# Integrated Multi-Trophic Aquaculture for Carbon Sequestration and Shellfish Production

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## 1 Abstract

Climate change threatens to impose serious hardships on human populations throughout the world, particularly low-lying island nations. Recent research has highlighted the role of macroalgae (kelps) in providing high rates of carbon sequestration due to their high net primary production and ability to create vast quantities of organic carbon detritus which, if it is sequestered into deep ocean waters (greater than 1000 m) has the potential to remain locked away from the atmosphere for hundreds and possibly thousands of years. New Zealand is well suited to this Greenfield form of carbon sequestration due to the presence of submarine canyons leading to very deep water around its continental shelf. Blue Carbon contrasts sharply from carbon sequestration by traditional terrestrial forestry. Terrestrial forestry is only able to store carbon in a living form and, therefore, reaches maximum storage capacity very quickly. Furthermore, commercial plantation forestry systems become net carbon emitters after 90 to 140 years due to the emissions produced in forestry management, logging, milling and transportation.

## 2 Climate Change

Climate change has aptly been described as humankind's greatest moral and technical challenge. A recent World Bank report predicts that more than 800 million people reside in areas that by 2050 will become dangerous climate hotspots (World Bank, 2018). If climate change causes a 3°C increase in average surface temperatures by 2100 (which is the expectation on our current trajectory) it is estimated to result in the extinction of 3 in every 5 species currently living (Flannery, 2008). Other studies (Thomas, et al., 2004), on the basis of mid-range climate-warming scenarios (temperature increases of 1.8–2.0°C for 2050, indicate that 15–37% of species in a representative sample of regions and taxa will be 'committed to extinction'. At higher levels of temperature increase (>2°C) and where there are limited options for migration the extinction prediction increased to 38–52%. These dramatic extinction events are due to the relatively rapid rate of this change which does not allow these species to genetically adapt quickly enough. Loss of migratory pathways further prevents many from moving to compatible ecological zones at higher latitudes.

However, as emphasised by Dr Robert Glasser,[1] and the World Bank report authors themselves, presentation of the individual impacts of climate change do not adequately portray the full impact of climate change due to the "cascading" effects which are likely to be far more harmful than the immediate impacts. These cumulative impacts are difficult to accurately quantify. For example, from 2006 to 2011 Syria experienced its large-scale crop failures due to the worst drought in at least 900 years (a drought made 2-3 times more likely on account of only 0.6°C average temperature increase[2]).

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[1] Visiting Fellow at the Australian Strategic Policy Institute and is the former UN Special Representative of the Secretary General for Disaster Risk Reduction.

[2] The earth is already committed to a 1.3°C increase; a delayed impact of our emissions to date (Flannery, 2008).

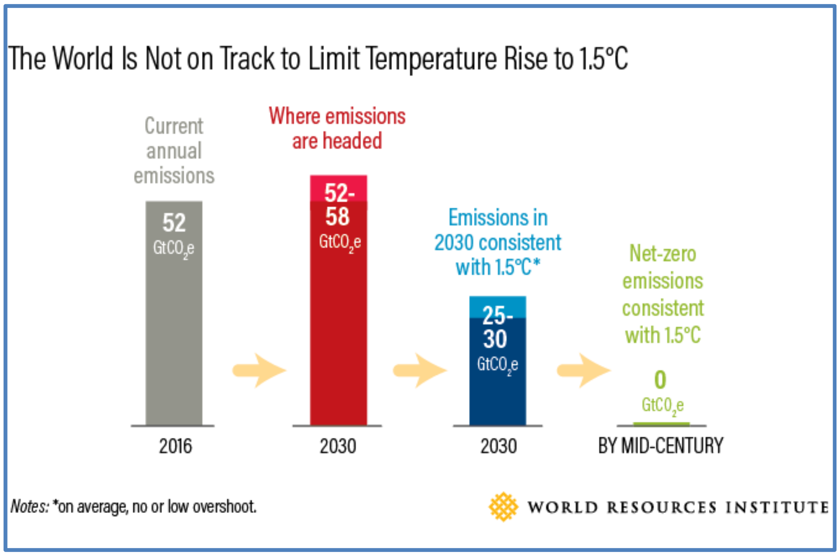

Figure 1 Current net emissions trajectory vs. that required to meet 2050 target of 1.5°C temperature rise (World Resources Institute, 2018)

This drought and the civil war have both contributed to the 6.6 million internally displaced persons and the mass migration of 5.6 million people[3] to Turkey, Europe and elsewhere; which in turn contributed to Brexit, the rise of populist governments, and an unprecedented threat to the EU's institutional survival (Glasser, 2018). The social and economic costs of this mass migration are, therefore, difficult to quantify. Likewise, it is impossible to predict the impact on humans of large-scale species loss, in a world in which we are intimately dependent upon plants, animals, insects and microbes for our food and oxygen; if their destruction alone is not enough cause for alarm.

Never before has an environmental phenomenon been scientifically studied as carefully and thoroughly as climate change. Yet its complexity and the existence of many positive feedback loops[4] make it a difficult event to model and predict. Many scientists are expressing concerns that these positive feedback loops may lead to a ***tipping point*** causing climate change to escalate at such a pace that human efforts, no matter how strenuous, will no longer be able to halt its progress (Curtin, 2018).

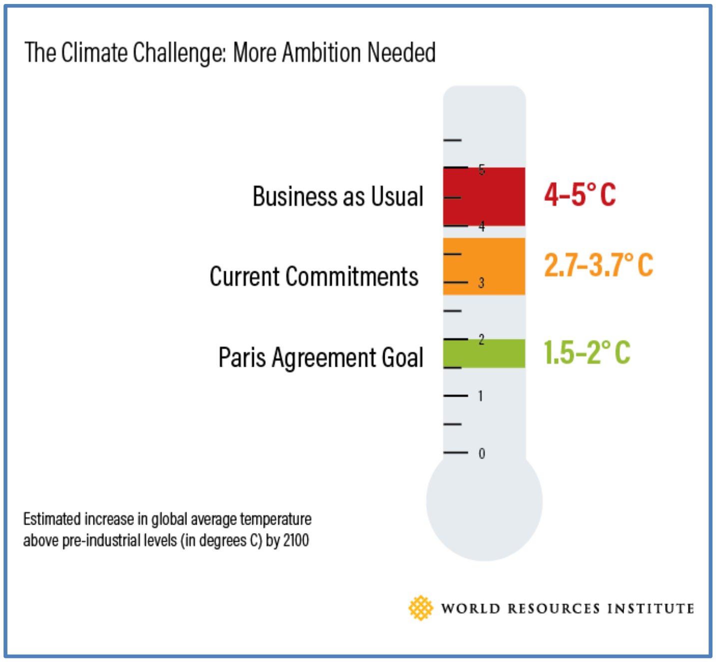

Figure 2 Global warming trajectory: No change vs. Current commitment vs. Paris goal (World Resources Institute b., 2018)

Estimates of the global emissions outcome of *current nationally stated mitigation ambitions* (as submitted under the Paris Agreement) would lead to global greenhouse gas emissions in 2030 of 52–58 Gt $CO_2$eq yr$^{-1}$ [5] (see Figure 1). Analysis reflecting these ambitions indicate **they would not limit global warming to 1.5°C**, even if supplemented by very challenging increases in the scale and ambition of emissions reductions after 2030 (IPCC, 2018). Instead our current trajectory is for a 2.7 - 3.7°C increase in average surface temperature (see Figure 2).

As can be seen in Figure 3 below, New Zealand's net emissions under the United Nations Framework Convention on Climate Change (UNFCCC) were 56.0 Mt $CO_2$-e in 2016 and

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[3] 2017 "Syria Regional Refugee Response – Overview". UNHCR Syria Regional Refugee Response. 2017

[4] For example retreating polar icecaps reduce the overall reflection of sunlight from the earth's surface and thus cause greater heat absorption (Flannery, 2008).

[5] 1 giga-tonne is one billion (1,000 million) tonnes.

emissions per person were the sixth[6] highest at 17.4 tonnes $CO_2$-e per capita amongst developed countries (NZ MFE, 2018).

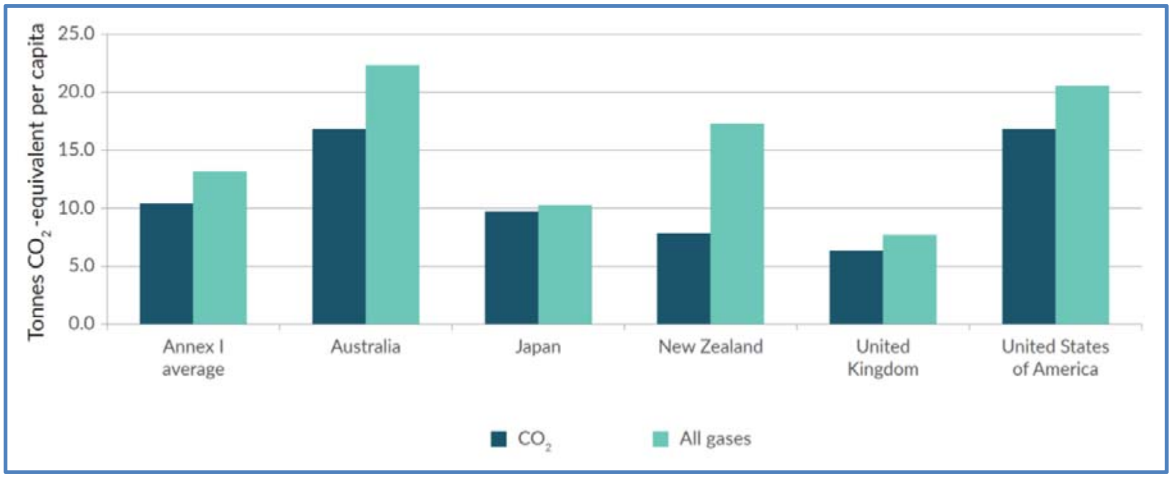

Figure 3 Comparison of per capita $CO_2$ equivalent GHG emissions in 2016 (NZ MFE, 2018)

By planting 1 billion additional trees over the next 10 years New Zealand can expect to sequester approximately 450 Mt $CO_2$ equiv. (author's calculations) based upon the current target to plant two thirds native trees and one third exotics. This will buy only 8 years emissions at the current annual net emission rate of 56 Mt $CO_2$ equiv. Even if New Zealand is able to reduce its existing annual emissions (in order to extend the benefit of these carbon offsets), these offsets (if in the form of commercial plantations) will themselves produce increased emissions in their maintenance, harvesting, processing and transporting. This is discussed in Section 5 below.

# 3 The Carbon Budget – Reaching Zero Emissions

While emissions reduction efforts (through reduced burning of fossil fuels and other GHGs) are a critical component of efforts to mitigate climate change; emissions reduction alone is insufficient to meet the 1.5°C target the IPCC claims are critical to achieve (IPCC, 2018). The 2018 IPCC SR15 report acknowledges that the 1.5°C target ***cannot be achieved*** without substantial capture and storage of carbon (CCS) which is ***already*** in the atmosphere through carbon negative technologies (i.e. not simply reduced emissions) (IPCC, 2018). Technologies for capture and geo-sequestration of atmospheric carbon are difficult and expensive[7] and at best unlikely to provide significant impact until 2060 (IPCC, 2018). Currently the most viable method of biological sequestration of atmospheric carbon is through *new* forest plantations or reafforestation of previously cleared native forests. However, even if this was socially and politically achievable, there is simply ***not enough non-food producing land*** available to achieve this (Flannery, 2008).

Furthermore, bio-sequestration of carbon with terrestrial vegetation (commercial forestry) has problems with **permanence**. The carbon in three quarters (75%) of wood products is mineralised (returned to $CO_2$) within 1 year of harvest; the remaining 25% of wood products last approximately 100 years (Ford-Robertson, 1996). With the exception of the approximately 25% of plantation wood that is used for durable wood products, and the limited quantities stored in soil, the only carbon stored by terrestrial plants is that which exists in the living plant. Most of the carbon in plant debris (lost branches and leaves) and processed wood of softwood species (the majority of commercial plantations), is quickly decomposed and returned to the atmosphere as $CO_2$. For this reason, plantations must repay the full value of carbon credits associated with the trees harvested in forests participating in the Emissions Trading Scheme (see Section 4.1 below).

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[6] In 2017 New Zealand's nearest neighbour Australia ranked 1st at about 23.97 tonnes $CO_2$-e per capita (OECD, 2017)

[7] Capturing and compressing CO2 may increase the energy needs of a coal-fired CCS plant by 25–40% (IPCC, Special report on Carbon Dioxide Capture and Storage, 2005)

Carbon captured in terrestrial forestry also runs the risk of unintentional reversal as a result of fire or other destructive events.

## 3.1 The New Zealand Emissions Trading Scheme (ETS)

As forests grow they convert atmospheric CO2 into organic hydrocarbons. By about 34 years P. radiata plantation forests have reached a net zero sequestration equilibrium (Tee, Scarpa, Marsh, & Guthrie, 2012). Up to this point the forest is sequestering carbon and accruing carbon credits which can be sold through the Emissions Trading Scheme. At the point of harvest, forest plantations incur a carbon liability equal to the carbon units removed during harvest. As forests are repeatedly grown and harvested the amount of carbon stored peaks and falls as shown in Figure 4. However, the amount of carbon sequestered never increases beyond that of the first cycle when the forest reaches maturity at about 30 years of age. After this there is no net gain from carbon credit revenue. The economic benefit following the first cycle is only the net present value gain (due to the fact that carbon credit revenue is received in advance of the post-harvest carbon liability). That is to say, for forests commencing from bare land, after cycle 1, foresters participating in the ETS benefit only from a cash advance (in the form of carbon credit sales) against the liability to be repaid at time of harvest.

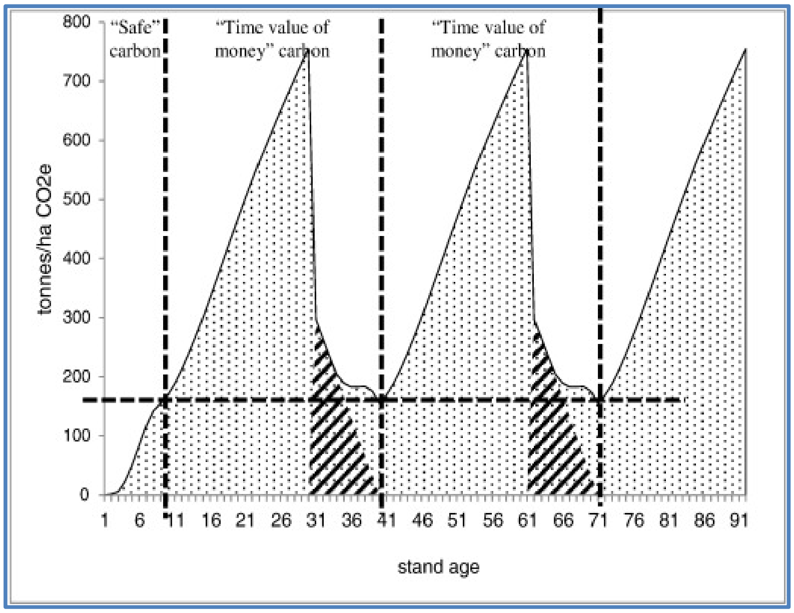

Figure 4 Carbon budget for typical NZ radiata pine forestry plantation (Evison, 2017)

# 4 Carbon Sink Efficiency

## 4.1 Problems with Permanence of Carbon Sequestration

Figure 5 illustrates the carbon pathways occurring in wood as it is generated in plantation forestry, harvested and, in part, turned into wood products. Eventually all the carbon drawn from the atmosphere is returned the atmosphere as either carbon dioxide ($CO_2$) or methane ($CH_4$). What is important is the relative portion of carbon which is locked out of the atmosphere compared with that which is circulating in the atmosphere and contributing to climate change. Methane, although shorter lived, is roughly 30 times more potent as a heat-trapping gas than $CO_2$ and is more likely to be produced when wood decomposes in anaerobic conditions such as landfill.[8]

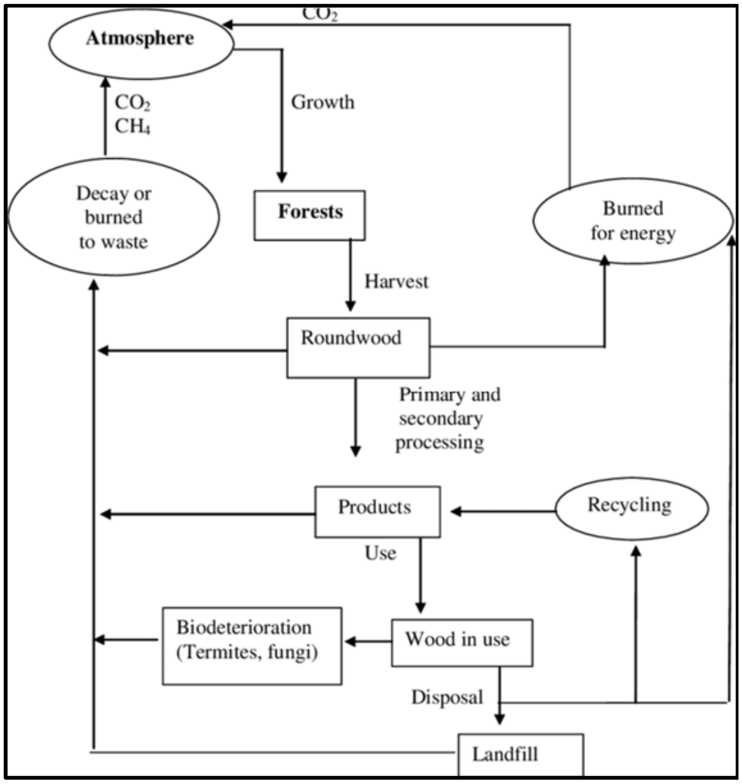

Figure 5 Life cycle of carbon in wood products (Ximenes, 2006)

Currently carbon trading schemes do not acknowledge any continuing carbon storage in wood products. This includes the New Zealand Emissions Trading Scheme which does not discount the post-harvest carbon liabilities for the portion of carbon that remains stored longer-term in wood products. The argument for not including carbon storage in wood products is that these products are simply replacing older wood products being burnt or rotting in landfill. While this may be true, the failure to replace this store or durable wood products would result in increased net emissions. It is akin to saying that planting new trees should not accrue carbon credits because they are simply replacing trees that are dying or being destroyed elsewhere. Furthermore, with continued growth and economic development the pool of existing durable wood products is increasing and, therefore, adding to the carbon sink (Ximenes, 2006).

As mentioned above, a major impediment to achieving large-scale bio-sequestration of carbon is the limited availability of suitable land surfaces on which to store carbon in a living form. The second impediment is the lack of opportunities to permanently (or at least for long-terms) lock up organic carbon which is no longer living. In this regard the opportunity to sequester kelp debris in deep ocean water provides a potential breakthrough for bio-sequestration.

Commercial plantations face another problem with respect to their contribution to carbon sequestration. Unfortunately, commercial plantations provide only a limited period of net carbon sequestration as the management and timber processing associated with these plantations is quite energy intensive and involves substantial carbon emissions. Modelling by Ford-Robertson suggests that a commercial forestry plantation may take as little as 90 years (or 3 rotations) before the carbon emissions associated with pruning, logging, milling and transport equal the carbon sequestered by trees (Ford-Robertson, 1996). The outputs of this model are shown in Figure 6. The graphic illustration shows 4 potential pathways of net carbon sequestration. The first pathway (1.) describes an unharvested

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[8] New research in the Journal Nature indicates that for each degree that Earth's temperature rises, the amount of methane entering the atmosphere from microorganisms dwelling in lake sediment and freshwater wetlands -- the primary sources of the gas -- will increase several times. (Yvon-Durocher, et al., 2014)

new plantation forest reaching a steady-state. The 2 pathway shows the impact of forestry management and processing emissions upon the net carbon balance in the case of New Zealand (where the electricity used in sawmills is mostly produced from renewable sources). Pathway 3 illustrates an improvement in the net carbon sequestration over time if the continued role of durable wood products is taken into account. Pathway 2a illustrates the net carbon sequestration position where electricity used in sawmilling is mostly generated from fossil fuels (such as is the case in Australia and the USA).

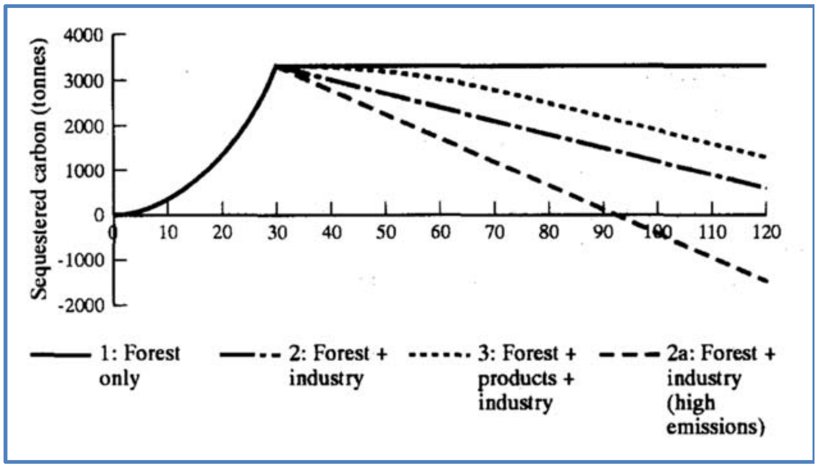

Figure 6 Illustration of net carbon storage from plantation forestry which is repeatably harvested (Ford-Robertson, 1996)

## 4.2 Carbon Sequestration with Kelp

Kelp cultivation has the potential to sequester carbon at many times the rate that can be achieved through terrestrial forestry plantation. Macroalgae naturally have very high productivity rates in terms of carbon capture during photosynthesis, with estimates of gross primary productivity of approximately 1600 g C $m^{-2}y^{-1}$ (5.87 kg $CO_2$ equiv./$m^2$/year). This compares favourably to global net primary productivity of crop land of 470 g C $m^{-2}y^{-1}$ (Hughes, 2012) or 1.72 kg $CO_2$ equiv./$m^2$/year.

Macrocystis pyrifera (Giant Kelp) grows to lengths of 20-30 metres and has a net primary production (NPP) in natural forests of around 5.2 kg dry matter/$m^2$/year (Rassweiler, 2018) (*5.25 kg $CO_2$ equiv./$m^2$/year*)[9] compared to an average of around 0.95 kg dry matter/$m^2$/year (*1.74 kg $CO_2$equiv./$m^2$/year*) for temperate radiata pine forest plantations. Macrocystis, therefore, draws down upon atmospheric carbon ***3 times*** faster per unit area than the fastest growing silviculture[10] systems. Its living biomass (~ 0.4 kg dry matter/$m^2$ on average) has a rapid turnover at a rate of about twelve times per year (Rassweiler, 2018). Another brown kelp endemic to New Zealand is Undaria pinnatifida. It has an NPP of over of 2.6 kg dry matter/$m^2$/ year (*2.79 kg $CO_2$ equiv./$m^2$/year*)[11] (Kraan, 2018)[12] which is 1.6 times the rate of radiata pine.

When populated with the perennial brown algae Ecklonia, a pilot CCRB (Coastal CO2 Removal Belt) farm in Korea was estimated (Chung, Oak, Lee, Shin, & Kim, 2013) to draw down ~10 t of $CO_2$ per ha per year (1 kg $CO_2$equiv./$m^2$/year). The carbon sink per 100 m of rope was 43.5 kg C for E. cava (*0.78 kg $CO_2$equiv./m2/year*) and 88.9 kg C for E. stolonifera (*1.60 kg $CO_2$equiv./m2/year*).

What makes kelp interesting is its potential to achieve a high degree of carbon sequestration permanence when grown in the proximity of deep ocean water. Organic matter that can survive decomposition (and conversion of the carbon back into $CO_2$) before it reaches depths of more than 1000 m, may remain in the form of dissolved organic carbon (DOC) and particulate organic carbon (POC) for hundreds to thousands of years, therefore, acting as near permanent deep ocean carbon sink. The extremely slow rate of decomposition of the DOC and POC in very deep

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[9] Like many seaweeds, Macrocystis pyrifera can compensate its ambient light and nutrient environment by storing carbon (C) and nitrogen (N) which are taken up in excess of that required for growth in the form of mannitol and laminarin. Consequently, carbon content in blades can range from 25 to 30 as a % of dry matter (Stewart, et al., 2009). $CO_2$ equivalent was calculated using a mean figure of 27.5%.

[10] e.g. pinus radiata

[11] Organic carbon content of Undaria pinnatifida is taken as 29.2% (Shim, Kim, Hwang, Choi, & Lee, 2017)

[12] In 2014, after natural detritus losses, China harvested 203,099 t dry weight of Undaria from a total area of 7693 ha. (Kraan, 2018)

water may be related to the lack of light, lack of oxygen and low temperatures in this deep ocean environment[13]. Figure 8 illustrates the process in which kelp forests continuously shed DOC and POC. The POC (and later the DOC) is derived from kelp sloughing off blades, and sometimes their entire vegetative structure, some of which eventually sinks to the ocean floor.

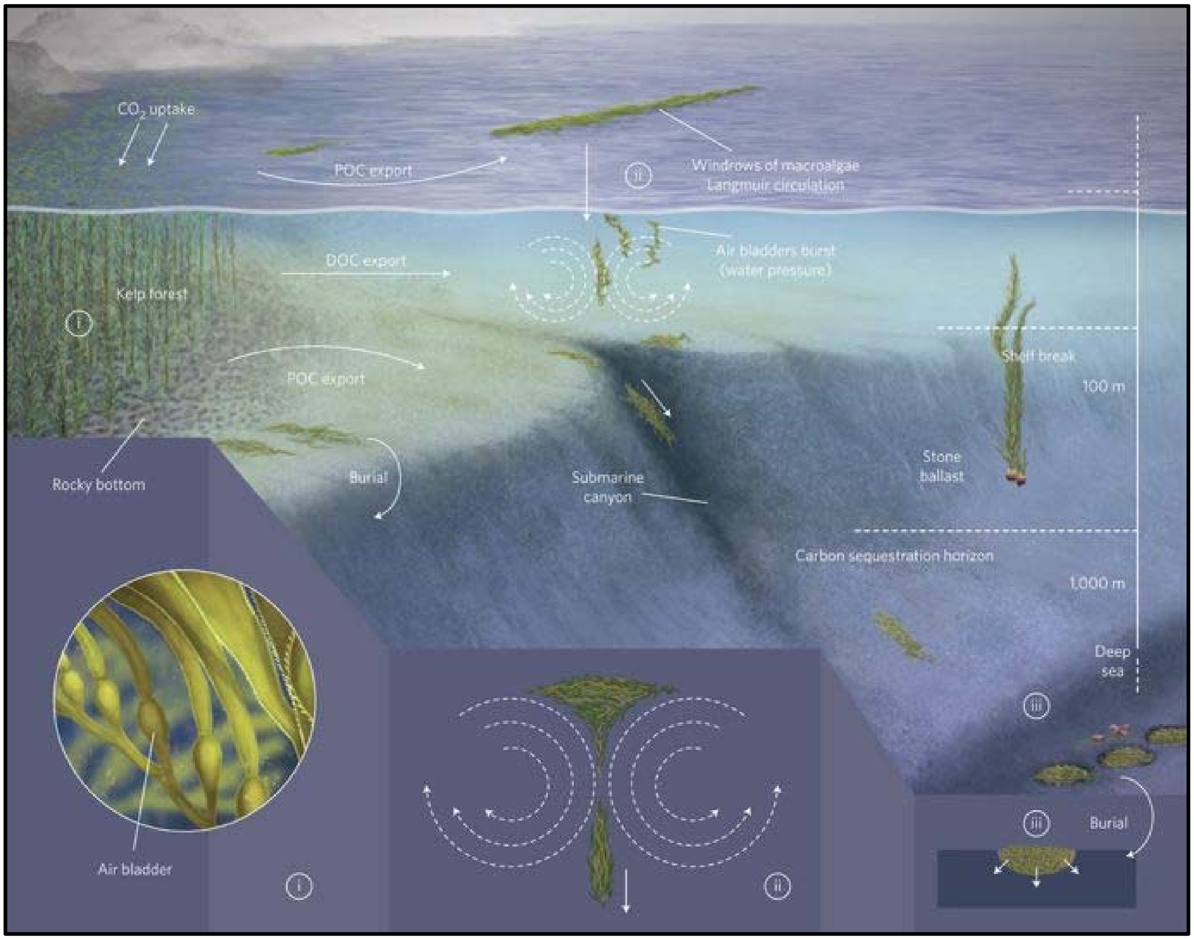

Figure 7 The Process of Sequestration of Macrocystis Kelp Detritis (Bayley, Marengo, Baker, & Pelembe, 2017)

## 4.3 Factors Affecting Quantity and Permanence of Carbon Bio-sequestration

Factors that are likely to promote the transfer of organic carbon (POC and DOC) from cultivation beds to deep sea environments where they are protected from decomposition will include:

- physical proximity to submarine canyons
- prevalence of favourable currents and down-wellings
- natural rate of subsidence of detritus
- availability of ocean floor sediments in which detritus may be incorporated and therefore shielded from heterotrophs (marine animals, protozoa, fungi, and bacteria)

Fast-growing autotrophs[14] generally produce labile detritus that decomposes rapidly, whereas slow-growing autotrophs produce recalcitrant detritus that decomposes slowly (Hunter, 2016). This works against the objective of maximising the mass of kelp detritus moving from cultivation beds into the deep waters where they would be protected from decomposition. A proportion of this released dissolved organic carbon (DOC) is highly labile and enters the bacterial loop and is rapidly remineralized back to $CO_2$. However, a proportion is known to be resistant to biological degradation and enters the refractory DOC pool. The marine DOC pool is the largest organic carbon pool on the planet and the refractory component is known to have a turnover period of 100s-1000s years (Hughes, 2012).

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[13] Researchers studying methane emissions in freshwater systems found that methane generation thrives on high temperatures. Methane emissions at 0°C rise 57 times higher when the temperature reaches 30°C (Yvon-Durocher, et al., 2014).

[14] organisms like plants that create their own food source from inorganic nutrients

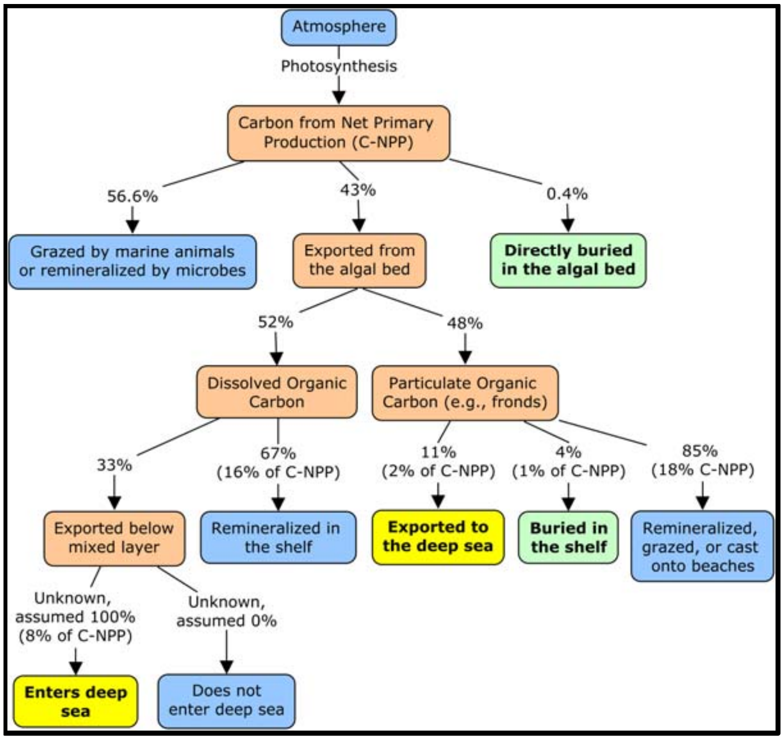

**Figure 8 Average estimated carbon flows in algae, based on Figure 3 in Krause-Jensen and Carlos M. Duarte 2016. Bolded cells represent longer-term carbon storage. Yellow cells represent carbon sequestered in the deep sea, which is unlikely to be reversed. Green cells represent carbon sequestered in shallower regions, with a possibility of reversal. Blue cells are "destinations" that will rapidly cycle carbon back into the atmosphere. Orange cells are intermediate stages. Percentages are rounded (Cage, 2018)**

With better understanding of the properties of recalcitrant detritus it may be possible to increase the percentage of this degradation resistant form of organic carbon produced by IMTA farms.

In the case of the east coast of New Zealand, the DOC and POC derived from kelp detritus could be potentially "locked up" in the Kermadec Trench (which is up to a depth of 8,000 m), and the organic carbon contained within locked away from exchange with the atmosphere (Krause-Jensen D, 2016). If, as described Figure 9, approximately 11.4% (Cage, 2018) of this organic carbon (as DOC and POC) can be sequestered below 1000 m for an average of 1000 years (compared to 30 years) it would increase the effective carbon sequestration per unit area of kelp by over 33 times. In the case of M. pyrifera (already 3 times more efficient in carbon sequestration per m$^2$) this would increase the rate of carbon sequestration to ***100 times greater than radiata pine plantation forestry/m$^2$***. Furthermore, if this sequestration into deep water can be achieved without mechanical harvesting, there would be little additional carbon emissions associated with this mariculture system. Alternately, mechanical harvesting may be warranted if it can be shown that physically depositing POC into deep ocean water substantially increases rates of long-term sequestration.

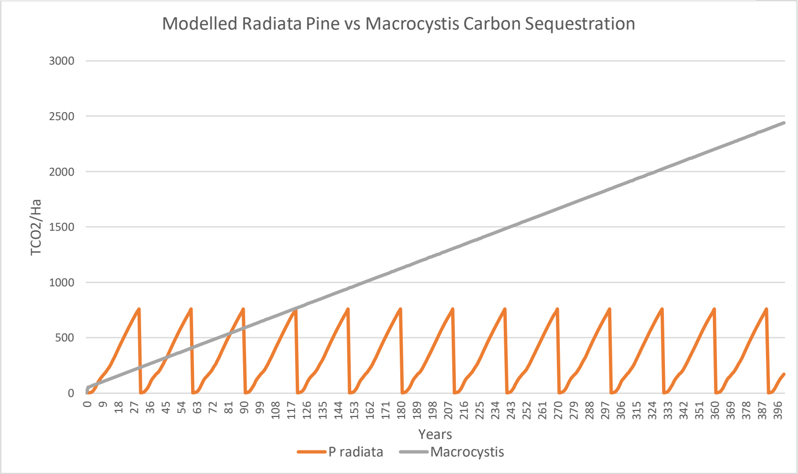

**Figure 9 Carbon sequestration modelling highlighting impact of permanence[15]**

Figure 10 below shows the complex web of carbon movement in the ocean. Organic detritus tends to sink but is continuously degraded by animals, zooplankton and bacteria. However, as discussed above, a significant portion of this reaches the deep ocean floor sediment where it can be stored for time scales of up to millions of years (Oceans and the Carbon Cycle Part A: Down to the Deep - The Ocean's Biological Pump, 2017).

Particulate organic carbon (POC), dissolved organic carbon (DOC), and dissolved CO$_2$ movement is also affected by down-wellings and up-wellings. Downwelling currents occur in areas where cold, denser water sinks. These downwelling currents bring carbon down to the deep ocean. Once there, the carbon moves into slow-moving deep ocean currents staying there for hundreds of years. Eventually, these deep ocean currents return to the surface in a

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[15] Hickson (2018) calculations based upon estimated carbon sequestration by Macrocystis and Pinus radiata (MPI NZ, 2017)

process called upwelling. Many upwelling currents occur along coastlines. When upwelling currents bring deep, cold ocean water to the surface, the water warms and some of the dissolved $CO_2$ is released back to the atmosphere.

A high priority trial will be to monitor the fate of Macrocystis pyrifera detritus in natural kelp forests off the coast of the South Island (preferably those located between a significant river mouth and a submarine canyon).

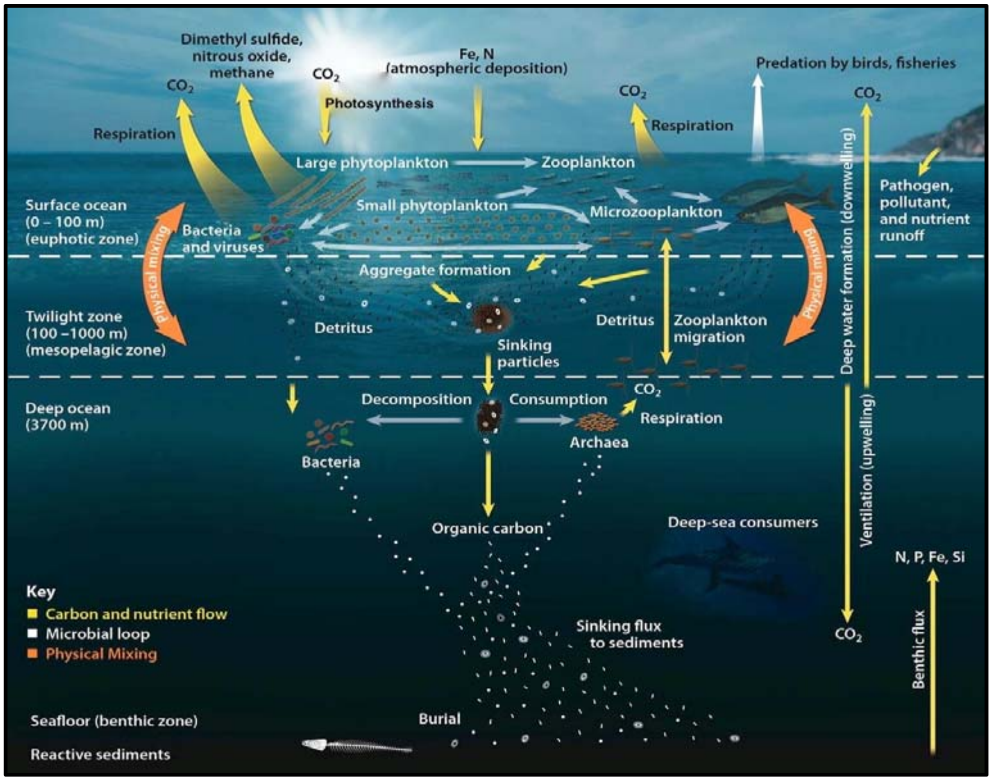

Figure 10 The Ocean Carbon Cycle. Image credit: Oak Ridge National Laboratory

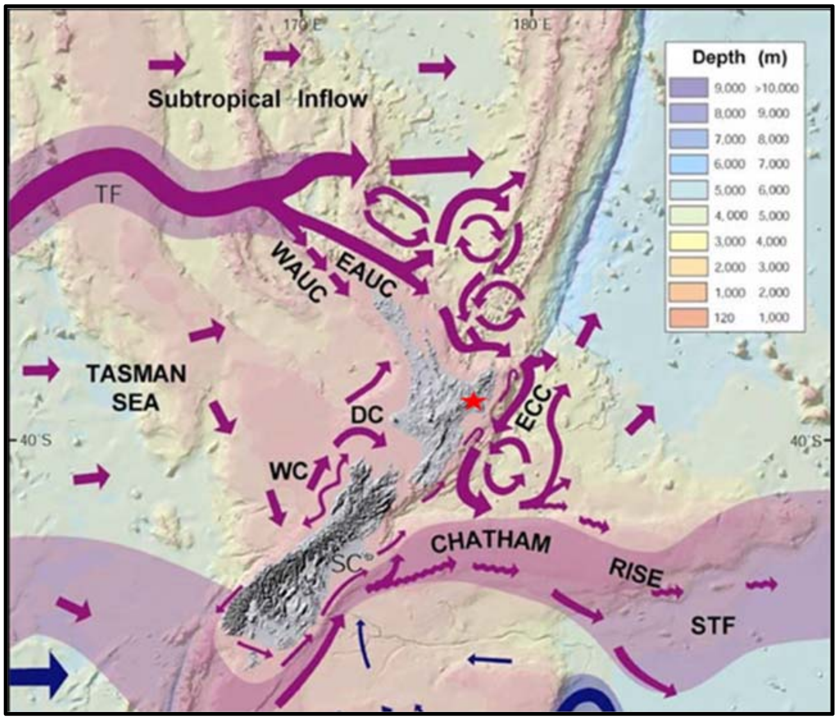

Figure 11 Surface currents around New Zealand. Image credit: NIWA

### 4.4 Carbon Dioxide as a Form of Carbon Sequestration

The ocean also provides the largest sink on the planet for carbon in the form of $CO_2$. While many $CO_2$ molecules that diffuse into sea surface waters diffuse back to the atmosphere on very short time scales, some of the carbon atoms from these original $CO_2$ molecules stay dissolved in the colder depths of the ocean for time scales of also hundreds to thousands of years (Oceans and the Carbon Cycle Part A: Down to the Deep - The Ocean's Biological Pump, 2017). Carbon dioxide ($CO_2$) at 2°C liquefies at 532 psi (approximately 367 m depth) and at 2°C and 2760 m this liquid carbon dioxide becomes denser (heavier) than sea water (Barry, 2018).

## 5 Oceanography

The east coast of New Zealand sees the convergence of the Subtropical and the Subantarctic Fronts (currents). Figure 11 above shows surface currents pushing north up the east coast of the South Island and south down the east coast of the North Island. While regional and seasonal patterns vary, overall the only option for this influx of coastal water (potentially containing kelp detritus), is to move eastward (and/or downward) into the trench.

## 5.1 Considerations for Siting Kelp Farms

Potential exists for growing kelp for carbon sequestration along the continental shelves of many countries throughout the world. Particularly attractive are countries such as New Zealand, USA (particularly Alaska and the entire East coast), Japan, Western Europe, Chile and some of the Mediterranean countries which have relatively close access to ocean floor in excess of 3000 m deep. Currently submarine longline aquaculture is best suited to water with depths up to 80 m, however, in future, production at depths of up to 200 m is likely to be feasible.

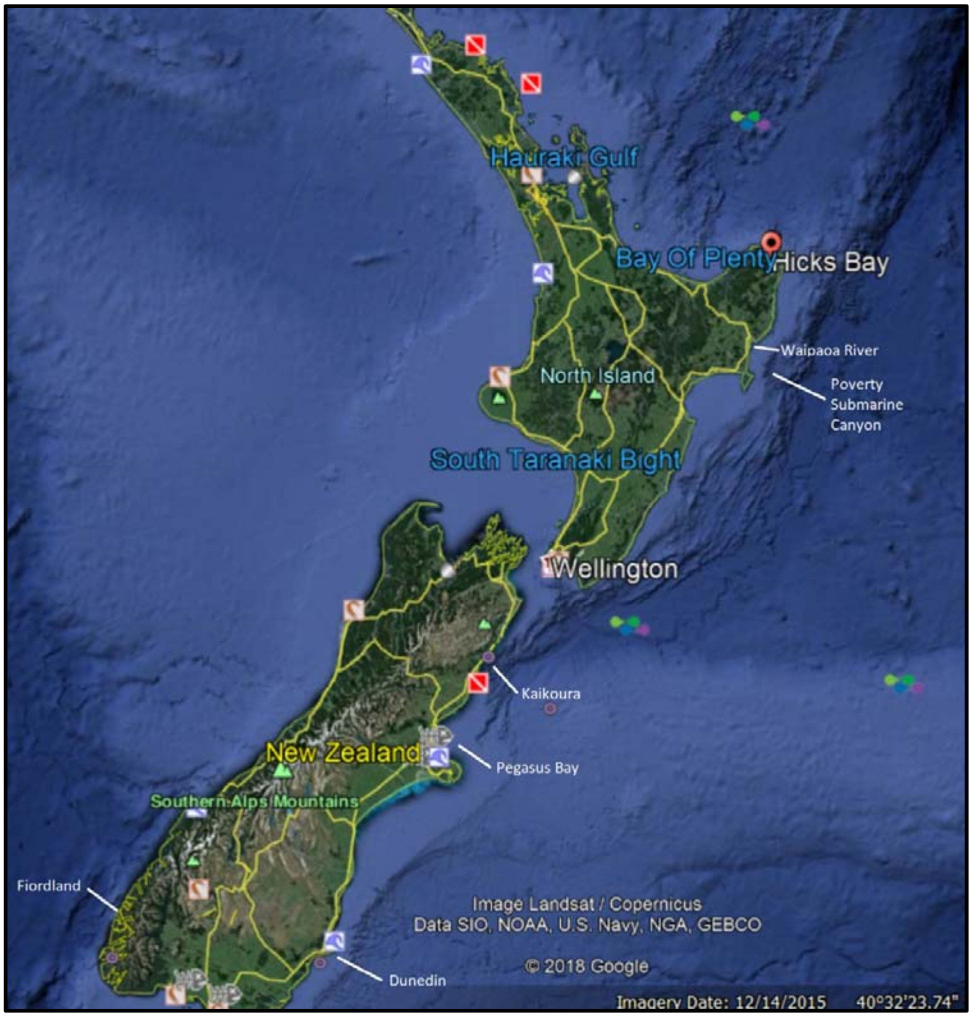

Figure 12 Topographical map of New Zealand showing continental shelves and deep water

In the South Pacific the Kermadec Trench, with depths of up to 8000 m, runs from Tonga down to the east coast of the South Island of New Zealand where it meets the Chatham Rise near Kaikoura. This provides potential opportunities to grow kelp offshore along the East coast of the North Island and have kelp detritus sequestered into the Kermadec trench.

South of the Chatham Rise a network of submarine canyons off Dunedin work their way eastward to deep water south of the Chatham Islands (see Figure 11). Deep water also exists adjacent to the Fiordlands, however, here there is little continental shelf on which to anchor longlines until north of Haast. Hawkes Bay provides a large area in which most of the water is less than 100 m deep.

An interesting area of <100 m shelf exists 20 km NE of the Mahia peninsular, and about 30 km to the SE of Gisborne, where the Poverty Submarine Canyons provide a steep escarpment down to the Kermadec trench. The Poverty Canyons receive sediment from the Waipaoa River, New Zealand's second largest river in terms of suspended sediment discharge (Alan Orpin et al International Poverty Slope Group, 2007). This sediment is rich in nitrates and phosphates which could potentially provide valuable nutritional support for kelp growth in this region. The sediment may also facilitate burial of kelp detritus and its transport down through the Poverty submarine canyon. Burial of this material may help protect the labile kelp detritus from degradation on its journey to the deep waters of submarine canyons (Leduc, 2018).

Approximately 15 million ha of the New Zealand continental shelf is less than 200 m deep and much of this rapidly increases to over 1000 m or more. If just one two thirds of this area was under kelp aquaculture, and this kelp was able to sequester at an average of 3.0 kg CO2 equiv./m2/year this would sequester (on the assumptions provided in Section 5.2) approximately 35 Mt $CO_2$/year for hundreds to thousands of years. This compares to the billion trees program which is likely to sequester an average of 30 Mt $CO_2$/year for about 30 years less emissions produced in their planting, management, harvesting, processing and transport.

# 6 Kelp cultivation in the New Zealand North Island

Integrated Multi-Trophic Aquaculture in the North Island is probably, at this stage, best suited to Undaria or Ecklonia cultivation as Macrocystis is not found north of Castlepoint. While these have approximately half to one third the rate of net primary production as Macrocystis, and therefore, a reduced rate of carbon dioxide uptake, they do have the advantage of not having pneumatocysts (gas bladders). These bladders at the base of each blade cause Macrocystis debris to float for a period of time, possibly increasing the rate of organic matter decomposition and re-mineralisation of the carbon to $CO_2$, before the bladders eventually burst and this debris sinks to the deep ocean floor. Further study is required to understand the relative capacities of these kelps for carbon sequestration.

## 6.1 Scope for Domestication of Macrocystis and Cultivation

Macrocystis pyrifera does not grow naturally as far North as Poverty Bay. Its current northern limit is Castle Point. This has been attributed to higher water temperatures in Poverty Bay (13 to 19°C). Macrocystis does not persist naturally in New Zealand waters where maximum temperatures exceed 18–19° C for several days (Hay, 1990). Its most successful natural growth is in geographic areas of upwelling and where the waters are high in nutrients and nearly always cold.

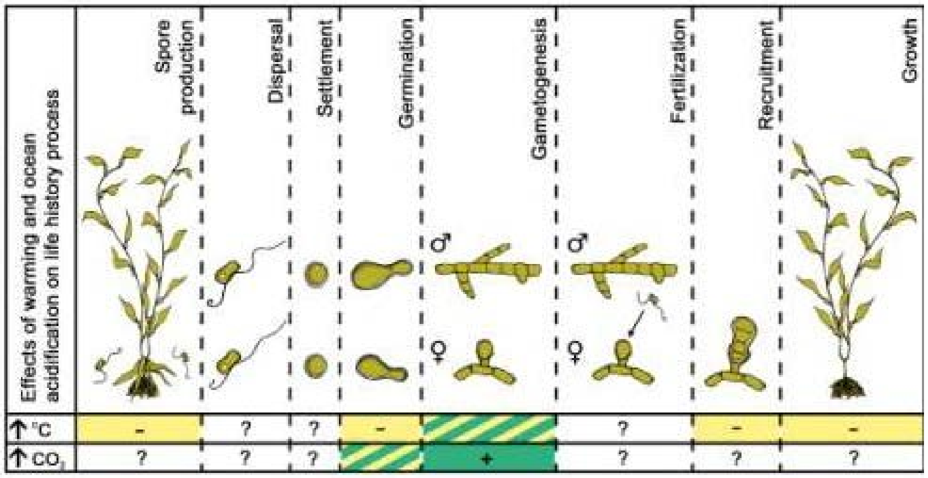

**Figure 13 Consequences of increased temperature and ocean acidification on the reproductive cycle of M. pyrifera (Harley, et al., 2012)**

Figure 13 shows the generalized consequences of increased temperature and ocean acidification on the life history phases of the kelp Macrocystis pyrifera. Yellow boxes with '-' suggest that the effect is deleterious to the algae, green boxes with '+' suggest a beneficial effect, boxes with hatches suggest no net effect, and white boxes with '?' suggest that there is inadequate knowledge to determine the net consequence.

M. pyrifera grows well in the Santa Barbara Channel of the Southern California coast where ocean temperatures generally vary from 13 to 17°C across the seasons. One study in the Santa Barbara Channel reports the kelp forests maintained their biomass and growth rate during a prolonged heatwave in which water temperatures often remained 3 to 5°C higher than usual in 2013-2015. Furthermore, M. pyrifera grows as far south as Bahia Tortugas (Turtle Bay) in Mexico where ocean temperatures range from 16 to 25°C. Therefore, it may well grow in Poverty Bay on a substrate of submerged long lines, if nutritional conditions are favourable.

However, if it did appear that rates of long-term carbon sequestration were significantly improved using Macrocystis, there appears to be substantial scope to selectively breed cultivars of M. pyrifera due to high levels of genetic diversity in the natural population (Camus & Buschmann, 2017). It may, therefore, be possible to select for strains which are more temperature tolerant, have higher rates of NPP, and maybe even strains which produce more recalcitrant detritus (that decomposes more slowly).

In a large scale aquaculture system, many of the temperature sensitive phases of the Macrocystis reproductive cycle would be conducted under controlled temperature and nutritional conditions in a hatchery. This would limit the need for temperature tolerance to the sporophyte phase growing in the open ocean. Breeding for temperature tolerance across all phases of the reproductive cycle would also have the potential benefit of supporting efforts to protect existing natural forests of Macrocystis from the impacts of climate change.

## 7 IMTA and Commercialisation of Carbon Sequestration

Cultivation of macroalgae together edible fish species is known as Integrated Multi-Trophic Aquaculture (IMTA). This has been undertaken commercially in China, North[16] and South America, and northern Europe. Seaweed cultivation in close proximity to shellfish can provide a local microclimate conducive to the production of edible shellfish. Kelp aquaculture forests appear to support shellfish production in 3 ways:

i. Provision of primary and secondary nutrients (Troell, et al., 2009),
ii. Providing a physical buffer to destructive wave action, and
iii. Reducing energy requirements for shell production (or shell deformities) as a result of local ocean de-acidification.

Shellfish species which should grow in IMTA in New Zealand include; green shell mussels, oysters, scallops, various clams and possibly local species traditionally harvested by local iwi.

Due to their ability to convert sunlight energy into organic matter, kelp forests (both natural and artificial) serve as an ecosystem foundation: feeding and sheltering diverse ocean species. Their protective nature allows them to become an important breeding area for many fish species. As such they act as a powerful fish attracting device and may help re-establish dwindling commercial fish stocks in the area.

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