Potential for paludiculture in New Zealand

Considerations for the Lower Waikato

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Prepared for NIWA: Future Coasts Aotearoa

May 2023

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Executive Summary

Paludiculture refers to the productive use of wet and rewetted peatlands, and provides an alternative to their exclusive protection. In New Zealand, peatlands form one of the many wetlands types found across the country. New Zealand wetlands support endemic flora and fauna, act as carbon sinks, represent a taonga for iwi and provide recreational opportunities. Of the nine wetland classes defined in New Zealand, swamps, bogs, fens, pakihi and gumland and some seepage systems can be found with a peat substrate and can therefore be defined as peatlands in the New Zealand context. Consequently, the productive use of swamps, bogs, fens, pakihi, gumland and peat substrate-related seepage systems can be classed as paludiculture. By comparison, wetlands classed as marsh, shallow water, ephemeral wetland, saltmarsh and some seepage are predominantly found with a mineral, not peatland, substrate. Production on these wetland habitats is not defined as paludiculture as it does not contribute to peat soil preservation, minimize carbon dioxide (CO2) emissions or subsidence.

Following European settlement, many New Zealand wetlands such as peatlands have been extensively drained and/or degraded for agricultural development and flood alleviation. This has extensive social and environmental impacts, including: soil degradation, compaction and subsidence, reduced long term productivity, biodiversity loss, greenhouse gas emission and reduced resilience. This increases the risk of flooding, droughts and saltwater intrusion. Driven by intensive land use practices such as high stocking densities and fertiliser use, drained peatlands in New Zealand are responsible for up to 6% of national agricultural greenhouse gas emissions. The Waikato region in particular contains approximately half of the country's peatlands, of which 80% have been drained for agricultural and horticultural use, emitting 10-33 $tCO^2e\ ha^{-1}\ yr^{-1}$. This has caused significant subsidence and annual greenhouse gas emissions.

The productive use of wet and rewetted peatlands (paludiculture) provides an alternative to their exclusive protection. It can prevent further degradation of peatlands, maintain peatland ecosystem function and retain the economic viability of the land. There are potential benefits to paludiculture, including the provision and/ or maintenance of ecosystem services, reduced greenhouse gas emissions (enhanced carbon sequestration), local climate cooling, commercial earnings from cropping and the potential for new peat formation.

Paludicrop species are diverse, ranging from trees, to grasses, mosses, herbs or berry-producing shrubs. They thrive under wet conditions and contribute to the formation of peat or peat conservation. The resulting biomass can provide an array of potential products including fodder, food, raw materials for bio-based construction and horticulture industries, and bioenergy. Each species will have specific soil chemical and hydrological requirements, which will also determine the type of management and harvesting mechanisms needed. Yields, together with their potential to reduce greenhouse gas emissions, will vary significantly depending on site conditions. An optimal compromise between biomass production, climate mitigation and peat preservation should therefore be sought when determining species type.

While there are numerous examples of paludiculture development in the northern hemisphere, there are limited examples in New Zealand, especially at scale. Examples in Europe, the USA, Canada and southeast Asia illustrate the potential of production of biomass and highlight the key considerations for developing paludiculture on rewetted peatlands. These include site-specific conditions such as the type and condition of peatland, historic drainage-based management, time under drainage, and potential mobilization of nutrients through rewetting. Rewetting and management of water tables in previously drained peatlands creates a mosaic of site conditions. Optimal growth conditions for paludiculture require year-round water levels near the surface to reduce loss of carbon and nutrients, manage methane and nitrous oxide emissions and preserve the peat body. Site-specific conditions will therefore determine the planning of paludiculture and its infrastructure requirements, such as water regulation and management, harvesting timing and techniques.

Not all formerly drained and degraded peatlands areas and species will be appropriate for rewetting to enable paludiculture production. Taking into consideration the site-specific challenges and barriers for paludiculture potential can help determine the suitability and economic viability at farm level and at scale. Where paludiculture is not viable, adaptive management to avoid further degradation through over-drainage, soil tillage and use of fertilizers could be pursued.

If restoration of natural river flow is a priority in a region, determining where rewetting may occur and identifying its potential impacts on existing land use or users is a necessary first step. Identifying the carbon potential and development of paludiculture is challenging so this report provides an overview of important considerations.

It is important to consider the economic viability of transitioning to paludiculture in New Zealand when deciding whether and where to promote it. New Zealand peatlands drained for agricultural production provide considerable economic value worth NZ$ 700 million per year (Meduna 2021b). While there is considerable technical and economic uncertainty in establishing paludiculture, continued drainage will become more expensive as peatland degradation continues over time. The cost-effectiveness of paludiculture should be compared with an appropriate baseline where conventional agriculture becomes less viable due to frequent inundation.

Investment in research and development would be needed to increase cost-effectiveness and the practicality of paludicultural production and harvest, especially if paludiculture was to be scaled up. The uptake of paludiculture at farm-level might also be influenced by limited supportive policies or perverse incentives that encourage ongoing drainage-based agriculture.

If paludiculture is to be encouraged in New Zealand, the development of markets for ecosystem services from paludiculture or rewetting of drained peatlands, including payments for ecosystem services (PES), recognised carbon market standards etc., could be explored to encourage private sector investment and provide incentives at farm level. Consideration of iwi and local land user perception of the positive and negative impacts of paludiculture are also important to draw on local knowledge, values and connections to the landscape, and to identify potential conflicts of interest.

Given these issues, paludiculture itself is “not a panacea” to protect peatland-based wetlands. However, it provides an opportunity for a paradigm shift in agricultural practice to diversify activities into a bio-based circular economy on peatlands. It also presents an opportunity to support New Zealand’s net zero carbon future. Continued drainage-based agricultural production on peatlands is likely to become increasingly cost-ineffective due to management, risk and greenhouse gas emissions factors. Drained peatlands will vary in their potential for rewetting and/or the development of paludiculture. However, criteria to identify prospective paludiculture sites in the context of the peatlands and wetlands of New Zealand could be developed. For paludiculture to be explored in New Zealand, and in the Lower Waikato in particular, promising examples from the northern hemisphere can be drawn on to find context-specific similarities. Further research would also be needed in the context of New Zealand on peatland site conditions, economic viability, social considerations and the enabling environment. This can help determine which paludiculture systems could be economic viable and competitive, sustainable at large-scale and whether additional investments or financial incentives are required to support the transition from drainage-based management.

1 Background and purpose

The project *Transforming coastal lowland systems threatened by sea-level rise into prosperous communities* – commonly referred to as the *Future Coasts Aotearoa* project – aims to inform adaptation to relative sea level rise by assessing the physical, socioeconomic and cultural effects of relative seal level rise and the potential of adaptation to support communities into the future.

This report supports the economic assessment of potential adaptation options for relative sea level rise, under Research Area 2, and explores the relevance of paludiculture to New Zealand as part of potential adaptation options. Specifically, this report contains:

- A review of literature on paludiculture (methods, products, benefits) and possible relevance to New Zealand, especially Lower Waikato
- Drawing on land under production in the Lower Waikato case study area, examples of:
    - Possible forms of paludiculture production e.g., sphagnum moss
    - Possible labour and capital requirements
    - Commercial values (if relevant) and opportunities associated with the paludiculture examples, and
    - Other values potentially associated with paludiculture e.g. carbon sequestration and habitat protection
- Further research or data needs relevant to an economic assessment of paludiculture in the *Future Coasts Aotearoa* project.

This reports will describe paludiculture in the context of productively using peatlands. In so doing:

- Chapter 2 introduces wetlands, their nature and types.
- Chapter 3 introduces peatlands in New Zealand.
- Chapter 4 introduces the concept of paludiculture, the drivers for it and its methods.
- Chapter 5 addresses challenges and considerations when contemplating exploring paludiculture in New Zealand.
- Based on this, Chapter 6 lists future possible research areas relevant to establishing paludiculture in new Zealand.

2 Wetlands

Wetlands are unique ecosystems, transitioning both terrestrial and aquatic systems where the water table is found either at or near the surface (Wetlands Initiative[1], Wetlands International[2]). They can be found across every climatic zone and contain an estimated 40% of the world's biodiversity, yet cover just 6% of the land surface (IPCC 2018, Wetlands International[2]). Examples of wetlands include rivers and deltas, inland lakes, swamps, flood plains and flooded forests, peatlands to coastal mangroves, rice-fields coral reefs, tidal mudflats and salt marshes. Wetlands play a vital role in the improving water quality and flood protection, together with the provision of food, raw materials, flood protection, water regulation, global climate regulation, genetic resources for medicines, and hydropower (IPCC 2018, Canterbury Regional Council[3]). They also hold significant cultural and spiritual importance, and tourism and recreational value.

Wetlands can be found across New Zealand, with nine wetland classes recognised based upon their function (Johnson and Gerbeaux 2016). These include: bog, fen, swamp, marsh, seepage, shallow

[1] http://www.wetlands-initiative.org/what-is-a-wetland Accessed 24 March 2023
[2] https://europe.wetlands.org/wetlands/what-are-wetlands/ Accessed 24 March 2023
[3] https://www.ecan.govt.nz/your-region/your-environment/our-natural-environment/our-regions-biodiversity/wetlands/importance-of-wetlands/

water, ephemeral wetland, pakihi and gumland, and saltmarsh. Each class is associated with their water regime and flow, drainage, fluctuation, periodicity, substrate (mineral or peatland), nutrient status and acidity (pH) (Table 1), together with their specific landforms, vegetation structural classes and key indicator plants (Table 2).

Table 1. Distinguishing features of New Zealand wetland classes. Source: Johnson and Gerbeaux 2016.

Wetland Class	Water origin (predominant)	Water flow	Drainage	Water table position cf. ground	Water fluctuation	Periodicity	Substrate	Nutrient status	pH
Bog	rain only	almost nil	poor	near surface	slight	wetness permanent	peat	low or very low	3–4.8
Fen	rain + groundwater	slow to moderate	poor	near surface	slight to moderate	wetness near-permanent	mainly peat	low to moderate	4–6
Swamp	mainly surface water + groundwater	moderate	poor	usually above surface in places	moderate to high	wetness permanent	peat and/or mineral	moderate to high	4.8–6.3
Marsh	groundwater + surface water	slow to moderate	moderate to good	usually below surface	moderate to high	may have temporary wetness or dryness	usually mineral	moderate to high	6–7
Seepage	surface water and/or groundwater	moderate to fast	moderate to good	slightly above to below surface	nil to moderate	permanent wetness to temporary dryness	peat, mineral, or rock	low to high	4–7
Shallow water	lake, river, etc., or adjacent groundwater	nil to fast	nil to good	well above surface: inundated	nil to high	wetness almost permanent	usually mineral	moderate	4–7
Ephemeral wetland	groundwater + rain	nil to slow	moderate to good	well above to well below surface	marked wet/dry alternation	seasonal, sometimes temporary wetness/dryness	mineral	moderate	5.5–7
Pakihi and gumland	mainly rain	almost nil	poor	below surface	slight to moderate	wetness near-permanent but prone to temporary drought	mineral or peat	very low to low	4.1–5
Saltmarsh	seawater, brackish water, salt spray, groundwater from land	moderate to slow	good	closely below surface between tides	tidal, or slight in supratidal zone	mainly tidal	mainly mineral	moderate	4.9–8

Table 2. Landforms, vegetation, and key indicator plants associate with wetland classes in New Zealand. Source: Source: Johnson and Gerbeaux 2016.

Wetland Class	Predominant landforms	Common vegetation structural classes	Some key indicator plants
Bog	usually almost level ground, including hill crests, basins, terraces	wide range including moss, lichen, cushion, sedge, grass, restiad, fern, shrub, and forest types	*Sphagnum*, *Oreobolus*, *Baumea tenax*, *Sporadanthus*, *Empodisma*, *Dracophyllum*, *Epacris*, *Leptospermum*, *Halocarpus*
Fen	slight slopes of bog margins, swamp perimeters, hillside toe slopes, alluvial fans	usually sedge, restiad, rush, fern, tall herb, or scrub types	*Schoenus pauciflorus*, *S. brevifolius*, *Empodisma*, *Chionochloa rubra*, *Hebe odora*, *Baumea teretifolia*, *Leptospermum*
Swamp	mainly on valley floors, plains, deltas	usually sedge, rush, reed, tall herb, and scrub types, often intermingled, and including forest	*Phormium*, *Carex*, *Coprosma*, *Gahnia*, *Typha*, *Cordyline*, *Dacrycarpus*, *Laurelia*, *Syzygium*
Marsh	slight to moderate slopes, valley margins, edges of water bodies	typically rush, grass, sedge, or shrub types	*Juncus*, *Carex*, *Agrostis*, *Cortaderia*
Seepage	moderate to steep hill slopes, scarps; heads and sides of water courses	usually low-stature moss, cushion, or sedge types; sometimes scrub or forest	*Carpha alpina*, *Montia*, mosses
Shallow water	ponds, pools, streams; margins of lakes, lagoons, rivers	submerged, floating, or emergent aquatics	*Myriophyllum*, *Potamogeton*, *Azolla*, *Bolboschoenus*, *Baumea*, *Ruppia*, *Schoenoplectus*, *Isolepis*
Ephemeral wetland	closed depressions especially on moraines, bedrock, dunes, tephra	marginal zones of turf and sedge sward, sometimes rushland and scrub	*Glossostigma*, *Lilaeopsis*, *Myriophyllum*, *Pratia*, *Isolepis*, *Carex gaudichaudiana*, *Eleocharis*
Pakihi and gumland	level to rolling or sloping land having impervious soils, including pakihi, gumland, and formerly forested land	mixtures of heaths and other small-leaved woody plants with restiads, ferns, sedges, lichens, mosses	*Empodisma*, *Baumea tenax*, *Gleichenia*, *Schoenus*, *Leptospermum*, *Dracophyllum*, *Nothofagus*, *Dacrydium*
Saltmarsh	margins of estuaries; wet coastal platforms	seagrass meadow, turf, herbfield, rushland, scrub, mangroves	*Zostera*, *Sarcocornia*, *Samolus*, *Apodasmia*, *Plagianthus divaricatus*, *Avicennia*

The most common wetlands types in New Zealand are swamp, marsh, pakihi and gumland, inland saline (saltmarsh), fen, bog and seepage. These areas have declined by 90% since pre-human times, with a total loss of 2,221,781 ha (Table 3). Comparatively, global wetland loss is reported at about 35% since 1970 (Convention on Wetlands 2021d). More recent research by Manaaki Whenua – Landcare Research with data from the New Zealand Land Cover Database[4] and Fresh Water Environment of New Zealand's Wetlands of National Importance Database[5] indicate that 6,000 ha of freshwater wetlands have been lost in the last 20 years alone (Dymond et al. 2021).

Table 3. Estimated contemporary and pre-human wetland area, by type (2008 estimate). Source: https ://data.mfe.govt.nz/tables/category/environmental-reporting/freshwater/wetlands/. Accessed 21 March 2023.

Wetland type	Area (ha) pre-human	Area (ha) contemporary (2008 estimate)	% 2008 of total
Swamp	1,501,008	89,922	36
Marsh	280,828	23,066	9
Pakihi and gumland	339,458	56,909	23
Inland saline	1,586	292	0
Fen	192,096.96	37,009	15
Bog	153,116	40,061	16
Seepage	2,990	2,043	1
TOTAL	2,471,082.96	249,302	100
Total loss since pre-human times		2,221,780.96	90

Of these remaining New Zealand wetlands, over a tenth can be found in the Waikato (28,226 ha) (

Table 4).

Table 4. Estimated contemporary and pre-human wetland area, by region (2008 estimate). Source: https://data.mfe.govt.nz/tables/category/environmental-reporting/freshwater/wetlands/. Accessed 21 March 2023.

Region	Area (ha) pre-human	Area (ha) contemporary (2008 estimate)	% 2008 of total
Northland	258,451	14,114	6
Auckland	57,851	2,639	1
Waikato	356,516	28,226	11
Bay of Plenty	43,089	3,304	1
Gisborne	67,008	936	0
Hawke's Bay	113,362	2,458	1
Taranaki	40,278	3,046	1
Manawatu-Wanganui	264,511	6,983	3
Wellington	122,804	2,774	1
Tasman	26,570	5,219	2
Nelson	769	6	0
Marlborough	12,785	1,545	1
West Coast	358,182	84,396	34
Canterbury	187,115	19,851	8
Otago	110,804	27,050	11
Southland	450,984	47,231	19
New Zealand	2,471,080	249,776	100
Total loss since pre-human times		2,221,304	90

Land that has a peat substrate can be defined as peatlands (Johnson and Gerbeaux 2016). These can be both wet or well-drained landforms. Specific wetland types that form and accumulate peat can be termed mires[6]. Of the nine wetland classes in New Zealand described above, bogs, fens, swamps, pakihi and gumland, and some seepage systems can be found with a peat substrate, and therefore are considered to be peatlands (Johnson and Gerbeaux 2016). For the purpose of this report and when

[4] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/ Accessed 24 March 2023
[5] http://tools.envirolink.govt.nz/dsss/freshwater-ecosystems-of-new-zealand/ Accessed 24 March 2023
[6] https://peatlands.org/peatlands/what-are-peatlands/

referencing paludiculture in the context of peatlands, these New Zealand wetlands with a peat substrate will be defined as peatlands.

3 Peatlands

Peatlands can be found across the globe, from arctic, boreal and temperate to tropical regions, and from lowlands up to the mountains. They cover approximately 3% of the global land area but hold almost 30% of global soil carbon biomass (Joosten 2009). While broadly defined as: "*Terrestrial wetland ecosystems in which waterlogged conditions prevent plan material from fully decomposing*" (International Peatland Society 2022), there are many peatland types ranging from moors, bogs, peat swamp forests, permafrost tundra, peat moss, muskegs, fens, seepage, pakihi and gumland etc. Each type can be distinguished by their land use, morphology and landscape position (Minasny et al. 2019, Johnson and Gerbeaux 2016). Peatlands in the context of New Zealand wetlands include:

- Bogs (ombrogenous mires), for example, are raised above the surrounding landscape and rain fed, making them acidic and nutrient poor. Wetland ecosystems that are still accumulating or forming peat can also be defined as mires (Joosten 2009).
- Fens (minerotrophic/geogenous mires) are often flat or located in depressions, receiving ground (lithogenous) or surface water and precipitation (soligenous) water and have a higher pH and richer nutrient content.
- Forested peatlands are often described as swamps, occurring in basins with an often permanent water table above the ground surface (Johnson and Gerbeaux 2016, FAO 2022). Swamps often have a combined substrate of both peat and mineral, and are often nutrient and sediment rich from surface and groundwater run-off.
- Pakihi and gumland can also extend to blanket peatlands, with very infertile acidic soils, an impervious horizon and often prone to temporary droughts (Johnson and Gerbeaux 2016).
- Seepage can be found on slopes where groundwater diffuses to the surface, with a range of raw or well-developed mineral soil or peat substrate (Johnson and Gerbeaux 2016). The variation in substrate influences nutrient status, pH and water table.

In peatlands, dead and decaying organic material (consisting of at least 30% dry mass – Joosten and Clarke 2002) is accumulated over time faster than plant material decomposes. A lack of oxygen due to water saturation creates anoxic conditions that prevents decomposition, and 'peat' is accumulated. Peatland vegetation varies significantly and can be composed of mosses*, graminoids* – grasses *(Poaceae),* sedges *(Cyperaceae)* and rushes *(Juncaceae),* forbs – annual broadleaf herbs and pteridophytes, shrubs – evergreen and deciduous and trees (Antala et al. 2022). Vegetation type is determined by a peatland's water source which governs its nutrient chemistry[7]. For example, the saturated anaerobic conditions of high acidity in rainfed peatlands in New Zealand restricts weeds and allows species such as *Empodisma* to outcompete other plants. As peat layers thicken over time, ground water sources are more distant and reliance on precipitation increases. As a result, *Sphagnum sp.* mosses and woody vegetation replace grasses and sedges. These mesotrophic peatlands have a higher pH and organic content, lower nutrient content and anaerobic soils.

Peatlands provide vital ecosystem services. Intact, wet peatlands can provide products for food, fibre and shelter, construction and energy materials, and also provide a place of cultural importance (FAO 2020). They can also support habitat for biodiversity and provisioning services such as water flow regulation, reducing flooding, droughts and saltwater intrusion (Minasny et al. 2019). Significant carbon stocks are stored in their soils, holding approximately 5-20% of global soil carbon, 18-89% of global terrestrial carbon biomass and 15-72% of atmospheric carbon (IUCN 2019a, IPCC 2022, Minasny

[7] https://peatlands.org/peatlands/types-of-peatlands/

et al. 2019, Turetsky et al. 2015). This accounts for more than twice the carbon stored in all above ground forests (Joosten and Couwenberg 2009, Temmink et al. 2022).

Due to their fragile hydrological interconnections between water, plants and peat, peatlands are particularly vulnerable to change (FAO 2022). Peatland degradation from drainage and/or subsequent wildfires for agriculture, forestry, mineral mining and other extractive industries, transport infrastructure and settlement expansion in addition to peat mining has occurred in approximately 15% of global peatlands (Ziegler et al. 2021, Garrett et al. 2022). This results in greenhouse gas (GHG) emissions, surface and groundwater pollution, loss of biodiversity, land subsidence and peat fires.

Conventional agriculture on lowland peatlands are inherently unsustainable (Johnson and Land 2019). Drainage of peatlands to enable agricultural production has diverse environmental and social impacts (Figure 1). It causes land degradation through soil degradation, compaction and subsidence, reduced productivity and resilience which increases the risk of flooding, droughts and saltwater intrusion. Over the long-term, this reduces peatland agricultural value and leads to substantial GHG emissions (Meduna 2021a).

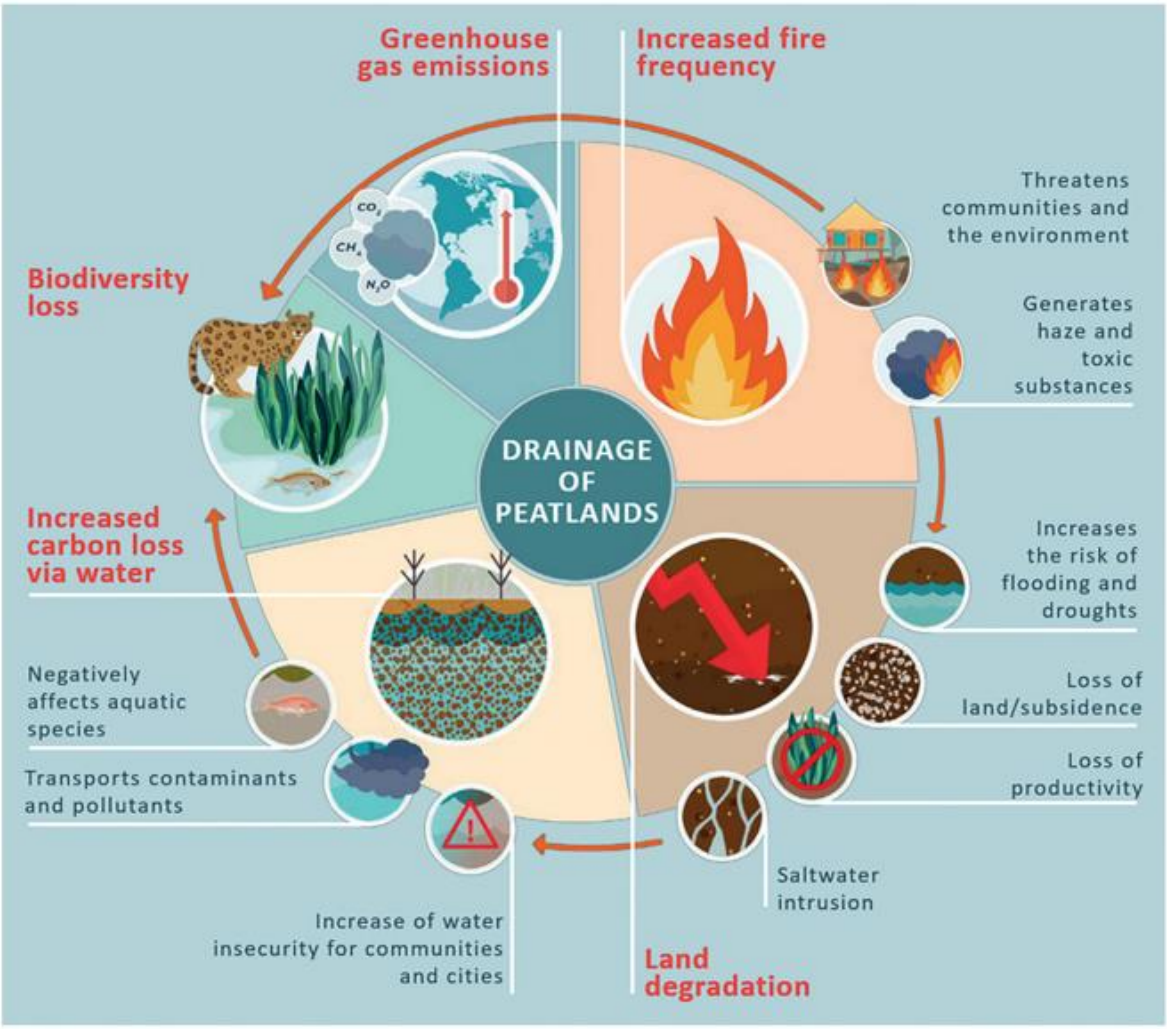

Figure 1. Environmental and social impacts of peatland drainage. Source FAO 2022. Peatland and climate change. Rome.

Degradation of peatlands can easily mobilise carbon stocks, creating a substantial source of GHG emissions (FAO 2022). This contributes to approximately 5% of global GHG (Joosten 2015), with drained peat soils releasing approximately 2.9 tCO2e ha^{-1} yr^{-1} (Campbell et al. 2015). They also release dissolved organic carbon (DOC) and particulate organic carbon into water ways, reducing water quality and altering vegetation and biodiversity over time (FAO 2022). Drainage for agriculture, for example, lowers the water table and fertilizer/herbicide inputs alter the gross primary productivity (GPP) and ecosystem restoration (ER) of peatlands. This alters decomposition rates, oxidising accumulated organic matter which then releases carbon dioxide (CO2), nitrous oxide (N2O) and methane (CH4) into the atmosphere (FAO 2022, Campbell et al. 2015). Fluctuation in water tables can also create alternate oxic and anoxic conditions that can lead to higher N2O emissions (Jurasinski et al. 2016). Organic nitrogen breaks down under oxic conditions which, if incomplete, will form and emit N2O. This is also impacted by available nitrogen (higher with mineral and organic fertilisation), temperature, carbon content and pH level. Peatlands under agricultural use emit 6.3 kg ha-1 a-1 per year and can significantly contribute to N2O emissions from national GHG budgets (Jurasinski et al. 2016.)

Drainage of peatlands and their use in conventional agriculture mineralises (oxidation) and shrinks and compacts peat, causing subsidence (depletion and consolidation of organic matter) and changes in water levels. Consequently, peatlands can shrink above the water table and compact further from livestock trampling, farm machinery and tillage. In many regions, including the Netherlands, Germany, the UK and Southeast Asia, subsidence from long-term drainage is a widespread problem. Subsidence increases drainage costs (creating a drainage-subsidence cycle), risk of coastal inundation and potential saltwater contamination of shallow aquifers, oxidation of carbon storage and the loss of ecosystem services. It can also damage infrastructure. If the water table is kept artificially low, peat height can fall by 2 cm per year on average (Meduna 2021a) (Figure 2). In addition, if the drained water table is lower than peat lakes, water can 'spill out' into the surrounding land.

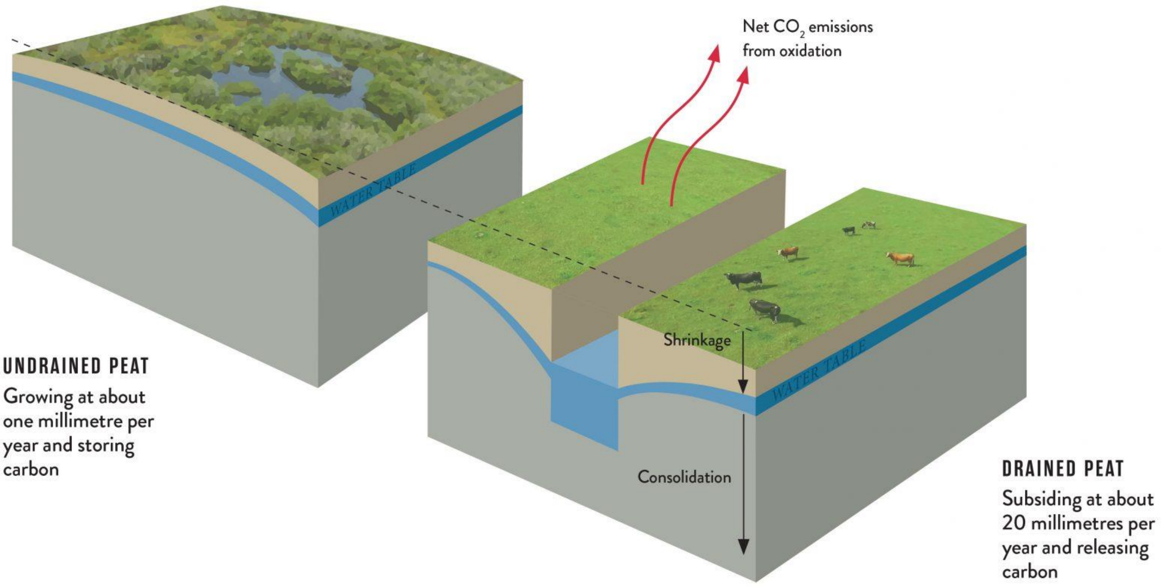

Figure 2. Undrained peat and subsidence in drained peat. Source: Meduna 2021a.

Peat soil that is compacted from peatland drainage remains acidic. This makes peatlands more susceptible to droughts as plant roots are unable to access deeper water during dry periods. Subsidence and soil degradation frustrate long-term peatland utilisation and are also responsible for almost 5% of the total global anthropogenic GHG emission (Wichtmann et al. 2016). The extent of peatland subsidence is dependent on time since drainage, land use, land and drainage management and peat type.

3.1 Peatlands in New Zealand

Peatlands can be found across New Zealand, in Northland, the West Coast, Waikato and Southland (Figure 3) (Minasny et al. 2019). Covering only about 1% of land area, peatlands in New Zealand store approximately one fifth of the country's biomass carbon (Schipper and Mcleod 2006).

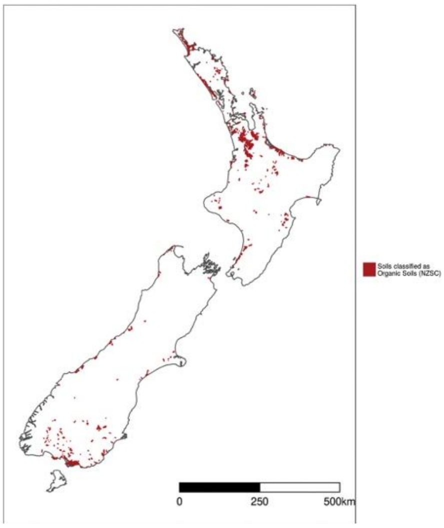

Figure 3. Distribution of peatlands in New Zealand. Source: Minasny et al. 2019

In warmer climates, peatlands are composed of mostly gramoids and woody vegetation[8]. Peatlands in cooler climates such as New Zealand are however rarely woody. The most common New Zealand swamp/wetland tree species, *Dacrycarpus*, do not form peat. The cooler, wetter climates of the northern hemisphere are often associated with peatlands that are predominantly built with *sphagnum spp*. Comparatively, species that make up peatlands in New Zealand are mostly composed of Southern Hemisphere families such as *Restionaceous* and *Cyperaceous* peats (Clarkson et al. 2016). *Restiad* bogs can be found in poorly drained environments and comprise of four main peat-forming species: *Empodisma robustum* (northern North Island), *E. minus* (central and southern North Island, and most of South and Stewart Islands), *Sporadanthus ferrugineus* (northern North Island), and *S. traversii* (Chatham Island) (Clarkson 2016).

Dissolved organic carbon (DOC) in New Zealand peatlands range widely, with lower average concentrations (7-184 mg l^{-1}) in ombotrophic peatlands (such as the Kopuatai peat dome) and higher concentrations (81-129 mg l^{-1}) found in the Torehape peatland, Waikato under drainage and peat harvesting (Moore and Clarkson 2007).

Intact peatlands have two layers, a relatively free-draining upper layer (the acrotelm) and a slower draining layer (the catotelm) underneath (Joosten & Clarke, 2002). The upper layer is quickly destroyed when peatlands are drained, and require a long time to reform after rewetting. Rewetted peatlands therefore lack the same ability as intact peatlands to regulate water flows.

Peatlands in New Zealand have been extensively drained and/or degraded for agricultural development (a loss of 73%, nearly 207,861 ha), closely associated with European settlement (Clarkson 2016). The majority of drained peatlands are currently classified as high producing exotic grassland[9]. They are associated with intensive land use practices such as high stocking densities and fertiliser use and are responsible for 1-6% of agricultural emissions in New Zealand (Ausseil et al. 2015). Peat soil has also been excavated for the horticultural industry, with two producers, one in Waikato and one in Southland[10].

Peatlands in New Zealand have as a result, suffered extensive (and ongoing) surface subsidence. This has significant implications for GHG emissions, production, water regulation, biodiversity and local economies and iwi. The remaining intact peatlands support threatened species of endemic flora and fauna, function as carbon sinks, represent a taonga for iwi and provide recreational opportunities[11]. To meet New Zealand's national and international biodiversity and climate goals, rewetting and restoration of peatlands is one option that might be considered.

[8] https://peatlands.org/peatlands/what-are-peatlands/#:~:text=In%20cool%20climates%2C%20peatland%20vegetation,most%20of%20the%20organic%20matter.
[9] https://www.forestandbird.org.nz/resources/restoring-peat-wetlands-our-climate-change-secret-weapon
[10] https://www.odt.co.nz/lifestype/magazine/peats-sake
[11] https://www.landcareresearch.co.nz/news/for-peats-sake/

3.1.1 Waikato region

The Waikato region contains approximately half of New Zealand's peatlands (approximately 94,000 ha which contains about 2,700 m^3 of peat[12]). Peatlands in the Waikato region are distinctive in their formation, largely from *Emphodisma* robustum, an endemic jointed wire rush from the Southern hemisphere vascular plants of the *Restionaceae* family – forming restiad peatlands (Campbell et al. 2015). Several extensive peatlands (up to 12 m deep) can be found in the region that developed from oligotrophic mires fed by deposits from former courses of the Waikato River over the last 10-14,000 years (Schlipper and Mcleod 2006).

80% of Waikato peatlands have been drained throughout the past century for year-round agricultural and horticultural use (Layton 2022). This accounts for about 40% of New Zealand's peatland resource. Most are used for dairy farming (approximately 1/3 of all the country's dairy farming production occurs in the Waikato region) but also produce much of New Zealand's blueberry harvest. Currently, 19,400 ha of peatlands remain in a natural (non-drained) state (Meduna 2021b, Pronger et al. 2014), including two wetlands of international significance and Ramsar Convention designated sites: Kopuatai bog (an intact raised Restiad bog) and Whangamarino wetland.

Depending on land use, drained peatlands in the Waikato emit between 10-33 tCO2e ha-1 yr-113 (Meduna 2021a). The rate of agricultural peat subsidence for the Waikato region has reduced significantly from 26 mm yr-1 (1963) and contemporary period (2007) subsidence rate of 19 mm yr-1 (Schipper and Mcleod 2006). Extrapolation indicates that 1 m of peat depth will be lost every 50 years. This ongoing subsidence is an important consideration in land management decision making.

4 Paludiculture

Intact peatlands and wetlands could theoretically continue to be protected entirely given their high value for nature conservation and carbon storage. Where drainage and degradation has occurred, one option to mitigate the loss of peat wetlands is to re-wet and or restore them either for their preservation or development of paludiculture (Figure 4).

> *"Paludiculture (lat. palus = swamp) is defined as the productive use of wet and rewetted peatlands under conditions in which the peat is preserved, subsidence is stopped and greenhouse gas emissions are minimized."* (Wichtmann et al. 2016).

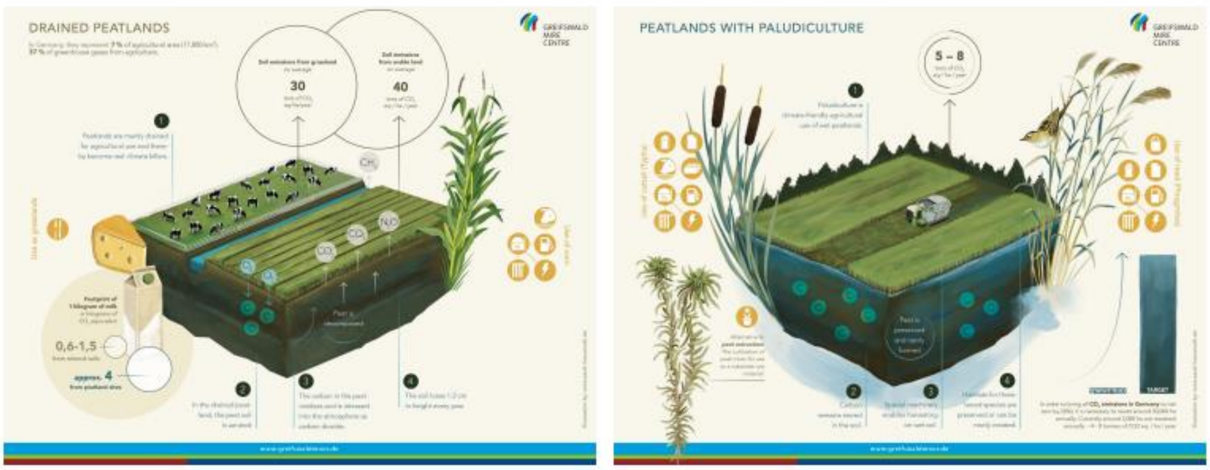

Figure 4. Drained peatlands and peatlands with paludiculture. Source: Griefswald Mire Centre 2021[14].

[12] https://www.waikatoregion.govt.nz/environment/land-and-soil/managing-land-and-soil/managing-peat/

[13] https://www.motu.nz/assets/Documents/our-work/environment-and-resources/climate-change-mitigation/emissions-trading/Offset-options-for-NZ2.pdf

[14] *https://greifswaldmoor.de/files/dokumente/Infopapiere_Briefings/202111_Opportunities-for-paludiculture-in-CAP-1.pdf*

The unique characteristics of peatlands make them particularly attractive for wetland production. First, peatlands are rich in organic matter. The waterlogged conditions prevent the decomposition of dead plant material, leading to the accumulation of peat. This peat accumulation creates a nutrient-rich soil that can support the growth of wetland-adapted crops, such as reeds, sedges, and rushes. Secondly, peatlands have a high water-holding capacity, which can help mitigate the effects of drought or flooding. The peat layer acts as a sponge, absorbing and storing water during wet periods and slowly releasing it during dry periods. This water regulation function can be particularly important in regions that experience water scarcity or flooding. If wetland agriculture were practiced on non-peat wetlands, it would require more rigorous nutrient and water management to ensure optimal crop growth.

Where high demand for productive land use is driving peatland drainage, paludiculture provides an alternative to the exclusive protection of peatlands. It can enable the use of peatland provisioning capacity without substantially compromising regulating ecosystem services (Wichtmann et al. 2016). Cultivated production of biomass from paludiculture can support tangible commercial products, such as harvesting for fodder, food, fibre and fuel. It can also support the production and provision of ecological and cultural services, such as flood regulation, reduced GHG emission and water denitrification.

Paludiculture as a sustainable land use option is explicitly referenced in several international initiatives such as the Intergovernmental Panel on Climate Change (IPCC) guidelines on National GHG Inventories on reporting of emissions and removals under the Kyoto Protocol, the Ramsar Convention on Wetlands and by the Food and Agriculture Organization (FAO) of the United Nations (Johnson and Land 2019).

Commercial potential in the production and use of biomass by-products from paludiculture (Wichtmann et al. 2010) exists – for example, developing innovative products for new and growing markets such as bioenergy or revitalising traditional land use such as reed cutting for thatching. Nevertheless, paludiculture is still early in its development and the scope for its implementation is poorly understood. Globally, paludiculture has limited in application, with less than 1% of Europe's 28.5 million ha of degraded peatlands being rewetted and only a fraction of this area being developed into paludiculture (Tanneberger et al. 2017).

4.1 Benefits

Paludiculture can be applied to support the ongoing functioning of healthy peatlands, or as part of a strategy to restore the productive functioning of peatlands previously drained for agricultural purposes ('rewetting)'. Rewetting can also protect existing peat wetland ecological services and functions and prevent further peatland degradation while paludiculture can retain the economic viability of the land (Layton 2022, Zeigler et al. 2021). Paludiculture preserves peat bodies and provides other ecosystem services (e.g. hydrological regulation, reduced GHG emissions and biodiversity conservation) and socio-economic benefits (production of above ground biomass for food, fibre, energy) (Schipper and Mcleod, 2006; Leifeld and Menichetti, 2018; Garrett et al. 2022). Over the long-term, accumulation of peat may potentially resume as rewetting of peatlands enables microbial recovery (Tanneberger et al. 2022). There are a diversity of products that can be developed from paludiculture biomass, including from fodder, food, raw materials for the production of horticultural growing substrates (e.g. *Sphagnum* spp.), bioenergy, bio-based construction materials (insulation, building materials, paper, bioplastics) (e.g. willow for wattle fences, reed for thatching, cattail for insulation).

Vital ecosystem services provided by intact or rewetted peatlands include carbon sequestration, improved flood regulation and water retention, water quality and nutrient removal, fire protection, biodiversity, etc. Provisioning ecosystem services, such as nutrition, water, raw materials, energy and medicine, can be used with paludiculture without compromising regulating services (Johnson and Land 2016).

Greenhouse gas fluxes. Rewetting for paludiculture production can reduce GHG emissions and potentially sequester carbon through peat accumulation over the long-term (Figure 5). The full climate impact of paludiculture is still being understood but life cycle assessments conducted in Finland (Lahtinen et al. 2022) aim to identify high emissions process stages in production to increase carbon benefits. Studies in Germany have also identified paludiculture GHG emissions to vary from 0-8 tCO2e h^{-1} y^{-1} (Tanneberger et al. 2022). After rewetting, CH4 emissions will be comparable to natural mires, but may vary in the first years after rewetting, for example, with higher emissions in nutrient rich peatlands and lower emissions in nutrient poor (Blain et al. 2014). N2O emissions after rewetting are small, varying between 0-50 kg N2Oe ha^{-1} a^{-1} (Jurasinski et al. 2016). When developing paludiculture, consideration of how different paludiculture crops and management will impact GHG fluxes, and their final use (i.e. as a long-term store of carbon in construction materials) is important. Monetisation of emissions reductions from rewetting of peatlands may also provide opportunity for income in paludiculture areas, but must be measurable, reportable and verifiable.

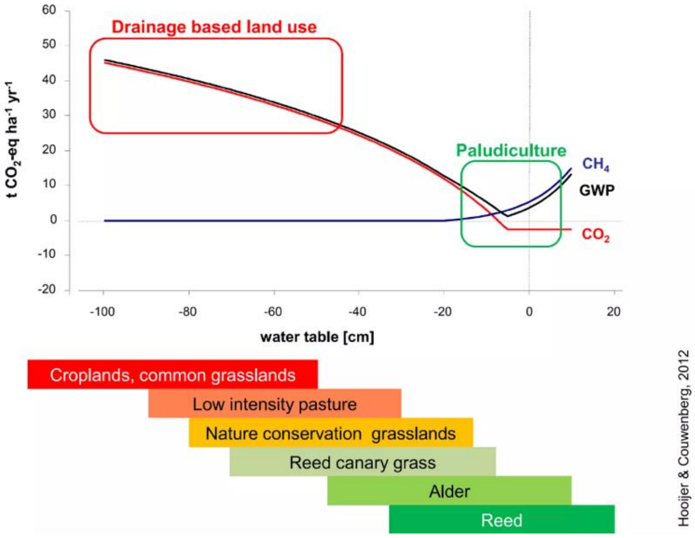

Figure 5. GHG emission balance of land use types. Source: Peters 2012. Adapted from Hooijer and Couwenberg 2012.

Biodiversity. Adjusting water levels in drained peatlands will cause significant shifts in vegetation composition. Rewetting can increase hygrophytic species (Tanneberger et al. 2021). Species composition will also change with continued succession from restoration. For example, Cattail (*Typha* spp.) will often rapidly colonize initially flooded areas with water tables above the surface. Reeds dominated by Common Reed (*P. australis*) or sedges (*Carex* spp.) are then likely to establish. The harvesting of paludiculture (e.g. mowing or grazing) will also reduce the accumulation of litter and increase light availability. This can have a significant impact on biodiversity (Tanneberger et al. 2021). This is likely to result in higher species-richness but is related to management types. For example, studies in Germany have found that cutting common reed decreases characteristic reed bird species but promotes waders such as *Vanellus vanellus* (Tanneberger et al. 2021).

Water regulation. Rewetted peatlands and mires under paludiculture can support water regulation, maximising ground water recharge and regulating water flow. This can reduce vulnerability to droughts. Where peatlands have been rewetted from natural reconnection with river systems, development of paludiculture on these systems can also support flood retention, although the implications for flood risk are complex and difficult to quantify (Mulholland et al. 2020). However this may be determined by the extent of subsidence. High water availability for evaporation will also impact local climate, having a cooling and humidifying impact. Paludiculture and the removal of drainage infrastructure can also support the nutrient retention mechanisms of peat soils, such as denitrification (Holsten and Trepel 2016).

4.2 Methods and approaches to paludiculture

There are many options for diversification of production through paludiculture (Lowland Peat 2021). Wet peatland cultivation can be conducted through permanent grassland paludiculture (e.g. wet meadows or wet pastures for spontaneous vegetation harvesting), or cropping paludiculture (e.g. artificially established crops).

4.2.1 Paludicrops

Paludicrop species are diverse, ranging from trees, to grasses, mosses, herbs or berry-producing shrubs (Abel, Schröder and Joosten 2016). They vary in their soil chemical and hydrological requirements, therefore, for each species, an optimal compromise between biomass production, climate mitigation and peat preservation can be sought within the context of the peatland site. This will also determine the type of management and harvesting mechanisms required for each paludiculture crop. For example, studies suggest that for the growth of peat forming paludicrops such as peat moss, alder and reed grown this is found with water levels 10 cm below the soil surface (Geurts et al. 2019). Other crops such as cattail, perform better with water levels 5 to 20 cm above the surface, which may increase CH4 emissions. Caution should be taken in the use of exotic paludiculture species which may become invasive. Yields will vary significantly depending on the site conditions, including nutrient status of water, climate, time of harvest etc. (IUCN 2019a).

Plants suitable for paludiculture, or paludicrops, are species that:

- thrive under wet conditions,
- produce a sufficient quantity and quality of biomass, and
- contribute to the formation of peat or peat conservation (Wichtmann and Joosten 2007).

The Greifswald Mire Centrum[15] has developed a Database of Potential Paludiculture Plants (DPPP)[16] which assesses the suitability of plants for paludiculture based on their: i) ability to preserve peat soil, ii) market potential; and, iii) existing implementation (Annex 1). The database provides a 'plant portrait', with information on plant characteristics and morphology, distribution and natural habitats, modes of cultivation and progradation, and use options (Abel et al. 2013) (Examples of paludiculture species and their productivity are highlighted in Table 6, with examples from Europe (Germany, the Netherlands, Poland and the UK), Canada and New Zealand. Detailed tables of paludiculture activities are available in Annex 2, Annex 3 and Annex 4. All costings, where available, have been converted to NZ$ to allow comparison.

[15] https://www.greifswaldmoor.de/home.html
[16] https://www.greifswaldmoor.de/dppp-109.html

Table 5). Paludiculture species of interest to New Zealand are most likely to fall in the columns entitled "Temperate" and "Subtropical" (FAO 2010).

Currently, the DPPP only has data for the Holarctic region (Abel and Kallweit 2022). Research by the University of Aarhus, Denmark and the University Nijmegen, the Netherlands is also identifying suitable paludiculture plants for Denmark and the Netherlands respectively. The University of Nijmegen is also identifying how to reduce CH4 and P emissions after rewetting (e.g. salinity pulses). Lessons learned from this research and the DPPP may be applied in the context of New Zealand peatlands.

Examples of paludiculture species and their productivity are highlighted in Table 6, with examples from Europe (Germany, the Netherlands, Poland and the UK), Canada and New Zealand. Detailed tables of paludiculture activities are available in Annex 2, Annex 3 and Annex 4. All costings, where available, have been converted to NZ$[17] to allow comparison.

[17] https://www.xe.com/currencyconverter/ Accessed with rates on 14 March 2023

Table 5. Examples of potential paludiculture species, their use category and distribution. Source: Database of Potential Paludiculture Plants.

Scientific name	Life form	Plant parts mainly used	Main use category	Paludi culture potential	Distribution (FAO ecozones)					Hol arctic
					artic	boreal	temp erate	sub tropic	tropic	
Abies balsamea	tree	wood, resin	raw material	**	X	X	X	-	-	X
Acorus calamus	forb/herb	root, leaf	food, medicine	**	-	X	X	X	X	X
Alnus glutinosa	tree	aboveground biomass, wood	raw material, fuel	***	-	-	X	-	-	X
Calla palustris	forb/herb	root, plant	food, medicine, ornamental	*	X	X	X	-	-	X
Echinochloa crus-galli	graminoid	aboveground biomass, seed	fodder	**	-	-	X	X	X	X
Ledum palustre	shrub	leaf	medicine, ornamental	**	X	X	X	-	-	X
Pistia stratiotes	forb/herb	plant	ornamental, fuel, fodder	**	-	-	-	X	X	-
Phragmites australis	graminoid	aboveground biomass	fuel, raw material	***	X	X	X	X	X	X
Sphagnum spp.	moss	biomass	agricultural conditioner, raw material	***	X	X	X	X	X	X
Schoenoplectus californicus	graminoid	stem, aboveground biomass	raw material, fuel	***	-	-	X	X	X	X
Symphytum officinale	forb/herb	root, leaf	medicine, food, ornamental	**	-	X	X	X	-	X
Thuja occidentalis	tree	wood, plant	raw material, fuel, ornamental	**	-	X	X	X	-	X
Trifolium fragiferum	forb/herb	aboveground biomass	fodder	**	-	X	X	X	-	X
Vaccinium oxycoccos	shrub	fruit	food	***	-	X	X	-	-	X
Zizania palustris	graminoid	seed, biomass	food, fodder, fuel	**	-	X	X	X	-	X

4.2.2 Options and examples for growing media

Sphagnum spp. (Peat moss) are commonly used for growing media, but is also used for reptile breeding and water filtration industries (Lambie and Soliman 2019). There is however wide variation in the natural productivity of Sphagnum spp. and not all species can be grown under specific climate (Table 6) (Mulholland et al. 2020). Nutrient content of water for *Sphagnum* spp. production may also influence it growth and suitability as growing material. *S. palustre* is particularly suitable for paludiculture as it establishes quickly and has high productivity (IUCN 2019a). Trials of cultivated *Sphagnum* in Germany achieved a 100% carpet thickness of 5-9 cm within 1.5 years with a maintained water table of 10 cm of ground surface. The antibacterial properties of *Sphagnum* spp. also highlight its potential to support medical applications (IUCN 2019a).

Table 6 Productivity of selected Sphagnum spp. in research trials. Source: Mulholland et al. 2020.

Sphagnum Species	Mean Biomass (g m^{-2} yr^{-1})	Climate	Location	References
S. cristatum	840	Hyper-oceanic	New Zealand	[1] & [2]
S. falcatulum	770	Hyper-oceanic	New Zealand	[1] & [2]
S. subnitens	590	Hyper-oceanic	New Zealand	[1] & [2]
S. fuscum	800	Humid	Germany	[3]
S. magellanicum	790	Humid	Germany	[3]
S. rubellum	960	Humid	Germany	[3]
S. palustre	575	Warm temperate, Humid	Georgia	[4]

[1] Stokes et al., 1999; [2] Gunnarsson, 2005; [3] Overbeck & Happach, 1957; [4] Krebs et al., 2016.

Cultivated *Sphagnum* biomass supplies the reptile and horticultural sectors, selling for NZ$980-390/490 per m^3. Global average production is 260 g m^{-2} yr^{-1}, or 3.7-6.9 t dry matter (DM) ha^{-1} yr^{-1} Current production costs are approximately NZ$ 98 m^{-3} based on production costs of NZ$ 48,900 $ha^{-1} yr^{-1}$ (Mulholland et al. 2020). The Netherlands exports nearly 40% of the global supply and New Zealand's production is worth NZ$ 5.1 million per year, with the majority exported to Japan for orchid production (IUCN 2019b). Trials in Germany suggest harvesting once every 3-5 years (Krebs et al. 2018), with productivity higher once complete cover is achieved.

Wild harvest of *Sphagnum* moss is already being practiced in the UK, Chile, USA, Canada and New Zealand. There is significant international market potential, selling between NZ$ 49-98 per m^3. Described as "Green Gold" (Yarwood 1990), *Sphagnum* farming is already established in New Zealand, with five species found on the West Coast of the South Island. For example, New Zealand's Besgrow *Sphagnum* moss is harvested from wetlands on the West Coast of Southland. It is renowned for its high quality (high water-permeability, long strands, longevity, high rot resistance) to support the horticultural and reptile industry.

The use of *Sphagnum* spp. to improve river health is also being explored. Farming of *Sphagnum* may also reduce the impacts of run-off on waterways in intensively grazed riparian zone where factors such as lower nutrient inputs, flood protection, shading and a shallow water table are provided for (Lambie and Soliman 2019). Further research is however needed on how these factors may affect harvest quality and whether *Sphagnum* growth is impacted by different nutrient inputs, pH changes, together with using peat versus pakihi as a growth substrate.

There are several challenges to scale *Sphagnum* production. These include sourcing suitable *Sphagnum* spores, irrigation – levelling of land, irrigation and water management are often needed to support sphagnum farming as extensive periods submerged under water will reduce or even halt their growth (Mulholland et al. 2020). While the species has low nutrient requirements, water quality is important as competition with weeds may occur when nitrogen and/or phosphorous levels are high (a significant issue in German sites) and the species is also intolerant of high calcium. Wild harvested *Sphagnum* may also bring vigorous contaminants, as seen in the Netherlands, with other wetland plants such as soft rush (*Juncus effusus)* and the moss *(Polytrichum commune)*. Soft rush could be removed through mowing, but the moss only after harvesting (Kumar 2017). However, over the long-term, these 'contaminants' were replaced by common cotton grass (*Eriophorum angustrifolium*). Harvesting presents significant challenges as any form of mechanical approaches will compress the crop surface. German trials have developed causeways alongside trial plots, suggesting some sacrificing of land is required.

4.2.3 Options and examples for bioenergy

Potentially, bioenergy may be derived from paludiculture as crops are converted to energy through chemical or thermal processes (e.g., composting). The greatest potential bioenergy crops from paludiculture are *Phragmites australis* and *Typha latifolia* (Biomass harvesting of reed canary grass and sedges in about 300 ha of fen meadows in Malchin, Germany is currently being developed as a biomass heating plant to provide heat to more than 500 households (IUCN 2019a). With a biomass yield of 800-1,200 t fuel, it provides an energy yield of 14.9 Gj per t FM (w 15%), the equivalent of 350,000 l of heating oil. This has saved 850 tCO2e yr^{-1} from bioenergy and approximately 10 tCO2-eq ha^{-1} yr^{-1} from rewetting.

Table 7). There is a range of biomass production potential for *P.australis*, indicating that genetic sourcing may be an important factor (Ren et al. 2019). Wichtmann and Joosten (2017) suggest that a harvest of up to 15 t ha^{-1} could be sustained. *T. latifolia* can grow in a range of climatic conditions, though is more common in shallower wetlands with optimal water levels 20-150 cm above the surface (Wichtman and Joosten 2017). The species also has high biomass production variability. Other potential crops include Rush species (*Juncus* effusus), *Phalaris arundinacea*, *Glyceria mazima* and *Carex* spp. sedges.

Biomass harvesting of reed canary grass and sedges in about 300 ha of fen meadows in Malchin, Germany is currently being developed as a biomass heating plant to provide heat to more than 500 households (IUCN 2019a). With a biomass yield of 800-1,200 t fuel, it provides an energy yield of

14.9 Gj per t FM (w 15%), the equivalent of 350,000 l of heating oil. This has saved 850 tCO_2e yr^{-1} from bioenergy and approximately 10 tCO_2-eq ha^{-1} yr^{-1} from rewetting.

Table 7. Ranges of potential paludiculture biomass production and higher heating value, and some key issues. Source: Mulholland et al. 2020.

	Phragmites australis **Common Reed**	**Typha latifolia** **Cattail/bullrush/** **Reedmace**
Potential biomass production (t ha-1 yr -1)	3.72-12.60	3.58-22.10
Higher heating value (MJ kg-1)	16.9-17.7	17
Potential issues	Unknown impact on management of CH4 fluxes Biogas production may be economically unviable Seedling growth in peat may be stunted Must be harvested at or dried <20% moisture content	Unknown impact on management of CH4 fluxes Biogas production may be economically unviable

Harvesting of *Typha spp.* in the Netley-Libau Nutrient Bioenergy project, Manitoba, Canada links lake nutrient management with bioenergy production of *Typha spp.* to restore wetland areas and product sustainable products. *Typha* is used to intercept and store nutrients (mainly nitrogen and phosphorous) and produce significant volumes of biomass for bioenergy (13 t ha^{-1}). Harvesting of the species removes the nutrients permanently from Lake Winnipeg, reducing nutrient loading and the effects of eutrophication (IUCN 2019a). *Typha* wood pellets provide an energy yield of 17-20 MJ kg^{-1} DM compared to just 17 MJ kg^{-1} of commercial wood pellets. Options and examples for food production.

4.2.4 Options and examples for food and fodder

Some wetland crops already cultivated for food such as celery (*Apium graveolens*) and water cress (*Nasturtium officinale)* in the UK. In Finland, berries lingonberry (*Vaccinium vitisidea*), cloudberry (*Rubus chamaemorus*), bog bilberry (*Vaccinium uliginosum*), and crowberry (*Empetrum nigrum*) are grown on peatland systems make up 14% of national production (>1 million tonnes) and are worth NZ$96 million per year (Salo 1996). In the USA, cranberries (*Vaccinium macrocarpon*) grow in acid sandy peat soil, with abundant fresh water and a suitable dormancy period to produce a crop for the following season. Cranberries are also commercially grown in Chile and the European variety, *V. oxycoccus* is grown in parts of central Europe, Finland and Germany[18]. Most blueberry production in New Zealand occurs in the Waikato and Hawkes Bay, covering approximately 400-620 ha of land with a value of NZ$ 41 million in 2016. The industry is expanding to undercover operations in both Northland and Southland[19].

Fodder and grazing crops such as reed canary grass (*Glyceria fluitans*), redtop (*Agrostis gigantea*), reed manna grass (*Glyceria maxima*), marsh foxtail (*Alopecurus geniculatus*) and lesser pond sedge (*Carex acutiformis*) can support livestock forage, but are of lower quality than conventional silage (Mulholland 2020). Livestock with low nutrient demands such as horses, Angus or Limousin cattle or water buffalo (*Bubalus arnee*) have been noted however to prefer fodder from fens (Müller and Sweers 2016). Water buffalo grazing of wet meadows in Gut Darß, Germany suggest they may be economically viable due to their ability to eat any riparian vegetation and hardiness. Per animal, yields ranged from NZ$ 6,540-9,130, providing high end products such as meat and dairy, as well as leather. However, prices vary with regional purchasing power and market research may be required for specific site suitability.

[18] https://www.cranberries.org/how-cranberries-grow
[19] https://www.tupu.nz/en/fact-sheets/blueberries-covered-cropping

4.2.5 Options and examples for construction materials

Phragmites spp. and other perennial reed grasses have been used throughout history for construction (thatching, insulation). In Europe, it is predominantly used for thatching which requires specific reed qualities. As a result, final product biomass is often 50% of initial harvest (Wichmann and Köbbing 2015). Biomass harvest yield can vary from 250-1000 bundles per ha. Reed is also used in garden screening and fencing in the UK, paper making, insulating material, panelling for construction (Köbbing et al. 2013). For example, production of thatch in Rozwarowo marshes in Poland, using well established market chains have also provided high biodiversity values (Tanneberger et al. 2009).

Other species include rushes such as *Juncus effusus* which is widely used for tatami mats (Japan) with great cultural significance and as flooring (UK). Depending on site conditions, cultivation of *J. effusus* can develop tall, thin-stemmed (sufficient nutrients and limited competition) or short and thick-stemmed (wet, low-grade agricultural land) (Mulholland et al. 2020). *Typha* spp. have also been used in the Danube valley, Germany to produce insulation plates which are in high demand (Witchman 2017).

4.2.6 Other potential paludiculture products

Paludiculture offers opportunities for the development of once traditional uses of wetland species. For example the recent increased interest in sustainable fibres for luxury clothing (i.e. as an alternative to cotton) have seen species such as nettle (*Urtica dioica*) developed on rewetted or intact peatlands and wetlands (Di Virgilio et al. 2015). Studies by Di Virgilio et al. (2015) suggest that 3-12t ha-1 of dry stalk yield can be produced, with other compounds valuable for the medicinal and cosmetic sectors. However, poor crop volume and processing costs hinder large scale production.

The restoration and rewetting of peatlands can also support other potential products such as whisky. For example, Whaiheke Whiskey[20] uses peat from the South Island from peatlands near Invercargill. As it is moss predominant, composed of *Sphagnum* moss, wire rush, sedges and flax, and there is an absence of tree lignin makes it less smoky, compared to whiskeys from Islay, Scotland for example.

5 Key considerations in developing paludiculture: challenges and opportunities for New Zealand

Large-scale changes are needed to encourage the maintenance of wetlands through paludiculture and or to encourage the transition from conventionally managed agricultural landscapes back to wetlands via rewetting and paludiculture. Changes may include changes in water management and associated infrastructure investments, current regulations and agricultural subsidies, market and supply development, and a willingness of land owners and users to support systems change at farm level. Land owners may be cautious to transition to alternative practices where transaction costs and future revenues may be uncertain. Conflicts may also arise between paludiculture-managed areas and those which remain under drainage-based management, in particular with high profitability such as from dairy farming.

Paludiculture development and production will not be viable in all drained peatland contexts. Factors such as biophysical limitations of the peatland (i.e. length of time drained, subsidence, saltwater intrusion, etc), economic viability (when compared to current drainage-based agricultural production baseline), legal conditions (i.e. where agricultural subsidence are adverse to the transition to paludiculture systems), and willingness to change will all influence the practicability and uptake of paludiculture at farm level. Tanneberger et al. (2020) uses four classes to determine the viability of paludiculture development:

[20] https://waihekewhisky.com/blogs/news/why-nz-peat-is-different

1. Any paludiculture is possible.
2. Permanent grassland paludiculture is possible but cropping paludiculture only after an administrative assessment.
3. Only permanent grassland is possible and an administrative assessment is needed to safeguard nature protection goals.
4. Ineligible: the area is not eligible for paludiculture.

Large, commercial scale paludiculture is not yet established in temperate Europe.

5.1 Site conditions

The type of peatland – how it was formed, dominant plant species, pH level, water source – together with its historic land use and rewetting plan will impact the type of paludicrop and harvesting potential. The Waikato peatlands, for example, have accumulated beyond the flood catchment area of the river resulting in peatlands with low nutrient and low mineral content (Meduna 2021a). By comparison, the fringes of Whangamarino swamp receive nutrients from the Piako river so are still nutrient-rich. Restoration of site specific conditions would therefore need careful planning and management of planting different species to enable succession and allow paludiculture crops to establish.

The historic long-term drainage-based management of agricultural systems has significant impact on the hydrology of peatlands including subsidence, biochemical oxidation, tillage and turning of the soil, design and maintenance of drainage ditches, etc. Dairy farming on peatlands, such as those in the Lower Waikato, presents high demands for deeper groundwater levels. To meet these demands and have optimal working and grazing conditions, permanent drainage is often preferred (de Vos et al. 2010). These conditions pose site-specific environmental, social and economic challenges in the transition to paludiculture.

Studies in Europe suggest that biodiversity and ecosystem functioning in rewetted peatlands differs to that of intact or near natural peatland (Kreyling et al. 2021). The result is that rewetting in highly drained areas may be more difficult than rewetting in areas that are less intensively drained. As a result, achieving the ecological and socioeconomic benefits of paludiculture may take more time – or be less effective – in highly drained areas, assuming everything else is the same.

Peatland time under drainage will have significant effect on subsidence rates and impact, and peat chemical change (from agricultural inputs and tillage). This influences the potential for peatlands to ‘recover’ from the impact of drainage to return to their full ecological function (oxidation may alter the physical parameters of peat) (Kreyling et al. 2021). For example, in highly degraded, long-drained peatlands, more intense water table fluctuations may occur due to decreased porosity. This can initiated CH_4 fluxes. Quantifying peatland subsidence rates is therefore key to inform land management decisions (Pronger et al. 2014).

Rewetting can also mobilize nutrients in agricultural soil, leading to eutrophication of water bodies and poor water quality (Kreyling et al. 2021). An inlet of nitrogen-rich surface or ground water is needed for sustained productive paludicrops, and to stimulate denitrification in anaerobic bacteria (to enable their use of NO_3 instead of O_2 in anaerobic conditions). If, however, harvesting of paludiculture biomass exceeds nutrient input, nutrient deficiencies may limit long-term productivity and economic returns. Soil pH may also be a determining factor for biomass yield, with, for example, optimal growth in species such as *Typha spp.* at pH>4.5 (Vroom et al. 2012). In heavily managed drained peatlands, removal of phosphate and other nutrients added to agricultural soil may also be required. There is also uncertainty of CH_4 emissions from peat decomposition through rewetting and paludiculture. Maintaining the water table below soil surface can therefore help to prevent increase CH_4 fluxes (van der Berg et al. 2019b).

It is important to consider site-specific challenges and barriers for rewetting peatlands and paludiculture production to identify the biophysical suitability and economic viability at farm level and at scale. If restoration of natural river flow is a priority, it will be difficult to determine where rewetting may occur and identify its potential impacts on existing land use/users as well as identification of the carbon potential and development of paludiculture.

5.2 Economic considerations

Drained peatlands under management for agricultural production provide considerable economic value, with agricultural production on peat soil worth NZ$ 700 million per year (Maduna 2021b). As degradation continues over time, continued drainage is likely to become more expensive for farmers (Pronger et al. 2014). The risk and frequency of flooding, inundation, reduced sustainability of wetlands and ponding due to uneven subsidence and reduced drainage gradients will be increased by continued peat loss and subsidence (Pronger et al. 2014). Climate change, including sea level rise and the potential for saltwater intrusion, will exacerbate these impacts (Clarkson et al. 2004). This can be expected to increase agricultural production costs to land owners. For example, in the Hauraki region, subsidence of some peat soils means that some land is now below sea level. Further degradation and continued drainage over time will therefore increase costs for drainage-based farming and land management (Pronger et al. 2014).

A transition from drainage-based agriculture to paludiculture, especially at scale, requires production to be economically viable (Wichtmann 2016). From farm-specific factors (production factors – capital, labour, acreage) impacting profitability include legal conditions and land user willingness to change. There is significant technical and economic uncertainty in establishing paludiculture. Currently, methods and reliable data are limited (Tanneberger et al. 2021). Data on site conditions (years of drainage, peatland type, pH level, subsidence etc.), management requirements, biomass yields, machinery and labour requirements are required to support cost and revenue predictions.

As a general observation, changes in land use from existing uses are unlikely to occur without costs. Transitioning from drainage-based production to less intensive paludiculture is likely to be associated with falls in the earnings associated with existing farming (NZ$ 700 million per year as per Maduna 2021b), so incentives are likely to be needed to encourage farmers to consider change.

In this respect, Tanneberger et al. (2021) notes that, for EU countries, the potential income from agri-environmental schemes such as the EU CAP has a significant impact on outcomes (e.g., by financially facilitating transitions). Careful consideration of funding frameworks is therefore required if paludiculture is to be encouraged. Taking into account how the drained peatland will be rewetted (say, by allowing the natural course of rivers to resume or thorough the installation of water control structures) is also an important consideration when determining the costs and potential revenue from paludiculture.

An economic analysis of paludiculture development and alternative uses (continued drainage-based management, rewetting without paludiculture) could be conducted to quantify potential impacts on ecosystem services, opportunity and transaction costs, potential revenue, external and internal costs of agricultural production, financial requirements of rewetting (especially if this will be determined by natural river course), planning etc (Schäfer 2016).

Costs of rewetting measures, including paludiculture development, have been conducted in Germany with costs estimated between NZ$ 2,140-3,124 per ha (Schäfer 2016). For example, the Blindowner Wiesen paludiculture project in Brandenburg rewetted an area of 130 ha, with an additional 192 ha of bordering reedbeds. Costs included track building, hydrologic and civil engineering, installation of a pontoon bridge and further costs (including initial construction and compensation payments) and totalled NZ$ 633,400 or NZ$ 2,015-4,984 per ha (Hasch et al. 2012).

Further research could be conducted to determine which paludiculture systems are most economically viable and competitive, sustainable at large-scale and whether additional investments or financial incentives would be required to support the transition from drainage-based management. For example, an analysis of cattail production in the Netherlands and its competitiveness showed that a transition to paludiculture systems would not be able to compete with the current dairy farming system under present conditions (de Jong 2021). Where paludiculture aims to scale up, innovation is also required to increase the cost effectiveness and practicality of production and harvest, and reduce high labour costs associated with weed control, trafficability etc. (Lowland Peat 2021).

5.2.1 Harvesting, logistics and capital

*Machinery***.** The cultivation of paludiculture on wet peatlands requires site-specific approaches and equipment for harvesting (Wichtmann et al. 2016) (Table 8). Machinery needs to be adapted to the wet conditions in paludiculture to minimise ground pressure and reduce the frequency and impacts of vehicle crossing. This may be developed by reducing vehicle weight, increasing ground contact surface (e.g. use of floatation wheels, balloon tyres, etc). The type of machinery required to mow, uptake and recover biomass will be determined by the groundwater level, vegetation (i.e. paludicrop), harvest season, location, size and typography of harvest area, requirements for biomass harvesting, peat degradation and soil conditions.

Table 8. Existing machinery for wet peatland sites. Source: Wichtmann et al. 2016.

Machinery	Example	Application	Benefits	Limitations
Adapted conventional agricultural machinery	Farm tractors with floatation wheels	Mowing Removal of biomass in moderately wet conditions	High mowing performance Biomass removal possible	In high water levels
Small machinery	Uniaxial tractors or small tractors with cutter bars	Mowing Management of peatlands to conserve and restore species and habitats	Limited impact on peatland	Low performance/high cost Small-scale application
Wheeled special machinery	Seiga machines with 2-3 axles and balloon tyres	Reed harvest	Low ground pressure	No longer produced Limited engine performance
Tracked special machinery	Specialised machinery and adaptation of snow groomers	Biomass harvest Conservation management	Low ground pressure	Conversions are mostly individual Soil damage may occur during turns

Logistics of biomass harvesting. The harvesting of biomass from paludiculture – including harvesting removal and pre-processing on site - can be challenging (Schröder, Dettmann and Wichmann 2016). There may be different requirements for processing of biomass, for example, fresh vs dry, long stems, chopped biomass, round bales, single bundles or bound to large bales). The frequency of harvesting biomass will also influence its quality and quantity. Harvesting of biomass in paludiculture often only takes place once a year due to the limited trafficability of peat soil. Development of paludiculture on rewetted peatlands therefore require parallel development of supportive harvesting infrastructure and logistics.

5.3 Enabling environments for paludiculture

Uptake of paludiculture at farm level may be limited where there are limited supportive policies or legal frameworks linked to paludiculture or carbon credits related to peatlands[21] and/or where there are ongoing policy incentives to maintain drainage-based agriculture. Provision of financial incentives to support paludiculture implementation as an alternative to drainage-based implementation might

[21] https://www.motu.nz/assets/Documents/our-work/environment-and-resources/climate-change-mitigation/emissions-trading/Offset-options-for-NZ2.pdf

be needed to enable a shift in land management. This could be linked to agricultural policy (e.g. revision of EU Post 2020 CAP to include incentives for paludiculture and removal of adverse subsidies) or peatland and paludiculture-specific carbon markets.

In the EU, counteractive incentives under the Common Agriculture Policy (CAP) artificially increase the profitability of drainage-based agriculture. This creates little incentive to shift production practice. Recognising the importance of paludiculture in sustainable production and provision of ecosystem services has been raised with Members of the European Parliament, European Commission and all Member States by Wetlands International and the Greifswald Mire Centre. Specifically Wetlands International proposes to encourage states to, integrate paludiculture into spatial planning and new CAP (Pillars I and II); make paludiculture eligible for CAP payments by qualifying paludicrops (reed, cattail, peatmoss etc) as agricultural activity; phasing out CAP funding for drained peatlands (direct payments, agri-environment climate schemes, investment promotion for drainage systems, etc) to enable the paradigm shift needed[22].

Long term support through legal frameworks to support the uptake of paludiculture in New Zealand is likely to require an alignment of policies to wetland biomass to be sustainable and profitable. To ensure the eligibility of paludiculture crops are recognised, changes in agricultural legislation may be required together with clear, longer-term policy signals to provide continuity of support and planning security (IUCN 2019) This includes the identification and phasing out of counter-productive subsidies and incentives to reduce the profitability of drainage-based agriculture. The development of markets for ecosystem services from paludiculture, including payments for ecosystem services (PES), recognised carbon market standards etc., may also be explored to encourage private sector investment and provide incentives at farm level.

In New Zealand, soils are reported as a net source of carbon under the Kyoto Protocol (Meduna 2021a). Improved management of soil carbon (in peat soils, this accounts for 12.5-20% of carbon stored in all vegetation in New Zealand), could also support mitigation and achievement of national climate goals. Currently, within existing policy, there is however no mechanism to support carbon credits earned from increasing soil carbon. Initiatives such as He Waka Eke Noa[23], the Primary Sector Climate Action Partnership, are recommending to build-in incentives to reduce farm-level carbon emissions and sequester carbon. This would reward farmers who implement actions and technologies that deliver measurable emissions reductions and maintain and/or increase sequestration. Further investment in the protection of intact peatland and wetland sites, and the restoration of degraded and drained peat soils is required to support reflooding and replanting. This could be coordinated with other ministries, such as the Ministry of Agriculture, to ensure that policy incentives support the transition to restoration and protection of wetlands and peatlands.

5.4 Social considerations of paludiculture

Rewetting of peatlands for their restoration and/or use for paludiculture will impact the landscape and local perception of peatlands (both positive and negative) (Deickert and Piegsa 2016). Identifying local use and connection to the landscape, peatland and use of wetlands is therefore important to draw on local and traditional knowledge (tangata whenua), and integrate stakeholder interests or address potential conflicts. The inclusion of a diversity of stakeholders in discussions can help to reduce the potential of conflicts of interest.

5.5 Implementation and sustainability of paludiculture

Variation in the suitability of rewetting and developing paludiculture on different peatland areas may impact the feasibility of wetland agriculture. When drained peatlands are rewetted for conservation purposes, there is often considerable spatial variation in water level. This creates a mosaic of site

[22] https://www.wetlands.org/news/lets-recognize-paludiculture-as-an-eligible-practice-in-the-eus-common-agricultural-policy/
[23] https://hewakaekenoa.nz/report/

conditions. To establish paludiculture, the water level needs to be near the surface throughout the year. This reduces loss of carbon and nutrients, preserves the peat body and provides optimal growth conditions to wetland plants. To enable stability of the water table, regulation and technical measures may be required.

Site conditions will determine the planning of paludiculture and its infrastructure requirements, such as the type of paludiculture crops (and net area that can be harvested) and land use practices, together with management approaches and harvesting timing and technique. For example, water reeds may be established in inundated areas, with a surrounding buffer of wetland meadows. Cattail fields require large nutrient supply and so can be used to irrigate fields whereas Common Reed grown in nutrient poor sites are good quality for thatching. Alder species for timber production can take place in dryer sites.

Rewetting peatlands requires different approaches depending on the peatland condition and supply of ground and surface water (Wichtmann and Schröder 2016). This may require a one-off measure to restore high water tables (e.g. ground sills, infilling of ditches, weirs and dams) or active management (adjustable weirs, pumping facilities, mobile pumps) of the water table. This will have cost implications at site level. One-off measures aim to restore peatlands by retaining water but will often result in significant water level fluctuation, reflecting natural dynamics. This does not usually support the optimum water tables required by paludiculture. Active management and regulation of water tables can balance seasonal fluctuations, potentially improve flood protection and be managed to reduce levels during harvest for trafficability of machinery.

The implementation of different uses of rewetted peatlands in one area may therefore provide greater value and diversification, if not challenging. Criteria to identify prospective paludiculture sites could therefore be developed in the context of the peatlands and wetlands of the Lower Waikato (Table 9).

Table 9. Example set of criteria to identify prospective paludiculture sites. Source: Haberi et al. 2016.

Criterion	Aim	Examples
Soil type	Organic soils only	Peat layer of at least 30 cm depth
Current land use	Restriction to agricultural land	Suitable: Arable land, grassland and fallow land
Habitat type/vegetation type	Restriction to suitable habitats and vegetation	Unsuitable: Forest, urban areas, water bodies Suitable: Reed beds, sedge stands, humid forb communities
Conservation status	Conservation objectives	Excluded: Core zones of national parks and biosphere reserves, pristine mires Conservation management: Maintenance of short grasslands as breeding habitat for birds; avoidance of shrub encroachment
Size of area	Economically viable land use	Minimise logistic effort: e.g. minimum area >15 ha and >100 ha within a radius of 10 km
Hydrogenetic mire type	Assessment of water and nutrient availability	Rewettability Suitability for different paludicultures
Degree of drainage	Assessment of the current status	Necessary rewetting measures
Catchment	Assessment of rewettability	Assessment of impacts on neighbouring areas; assessment of water supply

6 Future research

Following is a series of topics that could be valuable for researchers to improve understanding of the suitability of paludiculture in New Zealand. Some of these (such as economic assessment) may fit well within the *Future Coasts Aotearoa* project. Otherwise, they may require additional research funding.

Paludiculture can reduce the impacts of drainage-based agriculture in New Zealand. While there are numerous examples of paludiculture development in the northern hemisphere (Europe, the USA and Canada), there are limited examples in a New Zealand context, especially at scale (Meduna 2021b).

There is limited literature on the development of paludiculture in New Zealand, but information from Holarctic (Database of Potential Paludiculture Plants[24]) could be used to find similarities specific to the Lower Waikato region.

For paludiculture to be explored in New Zealand, and in the Lower Waikato in particular, further research will be needed to:

Site conditions

- Map peatland biophysical conditions (peat depth, current land use, habitat type, conservation status, pH level, identify P, NO2, CH4 and DOC levels in soil)
- Assess rewettability of the peatland. In particular if this aims to be conducted with the natural course of the river. This will determine the suitability of different paludiculture crops
  - Assess the degree of drainage – subsidence, time under drainage, method to drain
  - Assess water and nutrient availability
  - Map catchment to assess the potential impacts of rewetting on areas outside of the peatland (including outlying farmland, infrastructure, homes or other buildings etc).
- Identify suitable paludiculture species including:
  - Whether a diversity of crop types are more appropriate according to succession, water table level, nutrient level etc.
  - Best practices for their production, harvesting requirements and potential markets
  - Water table requirements and potential saltwater contamination.
- Identify and overcome *technical challenges for harvesting on wet and inundated peatlands*
- Identify alternative management for drainage based agriculture to reduce impact
- Map the carbon potential of rewetting the Lower Waikato, compared to business-as-usual drainage based agriculture
- Explore the potential for growing food crops displaced from organic soils (peatlands) on mineral substrate soils where their environmental impact may be lower.
- Explore the potential direct and indirect contribution of non-peat substrate wetlands (mineral substrate swamps, marshes, seepage, pakihi and gumland, saltmarsh, shallow water and ephemeral wetland) in maintaining and enhancing sustainable agricultural production[25], including productive impacts on wetlands (all classes) from water use, drainage and flow diversion, contaminants (nutrients, fertilizers and pesticides), land conversion, erosion and soil degradation, and extraction of biota.

Economics

- Conduct an economic analysis of the costs and benefits to transition to paludiculture system, restoration of peatland through rewetting and willingness of land users to transition land management approaches, including:
  - Cost Benefit Analysis of site specific paludiculture approaches to identify economic viability of crop types in the context of New Zealand or Lower Waikato site conditions
  - Life cycle assessment (LCA) of the commercial viability of paludiculture with and without a carbon credit system
- Identify and develop functional markets, value chains and production lines adapted to new types of biomass and developing business models
- Analyse the investment requirements for large-scale implementation, including diversification of income from paludiculture, carbon, PES, etc.

Enabling environment

[24] https://www.greifswaldmoor.de/dppp-109.html
[25] https://www.ramsar.org/sites/default/files/documents/library/bn13_agriculture_e.pdf

- Analyse the current policy on peatland-drainage based agriculture and land user/owner support to rewet and restore peatlands, and develop paludiculture. Including activities of Waikato Regional Council[26]
- Remove market distortions such as agricultural subsidies for drainage-based peatland agriculture, if appropriate
- Adapt policy to include and support wet peatland agriculture, including the development of initiatives such as payments for ecosystem services (PES) to provide incentives and compensate for the social and environmental costs and benefits of paludiculture
- Explore the potential of carbon credits and the policy requirements to support their development from paludiculture implementation as it is currently not possible to earn carbon credits from soil carbon (Meduna 2021b). If looking to develop carbon credits, consideration of clear baselines, monitoring and evaluation, and determining who to pay etc will be key.

Social considerations

- Conduct iwi-led community consultations to:
    - Explore land user awareness/ interest in the value of wet/ rewetted peatland restoration and their potential beyond drainage-based agriculture for paludiculture, carbon storage, provision of ecosystem services, etc.
    - Scope land user willingness to transition current land management approaches
- Exploration of land user awareness/interest in peatland restoration and potential paludiculture development.
    - Explore the role of iwi and Māori connection to land as a key driver for change, including any historic tangata whenua use of sustainable harvesting from wetlands to retain links between cultural identity, wetlands and well-being.

Paludiculture itself is *"not a panacea"*[27] for the protection of peatlands, but provides an opportunity to diversify activities into a bio-based circular economy on peatlands while maintaining livelihoods and developing innovative production. The type of paludicrop and production method will be site specific, depending on historic land use and drainage, the extent of peatland degradation and proposed rewetting management approach. The site-specificity of paludiculture development creates high levels of uncertainty for its implementation to determine successful outcomes and economic costs.

"*Paludiculture implies an agricultural paradigm shift"* (Greifswald Mire Centre, 2022). To enable large-scale/economic viability of paludiculture production a complete shift in management practices and wet-adapted machines are required. There are significant capital considerations at both farm and catchment level that will be determine by site conditions. Provided that markets exist, paludiculture can be made financially viable or can also be supported by subsidies or incentives that reflect and compensate for the wider benefits of peatland protection for society. Soil carbon has a potential to be a significant mitigation option to support New Zealand's climate commitments, with multiple co-benefits. The potential for increasing soil carbon is however complex. It is highly dependent on soil type, current management practices, climate, water source, etc. As a result, the cost of measuring soil carbon can be high.

The feasibility of rewetting drained peatlands, and the subsequent eligibility or economic viability of paludiculture development may vary significantly across peatland areas (Johnson and Land 2019). Where rewetting or paludiculture is not possible, options such as adaptive management that avoids over-drainage, soil tillage and the use of fertilizers is preferred, together with protection of wetlands on private land. Other mechanisms such as carbon credits or payment for ecosystem services related

[26] https://www.waikatoregion.govt.nz/environment/natural-resources/water/lakes/shallow-lakes-of-the-waikato-region/peat-lakes/#:~:text=The%20Waikato%20peat%20lakes%20form,Rukuhia%20and%20Moanatuatua%20peat%20bogs.
[27] https://www.iucn-uk-peatlandprogramme.org/sites/default/files/2019-11/COIFens_ProductiveLowlandPeatland.pdf

to improved management of peatlands and reduction of emissions may also be developed to provide financial incentives to shift from drainage-based practices.

Rewetting peatlands in New Zealand and implementing a systems changes could support the country's net zero carbon future. Soil carbon has a potential to be a significant mitigation option to support New Zealand's climate commitments, with multiple co-benefits. The potential for increasing soil carbon is however complex. It is highly dependent on soil type, current management practices, climate, water source, etc. As a result, the cost of measuring soil carbon can be high. The economic potential and viability is therefore currently unknown. To ensure the economic viability of a systems change to paludiculture when competing with current drainage-base agriculture, carbon credits could support land users achieve a positive net present value to make paludiculture an attractive proposition. There are promising results from Europe of the benefits of paludiculture for GHG reduction and more sustainable production on peatlands. However, further research is needed to understand the context of New Zealand peatlands and their potential for paludiculture, together with land user willingness to change and adapt to more sustainable land use systems for long-term vs short-term benefits.

7 Conclusion

In conclusion, paludiculture offers a promising alternative to conventional drainage-based agriculture on former peatlands in the Lower Waikato. By promoting the productive use of wet and rewetted peatlands, it can help maintain ecosystem functions, reduce greenhouse gas emissions, and contribute to the country's net-zero carbon goals. While not all rewetted peatlands can restore sufficient peatland function to enable paludiculture, identifying appropriate sites and learning from international experiences can pave the way for a paradigm shift in land management practices. The economic viability, social considerations, and enabling environment for paludiculture in New Zealand require further research and investment in innovation to ensure its successful adoption. Developing markets for ecosystem services and involving local communities and iwi are essential to foster support and maximize the benefits of this innovative approach. Investing in paludiculture research represents a valuable opportunity to diversify agricultural practices, support a bio-based circular economy, and provide a way to thrive with more natural river flows.

8 Acknowledgements

Paludiculture as an adaptation option in the Future Coasts Aotearoa project was identified by research partners *Te Puuaha o Waikato whaanau* with support from community-based researchers at Swampfrog. *Te Puuaha o Waikato whaanau* and researchers at Swampfrog specifically recommended that paludiculture be investigated as a potential option to enable communities in the Lower Waikato case study area to adjust to relative sea level rise.

Their contributions to this work is gratefully acknowledged.

9 Glossary of abbreviations and terms

Agrostis gigantea	redtop
Alopecurus geniculatus	marsh foxtail
Apium graveolens	celery
Bubalus arnee	water buffalo
CAP	Common Agriculture Policy
Carex acutiformis	lesser pond sedge
Carex spp.	sedge genus
CH4	methane
CO2	carbon dioxide
Cyperaceae	sedge family
Cyperaceous peat	peatlands predominantly made of sedge spp.
DM	dry matter
DOC	dissolved organic carbon
DPPP	Database of Potential Paludiculture Plants
Empetrum nigrum	crowberry
Empodisma	genus of rush species in the *restionaceae* family
Empodisma robustum	wire rush
ER	ecosystem restoration
Eriophorum angustrifolium	common cotton grass
EU	European Union
EU CAP	European Union Common Agricultural Policy
forbs	herbaceous plant that is not a grass or grass-like and do not become woody

FENZ	Fresh Water Ecosystems of New Zealand's (FENZ) Wetlands of National Importance Database[28] Geodatabase providing national data on characteristics of freshwater ecosystems
geogenous mire (fen) (also minerotrophic)	peatland situated in a depression fed by mineral rich ground or surface water and precipitation
GHG	greenhouse gas
Glyceria fluitans	reed canary grass
Glyceria maxima	reed manna grass
GPP	gross primary productivity
graminoids	herbaceous plants with a grass-like morphology (grasses, rushes and sedges)
hygrophytic species	species of plants that grow and thrive in wet conditions
IPCC	Intergovernmental Panel on Climate Change
Juncaceae	rush family
Juncus effusus	soft rush
mesotrophic peatlands	Peatlands with a thick peat layer, high organic content and acidic conditions
minerotrophic mires/ peatlands (also geogenous mire)	peatland situated in a depression fed by mineral rich ground or surface water and precipitation
mires	wetland types that form and accumulate peat
Nasturtium officinale	water cress
New Zealand Land Cover Database	New Zealand Land Cover Database LCDB v5.0[29]. A multi-temporal, thematic classification of New Zealand's land cover.
N2O	nitrous oxide
NO3	nitrate
O2	oxygen
oligotrophic mires	bogs and raised bogs, nutrient-poor and low biomass production
ombrotrophic peatlands/ ombrogenous mires (bog)	rain-fed only peatlands raised above the surrounding landscape, high in soil carbon but low in nitrogen and phosphorus
P	phosphorus
P. australis	Common Reed

[28] http://tools.envirolink.govt.nz/dsss/freshwater-ecosystems-of-new-zealand/
[29] https://lris.scinfo.org.nz/layer/104400-lcdb-v50-land-cover-database-version-50-mainland-new-zealand/

paludiculture	the productive use of wet and rewetted peatlands under conditions in which the peat is preserved, subsidence is stopped and greenhouse gas emissions are minimized
peat	Terrestrial wetland ecosystems in which waterlogged conditions prevent plan material from fully decomposing
PES	payments for ecosystem services
pH	quantitative measure of the acidity or basicity of aqueous or other liquid solutions
Phalaris arundinacea	reed canary grass
Phragmites australis	common reed
Phragmites spp.	common reed
Poaceae	grass family
Polytrichum commune	common haircap (a form of moss)
restiad bogs	peatlands predominantly made of restiad spp.
Restionaceous peat	peatlands predominantly made of restiad spp.
Rubus chamaemorus	cloudberry
sedges	Cyperaceae family
Sphagnum palustre	prairie sphagnum or blunt-leaved bogmoss
Sphagnum spp.	peat moss
Sporadanthus ferrugineus	Bamboo rush, giant wire rush
Sporadanthus traversii	Chatham Island bamboo rush
tCO2e	tonnes (t) of carbon dioxide (CUK equivalent (e))
Typha latifolia	broadleaf cattail, reedmace, bullrush
Typha spp.	cattail
Urtica dioica	nettle
Vaccinium macrocarpon	cranberries
Vaccinium oxycoccus	European cranberry
Vaccinium uliginosum	bog bilberry
Vaccinium vitisidea	lingonberry

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11 Annexes

11.1 Annex 1: DPPP – Plant Portrait

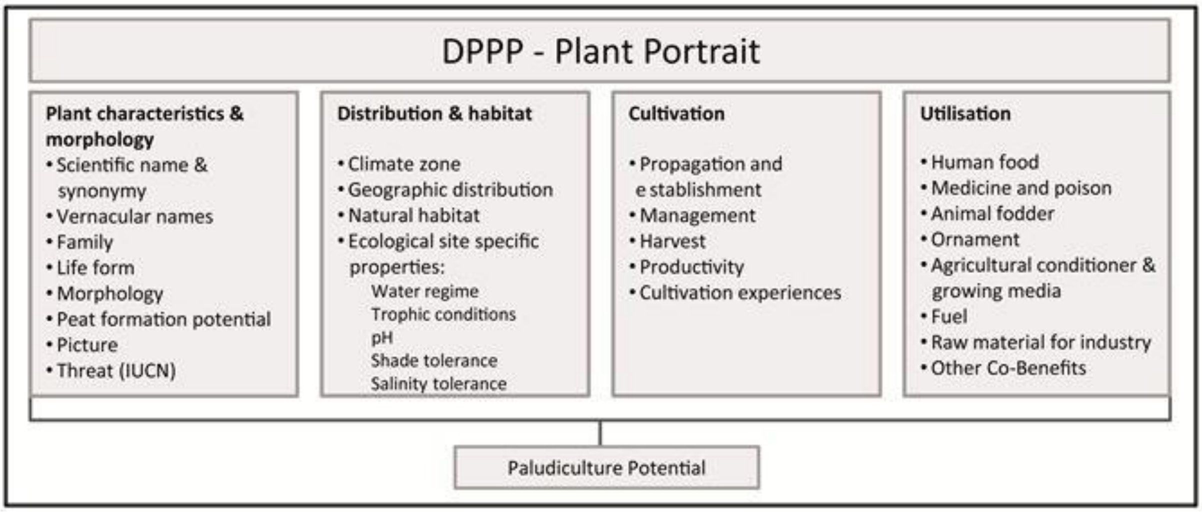

Figure 6. Characteristics of species and their paludiculture potential within the Database for Paludiculture Plant Potential

11.2 Annex 2: Examples of paludiculture species and their use

See Excel sheet

11.3 Annex 3: Examples of paludiculture around the world

Table 10. Global paludiculture examples. Source: Wichmann et al. 2016.

Country (Region)	**Germany (Mecklenburg-West Pomerania)**[30]	**Belarus (Grodno Region)**[31]	**Poland (Biebrza Podlasie)**[32]	**Indonesia (Kalimantan)**[33]	**China (Heilongjang Jilin)**[34]	**Canada (Manitoba)**[35]
Peatland type/ soil type	Fen (degraded valley mires, polders)	Raised bog and fen (cutover peatlands)	Fen (semi-natural)	Raised bog (degraded, deeply drained former peat swamp)	Lake edges (lake sediments, terrestrialisation mires)	Fen (flood mires, flood plains)
Land use to date	Drained grassland	Drainage and superficial peat cutting, then abandoned	Haymaking, later succession of shrubs and trees	Rice cultivation, abandonment	Traditional land use	Recreation, hunting, trapping, agriculture
Objectives	Climate protection, sustainable land use, biomass utilisation	Climate protection, species conservation, biomass utilisation	Habitat management, biomass utilisation	Prevention of peat fires, sustainable land use, climate protection	Biomass production (as raw material for pulp production)	Nutrient retention, biomass utilisation
Plant species	Common Reed, Reed Canary Grass and sedges	Common Reed, Reed Canary Grass and sedges	Mainly sedges	Multiple crops	Common Reed	Cattail
Harvest/transport	Converted snow groomers	Adapted tractors, converted snow groomers	Converted snow groomers	Manual	During frost, manual; common agricultural machinery	Adapted tractors
Utilisation of biomass	Energy and material use	Energy use: briquettes, pellets	Energy use: pellets	Food, timber, pulp	Paper, wicker work, forage	Energy use: loose biomass, bales, briquettes, pellets

[30] Schröder 2016
[31] Wichtmann, Kapitsa, Tanneberger and Tanovitskaja 2016
[32] Tanneberger, Gatkowski and Krogulec 2016
[33] Dommain 2016
[34] Köbbing 2016
[35] Grosshans 2016

11.4 Annex 4: Examples of UK-specific paludiculture projects

Table 11 UK-specific paludiculture projects. Source: Mulholland et al. 2020.

Project Name	Dates	Funder	Budget	Main UK Partners	Areas Investigated	Project Link	Publications
Sphagnum Farming UK - A Sustainable Alternative to Peat in Growing Media	**2018 To 2019**	Innovate UK - AGRI-TECH CATALYST	**£300,000**	Micropropagation Services Ltd.; Manchester Metropolitan University; University of East London; Lancashire Wildlife Trust	Sphagnum cultivation.	https://gtr.ukri.org/projects?ref=BB%2FR021686%2F1	In progress
Water Works Project	**2019 To 2021**	The People's Postcode Lottery Dream Fund	**£1M**	The Wildlife Trusts of Bedfordshire, Cambridgeshire and Northamptonshire; Cambridgeshire Acre; University of East London	Typha, Reed, Sphagnum, Glyceria and other cultivation	https://www.wildlifebcn.org/news/water-works	In progress
Wetland Conservation Biomass to Bioenergy	**2013 To 2015**	The Department for Energy and Climate Change (DECC)	**<£2M**	RSPB	Biomass production for energy – Reed, Typha, Fen biomass. Machinery and Harvest methods	https://decc.blog.gov.uk/author/sally-mills-rspb-reserves-bioenergy-project-manager/	Final report: https://tinyurl.com/yyhuvowz
CANAPE project	**2014 To 2020**	INTERREG European Regional Development Fund	**€5.5M (£4.57M[4])**	The Broads Authority	Converting surplus materials from conservation management into commercial products – reed and sedge.	https://www.broads-authority.gov.uk/looking-after/projects/canape	In progress