The influence of harvest frequency and regime on the performance of Filamentous Algae Nutrient Scrubbers treating agricultural drainage

A thesis

submitted in fulfilment

of the requirements for the degree

of

Master of Science (Research)

in Ecology and Biodiversity

at

The University of Waikato

by

Okeroa Waaka

2023

Abstract

Filamentous algae nutrient scrubbers (FANS) are ecologically engineered flow-ways that have recently been proposed as a potential on-farm method to treat agricultural drainage in New Zealand. The effectiveness of FANS systems to remove nutrients from polluted waters and to produce algal biomass as a harvestable by-product is heavily influenced by operational parameters. As filamentous algae grow on a flow-way, the thickness of the algal biomass increases and begins to reduce light penetration and nutrient assimilation. Therefore, periodic harvesting of the accumulated algal biomass plays a key role in determining the biomass production and nutrient removal performance of FANS systems.

The overall aim of this study was to investigate the influence of harvest frequency and harvest regime on biomass productivity and nutrient removal of an outdoor FANS system. The FANS system used in this study consisted of six flow-ways that were split into two sets of triplicate flow-ways named "FULL" and "PARTIAL". Harvesting of the FULL replicate flow-ways occurred once a week, where algal biomass accumulated along the entirety of the flow-way was collected. Harvesting of the PARTIAL replicate flow-ways occurred twice a week, where the algal biomass was collected in alternate meter sections (a total of 3-metre harvest length every 3 – 3.5 days).

The increased harvest frequency (3 – 3.5 days) and sectioned harvest regime implemented in the PARTIAL replicate flow-ways significantly improved biomass productivity (3.2 g DW m^{-2}. d) in comparison to the less frequent (7 – 7.5 days) and total harvest regime implemented in the FULL replicate flow-ways (0.9 g DW m^{-2}. d). However, there was no significant difference in nutrient removal rates between the PARTIAL and FULL replicate flow-ways. There is still limited understanding of how operational parameters can be optimized to maximise biomass productivity and nutrient removal in FANS systems on a year-round basis. However, the findings of this study demonstrate that an increased harvest frequency and sectioned harvest regime can improve the biomass yield of filamentous algae grown on an outdoor FANS system during spring to summer months.

Furthermore, this study has suggested the potential for Māori acceptance of FANS technology and algal biomass use. In person interviews with whanau and iwi members recalled use of algal biomass harvested from rivers and streams as fertilizer for vegetable gardens or bait for eel trapping. Moreover, the literature review and in person interviews highlighted the importance of identifying and using ngā kupu (words and terms) used by Māori to describe freshwater algae. The intergenerational observation and utilization of algae as a resource by Māori may reveal an awareness of biological processes that either differs or compliments a Western Science point of view. Incorporating this knowledge into current water and environmental management practices could be extremely beneficial for improving water quality of streams in Aotearoa New Zealand.

Acknowledgements

Tēnā koutou katoa,

There will never be enough words to truly express the immense gratitude that I have for those who have helped bring this thesis together. First and foremost, I would like to thank my immediate and extended whanau for their encouragement, love, and support throughout my life and academic journey. A special thank you to my mother Claudine, for encouraging me to pursue post-graduate study and for guiding me through the mātauranga shared within this thesis. My gratitude also extends to my whanau who are no longer here specifically my grandmother Bonnie, who every day inspires me to pursue my dreams. Thank you for teaching me the value of hard work, dedication, and perseverance.

My deepest gratitude to my supervisor Dr Ian Duggan without whom this thesis wouldn't have been written. I cannot thank you enough for all of the support and guidance you gave me throughout this thesis. I am most grateful for the insights you shared, and the encouragement given at times when I needed it most. Your passion for freshwater ecology has inspired me to become a great researcher one day. To my co-supervisor Dr Ruper Craggs, thank you for allowing me the opportunity to be a part of the important research you and the Aquatic Pollution Mitigation group at NIWA have undertaken. It has been a true privilege to share in your vast knowledge and expertise. To Dr Harizah Hariz, I genuinely cannot thank you enough for your invaluable support and technical guidance during the experimental phase of this research. All of your efforts, from assisting me in the set-up of the experiment to teaching me new sample analysis techniques and even braving the challenging weather conditions to accompany me on the farm for sample collection will never be forgotten. I wholeheartedly believe that without your assistance this thesis would not be possible. To the other members of NIWA's Aquatic Pollution Mitigation group Curtis, Valerio, and Yeri thank you for letting me tag along on sample collection days. I enjoyed every single one of our trips out to the farm as they were always filled with laughs and good chats.

Thank you to my interview participants Adam, Marie, and Claudine. It was a true pleasure to share in your collective wealth of knowledge and learn about your lived experiences with mātauranga, freshwater, and algae. Each korero gave me a new sense of excitement and curiosity about how science and mātauranga Māori can further enhance our understanding of ecosystem interactions.

I would like to thank the National Institute of Water and Atmospheric Research (NIWA) and Waikato Tainui College for funding this MSc through the New Zealand Ministry of Business, Innovation and Employment (MBIE) endeavour research programme.

Finally, a massive thank you to my fellow postgraduate students Brandon and Jazz. Although we had different classes or projects based elsewhere, being able to catch up with you both throughout this latest academic journey truly helped me to persevere.

Table of Contents

List of Figures

List of Tables

Glossary of Māori terms

Māori term	Meaning/translation
Awa	River
Hapū	Subtribe
Iwi	Tribe
Kai	Food
Kaitiaki	Guardian
Kaitiakitanga	Guardianship
Kākahi	Freshwater mussel
Kaupapa Māori	Māori way of doing things
Kōrero	Talk
Kōura	Freshwater crayfish
Kōwaro	Canterbury mudfish
Kupu	Words
Mahinga kai	Gathering of culturally significant food
Mana	Strength/power
Manaakitanga	Hospitality/kindness /generosity/support
Māori	Indigenous people of New Zealand
Maramataka	Māori lunar calendar
Marae	Meeting house
Mātauranga Māori	Māori knowledge
Mauri	A binding force between the physical and spiritual worlds
Ngāti Haua	Māori tribe from Tainui canoe
Ngāti Mahanga	Māori tribe from Tainui canoe
Ngāti Pikiao	Māori tribe from Te Arawa canoe
Ngāti Te Wehi	Māori tribe from Tainui canoe
Papatuanuku	Earth Mother
Pūkohu wai	Algae
Puna	Spring of water
Rahui	Prohibition of harvesting resources from an area
Ranginui	Sky Father
Rohe	Tribal territory or tribal homelands
Rongoā	Traditional Māori healing system
Taonga	Treasure
Tangata whenua	People of the land
Te Ao Māori	Māori world
Tikanga	Customs or practices
Wai	Water
Wāhi tapu	Sacred place
Whakapapa	Genealogy
Whanau	Family

Chapter 1

Introduction

1.1 Background

Land-use activities and land use changes have significant ecological consequences that are spread across local, regional, and global scales. The conversion of natural landscapes for human use is being driven at an unprecedented rate by the need to provide food, water, and shelter to a rapidly growing human population (Meyer and Turner, 1994; Foley et al., 2005). Agricultural land-use, in particular, has been highlighted as one of the most significant and pervasive human alterations to the global environment (Matson et al., 1997). It is often viewed as a double-edged sword; on one hand, agricultural land use offers an undeniable source of food security. However, on the other hand, agricultural land-use has been well documented to be associated with negative ecological impacts such as biodiversity loss and environmental degradation (Chapin et al., 2008; Kehoe et al., 2015; Tsiafouli et al., 2015). Our collective dependency on agricultural land-use presents us with a difficult dilemma, as these landscapes cover one third of the planets ice-free surface and account for 40% of all potentially productive land (Ramankutty et al., 2008). Although agricultural practices and intensity differs across the globe, the overall consequences remain the same: over-exploitation of natural resources for human consumption, at the expense of further deterioration in environmental conditions. The global need to balance our reliance on agricultural products and services with the need prevent further environmental degradation and biodiversity loss has never been more pertinent.

In New Zealand, the agriculture industry plays a key role in stimulating the country's tradeable economy, with products from this sector accounting for nearly 50% of all merchandise exports (OECD 2019; Ministry of Primary Industries 2021; Caradus et al., 2022). Moreover, the agricultural industry provides a significant number of employment opportunities. In the year 2019, approximately 5.8% of New Zealand's work force were employed within the agriculture sector (Ma et al., 2022). These figures are a reflection of the country's mild and wet temperate climate, low population to land ratio, and fertile soil, all of which have contributed to the agriculture industry becoming an integral part of New Zealand's social and economic identity.

New Zealand's agriculture industry is complex and comprised of many primary sub-sectors (sheep and beef, dairy, deer, goats, pigs, and timber), along with various forms of horticulture, cropping and viticulture (Brown et al., 2020). Grassland farming (sheep/beef and dairy) is the country's most profitable primary sub-sector, as it accounts for about two-thirds of New Zealand's agricultural exports (Apatov et al., 2015). An early quote by G. H. Holford encapsulates the perceived and true value of grassland farming to New Zealand's economy: "After air, light and water, the next most important thing is grass. We all know it exists in all lands to some extent, but there is no country in the world so dependent on grass as New Zealand" (Holford, 1933).

The Waikato region is at the heart of New Zealand's agricultural success, generating over 20% of the nation's primary exports (MBIE, n.d.). Dairy farming is the primary component of the regions agricultural production and exports, which is no surprise given that the majority of dairy herds (70.7%) are located in the North Island, with the greatest concentration (28.3%) situated in the Waikato region according to a recent report (LIC and DairyNZ, 2022).

That being said, this valuable industry is under mounting pressure to reduce its environmental impact, as concerns continue to grow over the amount of energy and water needed to operate dairy farms across the country, subsequently leading to large quantities of effluent and greenhouse gas emissions (Flemmer, 2012). Furthermore, the input of excessive nutrient loads from farmlands into waterways across the country is yet another issue of significance for farmers, environmental scientists, and policymakers alike (Rajanayaka et al., 2020).

Considering these issues, this introductory chapter will address the topic of water quality deterioration on a global and local scale. Furthermore, the specific impacts of agriculture will be examined with a particular focus on agricultural drainage in freshwater ecosystems. Additionally, this chapter will discuss algal bioremediation technology as a potential solution to mitigate New Zealand's agricultural water pollution issues. Finally, this chapter will discuss the importance of incorporating Mātauranga Māori (indigenous knowledge) into future environmental studies within New Zealand.

1.2 Water Quality Deterioration

Water quality deterioration is a global issue that confronts both marine and freshwater ecosystems (Harding et al., 1999; Smith, 2003; Smith et al., 2006; Duprey et al., 2016; Plew et., 2020). As such, water quality is considered a crucial aspect in the field of ecological research, largely due to the high global demand for water resources (Cominelli et al., 2009), its economic value (Ward and Michelsen, 2002), association with biodiversity loss (De'ath and Fabricius, 2010) and the link between declining water-quality and ecosystem health (Rapport et al., 1998). Surface and ground water quality is governed by a number of natural processes and anthropogenic factors. Climatic and geographic factors are the two primary natural processes that influence water quality. These processes include extreme rainfall events (downpours) resulting in high amounts of run-off, deposition of bedrock minerals by strong winds, and natural leaching of organic matter and nutrients from soil (Khatri and Tyagi, 2015; Ayana, 2019). The main anthropogenic factors that affect both surface and ground water quality include deforestation (Dessie and Bredemeier, 2013), urban expansion (McGrane, 2016), and agriculture (Shortle et al., 2001).

New Zealand's waters are no exception to the on-going issues of water quality deterioration. In fact, trends in the declining state of freshwater ecosystems have been well documented by environmental scientists for a number of years (Smith et al., 1996; Julian et al., 2017). Recent national-scale assessments of trends in water quality and ecological conditions were reported in 2015 and 2016 for lakes and rivers by Larned et al. (2016). This report analysed water quality states and trends for 461 river sites in New Zealand from 2004 to 2013. The key findings of this report illustrated a generally poor state of water quality for pastoral and urban land-covered sites. Additionally, the state of water quality in lowland sites was generally poorer than that at upland sites, and lowland urban and pastoral sites had the poorest overall water-quality. For urban streams, a recent report by Gadd et al. (2019) highlighted an improving trend in water quality for many sites from 2008 to 2017; however, the overall state of water quality in urban streams was still typically poor.

Nutrients, sediments, and pathogens are the key pollutants that influence water quality deterioration in New Zealand. However, excessive nutrient input is the key driver behind the declining state of freshwaters in New Zealand (Howard-Williams et al., 2010; Ballantine and Davies-Colley, 2014; Larned et al., 2016). Nutrients, specifically nitrogen (N) and phosphorus (P), are well known for their significant impact on rivers, streams, and lakes in New Zealand (Jarvie et al., 2010; Abell et al., 2011). Excessive inputs of nitrogen (N) and phosphorus (P) can contribute to eutrophication in aquatic ecosystems, which leads to a number of subsequent issues including toxic algal blooms, oxygen depletion, biodiversity loss, and habitat and vegetation loss (Carpenter et al., 1998).

1.2.1 Agriculture and Water Quality

Agriculture is, without a doubt, a significant contributor to water quality deterioration. Sediments, pesticides, fertilizers, and nutrients are the main agricultural pollutants that have the most detrimental impacts on water quality. Whilst most farmers generally do not intend for these pollutants to move from their operational activities and enter freshwater ways, they often do (Shortle et al., 2001).

Water pollution from an agricultural context is categorized into either point source or non-point (diffuse) source pollution. Point source, as the name suggests, is the source of pollution that can be easily identified. Industrial discharge, dairy sheds, piggeries, septic tanks, leachates from silage pits and farm dumps are primary examples of point source pollution (Ministry for the Environment, 2001). In New Zealand, point source pollution has largely (with a few notable exceptions) been reduced within past few decades or so, which has ultimately left non-point source pollution as the country's dominant water quality issue (Davies-Colley 2009; Howard-Williams et al. 2011; Davies-Colley, 2013). Non-point or diffuse pollution is defined by Campbell et al. (2005) as "pollution arising from land-use activities (urban and rural) that is dispersed across a catchment, or sub catchment, which does not arise as a process effluent, municipal sewage effluent, or farm effluent discharge" (p. 8). Diffuse pollutants (nutrients, sediments, and pesticides) can enter waterways by one of three main pathways: run-off, leaching and livestock. Run-off is the transportation of pollutants over the soil surface, mostly through rainfall events. This particular pathway of diffuse pollution is generally associated with stream flow and is New Zealand's largest source of diffuse pollution according to Howard-Williams et al. (2011). Leaching of pollutants has been recently defined by Cloy et al. (2022) as the flow or infiltration of water and both soluble and insoluble pollutants down through the soil profile into groundwater. Nitrate leaching, in particular, is a problem in many dairy farmed catchments across New Zealand. Foote et al. (2015) estimated that nitrogen leaching rates from dairy farms nationwide ranged from around 12–200 kg N ha^{-1} y^{-1}. Livestock urine is the dominant source of nitrate-nitrogen leached from soil in dairy farms and accounts for as much as 90% of total N leaching (Foote al., 2015; MfE 2019). Direct livestock access is another prominent pathway of diffuse pollution that impacts water quality. This includes the physical damage to vegetation, soils, and substrates in and on the edges of lakes, wetlands, and streams by livestock. This disturbance to landscapes in which agricultural farming takes place, increases its susceptibility to erosion, sediment loss and pollutant runoff (Howard-Williams et al. 2011).

1.2.2 Agricultural Drainage

A common practice in the agriculture industry is the use of drainage network surface (open drains) and subsurface (tile and mole) drains. These network drainage systems help to remove excess surface-runoff, whilst maintaining the physical, chemical, and biological condition of soils that is optimal for plant production and grazing (Lalonde and Hughes-Games 1997; Nguyen and Sukias, 2002). Agricultural drainage networks also provide an important habitat for many native animals (e.g., Giant and Banded Kōkopu, Canterbury mudfish, Australasian bittern, Mud snails, and Sandflies) (Young et al., 2000; Hudson and Harding, 2004; Eivers et al., 2018). Furthermore, agricultural drains are an important source of mahinga kai (watercress, eels, whitebait, and lamprey) for local iwi (Ministry for the Environment, 2001). Although these agricultural drainage systems offer many cultural and ecological benefits, the water within these subsurface drains or surface drainage ditches often accumulates a variety of pollutants (faecal material, nutrients, sediments, herbicides, and pesticides) from the surrounding farmland, which is then discharged into neighbouring downstream freshwater systems (Ministry for the Environment, 2001). Dissolved phosphorus, organic nitrate, orthophosphate, and particulate phosphate are the most common nutrients exported into freshwater systems via subsurface drainage (Grant et al., 1996; Tanner et al., 2005). Diffuse nutrients accumulated within agricultural drainage water contributes to the wider issue of deteriorating water quality within freshwater ecosystems. Eutrophication from high concentrations of dissolved inorganic nitrogen and dissolved reactive phosphorus in slow-moving water often promotes the nuisance growth of algae and aquatic weeds (Davies-Colley, 2013). The ecological consequences of eutrophication in farm waterways includes blocking of sunlight needed by aquatic vegetation, changing the quantity and type of food available to stream life, alteration of habitat for fish and invertebrates, and the depletion of dissolved oxygen levels (Ministry for the Environment, 2001). Deterioration of water quality also poses a threat to human health, restricting the use of water as a resource for drinking, fisheries, and recreational purposes (Foy and Withers, 2002; Davies-Colley, 2013). For instance, drinking water supplies with nitrogen levels exceeding that of 10 mg/l NO_3-N are known to cause methemoglobinemia (blue-baby syndrome), in infants and colorectal cancer (CRC) in adults (Avery, 1999; Wolfe and Patz, 2002; Richards et al., 2022).

1.3 Algal Bioremediation – Removal Mechanisms and Technology

Algae are a diverse polyphyletic group of aquatic organisms that are classified as either unicellular (microalgae) or multicellular (macroalgae). They, unlike higher terrestrial plants, lack roots, stems and leaves (Bajpai, 2019). Algae produce oxygen as byproduct of photosynthesis, which in turn increases the concentration of dissolved oxygen in the surrounding water. Algae primarily remove nutrients from their aquatic environment through biological uptake (nutrient assimilation) (Ray et al., 2015). However, other mechanisms such as adsorption, filtration, volatilisation, and precipitation are also involved (Sutherland and Craggs, 2017; Gonçalves et al., 2017). Due to their wide range of physiological and biochemical characteristics, both micro and macroalgae are able to naturally accumulate N and P from their aquatic environment. This accumulation of nutrients also allows the algae to produce a wide range of bioactive compounds (pigments, carbohydrates, proteins, and lipids) stored within the accumulated algal biomass that can be utilized for commercial purposes (Nguyen et al., 2022; Packer, 2009).

The concept of utilizing algae for their photosynthetic capability to remove nutrients from wastewaters was first proposed in the 1960s (Oswald and Golueke, 1960). Since then, advancements in our understandings of algal-based water treatment has allowed for the development of more cost-effective eco-technologies that are applicable to treat a wide range of polluted waters including municipal wastewater (Adey et al., 2011; Abou-Shanab et al., 2014; Ge et al., 2018), stormwater (Chimney et al., 2000) and dairy wastewater (Kebede-Westhead et al., 2003; Mulbry et al., 2005; Liu et al., 2016). For the treatment of agricultural pollutants, current on-farm mitigation options include the construction of riparian buffer zones within farmlands (Mander et al., 1997), which has demonstrated the capability to reduce the concentrations of N and P entering waterways. Moreover, in-stream mitigation measures such as constructed wetlands and denitrification bioreactors have been proven to reduce nutrient concentrations within waterways through the utilization of nutrient uptake by plants and microbes (Vymazal and Kröpfelová, 2009; Christianson et al., 2021). Whilst these mitigation options are indeed capable of reducing nutrient loads within agricultural landscapes, they have not been widely applied due to the large area of land required, high construction costs and inconsistent year-round performance (Muñoz et al., 2018; Park et al., 2022). As such, new cost-effective treatment systems are required now more than ever. Recent research efforts in the area of algal-based treatment technologies have since highlighted the potential use of filamentous algae to remove nutrients from agricultural wastewaters (Liu et al., 2016; Flores-Morales et al., 2020).

1.3.1 Filamentous Algal Treatment Systems – Algal Turf Scrubbers (ATS)

Algal turf scrubber (ATS) systems were originally developed in the early 1980s by Adey at the Smithsonian Institution, Washington D.C., U.S.A. (Adey et al., 2013). This system was proposed as a natural method to remove nutrients from stormwater and wastewaters using cultured algae. Specific nutrients such as nitrogen, phosphorus, and carbon dioxide are removed by the ATS system through direct uptake, chemical filtration, and precipitation (Dinkins et al., 2009). An ATS system is comprised of a shallow (inclined) trough or basin (also commonly referred to as a flow-way). Along the length of the flow-way is an overlying screen to which the algal “turf” community attaches. Nutrient enriched water is introduced to the system via a distribution manifold and runs down the length of the flow-way. Nutrient removal is achieved through biological uptake and nutrient assimilation into the accumulated algal biomass, which in turn produces oxygen as the water flows down the flow-way. The newly treated water is then pumped back into the original waterway source with a lower concentration of nutrients and a higher concentration of dissolved oxygen. Moreover, the accumulated algal biomass generated through this process of nutrient removal can be harvested and processed into high-quality compost material, livestock feed and biofuel products (Dinkins et al., 2009; Adey et al., 2011).

The first ATS systems were initially designed to biomimic coral reef primary productivity. These ATS systems were built to manage the quality of water under low nutrient and light conditions in marine microcosm and mesocosm models (Adey, 1983; Adey et al., 2013). Researchers observed high algal productivity within the algal turfs implemented at many coral reef sites across the eastern Caribbean, ranging from 5 to 20 g m^{-2} per day (dry weight) (Adey et al., 2011). Furthermore, the fieldwork undertaken in these early studies allowed researchers to understand the importance of oscillating (surge) motion that was generated through wave action as a potential primary driver behind high marine algal productivity (Carpenter et al., 1991; Adey and Loveland 2007; Adey et al., 2011). This observation led to the development of small land based ATS devices in the late 1980s, as researchers began to incorporate water flow and surge motion into ATS technology and combine this with operational aspects such as high light intensity and frequent harvest in order to achieve high levels of productivity. Small ATS units were also employed to treat nutrient enriched waters such as raw sewage and chicken manure. Successful removal of both N and P was observed in these studies, along with high levels of algal production for harvest (Adey and Loveland, 2007). By the early 1990s field-scale ATS systems began to be tested in other areas, such as large-scale finfish aquaculture and wastewater treatment (Adey and Loveland, 2011). One of the very first field-scale experiments investigated the use of ATS systems to treat secondary sewage effluent was conducted in the mid-1990s by Craggs et al. (1996a). The field-scale ATS system (152.4 m length and 6.5 m width, with a total surface area of 1012 m^2) was in Patterson, California, USA. The ATS system had a mean annual operational productivity of 35 g m^{-2} d^{-1} along with mean annual N and P removal rates of 1.1 ± 0.5 and 0.7 ± 0.2 g m^{-2} d^{-1}, respectively (Craggs et al., 1996a; Adey et al., 2011). Further up-scaling of ATS systems continued into the early 2000s by HydroMentia, Inc. who constructed a large 1-hectare ATS system in a canal near Lake Okeechobee, Florida, USA, with the purpose of treating agricultural drainage water primarily driven by cattle production. This ATS system was operated using three individual flow-ways that were 91 m in length and 1.5 m wide. The successful application of ATS systems to treat a range of polluted waters has been widely demonstrated in the USA. However, the use of filamentous algal treatment systems to reduce nutrient pollution within New Zealand’s waters is still very much in the early stages of development and application.

1.3.2 Filamentous Algal Treatment Systems – Filamentous Algal Nutrient Scrubber (FANS)

Filamentous algae nutrient scrubbers (FANS) are a novel algal treatment system that has recently been proposed as a potential on-farm method to treat nutrient enriched agricultural drainage waters in New Zealand (Hariz et al., 2022). In terms of functionality, FANS are a derivation of ATS with a gently sloped artificial flow-way and attachment substrate that enables the growth of filamentous algae. However, ATS and FANS systems differ slightly in the establishment aspect of algal species used for treatment. ATS systems are generally comprised of a non-specific algal consortia which are "self-seeded" (Mulbry et al., 2001; Mulbry et al., 2008b; Adey et al., 2013). Whereas FANS systems are primarily seeded in a controlled manner by rubbing algal biomass onto the FANS liner with select targeted filamentous algae species to allow rapid and uniform establishment (Hariz et al., 2023).

Recent studies have highlighted the nutrient removal capacity of FANS systems to be potentially higher than that of current on-farm mitigation options such as constructed wetlands. Sutherland and Craggs (2017) proposed that FANS systems could remove twice as much nitrogen and almost four times the amount of phosphorus (88 g N m^{-2} $year^{-1}$) (12 g P m^{-2} $year^{-1}$) than that of constructed wetlands (40 g N m^{-2} $year^{-1}$) (3 g P m^{-2} $year^{-1}$). Therefore, FANS systems could be a more appealing mitigation option due to the lower amount of land required in order to achieve the same or higher levels of nutrient removal. In terms of construction, the amount of time required to set-up a FANS system is much less (1-3 weeks for algal establishment) than a constructed wetland, which can take anywhere between 3-12 months to establish (Craggs et al., 2022). However, unlike constructed wetlands, which require little to no maintenance once established, FANS treatment systems require constant year-round management (periodic harvesting) in order to remain operational for nutrient removal and biomass accrual.

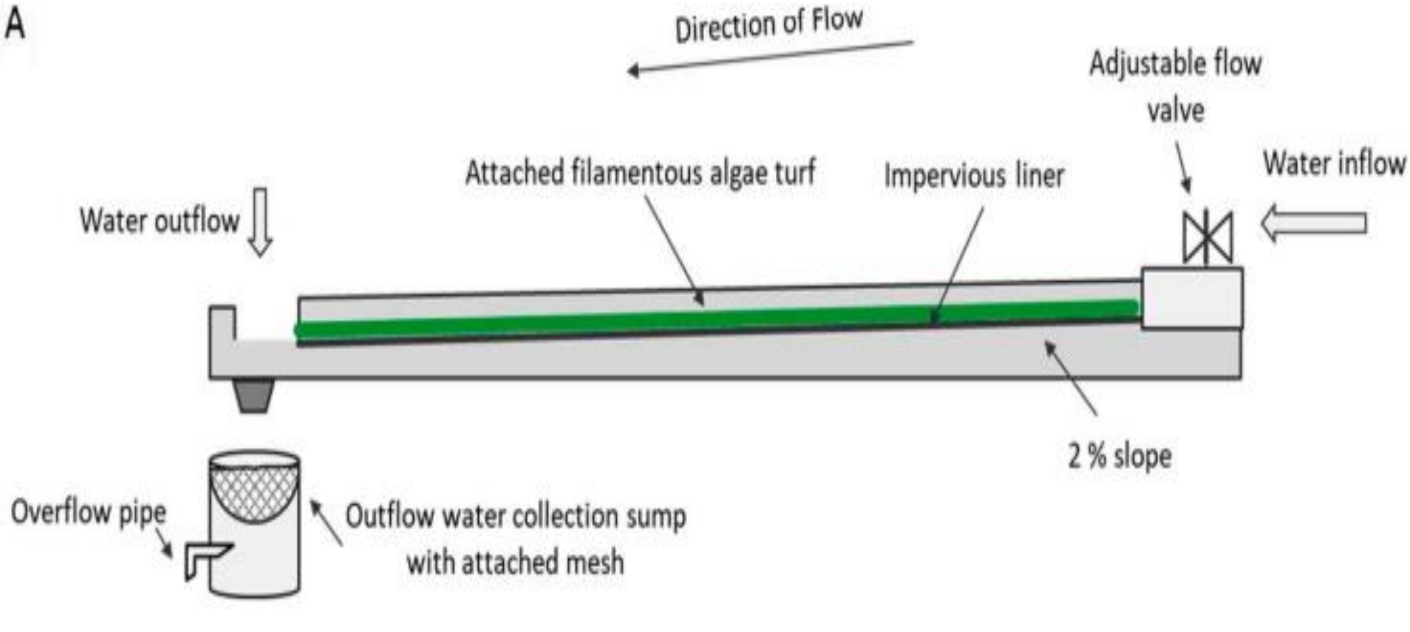

Figure 1.1: Schematic diagram of a Filamentous Algae Nutrient Scrubber System (after Hariz et al., 2023).

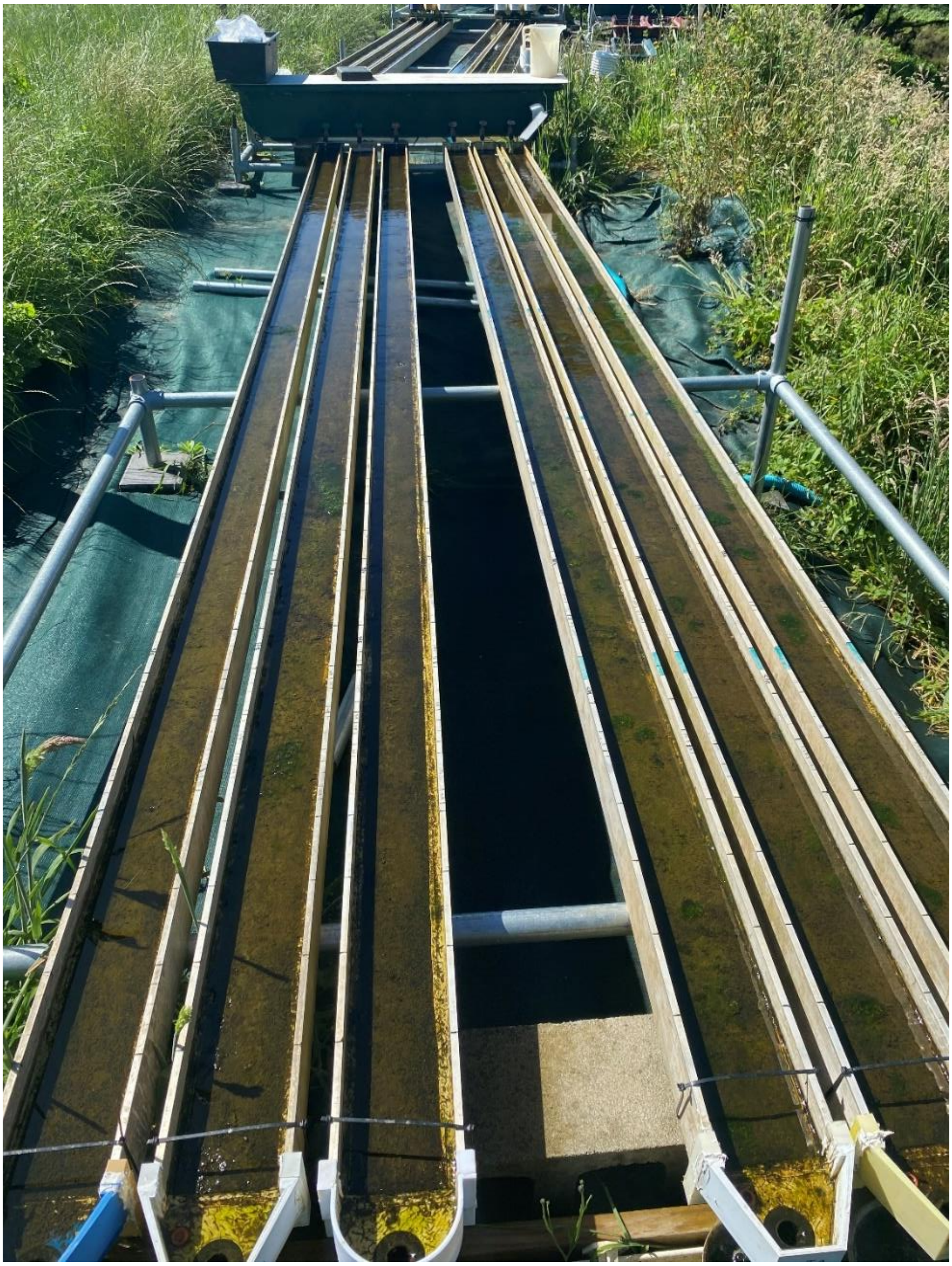

Figure 1.2: (Original photo) Outdoor-scale Filamentous Algal Nutrient Scrubber (FANS).

1.4 Environmental Factors Affecting Productivity and Nutrient Removal of FANS Treatment Systems

Algal growth and nutrient removal performance of FANS treatment systems, particularly those in outdoor settings, are heavily influenced by uncontrollable prevailing environmental factors such as ambient temperature, photoperiod, rainfall, and irradiance (Leong et al., 2021). This presents a challenge for the operation of these treatment systems as such factors are also dependant on local climate, season, and day/night cycles (Craggs, 2001). Enhancing our understanding of how these uncontrollable factors can influence the capability of FANS systems to remove nutrients and determine biomass growth is of paramount importance when looking to operate these treatment systems on a long-term year round basis.

I. Light

Light plays a key role in determining the overall success of FANS systems, as it provides the photon energy required to convert dissolved inorganic nutrients into algal biomass via photosynthetic reactions and processes (Sutherland et al., 2015a). The amount of light that is able to penetrate through to the algal cell and additionally, how well the algal cell can utilize the light energy, is the key determinant of nutrient removal efficiency and biomass productivity in FANS systems (Sutherland et al., 2020a). Enhancement in the amount of light available for photosynthetic processes can be achieved by ensuring an optimal water depth (design) in a FANS system. When light passes through the water column it is attenuated by particles and other dissolved substrates present that will either absorb or scatter the light (Kirk, 1994). A shallow water depth increases light availability and penetration within a FANS system, as a result of the reduction in distance required for light to travel through the water column and reach the algae on the bottom of the flow-way (Kim et al., 2018; Sutherland et al., 2020a). Moreover, a shallow water depth enables rapid gas exchange, which contributes to higher algal photosynthetic rates (Geider, 2013).

II. Temperature

Temperature is another key determinant of algal growth and nutrient removal in FANS systems. When ambient temperatures exceed or fall below a species' tolerance range, it impairs and reduces electron transport activity of the photosynthetic enzyme Rubisco. Temperatures outside of the adapted optimum reduces the ability of Rubisco to remain in an active form to differentiate oxygen from carbon dioxide, thereby reducing photosynthetic rates (Salvucci and Crafts-Brandner, 2004; Yamori et al., 2014). Operating an algal treatment system in an outdoor setting presents a great challenge, as fluctuating temperatures are an uncontrollable environmental factor that varies both daily and seasonally. Although this is an aspect of FANS systems that cannot be directly controlled, optimization can still be achieved through algal species selection. A recent study highlighted *Oedogonium* sp. as a potential candidate for year-round cultivation on FANS systems due to its wide range of temperature tolerance (Hariz et al., 2023c).

III. Turbulence

Turbulence can play a vital role in determining algal growth, biomass accumulation, sloughing frequency, and algal community composition in FANS systems (Blersch et al., 2013). Heavy rainfall and high prevailing winds are influential environmental factors that can cause turbulence in FANS systems. This leads to an increased sloughing of the accumulated algal biomass which can temporarily disrupt nutrient removal capacity if excessive amounts of biomass are washed from the system (Adey et al., 2011; Sutherland and Craggs, 2017). On the other hand, constant low-level turbulence can promote algal growth, and can be controlled to an extent through inflow rate. Increasing the inflow rate has been shown to enhance biomass productivity under certain nutrient loads, which improves nutrient transport and diffusion of light across the boundary layer to the algal cells (Blersch et al., 2013).

1.5 Operational Parameters Affecting Productivity and Nutrient Removal of FANS Treatment Systems

Environmental conditions play a significant role in determining the overall performance of FANS systems to treat polluted waters and produce biomass. Whilst these conditions are for the most part uncontrollable, enhancement of biomass productivity and nutrient removal in FANS systems is still attainable through the optimization of certain operational parameters, such as standing crop, species selection and harvest frequency (Sutherland and Craggs, 2017; Hairz et al., 2023a).

i. Standing Crop

Standing crop is the term used to describe the amount of attached algal biomass that remains on a flow-way after harvest events. This (standing crop) biomass is primarily the basis for growth within a FANS system. A high amount of standing crop allows for the enhancement of algal reproduction within a flow-way due to a higher rate of spore release (Sindelar et al., 2015). However, a standing crop that is too thick may potentially cause “self-shading” issues, where light is unable to penetrate through to the bottom layers of algal mat, thereby reducing overall growth and nutrient assimilation (Sutherland et al., 2020). Ensuring an optimal standing crop within a flow-way can contribute to optimizing the biomass production and nutrient removal efficiency of FANS systems.

ii. Species Selection

Algal species selection is perhaps one of the most important operational parameters of FANS systems as it affects future use of the biomass (Liu et al., 2020). Choosing a suitable species for wastewater treatment purposes can be based on four key criteria: high areal productivity, adaptability to varying conditions, competitive dominance over undesired species, and consistent biochemical composition (Lawton et al., 2013; Liu et al., 2020). Recent studies have identified a number of filamentous algae from the genera *Oedogonium*, *Rhizoclonium*, *Spirogyra*, *Microspora*, *Klebsormidium*, *Cladophora,* and *Stigeoclonium* as prime candidates that meet the previously mentioned criteria for biomass production and treatment of wastewaters (Lawton et al., 2013; Lawton et al., 2014; Liu et al., 2020). FANS systems are generally seeded and operated with a mixed assemblage of filamentous algae (Sutherland et al., 2020b; Park et al., 2022; Hariz et al., 2022). This is advantageous in terms of establishment, particularly if the algae are sourced from a nearby waterway. However, this may also present an issue if the collected biomass also contains a high amount of non-targeted species such as cyanobacteria and diatoms that may grow to dominate the targeted green filamentous algae, thereby reducing nutrient removal rates and producing low quality biomass (Lawton et al., 2013; Hariz et al., 2023b). FANS systems that are seeded and operated with a single species may offer a more consistent source of high-quality biomass and experience a reduction in the amount of biomass wash-off (Hariz et al., 2023b). However, maintaining a single species on an outdoor based FANS system may not be so easily attainable due to high maintenance (re-seeding) requirements.

iii. Harvest Frequency and Regime

Harvest frequency is an important operational parameter that can significantly influence the production and nutrient removal performance of any algal treatment system. An optimal harvest frequency can help to ensure that the algal biomass is maintained in a constant phase of exponential-growth by reducing self-shading and diffusion gradients (Craggs et al., 1996a). Frequency of harvest is dependent on biomass accrual rate which is governed by individual algal cell growth rate (Sutherland et al., 2020b). Therefore, harvest frequency varies seasonally, for example, Craggs et al. (1996b) suggested a one-week harvest interval during summer months and up to a month harvest interval during winter months. A number of long-term (ATS) wastewater treatment systems using filamentous algae have implemented a weekly harvest frequency (Ray et al., 2015; Kangas et al., 2017). Furthermore, harvest regime in conjunction with harvest frequency may also affect the removal of nutrients and biomass production in FANS systems. Total harvesting of flow-ways could potentially disrupt nutrient removal within FANS systems, which has prompted researchers such as Craggs & Sutherland (2017) to suggest that harvesting of flow-ways should occur in stages (strip harvesting and sectional harvesting) to ensure a sufficient amount of biomass is left on the flow-way for biomass growth and nutrient removal. To date, the effects of harvest frequency and harvest regime in FANS systems have only been examined in a single study (Sutherland et al., 2020b). This study found that increased harvest frequency improved both biomass yield and nitrogen removal rates.

1.6 Mātauranga Māori – An Indigenous Perspective

Mātauranga Māori is the modern term that is used to describe a wealth of knowledge that was brought to and developed further in Aotearoa New Zealand by early Polynesian settlers (Royal, 2009). Other recent definitions of mātauranga Māori include ‘the pursuit and application of knowledge and understanding of Te Taiao, following a systematic methodology based on evidence, incorporating culture, values and world view’ (Hikuroa, 2017), ‘the shared intellectual capital generated by whānau, hapū and iwi over multiple generations’ (Hudson et al., 2020), and ‘a system into which values are overtly interwoven’ (Mercier, 2018b). The wide application and various definitions of the term mātauranga Māori is but an indication of the depth of knowledge that exists within its use. Moreover, Ataria et al. (2018) emphasised a past, a present and a future meaning to term mātauranga Māori. A quote by Professor Whatarangi Winiata further encapsulates this viewpoint in his statement that “mātauranga Māori has no beginning and is without end. It is constantly being enhanced and refined. Each passing generation of Māori make their own contribution to mātauranga Māori” (Winiata, 2001, as cited in Mead, 2003, p. 459). In an environmental context, mātauranga Māori offers a unique and holistic perspective towards the management of environmental resources which is underpinned by historical restorative practices and resource usage (Mercier, 2018a).

1.6.1 A Whakapapa of Wai

Mātauranga Māori values, ethics, and conceptions surrounding freshwater are heavily derived from a complex network of genealogical relationships that originates from Māori creation stories (Stewart-Harawira, 2020). Each iwi or tribe had slight variations of the creation story. However, they generally began with the two primordial parents from whom all Māori are descended: Ranginui (Sky Father) and Papatuanuku (Earth Mother). From the separation of these two primordial parents, freshwater first appears in Te Ao Māori (the Māori World) in the form of rain that fell from the sky as Ranginui’s tear drops. Meanwhile, the sighs of grief from Papatuanuku appears in the form of mist. Through this creation story, Māori view freshwater as an atmospheric consequence of the separating of Ranginui and Papatuanuku. Furthermore, the personification of this relationship between land and sky helped Māori to understand their relationship with nature and allowed them to consider the consequences of their actions (Ngata et al., 2018). Other observations and understandings of freshwater by Māori can be seen in the way they view certain aspects of water. For instance, a key freshwater body was often associated with, or known to have, its own treasured species and kaitiaki (guardian) that would protect the wellbeing of the awa (river). For Māori, the wellbeing of a waterway is entwined to the physical and spiritual health of their community (Stewart-Harawira, 2020).

1.6.2 Mātauranga Māori and Environmental Research

Mātauranga Māori is becoming a constant presence on the environmental research stage in Aotearoa New Zealand. For instance, mātauranga concepts such as whakapapa, which is the distinct Māori way of organising and understanding the world through genealogy (Forster, 2019), is becoming widely accepted to establish environmental order and recognize place-specific relationships (Haami and Roberts, 2002). Whakapapa in a contemporary context has been demonstrated in studies such as Kawharu (2000) and Roberts et al. (1995) to guide natural resource use and management. Furthermore, a recent study by Collier-Robinson et al. (2019) demonstrated the implementation of whakapapa principles in the genomic research of two taonga species Kōura (Freshwater crayfish, *Paranephrops zealandicus*) and Kōwaro (Canterbury mudfish, *Neochanna burrowsius*). The authors of this study co-developed a responsive research programme with local hapū (a section or sub-tribe of a large tribe) Ngāi Tūāhuriri to combine mātauranga with genomic technology in an effort build resilience of the threatened taonga species. Another recent study by Michel et al. (2019) highlighted the use of mātauranga Māori and western science to inform the translocation of kākahi (Freshwater mussels *Echyridella menziesii* and *E. aucklandica*) in Roto Māhanga (the upper lake within Zealandia sanctuary), Wellington, New Zealand. This study provided both mana whenua (people of the land) and scientists the opportunity to share knowledge and work collaboratively to achieve positive ecological outcomes. There is great potential to use mātauranga Māori to enhance our understanding of (aquatic) ecosystem interactions and ecological processes that could help to assist in future research and decision-making in aquatic environments of Aotearoa New Zealand (Clapcott et al., 2018). The present study seeks to understand mātauranga Māori as it pertains to the lived experiences of whanau (family) and local iwi (tribe) in regards to how they perceive freshwater and freshwater filamentous algae. Most importantly, the implications of this study may help to facilitate an acceptance of algal bioremediation technology by Māori.

1.7 Thesis Aims and Objectives

The overall aim of this study was to investigate the optimal harvest frequency and harvest regime to maximise biomass production and nutrient removal in an outdoor FANS system. Furthermore, this study aimed to investigate the potential of mātauranga Māori principles and concepts that may contribute to the enhancement of algal treatment systems. Finally, this study aimed to provide a further stepping stone for the acknowledgement and incorporation of mātauranga Māori in future environmental studies within Aotearoa New Zealand.

Specific Objectives

1. To investigate whether shorter harvest intervals (3.5 days) and an alternate sectioned harvest regime may increase overall FANS biomass productivity and nutrient removal

due to thinner algal mats (reduced self-shading and increased nutrient distribution) in comparison to a longer harvest interval (one week) and total harvest regime.

2. To investigate whether a sectioned harvest regime will maintain a higher relative abundance of target seeded algal species over a longer period due to higher amount of algae retained on the FANS system.
3. To investigate whether a sectioned harvest regime will maintain a more consistent nutrient removal rate than a total harvest regime due to the higher amount of algae retained on the FANS system.

Chapter 2

Methods

2.1 Study Site

This study took place on a 94-hectare lowland dairy farm in the Waikato region near Morrinsville, New Zealand (37◦41’41.0"S, 175◦34’19.2"E). The farm is owned by the Paeahu Trust and is comprised of two dairy farming units; Farm No.1 is approximately 73 ha and Farm No.2, where the experiment was based is approximately 21 ha. The farm is predominantly in milk production from a herd of 420 (ryegrass) pasture fed cows. The Toenepi stream runs through the farmland and receives both surface and subsurface run-off waters from the adjacent paddocks through sub-surface drainage pipes. The Toenepi stream, along with Piakonui and Piakoiti streams all link together to ultimately flow into the Piako River, that drains into the Firth of Thames on the North Island of New Zealand. The water supply (nutrient source) for the FANS system used in this study was pumped directly from the Toenepi stream.

2.2 Filamentous Algae Nutrient Scrubber

The Filamentous Algae Nutrient Scrubber (FANS) system implemented in this study consisted of six replicate aluminium I-beams floways (size: 6 m length x 0.12 m width x 0.05 m depth). These replicate I-beam flow-ways were installed on a square base of scaffolding steel tubes above stream water level along an embankment of the Toenepi stream. Placement of the flow-ways reflected the direction of the water flow in the nearby stream (with the inflow upstream and the outflow downstream). A high-density polyethylene (HDPE) textured liner (size: 6 m x 0.12 m or 0.72 m^2) was installed along the base of each flow-way in order promote successful algal attachment as observed in other FANS studies (e.g., Maggs and Callow 2003; Blersch et al. 2017; Khoshkhoo et al. 2019).

At the head of these flow-ways, a trough (100 L x 25 cm width x 21 cm height, UV resistant plastic) with six adjustable valves was used to hold and evenly distribute farm drainage water pumped from the nearby stream. To provide sufficient flow throughout the day, farm drainage water was pumped from the Toenepi stream into eight 1000 L black IBC header tanks using a solar powered pump (200 W) with two 7 amp/hour 12 V rechargeable batteries.

The FANS system had two settings for flow (day and night) due to the abundance of power available to the main pump system. During the day, the solar powered pump was able to draw water directly from the stream and therefore the inflow distribution sump was set to pump 12 L min^{-1} of flow, with the valves of each flow-way set at 2 L min^{-1}. However, at night the solar powered pump would cease to draw water from the stream and instead the flow was sourced from the water stored in the eight header tanks. The inflow rate setting would then reduce to a 50% flow rate of 6 L min^{-1} so that the flow to each flow-way was 1 L min^{-1}. These flow rates were maintained throughout the entire experiment and checked twice a week upon completion of harvest protocols. For maintenance, the inflow trough was drained of water and cleaned after every harvest in order to reduce potential clogging of the flow-way valves. Stainless steel sieves with a 0.5 mm mesh were attached to the ends of each flow-way to catch any algal biomass that washed off. The outflow of water from each replicate flow-way was returned to the nearby stream via a 3 m length of PVC spouting and pipeline.

Figure 2.1: (Left) Study site (Paehau Trust farm) and Toenepi Stream. (Right) The FANS system experiment set-up along the stream bank. FULL harvest replicate flow-ways on the left-hand side and PARTIAL harvest replicate flow-ways on the right-hand side, closest to the stream.

2.3 Experiment Design

During this study two experiments were conducted over the spring-summer period (October 2022 – March 2023). The first experiment investigated two separate harvesting intervals. For this experiment, the FANS system was split into two sets of three replicate flow-ways named “FULL” and “PARTIAL”. Harvesting of the FULL flow-ways occurred once at the beginning of the week, where all algal biomass accumulated along each flow-way was collected (Fig. 2.2). Harvesting of the PARTIAL set of flow-ways occurred twice a week, with biomass collected from alternate meters (a total of 3-metre harvest area every 3.5 days). These harvesting protocols were maintained for ten weeks of monitoring until mid-January 2023 (Fig. 2.2).

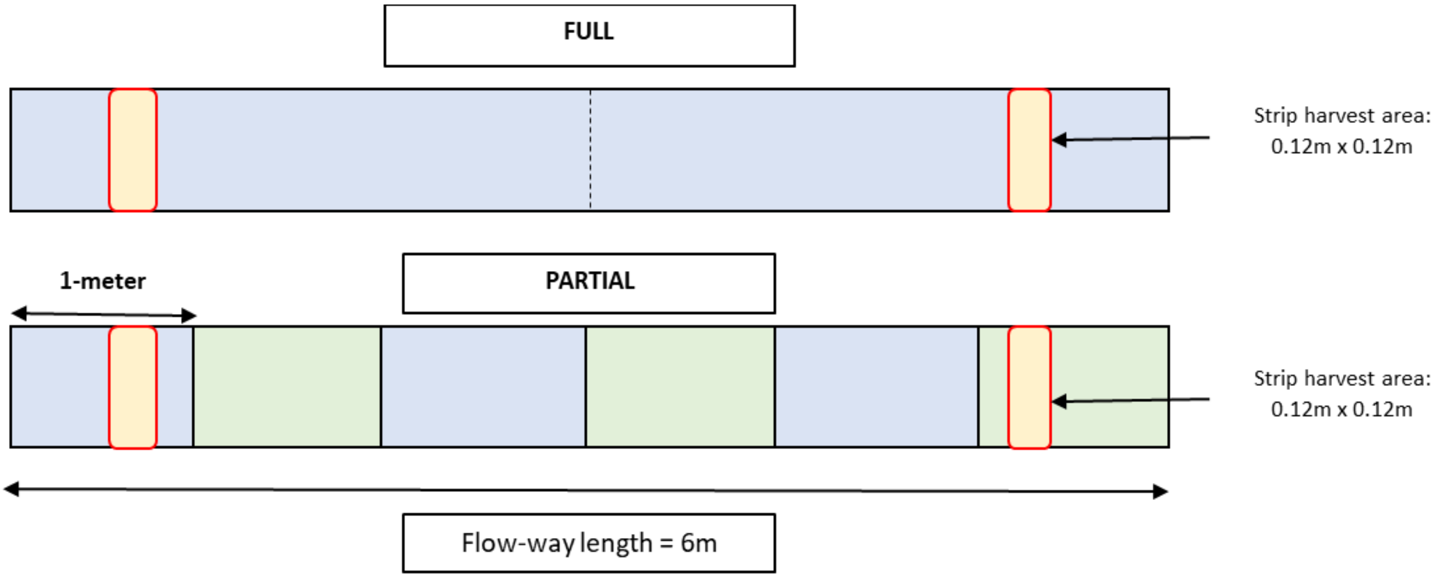

Figure 2.2: Schematic diagram of the harvested sections for the FULL and PARTIAL replicate flow-ways. Blue-coloured areas were harvested every Monday, and green-coloured areas were harvested every Thursday. Yellow coloured (biomass monitoring strip) sections were monitored once at the beginning of each monitoring week.

The second experiment was conducted between 16 January – 6 March 2023 with the harvest protocol of the FULL set of flow-ways changed. Each FULL flow-way was divided into 1-meter-long sections. Every week, within each 1-meter section all algal biomass was harvested except for a 20 cm strip at the top of the meter section. This 20 cm unharvested strip was then moved down the flow-way week by week until the 20 cm strip had reached the end of the meter section and then this harvest protocol repeated (Fig. 2.3).

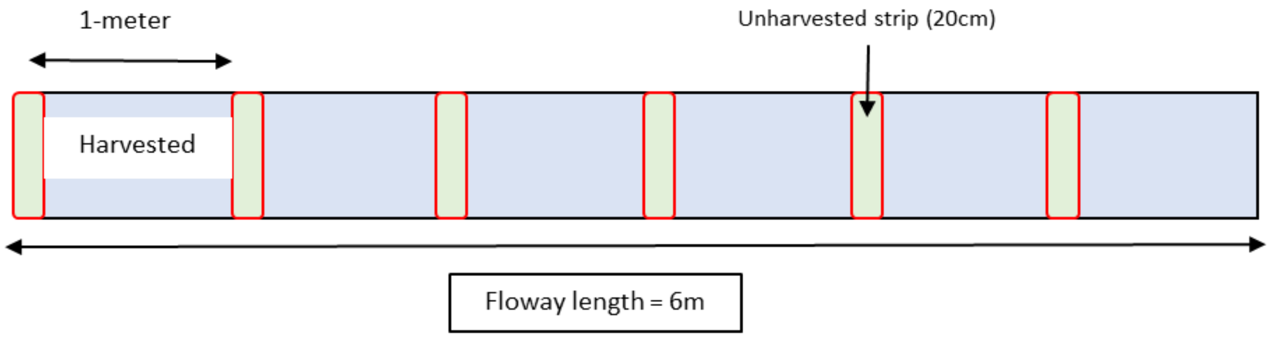

Figure 2.3: Schematic diagram of harvested and non-harvested sections along the FULL replicate flow-ways during experiment two.

2.3.1 Biomass Productivity Analysis

After the initial seeding phase, weekly biomass monitoring and water sampling was conducted from 25 October 2022. Harvest began with turning off the valves and allowing the water to drain from the flow-ways. The algal biomass on each flow-way was harvested by lightly running a plastic scraper along the length of the flow-way. The algal biomass was then scooped into a 2L jug and blended using a stick mixer (Living & Co SRO8310 600 W Stick Stainless Steel Mixer) for approximately 30 seconds to ensure homogenisation of the collected biomass. The total volume of the blended biomass was recorded for each flow-way before a 100 mL subsample was taken for dry weight analysis. The blended subsamples were dried overnight in an oven at 65 °C and weighed as total dried biomass (g DW). The harvest method (handheld scraping) used in this experiment allowed for a uniform coverage of biomass to be left on the liner as an initial standing crop for the following week. To quantify the initial standing crop (post-harvest biomass) of each FANS system a biomass monitoring strip method was used at the beginning of each week (growth cycle) throughout the duration of the experiment. The biomass monitoring method was conducted by scraping all of the attached algal biomass from a specified horizontal strip area at two sampling points on each replicate floway. For the FULL set of replicate flow-ways, two biomass monitoring areas (size: 0.12m x 0.12m) were selected at random from the top and bottom of each flow-way as indicated by the yellow square area in (Fig.2.2). For the PARTIAL set of replicate flow-ways, two biomass monitoring areas (size: 0.12m x 0.12m) were taken at random along the flow-way. However, samples were taken from both harvested and non-harvested sections (Fig. 2.2). The initial standing crop was calculated for biomass productivity based on the following formulas:

Entire FANS area: $0.12\ m \times 6\ m = 0.72\ m^2$

Strip area: $0.12\ m \times 0.12\ m = 0.01\ m^2$

Area Ratio: $0.72\ m^2/0.01\ m^2 = 72$

FULL Harvest FANS Initial Standing Crop (g DW)

= [(DW Top + DW Bottom)/2] X 72

PARTIAL Harvest FANS Initial Standing Crop (g DW)

= [(DW Blue Area + DW Green Area)/2] X 72

Biomass Productivity (DW g m^{-2} day^{-1}*)*

= [(FANS DW Harvested Biomass on Day 7 – FANS DW Initial Standing Crop Day 0) / 0.72 m^2*] / 7 days*

Algal biomass that washed from the flow-ways prior to monitoring days was collected from the outflow metal sieves and dried in an oven overnight at 65 °C. The percentage of biomass wash-off from each replicate flow-way was calculated based on total DW (g) of collected biomass wash-off relative to total harvested biomass using the following equation:

Biomass wash-off (%) = Biomass washed off (g DW) / Total Biomass Harvest (g DW) X 100 %

The weight of these wash-off samples was then included in the final biomass productivity calculations for each set of replicate FANS systems. Biomass productivity was calculated in g of DW biomass per m^2 per day (DW g m^{-2}.d) using the following equation:

Biomass Productivity (DW g m^{-2}*.d)*

= [(FANS DW Standing Crop Day 7 – FANS DW Standing Crop Day 0) + Washed Off Biomass (g DW) / 0.72 m^2*] / 7 days*

2.3.2 Nutrient Removal Analysis

Each week, 100 mL water samples were collected from the inflow distribution sump and the outflow of each replicate flow-way. The water samples were collected immediately before any monitoring protocols began and also five minutes after flow was restored to the entire FANS system post-harvest.

At the beginning of the week, a pre-harvest water quality sample was taken to represent the nutrient removal of both the FULL and PARTIAL flow-ways after seven days of algal biomass growth. Another pre-harvest water quality sample was then taken during the middle of the week, which represented the nutrient removal of both replicate flow-way treatment systems after three days of algal biomass growth. Likewise, a post-harvest water quality sample was taken to assess the difference in nutrient removal of both treatment systems after the harvest of all or partial sections of algal biomass. Collection of post-harvest water quality samples differed slightly between the FULL and PARTIAL replicate flow-ways. As the

FULL set of replicate flow-ways were harvested once a week, a post-harvest sample was required only on the first day of monitoring. Whereas the PARTIAL set of replicate flow-ways were harvested twice a week and therefore post-harvest water quality samples were collected on both monitoring days. Water quality analysis was undertaken at the National Institute of Water and Atmospheric Research (NIWA) facility in Ruakura, Hamilton, New Zealand. In preparation for water quality analysis, samples were filtered through Whatman GF/F glass microfiber filter papers (pore size: 0.45 µm, diameter: 47 mm). For nitrate analysis, 250 µl of filtered sample was dispensed across three replicate wells in a UV microplate and nitrate ($N\text{-}NO_3$) concentration was determined using a microplate reader via the ultraviolet spectrophotometric method (Standard Method Nitrate 4500-NO_3 – B). Dissolved reactive phosphate (DRP) was also determined using the microplate reader via the ascorbic acid method (Standard Method Phosphorus 4500-P). For DRP analysis, 200 µl of filtered sample was dispensed into three replicate wells of a microplate along with 50 µl standard reagent. The nutrient removal rate for each set of replicate flow-ways was calculated using the following formulas:

Nutrient Removal Rate (g m^{-2}. d) = (FANS Inflow Nutrient Concentration (g m^{-3}) – FANS Outflow Nutrient Concentration (g m^{-3})) x FANS Working Volume (m^{-3}d) / 0.72 m^2

A TPS WP-91 Dissolved Oxygen-pH logger (Model: WP91Z Rev 2.1) was used to record the temperature and pH of each replicate flow-way prior to the collection of water quality samples. The probes were placed into both the inflow trough and outflow of each flow-way until readings had stabilized, and the values recorded.

2.3.3 Relative Species Abundance

Every fortnight, pre-harvest subsamples of attached algal biomass were taken from a strip harvest area (0.12 m x 0.025 m, or 0.003 m^2) from each replicate flow-way for microscopic analysis, to assess the relative abundance of algal species present.

Live subsamples were prepared for microscopic analysis by adding 10 mL of filtered water to the sample containers, which were then shaken vigorously for 10-15 seconds and passed through a 200 µm sieve. This allowed for the separation of any epiphytic diatoms, midges, other visible organisms, and substrate attached to the collected algal filaments for ease of identification under the microscope. The remaining contents of the algal biomass and 10 mL of filtrate were analysed using an inverted microscope (Leica DMi1) under 100x magnification. Before examination, the biomass and filtrate were divided evenly onto five microscopic slides for each replicate flow-way subsample. A total of five representative photographs were captured (one per microscopic slide) and used for species identification.

For each photograph, an estimate of the percentage of filamentous algae as well as contaminants (diatoms and cyanobacteria) composition was given based on the surface area covered in the captured photograph. The estimated percentage compositions were then

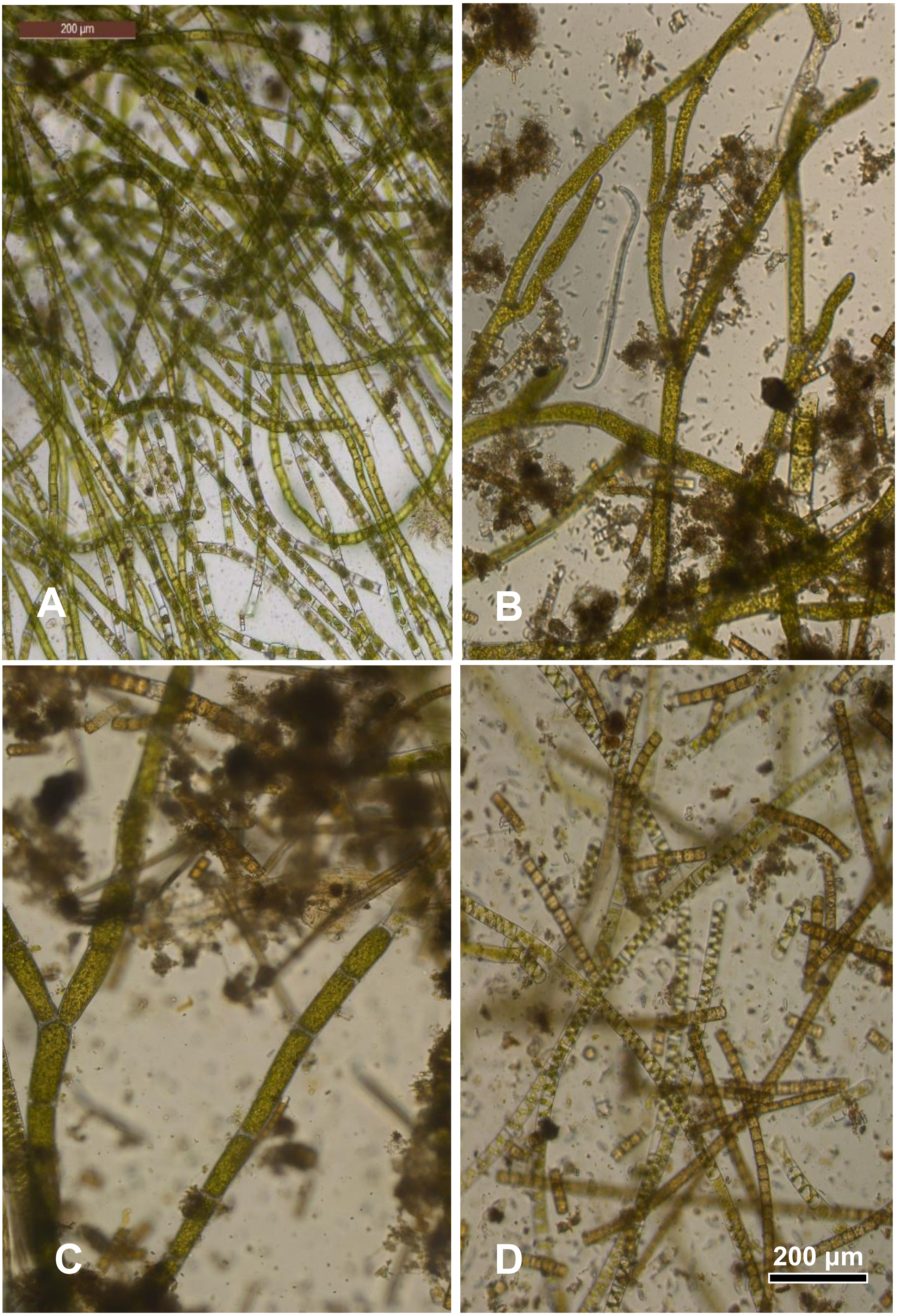

Figure 2.4: Images of common green filamentous algal species observed in this study. a. *Oedogonium* sp., b. *Cladophora* sp., c. *Rhizoclonium* sp., and d. *Spirogyra* sp. Scale bar is applicable to all images.

2.3.4 Outdoor Ambient Growth Conditions

Three weather event loggers were installed directly behind the inflow distribution sump, to record environmental variables such as light intensity (LI-COR LI-1500 light sensor data logger), ambient temperature (HOBO Pendant ® temperature data logger), and rainfall events (HOBO Pendant® event data logger) throughout the entire experiment. Frequency of recordings for light intensity and temperature occurred every 15 minutes, and rainfall events were recorded on a daily basis.

2.3.5 Statistical Analysis

Differences in biomass productivity, initial standing crop, nitrate removal rate, phosphate removal rate and biomass wash-off between treatments and experiments were tested using two-way analyses of variance (ANOVA). Data for each experiment was analysed separately using SigmaPlot software (Systat Software Inc., Point Richmond, CA, USA) with all data reported as means ± S.D.

2.4 Mātauranga Māori and Freshwater Algae: Research Objectives and Questions

As a part of this study interviews were conducted with both whanau (family) and members of Ngāti Hauā to gauge their understanding and knowledge of freshwater algae. The interviews were conducted in person and voice recorded; additionally written responses were provided by the participants; each interview took approximately one hour to complete. The objective of these interviews were as follows:

1.) To establish whakawhanaungatanga (a connection or relationship) with participants to allow for an ease of information sharing throughout the interview process.

2.) To establish trust between myself and the participants that any stories or knowledge shared would not be claimed by myself or anyone involved in this study and would belong solely to the holder of that knowledge.

3.) To create a wānanga environment that would encourage a reciprocal sharing of knowledge that would benefit both myself and the participants.

Six open-ended questions focusing on freshwater as a resource and a place of significance were asked of the participants in order to gain an understanding of what knowledge whanau and local iwi members held in relation to freshwater algae. The seven open-ended questions were as follows:

1. No hea koe? (Where are you from?)

2. Did you or your whanau have any relationship to freshwater sources such as streams, rivers, ponds and or lakes within your rohe?
3. Did you and your whānau interact with these water sources? If so, in what ways?
4. What korero if any, have you heard in relation to aquatic plants?
5. Are you aware of any traditional practices (i.e. – Rongoā or Mahinga kai) that may have incorporated the use of aquatic plants?
6. Would you or your whanau know of any Māori name that was given for algae?

Chapter 3

Results

3.1 ENVIRONMENTAL VARIABLES

3.1.1 Cumulative Rainfall

The frequency and cumulative sum of rainfall events recorded throughout the duration of this study varied greatly due to changes in seasonal weather conditions. The highest amount of cumulative rainfall (82 mm) observed throughout this study was recorded during the week of 26 October 2022 to 02 November 2022 (Fig 3.1). From mid-November to mid-December rainfall events remained relatively moderate and consistent with seasonal conditions. Conversely, an unusual amount of heavy rainfall was observed within the last three months of this study (January – March 2023), particularly during the week of 25 January and 15 February 2023, which recorded approximate sums of 75- and 78-mm of rainfall, respectively.

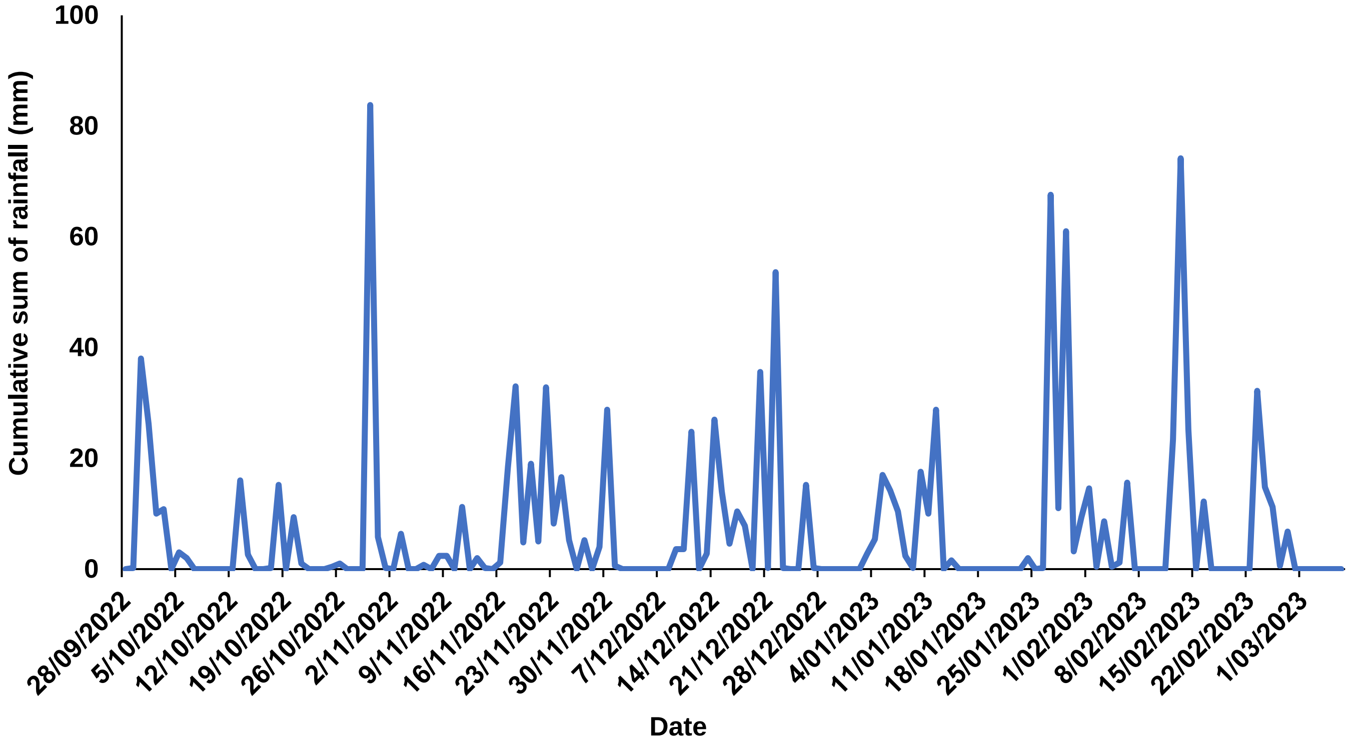

Figure 3.1: Summary of cumulative rainfall events recorded throughout the duration of this study (from 28 September 2022 – 6 March 2023).

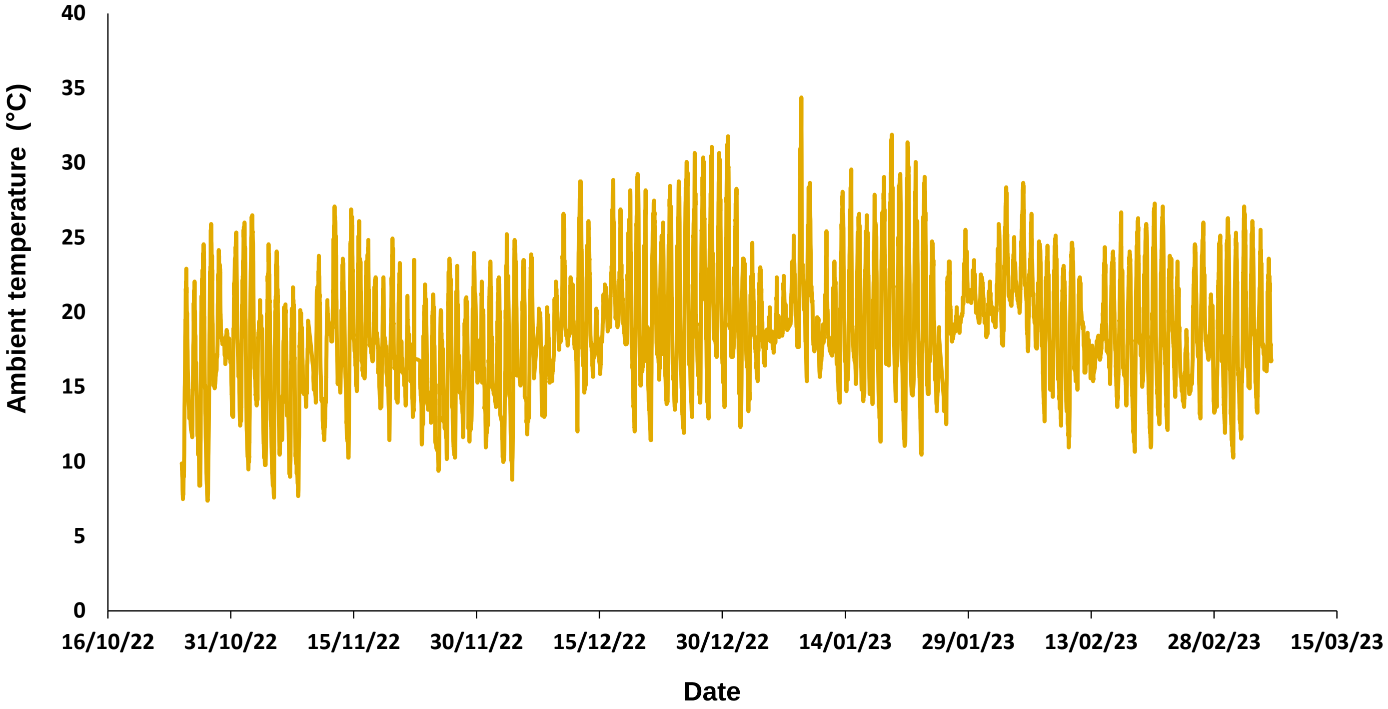

Figure 3.2: Summary of ambient temperature recorded throughout the duration of this study (from 16 October 2022 – 15 March 2023).

3.1.2 Ambient Temperature

Outdoor ambient temperatures recorded during the first two months of this study appeared to follow a typical trend in accordance with late spring and early summer seasonal conditions (Fig 3.2). From the 31 October 2022 to 30 December 2022 the ambient temperatures remained within a range of approximately 7 to 30°C. However, outdoor ambient temperatures observed throughout mid-January to late-February appeared to be cooler for the peak of the summer season. A notable drop in temperature was recorded during the week of 13 February 2023 consistent with the high cumulative sum of rainfall observed (Fig 3.1). The range of ambient temperature recorded from January to March fluctuated within a range of approximately 15 to 33°C.

3.1.3 Light Intensity

Trends in light intensity observed during the first two months of this study appeared to be typical for late spring to early summer seasonal conditions. However, once the experimental period reached mid-December (17 December 2022) there was a notable drop in light intensity recordings to approximately 600 µmol m^{-2}. s (Fig 3.3). Other drops in light intensity persisted into mid-January and early-February. The low light intensity values recorded during this time was consistent with heavy rainfall and low ambient temperature observed in (Fig 3.1 and Fig 3.2).

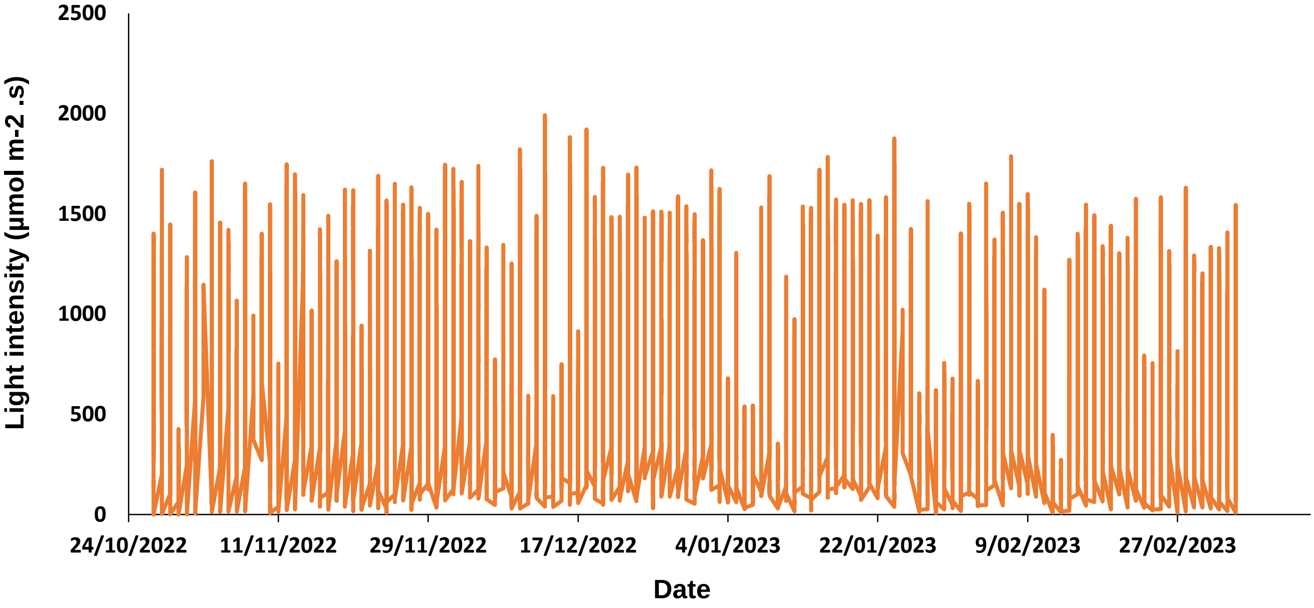

Figure 3.3: Summary of light intensity recorded throughout the duration of this study (from 22 October 2022 – 6 March 2023).

3.2 PARAMETERS OF ALGAL PRODUCTIVITY & GROWTH

3.2.1 Biomass Productivity

On average, biomass productivity was consistently higher in the PARTIAL replicate flow-ways (3.2 ± 1.4 g DW m^{-2}. d) than in the FULL replicate flow-ways (0.9 ± 0.7 g DW m^{-2}. d) for the duration of this study (Fig 3.4). The only exception was during the week of 15 February 2023; monitoring occurred only once during this period due to extreme weather conditions which prevented a mid-week harvest.

Biomass productivity ranged from 0.3 to 2.3 g DW m^{-2}. d for the FULL replicate flow-ways and 1.1 to 5.9 g DW m^{-2}. D for the PARTIAL replicate flow-ways. Biomass productivity varied significantly between each week of monitoring (ANOVA, $F_{12.362}$; $P = <0.001$). Moreover, there was a significant difference observed between treatments (ANOVA, $F_{377.929}$; $P = <0.001$).

In January 2023, algal growth conditions may have improved sufficiently to gradually increase biomass productivity for the PARTIAL replicate flow-ways from week to week. A low amount of cumulative rainfall was observed from 11 January 2023 to 25 January 2023 (Fig 3.1), while ambient temperatures remained within a 25°C to 30°C range (Fig 3.2). Additionally, the FULL replicate flow-ways had a substantial increase in average biomass productivity during this time that was not observed in previous monitoring weeks.

The experiment one (25 October 2022 – 09 January 2023) FULL harvest protocol produced more consistent results for biomass productivity that the experiment two FULL harvest protocol. A decrease in the biomass harvested from the FULL replicate flow-ways was the only adjustment made between experiment one and two, all other harvest protocols remained the same.

After changes were made to the harvest protocols for the FULL replicate flow-ways in experiment two, biomass productivity became more variable. However, this result may have been related to the increase in rainfall and other extreme weather events that occurred during late January to mid-February.

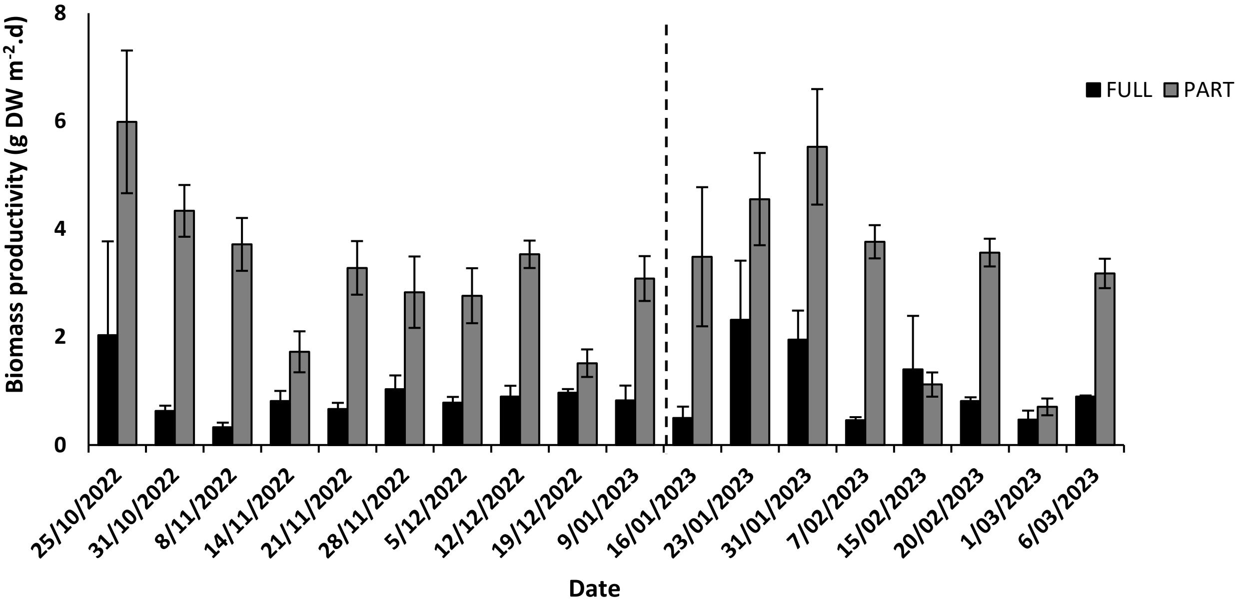

Figure 3.4: Average (+ S.D.) biomass productivity (g DW m^{-2}. d) for the FULL and PARTIAL replicate flow-ways across 18 weeks of monitoring. Dashed line represents the end of experiment one.

3.2.2 Initial Standing Crop

Overall, the average initial standing crop was higher in the PARTIAL replicate flow-ways (43.3 ± 18.0 g DW m^{-2}) than in the FULL replicate flow-ways (25.0 ± 10.5 g DW m^{-2}) and remained so throughout most of the study (Fig 3.5). The exceptions were the two monitoring weeks (09/01/2023 and 15/02/2023) where extreme weather events prevented a second mid-week harvest. Initial standing crop varied significantly among treatments (ANOVA, $F_{165.706}$; P = <0.001) and monitoring weeks (ANOVA, $F_{14.839}$; P = <0.001).

Initial standing crop for the FULL replicate flow-ways was lowest during the week of 31 January 2023 (10.1 ± 1.47 g DW m^{-2}) whereas the PARTIAL replicate flow-ways lowest initial standing crop was observed during the week of 15 January 2023 (13.2 ± 2.16 g DW m^{-2}). Although each treatment system recorded their lowest initial standing crop values during separate weeks, these observations could be related to the heavy rainfall that occurred during each of these monitoring weeks (Fig 3.1).

The first nine weeks of this study (25/10/2022 - 19/12/2022) appeared to have resulted in a more consistent average of initial standing crop for both the FULL and PARTIAL treatments, ranging from 17.3 to 72.4 (g DW m^{-2}. d). The remaining nine weeks of monitoring (9 January 2023 – 06 March 2023) observed a highly variable average of initial standing crop for both the FULL and PARTIAL treatments, ranging from 10.1 to 66.1 (g DW m^{-2}. d). This result may be in relation to the more settled weather conditions observed during late spring and early summer during experiment 1 (Fig 3.1 – 3.3).

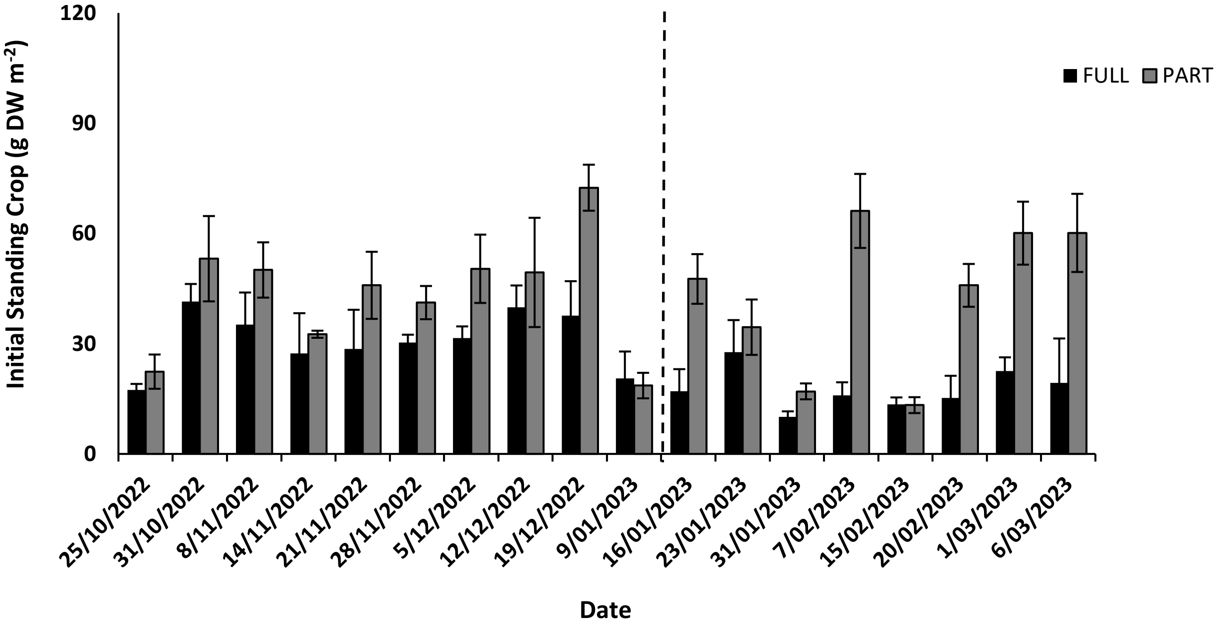

Figure 3.5: Average (+ S.D.) initial standing crop (g DW m^{-2}. d) for the FULL and PARTIAL replicate flow-ways across 18 weeks of monitoring. Dashed line represents the end of experiment one.

3.2.3 Biomass Wash-Off

The average biomass wash-off recorded during this study ranged from 0 to 1.8 g DW m^{-2}. d for the FULL replicate flow-ways and 0 to 1.5 g DW m^{-2}. d for the PARTIAL replicate flow-ways (Fig 3.6).

Overall, the average amount of biomass wash-off was slightly higher in the PARTIAL replicate flow-ways (0.38 ± 0.52 g DW m^{-2}) than the FULL replicate flow-ways (0.32 ± 0.60 g DW m^{-2}) across the duration of this study.

Biomass wash-off for the entire FANS system remained low during the first nine weeks of this study, ranging from 0.03 to 0.11 (g DW m^{-2}. d). In the remaining nine weeks (09 January 2023 to 06 March 2023), biomass wash-off increased significantly and ranged from 0.03 to 1.15 g DW m^{-2}. d. This result may have been related to the weather conditions observed during this time, where cumulative rainfall increased significantly from 25 January 2023 to 15 February 2023 (Fig 3.1).

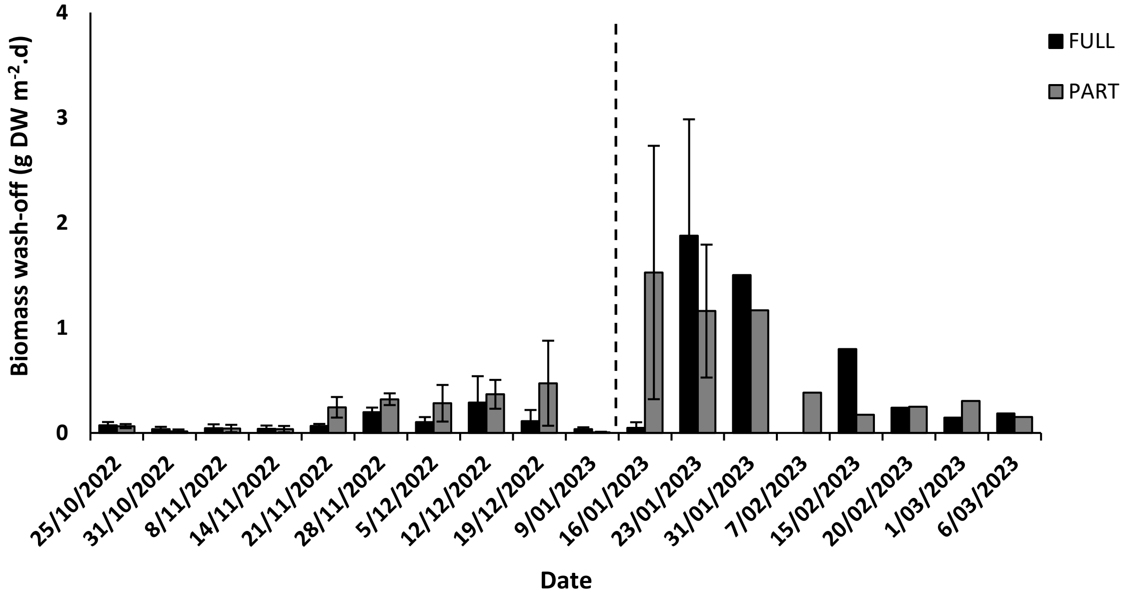

Figure 3.6: Average (+ S.D.) biomass wash-off (g DW m^{-2}. d) for the FULL and PARTIAL replicate flow-ways over 18 weeks of monitoring. Dashed line represents the end of

3.2.4 Nitrate Removal

Overall, the PARTIAL replicate flow-ways had a slightly higher nitrate removal rate on average (0.27 ± 0.18 g N m^{-2}. d) than the FULL replicate flow-ways (0.26 ± 0.18 g N m^{-2}. d) over the duration of this study (Fig 3.7). Nitrate removal varied significantly among monitoring weeks (ANOVA, $F_{0.160}$; $P = <0.001$). However, nitrate removal rates between treatments yielded no significant difference (ANOVA, $F_{0.00322}$; $P = 0.582$).

The lowest nitrate removal rates for both treatments were observed during the week of 21 November 2022 (0.09 ± 0.05 g N m^{-2}. d) for the FULL replicate flow-ways and (0.10 ± 0.06 g N m^{-2}. d) for the PATIAL replicate flow-ways.

Notably, the highest removal rates for both treatment systems were recorded during the week of 25 October 2022 (0.62 ± 0.02 g N m^{-2}. d) for the FULL replicate flow-ways and (0.64 ± 0.14 g N m^{-2}. d) for the PARTIAL replicate flow-ways.

This result may have been related to the initial seeding of the flow-ways that occurred one week before the first harvest of this study. Freshly seeded algae, combined with ideal algal growth conditions such as ambient temperature (Fig 3.2) and sufficient light intensity (Fig 3.3) observed during the week of 25 October 2022 may have contributed to this substantial reduction in nitrate as well as algal productivity that was not observed during other monitoring weeks.

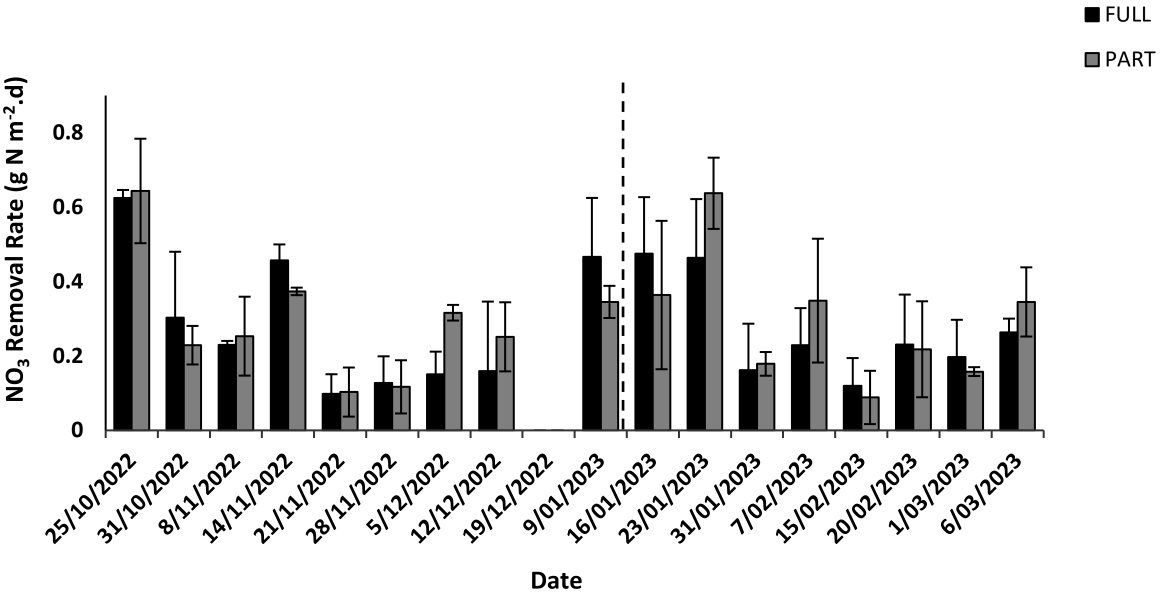

Figure 3.7: Average (+ S.D.) NO3-N removal rate (g N m^{-2}. d) for the FULL and PARTIAL replicate flow-ways over 18 weeks of monitoring. Dashed line represents the end of experiment one.

3.2.5 Phosphate Removal

The PARTIAL replicate flow-ways had a similar average phosphate removal rate (0.057 ± 0.041 g P m^{-2}. d) to the FULL replicate flow-ways (0.050 ± 0.037 g P m^{-2}. d) (Fig 3.8). When comparing the performance of both treatment systems between monitoring weeks there was a significant difference (ANOVA, $F_{11.890}$; P = <0.001). However, the comparison of phosphate removal rate between treatments alone yielded no significant difference (ANOVA, $F_{1.990}$; P = 0.163).

Phosphate removal varied greatly over the duration of this study, as there was no singular week of monitoring which collectively recorded either the highest or lowest PO_4 removal rate for both treatment systems.

The highest phosphate removal rate for the FULL replicate flow-ways occurred during the week of 16 January 2023 (0.12 ± 0.01 g P m^{-2}. d). This may have been as a result of the changes made to the harvesting protocols for the FULL flow-ways. The highest phosphate removal rate for the PARTIAL replicate flow-ways was recorded during the week of 06 January 2023 (0.13 ± 0.03 g P m^{-2}. d) which may have been as a result of an improvement in environmental conditions (low cumulative rainfall, increased light intensity, and moderate ambient temperatures) during this period of time (Fig. 3.1 – 3.3).

The lowest phosphate removal rate for the FULL replicate flow-ways was recorded during the week of 21 November 2022 (0.014 ± 0.012 g P m^{-2}. d). The lowest phosphate removal rate for the PARTIAL replicate flow-ways was recorded during the week of 09 November 2023 (0.007 ± 0.002 g P m^{-2}. d).

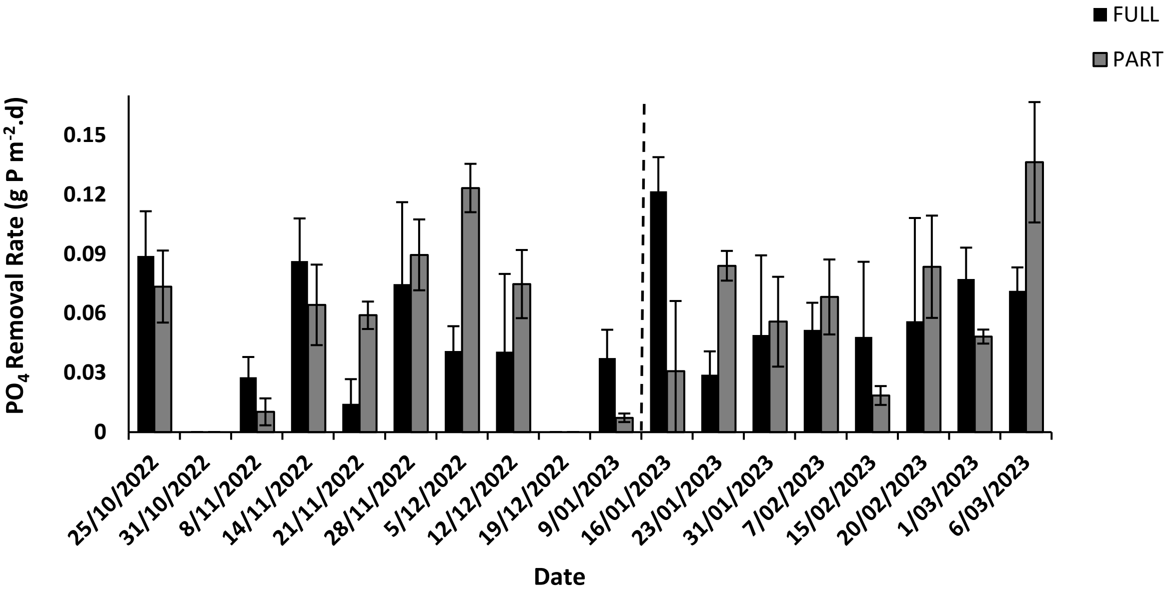

Figure 3.8: Average (+ S.D.) PO4 removal rate (g P m^{-2}. d) for the FULL and PARTIAL replicate flow-ways over 18 weeks of monitoring. Dashed line represents the end of experiment one.

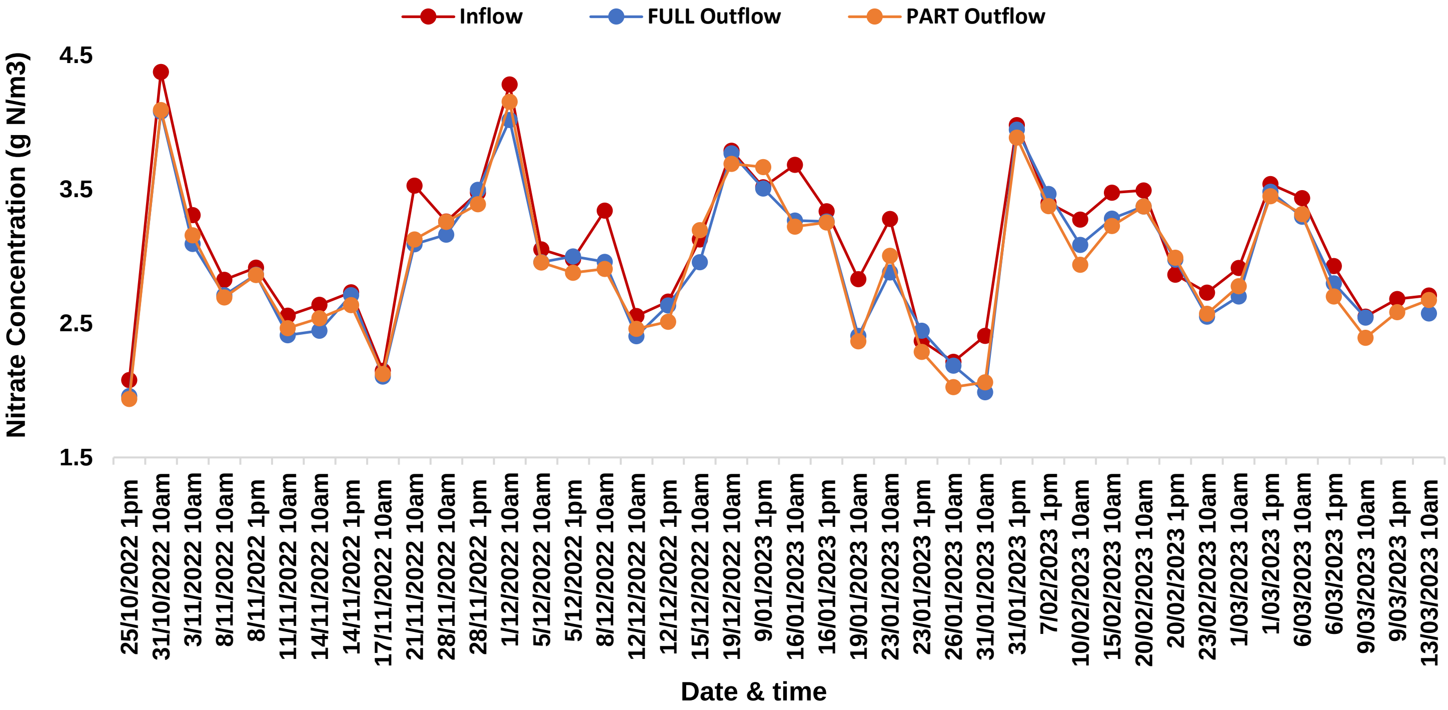

Figure 3.9: Concentration of phosphate (g P m^{-3}) over time for the inflow distribution sump, FULL and PARTIAL replicate flow-ways over 18 weeks of monitoring.

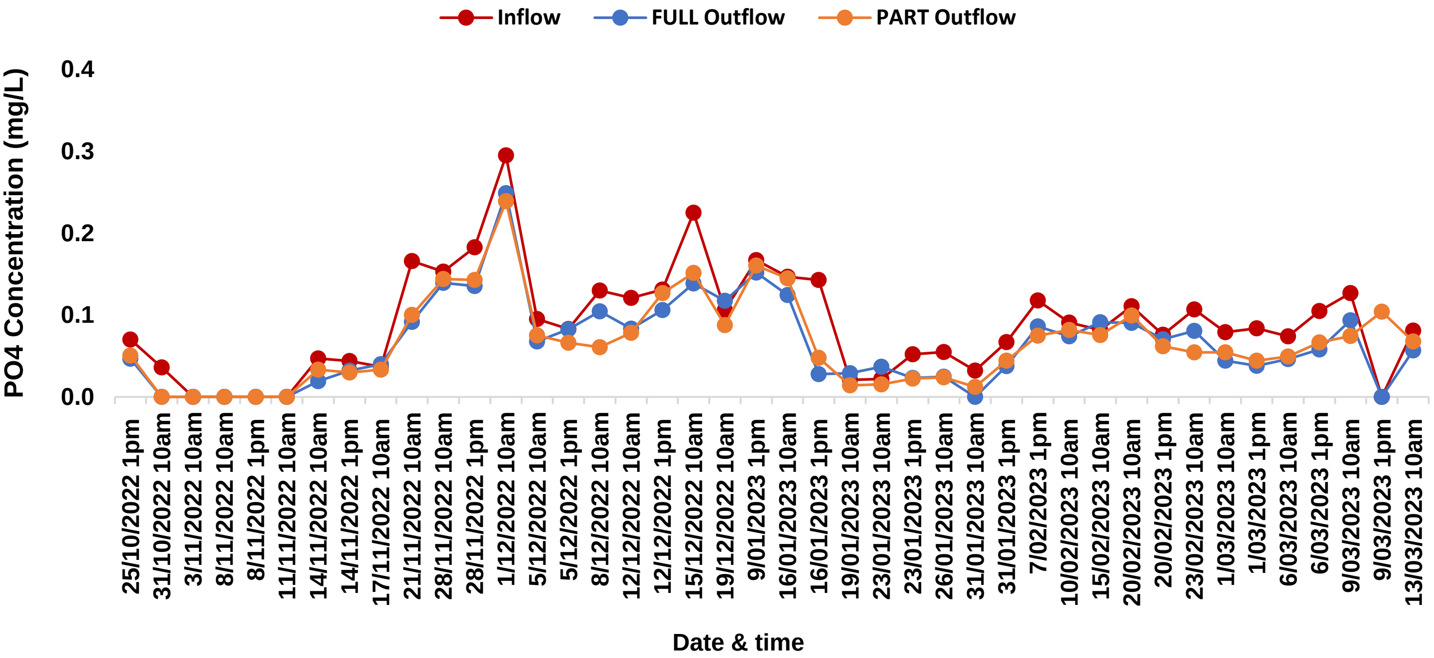

Figure 3.10: Concentration of phosphate (g P m^{-3}) over time for the inflow distribution sump, FULL and PARTIAL replicate flow-ways over 18 weeks of monitoring.

3.2.6 Relative Species Abundance

The average relative abundance of green filamentous algal species (*Oedogonium* sp., *Rhizoclonium* sp., *Cladophora* sp. and *Spirogyra* sp.) varied significantly among the FULL and PARTIAL replicate flow-ways throughout the duration of this study (Fig 3.11 – 3.12).

Overall, the FULL replicate flow-ways observed a highly variable abundance of diatoms, cyanobacteria, and green filamentous algal species throughout the duration of this study. *Oedogonium* sp. was the dominant algal species observed on the FULL replicate flow-ways from day 0 to 69. From day 69 to 127, *Spirogyra* sp. took over as the dominant algal species observed on the FULL replicate flow-ways. Relative species abundance from day 127 onwards appeared to be mixed between *Cladophora* sp*, Oedogonium* sp. and *Rhizoclonium* sp.

In contrast, the PARTIAL replicate flow-ways observed a relatively stable abundance of diatoms, cyanobacteria, and green filamentous algal species throughout the duration of this study. Within first 28 days of this study, relative abundances were split relatively evenly among the three predominant algal species (*Oedogonium* sp, *Rhizoclonium* sp, *Cladophora* sp.*)*. From day 28, onwards *Spirogyra* sp established on the PARTIAL replicate flow-ways and became one of the most dominant algae observed, alongside *Oedogonium* sp. and *Cladophora* sp.

Notably, other filamentous algal species (*Ulothrix* sp. and *Klebsormidium* sp.) were observed in greater relative abundance from day 28 to 69 on the PARTIAL replicate flow-ways. On the FULL replicate flow-ways, these taxa were observed in lower abundance relative to other filamentous algal species.

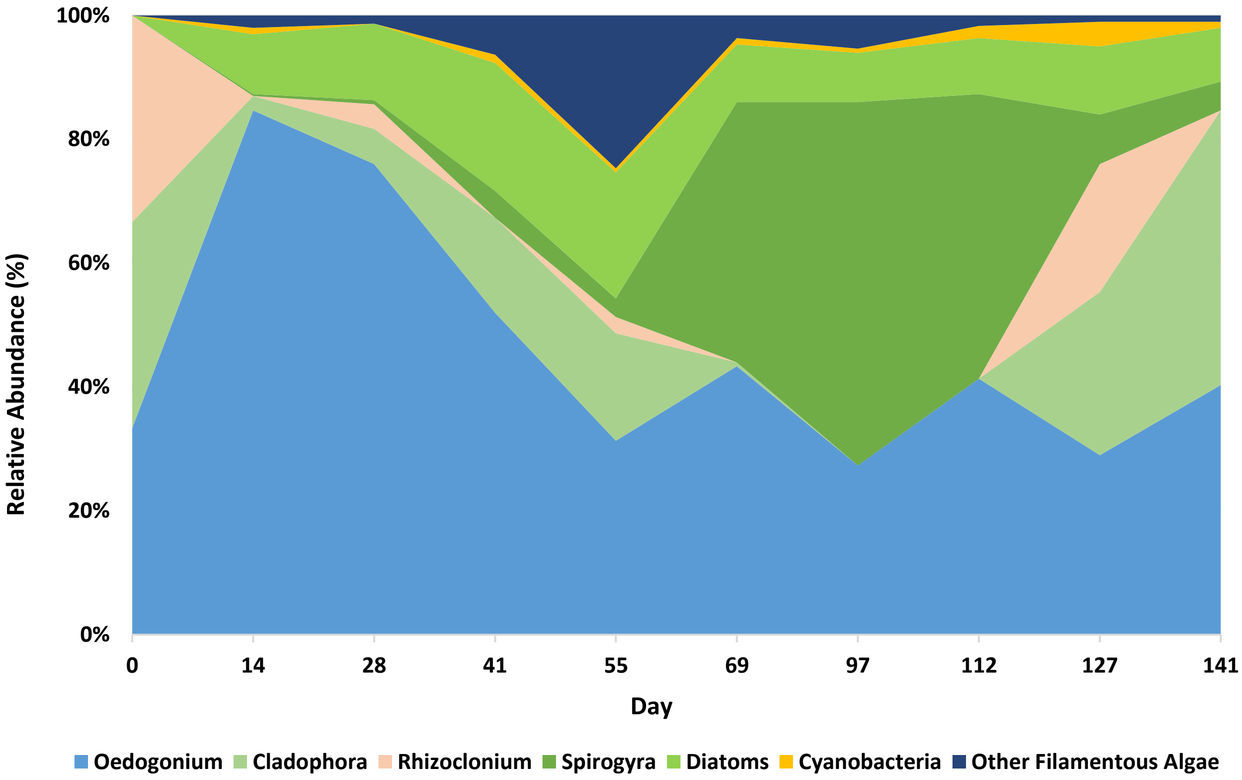

Figure 3.11: Average relative abundance (%) of the representative classes of algae observed on the FULL replicate flow-ways over the duration of this study.

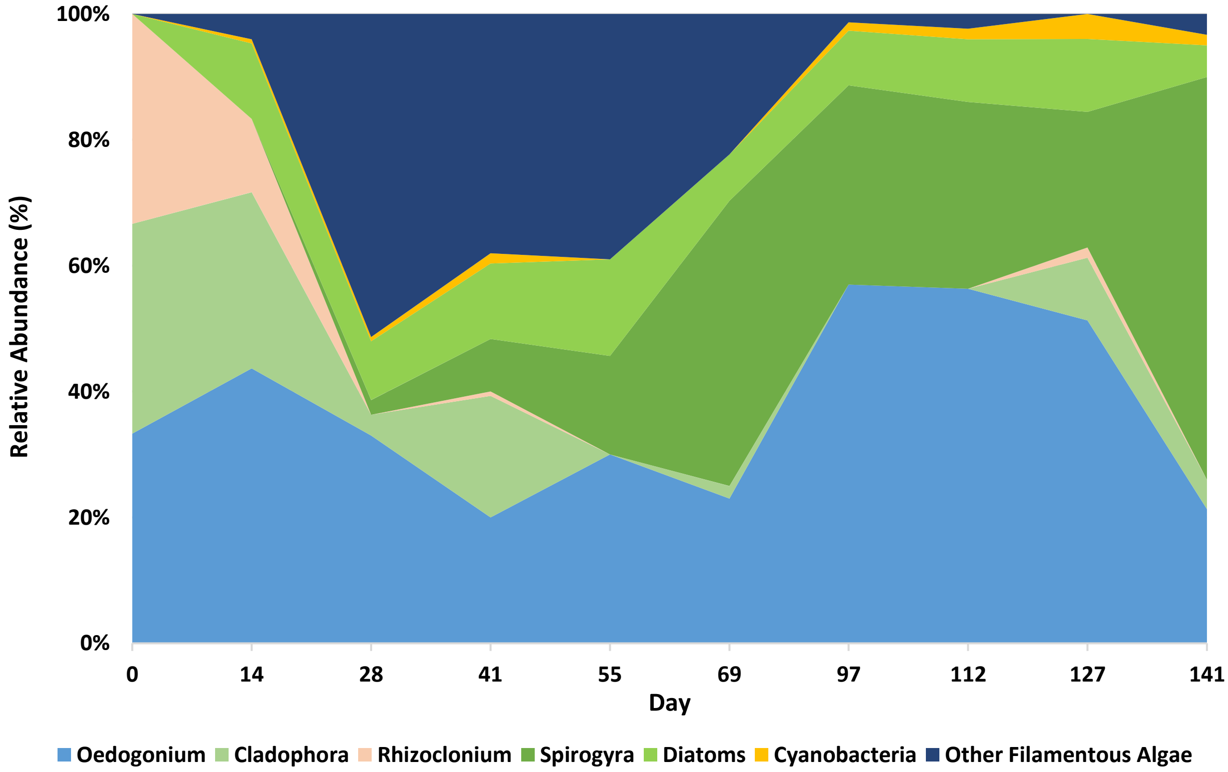

Figure 3.12: Average relative abundance (%) of the representative classes of algae observed on the PARTIAL replicate flow-ways over the duration of this study.

Table 1. Results of statistical analysis (ANOVA) test on the effects of FANS treatment and cycle on initial standing crop, biomass productivity, and nutrient removal.

Variable	**Effect**	**df**	**F**	**P**
DW Initial standing crop (g/m2)	FANS Treatment	1	165.706	<0.001
	Cycle	17	14.839	<0.001
	Treatment x Cycle	17	6.504	<0.001
	Residual	72		
Biomass Productivity (g DW biomass m^{-2} day^{-1})	FANS Treatment	1	377.929	<0.001
	Cycle	17	12.362	<0.001
	Treatment x Cycle	17	6.151	<0.001
	Residual	72		
Nitrate removal rate (g N g^{-1} DW biomass day^{-1})	FANS Treatment	1	0.00322	0.582
	Cycle	17	0.160	<0.001
	Treatment x Cycle	17	0.0113	0.399
	Residual	72		
Phosphate removal rate (g P g^{-1} DW biomass day^{-1})	FANS Treatment	1	1.990	0.163
	Cycle	17	11.890	<0.001
	Treatment x Cycle	17	5.576	<0.001
	Residual	72		

3.3 Mātauranga Māori and Freshwater Algae: Interview Key Findings

3.3.1 Interview One: Adam Whauwhau (Ngati Haua)

Adam grew up in the small rural town of Tauwhare which is located in the Waikato District on the outskirts of Hamilton, New Zealand. As a young boy he recalled spending a significant amount of time in the awa (Mangaonua Stream) near his marae Te Iti o Hauaa. Adam recalls the freshwater bodies near his marae as a place for recreational activities (swimming and sport) as well as a source for gathering mahinga kai (Tuna, kokopu, and watercress). In terms of traditional knowledge around the significance of aquatic plants, Adam shared a korero around his whanau's practice of harvesting watercress for medicinal purposes and briefly discussed the health and healing properties of watercress. Adam was unaware of any specific korero within his iwi pertaining to the significance of freshwater algae.

3.3.2 Interview Two: Marie Whareaitu (Ngati Mahanga)

As a child Marie grew up in the small rural town of Waitetuna located in the Waikato District, New Zealand. Marie and her whanau spent a lot of time in and around freshwater sources (Waikato River, Waitetuna River, and Waipa River) within the Waikato region. The korero that Marie shared with me in regards to freshwater algae was based around its traditional use. According to Marie, freshwater algae was known to her and her whanau as Puukohu wai. She said the name itself holds much whakapapa (genealogy), in translation Puu is base, kohu is cloudy and wai is water. Marie went on to explain that by naming this aquatic plant based on its appearance and where it can be found, this knowledge allowed her ancestors to determine how to best utilize the algae for medicinal or kai (food) purposes. Furthermore, Marie described a traditional tribal practice of harvesting algae from puna (spring of water) to feed the soil in her vegetable gardens as a fertilizer, similar to the use of fish bones.

3.3.3 Interview Three: Claudine Waitere (Ngati Mahanga/Ngati Te Wehi)

Claudine was born and raised in Kirikirroa (Hamilton), New Zealand. In her youth Claudine recalls spending an enormity of her time in and around the West Coast shores of Raglan Harbour, Aotea Harbour and Kawhia Harbour. Whakapapa (genealogy) was the main point of discussion that Claudine shared with me in relation to her traditional knowledge of freshwater algae. To her knowledge Puukohu wai is the generic term used by many tribes to describe marine and freshwater algae. In Claudine's tribal dialect (Tainui) freshwater algae is also known as Punakohu wai. Puna translated is source and Punakohu wai refers to all types of plant life that grow in or around freshwater springs. According to Claudine, algae was primarily used by her whanau to bait eel traps in the awa near her marae (Te Papatapu).

Chapter 4

Discussion

The overall objective of this study was to investigate the most optimal harvest frequency and harvest regime of a Filamentous Algae Nutrient Scrubber (FANS) system, in order to maximize algal biomass productivity and nutrient removal. This was achieved by comparing full and partial harvest of a triplicate pilot-scale outdoor FANS system.

4.1 Biomass Productivity

Harvest frequency had a significant impact on algal biomass productivity. During both experiments, biomass production was over three times higher in the PARTIAL replicate flow-ways (3.2 g DW m^{-2}. d) than in the FULL replicate flow-ways (0.9 g DW m^{-2}. d). More frequent harvest of the PARTIAL replicate flow-ways (every 3 – 3.5 days) appears to have stimulated higher algal growth than on the FULL replicate flow-ways, which were harvested every 7 – 7.5 days. The biomass productivity results of the present study compare favourably with those reported recently by Sutherland et al. (2020b), who examined the optimization of operational parameters (harvest frequency and harvest regime) in order to maximize the nutrient removal performance of FANS systems in Sydney, Australia. In their study, three small-scale outdoor FANS systems were set-up during the austral summer. Each FANS system had a different harvest regime; 1) Weekly, where all biomass was removed from the flow-ways every 7 days; 2) Fortnightly, where all biomass was removed from the flow-ways every 14 days, and 3) Strip, where only half of the biomass was removed in a strip down the length of the flow-ways every 7 days, allowing for biomass accrual to take place every 14 days on either side of the flow-way. Overall, the results of their study demonstrated a significant increase of biomass production in the weekly harvested FANS system (30.4 g DW m^{-2}. d) in comparison to the fortnightly (19.0 g DW m^{-2}. d) and strip (16.2 g DW m^{-2}. d) harvested FANS systems. Although the harvest frequency implemented in the present study (3 – 3.5 days) was more frequent than that of Sutherland et al. (2020b), a similar trend in biomass productivity was observed. In combination, these findings suggest that employing shorter harvest intervals can help to maximise biomass productivity in FANS systems.

The premise of implementing longer intervals between harvest events may be applicable when seasonal conditions are also considered. For instance, Craggs et al. (1996a) suggested weekly harvest intervals during times of peak solar irradiance and biomass production (summer months), while harvest intervals of up to a month could be maintained when solar irradiance and biomass production is at its lowest (winter months). Longer intervals between harvest events in FANS systems promote the development of thicker algal mats. In the present study, thicker algal mats were observed in the PARTIAL replicate flow-ways. Leaving unharvested sections of accrued biomass on the PARTIAL replicate flow-ways may have facilitated faster algal regrowth on the harvested sections and contributed to the higher productivity than the FULL replicate flow-ways. Furthermore, the total removal of biomass in FULL replicate flow-ways may have prevented the development of algal mats to the same degree of thickness and prominence than was observed in the PARTIAL replicate flow-ways. This observation aligns well with that of Sutherland et al. (2020b), who showed that frequent total harvesting of their flow-ways reduced the thickness of algal mats within their FANS system. Research by Craggs et al. (1996a) and Adey et al. (2011) emphasized the importance of harvest frequency to promote algal growth and maximise biomass production and nutrient removal.

Harvest regime is another key parameter that had a significant impact on algal biomass productivity. The PARTIAL replicate flow-ways were harvested in alternate meter sections, which allowed for a constant coverage of 50% biomass within this particular set of flow-ways at all times. During experiment one, the unharvested sections along the PARTIAL replicate flow-ways may have facilitated faster regrowth of algal biomass within the harvested sections compared with the fully harvested FULL replicate flow-ways. This observation is supported by a previous study by Sindelar et al. (2015), who noted the importance of maintaining algal seed. The authors of that study found that the algal biomass left on the flow-ways of their ATS system provided a constant source of algal recruitment, which led to faster rates of algal growth and ultimately higher rates of algal production. In an effort to explore this observation further, changes were made to the amount of algae harvested from the FULL replicate flow-ways in the present study, which initiated the commencement of experiment two. Rather than harvesting all algal biomass from the FULL replicate flow-ways, small 20 cm strips of biomass were left unharvested every meter, with the aim of enhancing algal growth. Following this change, biomass accrual improved slightly in the FULL replicate flow-ways. However, heavy rainfall and other extreme weather conditions during the final three months of this study likely hindered the effects of such changes to be fully realised. Further studies investigating the re-establishment of algal biomass along horizontal sectioned, or strip harvested flow-ways, would be beneficial for optimizing biomass productivity of FANS systems.

Initial standing crop may also have impacted algal biomass productivity. Overall, the PARTIAL replicate flow-ways had a higher initial standing crop (43 g DW m^{-2}) than the FULL replicate flow-ways (25 g DW m^{-2}) which could have contributed to the higher rates of algal biomass production. Contrary to this result, a recent study by Hariz et al. (2023a) examined the effects of operational parameters (inflow rate, initial standing crop, and harvest frequency) on the biomass productivity and nutrient removal performance of *Oedogonium* sp. on a laboratory-based FANS system at Ruakura, Hamilton, New Zealand. The authors of this study reported a greater increase in biomass production in a FANS system with a lower initial standing crop (60–70 g DW m^{-2}; 8.6 g DW m^{-2} day^{-1}) relative to the FANS system with a higher initial standing crop (100-110 g DW m^{-2}; 5.9 g DW m^{-2} day^{-1}). The authors of this study attributed the decrease in biomass productivity in the FANS system with a higher initial standing crop to a reduction in the rate of photosynthesis due to a thicker algal mat. This leads to increased self-shading, lower nutrient mass transfer rates and lower photosynthetic gas exchange. The contrast in results between the present study and that of Hariz et al. (2023a) could be attributed to the difference in experimental conditions, as data from the present study reflected an outdoor operated FANS system, whereas the FANS system in Hariz et al. (2023a) was operated under controlled laboratory conditions (light intensity of 600-650 µmol m^{-2} s^{-1}, 14:10 light and dark cycle, room temperature set at 22°C). Algal growth in an outdoor-based FANS system is challenged by prevailing environmental conditions, and therefore may require a higher standing crop than a laboratory-based FANS system in order to help stimulate algal growth and production.

Maintaining an optimal standing crop may also depend on season. Hariz et al. (2023b), suggested that during the summer higher solar irradiance may support a higher initial standing crop, as light can easily penetrate through to the bottom layers of an algal mat. Whereas a lower standing crop may be more suitable during winter months, when solar irradiance is lower.

4.2 Environmental Variables

The biomass productivity range for the PARTIAL replicate flow-ways (1.1 to 5.9 g DW m^{-2}. d) aligns closely with the productivity ranges reported recently by Hariz et al. (2023b) (1.2 to 4.5 g DW m^{-2}. d). The authors of that study examined the growth rates and nutrient uptake rates of four locally isolated filamentous algae species (*Cladophora* sp., *Oedogonium* sp., *Rhizoclonium* sp. and *Spirogyra* sp.) on an outdoor mesocosm-scale FANS system operated under ambient summer and winter conditions in Ruakura, Hamilton, New Zealand. Although the present study included data from spring to summer months and Hariz et al. (2023b) encompassed data from summer and winter conditions the similarity in biomass productivity range between the present study and Hariz et al. (2023b) demonstrates the influence of ambient environmental conditions on biomass productivity in FANS systems.

The present study was conducted across the spring to summer period of 2022-2023, during a time when ambient conditions fluctuated widely. Notably, biomass productivity improved significantly for the PARTIAL replicate flow-ways during January. This result was likely a reflection of the ideal ambient environmental conditions (low cumulative rainfall, moderate temperature, and high light intensity) for algal growth, observed during mid to late January (Fig 3.1 – 3.3). Conversely, a decline in biomass productivity was observed in both treatment flow-ways during the 15th week of monitoring, from 12 to 16 February 2023. This decline in biomass productivity coincided with a significant period of high rainfall (cumulative sum of rainfall for this period: 135 mm, Fig 3.1). Moreover, the high rainfall observed during this time prevented a second harvest, which could plausibly explain the significant drop in biomass productivity in the PARTIAL replicate flow-ways from the previous week of monitoring (7 February, 3.7 g DW m^{-2}. d) to the following week (15 February 2023, 1.1 g DW m^{-2}. d). Prolonged periods of high rainfall can cause excessive amounts of biomass to wash-off from the FANS system as a consequence of higher flow disturbance (Hariz et al., 2023c). Furthermore, increased catchment erosion can negatively impact the photosynthetic ability of FANS algae during excessive rainfall events due to smothering by the higher sediment load in the inflow water (Chen et al., 2015).

4.3 Nutrient Removal

There was no significant difference in nitrate or phosphate removal between the two harvest treatments in the present study, indicating that regardless of flow-way harvest frequency, regime or biomass retention, nutrient removal remains the same. This finding is consistent with that of Sutherland et al. (2020b), who observed no additional benefits in terms of nutrient removal with flow-ways that were harvested weekly (0.3 g N m^{-2} d^{-1}, 0.08 g P m^{-2} d^{-1}), fortnightly (0.3 g N m^{-2} d^{-1}, 0.06 g P g m^{-2} d^{-1}) and strip (0.3 g N m^{-2} d^{-1}, 0.05 g P m^{-2} d^{-1}). The lack of change in nutrient removal within the Sutherland et al. (2020b) study and in the present study suggests that nutrient removal is not always directly associated with biomass production (Siville and Boeing, 2020). This could be a consequence of the tendency of algae to assimilate an excess of nutrients required for growth (luxury nutrient uptake) (Powell et al., 2009)

Furthermore, the data from the present study has shown a similar trend in nutrient removal to that of Sutherland et al. (2020b), with the highest removal generally occurring post-harvest within both harvest treatment flow-ways. This result could be attributed to the cleaning and maintenance protocols that were carried out upon completion of harvest events. Sediment build-up within the inflow distribution sump was a common occurrence throughout the duration of this study, which subsequently led to clogging of the flow-way valves. As such, pre-harvest water quality samples were most likely a reflection of the low flow rate (due to clogged flow-way valves) and conversely, the post-harvest water quality samples reflected the more ideal flow rate conditions, which may have allowed for a more effective removal of nutrients post-harvest.

4.4 Relative Species Abundance

Overall, there was a significant difference in relative species abundances observed between the two-harvest treatment flow-ways in this study. The PARTIAL replicate flow-ways had a relatively stable abundance of four dominant algal species (*Oedogonium* sp., *Spirogyra* sp., *Rhizoclonium* sp., and *Cladophora* sp.), whereas the FULL replicate flow-ways had a highly variable abundance of the previously mentioned algal species, along with a greater presence of non-target algal species (diatoms and cyanobacteria) throughout the duration of this study. To date, no study has directly compared the effects of harvest frequency and harvest regimes on the relative abundance of algal species in FANS systems. However, algal community composition was discussed in a recent study by Siville and Boeing (2020), who investigated the optimal harvest rate of a laboratory-scale Algal Turf Scrubber (ATS) system to maximize algal biomass production. The authors of that study noted that inevitable changes in community composition within an algal treatment system over time include the establishment of less desirable filamentous diatoms (e.g., *Melosira* sp.), bacteria, and grazers (e.g., rotifers, ciliates). They stated that variations in community composition could negatively impact the relationship between algal growth, biomass production, and nutrient uptake. Moreover, a study by Sandefur et al. (2014) examined the productivity and nutrient removal rates of a pilot-scale attached growth system. These authors suggested that an undesirable species composition may have contributed to the underperformance (biomass productivity and TP removal) of one of their algal growth systems. Given the high relative abundance of diatoms and cyanobacteria observed in the FULL replicate flow-ways of the present study, it is plausible to suggest that a similar outcome to that of Sandefur et al. (2014) may have also occurred here.

4.5 Mātauranga Māori and Freshwater Algae: Perspectives, Insights, and Future Aspirations

Globally, there has been a shift in recognition of the many benefits that indigenous knowledge systems have to offer ecological research (Lyver et al., 2017). The intergenerational transmission of knowledge that exists within indigenous knowledge systems offers a deep temporal and spatial understanding of ecosystems that could help to generate more holistic environmental management practices.

In Aotearoa New Zealand, mātauranga Māori is the form of indigenous knowledge that encapsulates the interdependent relationship between people and nature. According to Harmsworth and Awatere (2013), this body of knowledge links indigenous Māori to ecosystems and governs how they see and understand ecosystems and ecosystem services. Māori values such as tikanga (customs and practices), mauri (life force), rāhui (prohibition), whakapapa (genealogy), kaitiakitanga (guardianship), wāhi tapu (sacred place) and manaakitanga (generosity) are viewed as tools through which Māori make sense of, experience, interact and interpret the natural environment (Marsden, 1989; Harmsworth and Awatere, 2013). Incorporating mātauranga Māori into environmental research offers a unique opportunity to examine the health of ecosystems from a local perspective that is heavily derived from these Māori values. This allows decision making to be centred around what is beneficial for the long-term sustainable use of a resource.

A recent report by Harmsworth (2021) highlighted the documentation and use of ngā kupu/te reo Māori (words and terms) as a potential starting point for the incorporation of mātauranga Māori in environmental research. This report gave examples of Māori terms used to describe water, wetlands, and soils in order to illustrate the relevance and depth of mātauranga Māori. In the present study, mātauranga was incorporated in a similar manner. Face-to-face interviews with whanau and members of local iwi (Ngati Mahanga and Ngati Haua) were undertaken in order to gauge their understanding and awareness of freshwater algae. Ngā kupu/te reo Māori given for aquatic plants was a common theme that arose from the interviews with each participant. When questioned about their awareness of freshwater algae, both Marie and Claudine used the Māori terms Pūkohu wai and Punakohu wai to describe freshwater algae. To their knowledge, Pūkohu wai (algae) was primarily used by their whanau to fertilize vegetable gardens and bait eel traps. The interview participants shared a highly positive view towards the potential of using algae harvested from FANS systems for fertilizing and bait trapping purposes.

Other observations of Pūkohu wai (algae) have been highlighted in an application by Dow AgroSciences (NZ) Ltd. to the Environmental Protection Authority (EPA). Appendix C: *Relationship of Māori to the Environment* of this application mentions “Māori understand that Pūkohu wai are valuable to waterways as they help to purify water by absorbing nutrients from streams and rivers – which is important for maintaining balance within and between Te Marae o Tangaroa and Te Marae o Tāne” (Environmental Protection Authority, 2016). Based on this observation and responses from interview participants in the present study, it appears likely that the application of FANS technology will be readily acceptable to Māori (e.g., on Māori owned farmland).

Kohuwai is another Māori term that has been commonly used to describe freshwater algae. An early publication by Beattie (1920) briefly described freshwater algae growing in a stream in Southland, New Zealand: “Kohuwai, also known as kohuai, said one of my informants, is a green sort of weed or moss in the bottoms of streams, and a small creek between Waikawa and Chasland's is called Wai-kohuwai because of its bed being so covered with this moss." (Beattie, 1920, p. 72).

Identifying ngā kupu (words and terms) used by Māori to describe freshwater algae is an important first step towards enhancing our understanding of the wider ecological processes associated with algae. By understanding the terminology used by Māori who observed and utilized algae as a resource many generations ago may reveal an awareness of biological processes that either differs or compliments a Western Science point of view. Incorporating such knowledge into current water and environmental management practices could be hugely beneficial towards improving the current status of water quality in Aotearoa New Zealand.

4.6 Limitations and a Mihi to Future Research

Time was the major limitation of the present study. I would have liked to include a broader range of iwi members in the discussions on Mātauranga Māori, in order to gain a wider tangata whenua (people of the land) perspective on water quality and freshwater algae. To my knowledge, local Te Arawa iwi (Ngāti Pikiao, Ngāti Whakaue, and Tūhourangi) members hold a wealth of knowledge pertaining to the generational observation of toxic algal blooms across a number of freshwater lakes within the Rotorua District. However, I was unable to speak with these iwi members in the project timeframe. Nevertheless, the mātauranga that was gathered in the present study through literature review and interviews with participants has indicated an acceptance of FANS technology by Māori and is merely a taste of the depth and vastness that indigenous knowledge systems have to offer ecological research. I hope that this thesis provides a small stepping-stone for future environmental studies within Aotearoa, New Zealand to consider the incorporation and acknowledgment of mātauranga Māori.

Chapter 5

Conclusion

This study has demonstrated that an increased harvest frequency (3 – 3.5 days) and a sectioned harvest regime was most optimal for maximising the biomass yield of filamentous algae grown on an outdoor FANS system. Biomass production was over three times higher in the PARTIAL harvest flow-ways (3.2 g DW m^{-2}. d) in comparison to the FULL harvest flow-ways (0.9 g DW m^{-2}. d). However, in terms of nutrient removal there was no significant difference observed between the PARTIAL and FULL harvested flow-ways. The results of this study has provided important insights how operational parameters can be optimized in order to enhance the biomass production performance of FANS systems during spring to summer months. Although, we are still limited in our understanding of how these particular operational parameters can be modified for the operation of FANS systems on a year-round basis. Particularly during winter months when outdoor ambient conditions are less favourable for algal growth. Therefore, future studies should investigate the optimal harvest frequency and harvest regime of FANS systems during these times of low biomass production. Moreover, subsequent studies could also further investigate the productivity of FANS systems with a different sectioned harvest regimes but similar standing crops.

In terms of the mātauranga gathered and presented in this study, it was evident that whanau and iwi members held a positive view towards the use of FANS technology. Highlighting the use of harvested algal biomass for fertilizer and bait trapping purposes. Moreover, the literature review conducted in this study demonstrated an awareness by Māori of the important role of algae as water purifiers. Therefore, reinforcing the potential acceptance of this technology by Māori, which will hopefully transpire to the wider use and application of FANS systems on Māori farmland in future.

References

Abell, J. M., Özkundakci, D., Hamilton, D. P., & Miller, S. D. (2011). Relationships between land use and nitrogen and phosphorus in New Zealand lakes. *Marine and Freshwater Research*, *62*(2), 162-175. https://doi.org/https://doi.org/10.1071/MF10180

Abou-Shanab, R. A., El-Dalatony, M. M., El-Sheekh, M. M., Ji, M. K., Salama, E. S., Kabra, A. N., & Jeon, B. H. (2014). Cultivation of a new microalga, Micractinium reisseri, in municipal wastewater for nutrient removal, biomass, lipid, and fatty acid production. *Biotechnology and Bioprocess Engineering*, *19*, 510-518. https://doi.org/10.1007/s12257-013-0485-z

Adey, W. (1983). The microcosm: a new tool for reef research. *Coral Reefs*, 1(3), 193-201.

Adey, W., & Loveland, K. (2007). Dynamic aquaria.(pp. 159-169). In: Oxford, UK: Elsevier Inc.

Adey, W. H., & Loveland, K. (2011). *Dynamic aquaria: building living ecosystems*. Elsevier.

Adey, W., Kangas, P., & Mulbry, W. (2011). Algal turf scrubbing: Cleaning surface waters with solar energy while producing a biofuel. BioScience, 61(6), 434-441.

Adey, W., Laughinghouse Iv, D., Miller, J., Hayek, L.-A., Thompson, J., Bertman, S., Hampel, K., & Puvanendran, S. (2013). Algal turf scrubber (ATS) floways on the Great Wicomico River, Chesapeake Bay: productivity, algal community structure, substrate and chemistry. Journal of Phycology, 49(3), 489-501. https://doi.org/10.1111/jpy.12056

Apatov, E., Fabling, R., Jaffe, A., Morris, M., & Thirkettle, M. (2015). Agricultural productivity in New Zealand: First estimates from the Longitudinal Business Database. Motu Economci and Public Policy Research.

Ataria, J., Mark-Shadbolt, M., Mead, A. T. P., Prime, K., Doherty, J., Waiwai, J., ... & Garner, G. O. (2018). Whakamanahia Te mātauranga o te Māori: empowering Māori knowledge to support Aotearoa's aquatic biological heritage. *New Zealand Journal of Marine and Freshwater Research*, *52*(4), 467-486. https://doi.org/10.1080/00288330.2018.1517097

Avery, A. A. (1999). Infantile methemoglobinemia: reexamining the role of drinking water nitrates. Environmental health perspectives, 107(7), 583-586.

Ayana, E. (2019). *Determinants of declining water quality*. World Bank.

Bajpai, P., & Bajpai, P. (2019). Characteristics of algae. *Third generation biofuels*, 11-15. https://doi/10.1007/978-981-13-2378-2_3

Ballantine, D. J., & Davies-Colley, R. J. (2014). Water quality trends in New Zealand rivers: 1989–2009 [journal article]. Environmental Monitoring and Assessment, 186(3), 1939-1950. https://doi.org/10.1007/s10661-013-3508-5

Beattie, H. (1920). *Nature-lore of the southern Maori*. New Zealand Institute.

Blersch, D., Kangas, P., & Mulbry, W. (2013). Turbulence and nutrient interactions that control benthic algal production in an engineered cultivation raceway. *Algal Research*, 2(2), 107-112. https://doi.org/https://doi.org/10.1016/j.algal.2013.01.001

Brown, C. O., Algera, P., Ball, R., Cameron, R., Horsfall, S., Konstantinou, E., ... & Stevenson, J. (2020). *Construction sector performance measurement: Learning lessons and finding opportunities*.

CASE STUDY New Zealand agriculture sector. BRANZ. https://www.resorgs.org.nz/2020/08/LR12087_NZ_Construction_Sector_Perf_Measurement_Case_Study_Agriculture_Sector.

Campbell, N., D'Arcy, B., Frost, A., Novotny, V., & Sansom, A. (Eds.). (2005). *Diffuse pollution*. IWA publishing.

Caradus, J. R., Goldson, S. L., Moot, D. J., Rowarth, J. S., & Stewart, A. V. (2023). Pastoral agriculture, a significant driver of New Zealand's economy, based on an introduced grassland ecology and technological advances. *Journal of the Royal Society of New Zealand*, *53*(3), 259-303. https://doi/10.1080/03036758.2021.2008985

Carpenter, R. C., Hackney, J. M., & Adey, W. H. (1991). Measurements of primary productivity and nitrogenase activity of coral reef algae in a chamber incorporating oscillatory flow. *Limnology and Oceanography*, *36*(1), 40-49. https://doi/abs/10.4319/lo.1991.36.1.0040

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological applications*, *8*(3), 559-568. https://doi.org/10.1890/1051-0761

Chapin III, F. S., Randerson, J. T., McGuire, A. D., Foley, J. A., & Field, C. B. (2008). Changing feedbacks in the climate–biosphere system. *Frontiers in Ecology and the Environment*, *6*(6), 313-320. https://doi/10.1890/080005

Chen, N., Li, J., Wu, Y., Kangas, P. C., Huang, B., Yu, C., & Chen, Z. (2015). Nutrient removal at a drinking water reservoir in China with an algal floway. *Ecological Engineering*, *84*, 506-514. https://doi.org/10.1016/j.ecoleng.2015.09.049

Chimney, M. J., Nungesser, M., Newman, J., Pietro, K., Germain, G., Lynch, T., ... & Moustafa, M. Z. (2000). *Stormwater Treatment Areas-status of research and monitoring to optimize effectiveness of nutrient removal and annual report on operational compliance.*

Christianson, L. E., Cooke, R. A., Hay, C. H., Helmers, M. J., Feyereisen, G. W., Ranaivoson, A. Z., ... & Ian, A. (2021). Effectiveness of denitrifying bioreactors on water pollutant reduction from agricultural areas. *Transactions of the ASABE*, *64*(2), 641-658.

Clapcott, J., Ataria, J., Hepburn, C., Hikuroa, D., Jackson, A. M., Kirikiri, R., & Williams, E. (2018). Mātauranga Māori: shaping marine and freshwater futures. *New Zealand Journal of Marine and Freshwater Research*, *52*(4), 457-466. https://doi.org/10.1080/00288330.2018.1539404

Cloy, J. M., Lilly, A., Hargreaves, P. R., Gagkas, Z., Dolan, S., Baggaley, N. J., ... & McKenzie, B. (2022). *A state of knowledge overview of identified pathways of diffuse pollutants to the water environment.* Centre of Expertise for Waters.

Collier-Robinson, L., Rayne, A., Rupene, M., Thoms, C., & Steeves, T. (2019). Embedding indigenous principles in genomic research of culturally significant species. *New Zealand Journal of Ecology*, *43*(3), 1-9. https://www.jstor.org/stable/26841832

Cominelli, E., Galbiati, M., Tonelli, C., & Bowler, C. (2009). Water: the invisible problem: access to fresh water is considered to be a universal and free human right, but dwindling resources and a burgeoning population are increasing its economic value. *EMBO reports*, *10*(7), 671-676. https://doi.org/10.1038/embor.2009.148

Craggs, Adey, Jessup, & Oswald. (1996a). A controlled stream mesocosm for tertiary treatment of sewage. Ecological Engineering, 6, 149-169.

Craggs, R., Adey, W., Jenson, K., St. John, M., Green, F. B., & Oswald, W. (1996b). Phosphorus removal from wastewater using an algal turf scrubber. *Water Science and Technology*, 33(7), 191-198. https://doi.org/10.1016/0273-1223(96)00354-X

Craggs, R. (2001). Wastewater treatment by algal turf scrubbing. Water Science and Technology, 44(11-12), 427-433.

Craggs, R.J., Park, J., Montemezzani, V., and Picken, C. (2022). Agricultural drainage treatment and nutrient recovery using Filamentous Algae Nutrient Scrubbers. *Nutrient Management in Farmed Landscapes.* Occasional Report No. 34.

Davies-Colley, R. (2009). Land use and water quality in New Zealand–an overview. Water (Basel), 162, 32-35.

Davies-Colley, R. J. (2013). River water quality in New Zealand: an introduction and overview. *Ecosystem services in New Zealand: conditions and trends. Manaaki Whenua Press, Lincoln*, 432-447.

De'ath, G., & Fabricius, K. (2010). Water quality as a regional driver of coral biodiversity and macroalgae on the Great Barrier Reef. *Ecological Applications*, *20*(3), 840-850. https://doi/10.1890/08-2023.1

Dessie, A., & Bredemeier, M. (2013). The effect of deforestation on water quality: A case study in Cienda micro watershed, Leyte, Philippines. *Resources and Environment*, *3*(1), 1-9.

Dinkins, K. C., Zivojnovich, M. J., & Stewart III, E. A. (2009). Review of large scale Algal Turf Scrubber® algae based water treatment systems and algal biomass production and use. *Proceedings of the Water Environment Federation*, *7*, 7972-7.

Duprey, N. N., Yasuhara, M., & Baker, D. M. (2016). Reefs of tomorrow: eutrophication reduces coral biodiversity in an urbanized seascape. *Global change biology*, *22*(11), 3550-3565. https://doi/10.1111/gcb.13432

Eivers, R. S., Duggan, I. C., Hamilton, D. P., & Quinn, J. M. (2018). Constructed treatment wetlands provide habitat for zooplankton communities in agricultural peat lake catchments. *Wetlands*, *38*, 95-108. https://doi/10.1007/s13157-017-0959-4

Environmental Protection Authority. (2016). *Application for approval to import or manufacture GF-2687 for release*. (Environmental Protection Authority application # APP202336).

Flemmer, C. (2012). Environmental input-output analysis of the New Zealand dairy industry. *International journal of sustainable development*, *15*(4), 313-333.

Flores-Morales, G., Díaz, M., Arancibia-Avila, P., Muñoz-Carrasco, M., Jara-Zapata, P., Toledo-Montiel, F., & Vega-Román, E. (2020). Removal of nutrients from Organic Liquid Agricultural Waste using filamentous algae. *Brazilian Journal of Biology*, *81*, 544-550.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., ... & Snyder, P. K. (2005). Global consequences of land use. *science*, *309*(5734), 570-574. https://doi/10.1126/science.1111772

Foote, K. J., Joy, M. K., & Death, R. G. (2015). New Zealand dairy farming: milking our environment for all its worth. *Environmental management*, *56*, 709-720. https://doi/10.1007/s00267-015-0517-x

Foy, R.H., Withers, P.J.A. (1995). The contribution of agricultural phosphorus to eutrophication. In: Proceedings 365. International Fertiliser Society, York, UK, 32 pp.

Forster, M. (2019). He tātai whenua: Environmental genealogies. *Genealogy*, *3*(3), 42. https://doi.org/10.3390/genealogy3030042

Gadd, J., Snelder, T., Fraser, C., & Whitehead, A. (2019). *Urban River and Stream Water Quality State and Trends, 2008-2017*. Ministry for the Environment.

Ge, S., Madill, M., & Champagne, P. (2018). Use of freshwater macroalgae Spirogyra sp. for the treatment of municipal wastewaters and biomass production for biofuel applications. *Biomass and bioenergy*, *111*, 213-223. https://doi.org/10.1016/j.biombioe.2017.03.014

Geider, R. (2013). Algal photosynthesis (Vol. 2). Springer Science & Business Media

Gonçalves, A. L., Pires, J. C., & Simões, M. (2017). A review on the use of microalgal consortia for wastewater treatment. *Algal Research*, *24*, 403-415. https://doi.org/10.1016/j.algal.2016.11.008

Grant, R., Laubel, A., Kronvang, B., Andersen, H. E., Svendsen, L. M., & Fuglsang, A. (1996). Loss of dissolved and particulate phosphorus from arable catchments by subsurface drainage. *Water Research*, *30*(11), 2633-2642. https://doi.org/10.1016/S0043-1354(96)00164-9

Haami, B., & Roberts, M. (2002). Genealogy as taxonomy. *International Social Science Journal*, *54*(173), 403-412.

Harding, J. S., Young, R. G., Hayes, J. W., Shearer, K. A., & Stark, J. D. (1999). Changes in agricultural intensity and river health along a river continuum. *Freshwater biology*, *42*(2), 345-357. https://doi.org/10.1046/j.1365-2427.1999.444470.x

Hariz, H. B., Lawton, R. J., & Craggs, R. J. (2022). Novel assay for attached Filamentous algae productivity and nutrient removal. *Journal of Applied Phycology*, *35*(1), 251-264. https://doi.org/10.1007/s10811-022-02857-1

Hariz, H. B., Lawton, R. J., & Craggs, R. J. (2023a). Effects of operational parameters on the performance of unialgal Oedogonium sp. filamentous algae nutrient scrubbers under controlled environmental conditions. *Journal of Environmental Management*, *326*, 116705. https://doi.org/10.1016/j.jenvman.2022.116705

Hariz, H. B., Lawton, R. J., & Craggs, R. J. (2023b). Nutrient uptake and biomass productivity performance comparison among freshwater filamentous algae species on mesocosm-scale FANS under ambient summer and winter conditions. *Ecological Engineering*, *189*, 106910. https://doi.org/10.1016/j.ecoleng.2023.106910

Hariz, H. B., Lawton, R. J., & Craggs, R. J. (2023c). Effects of seeding method and single versus mixed species assemblages on the performance of Filamentous Algae Nutrient Scrubbers (FANS) for the treatment of agricultural drainage. *Agricultural Water Management*, *280*, 108238. https://doi.org/10.1016/j.agwat.2023.108238

Harmsworth, G. R., & Awatere, S. (2013). Indigenous Māori knowledge and perspectives of ecosystems. *Ecosystem services in New Zealand—conditions and trends. Manaaki Whenua Press, Lincoln, New Zealand*, 274-286.

Harmsworth, G. R. (2021). *Te Ao Māori/mātauranga Māori to address regional council Research, Science and Technologies (RS&T) strategies and priorities*. Manaaki Whenua – Landcare Research. (Contract Report: LC4018)

Hikuroa, D. (2017). Mātauranga Māori—the ūkaipō of knowledge in New Zealand. *Journal of the Royal Society of New Zealand*, *47*(1), 5-10. https://doi.org/10.1080/03036758.2016.1252407

Holford, G. H. (1933, January). Grassland work overseas. In *Proceedings of the New Zealand Grassland Association* (pp. 1-4).

Howard-Williams, C., Davies-Colley, R., Rutherford, K., & Wilcock, R. (2010). Diffuse pollution and freshwater degradation: New Zealand perspectives. Issues and Solutions to Diffuse Pollution, OECD, Paris, 126-140.

Hudson, H. R., and J. S. Harding. (2004). *Drainage management in New Zealand. A review of existing activities and alternative management practices*. Department of Conservation.

Hudson, M., Whaanga, H., Waiti, J., Maxwell, H., Davis, K., Arahanga, T., Proctor, J., Sword, M., Ullrich, T., & Taitoko, M. (2020). Visualising Mātauranga Māori for iwi outcomes. *New Zealand Science Review*, *76*(1-2), 42-48.

Hydromentia, S. (2005). 154 Pilot Single Stage Algal Turf Scrubber (ATS) Final Report. South Florida Water Management District.

Jarvie, H. P., Withers, P. J. A., Bowes, M. J., Palmer-Felgate, E. J., Harper, D. M., Wasiak, K., ... & Armstrong, L. K. (2010). Streamwater phosphorus and nitrogen across a gradient in rural–agricultural land use intensity. *Agriculture, ecosystems & environment*, *135*(4), 238-252. https://doi.org/10.1016/j.agee.2009.10.002

Julian, J. P., De Beurs, K. M., Owsley, B., Davies-Colley, R. J., & Ausseil, A. G. E. (2017). River water quality changes in New Zealand over 26 years: response to land use intensity. *Hydrology and Earth System Sciences*, *21*(2), 1149-1171. https://doi.org/10.5194/hess-21-1149-2017

Kangas, P., Mulbry, W., Klavon, P., Laughinghouse, H. D., & Adey, W. (2017). High diversity within the periphyton community of an algal turf scrubber on the Susquehanna River. *Ecological Engineering*, *108*, 564-572.

Kawharu, M. (2000). Kaitiakitanga: a Maori anthropological perspective of the Maori socio-environmental ethic of resource management. *The Journal of the Polynesian Society*, *109*(4), 349-370. http://www.jstor.org/stable/20706951

Kebede-westhead, E., Pizarro, C., Mulbry, W. W., & Wilkie, A. C. (2003). Production and nutrient removal by periphyton grown under different loading rates of anaerobically digested flushed dairy manure 1. *Journal of Phycology*, *39*(6), 1275-1282. https://doi.org/https://doi.org/10.1111/j.0022-3646.2003.02-159.x

Kehoe, L., Kuemmerle, T., Meyer, C., Levers, C., Václavík, T., & Kreft, H. (2015). Global patterns of agricultural land-use intensity and vertebrate diversity. *Diversity and Distributions*, *21*(11), 1308-1318. https://doi/10.1111/ddi.12359

Khatri, N., & Tyagi, S. (2015). Influences of natural and anthropogenic factors on surface and groundwater quality in rural and urban areas. *Frontiers in life science*, *8*(1), 23-39. https://doi.org/10.1080/21553769.2014.933716

Kim, B.-H., Choi, J.-E., Cho, K., Kang, Z., Ramanan, R., Moon, D.-G., & Kim, H.-S. (2018). Influence of water depth on microalgal production, biomass harvest, and energy consumption in high rate algal pond using municipal wastewater. *Journal of Microbiolgy and Biotechnolgy,* 28(4), 630-637.

Kirk, J. T. (1994). *Light and photosynthesis in aquatic ecosystems*. Cambridge university press.

Lalonde, V., & Hughes-Games, G. A. (1997). *BC Agricultural Drainage Manual*. Ministry of Agriculture, Fisheries and Food.

Larned, S. T., Snelder, T., Unwin, M. J., & McBride, G. B. (2016). Water quality in New Zealand rivers: current state and trends. *New Zealand Journal of Marine and Freshwater Research*, *50*(3), 389-417. https://doi.org/10.1080/00288330.2016.1150309

Lawton, R., De Nys, R., & Paul, N. (2013a). Selecting reliable and robust freshwater macroalgae for biomass applications. *PLoS One*, 8(5), e64168. https://doi.org/10.1371/journal.pone.0064168

Lawton, R., de Nys, R., Skinner, S., & Paul, N. (2014). Isolation and Identification of Oedogonium Species and Strains for Biomass Applications. *PLoS One*, 9(3), e90223. https://doi.org/10.1371/journal.pone.0090223

Lawton, R., Cole, A. J., Roberts, D. A., Paul, N. A., & de Nys, R. (2017). The industrial ecology of freshwater macroalgae for biomass applications. *Algal Research*, 24, 486- 491. https://doi.org/10.1016/j.algal.2016.08.019

Leong, Y. K., Huang, C. Y., & Chang, J. S. (2021). Pollution prevention and waste phycoremediation by algal-based wastewater treatment technologies: The applications of high-rate algal ponds (HRAPs) and algal turf scrubber (ATS). *Journal of Environmental Management*, *296*, 113193. https://doi.org/10.1016/j.jenvman.2021.113193.

Liu, J., Danneels, B., Vanormelingen, P., & Vyverman, W. (2016a). Nutrient removal from horticultural wastewater by benthic filamentous algae Klebsormidium sp., Stigeoclonium spp. and their communities: From laboratory flask to outdoor Algal Turf Scrubber (ATS). Water Research, 92, 61-68. https://doi.org/https://doi.org/10.1016/j.watres.2016.01.049

Liu, J., Pemberton, B., Lewis, J., Scales, P. J., & Martin, G. J. O. (2020). Wastewater treatment using filamentous algae – A review. *Bioresource Technology,* 298, 122556. https://doi.org/https://doi.org/10.1016/j.biortech.2019.122556

Livestock Improvement Corporation/DairyNZ (LIC/DNZ). (2022). *New Zealand Dairy Statistics 2021-22*. Livestock Improvement Corporation Limited & DairyNZ Limited.

Lyver, P. O. B., Timoti, P., Jones, C. J., Richardson, S. J., Tahi, B. L., & Greenhalgh, S. (2017). An indigenous community-based monitoring system for assessing forest health in New Zealand. *Biodiversity and conservation*, *26*, 3183-3212. https://doi.org/10.1007/s10531-016-1142-6

Ma, W., Vatsa, P., & Bicknell, K. (2023). Transition to sustainable agriculture in New Zealand: challenges and the way forward. *New Zealand Economic Papers*, *57*(2), 119-124. https://doi.org/10.1080/00779954.2022.2144752

Mander, Ü., Kuusemets, V., Lõhmus, K., & Mauring, T. (1997). Efficiency and dimensioning of riparian buffer zones in agricultural catchments. *Ecological Engineering*, *8*(4), 299-324. https://doi.org/10.1016/S0925-8574(97)00025-6

Marsden, M. (1989) *The natural world and natural resources, Maori values systems and perspectives, Resource Management Law Reform*. Working Paper 29, Part A. Ministry for the Environment.

Matson, P. A., Parton, W. J., Power, A. G., & Swift, M. J. (1997). Agricultural intensification and ecosystem properties. *Science*, *277*(5325), 504-509. https://doi/10.1126/science.277.5325.504

McGrane, S. J. (2016). Impacts of urbanisation on hydrological and water quality dynamics, and urban water management: a review. *Hydrological Sciences Journal*, *61*(13), 2295-2311. https://doi.org/10.1080/02626667.2015.1128084

Mead, H. M. (2003). Tikanga Māori. *Living by Māori values*.

Mercier, O. R. (2018a). Mātauranga and science. New Zealand science review, 74, 83-90.

Mercier, O. R. (2018b). Mātauranga and science. *New Zealand science review*, *74*, 83-90.

Meyer, W. B., & BL Turner, I. I. (Eds.). (1994). *Changes in land use and land cover: a global perspective* (Vol. 4). Cambridge University Press.

Michel, P., Dobson-Waitere, A., Hohaia, H., McEwan, A., & Shanahan, D. F. (2019). The reconnection between mana whenua and urban freshwaters to restore the mouri/life force of the Kaiwharawhara. *New Zealand Journal of Ecology*, *43*(3), 1-10. https://www.jstor.org/stable/26841833

Ministry of Business, Innovation and Employment. (n.d.). *Primary industries*. https://www.mbie.govt.nz/business-and-employment/employment-and-skills/regional-skills-leadership-groups/waikato/regional-workforce-plans/regional-workforce-plan/priority-sectors-from-farm-to-port/primary-industries

Ministry for the Environment. (2019). *Nitrate leaching from livestock time series 1990–2017*. https://data.mfe.govt.nz/table/99876-nitrate-leaching-from-livestock-time-series-19902017/

Ministry for the Environment. (2001). *Managing waterways on farms: a guide to sustainable water and riparian management in rural New Zealand*. (ME number 385).

Ministry for Primary Industries. (2021). *Situation and outlook for primary industries*. https://www.mpi.govt.nz/dmsdocument/45451-Situation-and-Outlook-for-Primary-Industries-SOPI-June-2021

Mulbry, W., & Wilkie, A. C. (2001). Growth of benthic freshwater algae on dairy manures. *Journal of Applied Phycology*, 13(4), 301-306.

Mulbry, W., Kondrad, S., Pizarro, C., & Kebede-Westhead, E. (2008b). Treatment of dairy manure effluent using freshwater algae: algal productivity and recovery of manure nutrients using pilot-scale algal turf scrubbers. Bioresource Technology, 99(17), 8137- 8142. https://doi.org/10.1016/j.biortech.2008.03.073

Mulbry, W., Westhead, E. K., Pizarro, C., & Sikora, L. (2005). Recycling of manure nutrients: use of algal biomass from dairy manure treatment as a slow release fertilizer. *Bioresource technology*, *96*(4), 451-458. https://doi.org/10.1016/j.biortech.2004.05.026

Muñoz, R., Temmink, H., Verschoor, A. M., & Van Der Steen, P. (2018). Algal technologies for wastewater treatment and resource recovery. Water Science and Technology, 78(1), 1-2.

Ngata, T., Kim, N., Hammond, V., Dewes, A., Tapsell, P., Fraser, P., ... & Perley, C. (2018). *Mountains to sea: Solving New Zealand's freshwater crisis* (Vol. 71). Bridget Williams Books.

Nguyen, L., & Sukias, J. (2002). Phosphorus fractions and retention in drainage ditch sediments receiving surface runoff and subsurface drainage from agricultural catchments in the North Island, New Zealand. *Agriculture, ecosystems & environment*, *92*(1), 49-69. https://doi.org/10.1016/S0167-8809(01)00284-5

Nguyen, L.N., Aditya, L., Vu, H.P., Johir, A.H., Bennar, L., Ralph, P., Hoang, N.B., Zdarta, J., Nghiem, L.D. (2022). Nutrient removal by algae-based wastewater treatment. *Current Pollution Reports*, *8*(4), 369-383. https://doi.org/10.1007/s40726-022-00230-x

OECD (2019), *OECD Economic Surveys: New Zealand 2019*. OECD Publishing Paris. https://doi.org/10.1787/b0b94dbd-en

Oswald, W. J., & Golueke, C. G. (1960). Biological transformation of solar energy. In *Advances in applied microbiology* (Vol. 2, pp. 223-262). https://doi.org/10.1016/S0065-2164(08)70127-8

Packer, M. (2009). Algal capture of carbon dioxide; biomass generation as a tool for greenhouse gas mitigation with reference to New Zealand energy strategy and policy. *Energy policy*, *37*(9), 3428-3437. https://doi.org/10.1016/j.enpol.2008.12.025

Park, J. B., Montemezzani, V., Picken, C., Rendle, D., & Craggs, R. J. (2022). Effect of algal contact time and horizontal water velocity on the performance of Filamentous Algal Nutrient Scrubbers (FANS). *Journal of Environmental Management*, *312*, 114882. https://doi.org/10.1016/j.jenvman.2022.114882

Plew, D. R., Zeldis, J. R., Dudley, B. D., Whitehead, A. L., Stevens, L. M., Robertson, B. M., & Robertson, B. P. (2020). Assessing the eutrophic susceptibility of New Zealand estuaries. *Estuaries and Coasts*, *43*, 2015-2033. https://doi.org/10.1007/s12237-020-00729-w

Powell, N., Shilton, A., Chisti, Y., & Pratt, S. (2009). Towards a luxury uptake process via microalgae – Defining the polyphosphate dynamics. *Water Research*, 43(17), 4207- 4213. https://doi.org/https://doi.org/10.1016/j.watres.2009.06.011

Rajanayaka, C., Weir, J., Barkle, G., Griffiths, G., & Hadfield, J. (2020). Assessing changes in nitrogen contamination in groundwater using water aging: Waikato River, New Zealand. *Journal of Contaminant Hydrology*, *234*, 103686. https://doi.org/10.1016/j.jconhyd.2020.103686

Ramankutty, N., Evan, A. T., Monfreda, C., & Foley, J. A. (2008). Farming the planet: 1. Geographic distribution of global agricultural lands in the year 2000. *Global biogeochemical cycles*, *22*(1). https://doi/10.1029/2007GB002952

Rapport, D. J., Costanza, R., & McMichael, A. J. (1998). Assessing ecosystem health. *Trends in ecology & evolution*, *13*(10), 397-402.

Ray, N. E., Terlizzi, D. E., & Kangas, P. C. (2015). Nitrogen and phosphorus removal by the Algal Turf Scrubber at an oyster aquaculture facility. *Ecological Engineering*, *78*, 27-32. https://doi.org/10.1016/j.ecoleng.2014.04.028

Richards, J., Chambers, T., Hales, S., Joy, M., Radu, T., Woodward, A., ... & Baker, M. G. (2022). Nitrate contamination in drinking water and colorectal cancer: Exposure assessment and estimated health burden in New Zealand. *Environmental Research*, *204*, 112322. https://doi.org/10.1016/j.envres.2021.112322

Roberts, M., Norman, W., Minhinnick, N., Wihongi, D., & Kirkwood, C. (1995). Kaitiakitanga: Maori perspectives on conservation. *Pacific Conservation Biology*, *2*(1), 7-20.

Royal, C. (2009). Te Kaimānga: Towards a new vision for mātauranga Māori. *Te Ahukaramū. Charles Royal*.

Salvucci, M. E., & Crafts-Brandner, S. J. (2004). Mechanism for deactivation of Rubisco under moderate heat stress. *Physiologia Plantarum*, *122*(4), 513-519. https://doi.org/10.1111/j.1399-3054.2004.00419.x

Sandefur, H. N., Johnston, R. Z., Matlock, M. D., Costello, T. A., Adey, W. H., & Laughinghouse IV, H. D. (2014). Hydrodynamic regime considerations for the cultivation of periphytic biofilms in two tertiary wastewater treatment systems. *Ecological engineering*, *71*, 527-532. https://doi.org/10.1016/j.ecoleng.2014.07.070

Shortle, J. S., Abler, D. G., & Ribaudo, M. A. R. K. (2001). Agriculture and water quality: the issues. *Environmental policies for agricultural pollution control* (pp. 1-18). Wallingford UK: CABI Publishing.

Sindelar, H. R., Yap, J. N., Boyer, T. H., & Brown, M. T. (2015). Algae scrubbers for phosphorus removal in impaired waters. *Ecological Engineering*, *85*, 144-158. https://doi.org/10.1016/j.ecoleng.2015.09.002

Siville, B., & Boeing, W. J. (2020). Optimization of algal turf scrubber (ATS) technology through targeted harvest rate. *Bioresource Technology Reports*, *9*, 100360. https://doi.org/10.1016/j.biteb.2019.100360

Smith, V. H. (2003). Eutrophication of freshwater and coastal marine ecosystems a global problem. *Environmental Science and Pollution Research*, *10*, 126-139. http://dx.doi.org~10.1065/esor2002.12.142

Smith, V. H., Joye, S. B., & Howarth, R. W. (2006). Eutrophication of freshwater and marine ecosystems. *Limnology and oceanography*, *51*(1part2), 351-355. https://doi/10.4319/lo.2006.51.1_part_2.0351

Stewart-Harawira, M. W. (2020). Troubled waters: Maori values and ethics for freshwater management and New Zealand's fresh water crisis. *Wiley Interdisciplinary Reviews: Water*, *7*(5), e1464. https://doi.org/10.1002/wat2.1464

Sutherland, D., & Craggs, R. (2017). Utilising periphytic algae as nutrient removal systems for the treatment of diffuse nutrient pollution in waterways. Algal Research, 25, 496- 506. https://doi.org/10.1016/j.algal.2017.05.023

Sutherland, D. L., Howard-Williams, C., Turnbull, M. H., Broady, P. A., & Craggs, R. J. (2015a). Enhancing microalgal photosynthesis and productivity in wastewater treatment high rate algal ponds for biofuel production. *Bioresource technology*, *184*, 222-229. https://doi.org/10.1016/j.biortech.2014.10.074

Sutherland, D. L., Burke, J., & Ralph, P. J. (2020a). Flow-way water depth affects algal productivity and nutrient uptake in a filamentous algae nutrient scrubber. *Journal of Applied Phycology 32*(6), 4321-4332. https://doi.org/10.1007/s10811-020-02275-1

Sutherland, D. L., Burke, J., & Ralph, P. J. (2020b). Increased harvest frequency improves biomass yields and nutrient removal on a filamentous algae nutrient scrubber. *Algal Research*, *51*, 102073. https://doi.org/https://doi.org/10.1016/j.algal.2020.102073

Tanner, C. C., Nguyen, M. L., & Sukias, J. P. S. (2005). Nutrient removal by a constructed wetland treating subsurface drainage from grazed dairy pasture. *Agriculture, ecosystems & environment*, *105*(1-2), 145-162. https://doi.org/10.1016/j.agee.2004.05.008

Tsiafouli, M. A., Thébault, E., Sgardelis, S. P., De Ruiter, P. C., Van Der Putten, W. H., Birkhofer, K., ... & Hedlund, K. (2015). Intensive agriculture reduces soil biodiversity across Europe. *Global change biology*, *21*(2), 973-985. https://doi/10.1111/gcb.12752

Vymazal, J., & Kröpfelová, L. (2009). Removal of nitrogen in constructed wetlands with horizontal sub-sureface flow: a review. Wetlands, 29(4), 1114-1124.

Ward, F. A., & Michelsen, A. (2002). The economic value of water in agriculture: concepts and policy applications. *Water policy*, *4*(5), 423-446. https://doi.org/10.1016/S13667017(02)00039-9

Wolfe, A. H., & Patz, J. A. (2002). Reactive nitrogen and human health: acute and long-term implications. *Ambio: A journal of the human environment*, *31*(2), 120-125.

Yamori, W., Hikosaka, K., & Way, D. A. (2014). Temperature response of photosynthesis in C3, C4, and CAM plants: temperature acclimation and temperature adaptation. *Photosynthesis research*, 119(1), 101-117. https://doi.org/10.1007/s11120-013-9874-6

Young, R., Strickland, R., Harding, J., Stark, J., & Hayes, J. (2000). *The ecology of Spring Creek* (Vol. 611, p. 37). Cawthron Report No. 611.