The potential use of sphagnum moss to improve river health and as an economically and ecologically sustainable crop.

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The potential use of *Sphagnum* moss to improve river health and as an economically and ecologically sustainable crop. Envirolink 1880-WCRC173, 1929-WCRC176.

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Project and Client

- The West Coast Regional Council requested advice from Manaaki Whenua – Landcare Research on the potential use of Sphagnum moss to improve river health and as an economically and ecologically sustainable crop through Envirolink.

Objectives

- Undertake a literature review on *Sphagnum* moss growth on the West Coast, as well as any research that may contribute to knowledge about this kaupapa. Also, to conduct a review of the West Coast species and the economics of these in the global markets. Further, to research the optimal growth conditions for *Sphagnum*, including tolerance to nitrogen/dairy run-off and the transfer of optimal conditions to a farm context.

Summary and Conclusions

- The West Coast of the South Island of New Zealand is home to five species of *Sphagnum*, from which *Sphagnum cristatum* is commonly harvested commercially. *S. cristatum* may be more adaptive in response to climatic variability and increasing fertility. Information on growth rates of *Sphagnum* are limited in New Zealand and range between 0.4 and 1.3 kg dry weight/m^2/year.
- Although *Sphagnum* is considered to be adapted to low nutrient environments, research into the growth response of *Sphagnum* to nutrient additions has not been published for New Zealand species. However, international studies have shown a considerable range in growth responses of *Sphagnum* to a variety of fertiliser inputs that exhibited species and site specificity. *Sphagnum* may have a positive response to nitrogen additions up to an input rate of 20 kg N/ha/yr and is capable of assimilating up to 12 kg N/ha/yr; over this threshold, nitrogen uptake decreases. A threshold has not been established for other nutrients. However, the balance between nitrogen, phosphorus, potassium, and carbon availability is also critical for *Sphagnum* growth. The balance of these parameters has not been established for New Zealand *Sphagnum*.
- *Sphagnum* growth is affected by other factors besides nutrient availability, including shade and plant competition. Canopy cover is required for maximal *Sphagnum* growth, and shading of 20% is suggested as ideal. However, a balance between shade provision by vascular plants and competition for nutrients and light is required, particularly under scenarios with increased nutrient inputs as vascular plants may dominate *Sphagnum*, resulting in lower *Sphagnum* production.
- Depth to the water table and temperature also affect *Sphagnum* growth. Maximal quality of *Sphagnum* is suggested to occur when the water table is about 15 cm from the surface and warmer temperatures will likely improve *Sphagnum* growth but this requires further investigation.

- *Sphagnum* paludiculture is being developed overseas as a mechanism for the sustainable production of peat. However, the same techniques for establishing *Sphagnum* farming would likely also work for *Sphagnum* harvesting rather than peat production. Production of *Sphagnum* in artificially constructed *Sphagnum* farms averaged 3.7 t/ha/yr over 5 years.
- *Sphagnum* farming has also been explored using floating wetlands; however, production of *Sphagnum* using this technique was more expensive than terrestrial *Sphagnum* farming and may not be appropriate within the majority of farming systems as it requires a large water body.
- The West Coast Region is already a commercial *Sphagnum* production hub and supplies several international markets with an annual value of ~$4.5 million (NZD). The main importer of New Zealand *Sphagnum* is the orchid growing industry in Japan. There is international competition from several countries, particularly Chile, and this could potentially increase under the future scenario of increased production costs due to increased regulatory pressure on *Sphagnum* harvesting.
- Within the context of riparian zones in intensively grazed systems, *Sphagnum* farming shows potential to generate alternative profit and reduce the impacts of run-off on waterways. *Sphagnum* requires total stock exclusion due to the highly negative effects of trampling, grazing, excretory inputs, and compaction. The limited information on the nutrient profile of run-off suggests this will be within the capability of *Sphagnum* assimilation; however, any potential sites for *Sphagnum* farming would require investigation of the nutrient profile of the run-off. *Sphagnum* farming on riparian zones would also need to include provision of shade and protection from flooding. These two factors could perhaps be provided by including the planting of a hedgerow of vascular plants (e.g. mānuka or sedges) that might provide both shading and flood protection.
- Knowledge gaps
    - Growth response and tolerance of New Zealand *Sphagnum* to nutrient inputs and changes in pH and the effect of peat versus pakihi as growth substrate.
    - Relationship between New Zealand *Sphagnum* species and cyanobacteria, as this will impact nitrogen tolerance and utilisation
    - Pathogen susceptibility of New Zealand *Sphagnum*
    - Nutrient leaching rates and pathogen holding/release capacity of *Sphagnum*, as this will impact the use of *Sphagnum* as a water filter
    - *Sphagnum* physiological changes in response to farming strategy (i.e. nutrient and shading loadings, weed competition) that may affect product quality
- Recommendations: *Sphagnum* farming may be a potential land use for riparian zones implemented within intensive grazing systems if certain factors are provided for, including lower nutrient inputs, flood protection, shading, and a shallow water table. However, the growth and tolerance response of *Sphagnum* to common agriculturally derived nutrients is required for New Zealand species used for commercial production.

1 Introduction

Sphagnum moss has the ability to hold substantial amounts of water within and on its structure (Denne 1983; Johnson 1988) and has shown to be of considerable value in horticultural, reptile breeding, and water filtration industries (Denne 1983; Pouliot et al. 2015; Josh's Frogs 2016; Wichmann et al. 2017; Gibson 2018; Horizon Pool Supply 2018).

The West Coast region of the South Island of New Zealand has an active *Sphagnum* industry that peaked in the mid-1990s in response to increased demand from Japan (Denne 1983); however, the industry has been declining since the mid-2000s (Plant and Food Research 2016). In 2016, the export earnings for *Sphagnum* were still in the range of $5.1 million annually (Plant and Food Research 2016), with the majority of *Sphagnum* harvesting occurring on government-owned land (Whinam et al. 2003). There has been some pressure on the *Sphagnum* industry on West Coast as some government agencies seek to reduce or eliminate harvesting of natural *Sphagnum* sites on both privately and publicly owned land. There is also increasing concern about water contamination by intensive grazing land uses and how proposed changes to legislation will affect management practices in these land uses.

Paludiculture[1] of *Sphagnum* may offer a solution whereby riparian zones are retired for *Sphagnum* farming with the potential to decrease nutrients entering water ways, enhance biodiversity, maintain *Sphagnum* available for harvesting, and act as a potential second revenue for landowners in the grazing industry. While *Sphagnum* typically occurs in low nutrient environments, it has been shown to be adaptive to nutrient inputs up to a threshold and there are a number of overseas studies on the impact of elevated nutrients on *Sphagnum.* There are also large-scale, recently established, international paludiculture trials to assess the viability of *Sphagnum* farming and the practical steps to undertake this land use change and the economics associated with it.

2 Objectives

The objectives of this Envirolink project were to:

- undertake a literature review on *Sphagnum* moss growth on the West Coast, as well as any research that might contribute to knowledge about this kaupapa
- review West Coast species and the economics of these in the global markets
- research the optimal growth conditions for *Sphagnum*, including tolerance to nitrogen/dairy run-off and the transfer of optimal conditions to a farm context.

[1] Where paludiculture is defined as the practice of crop production on wet soils.

3 Sphagnum growth

Five species of sphagnum are present in the West Coast region of the South Island, New Zealand, including, *Sphagnum cristatum, S. australe, S. falcatulum, S. subnitens,* and *S. subsecundum,* none of which are endemic (Denne 1983). The species most commonly used for commercial production is *S. cristatum* (Denne 1983; Johnson 1988; Stokes et al. 1999). The extent of *S. subnitens* is such that it is now considered a weed in some wetland systems on the West Coast (Fife 2018), and its abundance can increase in harvested sites when *S. cristatum* is preferentially harvested (Stokes et al. 1999; Buxton 2017).

Different *Sphagnum* species have slightly different niche requirements: for example, compared with other species, *S. cristatum* tolerates drier conditions with higher fertility and may be more tolerant of changes in environmental conditions (Mark et al. 1979; Johnson 1988). It also has greater capacity for water storage and forms extensive carpets (Johnson 1988). *S. subnitens* also has a higher tolerance to dry conditions, but *S. falcatulum* requires permanent immersion in water, *S. australe* occurs in forests, and *S. subsecundum* prefers saturated areas with higher fertility, including running water (Denne 1983).

Limited data are available on the growth rates of *Sphagnum* on sites that have not been previously harvested. Denne (1983), using pigment innate time markers that were assumed to occur annually, estimated an annual growth rate of 76.5 mm/yr (to 0.7–0.8 kg/m^2/yr dry weight) for *S. cristatum* growing in the Kakapotahi area.

Buxton et al. (1990) determined the effects of site moisture contents and the presence of other vegetation on growth rates of *Sphagnum* that had not previously been harvested at Kawhaka. They found that a wet site with other vegetation had a growth rate of 25.5 (±19.5) mm/yr, and wet sites without other vegetation had a growth rate of 15.7 (±9.8) mm/yr. For drier sites, growth rates of *Sphagnum* with other vegetation was 15.0 (±11.2) and without other vegetation was 6.9 (±16.1) mm/yr. Thus, *Sphagnum* growth exhibited large variability within and between sites as affected by environmental conditions. Further, Buxton et al. (1996) determined *Sphagnum* growth on a previously non-harvested site to be 10.3 mm/yr at Pell Stream, near Springs Junction. They also measured *Sphagnum* growth over time regarding other dominant vegetation (Fig. 1) and showed *Sphagnum* growth is greater in autumn and spring and slower in summer, presumably in response to less precipitation. Of particular importance is the effect of different types of vegetation on *Sphagnum* growth, which at Hokitika was considerably lower in the open than when protected by other species.

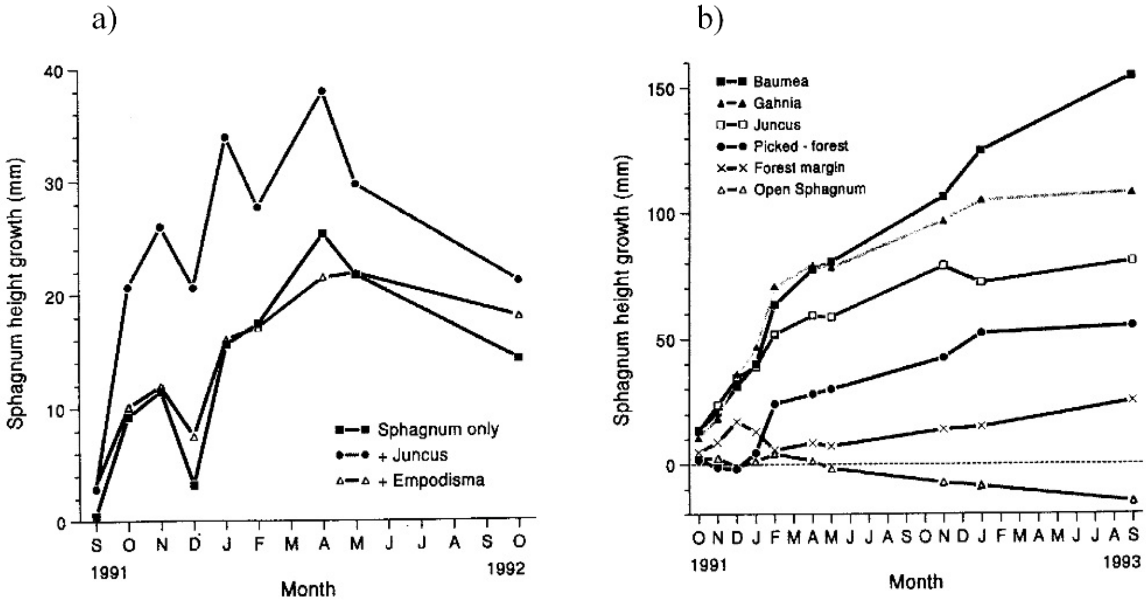

Figure 1 ***Sphagnum*** **growth at a) Maruia and b) Hokitika in relation to other vegetation (Buxton et al. 1996).**

It has been suggested that *Sphagnum* yields in New Zealand are in the range of 0.4–0.5 kg/m^2/yr under optimal conditions, but may be as low as 0.1 kg/m^2/yr in unmanaged natural systems (Thompson & Denne 1983 in Stokes et al. (1999)). However, Stokes et al. (1999) suggest that with appropriate management the yield of *S. cristatum* may be as high as 1.3 kg/m^2/yr.

On the West Coast of New Zealand, *Sphagnum* occurs on both peat and pakihi podzol soils; however, the definition of pakihi is ambiguous and may include as many as 22 soil series (Mew 1983). No distinction has been made in the published data as to the soil from which these *Sphagnum* growth measurements have been taken and it is not known if *Sphagnum* growth rates differ between peat and pakihi podzols.

3.1 *Sphagnum* regrowth after harvest

Management of harvesting practices can greatly affect *Sphagnum* regrowth (Buxton et al. 1990, 1996). Buxton et al. (1996) assessed the impacts of heavy versus moderate harvest, with and without reseeding (where reseeding is leaving a uniform layer of growing moss after harvest), on *Sphagnum* regrowth at Pell Stream and Ianthe forest. They found that regrowth rates were greater at plots with heavy harvesting with reseeding (Fig. 2). Under these experimental conditions, *Sphagnum* recovery was approximately 95% of the canopy cover of pre-harvest biomass at Pell Stream; however, harvesting without reseeding showed a significant reduction in *Sphagnum* regrowth. With respect to bulk density of *Sphagnum*, reseeding generally increases the bulk density of the *Sphagnum* and can greatly decrease the time between harvests. Buxton et al. (1996) estimate a recovery time of 9–11 years for the sites they studied, but this could possibly be as low as 2–3 years. Denne (1983) also estimated regrowth rates for sphagnum moss of between 1.6 to 12.7 years, reflecting an innate site specificity of *Sphagnum* regrowth.

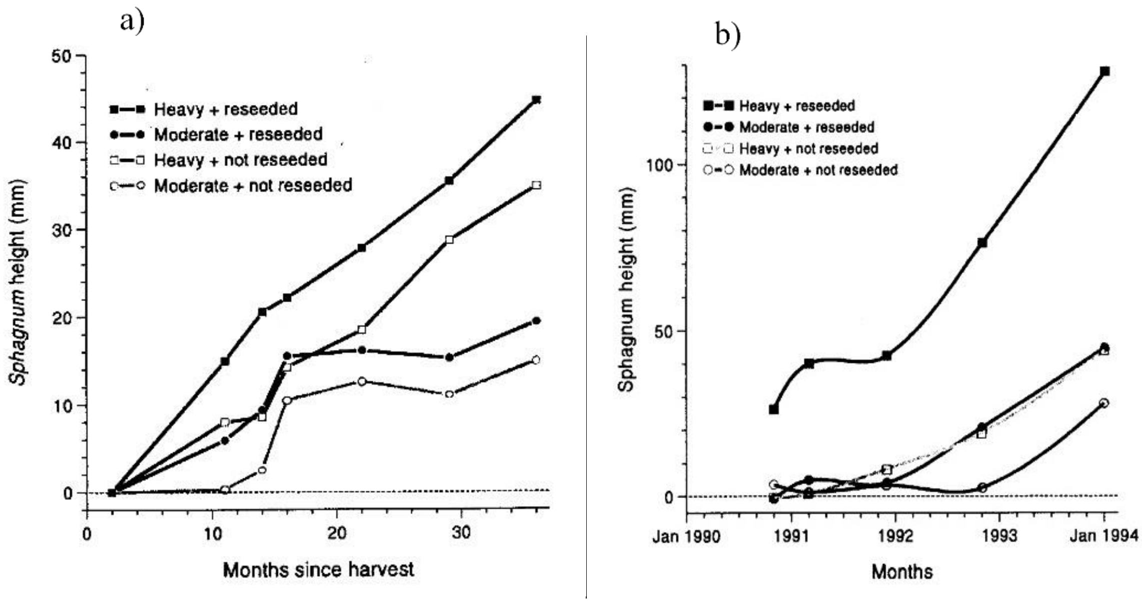

Figure 2 *Sphagnum* height growth after heavy or moderate harvesting, and with or without reseeding, at a) Pell Stream and b) Ianthe Forest (Buxton et al. 1996).

Whinam and Buxton (1997) suggest several important factors will enhance the sustainability of *Sphagnum* harvesting, including:

- Site is at an altitude less than 600 m
- 20% shade provided by other species of plants
- Site is large enough to allow harvest rotation
- Is harvested while avoiding heavy machinery that cause rutting (drainage)
- Site is left with an even surface to allow close contact between *Sphagnum* and the water table
- Adequate time is left between harvests to allow for complete recovery
- 30% of moss left for reseeding.

Harvesting of *Sphagnum* is still undertaken using manual labour; however, the method of transporting the baled *Sphagnum* from the harvesting site has been improved over time. Technological advancements within the *Sphagnum* industry have led to harvesting equipment that has less pressure impact per meter squared than manual collection (Buxton 2017). Buxton (2017) concluded that crushing of vascular plants and reseeding of *Sphagnum* with heavy machinery during harvest greatly improved regrowth compared with more traditional practices.

3.2 Factors affecting *Sphagnum* growth

3.2.1 Nutrients

Sphagnum has adapted to low nutrient environments, and accumulates nitrogen (N), calcium, magnesium, potassium (K), phosphorus (P), and sodium from rain water and soil pore water to enable growth (Denne 1983). The accumulation of cations also leads to a reduction in the pH immediately around the *Sphagnum* that can affect the growth of competing species (Vitt et al. 1975). *Sphagnum* accumulates these elements to differing extents as shown in the following order: K>P>N>magnesium, calcium (Pakarinen 1978). *Sphagnum* bog systems traditionally contain low concentrations of N due to low rates of mineralisation of plant material under the predominantly anaerobic conditions (Bayley et al. 2005). Therefore, *Sphagnum* plays an important role in N cycling by taking up N until it becomes N saturated, thus reducing the amount of ammonium available for competing plants (Bobbink et al. 2011).

Sphagnum can absorb N as water-borne nitrate, ammonium or amino acids, from rainfall and soil pore water (Pakarinen 1978). Uptake of ammonium occurs faster than nitrate (Fritz et al. 2014), and ammonium is the predominant form of N taken up by *Sphagnum*; with only very small amounts of nitrate being assimilated (Wiedermann et al. 2009a). As ammonium can be toxic to plants at high concentrations (Britto et al. 2001), *Sphagnum* incorporates N into amino acids (Kahl et al. 1997; Limpens & Berendse 2003) and changes in amino acid concentrations in response to N additions can be used to determine the physiological response of *Sphagnum*. Ammonium is converted to glutamine in *Sphagnum* (as in vascular plants) and is then converted to asparagine in stem material or arginine in the capitulum (Limpens & Berendse 2003). Nordin and Gunnarsson (2000) found that once concentrations of amino acids exceeded 2.0 mg amino acid N/g dry weight of *Sphagnum*, the growth declines. Limpens and Berendse (2003) suggest that the ability of *Sphagnum* to metabolise N is not as fast as its ability to take N from solution and therefore ammonium toxicity builds up, eventually decreasing growth. While *Sphagnum* can take up large amounts of N, equivalent to N application of 12 kg N/ha/yr, rates greater than this lead to a decrease in N uptake.

Because of the rain-fed nature of most of the wetland systems studied overseas, atmospheric deposition of N played an important role in supplying N to these systems. For example, Nordin and Gunnarsson (2000) reported atmospheric N loadings ranging from 0.3 to 1.1 g N/m^2/yr. In New Zealand, Parfitt et al. (2012) estimated N deposition on the West Coast to be 0.6 g N/m^2/yr. Therefore, atmospheric N deposition on the West Coast is within range of international studies and may be a factor in nutrient supply to *Sphagnum*.

Some *Sphagnum* species maintain a symbiotic relationship with cyanobacteria, which can fix atmospheric N and improve *Sphagnum* growth (Berg et al. 2013), and the growth response differs between species (Leppänen et al. 2015). Kostka et al. (2016) suggest that N fixing symbionts may supply as much as 20–30% of *Sphagnum* N. No evidence could be found assessing the presence or absence of cyanobacteria in *Sphagnum* present on the West Coast of New Zealand and, as N-fixation decreases with fertiliser N additions (e.g. Kox et al. 2016), this may affect N utilisation by *Sphagnum.* Further research in this area is required.

While it has been suggested that *Sphagnum* growth is N limited (Sonesson et al. 1980; Bragazza et al. 2004), the growth response of *Sphagnum* to N addition varies widely across species and sites. For example, several authors have reported that *Sphagnum* was N limited where N inputs were very low and was P limited where N inputs were high (e.g. (Aerts et al. 1992; Limpens et al. 2004; Lund et al. 2009). However, other authors have found either no growth response or depressed growth of *Sphagnum* under high N loadings (Aerts et al. 2001; Bobbink et al. 2011; Limpens et al. 2011; van den Elzen et al. 2017) or low N inputs (Gunnarsson & Rydin 2000). Heijmans et al. (2001) also found no change in overall *Sphagnum* biomass in response to N additions, but did report a change in morphology whereby there was an increasing number of capitula but of decreased size. Sustained improvements in growth from nutrient additions has not been proved for *Sphagnum*, whereby the growth response to N additions can be short lived. Gunnarsson and Rydin (2000) found elevated growth lasted for the first growth season and was less than the control after that. Limpens and Heijmans (2008) also found that while *Sphagnum* N concentrations returned to control levels 15 months after N and P additions ceased, P concentrations remained elevated.

N additions have also been shown to decrease the photosynthetic capacity of *Sphagnum*, and once *Sphagnum* tissue concentrations exceed about 13 mg N/g photosynthesis decreases (Granath et al. 2009). However, N additions may alter the species composition of *Sphagnum* as the growth response of *Sphagnum* can differ between species and may be related to the water table depth and nutrient tolerance in their preferential growth habitat (Granath et al. 2009).

Bragazza et al. (2004) suggest that the critical N threshold for *Sphagnum* growth is 1 g N/m^2/yr (10 kg/ha/yr), above which N:P and N:K ratios are close to saturation. However, the work of Nordin and Gunnarsson (2000) reported that 1 g N/m^2/yr was too high for the bog system. Bobbink et al. (2011) suggest that N thresholds are dependent on the type of wetland system (Fig. 3) and ranges between 0.5 and 3.0 g N/m^2/yr (5-30 kg N/ha/yr). Lamers et al. (2000) suggested that *Sphagnum* acts as N filter and that above 2 g N/m^2/yr (20 kg N/ha/yr) *Sphagnum* is less able to facilitate N removal due to N saturation.

Ecosystem type	EUNIS code	kg N ha^{-1} yr^{-1}	Reliability	Indication of exceedance
Raised and blanket bogs	D1[a]	5-10	##	Increase in vascular plants, altered growth and species composition of bryophytes, increased N in peat and peat water
Valley mires, poor fens and transition mires	D2[b]	**10-15**	#	Increase in sedges and vascular plants, negative effects on bryophytes
Rich fens	D4.1[c]	**15-30**	(#)	Increase in tall graminoids, decrease in bryophytes
Montane rich fens	D4.2[c]	15-25	(#)	Increase in vascular plants, decrease in bryophytes

a) The high end of the range applies to areas with high precipitation and the low end of the range to that with low precipitation; the low end of the range applies to systems with a low water table, and the high end of the range to those with a high water table. Note that water tables can be modified through management.
b) For D2.1 (valley mires), the lower end of the range applies (#).
c) For high latitude systems, the lower end of the range applies.

Figure 3 Critical loads of N in mires, bogs and fen habitats and indication of exceedance. ## reliable, # quite reliable and (#) expert judgement (Bobbink et al. 2011).

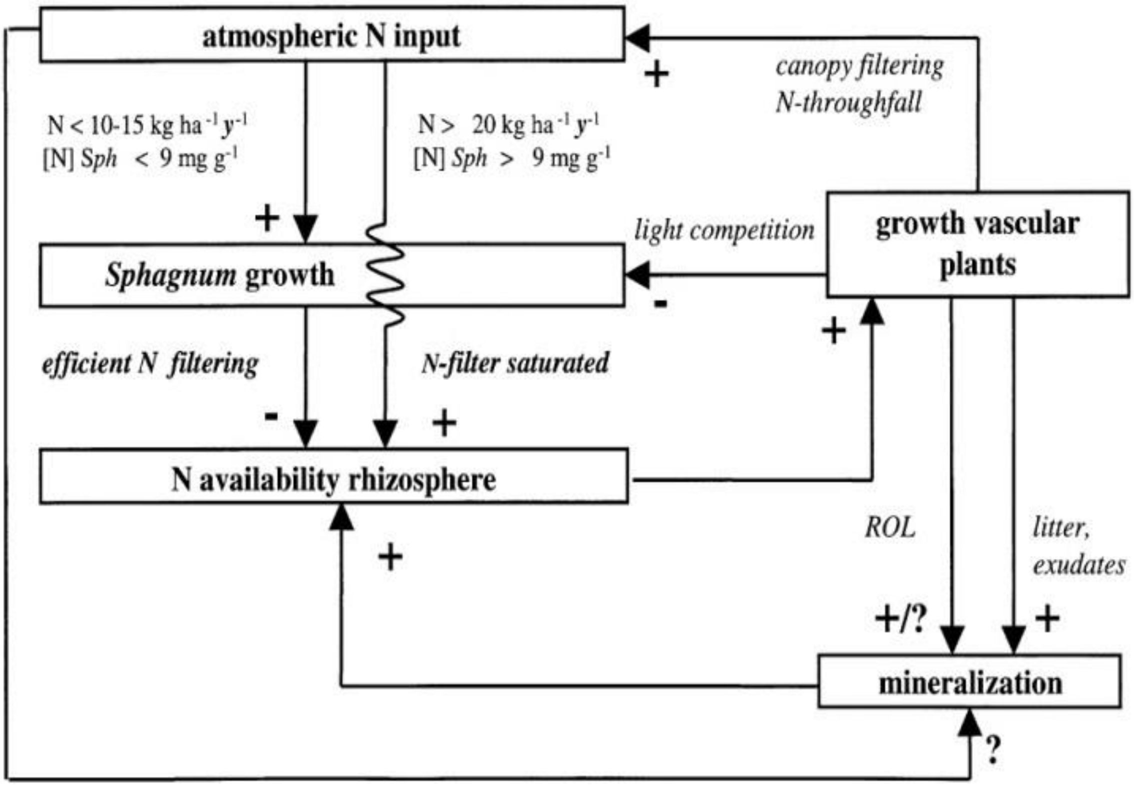

Figure 4 Possible feedbacks with different nitrogen loadings in *Sphagnum* rhizosphere (Lamers et al. 2000). [N] *Sph* = N concentration in *Sphagnum* and ROL = radial oxygen loss by roots.

Increasing N additions can increase the susceptibility of *Sphagnum* to pathogens; for example, Limpens et al. (2003) reported increasing *Sphagnum* necrosis by the fungal parasite *Lyophyllum palustre* with increasing rate of N addition (0, 40 or 80 kg N/ha/yr). They also found that the necrosis was mitigated by the addition of P. While compounds contained in *Sphagnum* leaves have anti-bacterial properties, effective anti-bacterial processes were only observed in concentrations much greater than that found naturally in *Sphagnum* leaves (Mellegård et al. 2009). This there may be an inherent pathogen risk associated with increased *Sphagnum* N contents; however, no literature could be located that assessed pathogenic risk for New Zealand *Sphagnum*.

Temmink et al. (2017), testing whether additions of P and K as well as N altered *Sphagnum*'s ability to maintain growth, found the application of N, P, and K led to an enhancement of *Sphagnum* growth (0.65–0.67 kg/m^2/yr). As they did not have a control treatment as part of their experiment, this cannot be confirmed. Carfrae et al. (2007) also reported that additions of P and K under conditions of elevated N alleviated the negative effects of N. Therefore, the balance of nutrient additions is important to maintain *Sphagnum* productivity, although further information is required to establish the appropriate ratio of these analytes to maintain growth in West Coast *Sphagnum*.

Sphagnum also accumulates P (Clymo 1963; Pakarinen 1978), concentrating about 30% of added P in the growing tips of the plants (Rydin & Clymo 1989). This increased uptake in P, however, does not necessarily correlate to increases in *Sphagnum* growth, for example, while Fritz et al. (2012) found that P additions of 1 g P/m^2/yr increased *Sphagnum* biomass, additions of 0.05–0.1 g P/m²/yr did not (Aerts et al. 2001). Fritz et al. (2012) also found that while additions of both N (4 g N/m²/yr) and P (1 g P/m²/yr) did not increase *Sphagnum* biomass, such additions did alter the morphology of the plant, so while it increased in height, the stem density decreased, leading overall to no change in biomass.

Temmink et al. (2017) studied the effect of nutrient additions on *Sphagnum* paludiculture in a previously intensively grazed peatland. They found that where atmospheric deposition led to the addition of 105–330 μmol N/L, the nutrients in irrigation water containing 13–40 μmol P/L, and 168 μmol K/L resulted in assimilation rates of 3.4 kg N/m²/yr, 1.7 kg K/m²/yr, and 0.4 kg P/m²/yr, respectively. Initial *Sphagnum* biomass production rates were reported to be between 6.5 and 6.7 t DW/ha/year.

Sphagnum peat has also been used historically to treat a range of wastewaters (see review by Couillard (1994)). For example, constructed wetlands with living *Sphagnum* have been used with some success to treat acid mine drainage (Gazea et al. 1996). Girt et al. (1987) also found that *Sphagnum* increased manganese concentrations but decreased iron, aluminium, and sulphate concentrations in mine drainage effluent.

One of the valuable qualities of *Sphagnum* moss to the horticultural industry is its low nutrient content (Schmilewski 2008); and using the moss to remove excess nutrients, and therefore increase the nutrient content of the dried material, may devalue the product. It would be valuable to test whether high nutrient-loaded *Sphagnum* released nutrients once processed into a horticultural media or filter and might be advantageous for some plants but perhaps not for others (e.g. orchids) or decrease water quality instead of improving it when used in water filters.

Several authors have reported that the response of *Sphagnum* to N differed between species, and it is likely that West Coast species may not respond in a similar manner to species studied in other countries. Therefore, more research on the response of West Coast *Sphagnum* species to N inputs is required.

3.2.2 Carbon/pH

As for all photosynthetic plants, *Sphagnum* requires adequate carbon dioxide (CO_2) to be able to maintain growth. In carbon rich substrates, such as peat, there are high amounts of inorganic carbon that result from the degradation of the ample peat resources (Patberg 2011). When the carbon-rich waters meet the area immediately around *Sphagnum* with a low pH, the inorganic carbon can be converted to dissolved CO_2 which is then available for *Sphagnum* uptake and photosynthesis.

Smolders et al. (2001) assessed the impact of dissolved CO_2 (up to 5000 μmol/L) on *Sphagnum* growth and found that plants at the control treatment (20 μmol CO_2/L) were carbon limited. Carbon limitation was indicated by increased chlorophyll to facilitate CO_2 uptake, less allocation of carbon to plant structure, and reduced growth compared with the treatment with greater dissolved CO_2. High inputs of dissolved inorganic carbon can, however, negatively impact *Sphagnum* by increasing the pH of the system, enhancing degradation of organic matter, increasing methanogensis, and promoting P mobilisation (Lamers et al. 1999). Therefore, increased pH could inhibit conversion of bicarbonates to dissolved CO_2 and impact photosynthesis. The negative effects of bicarbonate additions can be aggravated when combined with sulphate addition (Lamers et al. 1999). Sulphate and bisulphate additions also reduce *Sphagnum* biomass and length growth and photosynthetic capacity (Ferguson & Lee 1979, 1980), although the negative effects of sulphate on *Sphagnum* can be alleviated by adding N (Gunnarsson et al. 2004; Granath et al. 2009).

Clymo (1973) reported *Sphagnum* is generally intolerant of high pH and high calcium concentrations, although this is not always the case (Zuzana et al. 2016). Under conditions of high pH, *Sphagnum* has been shown to die-off (Lamers et al. 1999) and can bio-accumulate toxic levels of calcium (Zuzana et al. 2016). Changes in soil pH can also occur in response to fertiliser. For example, urea hydrolysis rapidly increases pH as urea is converted to ammonium (Cabrera et al. 1991; Tabatabai 1994) and ammonium is converted to nitrate decreasing pH, which can also occur for ammonium-based fertilisers applied to the soil (McLaughin 2010; Goulding 2016). No information on the response of *Sphagnum* to rapid changes in soil pH associated with fertiliser run-off could be located.

The interaction between nutrient additions, pH, and C limitation requires further investigation to determine the thresholds at which New Zealand *Sphagnum* production may be hindered.

3.2.3 Shade

Sphagnum grows better with some canopy cover (e.g. Buxton et al. 1990,1996), which acts as a physical support for growth, decreases desiccation by drying winds, and facilitates the formation of hummocks while promoting more even temperature and humidity (Gorham 1957; Boatman & Armstrong 1968; Pouliot et al. 2011).

Sphagnum generally grows alongside *Lepidosperma* and *Baumea* (sedges) in open mires, underneath *Leptospermum scoparium* (mānuka) and *Coprosma spp.* in shrublands, or under *Ulex europaeus* (Gorse) (Denne 1983). It is also a sub-canopy plant in native forest and with *Empodisma minus* or *Gleichenia circinata* in drier rush areas (Denne 1983).

Buxton et al. (1996) suggested that 20% canopy cover would be required for sustainable *sphagnum* production; however, anything more than this and there is a risk of the moss becoming straggly, with reduced commercial value (Denne 1983). Buxton et al. (1996) also found that drier post-harvest sites with no vegetation had significantly slower recovery growth rates than drier post-harvest sites with some canopy vegetation. Therefore, shade can mitigate the effects of less soil moisture. Shading can also influence the species of *Sphagnum* present at a site, for example, Ma et al. (2015) reported that hollow dwelling *Sphagnum* dominated over hummock dwelling *Sphagnum* under shading.

3.2.4 Plant competition

Sphagnum species are ecosystem engineers that alter their surroundings to maintain dominancy, including manipulating the water table, monopolising N, and excreting hydrogen ions to maintain a low pH, potentially inhibiting the growth of competing vascular plants (Andrus 1986; Wiedermann et al. 2009b).

However, there is some evidence that *Sphagnum* may not be able to compete effectively with vascular plants in situations with higher nutrient inputs (Heijmans et al. 2001; Nils et al. 2003; Breeuwer et al. 2008b; Temmink et al. 2017). For example, Wiedermann et al. (2009a) suggest that due to the small amount of nitrate assimilated by *Sphagnum*, applied nitrate would be available for uptake by vascular plants, leading to greater competition. Further, Heijmans et al. (2001) reported a negative relationship between *Sphagnum* and vascular plant biomass under elevated N (Figure 5), whereby *Sphagnum* production decreased with increasing vascular plant cover.

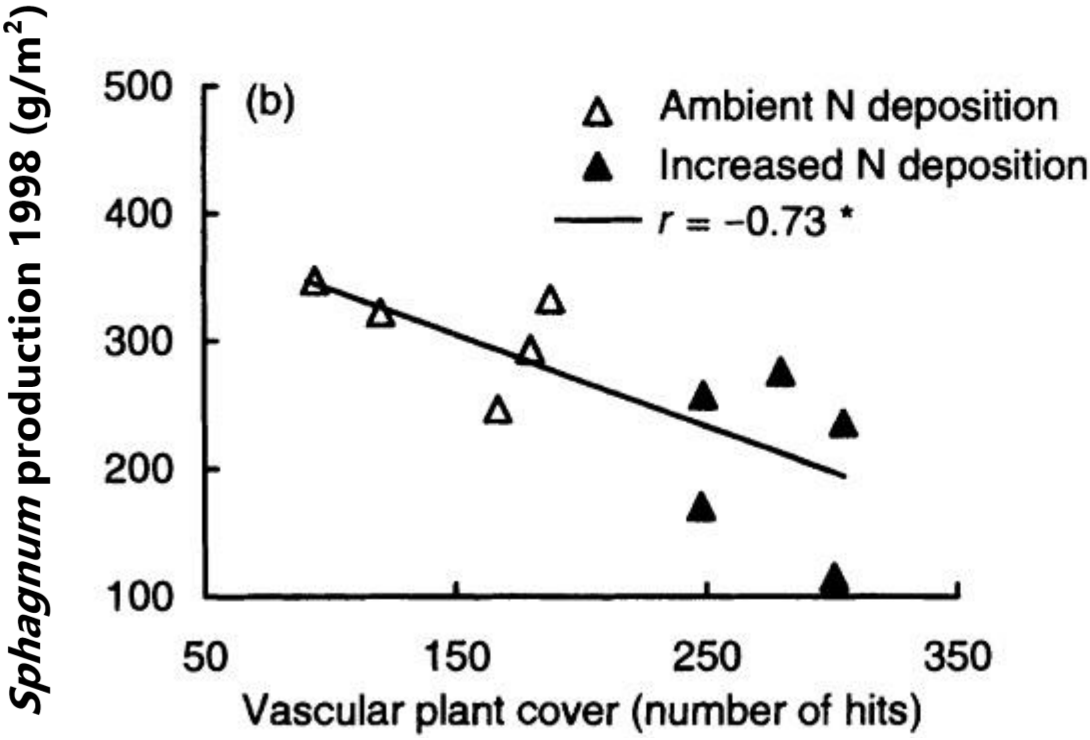

Figure 5 Relationship between Sphagnum production and vascular plant cover after three growing seasons of elevated nitrogen inputs. Level of significance: P<0.05 (Heijmans et al. 2001).

Weed invasion can also affect *Sphagnum* growth (Wichmann et al. 2017), particularly post-harvest in New Zealand, where *Ulex europaeus* (gorse) and *Erica lusitanica* (Spanish heath) can spread before the *Sphagnum* has recovered (Buxton 2017).

Competition between *Sphagnum* species can also occur (Fife 2018). *S. subnitens* can increase at sites where *S. cristatum* has been selectively harvested; however, *S. subnitens* is inferior for the production of *Sphagnum* products and can lead to less profitability (Stokes et al. 1999). Further, Stokes et al. (1999) suggest that *S. cristatum* can be maintained as the predominant *Sphagnum* species at harvest sites by 1) removing all the *Sphagnum* present, 2) reseeding only with *S. cristatum*, and 3) by compression of the peat surface near the water table.

3.2.5 Water table/flooding

Mosses have a simple physiology with little cellular differentiation and no protection layer to reduce moisture transfer to and from the atmosphere, therefore mosses require a high moisture environment to maintain their water balance (Denne 1983).

In a detailed study of the effect of water table depth on *Sphagnum* growth, Stokes et al. (1999) found that *S. cristatum* and *S. subnitens* exhibited a linear biomass growth response to water table depth, whereby growth increased with decreasing depth to the water table. The *Sphagnum* also exhibited exponential length growth with lessening depth to the water table. While they found that *S. cristatum* had the greatest biomass and length production of the *Sphagnum* species they assessed, they also suggest that, under drier conditions than those included in their study, *S. subnitens* may out compete *S. cristatum*.

Buxton et al. (1996) found no difference in growth rates between wet and dry sites, but did find a greater recovery of *Sphagnum* post-harvest in wetter sites compared with drier sites on the West Coast. Denne (1983) suggests that *S. cristatum* may be of a higher quality in environs where the water table is 15 cm or so below the surface.

Carfrae et al. (2007) found that the negative effects of high N inputs were greater when the water table was low. Therefore, maintaining a high water table under *Sphagnum* may have several benefits, including enhancing both the growth of target commercial species and the resilience and resistance of *Sphagnum* communities to nutrient inputs. However, in New Zealand, if *Sphagnum* production areas coincide with *Neochanna apoda* (brown mudfish) habitat then alteration of the natural fluctuation of the water table to maintain *Sphagnum* growth would not be recommended, as this will affect the habitat of this rare species (Buxton 2017).

Riparian zones are inherently prone to flooding from their neighbouring water courses (Collier et al. 1995). While Borkenhagen and Cooper (2018) found that *Sphagnum warnstorfii* was highly susceptible to the effects of long-term submergence, Rochefort et al. (2002) found that flooding generally improved growth in a range of *Sphagnum* species, perhaps reflecting differences in the length of submergence and the species tested.

Interestingly, Gao et al. (2016) found that riparian plantings of high-density *Sphagnum*, on 10% of the catchment, resulted in a decreased flood peak of between 1.8 and 13.4% during a 20 mm/hr rainfall event. In this scenario, Gao et al. (2016) assessed overland flow, i.e. water flowing across the land towards the water ways, rather than waterway level increasing and maintaining flow outside its banks in the riparian zones. No literature assessing the effect of fast-flowing flood water on *Sphagnum* could be located, and it possible that plants may be washed out of the ground during flooding events. Some protection would be afforded by the shade-providing companion plants, and it is possible that a buffer directly between the watercourse and the *Sphagnum* farming areas might be required to lessen disturbance of the site by flooding.

As with much of the literature, New Zealand *Sphagnum* species have not been assessed for their tolerance to flooding. Further testing is required to determine the susceptibility of New Zealand *Sphagnum* to flooding events.

3.2.6 Temperature

Sphagnum growth in New Zealand is also affected by temperature and is generally greater where it warmer, although this is based on limited data. Whinam et al. (2003) reported 61 mm/yr in Westport (MAT 12.2°C), 54 mm/yr in Hokitika (11.6°C), and 34 mm/yr in Kakapotahi (11.1°C). They also suggest that *Sphagnum* growth decreases where there are lower winter temperatures and that *Sphagnum* recovery is quicker on warmer, wetter sites.

International literature indicates that the response of *Sphagnum* to temperature is species specific. For example, Gunnarsson et al. (2004) found that *S. balticum* decreased in productivity with increased temperature, but *S. papillosum* increased. Breeuwer et al. (2008a) found that while all species increased in height and biomass with elevated temperature, the bulk density of the plant material decreased and the extent of change differed between the four species they tested. To establish the best possible sites to maximise *Sphagnum* production, further research into the effect of temperature for NZ *Sphagnum* species would be advantageous.

4 *Sphagnum* farming

Sphagnum farming a new concept currently being developed (e.g. (Pouliot et al. 2015; Wichmann et al. 2017), and is defined as "the sustainable production of non-decomposed *Sphagnum* biomass on a cyclic and renewable basis" (Buxton 2017) and is a form of paludiculture. Globally, *Sphagnum* farming is usually undertaken on peatland or floating wetlands.

Wichmann et al. (2017) compared three options for *Sphagnum* farming, including conversion from bog grassland, conversion from bog cut-over after peat harvest (Fig. 6), and floating *Sphagnum* mats. Within the conversion from bog grassland to *Sphagnum*, Wichmann et al. (2017) also investigated the costs and effectiveness of two forms of *Sphagnum* farming; 1) mechanical harvesting on S*phagnum* production areas with fewer causeways and more *Sphagnum* area; and 2) less area of *Sphagnum* production and greater causeways. In a review of the limited data on *Sphagnum* farming, Pouliot et al. (2015) found that maintenance of a stable water table was the greatest factor affecting *Sphagnum* production and therefore, Wichmann et al. (2017) established peatland conversion options with irrigation.

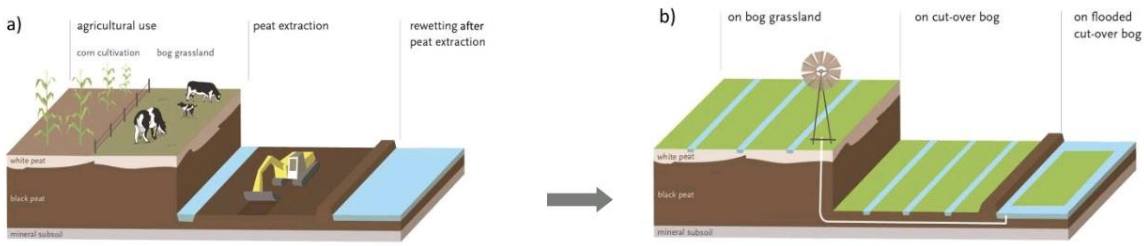

Figure 6 Land use a) before and b) after conversion to Sphagnum farming (Wichmann et al. 2017).

Wichmann et al. (2017) outline the steps, and costs of each step, of the conversion of bog grassland to *Sphagnum* farming. Briefly, the process involved the removal of the topsoil to provide an even surface that was more homogeneous for irrigation and unaffected by lime and nutrient additions. Then, depending on the ratio of causeway to *Sphagnum* production area, irrigation ditches (50 cm wide by 50 cm deep) were introduced and causeways built from the removed soil. *Sphagnum* diaspores were purchased and spread at a rate of 7.9 l/m^2 before mulching with straw. The most expensive components of the conversion were the costs of the irrigation system (35% of total cost) and the *Sphagnum* diaspores (47%). They estimated the establishment costs at €12.67–12.80/m^2 (equivalent to NZ$21.37–21.44/$m^2$) of net production area.

In the same study areas as Wichmann et al. (2017), Gaudig et al. (2017) found that *Sphagnum* biomass production averaged 3.7 t/ha/yr between 2007 and 2011, but had increased to 6.9 t/ha/yr between 2010 and 2011. The accumulated biomass over the 9 years since the sites were established averaged 19.5 t/ha and may have been P and K limited, so could have been able to produce more. Gaudig et al. (2017) also found that when a high water table could not be maintained, previously accumulated *Sphagnum* was subject to decomposition thereby decreasing biomass. They also found that water supply was of greater importance than nutrient provision for the maintenance of growth. Gaudig et al. (2017) also stated that the second most important factor for maintaining *Sphagnum* growth was the removal of competing plants, which was undertaken by mowing and removal of mown material to maintain about 30% vascular plant abundance.

Floating wetlands[2] (Fig. 7) have also been used in Germany and Japan and have shown some success for *Sphagnum* farming. Hoshi (2017) showed that floating wetlands were capable of producing *Sphagnum* rapidly but were dependent on seeding density and diversity. They found that after 3 months growth, the *sphagnum* cover increased from between 15–20% of the raft to 40–50%. The water in which this study was conducted had an ammonium concentration of less than 1 mg/L and P contents were not assessed.

[2] Floating wetlands are generally constructed on a planted raft that sits on top of the water column. The plant roots sit in the water column and are often used to treat wastewater, provide habitat, and enhance biodiversity.

Figure 7 Floating wetland Sphagnum farm Japan (Hoshi 2017).

Gaudig et al. (2014) also showed that *Sphagnum* established quickly on floating mats, and was greater in production than mechanically sown *Sphagnum* growing on peat, but was considerably less than manually sown *Sphagnum* growing on peat. Further, Wichmann et al. (2017) found that of all the *Sphagnum* farming options they assessed, the floating wetland option was the most expensive. Establishment costs ranged between €17.34 and €21.43/m², which equated to €9,625–11,833/tonne of *Sphagnum* produced and was 6–7 times higher than costs associated with conversion to terrestrial-based *Sphagnum* production.

Internationally, *Sphagnum* farming occurs predominantly on peat; however, on the West Coast *Sphagnum* naturally occurs on both peat and pakihi podzol soils. The techniques used for *Sphagnum* farming on peat should also be applicable to pakihi soils, although modifications to the techniques discussed in this report would need to be assessed on a site--by-site basis.

5 West Coast *Sphagnum* and the global market

Sphagnum has an established international market, and is exported for use in the horticultural, reptile breeding, and water filtration industries. Exports of *Sphagnum* are predominantly *S. cristatum* but some *S. subnitens* and *S. australe* are also exported from the West Coast region (Denne 1983).

Sphagnum moss is produced through a three-stage supply chain (Fig. 8). Once the plant is harvested it goes through its first stage – farmgate sales. The sold plants are then processed (second stage), and finally either sold domestically as fresh processed sales or exported to overseas markets (third stage). Plant and Food Research (2012) and the Ministry for Agriculture and Forestry (2008) estimated the total final (domestic and international) sales to be around $5.6 million. Based on Horticulture NZ estimates (Nixon 2015), the value of farmgate sales is often half the value of total final sales ($2.8 million). Nixon (2015) stated that the value of the processing stage could represent around 25% of the total final sales (i.e. $1.4 million). The Ministry for Agriculture and Forestry (2008) showed that the value of total domestic sales is around 20% of the export sales, estimated at $1.3 million. This leads to a value of $4.5 million for *Sphagnum* moss exports (Plant and Food Research 2012).

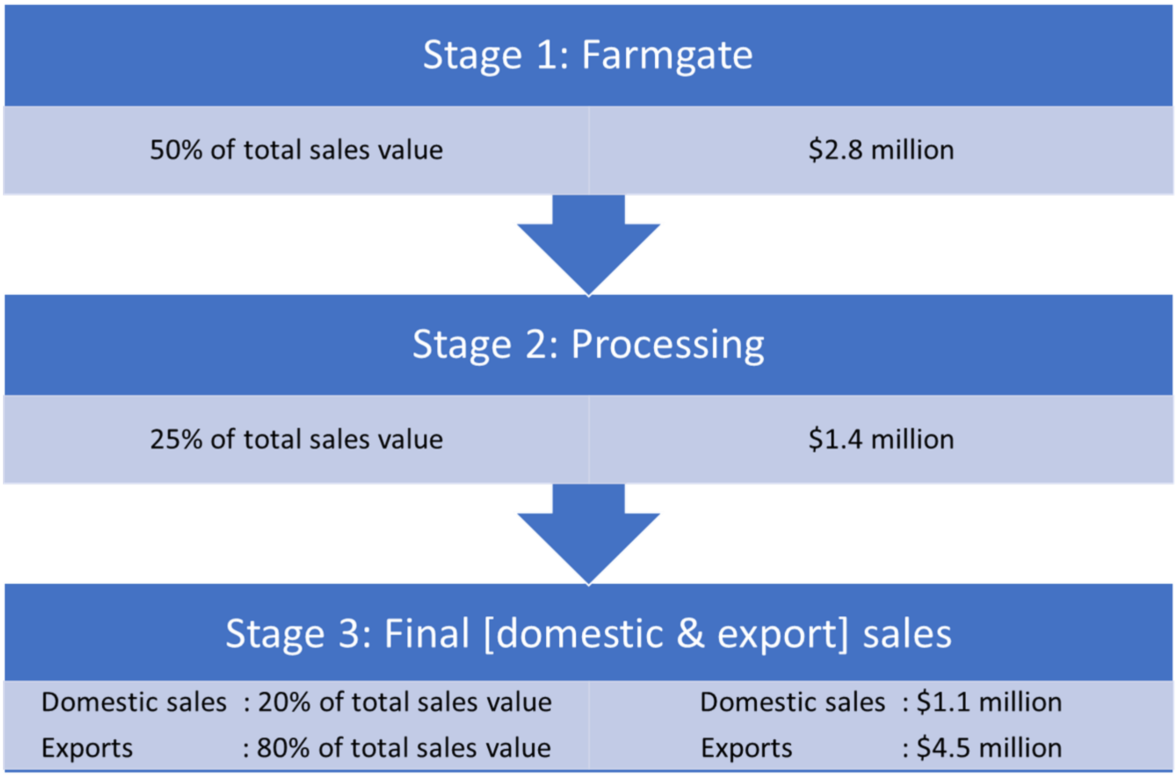

Figure 8 *Sphagnum* moss three-stage supply chain.

The *Sphagnum* industry is export focused, with most of the harvest being supplied to overseas customers, mainly orchid growers. The main export markets are Japan, ~80%, and Southeast Asia, ~20% (Ministry for Agriculture and Forestry 2008). There was a significant decline in the annual value of exports in the last two decades (Fig. 9). In the 1990s, the export of *Sphagnum* moss ranged from $13 to $18 million, which was reduced to $4.0–$4.5 million in 2011–2013 (Plant and Food Research 2012). This decline in export value was mainly due to tougher competition from other Pacific Rim producers and the high value of the NZ dollar.

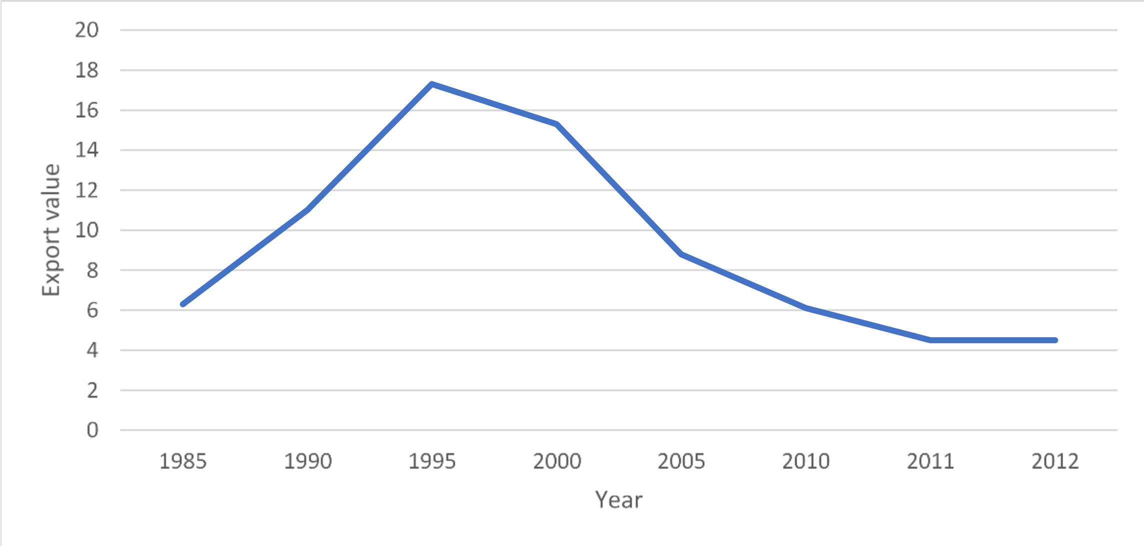

Figure 9 Export value (in million NZ dollars) of Sphagnum moss during the period 1985–2012.

International competitors in the *Sphagnum* market originate from Australia, China, and Chile (Orchard 1994), with Chile being perhaps New Zealand's greatest competition. There is an increasing trend in *Sphagnum* exports from Chile, and the average annual exports was 2,675 tonne/year between 2003 and 2012 (Díaz & Silva 2012). Chile exports to a greater number of countries than New Zealand, including Taiwan, USA, Japan, South Korea, Holland, China, Vietnam, and France (Díaz & Silva 2012). When the market peaked in New Zealand in the early 1990s, *Sphagnum* exports to Japan were about 700 tonne/year (Yarwood 1990); however, in 2018, New Zealand exports had decreased to about 70 tonne/year (Statistics New Zealand 2019). Compared with Chile, New Zealand supplies a smaller, and decreasing, portion of the global market.

It is possible that incoming regulatory restrictions will mean a further decrease in *Sphagnum* exports as the industry is impacted by the requirements for resource consents for *Sphagnum* harvesting and protection of wetland sites from disturbance. How the industry adapts to tightening restrictions on the availability of *Sphagnum* is yet to be determined, but the potential increase in production costs may lead to an increase in export price and therefore to a decrease in demand from foreign consumers. This has been seen in other industries, including the forestry industry where 1 unit increase in 'wood' prices decreases demand by 5.5 units (Nixon 2015).

6 Optimal *Sphagnum* production within a farm context

The West Coast Regional Council requires clarification of the potential role of *Sphagnum* farming on riparian zones. Therefore, we will assess the potential for newly established riparian zones within intensively grazed systems for *Sphagnum* farming. *Sphagnum* farming areas would need to be excluded from stock for several reasons, including trampling, compaction, nutrient additions, and grazing (Fig. 10).

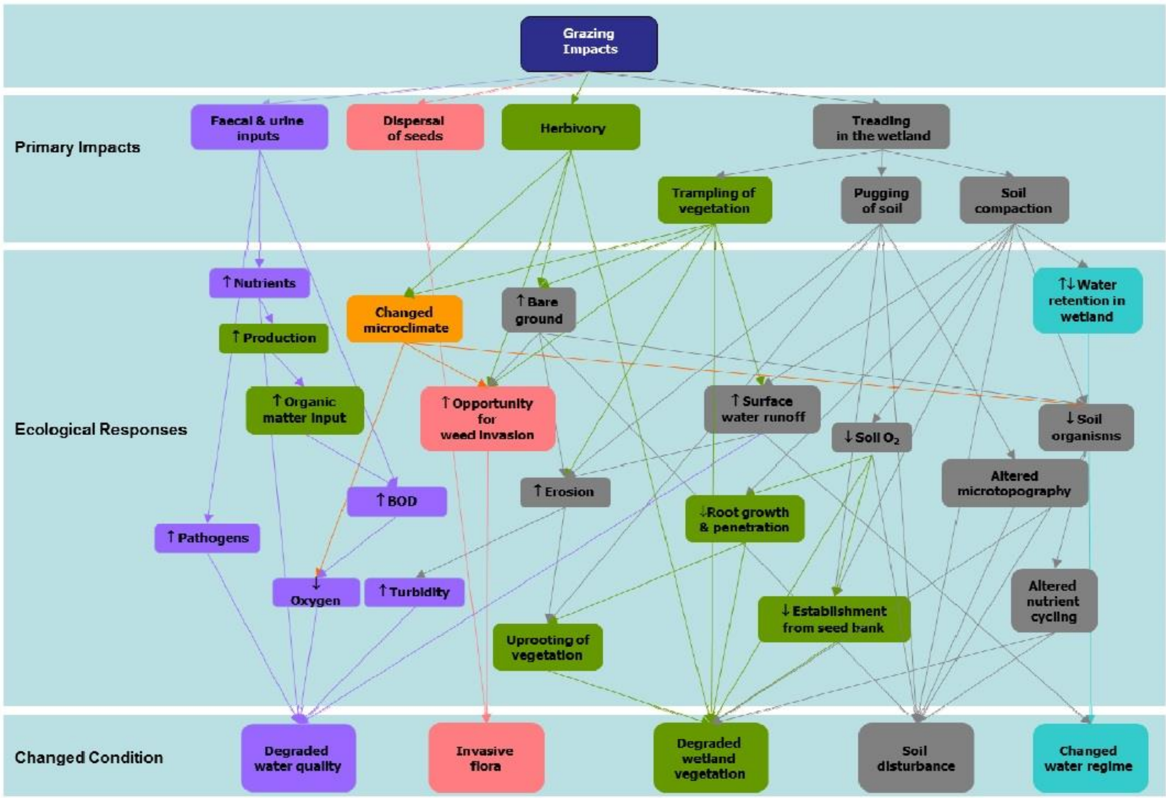

Figure 10 Impacts of grazing on wetland condition, where purple represents water properties, pink invasive flora, green vegetation, grey soil properties and blue water regime (Morris & Reich 2013).

Sphagnum has been shown to be particularly susceptible to grazing, which can cause long-term damage to the moss by forming drainage channels leading to a lower water table (Wahren et al. 2001; Morris & Reich 2013; Lindsay et al. 2014). Grazing behaviour differs between animals, but overall grazing by either ovine or bovine will result in a decrease in *Sphagnum* biomass and potentially a change in plant community composition towards faster growing plant species (Wahren et al. 2001; Morris & Reich 2013; Lindsay et al. 2014).

Grazing animals are somewhat ineffective in utilising the full nutrient content of consumed vegetation leading to high excretal concentrations of nutrients, in particular, nitrogen (urine) and phosphorus (dung) (Watkin 1957). In systems where grazing animals move between highly nutritious pasture grazing and less nutritious wetland areas, they increase the nutrient contents in the wetland directly by transferring nutrients from the higher nutrient pasture system to the lower nutrient wetland via excreta (Morris & Reich 2013; Lindsay et al. 2014). In particular, dairy cow urine contains ammonium (~90 mg/L), inorganic carbon (~329 mg/L), calcium (~28 mg/L), and sulphate (~228 mg/L) (Lambie 2012; Lambie et al. 2012), all of which may affect *Sphagnum* growth. However, exclusion of grazing stock to *Sphagnum* farming areas would eliminate urine from having a direct effect on moss survival and growth.

After grazing exclusion has been implemented, there may still be inputs of nutrients from surrounding grazed land where fertiliser and animal excreta contribute to nutrients entering neighbouring wetland systems (Steinman et al. 2003). Monaghan et al. (2000) measured run-off loses less than 0.05 g/m^2/year (0.5 kg/ha/year) for nitrate, ammonium, and phosphorus from a Southland free-draining soil. If we combine this with the atmospheric contribution of

0.6 g N/m^2/yr, we would have a potential total of approximately 0.7 g N/m^2/year (including 0.05 g/m^2/year for both ammonium and nitrate). This is well within the range of N inputs considered to be beneficial for *Sphagnum* growth of 2 g/m^2/year (20 kg/ha/year) as suggested by Lamers et al. (2000) but assumes that West Coast *Sphagnum* species behave the same an international species in response to N additions; and this has yet to be sufficiently established. Agricultural run-off can also be alkaline (Martínex-Suller et al. 2010), which can affect soil pH and therefore *Sphagnum* photosynthesis rates by altering the efficiency of the conversion of bicarbonates to dissolved CO_2.

As *Sphagnum* requires a certain level of shading by vascular plants to require maximal growth (Section 3.2.3), Whinam and Buxton (1997) suggest that 20% shading is optimal for *Sphagnum* growth. Strategies in the literature about how to acquire this level of shading referred predominantly to greenhouse *Sphagnum* production where shade cloth was put in place. However, this is unpractical on riparian zones and perhaps planting of mānuka (*Leptospermum scoparium*), *Lepidosperma* or *Baumea* as windrows or at random intervals among areas converted to *Sphagnum,* would generate sufficient wind and sun protection. It is also possible that protection of the *Sphagnum* areas from fast moving water during flood events may be required. Perhaps shade plants could be planted initially along the river/stream bank. This would depend on the width and length of the riparian zone and also the level of access required, i.e. whether access would be from waterways or farm raceways.

Sphagnum therefore has the potential to do well adjacent to grazed pastures if stock are excluded, shade is provided, competition with vascular plants is minimised, and nutrient inputs are maintained at a low level. The level of nutrient inputs has yet to be established for New Zealand *Sphagnum* and remains a knowledge gap in the potential effectiveness of establishing *Sphagnum* farming within a predominantly grazed landscape.

7 Knowledge gaps and conclusions

The paludiculture of *Sphagnum* has been initiated overseas to allow for the sustainable production of peat. In New Zealand, however, this technique could be used to effectively support the *Sphagnum* moss industry. The West Coast Regional Council are exploring the potential of *Sphagnum* to reduce nutrients derived from intensive agricultural industries from entering waterways. While there appears to be some promise in the utilisation of *Sphagnum* for this purpose, there are several knowledge gaps that require resolution, including:

- Unknown growth response of New Zealand *Sphagnum* species to nutrient inputs, e.g. nitrogen (ammonium and nitrate), phosphorus, potassium and carbon.
- Unknown threshold for New Zealand *Sphagnum* species to changes in pH, particularly increases in pH associated with the degradation of urea; a commonplace fertiliser in intensively grazed systems and a component of cow urine.
- Whether the growth response differs between peat and pakihi soils
- Whether New Zealand *Sphagnum* has a symbiotic relationship with cyanobacteria, as this will impact the N tolerance and utilisation
- Pathogen susceptibility of *Sphagnum*, perhaps most relevant to *Escherichia coli* and other pathogens commonly found in dairy run-off/effluent.

- Nutrient leaching rates and pathogen-holding/release capacity may also be an issue for some commercial *Sphagnum* products, in particular, the emerging water filter industry.
- The effect of changes in *Sphagnum* physiology in response to farming strategy (i.e. nutrient inputs, shading and weed competition) on the commercial viability of the product, different export markets will have different expectations of product quality.
- As *Sphagnum* farming requires the exclusion of animals, a cost/benefit analysis would also be valuable under the current economic climate to establish whether retirement of land to *Sphagnum* farming would be viable compared with maintaining a grazed regime.

Under the current Regional Land and Water Plan (West Coast Regional Council 2014) a resource consent would most likely be required for earthworks and soil disturbance on riparian zones and may need to be taken into consideration when establishing *Sphagnum* farming. Consultation with local iwi (e.g. Ngäi Tahu) would also be required to establish whether a land use change from grazing to *Sphagnum* farming on riparian areas would fit within their aspirations.

There are likely to be site-specific factors that influence the production of *Sphagnum* and its role in nutrient mitigation, such as soil, flood protection, pH, depth to the water table, nutrient addition profile, and access to the site either via land or water. Each potential site will therefore require a site assessment to determine the potential for *Sphagnum* farming. *Sphagnum* within a riparian zone context will also require maintenance over time, most likely to maintain the 20% shading threshold and remove weeds (which may include native species such as *Empodisma minus*) that can be prolific in riparian zones particularly after flooding (Donaldson 1997; Howell & Benson 2000; Catford et al. 2011).

In conclusion, for optimal *Sphagnum* production it is suggested that the water table be about 15 cm from the surface, shade provision at about 20%, substrate with a low pH, and the site be protected from flooding. Further provision for optimal sites will be reliant on determination of the optimal nutrient input profile for New Zealand *Sphagnum*, which is yet to be undertaken.

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