Caulerpa in the Bay of Islands: The Cost of Inaction

Avinash Govind, Economic Policy Advisor

Summary:

In the middle of 2021, divers discovered colonies of two exotic seaweed species – Caulerpa brachypus and Caulerpa parvifolia – growing in the waters around Aotea/Great Barrier Island. *(Biosecurity New Zealand, 2021)* Earlier this year, scientists discovered that the same Caulerpa species had spread to the Bay of Islands *(Botting, 2023)* Though biosecurity experts are actively working to contain these outbreaks, eradicating the seaweed will likely take multiple years.

In this paper, I first estimate the likely uninhibited growth path of Caulerpa species in the Bay of Islands, using a log-linear model that describes the spread of Caulerpa taxifolia – a similar seaweed species – across four Southern European regions, between 1989 and 2000, in terms of time, temperature, and fixed country effects. I then use this growth path to estimate the cumulative, tangible costs of failing to contain the spread of Caulerpa in the Bay of Islands, over thirty years.

Caulerpa taxifolia in the Mediterranean Sea

A Natural History:

When Prince Albert I of Monaco opened the country's Oceanographic Museum in a grand and imposing building nestled along its Mediterranean coast, he intended for it to serve as a monument to the marine sciences, designed to educate visitors, advance the field, and protect the region's delicate ecosystem. Just months after he opened the museum in 1911, Albert began touring European capitals and boasting about it to the scientific community, describing his new institution as a "palace worthy of intellectual humility," *(Oceano, 2021)* during a speech in Madrid.

To this day, visitors to the Oceanographic Museum can spend hours wandering through vast halls lined with thousands of carefully protected aquatic creatures, learning about the natural world as they gaze at the sea. A few times each year, the museum even hosts marine conservation conferences featuring relevant stakeholders . *(Oceano, 2021)*

But a little over four decades ago, the museum renovated its displays and sparked an ecological crisis that continues to affect much of the Mediterranean Sea.

In place of the corals that decorated their aquaria, the museum's designers decided to start growing beds of vivid green, imported seaweed that swayed underwater throughout the year, hoping to enhance the vibrancy of their displays. *(Meinesz, 2001)* Following the lead of other aquaria, they chose to grow Caulerpa taxifolia – an Australian algae species known for being resilient to environmental changes. *(NOAA Fisheries, 2024)*

Soon after, the museum began the redesign, completing it by the end of 1982. And at first, their plan appeared to work.

It was only years later, in 1984, that oceanographers began to worry. Early in the year, diving enthusiasts exploring the waters around Monaco discovered a small patch of seaweed growing just outside the museum and started tracking its growth. (*Meinesz*, 2001)

At first, some experts suspected that the patch would wither in the Mediterranean's frigid winter waters. In his 1999 book, Killer Algae, the French scientist Alexandre Meinesz recounted that Dominique Bezard, the museum's aquaria director, seemed to think that "the Caulerpa prairie seemed sparser in the winter." (*Meinesz*, 2001) But after observing the seaweed over multiple years and seasons, scientists began to realise that, in the wild, the features of Caulerpa taxifolia that had made it attractive to aquarium decorators were enabling it to spread out across the sea. (*Meinesz*, 2001)

Each time they checked in on the patch, observers found that it had grown and inched towards parts of the sea that native seaweed and fauna occupied. (*Meinesz*, 2001) By 1989, divers in France had discovered Caulerpa taxifolia colonies growing near Nice and Toulon; two years later, it had spread to Spain and Italy; and by the end of the decade, scientists estimated that the Caulerpa taxifolia colonies had grown to cover over 13000 hectares of the Mediterranean seabed. (*Meinesz*, 2001)

Though some European governments did attempt to control the spread of Caulerpa taxifolia, their campaigns were largely unsuccessful. In one case, the Croatian government even appeared to successfully eradicate the seaweed, only for scientists to return weeks later and find it reoccupying the country's seabed. (*Zuljevic & Antolic, 2002)* Today, large portions of the Mediterranean seabed remain covered in dense forests of seaweed, harming the region's economy, level of biodiversity, and aquatic populations.

Growth Rate:

In this section, I fit a pair of models describing the spread of Caulerpa taxifolia across four European regions between 1989 and 2001, using a constructed dataset based on research conducted by *Meinesz (Meinesz, 2001), and Meinesz*, *Belsher, and Thibaut* (*Meinesz*, *2001*).

The models suggest that the growth rate of Caulerpa taxifolia in the Mediterranean Sea was dependent on the temperature of the sea.

Model 1:

To understand the spread of Caulerpa taxifolia, I fit a model describing the algae's logged coverage to data collected from four regions bordering the Mediterranean Sea between 1989 and 2000 (*Meinesz, 2001*).

$$E(Ln(Coverage)) = \alpha + (\beta_1 * Time) + (\beta_2 * Time * Temperature) + (\beta_3 * France/Monaco) + (\beta_4 * Italy) + (\beta_5 * Spain)$$

Results:

This model explains 94.49% of the variation in the spread of Caulerpa across the Mediterranean Sea, indicating that the model fits the data quite well. Further, the errors associated with the model vary randomly around a mean of approximately zero, across every affected region, and are normally distributed.

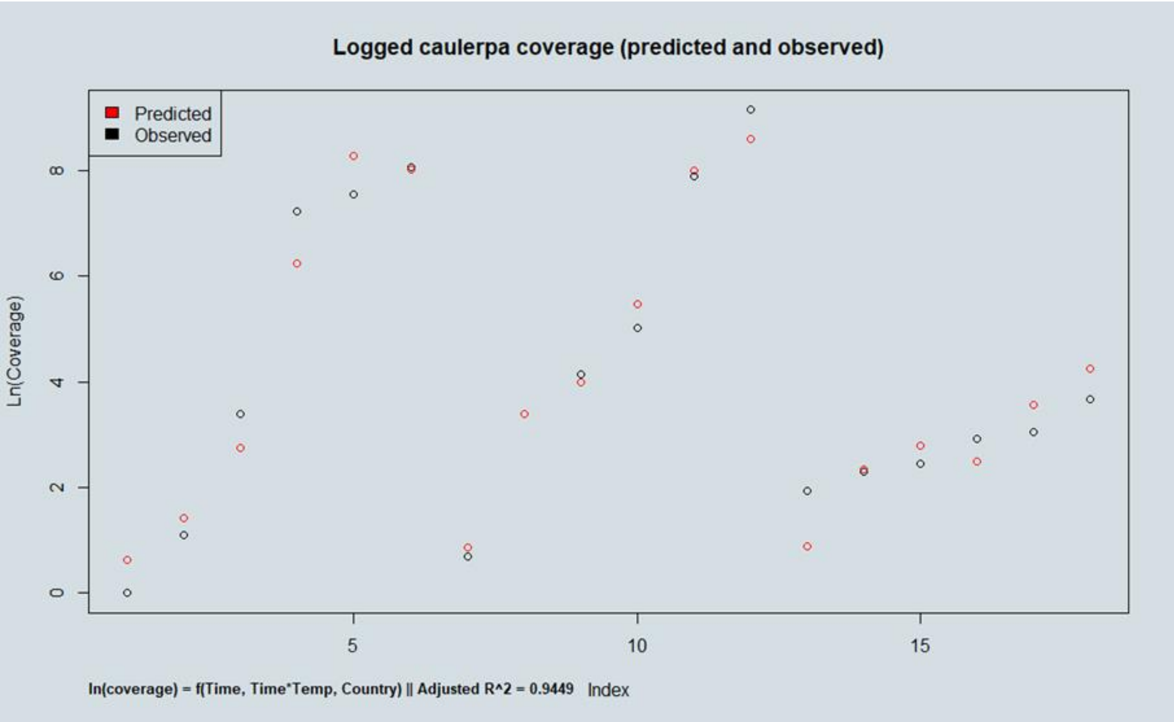
Table 1: Model 1 Regression Results.

Model Term	Estimate	p-value
Intercept	*0.8836*	*0.012*
Time	*1.8336*	*1.3e-05*
Time * Temperature	*-1.6597*	*6.2e-4*
France / Monaco	*-0.2468*	*0.57*
Italy	*2.3492*	*4.9e-4*
Spain	*-2.2660*	*6.48e-4*

The significance of the dummy variables France/Monaco, Italy, and Spain can be explained by the likely lag between when Caulerpa taxifolia first began to spread and when divers first observed its spread in each of the respective regions.

All the terms in this model, with the exception of France/Monaco, are statistically significant. The model's estimated effects imply that France/Monaco and Croatia detected their Caulerpa invasions at the same stage as each other, later in the invasion than Spain, and earlier in the invasion than Italy.

Figure 1: Model 1 – ln(Coverage) predictions



Limitation – Overfitting Risk:

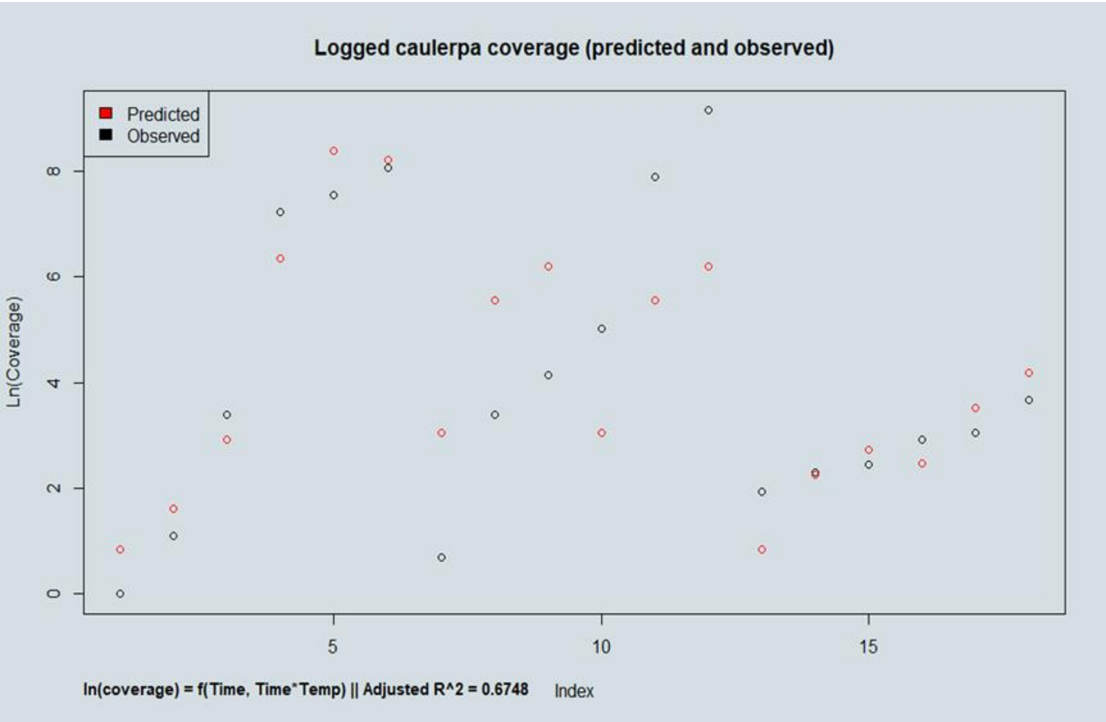
Model 1 contains six terms and was fitted to a coverage dataset containing eighteen observations, raising the risk that the model was overfit. To account for that, I fit an alternate model to the data.

$$E(Ln(Coverage)) = \alpha + (\beta_1 * Time) + (\beta_2 * Time * Temperature)$$

This model explains 67.48% of the variation in the spread of Caulerpa, indicating that it fits the data quite poorly. However, most of the errors associated with the model are linked to clear, and remarkably stable, fixed country effects, indicating that the model's estimates of the effects of Time and Time*Temperature on ln (Coverage) may still be valid.

The errors associated with the Spanish observations in the model's training data vary around a mean of approximately two; the errors associated with the Italian observations in the data vary around a mean of negative two; and the errors associated with the French/Monegasque and Croatian observations vary around a mean of approximately zero.

Figure 2: Alternate Model – ln(Coverage) predictions



Despite this, the estimated effects of Time and Time*Temperate on Ln(Coverage) in our alternate model are highly similar to the estimated effects of those variables on Ln(Coverage) in our original model – Model 1. This indicates that Model 1 likely not overfit.

Table 2: Alternate Model Regression Results

Model Term	Estimate – Alternate Model	Estimate – Original Model
Intercept	*0.8436*	*0.8836*
Time	*1.7910*	*1.8336*
Time * Temperature	*-1.6013*	*-1.6597*

Limitation – Temperature:

In both models described above, I used mean zonal anomalies as measures of temperature. However, mean zonal anomalies are highly crude and imprecise measures of temperature. As I continue to work on the development of cost-benefit analyses related to the spread of Caulerpa in the Bay of Islands, I intend to refine the models further.

Data Sources:

Temperature:

GISTEMP Team, 2024: GISS Surface Temperature Analysis (GISTEMP), version 4. NASA Goddard Institute for Space Studies. Dataset accessed 2024-01-10 at https://data.giss.nasa.gov/gistemp/.

Lenssen, N., G. Schmidt, J. Hansen, M. Menne, A. Persin, R. Ruedy, and D. Zyss (2019). Improvements in the GISTEMP uncertainty model. J. Geophys. Res. Atmos., 124, no. 12 (2019)

Coverage:

Meinesz, A., Belsher, T., Thibaut, T. et al. The Introduced Green Alga Caulerpa Taxifolia Continues to Spread in the Mediterranean. Biological Invasions 3, 201–210 (2001).

Zuljevic, A., & Antolic, B. (2002). Appearance and eradication of Caulerpa taxifolia in Croatia. International Caulerpa Taxifolia Conference Proceedings.

Meinesz, A. (2001). Killer Algae. University of Chicago Press; a book about the spread of Caulerpa in the Mediterranean, written by one of the main researchers involved in responding to the outbreak

Implied Growth Rate

Both the original and alternate growth models described above imply that the growth rate of Caulerpa taxifolia in an area is dependent on the average combined land-surface air and sea-surface temperature anomalies in that area.

The expected logged growth rate of Caulerpa in a given area can be calculated using the equation:

$$E(r) = \frac{dE\big(Ln(Coverage)\big)}{dTime}$$

Using results from Model 1, as described above:

$$E(r) = \frac{dE\big(Ln(Coverage)\big)}{dTime}$$

$$\Leftrightarrow E(r) = 1.8336 - (1.6597 * Temperature)$$

Estimating Caulerpa growth path in the Bay of Islands

Growth Rate

Between 2010 and 2022, the annual mean average zonal combined land-air and sea-surface temperature anomaly for the region encompassing the Bay of Islands was 0.697692.

Assuming that this continues over the next thirty years and that the Caulerpa species found in the region exhibit similar growth characteristics to Caulerpa taxifolia, an expected average annual logged growth rate of Caulerpa in the Bay of Islands can be calculated using the expected growth rate equation derived in the previous section.

$$E(r) = 1.8336 - (1.6597 * Temperature)$$

$$= 1.8336 - (1.6597 * 0.697692)$$

$$= 0.67564$$

Growth Path Equation

The growth path of Caulerpa in the Bay of Islands can now be estimated by inserting the expected growth rate of the seaweed into the standard logistic population growth function.

$$E(Coverage_t) = \frac{K}{1 + \left(\frac{K - C_0}{C_0}\right) e^{-E(r)*t}};$$

$where\ E(r) = Expected\ logged\ growth\ rate, C0 = inital\ coverage, t = time,$
$K = maximum\ coverage$

Assumptions:

Based on a depth map produced by Toitu Te Whenua Land Research New Zealand (LINZ) (Toitu Te Whenua Land Research New Zealand, 2012) and conversations with the Northland Regional Council's marine biosecurity team, I assume that the maximum possible coverage of Caulerpa in the Bay of Islands is 20,086 hectares (Figure 1).

This represents the area within the Bay of Islands that is bounded by land and the Bay's 30m nautical depth contour.

Figure 3: Area within the Bay of Islands that could be colonised by Caulerpa species

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When divers discovered Caulerpa growing in the Bay of Islands, the seaweed occupied 10 ha of the area's seabed. For this reason, I assume that the initial coverage of Caulerpa in the Bay of Islands is 10ha.

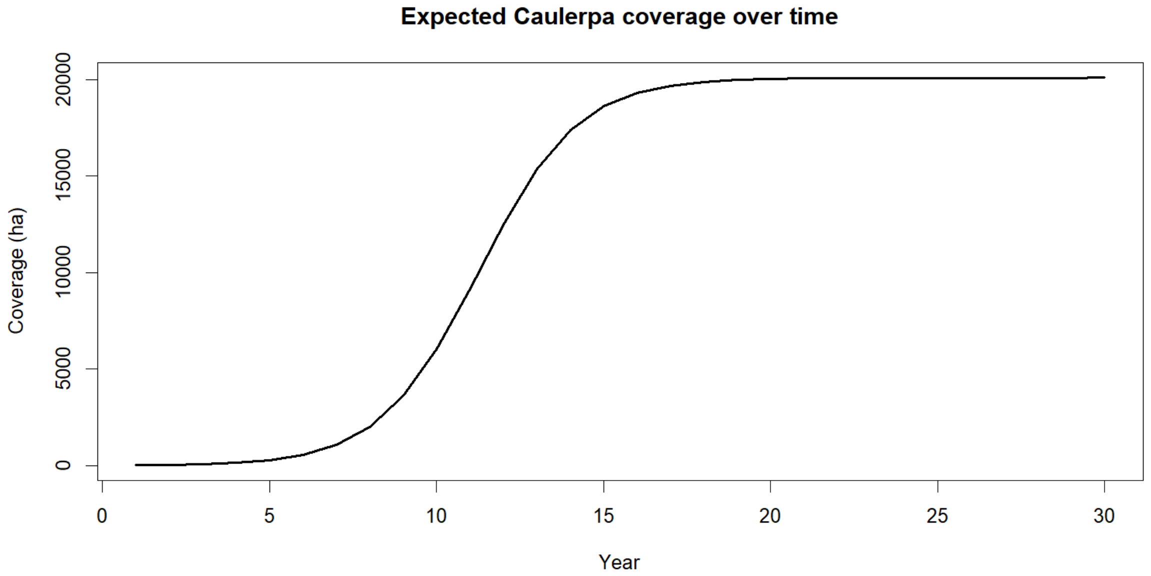
Growth Path

Based on the assumptions listed above, the coverage of Caulerpa in the Bay of Islands is likely to follow the path described in Table 3 and Figure 4, over the next thirty years.

Table 3 : Expected growth of Caulerpa over the next thirty years

Year	Caulerpa Coverage (ha)
1	*19*
5	*290*
10	*6000*
15	*19,000*
25	*~20,000*
30	*~20,080*

Figure 4: Growth path of Caulerpa in the Bay of Islands



Notably, the growth model described above suggests that, within fifteen years, Caulerpa colonies are likely to occupy 95% of the total area that they can likely occupy, within the Bay of Islands.

Economic Caulerpa-related Costs in the Bay of Islands

This preliminary analysis does not consider the recreational costs associated with an uncontrolled Caulerpa outbreak in the Bay of Islands.

Value of Caulerpa-related sectors in the Bay of Islands:

Table 4 : Value of the Bay of Islands' marine economy.

Sector	Average GDP [2018 – 2023] ($m)
Fishing and Aquaculture	*4.2*
Accommodation and Food Services	*57.6*
Transport Equipment Manufacturing	*3.4*

The economic sectors likely to be affected by the spread of Caulerpa generate $65.2 million in GDP each year, on average, around the Bay.

All of the GDP measures in this paper are based on Infometrics' estimates of the GDP generated by relevant industries within the statistical areas bordering the Bay. (Infometrics, 2024)

Across every affected sector, I assume that the spread of Caulerpa will have a uniform economic impact across all affected areas.

Estimating Caulerpa Impact:

For each sector of the Bay of Islands' economy:

$$Cost_t = \frac{Caulerpa_t}{Caulerpa_{Max}} * Cost_{Max};$$

$$PV(Cost)_t = Cost_t * \frac{1}{(1+0.05)^t},$$

$where\ Cost_{Max} = E(impact) * GDP,$
$Caulerpa_t = Caulerpa\ coverage\ at\ time, t$
$Caulerpa_{Max} = Maximum\ Caulerpa\ coverage\ in\ the\ Bay\ of\ Islands$

Cumulative cost over n years:

$$\text{PV}(Cost) = \sum_{t=1}^{n} PV(Cost_t)$$

Caulerpa impact on Fishing and Aquaculture:

Assumptions:

Soon after Caulerpa taxifolia began to spread across France, marine biologists observed that the mean biomass of fish in areas occupied by Caulerpa declined by approximately fifty-seven percent at depths of between two and ten metres, and by approximately forty-two percent at depths of between ten and thirty metres. (Harmelin, 1999)

This analysis assumes that:

- Lower Bound: At maximum coverage, Caulerpa reduces Fishing and Aquaculture output by 42%.
- Upper Bound: At maximum coverage, Caulerpa reduces Fishing and Aquaculture output by 57%.

Table 5 : Estimated impact of Caulerpa on the Bay of Islands' Fishing and Aquaculture sector.

Cumulative Time Period (years)	Cumulative PV – Lower Bound ($)	Cumulative PV – Upper Bound ($)
10	*795,000*	*1,089,000*
20	*7,790,000*	*10,600,000*
30	*12,900,000*	*17,600,000*

Over thirty years, it is estimated that "doing nothing" to prevent the spread of Caulerpa will cost the Fishing and Aquaculture sector in the Bay of Islands between $13 - $18 million.

Caulerpa impact on Accommodation and Food Services:

Assumptions:

This analysis assumes that:

- Lower bound: At maximum coverage, Caulerpa reduces Accommodation and Food Services output by 5%
- Upper bound: At maximum coverage, Caulerpa reduces Accommodation and Food Services output by 15%

Table 6 : Estimated impact of Caulerpa on the Bay of Islands' Accommodation and Food Services sector.

Cumulative Time Period (years)	Cumulative PV – Lower Bound ($)	Cumulative PV – Upper Bound ($)
10	*1,290,000*	*3,880,000*
20	*12,700,000*	*38,000,000*

30	*21,000,000*	*63,100,000*

Over thirty years, it is estimated "doing nothing" to prevent the spread of Caulerpa will cost the Accommodation and Food Services sector in the Bay of Islands between $21 - $63 million.

Caulerpa impact on Transport Equipment Manufacturing:

Assumptions:

Multiple environmental economists and ecologists have noted that an uncontrolled Caulerpa outbreak in the Bay of Islands could cause foreign ports to restrict the movement of ships that visit the area. Even without official restrictions, there is a chance that private vessels owners could avoid ports around the Bay of Islands.

This could severely impact the local Transport Equipment Manufacturing (TEM) sector – which is dominated by ship/boat repair firms.

This analysis assumes that:

- Reputational damage and foreign berth restrictions kick in once Caulerpa occupies 5% of the Bay of Islands.
- Lower bound – at maximum coverage, Caulerpa reduces TEM output by 10%.
- Upper bound – at maximum coverage, Caulerpa reduces TEM output by 30%.

Table 7 : Estimated impact of Caulerpa on the Bay of Islands' Transport Equipment Manufacturing sector.

Cumulative Time Period (years)	Cumulative PV – Lower Bound ($)	Cumulative PV – Upper Bound ($)
10	137,000	410,000
20	1,470,000	4,410,000
30	2,460,000	7,370,000

Over thirty years, it is estimated that "doing nothing" to prevent the spread of Caulerpa will cost the Transport Equipment Manufacturing sector in the Bay of Islands between $2.5 - $7.3 million.

Total Direct Economic Impact on the Bay of Islands:

Overall, I estimate that the cumulative tangible costs of an uncontrolled Caulerpa outbreak in the Bay of Islands are likely to range between $36 million and $88 million over the next thirty years.

Table 8 : Estimated impact of Caulerpa on the Bay of Islands' economy.

Cumulative Time Period (years)	Cumulative PV Cost – Lower Bound ($m)	Cumulative PV Cost – Upper Bound ($m)
10	*2.26*	*5.4*
20	*22.0*	*53.0*
30	*36.4*	*88.0*

Sensitivity Analysis:

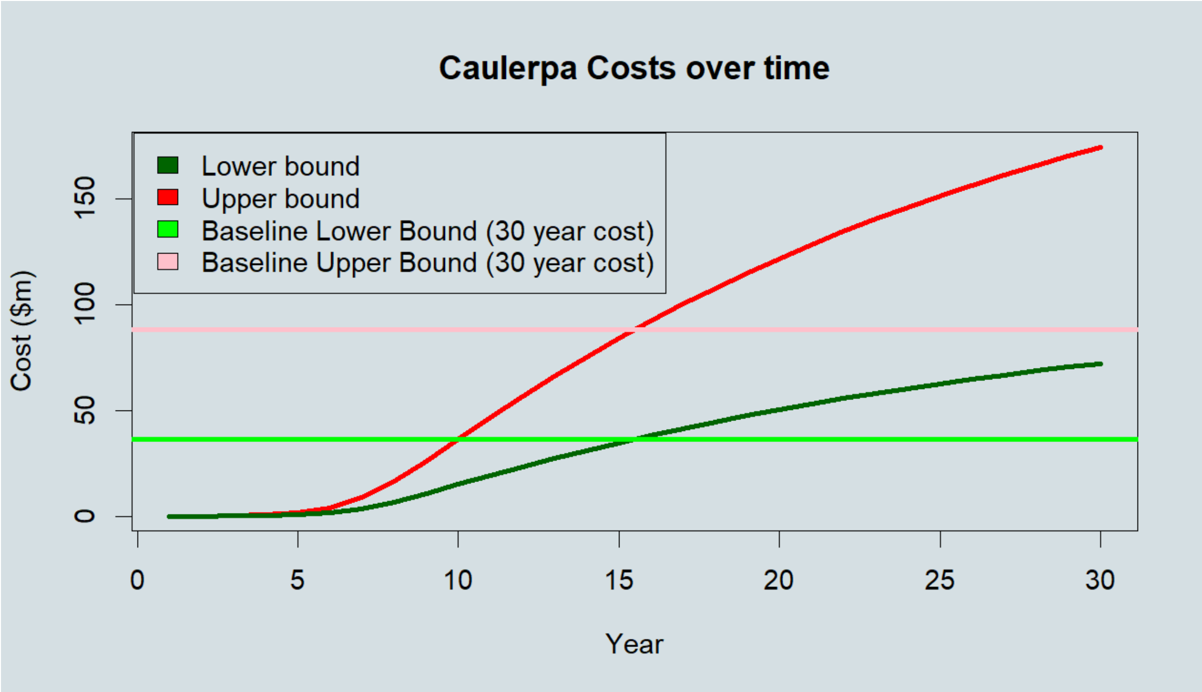
Given that the baseline growth rate and impact assumptions used in this report are likely to be conservative, I also calculated the cumulative thirty-year costs associated with the outbreak under a range of less restrictive assumptions.

Table 9 : Estimated impact of Caulerpa on the Bay of Islands' economy under different assumptions.

Scenario	Total cost over a 30-year period Lower Bound ($m)	Total cost over a 30-year period Upper Bound ($m)
Baseline	*36.4*	*88.0*
Growth rate is 50% higher than expected	*48.1*	*116.2*
Impacts are 50% more severe than expected	*54.7*	*132.1*
Growth rate is 50% higher than expected, and impacts are 50% more severe than expected	*72.1*	*174.3*

Notably, if Caulerpa grows 50% faster than assumed earlier in this report, and the impact of an uncontrolled outbreak on economic activity is 50% more severe than assumed earlier in this report, the total cost of "doing nothing" to prevent the spread of Caulerpa in the Bay of Islands will likely range between $72.1 - $174.3 million, over thirty years.

Figure 5: Caulerpa Costs over time – sensitivity analysis



Under these conditions, the cumulative lower bound cost of a Caulerpa outbreak will exceed $36.4 million (the cumulative, 30-year baseline lower bound cost of the outbreak), and the upper bound costs associated with the outbreak will exceed $88 million (the cumulative, 30-year baseline upper bound cost of the outbreak) within 15 years.

Conclusion

Assuming that the behaviour of Caulerpa brachypus and Caulerpa parvifolia in the Bay of Islands are likely to be broadly similar to the behaviour of Caulerpa taxifolia in the Mediterranean Sea, the uncontrolled spread of the seaweed could, potentially, cost the region's economy millions of dollars.

Based on the assumption outlined above, Caulerpa colonies could cost the Bay of Islands' economy between $40 -$98 million, in present value terms, over the next thirty years.

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