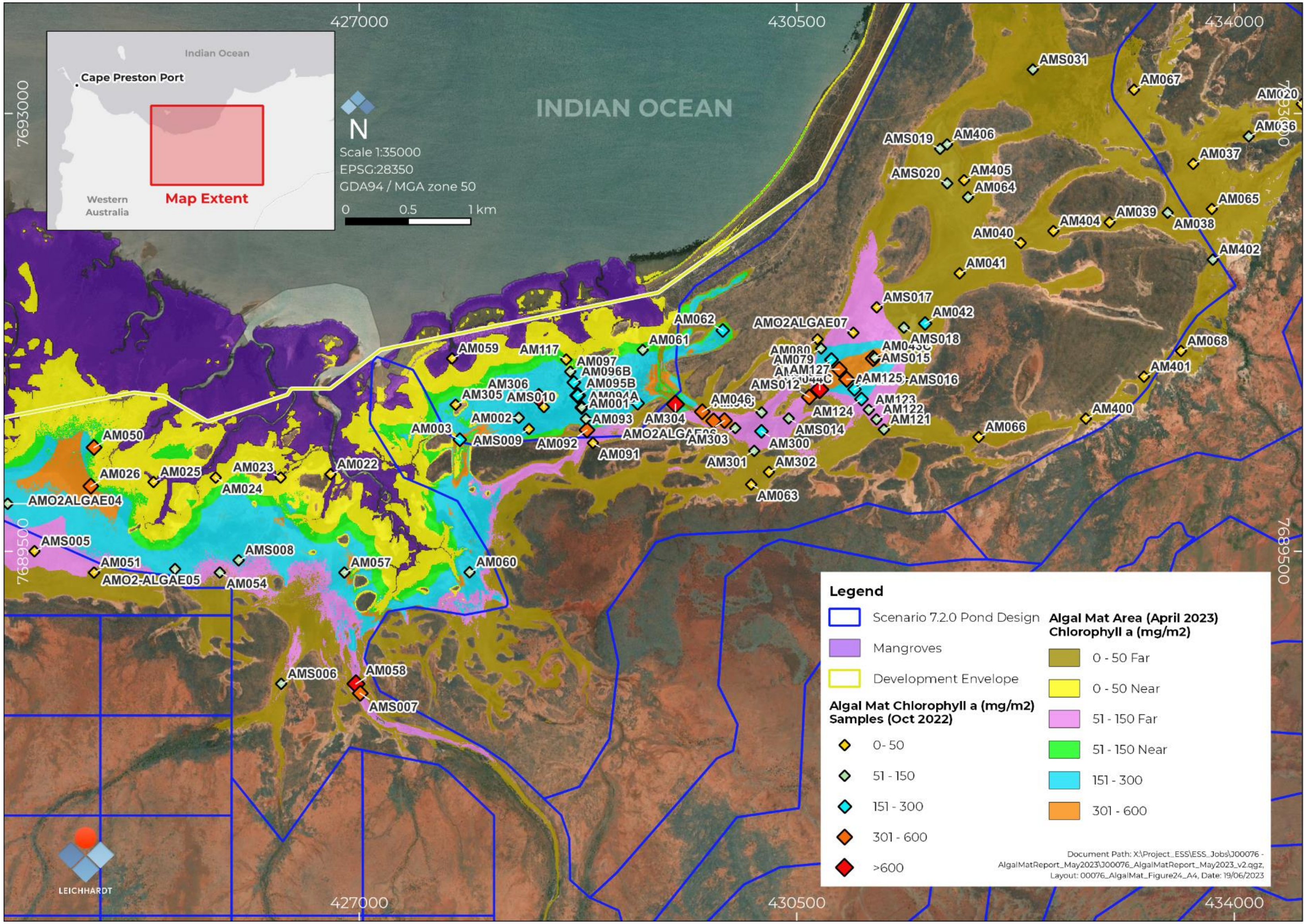

Figure 19 Map of Microbial Mat in the Eramurra study site with layout 7.2.0 (middle)

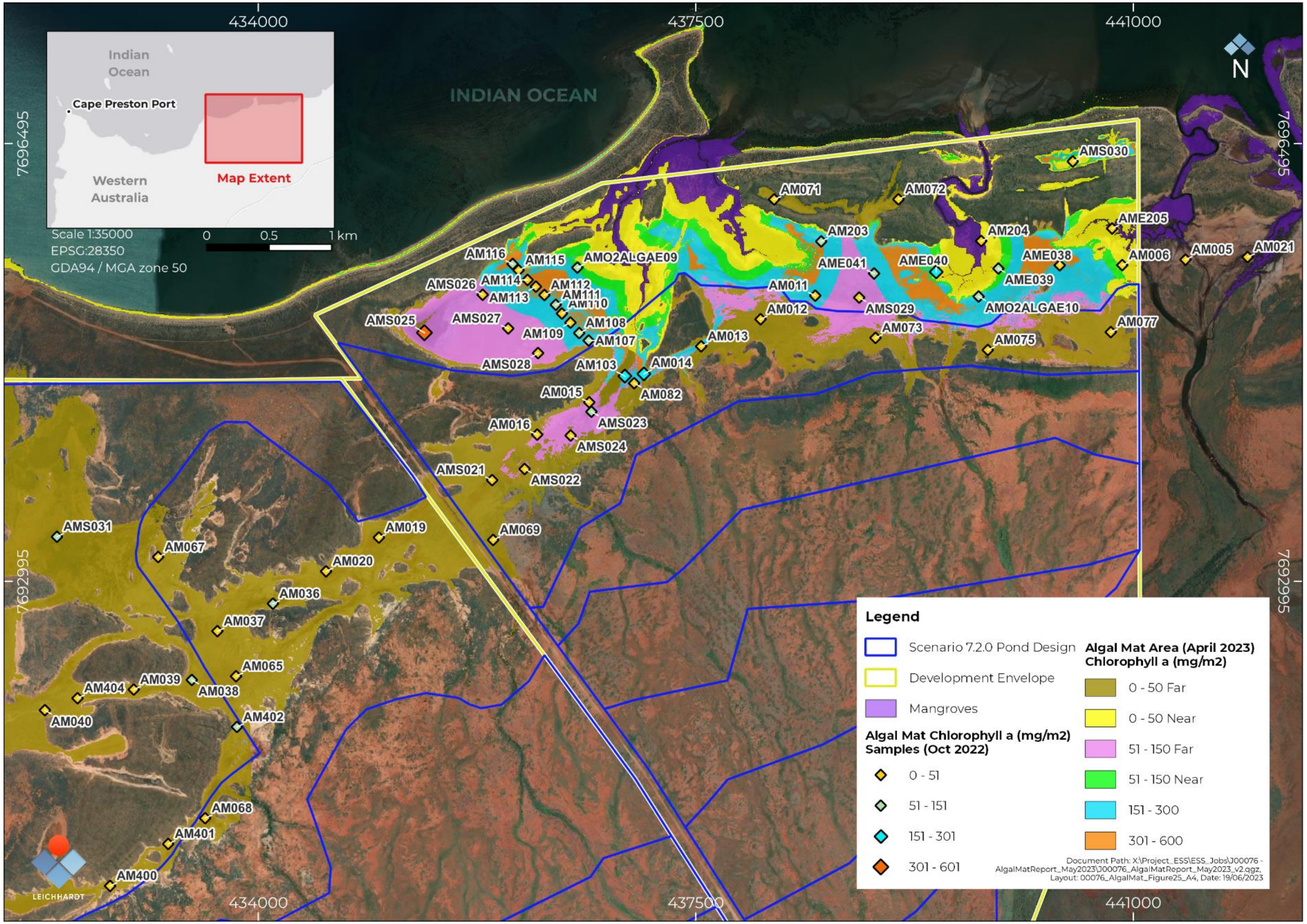

Figure 20 Map of Microbial Mat in the Eramurra study site with layout 7.2.0 (east)

7 Conclusion

Tidal benthic mats are recognised as important habitats that have some environmental values that would still be preserved if the area becomes a solar salt field. The environmental values that are common to both environments are:

- Bird habitats for shelter and feeding.
- Erosion protection.
- Biodiversity and biomass storage.
- Invertebrate and fish grazing on the fringe to the seaward side

The nutrient flow from natural tidal benthic mats is largely unknown but there are some estimates of Total Organic Carbon (TOC) that suggest that the mats are important contributors. Total Nitrogen (TN) fluxes are less known and although it has been determined that the TN fixed in the natural benthic mats is significant it is not known how much this flows out to the near shore environment as there appears to be differing accounts. It is important to distinguish between water shed from the catchment which is normally not restrained by the construction of salt fields and tidal flushing.

The mat in the intertidal zone at Eramurra is similar in microbial composition to that found in other Pilbara areas. The main species identified with a light microscope are filamentous Cyanobacteria from the *Microcoleus* genera with some *Oscillatoria*. Undoubtably other bacteria are present as well but were not identified. Chlorophyta and other algae orders are poorly represented.

The tidal range for the most active mat was well defined and, as noted by other authors, in the range of 1.5 and 1.9 metres AHD. There was also a distance function whereby the mat was found primarily between 175 and 2,000 metres from the nearest tidal creek. There are obviously other factors affecting distribution, including disturbance, tidal restriction and ponding from surface runoff.

Chl a was identified as a useful indicator of primary production. In the same localised region, it was shown to be directly proportional to the potential productivity. This relationship would not be transferable to comparing different habitats. Testing of Chl a is a simple procedure and relatively repeatable. Repeated sampling at one site were variable but the variation was statistically different between sites. Analyses of subsamples were consistent. The site variation was put down to changes over time and spatial variability.

As reported elsewhere, the mat has an ability to desiccate and 'deactivate' the Chl a. The organisms go into a survival mode until the next suitable period. The chlorophyll as analysed for Chl a is rapidly activated after a very short time of being re-wet (fifteen minutes in some cases). This meant that the environmental Chl a concentration was influenced by the time that elapsed before the last wetting. This short amount of time for activation precludes cell division or growth of biomass. To gain an accurate estimate of biomass or potential Chl a 'activity' all samples were wet for 24 hours before analysis. Long enough for the Chl a to be reactivated but too short for cell division to be significant. This meant that the resulting Chl a distribution represents the potential activated Chl a for the samples.

A model of the likely activated Chl a concentration was constructed using the distance from the creeks and tidal height. This was also discussed in the previous report by *actis* Environmental Services, Benthic Mat Study Eramurra Solar Salt Project (2022). The map was manually adjusted to include areas that formed basins (depressions within the playa) as determined by LiDAR surveys, and indicated by high Chl a samples that were exceptional compared to the base model.

The most important aspect of a mat is its productivity, and its potential to support the nutrient requirements of the near shore environment by exporting biomass. Productivity can only be measured *in situ* and the procedure limits the number of sites and time that it can be measured. These more detailed studies provide an accurate estimate for a single instance but limits extrapolation to whole ecosystem estimates. It remains an important method to provide benchmarks and mechanisms affecting productivity.

Chl a is a factor of productivity but it cannot be used as a direct measure. There are several other factors that will influence productivity. These include available sunlight, nutrients and not being desiccated. However, if certain assumptions are made, including using a benchmark, it is possible to compare areas to make relative comparisons between potential productivity using only Chl a. These assumptions include same incident light across the mat and relative efficiencies of converting light energy to productivity in the relative monoculture (similar species composition). These assumptions are reasonable in a defined localised area.

The Chl a concentrations were benchmarked against published productivity with supporting Chl a concentrations results to give an estimate of maximum productivity for each Chl a at Eramurra. This was judged to be valid as the estimates were from similar environments and bacteria groups. This productivity value is for activated mat. This can be further refined by estimating time that the mat is wet (7-day period) and active.

The work in this report is not designed to be substitute for a detailed study of the mat productivity. It is proposed that it is a useful estimate of relative productivity between areas at the same location and time. That is, the relative environmental importance of each area to the near shore nutrient balance. The resulting productivity is an approximate of what may be measured in the field.

The work determined that Chl a concentration ranged across the mud flat. For simplicity of modelling the Chl a concentration across the tidal flats some grouping is needed. The lower two Chl a bands, 0-50 and 51-150 $mg.m^{-2}$ were each further divided into two sub bands representing the different flooding times.

The resulting calculation using benchmark productivity values measured in other studies at other locations allowed for the generation of hypothetical productivity amounts for each chlorophyll band.

Table 14 Estimate of total Net Productivity

Chl a	**Development Envelope**	**Scenario 7.2 IDA Mat V14**	
$mg.m^{-2}$	Percent of productivity	Percent of productivity	Description
301-600	19%	3%	Very active mat 301-400mg/m^2
151-300	37%	4%	Active mat 151-300 mg/m^2
51-150	10%	5%	Limited activity far 51-150 mg/m^2
51-150	7%	1%	Limited activity near 51-150 mg/m^2
0-50	11%	8%	Low far 0-50 mg/m^2
0-50	16%	1%	Low near 0-50 mg/m^2
Total %	**100%**	**23.4%**	

An area has been excised from the pond layout Version 7.2.0 to preserve heritage and contributes 1.8% of the productivity. It is outside of the pond layout but may be isolated from tidal flooding and therefore the mat productivity would be lost to the total contribution to the near shore environment. This would make the total loss of productivity as 25.2%

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9 Glossary

Term	Definition
ºC	Degrees Celsius
AHD	Australian Height Datum
ANOVA	Analysis of variance
BOM	Bureau of Meteorology
C	Carbon
Chl a	Chlorophyll a
cm	Centimetre
CO_2	Carbon Dioxide
Development area	The area in which project disturbance may occur
Development envelope	The area in which project disturbance may occur
Disturbance area	The proposed project footprint
Eramurra	Eramurra Solar Salt Project
F value	A measure of how much the means of different groups of data differ from each other
GIS	Geographic Information System
GPS	Global Positioning System
h	Hour
H^+	Hydrogen
ha	hectare
IDA	Indicative Disturbance Area
kW	Kilowatt
kWh	Kilowatt hour
Leichhardt Salt	Leichhardt Salt Pty Ltd
LiDAR	Light Detection and Ranging remote-sensing
m	Metres
mg	Milligram
MJ	Mega Joule
mmol	Millimole
N	Nitrogen
N_2	Nitrogen gas
NH_4^+	Ammonium
nmol	Nanomole
NO_2^-	Nitrate
NO_3^-	Nitrite
O_2	Oxygen gas
P	Probability
PAR	Photosynthetically active radiation
pH	A scale used to specify the acidity or basicity of an aqueous solution
s	Second
TN	Total Nitrogen
TOC	Total Organic Carbon
W	Watt
yr	Year
µmol	Micromole

10 Appendix

10.1 Raw data - wet samples

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
1	SSA039R	31/03/2022	170	150	Wet
2	SSA075R	31/03/2022	5	9	Wet
3	SSA077R	31/03/2022	14	9	Wet
4	SSA110R	31/03/2022	98	34	Wet
5	SSA111R	31/03/2022	15	28	Wet
6	SSA112R	31/03/2022	55	73	Wet
7	SSA113R	31/03/2022	58	63	Wet
8	SSA114R	31/03/2022	44	52	Wet
9	SSA115R	31/03/2022	33	41	Wet
10	SSA116-TopR	31/03/2022	21	42	Wet
11	SSA204R	31/03/2022	77	48	Wet
12	SSA205R	31/03/2022	5	18	Wet
13	AM001	24/05/2022	250	53	Wet
14	AM002	24/05/2022	75	49	Wet
15	AM003	24/05/2022	260	80	Wet
16	AM005	26/05/2022	7	9	Wet
17	AM006	26/05/2022	5	9	Wet
18	AM011	26/05/2022	43	62	Wet
19	AM012	26/05/2022	5	9	Wet
20	AM013	26/05/2022	25	16	Wet
21	AM014	23/05/2022	200	110	Wet
22	AM015	23/05/2022	12	9	Wet
23	AM016	23/05/2022	8	9	Wet
24	AM019	5/06/2022	5	9	Wet
25	AM020	5/06/2022	8	15	Wet
26	AM021	26/05/2022	5	9	Wet
27	AM022	6/06/2022	5	59	Wet
28	AM023	6/06/2022	19	11	Wet
29	AM024	6/06/2022	6	9	Wet
30	AM025	6/06/2022	12	9	Wet
31	AM026	26/05/2022	590	170	Wet
32	AM027C	26/05/2022	290	94	Wet
33	AM036	5/06/2022	67	33	Wet
34	AM037	5/06/2022	5	9	Wet
35	AM038	26/05/2022	110	97	Wet
36	AM039	5/06/2022	8	9	Wet
37	AM040	6/06/2022	36	9	Wet
38	AM041	5/06/2022	13	9	Wet
39	AM042	5/06/2022	180	31	Wet
40	AM043C	27/05/2022	550	84	Wet

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
41	AM044C	27/05/2022	820	110	Wet
42	AM045	24/05/2022	57	88	Wet
43	AM046	24/05/2022	580	210	Wet
44	AM050	26/05/2022	470	110	Wet
45	AM051	26/05/2022	11	9	Wet
46	AM054	6/06/2022	110	35	Wet
47	AM057	6/06/2022	87	54	Wet
48	AM058	6/06/2022	670	140	Wet
49	AM059	24/05/2022	7	69	Wet
50	AM060	6/06/2022	90	91	Wet
51	AM061	24/05/2022	120	130	Wet
52	AM062	24/05/2022	290	140	Wet
53	AM063	24/05/2022	21	16	Wet
54	AM064	5/06/2022	57	18	Wet
55	AM065	5/06/2022	5	9	Wet
56	AM066	5/06/2022	41	9	Wet
57	AM067	5/06/2022	38	16	Wet
58	AM068	5/06/2022	40	23	Wet
59	AM069	23/05/2022	5	9	Wet
60	AM071	26/05/2022	13	14	Wet
61	AM072	26/05/2022	5	12	Wet
62	AM073	26/05/2022	5	9	Wet
63	AM075	26/05/2022	5	9	Wet
64	AM077	26/05/2022	13	12	Wet
65	AM078B	27/05/2022	270	36	Wet
66	AM079	24/05/2022	71	30	Wet
67	AM080	24/05/2022	5	9	Wet
68	AM082	23/05/2022	27	9	Wet
69	AM083	26/05/2022	57	23	Wet
70	AM084	26/05/2022	120	35	Wet
71	AM085A	26/05/2022	220	60	Wet
72	AM086A	26/05/2022	450	60	Wet
73	AM087C	26/05/2022	290	94	Wet
74	AM088B	26/05/2022	500	96	Wet
75	AM089	26/05/2022	14	20	Wet
76	AM091	24/05/2022	40	62	Wet
77	AM092	24/05/2022	520	120	Wet
78	AM093	24/05/2022	110	65	Wet
79	AM094A	24/05/2022	260	42	Wet
80	AM095B	24/05/2022	320	88	Wet
81	AM096B	24/05/2022	210	92	Wet
82	AM097	24/05/2022	150	100	Wet
83	AM098	26/05/2022	5	9	Wet

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
84	AM099	26/05/2022	54	18	Wet
85	AM100	26/05/2022	10	13	Wet
86	AM101	26/05/2022	12	9	Wet
87	AM102	26/05/2022	57	24	Wet
88	AM103	23/05/2022	290	93	Wet
89	AM107	23/05/2022	68	29	Wet
90	AM108	23/05/2022	59	33	Wet
91	AM109	23/05/2022	40	51	Wet
92	AM110	23/05/2022	26	33	Wet
93	AM111	23/05/2022	99	57	Wet
94	AM112	23/05/2022	43	46	Wet
95	AM113	23/05/2022	37	69	Wet
96	AM114	23/05/2022	9	61	Wet
97	AM115	23/05/2022	31	35	Wet
98	AM116	23/05/2022	99	53	Wet
99	AM117	24/05/2022	21	34	Wet
100	AM121	27/05/2022	52	10	Wet
101	AM122	27/05/2022	63	21	Wet
102	AM123	27/05/2022	140	35	Wet
103	AM124	27/05/2022	160	20	Wet
104	AM125	27/05/2022	220	29	Wet
105	AM126C	27/05/2022	570	91	Wet
106	AM127	27/05/2022	520	62	Wet
107	AM200	26/05/2022	550	120	Wet
108	AM201	26/05/2022	82	57	Wet
109	AM203	26/05/2022	76	33	Wet
110	AM204	26/05/2022	10	90	Wet
111	AM300	24/05/2022	190	35	Wet
112	AM301	24/05/2022	99	94	Wet
113	AM302	24/05/2022	14	20	Wet
114	AM303	24/05/2022	75	70	Wet
115	AM304	24/05/2022	620	89	Wet
116	AM305	24/05/2022	35	62	Wet
117	AM306	24/05/2022	610	71	Wet
118	AM400	5/06/2022	29	20	Wet
119	AM401	5/06/2022	46	53	Wet
120	AM402	5/06/2022	130	42	Wet
121	AM404	5/06/2022	20	10	Wet
122	AM405	5/06/2022	18	9	Wet
123	AM406	5/06/2022	69	36	Wet
124	AME038	26/05/2022	5	9	Wet
125	AME039	26/05/2022	76	110	Wet
126	AME040	26/05/2022	190	150	Wet

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
127	AME041	26/05/2022	71	59	Wet
128	AME059	26/05/2022	120	34	Wet
129	AME060	26/05/2022	5	9	Wet
130	AME061	24/05/2022	410	140	Wet
131	AME062	24/05/2022	150	89	Wet
132	AME063	26/05/2022	200	81	Wet
133	AME064	26/05/2022	210	97	Wet
134	AME065	26/05/2022	92	69	Wet
135	AME066	26/05/2022	130	130	Wet
136	AME205	26/05/2022	7	20	Wet
137	AMO2ALGAE02	26/05/2022	260	120	Wet
138	AMO2ALGAE03	26/05/2022	420	110	Wet
139	AMO2ALGAE04	26/05/2022	96	89	Wet
140	AMO2-ALGAE05	6/06/2022	120	87	Wet
141	AMO2ALGAE06	24/05/2022	400	99	Wet
142	AMO2ALGAE07	27/05/2022	36	23	Wet
143	AMO2ALGAE09	23/05/2022	110	160	Wet
144	AMO2ALGAE10	26/05/2022	55	61	Wet
145	AM095A	24/05/2022	310	72	Wet
146	AM096A	24/05/2022	180	90	Wet
147	AM088A	26/05/2022	440	91	Wet
148	AM087A	26/05/2022	270	76	Wet
149	AM027A	26/05/2022	210	67	Wet
150	AM044A	27/05/2022	780	110	Wet
151	AM043A	27/05/2022	340	46	Wet
152	AM043B	27/05/2022	480	40	Wet
153	AM044B	27/05/2022	680	95	Wet
154	AM126B	27/05/2022	490	82	Wet
155	AM126A	27/05/2022	310	60	Wet
156	AM094B	24/05/2022	92	60	Wet
157	AM094C	24/05/2022	82	67	Wet
158	AM095C	24/05/2022	210	59	Wet
159	AM096C	24/05/2022	49	72	Wet
160	AM088C	26/05/2022	320	160	Wet
161	AM087B	26/05/2022	220	160	Wet
162	AM027B	26/05/2022	120	52	Wet
163	AM086B	26/05/2022	160	75	Wet
164	AM086C	26/05/2022	370	48	Wet
165	AM085B	26/05/2022	84	47	Wet
166	AM085C	26/05/2022	110	45	Wet
167	AM078A	27/05/2022	260	36	Wet
168	AM078C	27/05/2022	200	49	Wet

10.2 Raw data - dry samples

Number	Sample Code	Date	Chlorophyl a ($gm.m^{-2}$)	Phaephytin ($mg.m^{-2}$)	Treatment (Dry/Wet)
1	SSA001	8/08/2021	23.0	31.7	Dry
2	SSA002	11/08/2021	41.5	37.5	Dry
3	SSA003	7/08/2021	6.2	29.8	Dry
4	SSA005	24/09/2021	2.1	4.1	Dry
5	SSA006	24/09/2021	6.5	2.4	Dry
6	SSA011	24/09/2021	74.7	51.4	Dry
7	SSA012	24/09/2021	1.0	4.0	Dry
8	SSA013	24/09/2021	147.2	58.6	Dry
9	SSA014	24/09/2021	124.7	118.6	Dry
10	SSA015	23/09/2021	3.8	2.0	Dry
11	SSA016	23/09/2021	3.8	3.2	Dry
12	SSA017	23/09/2021	1.0	1.1	Dry
13	SSA018	6/08/2021	2.9	9.0	Dry
14	SSA019	6/08/2021	1.7	5.0	Dry
15	SSA020	6/08/2021	9.7	11.9	Dry
16	SSA021	24/09/2021	0.2	4.9	Dry
17	SSA022	12/08/2021	3.3	128.0	Dry
18	SSA023	12/08/2021	12.2	16.8	Dry
19	SSA024	12/08/2021	5.3	4.5	Dry
20	SSA025	12/08/2021	4.1	2.0	Dry
21	SSA026	12/08/2021	283.7	208.8	Dry
22	SSA027	13/08/2021	112.7	49.9	Dry
23	SSA036	6/08/2021	28.6	36.4	Dry
24	SSA037	6/08/2021	1.2	0.8	Dry
25	SSA038	6/08/2021	1.1	0.1	Dry
26	SSA039	6/08/2021	2.0	3.1	Dry
27	SSA040	4/08/2021	20.5	14.0	Dry
28	SSA041	7/08/2021	13.0	3.0	Dry
29	SSA042	6/08/2021	25.7	11.1	Dry
30	SSA043	7/08/2021	60.6	51.6	Dry
31	SSA044	7/08/2021	180.2	98.3	Dry
32	SSA045	7/08/2021	46.6	78.0	Dry
33	SSA046	7/08/2021	290.4	181.9	Dry
34	SSA050	12/08/2021	178.0	196.0	Dry
35	SSA051	12/08/2021	2.8	9.3	Dry
36	SSA054	12/08/2021	34.5	23.1	Dry
37	SSA057	11/08/2021	43.7	20.1	Dry
38	SSA058	8/08/2021	95.4	93.1	Dry
39	SSA059	7/08/2021	6.9	28.6	Dry
40	SSA060	7/08/2021	76.5	56.1	Dry
41	SSA061	8/08/2021	34.4	33.1	Dry
42	SSA062	8/08/2021	9.9	10.2	Dry

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
43	SSA063	7/08/2021	18.7	36.2	Dry
44	SSA064	4/08/2021	38.0	27.6	Dry
45	SSA065	6/08/2021	1.5	1.6	Dry
46	SSA066	7/08/2021	19.0	16.2	Dry
47	SSA067	6/08/2021	4.2	2.8	Dry
48	SSA068	8/08/2021	9.8	20.4	Dry
49	SSA069	23/09/2021	0.3	1.2	Dry
50	SSA073	24/09/2021	4.0	1.6	Dry
51	SSA075	24/09/2021	2.8	2.5	Dry
52	SSA077	24/09/2021	8.7	3.3	Dry
53	SSA078	7/08/2021	134.0	69.0	Dry
54	SSA079	7/08/2021	8.5	16.0	Dry
55	SSA080	7/08/2021	1.6	6.7	Dry
56	SSA082	24/09/2021	2.1	1.1	Dry
57	SSA083	12/08/2021	14.7	2.7	Dry
58	SSA084	13/08/2021	36.4	29.6	Dry
59	SSA085	13/08/2021	131.6	46.6	Dry
60	SSA086	13/08/2021	127.5	53.4	Dry
61	SSA087	13/08/2021	127.4	80.9	Dry
62	SSA088	13/08/2021	205.9	147.3	Dry
63	SSA089	13/08/2021	2.9	14.8	Dry
64	SSA091	8/08/2021	16.7	32.3	Dry
65	SSA092	8/08/2021	57.6	48.9	Dry
66	SSA093	8/08/2021	77.0	71.0	Dry
67	SSA094	11/08/2021	69.7	34.5	Dry
68	SSA095	11/08/2021	105.6	81.5	Dry
69	SSA096	11/08/2021	99.7	60.5	Dry
70	SSA097	11/08/2021	7.9	5.7	Dry
71	SSA098	12/08/2021	2.2	0.3	Dry
72	SSA099	12/08/2021	18.0	16.4	Dry
73	SSA100	12/08/2021	12.5	6.8	Dry
74	SSA101	12/08/2021	7.0	2.2	Dry
75	SSA102	12/08/2021	29.7	12.3	Dry
76	SSA103	24/09/2021	183.4	27.7	Dry
77	SSA107	23/09/2021	12.5	11.1	Dry
78	SSA108	23/09/2021	120.0	27.4	Dry
79	SSA109	23/09/2021	33.7	33.8	Dry
80	SSA110	23/09/2021	19.9	10.8	Dry
81	SSA111	23/09/2021	24.3	29.0	Dry
82	SSA112	23/09/2021	21.9	43.7	Dry
83	SSA113	23/09/2021	18.8	49.5	Dry
84	SSA114	23/09/2021	16.5	54.9	Dry
85	SSA115	23/09/2021	8.2	12.9	Dry

Number	Sample Code	Date	Chlorophyl a (gm.m^{-2})	Phaephytin (mg.m^{-2})	Treatment (Dry/Wet)
86	SSA116	23/09/2021	12.9	25.9	Dry
87	SSA117	11/08/2021	5.4	2.8	Dry
88	SSA121	7/08/2021	17.6	3.6	Dry
89	SSA122	7/08/2021	18.4	1.6	Dry
90	SSA123	7/08/2021	21.9	10.8	Dry
91	SSA124	7/08/2021	15.8	11.9	Dry
92	SSA125	7/08/2021	81.0	17.6	Dry
93	SSA126	7/08/2021	61.8	31.0	Dry
94	SSA127	7/08/2021	29.9	53.0	Dry
95	SSAE038	16/12/2021	64.1	111.1	Dry
96	SSAE039	16/12/2021	20.6	22.2	Dry
97	SSAE040	16/12/2021	135.8	259.2	Dry
98	SSAE041	16/12/2021	38.9	74.6	Dry
99	SSAE059	15/12/2021	49.5	30.5	Dry
100	SSAE060	15/12/2021	1.8	0.7	Dry
101	SSAE061	15/12/2021	80.8	214.5	Dry
102	SSAE062	15/12/2021	65.0	69.4	Dry
103	SSAE063	15/12/2021	75.3	83.8	Dry
104	SSAE064	15/12/2021	37.2	50.6	Dry
105	SSAE065	15/12/2021	33.2	94.7	Dry
106	SSAE066	15/12/2021	45.0	80.8	Dry
107	SSAE071	16/12/2021	5.5	10.6	Dry
108	SSAE071A	16/12/2021	11.5	16.1	Dry
109	SSAE072	16/12/2021	2.4	3.5	Dry
110	SSAE085R	15/12/2021	31.7	28.5	Dry
111	SSAE099R	15/12/2021	10.3	8.2	Dry
112	SSAE102R	15/12/2021	40.0	19.1	Dry
113	SSAE200	15/12/2021	99.2	176.2	Dry
114	SSAE201	15/12/2021	74.1	76.6	Dry
115	SSAE203	16/12/2021	17.8	25.2	Dry
116	SSAE204	16/12/2021	22.2	54.1	Dry
117	SSAE205	16/12/2021	9.6	30.0	Dry