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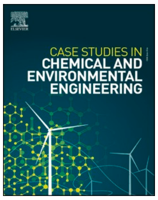

Case Report

Quo vadis - Development of a novel peatland-based recirculating aquaculture multi-trophic pond system (RAMPS) in the Irish midlands with a global orientation

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ABSTRACT

Development of peatland-based, recirculating freshwater aquaculture that is efficient and economically viable presents considerable benefits for society including supporting communities transitioning to low-carbon economies. This case study constitutes the first peatland-based process that uses fish cultivation waste to produce duckweed and microalgae biomass which are potential sources of high-value proteins, bioactives and further products that can be extracted using a biorefinery approach. The novel site has successfully supported freshwater aquaculture production using an effective circularity model and highlighted the potential of supporting new innovation such as biorefining bioactives from some 2000 indigenous peatland microalgae species for potentially beneficial health and adjacent applications. Additionally, it has demonstrated the appropriateness of digital transformation such as connecting on site monitoring with living-laboratory analysis. This paper details the challenges of food security given the impact of climate variance on open ecosystem performance. The findings of this case study inform key strategic polices governing food sustainability, bioeconomy and climate action from a bottom-up perspective. Key technical bottlenecks are discussed. Future research will consider efficiencies in biomass production and value-streams for new business innovations, including use of appropriate digital technologies though integrated multi-actor HUB framework enabling precision paludiculture for end-to-end monitoring, sustainable products/services and bespoke training.

1. Introduction

Food security refers to "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" [1]. The world is now on the verge of a global food crisis and geopolitical challenges. The United Nations Sustainable Development Goal (UNSDG) number two aims to end world hunger, achieve food security and improve nutrition and promote sustainable agriculture. According to the most recent UNSGD update, food supply systems and global food security have been undermined by a combination of issues including climate change, COVID-19 and conflicts [2]. According to the FAO's most recent report on the state of the world's food security and nutrition, between 690 and 782 million people worldwide are facing hunger, which is 122 million more than pre COVID-19 [3]. In addition to climate change impacts, this increase has also been attributed to the cost of living crisis as a result of rising food and energy prices. This has been further accelerated by the ongoing conflict in the Ukraine [3]. The Ukraine, known as Europe's bread-basket, together with the Russian Federation, supply 30 % of the world's wheat, 20 % of its maize and 80 % of its sunflower seeds. As a result, the conflict has triggered food shortages, most impacting the world's poorest and most vulnerable people [2].

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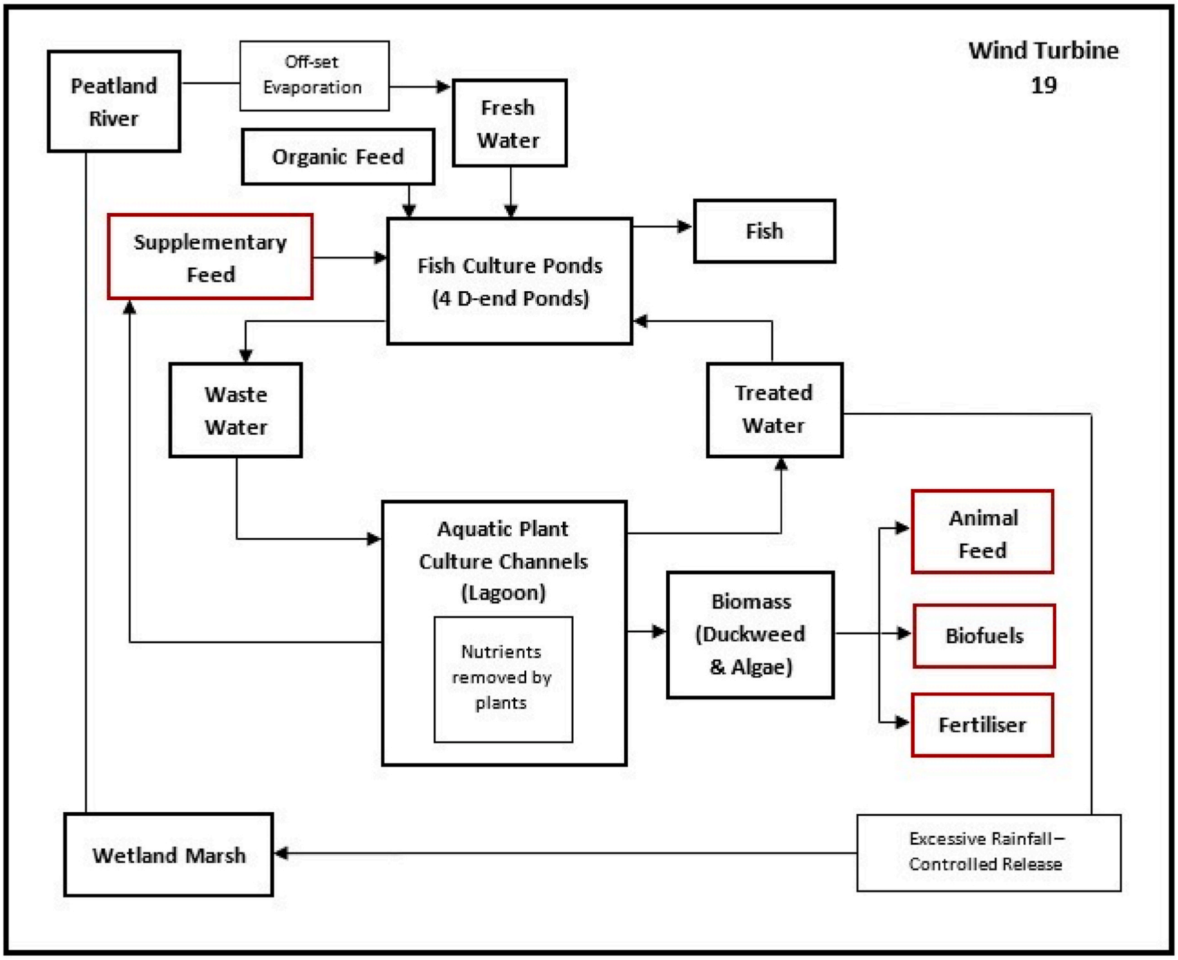

Fig. 1. Flow diagram of the full recirculating aquaculture multi-tropic pond system (RAMPS) process. Red boxes indicated elements of the process that are currently under active investigation to determine efficacy. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Ireland, much like Europe and indeed the rest of the world, is now focused on the development of a climate smart, local and environmentally sustainable agri-food sector (Food Vision 2030) which will aid in the UNSDG's aim to ensure food security for all [4,5].

Globally, aquaculture is considered one of the fastest growing food producing industries and key to improving food security [6–9]. Its rapid growth is paralleled by increased demand for aquaculture products due to a growing global population, and ongoing depletion in wild capture stocks [8,10,11]. However, this growth of the aquaculture industry is mostly centred in Asia. Europe has a largely stagnant industry, and this applies in particular to freshwater aquaculture [12]. Aquaculture provides a reliable source of food [11,13] as well as a rich source of protein [7]. Moreover, aquaculture is characterised by efficient protein utilisation and feed conversion, compared to other forms of animal-husbandry [14,15]. With that being said, development of more sustainable processes is required in order to limit the impact aquaculture has on the environment and climate as well as to contribute to the mitigation of any potential impacts, as set out by the European Green [16]. Irish aquaculture production was predicted to expand to 81,700 tonnes per annum by 2023. However, its growth and development has been hindered by several factors including the adoption of important European environmental protection directives that have limited the availability of space and resources [7,10]. As part of Ireland's National Strategic Plan for Sustainable Aquaculture Development, Bord Iascaigh Mhara (BIM), the Irish State agency responsible for developing the Ireland's seafood industry, undertook a study to assess the novel use of peatlands for paludiculture *i.e.* [7,14],farming on rewetted peat. Peatlands are wetlands characterised by a build-up of dead plant material over extended periods of time, which slowly decompose under wet conditions. The build-up of the decaying plant material and poor drainage have resulted in raised peatland bogs. For centuries, peatlands were considered resources that could be exploited for economic benefit e.g., production of fuel, soil-improver, and adsorbents. Much of modern peatland use has been non-sustainable, leaving behind large areas of cut-away bog that are of limited value for agriculture or biodiversity. Peatlands are now protected under multiple European environmental protection directives due to their scarcity. This creates new opportunities to change land use, to enhance sustainability and the Irish bioeconomy, and to generate a Just Transition. As part of land use change, BIM developed Ireland's first trial peatland-based integrated multi-trophic aquaculture (IMTA) system adhering to organic principles to ensure that the surrounding peatlands remain protected [7].

This paper will review performance of the IMTA system over the past three years to determine strengths and weaknesses, and generate a vision for the future of a recirculating aquaculture multitrophic pond (RAMP) model.

2. Novel aquaculture system

The RAMP system combines an integrated multi-trophic aquaculture (IMTA) system, where two or more organisms are farmed together, with aspects of a recirculating aquaculture system (RAS), where water is

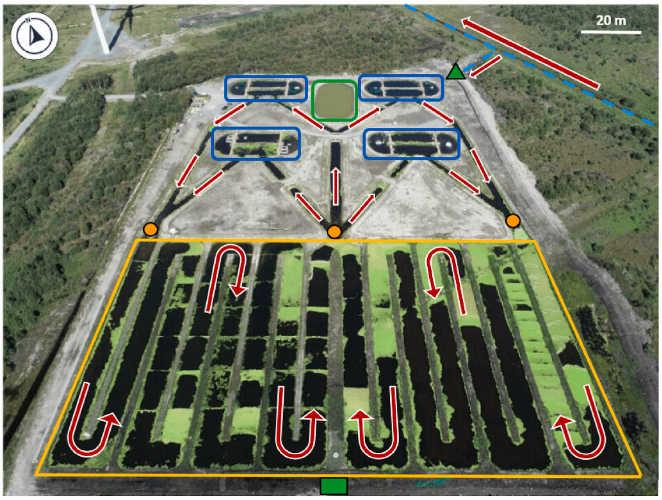

Fig. 2. Overhead view of the full RAMP system. Culture ponds (blue rectangles), reservoir (green rectangle) and treatment lagoon (orange box) are visible. Paddlewheel (orange circles) locations outside of the culture ponds have been indicated. Peatland/bog river (blue dashed lines) has been included along with the intake point (green triangle) and overflow point (green rectangle). Red arrows indicate water flow in and around the system. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

cleaned and filtered before being recycled back through fish culture ponds/tanks under a controlled environment. The RAMP system expands on the IMTA system by placing the technical advances of the latter, in the wider context of the bioeconomy, and the Just Transition. The system comprises a semi-closed system. Pond water/system water is filtered by duckweed (Lemnaceae) and naturally occurring microalgae [11,17], both of which contribute to removal of nitrogen and phosphorus from the water column. Water levels are primarily topped up by rainfall. Water intake from the adjacent bog river only occurs during warmer periods of the year to compensate for evaporation. No effluent is released unless excessively high levels of rainfall are experienced at which point the water enters a wetland marsh before flowing back into the bog river upstream of the intake point [9,18,19]. See Fig. 1 for a flow diagram of the full RAMPS process.

The 57,500 m^3 farm sits within a 5.4 ha site in the middle of the Mount Lucas wind farm which, in turn, is located within a degraded peatland. The system consists of four split pill ponds for culturing, a sixteen-channel lagoon for wastewater treatment and a central reservoir [6,7,10,14], as shown in Fig. 2. Water movement occurs via paddlewheels and airlifts strategically positioned throughout the farm. These are powered by electricity produced from one of the wind turbines located to the south of the farm (Fig. 2). The flow rate in the channels is approximately 0.02 $m\ s^{-1}$ and it takes around 4h to achieve a full water exchange in the system [11,13].

The farm can culture brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), European perch (*Perca fluviatilis*), gibbous duckweed (*Lemna gibba*) and common duckweed (*Lemna minor*) [6,10,11,13–15]. The system is designed to hold a maximum of 32,000 kg of fish and can produce a maximum of 35,000 kg of fish per annum. Fish are stocked at organic farming standard levels ($<$20 kg/m^3 perch, $<$25 kg/m^3 trout) to ensure optimum conditions [11]. The fish are cultured within the D-ends of each pond. Each pond contains two paddlewheels and airlifts for water flow and oxygen generation. Each pond also holds oxygen probes, temperature probes, a pH probe and an NH_3 probe to ensure optimum growth conditions for the fish and, automatic feeders to periodically provide fish feed, see Fig. 3 [6,10,11,14]. Mesh screens separate the D-ends from the rest of the pond. The mesh size varies between 7 and 25 mm and the mesh is designed to hold different categories (sizes) of fish [11]. The remaining sections of the pill ponds between the D-ends are utilised for wastewater treatment via naturally occurring microalgae [8,11,17]. Most of the bioremediation occurs within the treatment channels where the duckweed is cultured. Each channel is 100 m long, 8 m wide and up to 0.8 m deep. The duckweed filters the wastewater as it passes through the sixteen channels (two sets of eight) before the water re-enters the culture ponds [11] (Fig. 2).

Since the establishment of the pilot peatland-based aquaculture

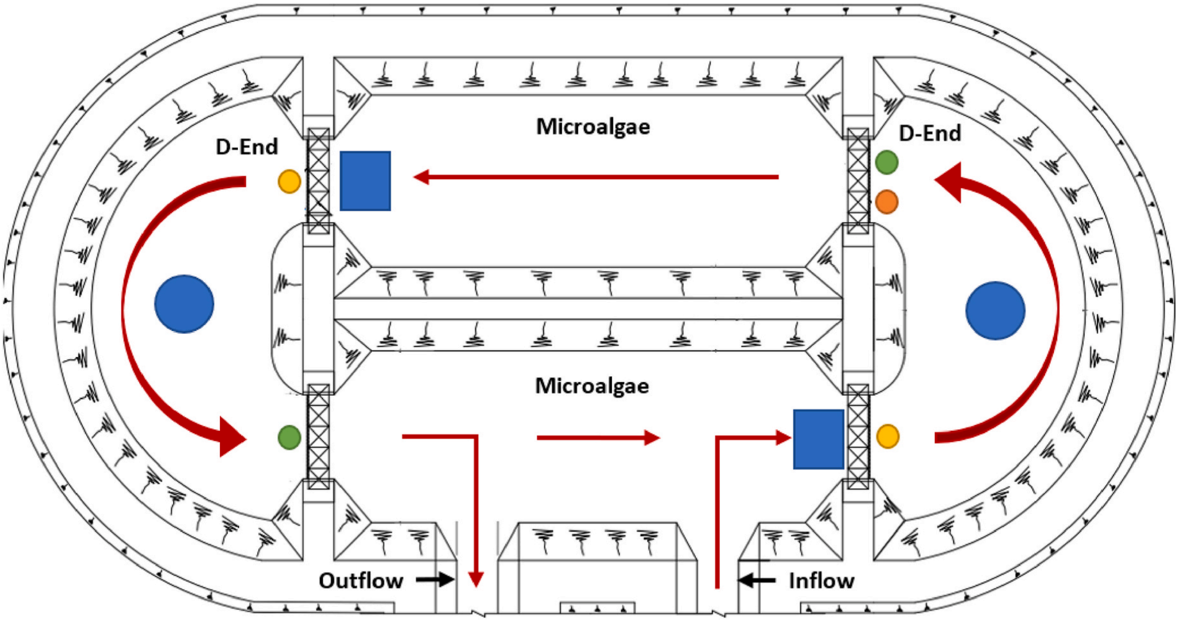

Fig. 3. Schematic of the culture ponds within the system. Paddlewheels (blue circles) and airlifts (blue squares) provide water flow (red arrows) and oxygenation of the water. The d-ends each side of the pond are where fish are held. Sections between each d-end allow for some waste water bioremediation using naturally occurring microalgae. Microalgae also provide some oxygenation during the warmer days via photosynthesis. Locations of all oxygen and temperature probes (green circles), pH and NH_3 probes (orange circle) and automatic feeders (yellow circle) within each pond have been included. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Breakdown of all research conducted on Mount Lucas aquaculture facility, including; original research, review articles and case reports, indicating their respective research/concepts and highlighting what future research needs to be conducted.

Reference	Paper	Research/Concept	Future Research
[7]	Original Research	• Physicochemical monitoring over a 4-month period. •Ecotoxicological analysis over a 4-month period using 2 different bioassays.	•Expansion of physicochemical monitoring period. •Expansion of ecotoxicological analysis time period & inclusion of additional bioassays. •Additional ecotoxicological assessment on surrounding peatlands & on fish health.
[19]	Review	•Review of the challenges, opportunities, and potential solutions for the post-COVID-19 era that focuses on intensive sustaining of agri-food supply chain in tandem with meeting the high de-mand for new green deal innovation	•Need for commercially demonstrating bio-based products at scale for circular bioeconomy that also matches balanced with biodiversity and ecology (Green Innovation). •Use of appropriate sustainable models, such as adopting Safe by Sustainable by Design framework
[9]	Review	•Review of a triple helix (academia-industry-authority') approach to aid in addressing climate change and environmental degradation by developing a reference blueprint for the safe and just transitioning to a low carbon economy	•Need for engaging multi-stakeholders using integrated Triple, Quadruple (+society), or even Quintuple (+Environment) Helix to address technical and economic viability in new high value products generated such as via circular economy and to de-risk for investment
[14]	Original Research	•Monthly physicochemical monitoring over a 10-month period. •Monthly microscopic identification (Genus) of algae over a 10-month period. •Molecular identification of entire algal population.	•Breakdown of molecular analysis to include individual months & locations. •Expansion of monitoring period for inclusion of all seasons. •Inclusion of cyanobacteria identification in molecular analysis.
[10]	Original Research	•Bi-weekly physicochemical monitoring from December 2019 to October 2020. •Bi-weekly algae & cyanobacteria monitoring from December 2019 to October 2020. •Monitoring of weather conditions monitoring from December 2019 to October 2020.	•Inclusion of composite sampling. •Further expansion of monitoring period to a full year. •On-site monitoring of weather conditions.
[6]	Case Report	•Summary of physicochemical, ecotoxicological, algal and cyanobacterial analysis over a 2-year period. •Identification of potential support of research to UN SDG's.	•Need for investigation into the long-term commercial profitability and sustainability of peatland innovations that have the potential to contribute to a new Green economy.
[18]	Review	•Review on the use of smart digital technologies to address efficacy of peatland-based products and services to aid in the just transition away from peat extraction to a low carbon economy.	•Use of end-to-end digital monitoring tools in the field (culture ponds) in addition to waste stream channels to assess phytoremediation of ammonium and phosphate by microalgae, duckweed, along with use of unmanned aerial vehicles to assess coverage of duckweed that takes up fish culture waste and returns clean water to fish ponds.
[11]	Original Research	•Overview of all monitoring processes conducted *in-situ* between 2019 and 2020.	•Operation of the described IMTA system in different climates using different species of fish and duckweed. •Management of the pH of an IMTA system, with emphasis on avoiding alkaline pH values •Management of flow rates considering the need for water mixing, energy costs but also the sensitivity of duckweed to disturbance •Quantitative assessments of the relative role of duckweed, algae and bacteria in disseminating ammonia/ammonium •Development of methodology for cost effective harvesting, drying and after-use of duckweed biomass
[13]	Original Research	•Analysis on efficacy of nitrogen and phosphorus removal by duckweed.	•Life Cycle Assessment needs to be conducted.
[15]	Original Research	•Monitoring uptake rate of nitrogen and phosphorus by duckweed species, algae and bacteria in the system.	•Balance between algae and duckweed needs more investigation.
[17]	Original Research	•Reference to physicochemical monitoring over a 4-month period. •*In-situ* algae & cyanobacteria monitoring over an 11-month period. •Molecular identification of zoosporic parasites over a 4-month period. •Monitoring of weather conditions over a 4-month period.	•Inclusion of a composite sampler. •Expansion of monitoring period to include all seasons. •Expansion of molecular analysis to include individual months and locations. •Inclusion of on-site weather monitoring.
[8]	Viewpoint Article	•Discusses how digital transformation can help support and meet expansion needs of fisheries/aquaculture industries. •Discusses how digital transformation can meet key challenges that will meet several UNSDG's.	•Appropriate integration of suite of digital sensors in IMTA system to ensure optimal performance and efficiency including development of mobile phone management app for analysis of data generated and for decision making. •Harmonised use of on-site laboratory and in field monitoring for real-time assessments, and to

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Table 1 (*continued*)

Reference	Paper	Research/Concept	Future Research
			develop innovation including new green certification based on full ecotoxicological battery testing for environmental compliance.

facility began in 2019, multiple research studies have been conducted, as shown in Table 1. These have included physicochemical monitoring, duckweed biomass analysis, ecotoxicological assessments, and analysis of cyanobacteria and algae using microscopy and molecular tools. See Table 2 for a summary of results determined in all original research conducted on the Mount Lucas fish farm during the case study series. Studies have indicated that additional research and development is required to further improve and advance this RAMPS process. For example; Paolacci et al. [13] successfully demonstrated the feasibility of using duckweed to maintain good water quality within the system, whilst also generating high, protein-rich biomass yields. However, life cycle assessments need to be conducted, especially in terms of environmental costs, in order to determine the economic feasibility and commercial viability of duckweed-based wastewater treatment. Additionally, Paolacci et al. [15] also demonstrated the abilities of both duckweed and algae to remove the nutrient load, however a better understanding of the relationship between both is necessary as the competing processes are limiting capabilities. Moreover, this recirculating aquaculture system has been found to be even more complex than originally thought. For example, O'Neill et al. [14] revealed a combined total of 982 algal species from 341 genera across nine phyla in the system, which emphasised a significant underestimation in the quantity and diversity of beneficial or potentially harmful algae in the RAMPS-microbiome. All these species may be affected by changes in culture conditions as well as due to exposure to variances in climate, such as frequent successive storms [14]. At present the importance of such substantial biodiversity is not well documented. In addition, research has also intimated how the site can advance many of the UNSDGs [10]. For example, O'Neill et al. [10], for the UNSDG's, as well as reviews that discuss the use of the novel system in providing support for developing a sustainable Irish agri-food industry, there is potential for use of smart digital technologies to address efficacy of peatland-based products and services to aid in the just transition away from peat extraction to a low carbon economy. Digital transformation can also help potentially support and meet expansive diversification needs of fisheries/aquaculture industries [8,18]. Use of integrated multi-actor digital HUB framework will further support and accelerate peatland innovation including testing the tech, access to finance, business canvas development and marketing delivered across the full spectrum of technology readiness levels to achieve an effective RAMP system contributing to a Just Transition [9].

3. Future direction

Although strides have been made in the development of this innovative aquaculture site, much more work is still left to be done. For a better understanding of this complex process, research needs to include; expansion of all monitoring processes that consider; 1) different times of the day, 2) different months of the year and seasonal variation, and different weather conditions. It is also necessary to perform a full life cycle assessment on the entire process with a much more detailed analysis on the environmental costs. Future impact assessment for this novel site is illustrated in Fig. 4. In addition to the need for more in-depth research and analysis, there is also a need for further investigation into the long-term commercial profitability and sustainability of peatland innovations that have the potential to support a new green

Table 2

Summary of all analysis and results of all original research conducted on the Mount Lucas fish farm case study series. Summary includes the main test methods employed and the overall results identified.

Reference	Testing	Overall Results
[6]	Physicochemical Analysis (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, DO, BOD, T, pH, SS, DS, H, A) of all areas within the farm (4 culture ponds, entry & exit point of the treatment lagoon, reservoir, holding tank at farm exit point) (2019–2020).	Potential issues with NO_2^-, BOD, & SS within some areas resulting in mitigation processes being employed – additional aeration & filtration.
	Flow Cytometry analysis on algal & cyanobacteria populations within the culture ponds & treatment lagoon (2019–2020).	Direct cell counts determined for both algae & cyanobacteria with fluctuations observed during unforeseen events.
	Weather variance analysis (T & rainfall) during analysis period (2019–2020).	Excessive levels of rainfall (>197mm) experienced during study demonstrated effects changes in normal weather variances (70mm). Resulted in knock on effects to algae & cyanobacterial populations as well as some fish mortalities.
[7]	Physicochemical Analysis (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, DO, BOD, COD, T, pH, SS, H, A) & comparison between system intake & output water (2019).	Differences observed in NO_2^-, NO_3^-, PO_4^{3-} & COD. Results similar to or below concentrations reported in 20 aquaculture research studies.
	Ecotoxicological analysis (*Pseudokirchneriella subcapitata* algal bioassay [ISO 6982:2012] & *Daphnia magna* crustacean bioassay [ISO 6341:2012] & comparison between system intake & output water (2019).	Introduction of aquaculture into peatlands deemed unlikely to cause major adverse effects on the ecosystem & organisms within.
[11]	Physicochemical Analysis (NH_4^+, NH_3, NO_2^-, NO_3^-, PO_4^{3-}, DO, CHL, TB, cyanobacteria) on water quality (2019 & 2020)	Water quality parameters compared to optimum levels for perch & trout – increased PO_4^{3-} levels observed.
	Fish production of perch & trout in 2019 and 2020.	Initial fish biomass – 4773 kg (2019) & 20437 kg (2020). Feed applied – 32,623 kg (2019) & 31613 kg (2020). Net Yield – 13,657 kg (2019) & 7443 (2020).
	Energy consumption of process in 2019 & 2020.	Electricity (provided by wind turbine) 112090 kWh (2019) & 178863 kWh (2020). Diesel (generator during turbine shut down for maintenance) 218 L (2019) & 255 L (2020).
	Duckweed Production	45.6 % surface coverage (2019) & 91.1 % surface coverage (2020).
[13]	Analysis of capacity of duckweed to produce biomass using aquaculture wastewater (2019)	Total dry biomass produced for the year between 38 & 48 tonnes per ha. 100 % biomass production observed during summer months.
	Analysis of capacity of duckweed for aquaculture wastewater remediation (2019)	N reduction of up to 1.70 tonnes per annum. P reduction of up to 0.39 tonnes per annum.
[14]	Physicochemical Analysis (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, DO, BOD, T, pH, SS, DS, H, A, C) (2020)	All parameters except BOD, NO_2^-, PO_4^{3-} and SS were within guidance water quality values.
	Microscopic & molecular identification (Illumina & MinION sequencing) of algal populations within the entire	Microscopic analysis identified a minimum of 20 genera of algae all of which were suspected of having multiple species. Molecular analysis identified 982 species of algae across 341 genera demonstrating that the system is even more complex than originally thought.
[15]	Analysis of nutrient removal (bioremediation) observed within	N removal – 31 % duckweed, 33 % phytoplankton, 36 % biofilm.

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Table 2 (*continued*)

Reference	Testing	Overall Results
	the aquaculture system by duckweed, phytoplankton & biofilm (2020)	P removal – 29 % duckweed, 38 % phytoplankton, 33 % biofilm. Duckweed & phytoplankton displayed competition. N removal 5x higher than P.
[17]	Weather variance analysis (T & rainfall) to determine whether unexpected changes in weather conditions impacted on dramatic loss of microalgal populations observed in the trial fish farm. (2020)	Changes in weather conditions displayed no correlating relationships.
	Physicochemical analysis (NH_4^+, NO_2^-, NO_3^-, PO_4^{3-}, DO, BOD, T, pH, SS, DS, C, A) for a 4-month period when issues within the farm was observed (dramatic loss of microalgal levels). (2020)	Elevated periods of BOD levels but no correlating relationships with weather Conditions, other physicochemical parameters
	Microalgae & cyanobacterial analysis via an AlgaeTorch® (ISO 10260:1992) for real time population monitoring (2020).	Monitoring of algae & cyanobacteria populations, identifying a main period where dramatic loss of populations was observed.
	Molecular identification (MinION) analysis to identify presence of any organisms that may have caused dramatic loss of algal population	Identification of 14 species of zoosporic parasites (capable of causing sudden & considerable microalgal cell death) across 5 genera across all areas of the farm which coincided with dramatic loss of microalgal populations within the farm.

NH_4^+ = ammonium, NH_3 = ammonia, NO_2^- = nitrite, NO_3^- = nitrate, PO_4^{3-} = orthophosphate, DO = dissolved oxygen, BOD = biochemical oxygen demand, COD = chemical oxygen demand, SS = suspended solids, H = hardness, A = alkalinity, DS = dissolved solids, TB = turbidity, CHL = chlorophyll, N = nitrogen, P = phosphorus, C = conductivity.

bioeconomy. It is thought that the use of the system for just fish culturing processes is not commercially viable on its own. Additional components including duckweed and potentially algal cultivation and processing hold great potential to add further commercial value [20]. However, potential limitations need to also be investigated e.g., market availability, annual production limitations, stability of production and standard quality of product [13,15]. Future use of the multi-actor helix hub framework will enable an integrated approach to supporting and enabling the development of paludiculture innovation at this pilot demonstrator RAMPS site in addition to serving as an important interface between informing top down strategic polices and implementing bottom up research and development activities. This HUB framework will also facilitate appropriate implementation of digital innovation to accelerate core aquaculture and circularity activities along with business model development for sustainable and viable products and services.

CRediT authorship contribution statement

Emer A. O'Neill: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Vlastimil Stejskal:** Writing – original draft, Methodology, Data curation. **Simona Paolacci:** Writing – original draft, Methodology, Data curation. **Marcel A.K. Jansen:** Writing – review & editing, Writing – original draft, Visualization, Supervision. **Neil J. Rowan:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

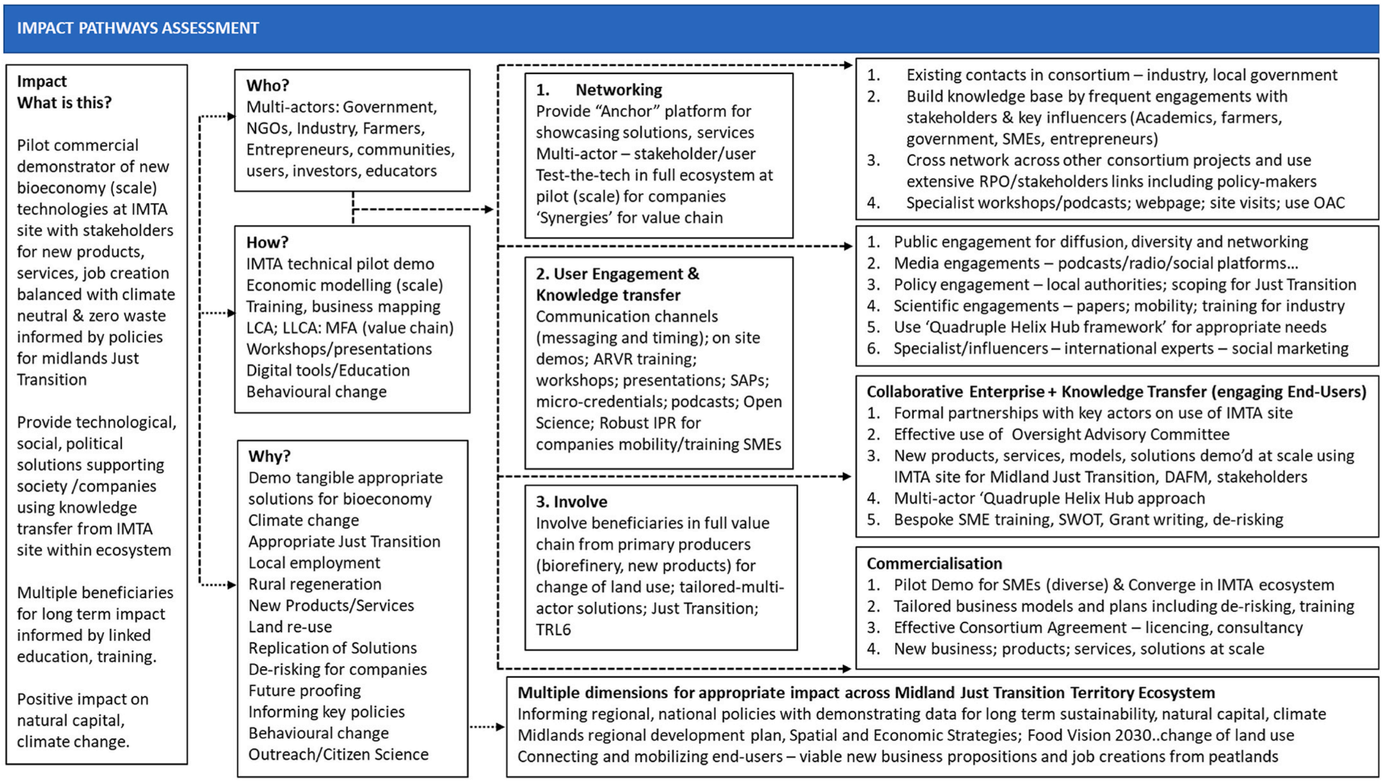

Fig. 4. Peatland-based bioeconomy demonstration model farm impact pathways assessment.

Data availability

No data was used for the research described in the article.

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