AOTEAROA LAKES

CITIZEN SCIENCE FOR OUR LAKES

Lake Rotoroa

Invasive Macrophyte Assessment March 2022

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Ko au te roto ko te roto ko au

1 Introduction

Lake Rotoroa is a 14.6 hectare dune lake in the Hawke's Bay region and is one of three lakes that make up the Putere Lakes complex. It has a maximum depth of 16.2 m and stratifies[1] seasonally. The surrounding catchment has a mix of agricultural and forestry land use activities. Relatively little is known about the health of this lake however, regular surface water quality monitoring is currently underway. In order to contextualise the water quality data Aotearoa Lakes conducted a qualitative in lake assessment on the 3rd of January 2022. The purpose of the assessment was to gather information on subsurface conditions, littoral[2] health, and the impacts from invasive macrophytes (underwater plants).

Lakes are some of the most impacted ecosystems globally. In Aotearoa New Zealand, 75 % of monitored lowland lakes and 23% of monitored upland lakes are considered as being in either poor or very poor condition (LAWA, 2020). Typical drivers behind declining lake health include increased nutrient input (eutrophication) and invasion by pest species.

Lakes are mostly gravitational sinks for surface water runoff and are therefore disproportionally vulnerable to changes in the surrounding catchment area. As a result, agricultural and forestry activities within the catchment would have contributed to the current state of Lake Rotoroa. In addition to the impacts associated with the land use activities, Lake Rotoroa is subject to the effects of invasive macrophytes. The lake has well established beds of invasive Hornwort (*Ceratophyllum demersum*) and Canadian pond weed (*Elodea canadensis*). Pockets of native species including *Myriophyllum propinquum*, *Chara globularis* and *Nitella hyaline* can still be found in parts of the lake.

Hornwort is a perennial, free-floating submerged macrophyte that has no true roots and uses modified leaves that anchor to a substratum, these modified structures are capable of absorbing nutrients in a similar way to typical roots (Eliašová et al., 2021). Elodea on the other hand use typical roots for anchorage and nutrient absorption (Wen et al., 2022). Both species have a high degree of plasticity which allows them to adapt to and colonise a wide range of environments (Hyldgaard and Brix, 2012).

Macrophytes are considered ecosystem engineers and play key roles in many ecosystem functions. They shape the physical properties of aquatic ecosystems; they alter hydraulics by restricting water flow, aid in sediment particle settlement, influence light availability by shading and assimilate dissolved nutrients, all of which contribute to maintaining a clear water state (Wijewardene, Wu, Fohrer and Riis, 2022). They also provide environmental heterogeneity, habitat and food resources for in lake biodiversity (Wen et al., 2022).

Having healthy macrophyte assemblages are crucial to maintaining these ecosystem functions. Different macrophyte species perform different roles and are better or worse at

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[1] The formation of distinct thermal layers, consisting of a hypolimnion (bottom very cold layer of water), a metalimnion (middle layer where the temperature change is large) and epilimnion (warm surface layer).
[2] The nearshore zone of a lake where sunlight penetrates all the way to the sediment and allows for aquatic plant growth.

specific ecosystem functions. As a result, having a diverse macrophyte species assemblage allows for functional redundancy and better resilience. Rapid colonisation by invasive species typically results in a monoculture and loss of functional redundancy, this leads to impaired ecosystem functions.

2 Summary of observations

- The lake was heavily stratified at the time of the survey. Surface temperatures ranged from 26°C along the shallow margins to 24°C in open water. There was a distinct thermocline at 4 m where the temperature dropped to 17°C, the temperature dropped further to 14°C at 5 m then dropped again to 12°C at 8 m.

- Visual clarity was poor, and the visibility was estimated at 1.5 – 2 m at a depth of 0 – 3 m, this dropped to 1 m visibility at a depth of 4 – 5 m, then decreased further to 0 - 0.5 m past a depth of 6 m.

- Limited to no light penetration was observed past 6 m.

- Two species of invasive macrophytes were sighted, Hornwort (*Ceratophyllum demersum*) (maximum depth extent 8 m) and Elodea (*Elodea canadensis*) (maximum depth extent 2.5 m).

- Where present these invasive macrophytes had almost 100% cover.

- Five species of native macrophytes were sighted *Chara globularis*, *Nitella hyaline, Nitella leonhardii, Myriophyllum propinquum* and *Myriophyllum triphyllum.*

- Eels (unknown if they were short or long fins) and smelt (*Retropinna retropinna*) were sighted.

- Epiphytic algae were commonly seen covering large sections of macrophytes.

- Large amounts of decomposing organic material past 6 m, most of which was dead Hornwort.

- Signs of anoxia throughout the survey area.

- Benthic algal mats visible past 6 m deep.

- Sulphur precipitate was sighted from 5 m and deeper with the thickest layer occurring in the overlying water above decomposing organic material.

3 Incursion and extent

Lake Rotoroa has multiple access points including boat access, this makes the lake prone to invasion by exotic species (fauna and flora) however, public access is limited which reduces this risk. Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*) incursion is likely due to the dispersal of asexual propagules, these species have a high rate of fragmentation and fragment regeneration (Redekop, Hofstra and Hussner, 2016).

Both Hornwort and Elodea have been shown to be very successful in lowland New Zealand lakes. Their ability to adapt and exploit opportunities in our waterways has allowed them to proliferate with great efficiency.

Our survey, conducted on the 3rd of January 2022, was restricted to the northern half of the lake (Figure 1) where we found Hornwort had already formed large, dense beds across the littoral zone making it the dominant macrophyte species in this area. Anecdotal evidence suggests that the southern part of the lake had less invasive macrophyte growth and that the northern section was the most densely colonised area. This could be a result of flow, there is an outlet on the northern tip of the lake so macrophyte propagules/fragments could be washed toward the northern end of the lake where they settle and establish. Further surveys are needed to confirm this.

Figure 1: Lake Rotoroa survey area

Hornwort beds formed an almost continuous band around the survey area extending from the lake margin to a maximum depth of 8 m (Figure 2). Past 6.4 m deep the Hornwort beds begin to die off and there was a noticeable drop in overall plant condition as we approached the maximum depth extent. The upper extent of the Hornwort beds was variable, in some areas the beds started past the emergent riparian vegetation (1 – 1.5 m deep) and in others directly adjacent to the bank (0.5 m).

Figure 2: Approximate macrophyte delimitation – *green areas represent dense Hornwort beds, orange areas represent dense Elodea beds and yellow areas represent moderate cover of Elodea.*

Image 1: Upper extent of Hornwort in shallow area adjacent to native charophyte meadows

Image 2: Mid-section of a dense Hornwort bed sloping from the shallows to the lower extent

The shallow (0.5 – 1m) area surrounding the entry point (wooden jetty on the northwest corner of the lake) was dominated by *Chara globularis* meadows, *Nitella hyalina and Nitella leonhardii* was also present in small clumps. In this area the upper extent of the Hornwort beds was governed by these native charophyte meadows. That being said, clumps of Hornwort and stems of Elodea were frequently seen amongst the native vegetation cover. It is likely that over time Hornwort and Elodea will overrun this area as fragmentation of the charophyte meadows is already evident. However, the condition of Hornwort in the shallower areas (0 – 0.8 m) was poor at the time of the survey and appeared pale yellow and flaccid. This may be a result of high temperatures and light intensity, surface water temperature in these areas was recorded at 25 - 26°C.

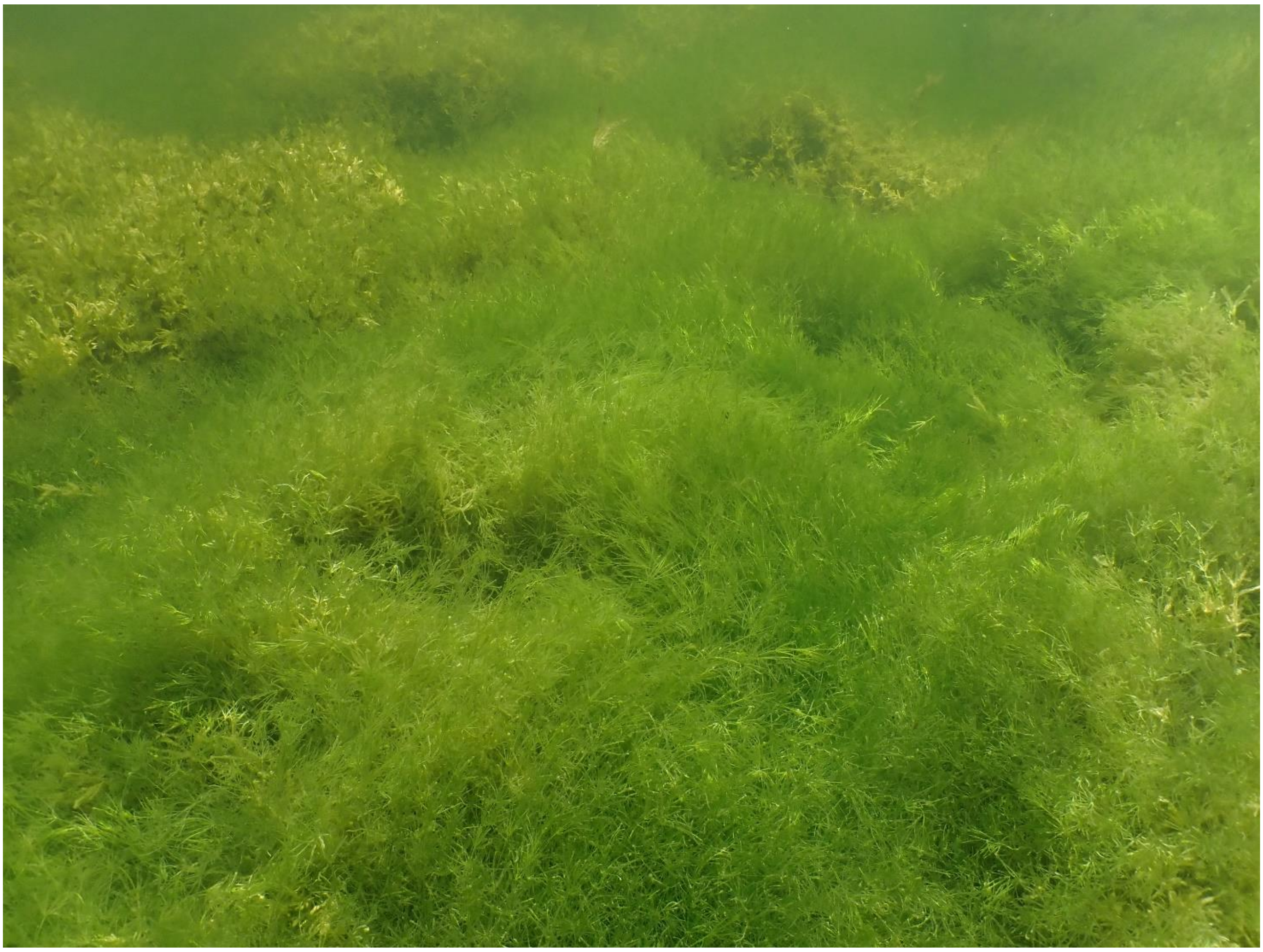

Image 3: *Chara globularis* in the shallow charophyte meadows around the access point

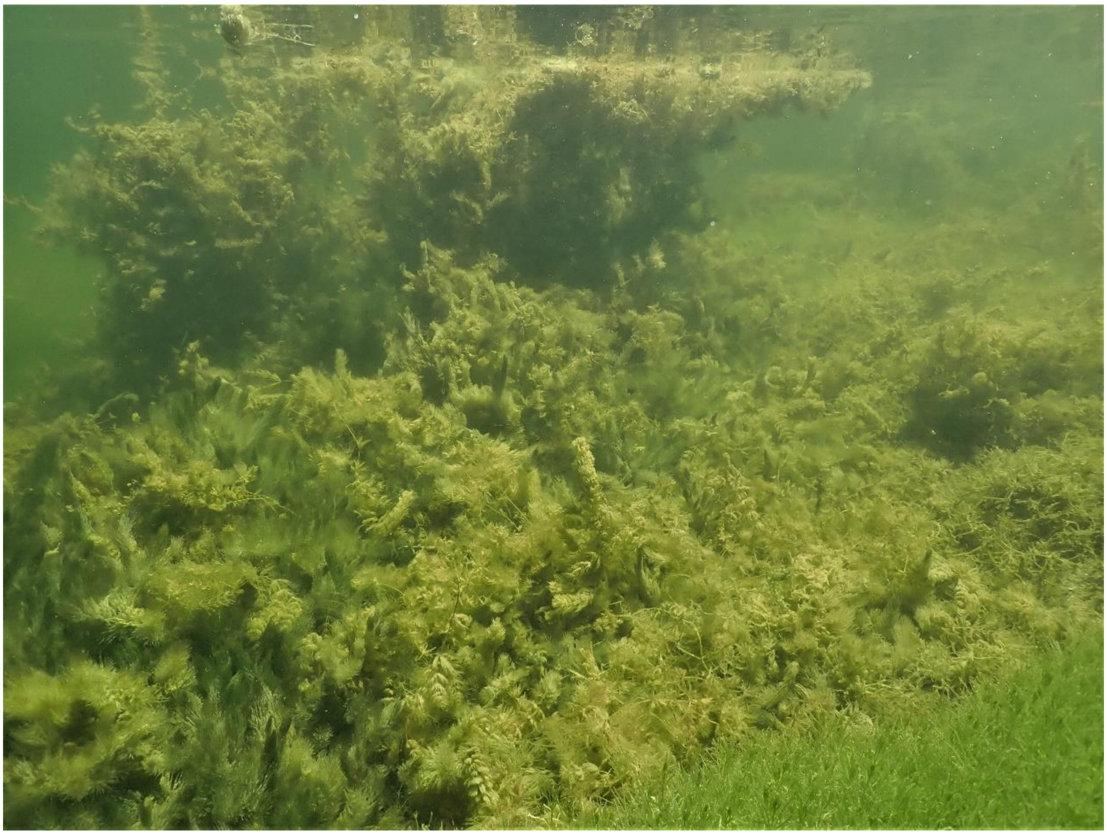

Image 4: Damaged Hornwort in the shallows – *yellow damaged tissue indicative of sun damage/bleaching and high temperatures*

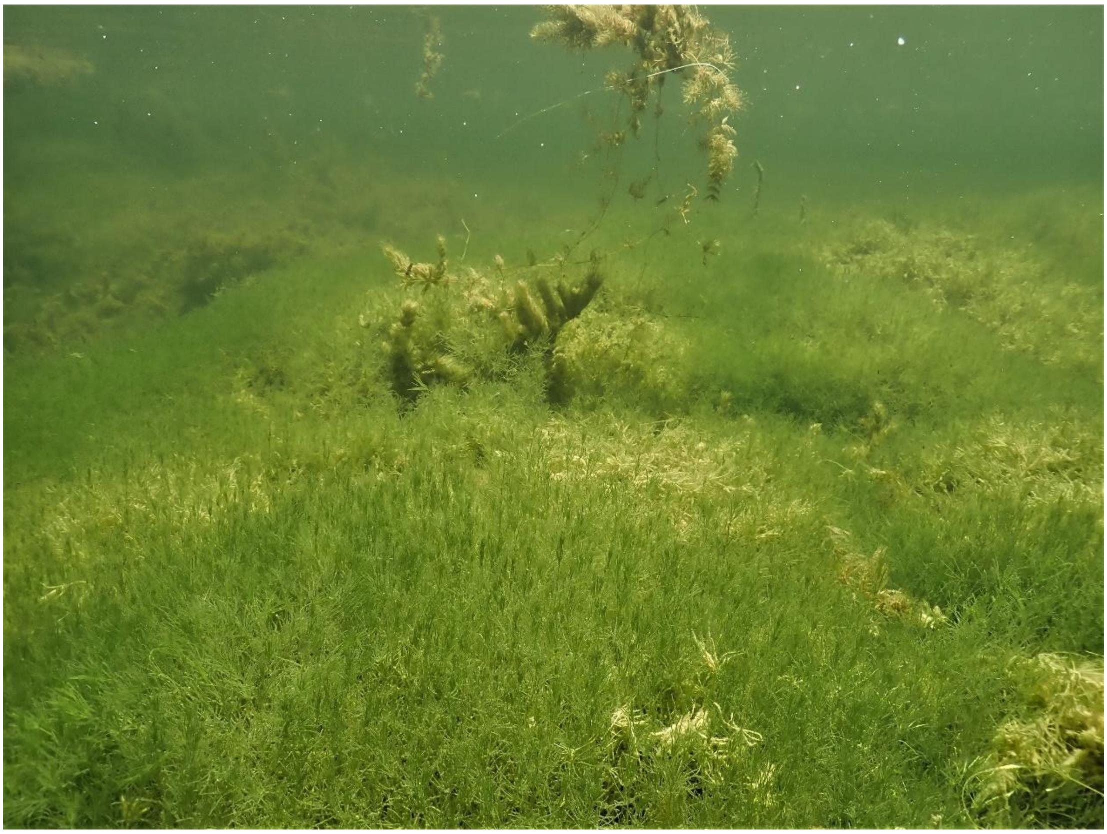

Image 5: Hornwort establishing within the charophyte beds – *small clumps of Hornwort had begun to establish amongst the charophytes, this could eventually lead to these beds becoming overrun*

Elodea, while more contained than Hornwort, had also formed well established beds along the littoral areas in the northern section of the lake (Figure 2). These beds were discrete in nature with well-defined boundaries. Elodea beds tended to occur in shallow areas (0.5 – 2m) around emergent raupō beds (*Typha orientalis*) and sandy slopes that run along the northern bank. The lower extent was much shallower than the Hornwort with a maximum depth extent of 2.5 m, this could be a result of light limitation.

Image 6: Upper extent of Elodea – *Elodea beds extending into the emergent riparian vegetation*

Image 7: Lower extent of Elodea – *tall growing Elodea at 2.5 m deep*

Both Hornwort and Elodea beds effectively excluded the establishment of other species, including each other (where Hornwort was present limited to no Elodea was see and vice versa). This created large sections of monocultures across the survey area. Majority of the native macrophytes were seen in the shallows around the lake margin (0.5 – 2 m). Stems of native *Myriophyllum propinquum* and *Myriophyllum triphyllum* was seen in some locations and amongst the Hornwort beds but the deeper stands were in poor condition and often covered with epiphytic algae.

Image 8: Native Myriophyllum adjacent to the emergent riparian vegetation

Image 9: Myriophyllum covered with epiphytic algae

The in-lake conditions appear to support a high biomass of exotic macrophytes with little competition from native species. This is corroborated by the 2017 LakeSPI Invasive Impact Index of 97% which is the highest of all monitored lakes in the Hawke's Bay region (Burton, 2017). The native macrophyte assemblage lacks diversity and is largely composed of slow growing short stature charophytes (*Chara globularis* and *Nitella hyalina*) with no large floating leaves. This means tall fast-growing species like Hornwort and Elodea have little to no competition and can easily dominate the littoral areas of the lake (Hofstra, Adam and Clayton, 1995). This displacement of native macrophytes is exacerbated by sparse establishment of native vascular species (*Myriophyllum propinquum* and *Myriophyllum triphyllum*), which tend to form open stands with spaces between stems in which exotic species can establish (Hofstra, Adam and Clayton, 1995).

4 Limiting factors

Both Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*) have a high degree of plasticity meaning they can adapt to various conditions (Hyldgaard and Brix, 2012). The extent of these invasive macrophytes is largely limited by in lake conditions like light availability, temperature, and water quality however, some self-regulation is likely as tall dense beds can limit new growth (Best, 1980; Schwarts and Howard-Williams, 1993; Riis et al., 2012).

Light availability is one of the principal limiting factors in Lake Rotoroa. Being a eutrophic lowland lake, the visual clarity is often poor due to a high algal biovolume. Dong et al (2021) and Wen et al (2022) found that the photosynthesis of submerged macrophytes was inhibited when water depth was more than 1.5 times the transparency. Generally, submerged macrophytes can only survive at depths where light intensity reaches at least 1% of that on the water surface (Wen et al., 2022).

The maximum depth extent for Hornwort in Lake Rotoroa was 8 m however, past 6 m deep there was a noticeable drop in physical condition. The dense Hornwort beds began to die off from 6.4 m deep and very few live stems were seen past 7 m. During the survey visual clarity was an estimated 1 – 2 m from a depth of 0 – 4 m, it then decreased to 0 - 0.5 m past a depth of 5 m. Limited to no light penetration was observed past a depth of 6 m.

Hornwort can adapt to varying light levels meaning that an established bed could photosynthesize to a deeper depth than would otherwise be expected (Fair and Meeke, 1983). Elodea on the other hand is less adapted to extreme low light conditions which could explain why the maximum depth extent recorded was 2.5 m. An adaptation to low light exhibited by both Hornwort and Elodea is growing taller in order to utilise light from shallower depths (Wen et al., 2022). Despite this ability to grow taller Elodea cannot compete with the faster growth rate seen in Hornwort (Riis et al., 2012). Elodea could have existed in this lake prior to Hornwort establishment but would have quickly become overrun and pushed into discrete areas along the shallow margins of the lake where Hornwort appears to struggle.

Hornwort has the added advantage for being able to form dense floating rafts on the surface, this growth pattern effectively shades out the area below it and limits any new macrophyte growth.

High light intensity can also negatively affect Hornwort and Elodea. Hornwort in Lake Rotoroa appears to be more susceptible to the effects of direct sunlight. Bleaching and masses of dead Hornwort can be seen at the surface and in the shallows. The lack of shade along the margins of the lake exacerbates the issues.

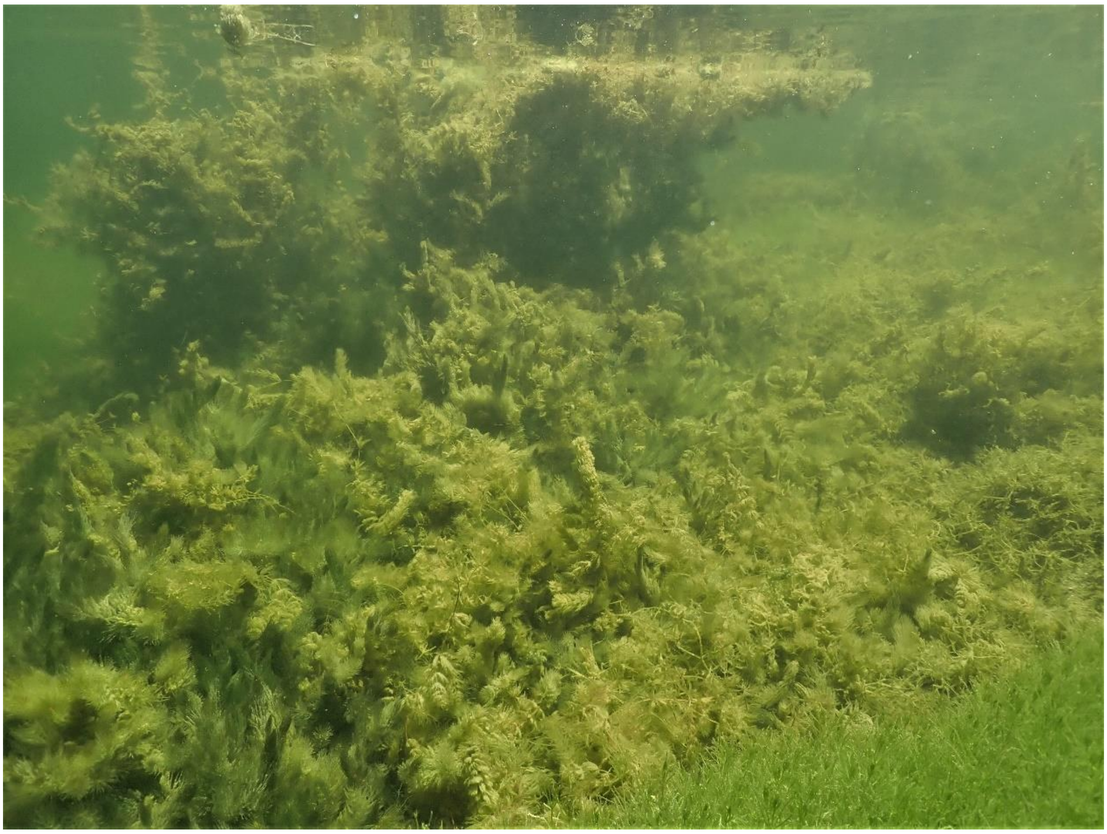

Image 10: Floating mats of damaged Hornwort along the shallow margins – *yellow damaged tissue indicative of sun damage/bleaching and high temperatures*

The maximum growth period for Hornwort typically occurs earlier on in the year compared to Elodea which may explain why it has managed to colonise bulk of the available habitat space. Additionally, Elodea relies more on substrate characteristics as it is a rooted plant whereas hornwort can potentially exploit a wider range of conditions (Best, 1977; Best and Meulemans, 1979).

In general, both Hornwort and Elodea prefer circumneutral pH conditions with low turbidity and salinity however, Hornwort has been found to flourish at slightly higher pH values (7.6 – 8.8) (Eliašová et al., 2021).

Ammonia in low concentration across short periods can promote Hornwort growth while chronic exposure is toxic (Best, 1980; Eliašová et al., 2021). Pulses of ammonia are common in lakes surrounded by agricultural and livestock land use activities which could have contributed to the rapid Hornwort colonisation. Past 6 m deep there is a build-up of decomposing organic material, majority of which is dead Hornwort. This decomposition leads to anoxia and increased sediment ammonia concentrations both of which limit Hornwort growth. This creates a degree of self-regulation and may contribute to maintaining a steady biomass.

Image 11: Thick layer of decomposing Hornwort and organic material in the deeper sections of the lake – *the haze seen in the photo is a sulphur precipitate*

Kassa, Mengistu, Wondie and Tibebe (2021) found that hornwort occurred more frequently in areas with higher total phosphorus and dissolved reactive phosphorus. Much like ammonia elevated phosphorus concentrations are commonly associated with agricultural activities in the contributing catchment. The nutrient concentration in Lake Rotoroa is likely elevated and could be one of the reasons the lake is able to support a high biomass of exotic macrophytes. Groundwater discharge can also significantly contribute to nutrient budgets of lakes by delivering high concentrations of available phosphorous into the water column (Périllon and Hilt, 2019). Not much is known about the groundwater quality in the underlying aquafer or its connectivity to Lake Rotoroa, additional investigation would be needed to quantify the potential nutrient contribution from groundwater discharge. Hornwort does not have roots and can exploit higher concentrations of dissolved phosphorus in the water column, this may explain the large biomass seen in Lake Rotoroa.

5 Environmental effects

Invasive macrophytes like Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*) cause a range of detrimental environmental effects. These macrophytes form extensive dense beds that create microclimates and fundamentally alter the environment around them.

5.1 Changes to littoral environments

Hornwort form large buoyant mats that shade out large areas. This creates low light environments and prevents new macrophyte growth from occurring. Elodea forms tall dense beds and can also create a shading effect. Thus, these macrophytes can alter the light availability in the littoral zone.

Dense macrophyte beds can attenuate incoming flows and potentially limit the distribution of external organic material. These dense beds also cause stagnation and enhanced deposition of fine sediments that would otherwise be eroded. This attenuation effect creates muddy organic rich conditions in the littoral zone, these conditions promote anoxia, increased ammonia release and sediment nutrient remobilisation. The stagnation in and around these dense macrophyte beds can create temperature gradients of up to 10°C per meter, this is affected by wind and wave action but dense beds such as the ones at Lake Rotoroa can maintain these extreme gradients for prolonged periods. The surface water temperature in the dense Hornwort beds was 25 – 26°C during the survey, the surface water temperature was lower in open water and ranged from 23 - 24°C.

The combination of these effects has altered vast sections of the littoral zone and the ecosystem functions/services it provides. The littoral zone is typically where in-lake biodiversity is greatest. Most native freshwater fauna prefer cooler water temperatures (16 - 19°C) and have upper temperature tolerances of 21°C. They are also averse to prolonged periods of anoxia. The conditions created by dense exotic macrophyte growth can displace native species and cause a reduction in biodiversity. This loss in biodiversity often translates into a loss of ecosystem function and decline in overall lake health.

5.2 Water quality and sediment impacts

Increases in invasive macrophyte biomass is often associated with an increase in ecosystem productivity via enhanced phosphorus cycling from sediment and the contribution of organic matter (Carpenter and Lodge, 1986). The released nutrients feed planktonic biomass and the increased planted area support high juvenile fish numbers, shielding them from predators. The juveniles then exert additional predation pressure on gazers and zooplankton which alleviates the pressure on phytoplankton, thus shifting the system to a more algal dominant state (Carpenter and Lodge, 1986). It is unclear if this prey shielding effect play a role in Lake Rotoroa. Eels and smelt were the only vertebrates sighted during the survey, but no formal assessments were done.

The sediment characteristics in Lake Rotoroa change along a depth gradient. The sandy beaches surrounded by Raupō have limited surficial organic silt. The substrate becomes muddy within the dense macrophyte beds with a thick layer of organic silt. Past 6 m the Hornwort begins to die off and there is an extensive layer of dead Hornwort material, this layer was up to 30 cm thick along the lower boundary of the dense Hornwort beds.

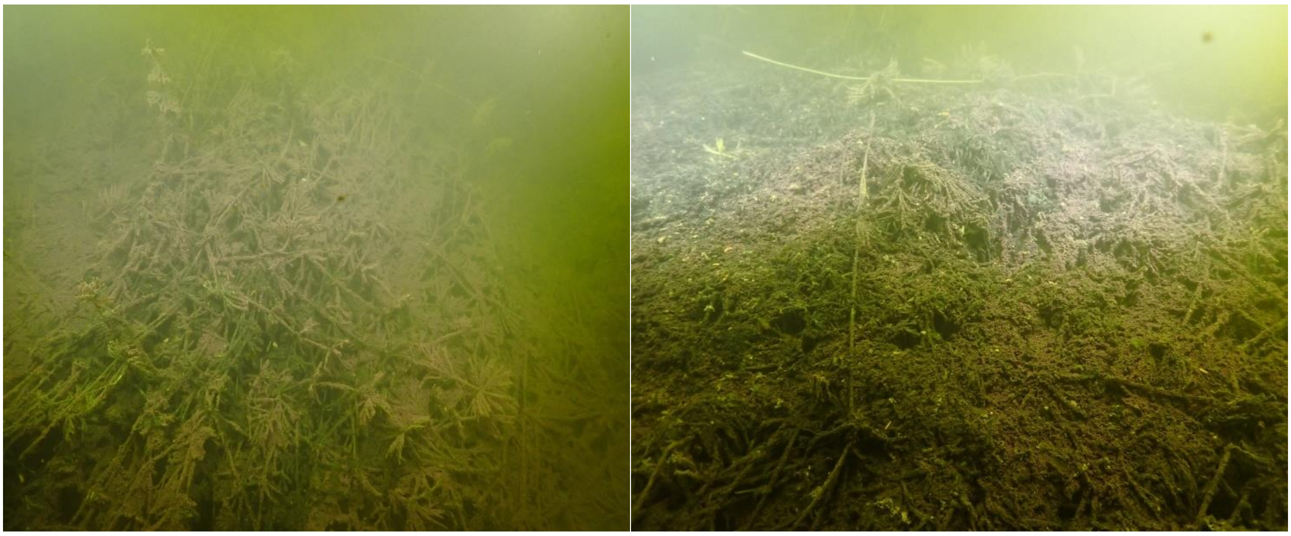

Image 12: Thick layer of decomposing Hornwort and organic silt

Beneath this organic layer there was approximately half a meter of soft silt before more firm consolidated sediment was felt. From 6.7 to 7.5 m deep (approx. 20 – 25 m from shore) the sediment firms up and has a coarser grain size with a surficial layer of organic silt. Signs of anoxia and benthic algal mats were seen throughout the survey area, particularly within the invasive macrophyte beds and along the lower bed boundary (>6 m).

Image 13: Patches of benthic algal growth amongst the decomposing organic material

The incomplete decomposition of plant detritus has been considered as one of the important factors that cause sediment accumulation and lake aging, especially in eutrophic shallow lakes (Si et al., 2020). The continuous build-up of organic rich sediment can increase the extent of the littoral zone and open new areas for macrophyte colonisation. This could ultimately lead to an expansion in Hornwort extent over time. Eventually the littoral sediment properties start to limit submerged growth in favour of emergent plants that prefer a higher organic content, this is another way excessive macrophyte growth can accelerate natural lake succession.

The build-up of organic matter occurs because the rate of decay slows down as decomposition continues so new material decomposes faster than old material. As this old material is buried the rate of decay reduces further thus you have a build-up of persistent organic matter (Carpenter and Lodge, 1986). As more plant material is deposited the depth to which sediment properties are affected increases.

Dead macrophyte material releases phosphorus readily and eventually nitrogen (Pomogyi, Best, Dassen and Boon, 1984). Elevated total Phosphorus, total nitrogen, ammonia, total organic carbon and conductivity are commonly measured in the overlying water above decaying macrophytes (Si et al., 2020). This decomposition process also stimulates bacterial metabolism which consumes oxygen and releases carbon dioxide, this causes a drop in pH and dissolved oxygen concentration (Si et al., 2020). This anaerobic decomposition promotes the release of labile sulphur which contributes to the visible precipitate (Wium-Andersen, Anthoni and Houen, 1983). A sulphurous layer was seen in the overlying water above the decomposing Hornwort and in some areas this layer was seen as shallow as 5 m. The persistence and extent of this sulphurous layer is unknown, but it is likely that in-lake biodiversity would be affected by chronic exposure to this sulphur precipitate.

Image 14: Sulphur precipitate in the overlying water above decomposing organic material

5.3 Displacement of native species

The low native macrophyte diversity in Lake Rotoroa largely consists of Chara and Nitella species, all of which are short stature, slow growing macrophytes with no leaves, the taller Myriophyllum species are sparsely distributed and don't produce large leaves. These growth forms facilitate greater colonisation potential for exotic plants as they offer little competition for light and other resources (Hofstra, Adam and Clayton, 1995). de Winton and Clayton (1996) found native seed numbers and species richness was often lower in lakes dominated by adventive weeds such as Hornwort and Elodea.

Hornwort does not rely on typical root structures and can form dense floating mats that shade out large sections of the littoral zone. This allows them to exploit a greater area of the lake and outcompete lower growing species. Their growth patterns coupled with a high fragmentation and fragment regeneration rate has allowed it to dominate the littoral zone

Both Hornwort and Elodea are faster growing and taller than native macrophytes. They can establish in the gaps between the stems of native species, this cause fragmentation of native macrophyte beds and creates tall stands of invasive species that shades out everything below it. This is one of the ways that these adventive species quickly overrun the littoral zone and displace native macrophytes.

Image 15: Stems of Hornwort and Elodea establishing amongst the native charophyte beds

The displacement of seed producing native species reduces the replenishment of seed banks in the lake which further limits the future re-establishment of native macrophytes (de Winton and Clayton, 1996). Seed numbers beneath adventive macrophyte beds can be less than 5% of those present under native vegetation (de Winton and Clayton, 1996).

The formation of dense Hornwort beds and continuous deposition of organic material alter sediment conditions and prevent native seeds from germinating (Hofstra, Adam and Clayton, 1995). This inhibition of seed germination can occur as a result of seed burial or alterations to the sediment chemistry (lowering of pH and elevated concentrations of ammonia and sulphides) that cause germination failure and seedling mortality (de Winton and Clayton, 1996).

6 Additional observations

Only two in-lake vertebrates were sighted during the assessment, the first was schools of smelt (*Retropinna retropinna*) in the shallow areas around the Raupō. Several eels were sighted at a distance however due to the poor visibility it is unknown whether they are longfins or shortfins. Interestingly we observed an eel in the shallows (2 m depth) that was almost entirely buried in the sediment. Eels are known to bury themselves into the substrate and become inactive at temperatures around 10°C (Graynoth and Jellyman, 2002). Considering the extreme temperature difference in the lake with bottom water temperatures reaching 12°C it is plausible that this eel had buried itself in response to the cold.

Image 16: Eel buried in the sediment

As mentioned above there were large sections of macrophytes covered by epiphytic algae. This epiphytic biofilm was most pronounced along a band between 3 – 4 m deep. The formation of epiphytic algae is likely limited by macrophyte shading and light availability which may explain why it was more prominent on the outer edge of the dense Hornwort beds at a specific depth.

Image 17: Large sections of Hornwort densely covered by epiphytic algae

Image 18: Close up of epiphytic algae smothering the apical portion of a Hornwort stem

This epiphytic algal growth appeared to be more common on Hornwort and native Myriophyllum species despite both species being considered as allelopathic active macrophytes (Wijewardene, Wu, Fohrer and Riis, 2022). Myriophyllum species have been shown to be less resistant to colonisation by epiphytic algae (Wijewardene, Wu, Fohrer and Riis, 2022) however, there did not appear to be any host specificity between Hornwort and Myriophylum during the survey. (Wijewardene, Wu, Fohrer and Riis, 2022) found host specificity is lower in eutrophic waters when compared to oligotrophic conditions.

Epiphytic algae can reduce the intensity and quality of light able to be absorbed by the macrophyte host and they also compete for nutrients (Klančnik, Gradinjan and Gaberščik, 2015; Li et al., 2020). In this way the epiphytic growth could contribute to regulating Hornwort extent in Lake Rotoroa.

Limited to no epiphytic growth was seen on native charophyte species and no growth at all was seen on Elodea, this is potentially a result of allelopathic effects from polyphenolic and sulphur compounds or a preference for more complex host morphology (e.g., high perimeter to surface area ratio and high fractal dimension) (Best, 1977; Pettit et al., 2016).

7 Conclusion

Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*) have formed extensive beds throughout the littoral zone of Lake Rotoroa. Hornwort is the dominant macrophyte in the survey area and where present has an almost 100% cover. This creates large, continuous sections of monoculture along the lake margin that have displaced most of the native macrophyte species, all of which are now constrained to discrete pockets and isolated stems.

In addition to the displacement of native macrophytes these large monocultures of Hornwort and Elodea create a situation where if they were to be removed there would be little functional redundancy in ecosystem functions like nutrient assimilation and habitat provision.

The increased deposition of organic material caused by the high biomass of Hornwort has created unfavourable sediment conditions for native macrophyte seed germination and re-establishment. This decomposing organic matter has likely contributed to the current trophic state through nutrient release and remobilisation.

Considering the current extent of Hornwort and Elodea in the lake it is likely that the entire littoral zone will eventually become colonised by these invasive macrophytes if no control is undertaken.

8 Management considerations

There are a variety of management options that can be utilised for Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*) control. Macrophyte removal options are typically grouped into either chemical control (herbicides) or physical/manual removal. Each of these options have certain application limitations and their effectiveness varies depending on the site-specific conditions and constraints.

Herbicides such as Diquat and Endothall can be very effective but may cause adverse effects. These herbicides have been successfully used in New Zealand Lakes and the associated environmental concerns can be effectively managed. Both Hornwort and Elodea are prone to fragmentation and cutting/disturbance of plant material produces propagules that can spread the incursion. This makes successful control via manual removal difficult.

Smothering invasive macrophytes using woven mats, hessian bags and tarpaulins have been used with some success elsewhere in New Zealand however it is not a suitable option for Hornwort. Hornwort does not rely on typical roots for anchorage or nutrient absorption and can form floating mats, this will allow them to establish on/above the mats. If mats are used over the dense Hornwort beds the disturbance will likely cause further dispersal of fragments, these fragments will settle on top of the mat and begin to grow. The subsequent removal of the mats will disturb the newly established Hornwort and cause further dispersal. Smothering could be a viable option for Elodea in Lake Rotoroa. Unlike the extensive tall and floating Hornwort beds the Elodea beds remain rooted in the sediment, are small and are confined to the shallow gently sloped margins. It is likely that a combination of manual removal, herbicides and strategic smothering will result in the best outcome.

Despite the impacts Hornwort and Elodea are currently causing in the lake they are still performing key ecosystem functions like nutrient assimilation, habitat provision and regulation of in-water conditions. As a result, the management/control of these invasive macrophytes should be approached with caution and with consideration of the potential collateral effects.

Removal of tall macrophyte beds increases light availability and reduces self-shading, this could promote rapid recolonisation of the cleared area by fast growing invasive species. Clearing large sections of the littoral zone also removes habitat for native fauna, staging the macrophyte removal to ensure some refugia remains at all times should be considered.

Hornwort has been used in restoration efforts in the northern hemisphere as a means of maintaining a clear water state (Dai et al., 2014). The correct biomass of Hornwort has been shown to significantly reduce the concentrations of total phosphorus, dissolved reactive phosphorus, ammonia and chlorophyll-a, this leads to a corresponding drop in turbidity and increase in visual clarity (Dai et al., 2012 b; Dai et al., 2012 a). Dai et al (2012 a) found that 20% is probably the optimal restoration coverage area for Hornwort in eutrophic shallow lakes. Significant alterations in water quality were not noted past 20% coverage. It is important to note while planning any macrophyte control strategies that studies suggest the removal of >30% of the submerged macrophytes in a lake with high nutrient input was sufficient to trigger a regime shift to an alternative stable state with higher phytoplankton biomass (Kuiper et al., 2017 (Thiemer, Schneider and Demars, 2021). One way to avoid this shift in trophic state is to restore native charophyte beds while invasive species are being controlled/removed.

It has been demonstrated that submerged macrophyte restoration could influence sediment–water phosphorus processes in shallow lakes by absorbing inorganic phosphorus from the water and sediment and retaining it in plant material (Vincent, 2001; Marcus et al., 2003; Zhang et al., 2011; Dai et al., 2012 b).

Dense charophyte meadows can cause long-term immobilisation of nutrients (Hilt et al., 2006). In calcium-rich lakes phosphorus is co-precipitated with calcium carbonate above the charophyte beds thus removing the available phosphorus from the water column (Hilt et al., 2006). Charophytes are also able to deliver oxygen to the sediment which enhances nitrification/denitrification processes and prevents iron-bound sediment phosphorus from being released into the overlying water (Hilt et al., 2006). Native charophytes have an added advantage as they are wintergreen and do not die off in the same quantities as other macrophytes, this means they do not add to the oxygen depletion through decomposition and are able to maintain their nutrient assimilation capacity year-round.

Restoring native charophyte beds in Lake Rotoroa should be considered as a key management objective. Studies suggest that 50% is the optimal submerged macrophyte coverage for improvements in water quality in temperate shallow lakes (Zhang et al., 2021). Achieving this amount of cover may not be possible however even lower cover can create positive environmental effects.

9 Recommendations

1. **Invasive macrophyte delimitation survey**
   The delimitation survey will provide quantitative information regarding the total lake wide extent of both Hornwort (*Ceratophyllum demersum*) and Elodea (*Elodea canadensis*). It will also identify key location where their establishment is greatest and help inform management/control strategies.

2. **Pathways and Incursion risk assessment**
   All three of the Putere Lakes have been colonized by invasive macrophytes. Both Hornwort and Elodea exist in Lake Rotonuiaha and Elodea is the only macrophyte in Lake Rotongaio. An assessment of the likely transfer pathways between the lakes and the risk of recolonisation should be done. This is crucial to the successful management of these lakes as macrophyte control could be futile unless the potential reintroduction of invasive species is managed.

3. **Detailed assessment of in-lake fauna**
   Biodiversity surveys, using eDNA, standard netting and underwater searching for key species that are hard to detect using molecular methods (kākahi and kōura), will help fill knowledge gaps regarding in lake ecology. Knowing what fauna exists in the lake will guide the selection of invasive macrophyte control tools and provide a better understanding of the system.

4. **Bathymetry and residence time**
   Bathymetry and residence time assessments will aid in establishing nutrient budgets (including translating external loads to in-lake loads), water balances and in-lake process models. It will also provide useful information for the invasive macrophyte management, knowing the depth, slope and location of macrophyte beds will guide the selection of the best methods.

5. **Options assessment for macrophyte control**
   Hornwort and Elodea occupy the similar habitats, so it is important to plan control options for both species. Each option should be considered based on the likely effectiveness and viability of use in Lake Rotoroa.

6. **Catchment management options assessment**
   Investigate external nutrient loads and assess potential catchment management options aimed at reducing nutrient and contaminant loading to the lake.

7. **Floating wetlands**
   Floating wetlands can provide shading, decontamination (through biofilm production), and nutrient assimilation functions. The grown plants can be harvested and used for riparian planting elsewhere in the catchment. Baskets of bio balls can be attached to the bottom of the rafts to increase the surface area for beneficial bacteria and provide midwater refugia for zooplankton.

8. **Restore charophyte meadows**
   Restoring charophyte meadows will assist in maintaining lake health by absorbing nutrients, stabilising sediment and creating habitat for in-lake fauna. Restoration can be via natural regeneration (pending seed bank viability) or by cultivating seedings from the in-lake seed bank and replanting them. If there is no viable seed bank or the sediment condition no longer supports natural regeneration, interventions like RotoTurf could be used (natural fibres mats with seeds that are laid over the lakebed to accelerate macrophyte regeneration and sediment stabilisation).

9. **Kākahi rafts**
   Adult kākahi can filter up to 1.5 litters of water per mussel per hour and can filter the entire volume of a small lake relatively quickly if present in large enough numbers. It is unknown if kākahi were once found in Lake Rotoroa and no signs of them were seen during the survey (appropriate in-lake habitats were checked for live musses and shell hash during the assessment). Introducing kākahi on suspended rafts could create natural filtration capacity and aid in the overall restoration.

10. Restoration and management strategy

Create a restoration and management strategy that clearly discusses the expectations and project objectives. Include and operational section that outlines what interventions will be used, where they will be used and when they be used. A monitoring plan including methods and specific metrics aimed at assessing the effectiveness of the interventions as well as progress toward the project goals should be part of the strategy.

10References

Best, E. and Meulemans, J., 1979. Photosynthesis in relation to growth and dormancy in Ceratophyllum demersum. Aquatic Botany, 6, pp.53-65.

Best, E., 1977. Seasonal changes in mineral and organic components of Ceratophyllum demersum and Elodea canadensis. Aquatic Botany, 3, pp.337-348.

Best, E., 1980. Effects of nitrogen on the growth and nitrogenous compounds of Ceratophyllum demersum. Aquatic Botany, 8, pp.197-206.

Burton, T., 2017. Assessment of lakes in the Hawke's Bay Region using LakeSPI. Client report No: 2017070HN

Carpenter, S. and Lodge, D., 1986. Effects of submersed macrophytes on ecosystem processes. Aquatic Botany, 26, pp.341-370.

Dai, Y., Jia, C., Liang, W., Hu, S. and Wu, Z., 2012. Effects of the submerged macrophyte Ceratophyllum demersum L. on restoration of a eutrophic waterbody and its optimal coverage. Ecological Engineering, 40, pp.113-116.

Dai, Y., Tang, H., Chang, J., Wu, Z. and Liang, W., 2014. What's better, Ceratophyllum demersum L. or Myriophyllum verticillatum L., individual or combined? Ecological Engineering, 70, pp.397-401.

Dai, Y., Wu, S., Chang, J., Jia, C., Liang, W. and Wu, Z., 2012. Effects of Ceratophyllum demersum L. restoration on phosphorus balance at water–sediment interface. Ecological Engineering, 44, pp.128-132.

de Winton, M. and Clayton, J., 1996. The impact of invasive submerged weed species on seed banks in lake sediments. Aquatic Botany, 53(1-2), pp.31-45.

Dong, B., Zhou, Y., Jeppesen, E., Shi, K. and Qin, B., 2021. Response of community composition and biomass of submerged macrophytes to variation in underwater light, wind and trophic status in a large eutrophic shallow lake. Journal of Environmental Sciences, 103, pp.298-310.

Eliašová, A., Hrivnák, R., Štefánová, P., Svitok, M., Kochjarová, J., Oťaheľová, H., Novikmec, M. and Pal'ove-Balang, P., 2021. Effects of ammonium levels on growth and accumulation of antioxidative flavones of the submerged macrophyte Ceratophyllum demersum. Aquatic Botany, 171, p.103376.

Fair, P. and Meeke, L., 1983. Seasonal variations in the pattern of photosynthesis and possible adaptive response to varying light flux regimes in Ceratophyllum demersum L. Aquatic Botany, 15(1), pp.81-90.

Graynoth, E. and Jellyman, D. J., 2002. Growth, survival, and recruitment of juvenile shortfinned eels (Anguilla australis) in a large New Zealand coastal lake, New Zealand. Journal of Marine and Freshwater Research, 36:1, pp. 25-37.

Hilt, S., Gross, E., Hupfer, M., Morscheid, H., Mählmann, J., Melzer, A., Poltz, J., Sandrock, S., Scharf, E., Schneider, S. and van de Weyer, K., 2006. Restoration of submerged vegetation in shallow eutrophic lakes – A guideline and state of the art in Germany. Limnologica, 36(3), pp.155-171.

Hofstra, D., Adam, K. and Clayton, J., 1995. Isozyme variation in New Zealand populations of Myriophyllum and Potamogeton species. Aquatic Botany, 52(1-2), pp.121-131.

Hyldgaard, B. and Brix, H., 2012. Intraspecies differences in phenotypic plasticity: Invasive versus non-invasive populations of Ceratophyllum demersum. Aquatic Botany, 97(1), pp.49-56.

Kassa, Y., Mengistu, S., Wondie, A. and Tibebe, D., 2021. Distribution of macrophytes in relation to physico-chemical characters in the south western littoral zone of Lake Tana, Ethiopia. Aquatic Botany, 170, p.103351.

Klančnik, K., Gradinjan, D. and Gaberščik, A., 2015. Epiphyton alters the quantity and quality of radiation captured by leaves in submerged macrophytes. Aquatic Botany, 120, pp.229-235.

Koyama, M., Yamamoto, S., Ishikawa, K., Ban, S. and Toda, T., 2014. Anaerobic digestion of submerged macrophytes: Chemical composition and anaerobic digestibility. Ecological Engineering, 69, pp.304-309.

Li, D., Zhang, S., Adyel, T., Liu, K. and Gong, L., 2020. Negative effects on the leaves of submerged macrophyte and associated biofilms growth at high nitrate induced-stress. Aquatic Toxicology, 226, p.105559.

Périllon, C. and Hilt, S., 2019. Groundwater discharge gives periphyton a competitive advantage over macrophytes. Aquatic Botany, 154, pp.72-80.

Pettit, N., Ward, D., Adame, M., Valdez, D. and Bunn, S., 2016. Influence of aquatic plant architecture on epiphyte biomass on a tropical river floodplain. Aquatic Botany, 129, pp.35-43.

Pomogyi, P., Best, E., Dassen, J. and Boon, J., 1984. On the relation between age, plant composition and nutrient release from living and killed Ceratophyllum plants. Aquatic Botany, 19(3-4), pp.243-250.

Redekop, P., Hofstra, D. and Hussner, A., 2016. Elodea canadensis shows a higher dispersal capacity via fragmentation than Egeria densa and Lagarosiphon major. Aquatic Botany, 130, pp.45-49.

Riis, T., Olesen, B., Clayton, J., Lambertini, C., Brix, H. and Sorrell, B., 2012. Growth and morphology in relation to temperature and light availability during the establishment of three invasive aquatic plant species. Aquatic Botany, 102, pp.56-64.

Schwarts, AM. and Howard-Williams, C., 1993. Aquatic weed-bed structure and photosynthesis in two New Zealand lakes. Aquatic Botany, 46, pp. 263-281.

Si, T., Chen, H., Qiu, Z., Zhang, L., Ohore, O. and Zhang, S., 2020. Bacterial succession in epiphytic biofilms and deciduous layer sediments during Hydrilla verticillata decay: A field investigation. Journal of Environmental Sciences, 93, pp.193-201.

Thiemer, K., Schneider, S. and Demars, B., 2021. Mechanical removal of macrophytes in freshwater ecosystems: Implications for ecosystem structure and function. Science of The Total Environment, 782, p.146671.

Wen, Z., Wang, H., Zhang, Z., Cao, Y., Yao, Y., Gao, X., Tian, Y., Su, H., Ni, L., Xiao, W., Cai, Q., Zhang, X. and Cao, T., 2022. Depth distribution of three submerged macrophytes under water level fluctuations in a large plateau lake. Aquatic Botany, 176, p.103451.

Wijewardene, L., Wu, N., Fohrer, N. and Riis, T., 2022. Epiphytic biofilms in freshwater and interactions with macrophytes: Current understanding and future directions. Aquatic Botany, 176, p.103467.

Wium-Andersen, S., Anthoni, U. and Houen, G., 1983. Elemental sulphur, a possible allelopathic compound from Ceratophyllum demersum. Phytochemistry, 22(11), p.2613.

Zehnsdorf, A., Hussner, A., Eismann, F., Rönicke, H. and Melzer, A., 2015. Management options of invasive Elodea nuttallii and Elodea canadensis. Limnologica, 51, pp.110-117.

Zhang, X., Zhang, J., Li, Z., Wang, G., Liu, Y., Wang, H. and Xie, J., 2021. Optimal submerged macrophyte coverage for improving water quality in a temperate lake in China. Ecological Engineering, 162, p.106177.

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