Effects on primary production of proposed iron-sand mining in the South Taranaki Bight region

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A report prepared for Trans-Tasman Resources, Ltd.

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Executive Summary

Trans-Tasman Resources Ltd (TTR) propose to mine iron-sands in the South Taranaki Bight (STB) region. These activities will release sediment into the water column. The increased suspended sediment in the water column will affect the optical properties of the water, specifically its clarity and colour, which may affect the STB ecosystem. Optical effects of mining (as distinct from "mass effects") include changes to light attenuation, which affects the amount of primary production (PP) by reducing light availability for algae in the water and on the seabed.

The optical effects of mining are predicted based on applying an optical model to the results of a sediment transport model (Pinkerton & Gall 2015; Hadfield & Macdonald, 2015). The accuracy and reliability of the effects on PP are hence dependent on the performances of the sediment transport and optical models, which are not assessed in this report. The results presented here are specific to the Sediment Model Domain (SMD), part of the STB with an area of ocean of ~13,300 km^2.

Effects on PP have been predicted based on optical models that predict the impacts of mining at two different locations: site A (inner limit of proposed mining) and site B (outer limit of proposed mining). Predictions are based on sediment transport modelling of mining at the full rate proposed in the mining application, 50 million tonnes per year.

1. The main results of the revised optical models are:
    (a) Light in the water column, integrated over the whole SMD region and averaged by year, is predicted to be reduced by 1.9% (mining at site A) and by 1.6% (mining at site B).
    (b) With no mining, about 28.6% of the seabed of the SMD receives more than 0.04 mol photons m^{-2}d^{-1}. This is an estimate of the approximate minimum light requirements for MPB to grow (Gattuso et al., 2006) (though it is possible that MPB can grow at lower light levels than this). The area is predicted to reduce to 27.1% overall (mining at site A) and to 27.3% overall (mining at site B).
    (c) The total amount of light at the seabed over the whole SMD averaged over a year is predicted to reduce by 23% (mining at site A) and by 15% (mining at site B).
    (d) Most of the reduction in sea bed light is predicted to occur in a band spreading east from the mining site.

2. Based on the prediction of the optical model, estimates of likely reductions in primary production ("PP") by phytoplankton in the water column and PP by macroalgae (seaweed) and microphytobenthos (MPB) on the seabed were made. These estimates are almost exclusively based on literature values from outside of the SMD, as no useful local information is available. Five changes are considered in the context of assessing the optical effects of mining on the ecology of the SMD:
    (a) Changes to PP in the water column by phytoplankton.
    (b) Changes to PP by macroalgae
    (c) Changes to PP on the seabed by microphytobenthos.
    (d) Changes to total PP (i.e., the sum of all sources of PP) in the SMD.

(e) Changes to energy flow to the seabed ecosystem. Energy available to animals in/on the seabed comes from the combination of local (seabed) PP and the transfer (flux) of organic matter from the water column to the seabed.

In all cases it was not possible to predict changes to absolute production, rather estimates are based on proportional changes to the background condition.

3. The following issues are critical in estimating the possible changes in PP in the SMD resulting from optical effects, and none of these is well known:

(a) The degree to which photo-saturation and photo-adaptation by phytoplankton and MPB will offset the effect of reductions in light on PP.
(b) The relative importance of MPB and phytoplankton for total PP in the SMD. PP by phytoplankton will dominate, but the contribution of PP from MPB is not well known.
(c) The proportion of the total flux of organic carbon to the benthic ecosystem that is due to sedimenting SMD-produced water column carbon compared to advected or local benthic production by MPB.

4. Using optical modelling results and expert estimates for the above factors, we predict that mining will:

(a) Reduce water column PP averaged over the SMD by 1.0% (mining at site A) and by 0.8% (mining at site B).
(b) Likely have small effects on macroalgal production. The distribution of macroalgae is poorly known for much of the SMD, and effects are hard to predict quantitatively. However, known macroalgal habitats, including the Traps, are in areas where the impacts of the mining operation are predicted to be small.
(c) Reduce benthic PP averaged over the SMD by 19% (mining at site A) and 13% (mining at site B).
(d) Reduce total (i.e. water column plus seabed) PP averaged over the SMD by 1.9% (range 1.6–2.2%) due to mining at site A, and by 1.4% (range 1.2–1.7%) due to mining at site B.
(e) Reduce energy flow to the seabed ecosystem averaged over the SMD by 5.8% (range 3.1–11.9%) by mining at site A, and by 4.1% (range 2.3–8.3%) by mining at site B.

5. The proportional reduction in benthic PP, and hence fixed carbon flux to the seabed, is expected to occur mostly in an area east of the mining site, where the “median plume” is predicted to move over a relatively shallow (20-40 m deep) sandy area, which forms part of the Patea Banks. Here, area-specific reductions of carbon flux to the benthos of up to 40% can be expected.

6. The optical effects of mining on PP by phytoplankton and by MPB are likely to cease shortly after mining stops. As suspended sediment from mining is fully flushed out of the SMD region (a process predicted to take a few months; Hadfield, 2013) phytoplankton and benthic biomass and PP may be expected to return to pre-mining levels rapidly.

7. There is high interannual variability in PP by phytoplankton in the SMD. Satellite data show that the annual-average chl-a in the SMD has a standard deviation of 18%. Background interannual variability in phytoplankton PP is likely to be of a similar magnitude. This means that a chronic decrease in phytoplankton PP of 1% due to mining is very unlikely to lead to fundamental structural change.

8. There is also high interannual variability in the amount of light reaching the seabed in the SMD. Satellite-derived estimates show that the annual-average total light reaching the seabed in the SMD has a standard deviation of 25%, with annual-averages of between +36% to -32% of the long term mean predicted from 6-years of satellite observations. This suggests that receiving communities are predisposed to tolerate interannual variability in benthic photosynthesis of magnitudes similar to that expected from mining (15–23%), though mining will exacerbate low light episodes. Mining is unlikely to lead to unnaturally low benthic production in the SMD outside of the envelope of background variability in any given year.

9. Additional effects of mining activity (effects of sediment deposition on the bottom on MPB production and effects of nutrient pore water release by mining activity) were considered using available modelling and literature information, respectively, and are considered to be insignificant.

10. Our analyses of the relevant available field data, coupled with modelling of the character of the sediment plume from mining operations, its trajectory and duration, and its optical effects, and our analyses of these effects on primary production in the SMD region strongly support the assessment that region-wide effects of iron-sand mining on short-lived organisms (living less than a year or two) will be indistinguishable within natural oceanographic variability. Effects at local scale proximal to the mining operations will likely manifest primarily as decreases in MPB production and organic carbon availability to benthic consumers that may exceed natural variability and may propagate locally to organisms that feed primarily on MPB and in turn to their predators, which may be more wide-ranging.

11. Further refinement of our assessments would require collecting substantial additional field data to address key uncertainties, particularly the magnitude of benthic production across the Patea Banks. The inherent variability in the relevant oceanographic variables, the dynamic nature of the South Taranaki Bight itself, and the significant gaps in basic understanding of some relevant parameters mean that this would require a long and expensive field campaign. Notwithstanding the current limitations in understanding, we are confident that the judgements we offer in this report represent sound scientific assessments that lie well within the bounds of reasonable probability.

1 Introduction

Trans-Tasman Resources Ltd. (TTR) proposes to mine iron-sands within the South Taranaki Bight (STB) region (Figure 1-1). These activities will release sediment into the water column. The probable spatial patterns of suspended sediment concentrations (SSC) from a mining plume have been simulated, using a sediment transport model (see “Sediment Model Domain”, SMD in Figure 1-2)for a range of size classes and driven by the expected mining operations (Hadfield, 2013; Hadfield, 2015). Expected rates of sediment extraction are on the order of 8,000 tonnes per hour; assuming an 80% operational status for the mining operation the annual target is approximately 50 million tonnes per year.

There are two main types of effects from changes in water column SSC: (1) ‘Mass Effects’ (smothering or disruptive effects of suspended sediment on organisms); and (2) ‘Optical Effects’, which impact water clarity and the penetration of light into the water column. Reduction of light within the water column can impact production of suspended and benthic plants. This report provides data to address the significance of changes in the optical properties of the water column for primary productivity (PP). It also considers minor effects resulting from sediment mining: sediment accumulation on the bottom away from the mining pit and release of pore water nutrients by sediment extraction.

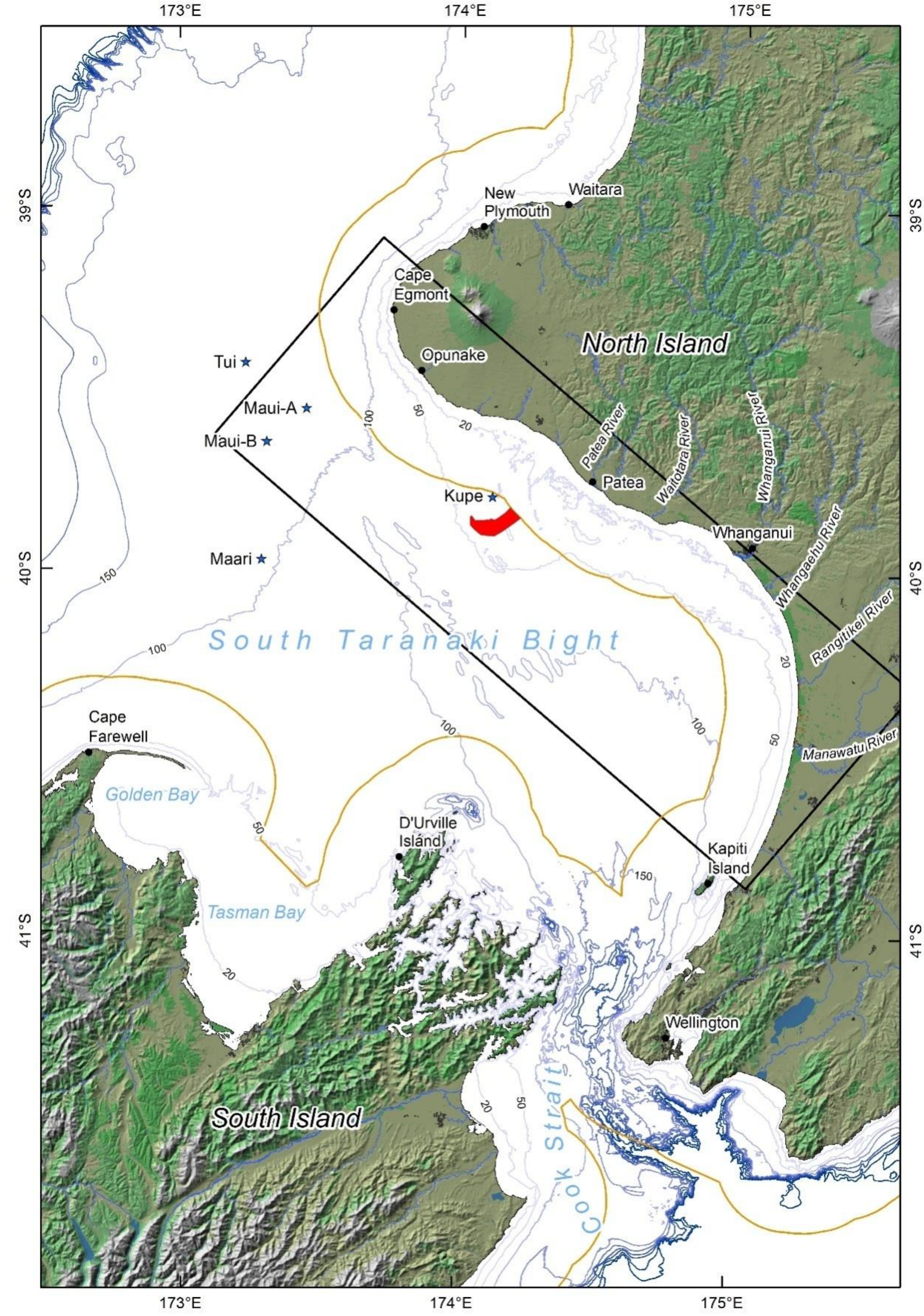

Figure 1-1: The South Taranaki Bight (STB) region showing the Sediment Model Domain (SMD) (oblique black rectangle). The approximate iron-sand mining location is shown in red.

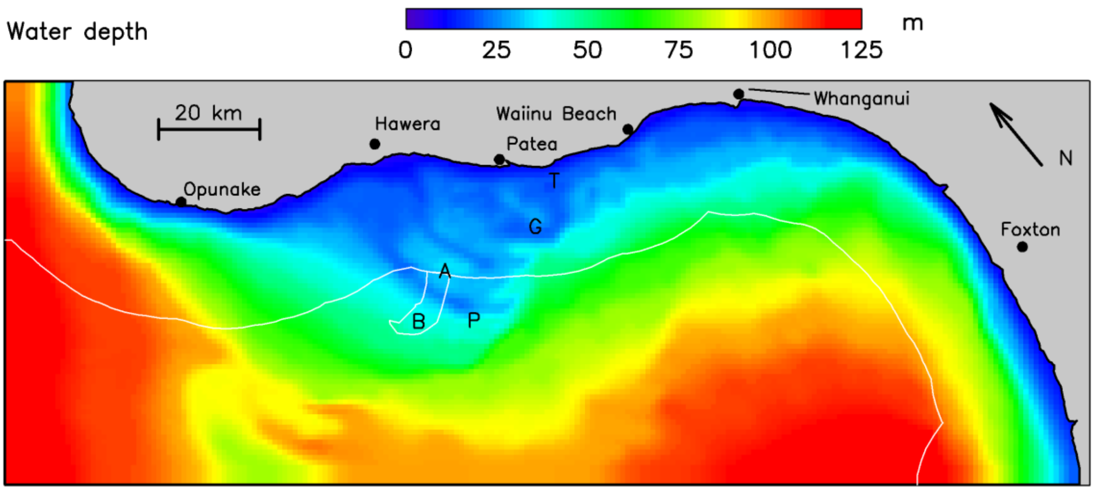

Figure 1-2: The Sediment Model Domain (SMD) which is part of the South Taranaki Bight (STB) region Colours show the depth of water. The projection and region limits follow those used for the hydrodynamic modelling (Hadfield, 2015). Note that the region is rotated relative to grid north. The approximate iron-sand mining location is the white polygon near the middle of the region. Also shown is the limit of the territorial sea (12 nm offshore) and towns (black). Simulations of mining were undertaken for scenarios of mining at the inner limit of the proposed mining area (site A, labelled "A") and outer limit of the proposed mining area (site B, labelled "B"). Graham Bank is labelled "G", the Traps (North and South) is labelled "T" and Patea Banks is labelled "P".

2 Spatial scales of ecosystems

Marine ecosystems generally have open boundaries, and defining the spatial scale on which to consider impacts on such systems can be difficult. In addition different components of ecosystems have different spatial footprints, with higher trophic-level organisms usually moving over a greater spatial extent than lower trophic-level organisms. In this report we are concerned primarily with primary production, the domain of phytoplankton and phytobenthos. Most phytoplankton and benthic phototrophs in the STB will live and die within a few km. However, some fish and other higher trophic-level organisms may move greater distances, and depend on a variety of food resources and locations. Impacts on primary production in one location can thus affect other places, and the STB ecosystem should be viewed as an interlocking matrix of the life ranges of different organisms.

Our investigation is based on the SMD of Hadfield (2013), which was selected on the basis of hydrography (current patterns, boundary conditions, size) and the proposed mining area, and not with reference to any ecological considerations. We note that the SMD is approximately half the size of the area generally referred to as the "South Taranaki Bight", but that the latter is not formally or uniquely defined. However, based on sediment modelling, the potential effects of proposed sand-mining activities on primary productivity are likely limited almost entirely within the boundaries of the SMD almost all of the time; effects outside the SMD are considered to be very minor, infrequent, and likely indistinguishable from background variation.

3 Predicted effects on primary production

3.1 Water column primary production

3.1.1 Factors affecting phytoplankton PP in the SMD

The STB regional oceanography and the factors leading to phytoplankton blooms in this region have been studied (Bowman et al., 1983; Bradford et al. 1986; Zeldis et al., 2013). It is believed that, in general, phytoplankton PP in the SMD is limited by the supply of nutrients to the region rather than by light availability. Nutrients (especially nitrate, but also silicate and phosphate) enter the SMD area from three sources: (1) downstream oceanographic effects from upwelling off Kahurangi/Farewell Spit; (2) intrusions of water through Cook Strait; (3) river water bringing land-run off into the coastal region.

Wind patterns drive much, but not all of the circulation variation in the SMD (Hadfield and Macdonald, 2015). The nutrient supply process (1) is likely to be most important in leading to phytoplankton blooms in the central SMD. Water upwelled off Farewell Spit and advected into the SMD is likely to contain higher nutrients than water in the SMD. As this higher nutrient water moves through the SMD it supports new, local phytoplankton production. When advected waters enter shallower portions of the SMD, mixing depths are constrained and phytoplankton have better access to both nutrients and light. The relationships between photosynthesis, light and growth interact with nutrient limitation. When nitrogen is limiting, the carbon to nitrogen (C:N) and carbon to chlorophyll ratios within cells tend to increase, as carbon is accrued by photosynthesis faster than nitrogen becomes available to synthesise proteins and photosynthetic pigments. Thus cell growth rate decreases for a given rate of photosynthesis as nitrogen becomes increasingly limiting (Spilling et al., 2015). Torres et al. (2015), for example, show what appears to be advection of water enriched in chlorophyll, which has been fuelled by Kahurangi upwelling, into the SMD across its southwest boundary.

How important is advected fixed carbon and nitrogen? Advection of carbon and nitrogen are not expected to be influenced by the mining operation, but could be important in regulating the background conditions against which changes need to be viewed. The circulation models (Hadfield 2013; Hadfield and Macdonald 2015) and their outputs allow calculation of advective exchanges in and out of the SMD. Flow vector analyses for the oceanic boundaries of the SMD yield average exchange values of 0.244×10^6 m^3 s^{-1} and 0.230×10^6 m^3 s^{-1} in winter and summer, respectively. Converting these values into daily volumes and comparing them to the total water volume of the SMD (4.30×10^{11} m^3; Dr. Helen MacDonald, NIWA, pers. comm.) allows estimates of daily exchange rates of 4.8 and 6.0 %, respectively, assuming the whole water column is mixing. These results suggest that average residence time of water in the SMD is of the order of ~ 2-3 weeks and, as individual phytoplankton cells may only live for a day or two before they are eaten, die, or otherwise leave the photic zone, lends support to the idea that most phytoplankton production occurs *in situ* in the SMD, although advection cannot be fully ignored as a source or sink of organic matter.

3.1.2 Changes to phytoplankton PP due to mining

Additional suspended sediment introduced into the water column by mining will affect water clarity and water colour. Changes in colour (spectral signatures) of light could affect phytoplankton growth but are likely to be less important than changes to the intensity of light in the water column (Falkowski & Raven, 1997).

Mining and resulting sediment release will reduce the intensity of light in the water column because the sediment absorbs and backscatters light and hence reduces light penetration through the water. Reduced light in the water column will reduce the amount of growth of phytoplankton, but the effect is neither linear nor easily predictable. The effect of changing light effluence (E) on phytoplankton photosynthetic rate (P) is usually described by a "P-E curve" (Kirk, 2011). P-E curves have two main parts. At low light intensity, production is proportional to light intensity, i.e., more light means more phytoplankton photosynthesis. At some point, however, phytoplankton production becomes saturated with respect to light intensity ("photo-saturation"). Above this light intensity, normally called the saturation intensity (E_k), increasing the light intensity does not increase photosynthetic rate, and light energy is spilled rather than used for primary production. Phytoplankton are constantly changing their light-capture physiology (and hence the shape of their P-E curves) to maximise their growth rates – this is called photo-adaptation. The shape of the P-E curve and the fact that phytoplankton can photo-adapt quickly to better use different lighting conditions means that a reduction in the amount of light in the water column will lead to lower phytoplankton PP, but the change in PP will be less than (maybe much less than) proportional to the change in light availability. Given the general acceptance that nutrients are in limiting supply in the SMD (Bradford et al., 1986), any increase in light limitation can increase the relative availability of nutrient relative to carbon and lead to, for example, increased cell chlorophyll content that will enhance light harvesting. It is likely that the reduction in phytoplankton PP will be substantially lower than the changes in average light in the water column because photo-adaptation by phytoplankton will be able to offset the effect of lower light. The proportional impact of reduced water column irradiance will also be reduced should phytoplankton be constrained within a mixed layer that is significantly shallower than Z_{eu}, although Z_{eu} and mixed layer depth are similar near the mining site. Model data predict summer mixed layer depths of 15-25 m (Dr. Helen Macdonald, NIWA, pers. comm.), which compare well with those presented by Bradford et al. (1986), and are shallower than model estimates of Z_{eu} for much of the model domain (Pinkerton & Gall, 2015). The biggest reductions in water clarity do, however, occur in areas that are 20-35 m deep, where the euphotic zone depths tend to be close to the mixed layer depths, and thus this effect is likely to be small.

It is not possible to estimate the degree to which phytoplankton will photo-adapt to reduced water clarity in the SMD following the proposed mining operation, nor the interactions with mixed layer depth and nitrogen limitation on photo-saturation. Obtaining the necessary information would entail a very extensive field operation. Even then, the reliability of the predictions would likely be low, as variability in phytoplankton populations and their physiology is normally quite substantial. Bradford et al. (1986), for example, show that one photosynthetic parameter – the rate of carbon fixation per unit chlorophyll – varies within the SMD from <2 to >8 mg C (mg chla)$^{-1}$ h^{-1} during one study cruise. Acknowledging the uncertainties in the estimate, and given that photo-saturation and photo-adaptation will reduce the extent to which reduced water clarity will directly impact on photosynthesis, we suggest that a reasonable estimate of the change in average water column PP across the SMD as a result of shading by sediment is half the change of water column light, i.e., a 10% reduction in water column light would lead to a 5% reduction in phytoplankton PP.

3.1.3 Changes to water column light intensity

We calculated the amount of light energy in the water column as the integral of irradiance by depth to the total water depth. Calculations were made for each 1 km^2 cell in the SMD model domain for each model realisation over the two years of model simulations and summed. This integral increases with distance away from the coast because suspended sediment, chromophoric dissolved organic matter (CDOM) and elevated phytoplankton concentrations near the coast remove light from the water, and because offshore water columns are deep enough for total depth to easily exceed euphotic depth. In a mixed water column the amount of light absorbed by phytoplankton will be proportional to this integral, and it is thus a measure of energy potentially available for photosynthesis. The modelled effects of mining on this water column light integral are summarised in Table 3-1.

There are large reductions in light in the water column close to the location of mining, with maximum reductions of 46 or 27% depending on where the mining takes place (site A or site B), while the median change was <0.5%, indicating that most of the SMD was virtually unaffected (Pinkerton & Gall 2015, table 6-4. Note that the maximum depends on the resolution of the modelling – cells smaller than the 1 km scale used here would give higher maximum changes and vice versa. Given the tendency for the mining plume to spread as temporary packets over the SMD, the change in water column light averaged over the SMD is a more integrated measure of the predicted effect of mining on primary production in the water column than a point estimate near the mining site. The modeled mean change in water column light due to mining at site A over the SMD region was **-1.9%** and for mining at site B it was **-1.6%.** The reduction in primary production by phytoplankton at the scale of the SMD is hence estimated to be about 0.8 – 1.0%, and this effect was focused close to the operational site.

Table 3-1: Modelled effect of mining on water column light flux. The change in mean water column light over the Sediment Model Domain (SMD) is used to estimate the effect of mining on primary production by phytoplankton at the scale of the SMD. A factor of 50% is used to account for photo-adaptation of phytoplankton.

Measure of water column light	**Background**	**Site A**	**Site B**
Mean water column light over entire SMD (mol photons m^{-2} d^{-1})	5.5	5.4	5.4
Change in Mean water column light over the SMD (%)		-1.9	-1.6
Maximum change per 1 km^2 cell (%)		-45.5*	-26.6*
Predicted mean change in phytoplankton primary production over SMD (%)		-1.0	-0.8

* “Maximum change” is predicted to occur at the point of active mining, essentially within the 1 km cell centred on mining activity. This maximum value is hence sensitive to the spatial resolution of the sediment model (here 1 km^2) and of low ecological significance.

Bradford et al. (1986) measured phytoplankton production *in situ* in the South Taranaki Bight and adjacent waters, and as far as we are aware these are the only direct estimates. Their estimates exhibited variability at several scales of space and time: on the order of 50% within 2-5 days across the SMD. We note that predicted effects of changes in light flux on phytoplankton primary production caused by mining at the SMD scale are significantly smaller than these estimates of variability from field measures and that the predicted effects would almost certainly be statistically insignificant – essentially undetectable when considering the SMD as a whole. Biomass-normalized production estimated by Bradford et al. (1986) was typically in the range of 2-6 mg C (mg chl a)$^{-1}$ h^{-1}, values indicating nutrient-limitation, although Bradford et al. (1986) also indicated that they considered phytoplankton production in the South Taranaki Bight region to be controlled by mixing depth or advection (presumably of nutrients) and grazing.

The literature demonstrates that nutrient levels in sediment pore waters can be considerably higher than in the overlying water column (e.g., Hochard et al. 2012) leading to the hypothesis that mining activity, which would release sediment pore water in direct proportion to mining rate, could stimulate primary production in the SMD. Using a conservative value of 50 µM for the pore water sediment concentration of ammonium (many literature values are higher), estimates of 8,000 tonnes sediment mined h^{-1}, mining during 80% of each day, and values for sediment bulk density and porosity from Dr. M. Dearnaley (HR Wallingford, 2015), we estimated a release rate of 70 mol NH_4^+-N h^{-1} by average mining activity, or 1680 mol N d^{-1}. Averaged over the water volume of the SMD (4.30 x 10^{11} m^3, as above), yields a daily average increase in NH_4-N concentration over the SMD of 3.9 x 10^{-3}nanomolar. This value is well below the sensitivity of conventional ammonium-N measurement techniques (typically ~100 nanomolar), i.e., an undetectable and insignificant change. Note, however, that added ammonium will disperse almost exactly as the sediment plume disperses, supporting a slight increase in primary production that depends on how rapidly the plume disperses and how rapidly light limitation by the sediment plume is relieved, so a slight increase in production may occur locally. This increase is estimated to be <1% of the reduction in water column PP caused by the shading so is insignificant at the scale of the SMD.

3.2 Benthic (seabed) primary production

3.2.1 Benthic primary producers

The consequences of reduced light at the seabed for benthic PP depend on what macroalgae (seaweed) and benthic microalgae or microphytobenthos (MPB) are present. Areas with a hard substrate and where more than about 0.1–1% of surface light often reaches the seabed are likely to have macroalgae present. Hard substrate in the SMD occurs at the Traps (Figure 1-2), in other small rocky outcrops and shell debris fields and cobbles around the deep margins of the banks, and in some rocky reef areas. Where macroalgae are present, reductions to the average light at the seabed will potentially reduce their growth rates, if they are light limited, and may reduce the area over which they can live if their minimum light requirement (the compensation irradiance) is no longer met.

Microphytobenthos (MPB) may be present where there is no hard substrate but where seabed daily light is more than their compensation irradiance (Huettel et al., 2014). When MPB are present, reductions in the average light at the seabed will again potentially reduce their growth rates and the area over which they can live. We have no measurements confirming the presence or absence of MPB in the SMD but it is likely they occur there as they are known to live in similar environments in other parts of the world (e.g., Cahoon, 1999; Huettel et al., 2014). Photography of bottom habitats in the area of the proposed mining activity reveals sediment-water interface features consistent with the presence of MPB (colour, sediment coherence). Thus we assume non-trivial concentrations of MPB across areas of the SMD with adequate sea floor irradiance.

3.2.2 Light at the seabed

The amount of light reaching the seabed was modelled before and after mining over the SMD and results are summarised in Table 3-5 (p. 26) and Figure 3-1 (a & b).The average proportions of the seabed in the SMD with mean light intensity greater than two limits (0.04 and 0.4 mol $m^{-2}d^{-1}$) were estimated to be 29% and 11% of the SMD respectively (3805 km^2 and 1494 km^2).Within the area with 0.4 mol m^{-2} d^{-1} under background conditions, the median reduction is 8.5%, while a 10% reduction in light dose is expected for 43% of the area, a 20% reduction for 31% of the area and a 50% reduction for 13% of the area (Figure 3-1, a & b).

The value of 0.4 $molm^{-2}d^{-1}$ corresponds to MPB depth limits reported from other ecosystems (Cahoon, 1999), but lies above the lowest light level reported to support viable MPB, which is closer to 0.04 $molm^{-2}d^{-1}$(McGee et al., 2008). A value of 0.4 mol m^{-2} d^{-1} is approximately equivalent to 1% of light incident to the sea surface, the value used earlier as the base of the euphotic zone for phytoplankton, and is likely to represent an irradiance at which sufficient carbon is fixed to support a small amount of secondary productivity. Attard et al. (2014) report instantaneous compensation irradiance for Arctic MPB of 4 to >60 µmol m^{-2} s^{-1},which converts to 0.2 to >2 mol m^{-2} d^{-1}, assuming a 12 h day, suggesting that 0.4 mol m^{-2} d^{-1} is a conservative value to use. Based on optical modelling of the background scenario, the area where benthic production can be expected is that bounded by the 30-35 m contour, and mainly comprises a series of ridges, the Patea Banks, which rise more or less steeply to less than 20 m depth in a sector between north and east of the proposed mining site. Graham Bank and the North and South Traps (<2 km apart) are located within this area (Figure 1-2). Under background conditions, models suggest that water clarity close to shore is naturally variable, and benthic communities in this area are likely to be pre-adapted to a variable irradiance regime. Short exposures to low irradiance can be accommodated by benthic communities, but a chronic alteration in light dose can be expected to impact on system integrity. Based on six complete years of MODIS-Aqua satellite data, the standard deviation of the total amount of light at the sea-bed in the SMD in a one year period was 25%. In the period for which we have satellite observations (2002–2008), years were observed when the total annual light at the seabed was up to 35% greater than average and years when it was up to 32% lower than average. The predicted change in seabed light over an annual period due to mining (15–23%) lies well within this range of natural variability in seabed light.

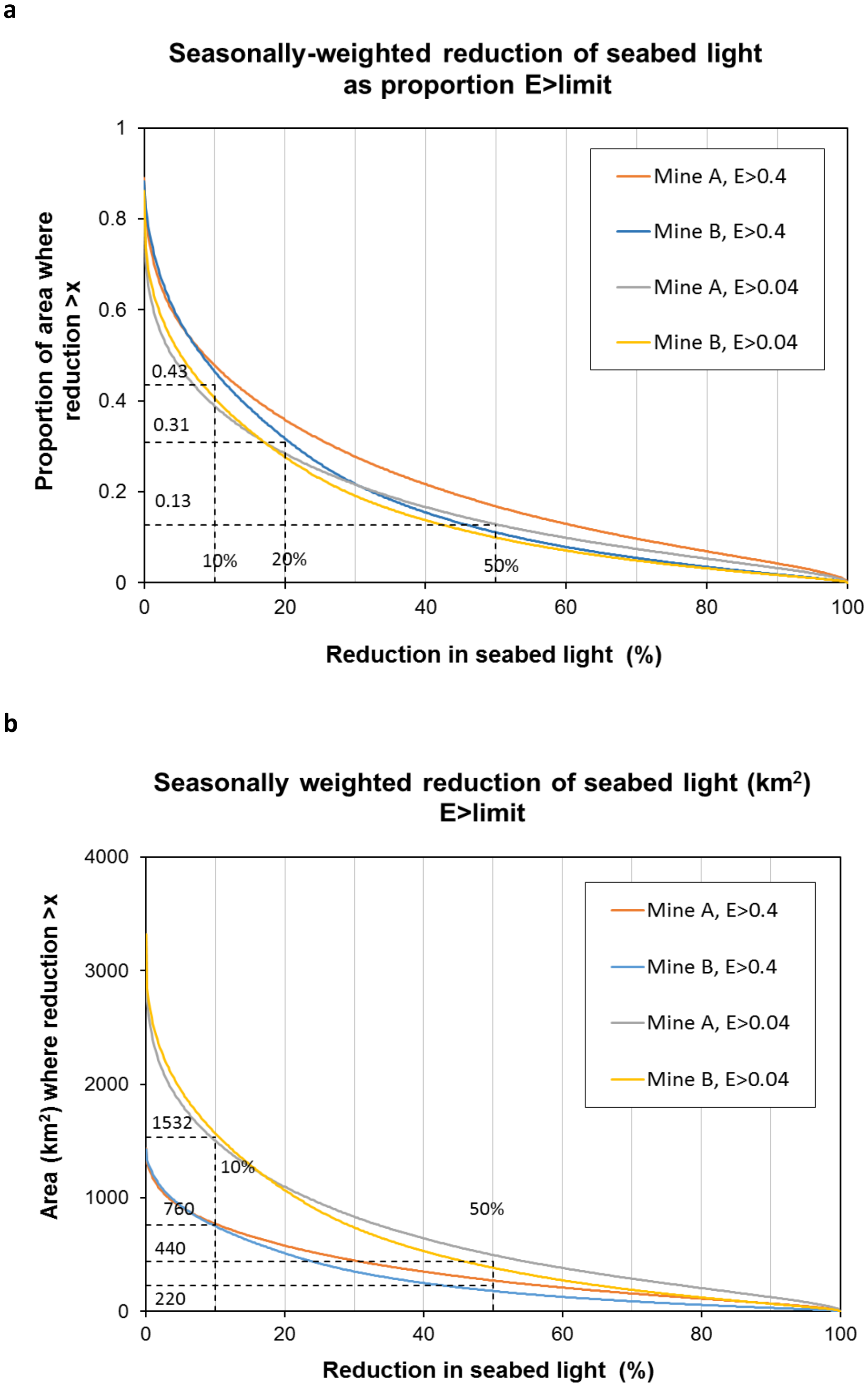

Figure 3-1.Predicted effect of proposed mining at site A and site B on seabed light in the Sediment Model Domain (SMD), part of the South Taranaki Bight (STB). The y-axis shows the proportion of the seabed area of the SMD that, in the absence of mining receives more than 0.4 or 0.04 molm^{-2}d^{-1}, and with mining has this light reduced by the amount shown on the x-axis (% reduction). The figures shown by the dashed lines are the averages of the four lines. For example, about 43% of the area of seabed in the SMD that has "enough light for microphytobenthos" will experience a reduction in light of more than 10%. But, only about 13% of the SMD which is likely to have MPB will experience a reduction in light of more than 50%. These plots have seasonal weightings included in light at the seabed – the weighting is a sinusoid of annual period so that midsummer is 3

times greater than midwinter, and the mean is unity. This seasonal weighting allows for light to be more important for PP by MPB in the summer than the winter.

The effect of mining is to reduce the amount of light reaching the seabed because the sediment plume absorbs and backscatters some light in the water column. Consequently, there are large reductions in light at the seabed close to the location of mining, with maximum reductions in model cells centred on the modelled mining sites (A and B, Figure 1-2) of 91–95%, depending a little on where the mining takes place (site A or site B). Note that this maximum reduction depends on the spatial resolution of the modelling (how big the "cells" are in the model); smaller cells (higher resolution modelling) would give a higher maximum change in smaller cells and vice versa. Dispersal of the plume from the mining site is expected to be as irregular streams and packets, depending on prevailing wind stress, and areas of sea bed away from the mining site will experience a range from little effect, to substantial effect infrequently, to frequent substantial effect.

While it was reasonable to consider the impact of reduced water clarity on phytoplankton on an SMD-wide basis, it is less so for spatially fixed benthic communities. While other areas are impacted to some degree, the area most affected by the activity is slightly south of east of the mining site, where the median plume tends to run parallel to the shore over the 20-30 m depth zone on the southern slope of the Patea Banks, including over Graham Bank. This is the area where the most chronic effect of declining water clarity can be expected on benthic primary producers.

3.2.3 Effects of changes in seabed light on macroalgae

PP by macroalgae is likely to be small relative to water column (phytoplankton) PP because of the small area of hard substrate at the scale of the SMD and the restriction of macroalgae to the bottom vs. the 3-dimensional distribution of phytoplankton. However, despite the sparse distribution of suitable substrate for macroalgae, their importance as substrate and habitat for many organisms may be disproportionately important relative to their overall productivity, at least locally. The optical model predicts that the most substantial reduction of total light energy reaching the seabed will be to the east of the mining site. This area includes a number of shallow rock outcrops, mostly northeast of the proposed mining site (Beaumont et al. 2013, figure 7), including Graham Bank (Figure 1-2), which currently receive sufficient light for macroalgal growth. Model predictions suggest that this area will be reduced to approximately 50% of the background irradiance during mining at site A and 75% during mining at site B, though the shallowest parts of Graham Bank will continue to receive more than 1 mol m^{-2} d^{-1}, on average. Mining impacts can thus at times be expected to significantly impact on growth of any macroalgae on Graham Bank, though elimination is unlikely.

The area of the Traps is more than 20 km away from the mining site (Figure 1-2), and is known to support macroalgae. It is likely to be affected by changes in bottom irradiance, but an annual average of more than 1 mol m^{-2} d^{-1} of light is anticipated to reach the sea bed there under all model scenarios, integrated reductions in sea floor irradiance and euphotic depth are less than 10%, and impacts on macroalgae at those sites can be expected to be minor. The median number of days with more than 1% incident light at the average seabed depth in the 1 km^2 model pixels in which the Traps are located (18 m) is predicted to reduce from 138 days/year (background) to 106 d/y (mining at site A) and 127 d/y (mining at site B; table 6-1, Pinkerton & Gall, 2015). The median euphotic zone depth at the Traps is predicted to reduce from 14.9 m to 13.3 m (mining at site A) and 14.4 m (mining at site B). So, as at Graham Bank, some reduction in macroalgal growth and coverage may occur at the Traps.

The other location where attached algae are recorded within the area of interest are south and southeast of the proposed site, between the 40-50 m contours, where attached coralline red algae were growing (Beaumont et al., 2013, figure 55 d). Coralline algae are well known to be tolerant of extreme low irradiance, and their occurrence in association with biogenic habitat (shells) at this depth is not surprising. However, comparing the area indicated as habitat for deep corallines by Beaumont et al. (2013, figure 55 d) with the projected impact on seabed light (Pinkerton & Gall, 2015, figure 6-21) shows that it is likely to be virtually unaffected by mining at site A and only intermittently by mining at site B.

3.2.4 Effects of changes in seabed light on microphytobenthos (MPB)

Overall, the prediction is that mining may reduce the area receiving more than the 0.4 and 0.04 mol m^{-2} d^{-1} thresholds by 14-17%, and 6-7% (respectively), depending on the scale and exact location (Pinkerton & Gall, table 6-4). The area of seabed expected to see the greatest reduction in irradiance due to mining is over the eastern Patea Banks, where the dominant benthic primary producer is likely to be MPB (Figure 1-2).

In addition to reduction in the area likely to support MPB, chronic reduction in light dose is expected to impact primary productivity. However, there is no information on background primary productivity of MPB in the SMD, and estimating the scale and significance of any change is difficult. Pinkerton (2014) assumed that growth rates of MPB in the SMD are likely to be predominantly limited by light availability rather than nutrient concentrations, temperature or other factors, such that a 1:1 relationship between reduction in light and reduction in photosynthesis would ensue. This assumed a linear P-E relationship, rather than the saturating model described for phytoplankton in Section 3.1.1 above. There is some literature data to support a linear relationship (e.g., Jahnke et al., 2008) and some that refutes it (Longphuirt et al., 2007; Attard et al., 2014) but an assumption of linearity, rather than saturation, is a conservative approach. Linear relationships in the literature, however, are often at different slopes for populations at different depths and different seasons (e.g., Jahnke et al., 2008), so below we have tested the sensitivity of the model to this possibility.

Like phytoplankton, MPB can become photo-saturated and are able to photo-adapt to reduced light (Cahoon, 2014). The literature identifies multiple mechanisms by which MPB may increase photosynthetic efficiency at low light levels. MPB cells may increase the numbers of photosynthetic units (pigment-protein complexes responsible for light reactions), a substantial shift in cellular resource allocation that is known to occur on the order of hours during diel changes in light flux. Deeper waters with lower light flux are also exposed to shifts in the spectral composition of ambient light, with relatively higher proportions of blue light. One adaptive response is an increase in the proportion of blue light-absorbing accessory pigments, such as fucoxanthin, in the photosynthetic unit (Jesus et al., 2009; Cahoon et al., 1992). Additional modes of adaptation are highly likely but less well studied (Serodio et al., 2007). These may include: 1) shifts in MPB species composition toward low-light efficient species, 2) expression of more efficient enzymes in the photosynthetic process, 3) physiological shifts favouring rapid electron fluxes among pigment-protein complexes in the light reactions, and 4) alterations of carboxylases and other enzymes in the dark reactions.

Photo-adaptation of MPB would make the change in PP by MPB less than proportional to changes in light. To investigate the degree to which photo-adaptation may affect the change in PP by MPB, Cahoon (2014) combined data on the shapes of the P-E curves of MPB from several studies

(Barranguet et al., 1998, Hartig et al., 1998, and Uthicke, 2006) by normalising α (slope of the P-E curve, in this case normalised to biomass rather than area) and E_k (saturating irradiance), and then calculated a linear regression (Equation 3-1). The normalisation by α_{max} and E_{kmax} was done within each study separately assuming that there was an α_{max} and E_{kmax} value that applied to each "community" of MPB that occurred in a given area at a given time under a given set of environmental conditions.

$$\frac{\alpha}{\alpha_{max}} = 0.68 - 0.275\frac{E_k}{E_{kmax}} \qquad \text{[Equation 3-1]}$$

This regression was significant (F=4.16, df=1,54, p=0.0462; Cahoon 2014). The negative slope indicates that at lower light α/α_{max} increases, implying that MPB become more efficient at using light for PP, i.e., the regression provides evidence of photo-adaptation. The production rate of MPB, normalised to biomass, P_B, can be calculated as the product of α and E_k (Equation 3-2; Figure 3-). It can be seen from Figure 3- that reductions of E_k in the upper half of the E_k range lead to reductions in P that are less than proportional (i.e. the curve is quite flat). In contrast, in the lower half of the E_k range, reductions in E_k lead to reductions in P that are more than proportional (i.e., the curve is steeper than the dashed line) although the MPB production rate is always greater than that in the absence of photo-adaptation (the blue line is always above the dashed line in Figure 3-2).

$$P \propto \frac{E_k}{E_{kmax}}\left(0.68 - 0.275\frac{E_k}{E_{kmax}}\right) \qquad \text{[Equation 3-2]}$$

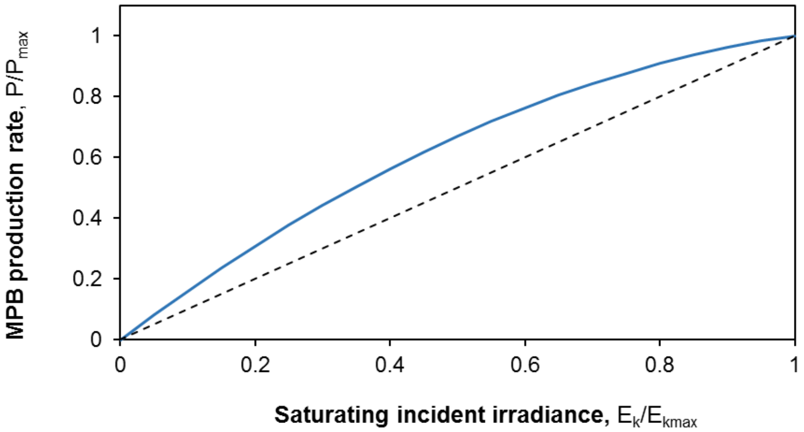

Figure 3-2: Production rate (P) of microphytobenthos (MPB) at saturating irradiance (E_k) as a function of E_k. The blue line is estimated by Equation 8-2, assuming a maximum production rate of 1. The dashed line shows the relationship in the absence of photo-adaptation.

Cahoon (2014) suggested that Equation 3-2 can be used to estimate likely changes to MPB production in the SMD due to the shading effect of suspended sediment from the mining plume. As this relationship is biomass specific, it can be converted to area only by combining with an estimate of biomass, or rather an estimate of the variability of biomass across space (particularly depth) and time (season).Cahoon (2014) noted that two further assumptions are required: 1) MPB in the SMD adjust their photosynthetic physiologies with respect to ambient irradiance similarly to the MPB studied in the literature, specifically the three studies from which the regression equation above was derived. That is a reasonable assumption, given the overlap in likely light regimes; 2) MPB in the SMD are adapted to ambient light fields such that they are more or less functioning at optimum photosynthetic rates, i.e., E_k for them is at or above average maximum ambient light flux they experience and there is no saturation effect. Given that organisms are adapted to live in the environment in which they are found, and that viable MPB are found elsewhere at depths and light levels similar to those found in much of the SMD and often show this behaviour, this is also likely to be a safe assumption.

The assumption of no change in biomass by location, depth and season is less reasonable, but there are no data for estimating the likely variability of MPB biomass over space and time for the SMD. Perhaps the most useful literature dataset comes from Nelson et al., (1999), who showed, for the South Atlantic Bight, substantial (50%) variability among replicate samples, but a distinct seasonal trend (summer up to five times winter) and a midwater depth optimum at 27-35 m, declining at shallower and deeper depths. These authors noted the importance of storm events in driving biomass down, a process likely to be important in the exposed sections of the Patea Banks especially in shallow water, during winter. We conducted a sensitivity analysis of the effect of seasonal changes to the biomass of MPB by assuming that absorption of seabed light by MPB was three times higher in midsummer than in midwinter, with an annual sinusoidal variation over the year. The modelling showed that the proportional reduction in light at the seabed was not substantially changed by such seasonal variation in MPB biomass.

Pinkerton (2014) assumed biomass and biomass-specific production, P_{max}, to be constant over time and depth, to allow estimates of differences between seabed irradiance with no mining (background) and with mining at site A and site B to be used to assess the proportional change to MPB production within the SMD. Adding the effects of photo-acclimation into this analysis only required the appropriate E_{kmax} value to be determined, i.e., where on the curve in Figure 3- are the MPB in the background case? To do this, we estimated E_{kmax} as the 95th percentile of the modelled seabed light over the whole area at each model time-step, assuming P_{max} was constant and constraining E_k/E_{kmax} to be less than 1.

The results of applying these methods are shown in Table 3-2.Mining is predicted to reduce PP by benthic primary producers (MPB) by ~19% (mining at site A) or ~13% (mining at site B) (Table 3-5). As discussed above, most of this estimated change is accounted for by reductions in irradiance over the eastern part of the Patea Banks, where integrated irradiance is reduced by 30-50%. Of the assumptions made in this estimation most likely to bias, rather than scatter, this estimate is the assumption of constant biomass by depth and time.

Table 3-2: Estimates of changes to microphytobenthos (MPB) primary production (PP). "95th %" means the 95th percentile. "Change in E" is the changes in average irradiance at the seabed. "Factor" is the ratio of the change in PP to the change in seabed light (an indication of the effect of photo-adaptation).

	Summary of how E_{kmax} was calculated	**Mining at site A**			**Mining at site B**		
		Change in E	Change in PP	Factor	Change in E	Change in PP	Factor
	95th % across all cells for each time	0.227	0.193	0.85	0.155	0.134	0.87

3.2.5 Effects of sedimentation on microphytobenthos

The sediment transport model (Dr. M. Dearnaley, HR Wallingford, 2015) describes the expected deposition of sediment on the sea bottom outside the mining pit, where most of the effluent sediment is expected to be deposited during normal mining operations. Average values of sediment deposition over the SMD are on the order of 0.5 to 1 mm per year, which would be almost indistinguishable from background. Microphytobenthos are adapted to an episodically disturbed sediment-water interface environment in which both physical perturbation ("resuspension events" induced by high flow velocities) and biological activity (deposit feeding and other bioturbation, particularly by benthic macrofauna) are the norm. Many microphytobenthos species are motile, e.g., flagellated forms, most monoraphic diatoms and biraphic diatoms. The diatoms, in particular represent an assemblage highly adapted to life at the sediment-water interface in continental shelf ecosystems, e.g., Cahoon & Laws, 1993; McGee et al., 2008). The distinction between phytoplankton and MPB is not a clean one, however, as an intermediate group, sometimes termed "tychopelagic", denoting microalgae that are easily resuspended into the water and then settle back to the bottom (Cahoon &Laws, 1993), can be found in both assemblages. Tychopelagic forms are adapted to disturbance and resulting fluctuations in access to light and nutrients.

3.3 Effects on total primary production and fixed carbon flow to benthos

3.3.1 Summary of effects

Our estimates of the effects of mining activities on primary production are thus that (a) effects on planktonic production will be minor at the scale of the SMD, and difficult to distinguish from background variability, and (b) effects on macroalgae are likely to be small at the scale of the SMD, with little impact on deep coralline algae, which are well-adapted to very low light levels. In some situations, e.g., a possible reduction in colonisation depth and growth rates at the Traps, more locally significant impacts may occur. Isolated rocky reef outcrops immediately east of the proposed mining site, which rise to 17m below chart datum, potentially support macroalgae, and during mining operations at Site A these could be more severely impacted. Effects on MPB are predicted to be more substantial, but are expected to be focussed on the eastern side of the Patea Banks (Figure 1-2), where frequent, substantial reductions of irradiance relative to background can be expected. This area includes deeper MPB habitat, where a small absolute decrease in irradiance can reduce irradiances below the threshold for MPB growth but where MPB biomass may naturally be expected to be low. Impacts of mining activities on fixed carbon flux within the SMD will thus depend largely on the extent to which local MPB production is important to benthic communities on the Patea Banks. The fact that predicted variations in seabed light due to mining are likely to be well within natural interannual variability, however, is also relevant to determining the likely ecological significance of such effects.

Our ability to quantitatively predict effects on MPB primary production is limited by the absence of useful information on primary producer dynamics and P-E curves. Our best estimates are that reductions will be slightly less than proportional to the reduction in light reaching the sea floor. The question then is how to place reduction in the context of carbon flux to benthic communities on the eastern Patea Banks? The significance largely depends on the relative importance of MPB production and transfer rates of carbon from the water column, (sedimenting carbon is not expected to change significantly as planktonic production is not expected to change significantly, and carbon advected from further away from the mining site will not be affected by mining). In the absence of either New Zealand-specific or useful international data, we are forced to address this by combining literature values of the ratio of planktonic to benthic production and of planktonic production to carbon export to sediments.

3.3.2 Ratio of water column to benthic primary production

A recent review of the biogeochemistry of permeable sediments (Huettel et al., 2014) stated that: "Primary production of the benthic phototrophs is a major source of organic matter in permeable coastal sands and is within a factor of two of primary production in the overlying waters." In general, such approximations relate to production integrated over a depth range and as depth increases below the benthic biomass optimum, the relative and absolute contributions of MPB will tend to decrease. Jahnke et al. (2008) describe an example where benthic production declined 5-fold from 14 to 40 m, showing how the ratio of water column:benthic production will increase substantially as Z_{eu} is approached. For an integrated coastal zone, values of 2:1 planktonic:benthic production are conservative based on the data produced in Huettel et al. (2014), while at depths approaching Z_{eu}ratios where five-fold reductions in benthic production are reported, 10:1 may be more realistic (Cahoon, 1999).

3.3.3 Detrital flux transfer between the water column and sea-bed

Transfer rates of material from the water column to the seabed in shallow (<250 m), energetic shelf-seas are also poorly known and are very difficult to measure. In a review of transfers between the water column and seabed in open waters, Boyd & Trull (2007) state: "The fraction of [water column PP] exported from the surface ocean is generally in the range of 2–20%". How this translates to shallow coastal regions in unclear, but in a food web model of the Hauraki Gulf (Pinkerton, 2011), the fraction of water column PP transferred to the seabed was 17% and respiration measurements from the Hauraki Gulf suggest a similar result (Dr John Zeldis, NIWA, pers. comm.). The amount of flux transfer between the water column and the seabed in the SMD is not known and obtaining this information is not practicable. For the purposes of considering the effects of mining in the SMD and acknowledging the considerable variation under natural conditions, we elected to estimate the proportion of water column PP which is transferred to the benthic ecosystem as 15% (range 5–25%). It is possible that the true value is less than or greater than this range. The SMD is more energetic than the Hauraki Gulf so the figure may be lower.

3.3.4 Changes at local scale

Combining these estimates allows an approximation of the proportional change in carbon flux to the benthos for given changes in MPB photosynthesis. Thus, an area where MPB production is expected to reduce by 20% (cf Figure 3-1) would have an overall reduction in carbon loading of 15% (range 13-18%) for a 2:1 PP:MPB ratio and 8% (6-13%) for a 10:1 PP:MPB ratio (Table 3-3). Where expected reduction in MPB production is 50%, total carbon flux reductions of 38% (range 33-45%) and 20% (range 14-33%) would be expected for the same scenarios. In the context of the SMD, the area of seabed that is predicted to receive more than 0.4 mol m^{-2} d^{-1}, integrated over the 2-year model timeframe under background conditions, and that is able to support productive MPB was 1494 km^2. Of that area, Figure 3-1 has shown that 31% is expected to receive reductions in bottom-reaching PAR of more than 20%, and thus might expect carbon accrual reductions of the order of 8-15%, and

13% of the colonisable area might expect PAR reductions of more than 50%, which translate to ~20-38% reductions in benthic carbon flux.

Table 3-3.Calculations of area-specific reductions in flux of carbon to the sea floor for given reductions in MPB photosynthesis assuming only MPB and PP were contributing and that PP contribution is not affected. To estimate the proportional change, the productivity of MPB is taken as X. Planktonic production is assumed to vary from 2X to 10X, and the proportion of planktonic production exported to the benthos is varied between 5, 15 and 25% (see text for derivation of values)

Calculation assumptions						
PP:MPB production ratio	2	2	2	10	10	10
PP export rate	5%	15%	25%	5%	15%	25%
Proportional reduction in total carbon flux to the benthos from a given reduction in MPB production						
50% MPB reduction	45%	38%	33%	33%	20%	14%
20% MPB reduction	18%	15%	13%	13%	8%	6%

3.3.5 Changes at the scale of the Sediment Model Domain

The approach above can be developed to determine the impact of changes to PP and MPB production on a domain-wide basis. First we weight benthic PP as a proportion of planktonic PP, using the area occupied by MPB and assuming a ratio of integrated benthic production to planktonic production in the area occupied by MPB (Table 3-4). Values used are based on Huettel et al. (2014) and are 30 or 50% for the upper MPB zone and 0 or 10% for the lower MPB zone (Table 3-4). These values are consistent with those used in Section 3.3.2 above (Table 3-3). These domain-wide calculations assume that there is no net advection of fixed carbon into or out of the SMD. A net influx of carbon would reduce the proportional change, whereas a net efflux across the domain boundaries would increase the proportional effect.

Table 3-4: Scenarios of production by microphytobenthos compared to water column. Four scenarios were used to assess the rate of net primary production (PP) by microphytobenthos (MPB) compared to net PP by phytoplankton in the overlying water column. All use the proportions of the area of the SMD with more than a given amount of light estimated from the background optical model.

	PP by MPB as proportion of PP by phytoplankton in overlying water column		Proportion of area of SMD (%) receiving a certain mean light at the seabed		
Scenario	E>0.4 mol m^{-2} d^{-1}	0.4>E>0.04 mol m^{-2} d^{-1}	E>0.4 mol m^{-2} d^{-1}	0.4>E>0.04 mol m^{-2} d^{-1}	Average PP by MPB as proportion of that by phytoplankton in the SMD (%)
1	0.5	0.5	11.2	17.4	7.4
2	0.5	0	11.2	17.4	5.6
3	0.3	0.1	11.2	17.4	5.1
4	0.3	0	11.2	17.4	3.4
Mean of four scenarios					5.4

We use Table 3-4 to develop an “average” scenario where over the entire domain MPB produce 5.4% of the planktonic production, the low value mainly being due to the bulk of the domain being too deep for MPB to grow. We define a “base case” simulation as: (a) detrital flux of 15% of water column PP (for “typical” coastal system); (b) average PP by MPB equivalent to 5.4% of water column PP, to calculate an overall fixed carbon flux to the seabed equivalent to ~20% (15 + 5.4%) of planktonic PP across the entire SMD (Figure 3-3). The impacts of changing conditions due to mining operations can then be estimated (Figure 3-3; Table 3-5). Changes to PP of phytoplankton based on changes to water column light and allowing for photo-adaptation by phytoplankton (Section 3.1.1) are ~1%. Changes to PP of microphytobenthos (MPB) are based on changes to light reaching the seabed, allowing for photo-adaptation by MPB (Section 3.2.3), which are integrated to 13% (mine A) – 19% (mine B) across the domain. The effect of the detrital flux being in the range 5–25% and the relative PP of MPB to phytoplankton being in the range 3.4–7.4% were considered. Detailed results are given in Table 3-5. The base case estimates most likely values based on information currently available and “worst-case” scenarios (largest effect) are summarised in text below. The worst-case scenarios correspond to low detrital flux rates and high PP by MPB because this makes the shading effect on the seabed more important compared to shading in the water column.

Averaged over the whole SMD area, mining at a planned rate of 5×10^7 tonnes year^{-1} is estimated to reduce **total primary productivity** (water column plus benthic) by 1.9% (mining at site A) and by 1.4% (mining at site B). The “worst-case” estimates are for a reduction in total PP over the whole SMD of 2.2% (mining at site A), and a reduction of 1.7% (mining at site B).

Averaged over the whole SMD area, mining at the planned rate is estimated to reduce **organic carbon (“food”) input to soft-sediment habitats** by 5.8% (mining at site A) and by 4.1% (mining at site B). The “worst-case” estimates are for a reduction of organic carbon flow to the seabed averaged over the whole SMD of 11.9% (mining at site A) and a reduction of 8.3% (mining at site B).

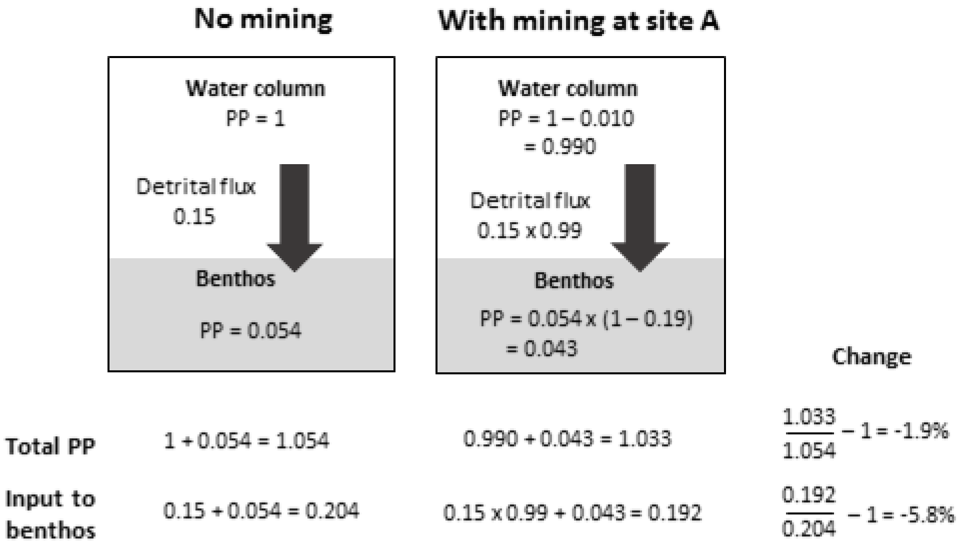

Figure 3-3: Model used to predict the effect of mining on primary productivity. The schematic shows how changes can be predicted in total primary production (PP) in the SMD ecosystem and organic carbon (a proxy for food or energy) flow into the soft-sediment ecosystem. The soft-sediment benthic ecosystem receives carbon from particulate and dissolved detrital flux from the water column and from local PP by benthic microalgae or microphytobenthos (MPB). In the example shown, the model assumes: (a) detrital flux of 15% of water column PP; (b) average PP by benthic microalgae equivalent to 5.4% of water column PP. Changes to PP of phytoplankton (1.0%) are based on changes to water column light allowing for phytoplankton photo-adaptation (Section 3.1.1). Changes to PP of MPB (19%) are based on changes to light reaching the seabed allowing for MPB photo-adaptation (Section 3.2.4).

Table 3-5: Predicted changes to optical properties and primary production. Optical properties for estimating effects on primary productivity (PP) by phytoplankton and microphytobenthos (MPB) in the Sediment Model Domain (SMD), part of the South Taranaki Bight (STB).

Parameter	Measure	Background	Mining at site A	Mining at site B
Integrated water column light as proportion of surface	SMD mean (m)	5.5	5.4	5.4
	Mean change over SMD (%)		-1.9	-1.6
	Highest point change (%)		-45.5	-26.6
Water column PP	Mean change over SMD (%)		-1.0	-0.8
	Highest point change (%)		-22.7	-13.3
Prop seabed area with light >limit (mol/m^2/d)	Area with E>0.04 (% of SMD)	28.6	26.6	26.9
	Area with E>0.4 (% of SMD)	11.2	9.4	9.7
	Change in area with E>0.04 (%)		-6.8	-6.0
	Change in area with E>0.4 (%)		-16.5	-13.8
Light at the seabed	Mean total over SMD (Gmol/d)	3.3	2.5	2.8
	Change in SMD total (%)		-22.8	-15.5
	Highest point change (%)		-95.1	-91.8
Benthic PP (MPB)	Mean change over SMD (%)		-19.3	-13.4
	Highest point change (%)		-80.7	-79.7
Total PP (water column plus benthic) over SMD	Best estimate of change (%)		-1.9	-1.4
	Lower limit of likely change (%)		-1.6	-1.2
	Upper limit of likely change (%)		-2.2	-1.7
Energy flow to seabed, total over SMD	Best estimate of change (%)		-5.8	-4.1
	Lower limit of likely change (%)		-3.1	-2.3
	Upper limit of likely change (%)		-11.9	-8.3

4 Discussion

4.1 Reliability of predictions of optical effects

This report uses results from optical modelling, which predicts the effects of a plume of fine sediment released as part of the proposed iron-sand mining operation on the optics of the SMD waters (Pinkerton & Gall, 2015). The accuracy and reliability of the predicted optical effects are dependent on the performance of the hydrodynamic model (Hadfield & Macdonald, 2015). We believe the information presented here is of an adequate quality to be useful in assessing the likely effects of the proposed iron-sand mining on primary production and fixed carbon flow to the benthic ecosystem.

4.2 Reducing uncertainty in predicted PP changes

We believe the information presented in this report represents the best available information for understanding the likely effects of the proposed iron-sand mining in the SMD on primary production, taking into account factors such as cost, effort and time. It would be difficult (scientifically and operationally) to estimate the reduction in phytoplankton PP more precisely. The best that can reasonably be done is to estimate that it lies within the broad range given above. Greatest sensitivity is to the relationship between photosynthesis and irradiance (P-E). The two key characteristics of a P-E curve are the light intensity at the transition between the linear and saturated parts (E_k), and the maximum (saturated) photosynthetic rate (P_{max}). These two factors vary considerably with factors including the type of phytoplankton, light climate (e.g., surface light intensity, depth of mixing), nutrient availability, water temperature, and photo-adaptation over biologically relevant time scales. Trying to predict the consequence of reduced light in the water column on phytoplankton production in the SMD would require two tasks: (1) an extensive field campaign to measure factors including P-E curves, water column vertical mixing rates and nutrient dynamics. This would need to encompass much of the SMD over at least one annual cycle; (2) development of a phytoplankton production model capable of representing the light climate of the SMD, nutrient supply (including nutrient regeneration due to zooplankton grazing/bloom decay), and the corresponding phytoplankton P-E curves. Precision of this model is likely to be low even given such a research campaign.

The global understanding of photosynthesis by MPB and its relative role in benthic ecosystem carbon flow is poor, as are the factors that affect these processes, yet the greatest impact of the proposed mining activity is mediated through this mechanism. Estimates of the range of possible impact based on literature values vary substantially depending on which values are used, and while we are confident that the activity can only reduce benthic production, the broad prediction envelope cannot easily be narrowed. Difficulties greater than those for PP measurements would be faced in trying to reduce uncertainties in the effect of mining on productivity by MPB; a lengthy scientific study would be unlikely to yield statistically significant predictions that differ from a “zero-impact” null hypothesis due to temporal and spatial variability in biomass and activity of the community. Indeed, the only study we are aware of describing oxygen dynamics in moderately deep sediments in New Zealand, in this case the Hauraki Gulf at 1-4% light depth and Firth of Thames at 0.02 to 11.2 % light (Giles et al., 2007), found no net oxygen production and statistically insignificant gross oxygen production by MPB, with the last in part reflecting the degree of variability within sites.

4.3 Reversibility of changes to phytoplankton and benthic PP

When mining stops, suspended sediment will gradually be flushed out of the South Taranaki Bight region. Hydrodynamic modelling suggests that this process would take at most a few months (Hadfield, 2013; Hadfield & Macdonald, 2015; note flushing rate estimates of ~5% day^{-1} in section 3.1.1). Phytoplankton and MPB may be expected to respond very quickly (a few days) to changes in water clarity. Hence, phytoplankton and benthic PP would be expected to return to pre-mining levels within at most a few months after the cessation of mining as biomasses recover. Mining will not influence the oceanographic setting, supply of nutrients to the region, the water column light climate, or the magnitudes or patterns of phytoplankton or MPB production once any suspended sediment has left the region. MPB are likely to recolonize seabed sediments deposited from the mining plume in a few weeks or months.

4.4 Wider ecosystem effects of mining via optical effects

Phytoplankton PP and biomass in the water column in the SMD naturally change from year to year – there is high inter-annual variability in PP in the SMD - because total PP depends on variable oceanographic and climate-driven processes. Six years of ocean colour satellite measurements of chl-a concentration were used to investigate the variability in phytoplankton biomass. The standard deviation (s.d.) of the average chl-a concentration calculated over a calendar year in the SMD as a proportion of the mean was 18%. Inter-annual variability in phytoplankton PP is likely to be of a similar magnitude. The facts that the phytoplankton PP averaged across the SMD model area is predicted to change by less than 1% due to mining, and that the natural, inter-annual s.d. of average chl-a is 18% imply that there is little risk of ecosystem perturbation arising from changes in water column PP due to mining. The same is true for light at the sea-bed, which is likely to vary more from year to year than is predicted to occur due to mining, at the scale of the SMD. There remains a very small risk because the change in phytoplankton PP and seabed light from mining is chronic - i.e., the mining will always lead to a net negative perturbation rather than just adding additional variability to that occurring naturally.

There is potentially a greater risk of ecological effects from mining due to changes to fixed carbon flux at the seabed from MPB PP than from the small changes expected in phytoplankton PP. Although predicted changes in fixed carbon flux to the benthic systems averaged over the SMD are small, similar to or less than inter-annual variability, it is necessary to consider that the effect is not evenly spread but spatially constrained. While much of the area currently viable for colonisation by MPB is only marginally affected, the plume-impacted area immediately east of the mining location is predicted to be impacted by reductions of up to 40% in carbon flux. Impacts on higher trophic levels depend on the importance of MPB in this area as a primary food source and the nature of the benthic consumer population. While modelling can provide guidance on the possible scale of impacts, the absence of any validation data on this critical issue cautions careful interpretation. The nature of the receiving area and its fauna can provide some insight. It mostly lies between 20-30 m depth, though rising to 15 m and falling to 40 m in places, and is described by Beaumont et al. (2013) as visually barren sand ripples (medium to coarse sand) with "*low abundances and species richness of both infauna and epifauna organisms*". Communities in these sandy regions were dominated by suspension feeders and consistent with those continually recovering from frequent disturbance. Occasional rocky outcrops supported a more diverse fauna and some fields of *Tucetona* (a conspicuous large, robust suspension-feeding bivalve) were present. Considerations of the potential impacts of modelled estimates of reductions in benthic photosynthesis need to take into account the sparse and depauperate fauna characteristic of the receiving environment, which is likely to be adapted to episodic disturbances. The condition of the longer lived elements of the benthic community in this part of the Patea Bank is not known, but may provide a more sensitive integrator of variability and trends in benthic carbon flux than direct measurements of MPB themselves.

Thus, we conclude that the inherent variability in the physical environment will ameliorate SMD-scale impacts of mining on PP. Local impacts in habitats more frequently and intensely impacted by the mining plume may be detectable, particularly elements of the benthos. Our analyses of the relevant available field data, coupled with modelling of the character of the sediment plume from mining operations, its trajectory and duration, and its optical effects, and our analyses of these effects on primary production in the SMD region strongly support the assessment that region-wide effects of iron-sand mining on short-lived organisms (living less than a year or two) will be indistinguishable within natural oceanographic variability. Effects at local scale proximal to the mining operations will likely manifest primarily as decreases in MPB production and organic carbon availability to benthic consumers that may exceed natural variability and may propagate locally to organisms that feed primarily on MPB and in turn to their predators, which may be more wide-ranging.

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