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Review

Digital transformation of peatland eco-innovations ('Paludiculture'): Enabling a paradigm shift towards the real-time sustainable production of 'green-friendly' products and services

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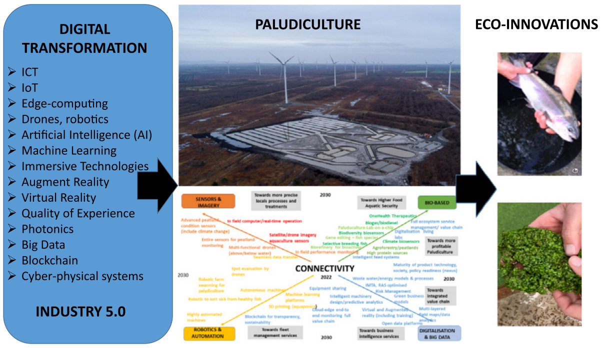
HIGHLIGHTS

- Paludiculture is an emerging sector transitioning towards a sustainable green sector
- Harnessing digital transformation will enable peatland eco-innovations across the full value chain
- Mount Lucas is a paludiculture demonstrator for digital transformation
- Digital technologies developed for Agriculture 4.0 and Industry 5.0 will advance paludiculture
- Digitisation will future-proof paludiculture for climate change and sustainable eco- intensification

GRAPHICAL ABSTRACT



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ABSTRACT

The world is heading in the wrong direction on carbon emissions where we are not on track to limit global warming to 1.5 °C; Ireland is among the countries where overall emissions have continued to rise. The development of wettable peatland products and services (termed 'Paludiculture') present significant opportunities for enabling a transition away from peat-harvesting (fossil fuels) to developing 'green' eco-innovations. However, this must be balanced with sustainable carbon sequestration and environmental protection. This complex transition from 'brown to green' must be met in real time by enabling digital technologies across the full value chain. This will potentially necessitate creation of new green-business models with the potential to support disruptive innovation. This timely paper describes digital transformation of paludiculture-based eco-innovation that will potentially lead to a paradigm shift towards using smart digital technologies to address efficiency of products and services along with future-proofing for climate change. Digital transform of paludiculture also aligns with the 'Industry 5.0 - a human-centric solution'. However, companies supporting peatland innovation may lack necessary standards, data-sharing or capabilities that can also affect viable business model propositions that can jeopardize economic, political and social sustainability. Digital solutions may reduce costs, increase productivity, improve produce develop, and achieve faster time to market for paludiculture. Digitisation also enables information systems to be open, interoperable, and user-friendly. This constitutes the first

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study to describe the digital transformation of paludiculture, both vertically and horizontally, in order to inform sustainability that includes process automation via AI, machine learning, IoT-Cloud informed sensors and robotics, virtual and augmented reality, and blockchain for cyber-physical systems. Thus, the aim of this paper is to describe the applicability of digital transformation to actualize the benefits and opportunities of paludiculture activities and enterprises in the Irish midlands with a global orientation.

Contents

1. Introduction

The onset of COVID-19 pandemic and commensurate disruption to supply chains worldwide has created opportunities for developing new solutions to pressing societal challenges (Rowan and Laffey, 2020a; Rowan and Laffey, 2020b; Rowan and Galanakis, 2020). However, a panoply of factors impact the sustainability of green innovations, but could be ameliorated by enabling real time data management, usage and protection by engaging and implementing the vision of Industry 4.0 (a.k.a the fourth industrial revolution, digital transformation) in the agriculture and food sectors. The occurrence of COVID-19, an unpredictable and unexpected event that had severe worldwide consequences, coincided with the launch of the European 'Green New Deal', which was aimed at implementing solutions to combat climate change by supporting the sustainable intensification of eco-innovation, products and services (Rowan and Pogue, 2021). The European Just Transition initiative embraces and develops the vision of sharing knowledge openly to enhance societal inclusiveness, regenerate communities and ultimately promote a low carbon economy (Rowan and Casey, 2021). These ambitious programs and the attainment of their goals will be shaped and impacted by other mitigating factors including extreme weather events brought on by climate change (Weiskopt et al., 2020), the global energy crisis brought on by the Ukraine war and threat to the "breadbasket" of Europe and food production and security (http://www.dw.com). Despite the slowdown in carbon emissions caused by successive "lockdowns" worldwide, the current global models for business and production means the world continues to head in the wrong direction on carbon emissions in spite of the narrowing window of less than a decade to contain a catastrophic rise in global temperatures (Intergovermental Panel on Climate Change (IPCC), 2022). The world is not on track to limit warming to 1.5 °C and only a major transition in the energy sector including a substantial reduction in fossil fuel use, widespread electrification, improved energy efficiency and the use of alternative fuels can halt what is becoming an irreversible warming trend (O'Sullivan, 2022). Mondejar et al. (2021) noted that changing climatic conditions are accomplished by high and low stress, altered rainfall patterns, elevated carbon dioxide, increased frequency of extreme weather events like flooding, droughts, cyclonic disturbances and increased saline soils. Okolo et al. (2019) reported that increased stress negatively influences agroecosystems' natural resilience; this is expected to cause dramatic environmental changes on a world scale that can affect supply chains for food, feed and clean energy. The reader is also directed to the published work of Mondejar et al. (2021) for applications of digital technologies that provide sustainable solutions to different agriculture problems.

Peatlands are a unique ecosystem that constitute an important carbon sink globally (Ziegler et al., 2021; O'Neill et al., 2022) and also represents an environment that may potentially provide a win-win scenario for new activities that could bring economic and social benefits while simultaneously contributing to reduce the harm to the climate (Rowan and Galanakis, 2020; Ziegler et al., 2021). The globalization of the current crisis (climate change, pandemics, population growth and food security) emphasise that solutions can only be found through global actions to co-create and implement solutions for these complex societal challenges and make the United Nations' Sustainability Development Goals set for 2030 a reality (Rowan and Casey, 2021).

Peatlands are a type of wetland that covers 3% of global land surface and currently approximately 15% of peatlands are degraded due to drainage for agriculture, forestry, and peat mining as a fossil fuel (Urák et al. 2017; Ziegler et al., 2021; O'Neill and Rowan, 2022), Ziegler et al. (2021) reported that the adverse consequences of intensive peatland degradation can contribute to inter alia undesirable greenhouse gas emissions, biodiversity loss and pollution of receiving waters. However, "rewilding" peatlands through controlled wetting can promote biodiversity and sustainable economies through the unique practice of paludiculture (production under permanently wet, peat-conserving and potentially peat-forming conditions, https://www.eurosite.org/). Indeed, peatlands are one of the world's most vital ecosystems, supporting a range of rare and stress-hardened plants and species, cleaning and filtering water, and mitigating flooding (Rowan and Casey, 2021). Peatlands cover just 3% of the planet, but store twice as much carbon as all the world's forests combined (Sargent, 2022). Ireland is rich in peatlands, which cover 20% of the land mass with near perfect conditions for peat soils and lock in 75% of all soil organic carbon (Rowan and Casey, 2021). Irish peatlands are estimated to actively capture around 57,000 t of carbon per year (Sargent, 2022) and constitute an important resource for carbon removal from the atmosphere and for enhancing sustainable carbon cycles (O'Neill et al., 2019).

Traditionally, use of wet peatlands (or 'paludiculture') is a potentially exciting means of alternative land use worldwide as this can lead to new sustainable employment opportunities for farmers and create opportunities for communities to fairly transition to a low carbon economy (Ziegler et al., 2021). However, promotion of paludiculture needs robust, evidence-based, collaborative research from pilot (pre-commercial) studies across a diversity of paludiculture activities to inform appropriate sustainable business models, such as for production of, fuel, fodder, food and construction materials (Wichmaan et al., 2016; Ziegler et al., 2021). Ziegler et al. (2021) and others (Tan et al., 2021; O'Neill et al., 2022) noted that support for the sustainable intensification of wet peatlands is a novel concept. O'Neill and co-workers (2019) reported for the first time the development of an innovative integrated multi-trophic aquaculture (IMTA) system for sustainable foods in peatlands of the Irish midlands. This freshwater IMTA system exploited a naturally occurring ecosystem of bacteria, algae and duckweed in ponds for managing waste and ensuring water quality and was powered by wind turbines. The described recirculating aquaculture process does not rely on complex end-of-circuit solutions for maintaining waste effluent treatments (Rowan and Galanakis, 2020; Galanakis et al., 2021).

Current freshwater aquaculture production systems are resource-constrained and the production systems are unlikely to meet the increasing demand for aquatic foods, which is foreseen as one solution for feeding the growing world populations that is estimated to reach approximately 10 billion by 2050 (Rasmussen et al., 2018; Xia et al., 2022). Moreover, there is increasing anthropogenic-mediated destruction of natural resources caused by increasingly frequent extreme weather events that will affect the supply of safe, affordable, and nutritious food (Weiskopt et al., 2020). Aquatic ecosystems encompass about 75% of planet's surface, including that represented by the wet peatlands, which present new opportunities to intensify and diversify eco-innovation transnationally (Rowan and Casey, 2021; FAO, 2020). A knowledge gap that will have to be filled is the development and implementation of disruptive technologies in aquaculture to promote green, sustainable and profitable production models (Xia et al., 2022). Digitalization of aquaculture systems represents a new frontier and will be transformative by allowing development of precision farming solutions improve yields of food rich in high quality protein and omega-3 fatty acids (Mondejar et al., 2021; Rowan and Casey, 2021). The development and adaption of sophisticated innovations, along with open knowledge and technology exchange, is required to meet hurdles presented by low-environmental impact aquatic-based innovations (O'Neill et al., 2022).

There is increasing interest in adapting digital technologies such as artificial intelligence (AI) and machine learning, the Internet of Things (IoT), sensors, drones, blockchain for improving adjacent industries (Hrustek, 2020; Mondejar et al., 2021). Indeed, the disruptive approach of Industry 4.0 has started to be felt in some traditional agri-food activities and cyber-physical systems, IoT, AI and machine learning, big-data and analytics, and cloud technology have been integrated with agricultural machinery with exciting possible benefits (Tsolakis et al., 2019; Hrustek, 2020; Arvanitis and Symenonaki, 2020) (Table 1). Collectively, application of these next-generation digital technologies can support and accelerate Open knowledge exchange worldwide and can inform real time development of exciting new technologies to meet the challenges of today; although, the diversity and complexity of agri-food activities makes sector-customized solutions a challenge and a priority (Mondejar et al., 2021). Hrustek (2020) noted that digital transformation will help inform stability for the sustainable development of the global economy including preventing or mitigating against the impact of uncertainties created by increased frequency of extreme weather events and new global crisis (financial, health, war, food and water). Hrustek (2020) also advocated that organisations must understand the key drivers of digital transformation that affect technology development and industry. Similarly, for development and future intensification of peatland innovation, a balance must be achieved between striding towards a high rate of economic progress and protecting the environment that enables delivering a climate friendly and sustainable production sector (Mondejar et al., 2021; Weizkopt et al., 2020).

The vision outlined by the authors in the present commentary is that digital transformations can inform technological, societal and political drivers of peatland, as it has for agricultural innovation. Moreover, 4IR should be deployed with the objective of enhancing the quality of life of the billions of people worldwide through creating a system that is secure and fair and establishing a framework that monitors and promotes sustainable practices (Shamin et al., 2019; Hrustek, 2020). Moving forward, peatland innovations should become an integral component of the value chain in the economy, providing products and services to society and informing food security and stability while promoting environmental, economic and social sustainability (Rowan and Galanakis, 2020). However, implementing innovative sustainable technologies typically requires far-reaching changes of the macro environment in which innovating companies operate where there is a need to strategically create an appropriate supportive external environment, such as collective system building (Planko et al., 2016; Zeigler, 2020) and quadruple helix innovation hub approach (Rowan and Casey, 2021). Commensurately, there will be a focus on achieving compliance with environmental and quality regulations as seen in agriculture sector (Hrustek, 2020). The aforementioned also aligns with the tenets of Industry 5.0 that provides a vision of the industry that looks beyond efficiency and productivity as the sole goals, but reinforces the role and the contribution of industry to society (Skobelev and Borovik, 2017a, 2017b; Nahavandi, 2019). It complements the fourth industrial revolution named Industry 4.0 by using digital transformation to place research and innovation at the service of the transition to a sustainable, human-centric and resilient industry. Industry 4.0 combines physical world of real things with their 'virtual twins' (Table 1).

Peatland innovation will also potentially mitigate against impact of reduced water supply and the environmental impact of intensive plant and livestock production to meet increased animal and human needs for high quality food production (Rowan and Casey, 2021; O'Neill et al., 2022), where the Food and Agriculture Organization (FAO, 2020) advocates adoption of digital technologies to enhance productivity and ensure food safety. Hrustek (2020) highlighted similarities to applying digital technologies to the agriculture sector where it is also envisaged that peatland innovation will require standardization and will be made available across the entire value chain where creative and adaptable approaches will be required to support sustainable development of paludiculture. It is likely that peatland innovation will also be advanced by applying smart and precise processes including process automation and robotics, peatland applications and information systems, cyber-physical systems, related tools and machines, and collection and evaluation of large amounts of data (Mondejar et al., 2021). Lessons learnt from sustainable practices in adjacent agriculture infers that sustainability across the peatlands will be centred on delivering flexibility in tandem with efficiency where future digital transformative activities will help unlock complex economic and societal challenges (Rowan and Pogue, 2021). However, the complexity and diversity of such data is likely to be vast and will require systematic approaches to make digitalization sustainable, including life cycle assessments (LCA) (Ruiz-Salmón et al., 2020; Ruiz-Salmon et al., 2021; Laso et al., 2022), material flow analysis (MFA, Abualtaher and Bar, 2019), principle component analysis (Naughton et al., 2020), bioinformatics to mitigate mislabelling in worldwide seafood market and to protect consumer health (Vindigni et al., 2021) and so forth. Cooney and co-workers

Table 1
Digital technologies – definitions and applications in peatland ecosystems.

Digital technologies	Peatlands use
Information and communications technology (ICT) encompasses the capture, storage, retrieval, processing, display, representation, presentation, organization, management, security, transfer, and interchange of data and information.	Connects Peatlands ecosystem
Internet of things (IoT) – network of smart, interconnected devices and services capable of sensing or listening to requests and perform actions using actuators. IoT enables network sensors to remote connect, track and manage products and systems.	Aquatic systems Agroforestry Vertical farming
Cloud computing – use of tools and applications (such as data storage, servers, databases, software) based on a network of severs through the internet. It enables user to rent computer resources on demand to store files and applications in a virtualised servers and access all data via the internet.	Connects peatland ecosystem
Artificial Intelligence (AI) defines machines achieving human-like cognitive functions (ex. learning, reasoning, interacting) that comprises different forms of cognition and meaning understanding (such as speech recognition) and human interaction (signal sensing, smart control, simulators) rooted in algorithms and software.	Sensors, chips, robots, logistics, autonomous machines
Machine learning (ML) – a subset of AI, use and development of computer systems that learn and adapt without following explicit instructions, by using algorithms and statistical models to analyse and draw inferences from patterns in data.	Automated processes across peatland
Big data – continuous increase in data & technologies that needs to be collected, stored, managed and analysed. Complex and multidimensional that impacts processes, technologies. Characterised by Volume (amount of data sets), Velocity (speed of data processing), Variety (types/sources of data), Veracity (quality of data analysed).	Full peatland innovations and value chain
Blockchain is a shared digital, immutable ledger that facilitates the process of recording transitions and tracking assets in a business network using cryptographic algorithms). Blockchain protocols aggregate, validate, and relay transactions within the blockchain network. The blockchain system records the transactions in sequence. A transaction may contain a value transfer or a smart contract invocation. Almost anything of value can be tracked or transacted on a blockchain network, reducing risk and costs in business.	Traceability, security of processes across peatlands, novel business models
Photonics is a multidisciplinary field related to light including energy generation, detection, and process management. Photonics is the scientific study or application of electromagnetic energy whos basic unit is the photon, incorporating optics, laser technology, electrical engineering, material science, and information storage and processing. Photonic applications use the photon in the same what that electronic applications use the electron. Agri-photonics is a growing area of precision agriculture (Massaro et al., 2020).	Disease mitigation. Optic sensing to for protein levels in foods, water quality and fish health
Augmented reality – a technology that superimposes a computer-generated image on a user's view of the real world; thus, provide a composite view.	Training
Virtual Reality – the computer-generated simulation of a 3D image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as helmet with screen inside or gloves fitted with sensors.	Training
Quality of Experience (QoE) – is the degree of delight or annoyance registered by the use of an application or service.	Training
Logistics – the detailed organization and implementation of a complex operation.	Peatlands eco management
Robotics – a branch of technology that deals with the design, construction, operation and application of robots. In multi-robot or swarm robot systems, the robot collaborate to complete predefined tasks.	Aquaculture feed, monitoring
Cobot, or collaborative robot, is a robot intended for direct human robot interaction with a shared space, or where humans and robots are in proximity.	Food processing, in field logistics
Digital twin – a digital win is a virtual model designed to accurately reflect a physical object.	Wind turbine fitted with various sensors for control
Edge Cloud – Edge computing is developed as complement to cloud computing, encompassing storage and compute assets located at the edge and interconnected by a scalable, application-aware network that can sense and adapt to changing needs, securely & in real time	Peatland ecosystem networking
Cybersecurity or information technology (IT) security – is the practice of protecting critical systems and sensitive information from digital attack. It is how individuals and organisations reduce the risk of a cyber attack where cyber security code function protects the devices (smartphones, laptops, tables).	Security of production, products and services
Cyber-physical systems refer to systems where software and hardware components are seamlessly integrated towards performing well defined tasks.	Security of processes.

(2021) investigated impact categories that can also be applied to evaluate emerging peatland aquaculture systems, namely using LCA and included global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), freshwater and marine ecotoxicity potential (EAETP and MAEPT), cumulative energy demand (CED), net primary production use (NPPU) and water use. Rowan and Casey (2021) evaluated the maturity of paludiculture eco-innovation in terms of technology, society and policy readiness levels (O'Neill et al., 2022). The present article expands on the scope of the previous articles by:

- Addressing what digital transformation of the peatlands simply means and its' application to supporting sustainability in order to embrace wide opportunities for the development of green enterprises, job creation and to improve competitiveness of the region with global orientations.
- Describes and explores current state-of-the-art knowledge on sustainability across a diversity of peatland innovation, and adjacent activities, framed upon the use case of a novel freshwater paludiculture site in the Irish midlands and digital transformation.
- Unlocks challenges and opportunities for the development of peatland innovation as it relates to environmental, economic and societal sustainability informed by digital transformations. This includes the likely impact of climate change and the uncertainty arising from extreme weather events, habit loss or biodiversity disruption and mitigation using effective precision systems.

2. Development of aquaculture, aquaponics and adjacent green innovation in the Irish peatlands

Aquaculture is the fastest growing sector in agriculture and has a long history of contributing high-quality proteins to humans (O'Neill et al., 2022). Aquaculture is diversifying compared to other agriculture sectors in terms of fish species, feeds, production systems, diseases, products, business sectors and marketing (FAO, 2020; Yue and Shen, 2022). Developing live feeds, including microalgae, rotifers, and brine shrimp in hatcheries have bridged the bottleneck in aquaculture of some marine species (Yue and Shen, 2022). Selective breeding has enabled progression of quantitative genetics that has improved traits in over 60 commercial aquaculture species (Gjedrem and Robinson, 2014). This includes QTL (quantitative trait locus) mapping and maker assisted selected (MAS) that have been a basis for trait selection. Improved feed formulations to meet the nutritional requirements of each fish species have improved feed conversation rates, reduced costs and improved product quality (Tacon and Metian, 2015). Technologies and innovations for disease mitigation and management have controlled diseases in aquaculture (Kelly and Renekdas, 2020; Pogue et al., 2021). However, it will be very challenging to meet increasing demand for seafood seen as a viable option with a low environmental impact for feeding the growing world population (FAO, 2020). It is important to support and enable product diversification from aquaculture and adjacent activities that are likely to be impacted by disruptive environmental conditions, reduced supply of fish meal and oils and extreme weather events brought on by climate change (Shen et al., 2020). These challenges, and opportunities have stimulated innovations in aquaculture (Ab Rahman et al., 2017; O'Neill et al., 2022), such as genomic selection (Houston et al., 2020; genome editing (Gratacap et al., 2019), information and digital technology (Hassan and De Filippi, 2021), recirculating aquaculture systems (RAS), development of renewable energies such as solar (Aich et al., 2020) and wind (O'Neill and Rowan, 2022; O'Neill et al., 2022), vaccines (Shefat, 2018), and novel business strategies with blockchain (Anderson et al., 2019).

The Mount Lucas peatland site covers ca. 4 ha in the Irish midlands, has also a strong trajectory to support and enable green innovation and social enterprises including vertical farming, honey production, exotic fungi/mushroom cultivation, agro-forestry including provision for dark-sky eco-tourism (Fig. 1). An advantage of peatland-based aquaculture is that it harnesses water from rivers and lakes and doesn't have the possible threats from potential pollutants in raw, untreated wastewater, such as agricultural run-off (O'Neill et al., 2020). The emphasis is on creating a balanced system in the four 1000m^3 fish ponds, which were created using a natural glacial till (Fig. 1). The duckweed area is 1.2 ha, linked by channels to the pond. The full volume of water is exchanged every 4 h. Among the many green boxes the project ticks is low freshwater use, with any additional water requirements normally taken care of by the Irish weather (O'Neill et al., 2019). The Mount Lucas site has a licence for 25 t of fish biomass, which works out at 13 t perch and 12 t of trout that are produced for high value markets across Europe (O'Neill et al., 2020). The underlying principle is define process for replication across peatland where the limited tonnage of fish biomass is dictated by 'organic status'. Thus, Mount Lucas hosts a blend of traditional social enterprises with emerging green technologies, products and services that requires digital transformation to effectively manage their potential along the full value chain that includes efficient wastewater recirculation and bioprospecting of bioactives. Digital transformation can also highlight the maturity of key innovations that will potentially meet several sustainable development goals of the United Nations (Galanakis et al., 2021; Rowan and Casey, 2021; O'Neill et al., 2022).

3. Exploiting digitization to integrate and unlock vertical and horizontal value chains

A definition of key terms and technologies that underpin digital transformation can be found in Table 1 that also connects with the envisaged peatland aquaculture innovations.

Vertical integration of processes crosscut the whole value peatland ecosystem from procurement of monitoring equipment and smart feeding regimes to optimised fish biomass to diversification of activities to include recycling of wastewater for irrigation of vertical farming and exploitation of the extensive "wilded" ecosystem for pollination/ecosystem service management. Essentially, all data generated from production processes is considered from the perspective of real-time efficiency, quality, risk mitigation and organization planning by digital technologies that will be optimised into an integrated system (Savastano et al., 2018).

Horizontal integration extends beyond the internal operations at Mount Lucas peatland site from suppliers to end-users including all key stakeholders. In recent times, seamlessly connecting this broad holistic ecosystem can be potentially met by the Quadruple Helix 'Empower Eco™' Concept that unites academia, industry, government and society regionally (Rowan and Casey, 2021). Digitization is the foundation for the development of new strategic plans and enable opportunities in real-time through specialist training across the water-energy and food nexus that will also stimulate new social enterprises, greater community engagement, and job creation in paliduculture. For example, exploiting the European Digital Innovation Hub (EIDH) concept at Mount Lucas will manage the digital transformation of bespoke peatland eco-innovations, along with connecting this site trans-regionally with complementary EIHDs to create and add value (Galanakis et al., 2021). Funding instruments such as Horizon Europe MSCA RISE, Erasmus Plus, European Just Transition and Interreg

Fig. 1. Aerial view of Mount Lucas peatland site in the Republic of Ireland for development of aquatic innovations powered by wind turbines. The wind turbine indicated (WT) provides all electrical requirements for the production site (red). The site consists for 4 D-end split culture ponds (blue), a 16-channel treatment lagoon (green) which contains algae and duckweed, and a water reservoir (yellow) for the system. Water is taken is from an adjacent bog river (− − -). This occurs only to compensate for loss of water from the system via evaporation. Discharge from the system only occurs during times of excessive rainfall whereby filling the overflow tank (orange). The site is situated in the middle of a peatland which is undergoing natural restoration.

programmes can support and accelerate horizontal integration and at Mount Lucas will be matched with balanced rural enterprise and growth for economic, political and societal sustainability (Rowan and Casey, 2021; Rowan and Pogue, 2021).

Digitization provides access to an integrated network of unexploited big data with potential benefits to society and to the environment (Mondejar et al., 2021); moreover, it is the integration of digital technologies into everyday life. Appio et al. (2021) noted that our ability to make well-informed decisions underpinning how to efficiently use natural resources and services has a significant impact on sustainability and equal access. The Food Standards Agency UK (2021) highlighted the role of digital innovation as emerging technologies that will positively impact on the UK food system. Moreover, the Food Standards Agency UK (2021) stated "digital technologies are been adopted rapidly across the value chain that includes discrete applications at the field, farm and factory level that includes automation, robotics and performance monitoring – mostly aiming at process optimisation; at the consumer level with a multitude of innovative new internet-enabled food distribution platforms and services; and increasingly at an integrated system level, connecting actors at all stages of the value chain, including supply chain management, and secure and gap-less digital traceability of food items from farm to fork". It loosely grouped digital technologies (DT) across three main categories, (a) DTs applied directly to food production processes (such as sensor-based agriculture, traceability, monitoring of production and delivery) where resulting flow of information is based on input data from the food; (b) DTs that generate information relevant to food from input data, but not directly gathered from the actual food (such as social marketing for customer awareness, behaviour and choice); (c) DT platforms used to aggregate and transmit data securely (cyberphysical), record keeping and for making decisions either automomously or with human input. It is appreciated that digitization is a vast topic; consequently, this article will provide examples of digital technologies that are currently applied to, or will future enable peatland innovation with particular relevance to the development of the Mount Lucas site in the Republic of Ireland.

3.1. Robotics

No robotics are currently deployed at Mount Lucas; but, are being used and developed elsewhere for feeding, cleaning ponds (Osaka et al., 2010; Yue and Shen, 2022), oral or injecting vaccines (Lee et al., 2013), monitoring behaviours and removing diseased fish (Antononucci and Costa, 2020), all labour intensive and costly processes (Lucas et al., 2019). For the first time, consumption of farmed fish has exceeded that of wild-caught fish, and by 2030, digitization of aquaculture (such as by use of robotics) and aquaculture production will potentially contribute for two-thirds of fish that humans consume (Connolly, 2018). Robotics can facilitate risk mitigation and improve profit margins and sustainability (Table 1). For example, in the salmon industry automated underwater robots have been deployed for cleaning and inspecting nets and have reduced human operations (Paspalakisk et al., 2020) and have been used to evaluate fish health and monitor and prevent escape of farmed fish (Ohrem et al., 2020). Some of the advantages of robots is that they more profitable as they can work continuously and can be substituted to address none-ideal human workforce conditions, labour intensity and sophistication. The high density of fish during aquaculture increases the risk of disease, which reduces production and profits. Cermaq are overcoming this problem using robotics to sort diseased or harmed fish from good quality fish for processing (Connolly, 2018). SINTEF (an independent research organization in Norway) is developing underwater robots to examine and repair nets for marine aquaculture and contributing to the cost-effectiveness and sustainability of the salmon industry (Connolly, 2018). A survey of the literature revealed that several academic/industry partnerships, Innovasea (https://www.innovasea.com/), Cermaq (https://www.cermaq.com/), Robotfish (https://www.edlbf.com/), SeaVax (https://theexplorer.no/), and Sublue (https://www.sinfet.no/en/) are developing robotics for aquaculture (Yue and Shen, 2022). Moreover, with the development of Industry 5.0 human centric technologies (Xu et al., 2021), collaborative robots (cobots) will play vital roles in agriculture, paludiculture and food production along the full value chain. These cobots will work closely with human operators to perform dangerous and less popular menial tasks along with more labor-intensive, monotonous and repetitive jobs (Wong et al., 2022). Cobots can also be used as transportation for in-field logis0ics applications (Ducket et al., 2018).

3.2. Drones and satellites

In terms of aquaculture, drones can function above and below the water (Sousa et al., 2019; Yue and Shen, 2022). Connolly (2018) noted that drones can be used for monitoring offshore fish farms such as for inspecting under water cages for damage and holes. Drones can be used to monitor duckweed coverage and production in the ponds of the Mount Lucas peatland site where they can contribute to increase operational efficacy of wastewater treatment, quality and recirculation (O'Neill et al., 2019). Yue and Shen (2022) noted research institutes and industries developing drones for deployment in aquaculture include Subblue (https://www.subblue.com/), Apium Swarm Robotics (http://apium.com), Blueye Pioneer (https://www.avetics.com/) and SeaDrone (https://seadronepro.com/). Connolly (2018) reported that drones produced by Apium Swam Robotics can be deployed en masse to survey the oceans and use sensors for analysis. Whereas Blueye Pioneer produced drones that provide live streaming of underwater exploration using a Blueye app on a smartphone, computer or headset/goggles. Drones can be used to collect data that would be challenging for humans to obtain and can contribute data that can be used to generate new algorithms for developing technologies (Yoo et al., 2020). Drones enable surveying of large areas and could be used to survey and monitor the status of the entire Irish peatlands (ca. 80,000 ha) and the collected data used to assist planning and monitoring of rewetting, rewilding and to support eco-innovation developments. Salidrone (https://salidrone.com/) is collecting data for evaluating fish stocks and environmental conditions and by integrating AI and cloud computing the cost of aquaculture can be reduced and the operational performance of aquaculture improved (Chen and Zhang, 2017). The potential of drones for aquaculture is enormous and currently the drone market is estimated to be worth $5.1 Billion by 2025 (Yue and Shen, 2022).

Other adjacent studies have reported on the use of sensors for measuring water parameters can advance aquaculture (Xing et al., 2019; Su et al., 2020). Science Foundation Ireland (2021) reported on new 'Terrain_AI' project between academic researchers and Microsoft Ireland focused on digital transformation that includes novel multimodal sensing technologies, IoT devices, Microsoft Azure-informed AI and cloud-based innovation to monitor carbon sequestration of peatlands and other land types to improve our understanding of the relationship between human activity and land use and how this may relate to climate change. Terrain-AI will build artificial intelligence (AI) models that can inform more effective and sustainable management practices, leading to significant carbon reduction. Data will be captured from satellites, airborne platforms, as well as in-field instruments, from 14 test sites strategically located across Ireland. This digital project will help improve our understanding of the interactions between the land and human activities that lead to carbon emissions that will also support and enable comparison between peatlands and all land types including grasslands, croplands, forestry, wetlands, to urban areas. This will integrate the aforementioned-generated data into a modelling framework that will inform more effective policies to reduce carbon emissions. Terrain-AI will also help to inform future land use practices that will achieve reduced carbon outputs such as, precision aquaculture and farming, carbon sequestration of grassland, and new approaches to public transport, along with other adjacent needs such as tree planting in urban areas. Terrain-AI will design a cloud platform that can use the insights from these Irish findings that will be shared with other countries to enable everyone to explore land usage and carbon reduction in their respective geographical jurisdictions. Notable, Microsoft has been carbon neutral across the world since 2012 and is committed to achieving carbon negative status by 2030; it seeks to promote sustainable development and low-carbon business practices through the use of cloud-enabled technologies (Science Foundation Ireland, 2021). This builds upon delivery of Airband project in partnership with Teagasc (https://www.teagasc.ie/) tohelp the farming community to stay connected, where Terrain-AI will explore how we can leverage technology to reduce carbon emissions across different land types. This Triple HUB approach combines Earth Observation, Geocomputation and Climate Modelling with stakeholders that will collect high quality data, extract verifiable information and generate the facts to enable society make informed decisions about changing how we manage our climate and environment. It will deliver unique insights to help landowners and planners make better informed decisions to reduce carbon emissions. This platform leverages off the latest in AI and IoT technologies where open sharing of data and insights will collectively inform new solutions to reduce carbon emissions globally and will support the delivery of a net zero future.

3.3. Sensors

Many of the drones and robots use sensors to navigate underwater to collect data such as physicochemical parameters, or above water for geosurvey and referencing (Yue and Shen, 2022). Connolly (2018) noted the biosensors, such as those produced by Sense-T can improve efficiencies across he salmon to oyster industry by analysis of oxygen levels and water temperature; even extended to measuring heart rate and metabolism. Sensorex devices are used to monitor dissolved oxygen levels and pH to create appropriate environment for improve shrimp efficiency and yields (Connolly, 2018). The company YSI has also developed handheld sensing devices for automatic feeding technology and transportation tanks that maintains ideal environment for fish (Connolly et al., 2018). Recent studies at Mount Lucas has focused on the monitoring water physicochemical parameters along with matching use of handled algal-Torch for monitoring algal populations to that of using flow cytometry for real time determinations in living laboratories (O'Neill et al., 2022).

Biosensors have been exploited to advance the aquaculture industry for determining DO levels, water salinity and temperature (Antononucci and Costa, 2020). Svendsen et al. (2020) has used biosensors to monitor heart rate and other physiological conditions in salmon. While Zhou et al. (2019) described the potential of using underwater sensors linked to the internet to inform efficacy of feeding based upon hunger status of cultured fish in various aquatic environments including ponds and rivers. Yue and Shen (2022), reported on a European consortium project comprising academia and aquaculture companies that are developing an automated/integrated platform to detect and monitor chemical contaminants, harmful algal blooms, pathogens and toxins. Mount Lucas aquaculture can be advanced by developing and testing sensors combined with cloud management along with mobile phone apps to help inform the establishment of an optimised environment for fish and feeding; Yue and Shen (2022) also advocate need for sensors to monitor stress levels in individual fish species and emergence of pathogens in water, where devices could be inserted into live fish in such a manner to support detection on land, boats or satellites. Measurement of changes in microalgae species in the aquaculture pond (O'Neill et al., 2022; O'Neill and Rowan, 2022), and disruption brought on by flooding to IMTA system due to frequent storms were attributed to climate change (O'Neill et al., 2022).

3.4. Photonics

Optical and photonic technologies are currently adopted to measure crop health and agri-food quality using remote sensing data in the visible, near-infrared, and thermal-infrared wavebands (Massaro et al., 2020) (Table 1). Agri-photonics constitutes a new area of research that encompasses electronic and opto-electronic technological advances implemented on unmanned aerial vehicle (UAV), decision support systems (DSS), multispectral imaging, and precision agriculture sensing. Traditional methods in agriculture cultivation is labour-intensive and struggles to meet the increasing demands of our growing populations. Optics and photonic technologies have been proven as state-of-the-art-solutions for helping with crop production and harvesting technologies (Yeong et al., 2019); thus, have potential applicability for transforming peatland innovations.

3.5. Artificial intelligence and machine learning

Artificial intelligence (AI) can help inform reliable and appropriate decision making based upon large data sets measured using digital devices, such as drones, robots, and sensors (Yue and Shen, 2022) (Table 1). An Australian company, the Yield, provides a diverse suite of technologies for all types of agriculture which it uses Sensing + Aqua technology to enable predictive analytics for enhanced data-driven decision- making (Connolly, 2018). This author also noted that nearly 32% of wild-fish caught are procured unsustainability where AI through cameras and data collection can identify species, reduce overexploitation of fish species, and enable greater accountability of harvesting methods. It is envisaged that research from this peatland site will be linked to the Terrain-AI project (Science Foundation Ireland, 2021). Indeed, the need to rapidly develop aquaculture and adjacent innovations is reflected in many global partnerships between academia and aquaculture industry. Such efforts are deploying AI to inform decision making (Evensen, 2020) that can reduce reliance on labour intensive practices such as feeders, water quality, harvesting and processing. Josthiswaran et al. (2020) highlighted the potential of using AI in enhancing control systems in aquaculture, such as in the area of reducing waste streams and improving costs. However, there is commensurate opportunities to use machine learning and development of algorithms based on increased data sets through Open Innovation and knowledge exchange for advancing the industry linked to academia and digital companies. One research effort is to apply deep learning technologies in aquaculture, e.g. for fish classification, counting, behaviour monitoring, and fish fillet defect detection (Sun et al., 2020, Yang et al., 2021a, 2021b). Deep learning has outperformed the traditional machine learning algorithms in many application areas. However, one major drawback of deep learning is that it requires a large dataset to train the model, which is a significant challenge for applying deep learning in aquaculture.

Digital transformation can also advance bioprospecting of key bioactives from microalgae, duckweed and other peatlands resources for one health application. For example, AI can be used to potentially screen and inform the appropriate type of bioactives that elicit pro- and anti-inflammatory responses for fish welfare with view to fortification of feed (Murphy et al., 2020a; Murphy e al., 2020b; Murphy et al., 2022; Pogue et al., 2021). Masterson et al. (2020) reported on the use of lentinan from Shiitake mushroom to ameliorate against clinical isolates of *Klebsiella pneumoniae* exhibiting antimicrobial resistance using novel lung infection models. Commensurately, Felix and Angnes (2018) also highlighted increased interest in electro-chemical immunsensors that may potentially disruptive the bioprospecting of such high value peatland products; such immunosensors explore measurements of an electrical signal produced from an electrochemical transducer. Moroever, this signal can be voltammetric, potentitiometric, conductiometric, or impedimetric that can be harnessed as tools since they are specific, simple, portable, generally disposable, and can carry out in situ or automated detection (Felix and Angnes, 2018). Use of bioinformatics linked to machine learning can be applied to understand diversity and richness of microbial and algal species in the aquaculture ponds (O'Neill et al., 2022). Use of drones and satellites can support and enable digital transformation of in situ living labs connected to environmental test beds at Mount Lucas (Rowan and Casey, 2021).

3.6. Immersive technologies, augmented reality (AR), virtual reality (VR)

Augmented reality is an interactive experience within which digital and context-based content is overlayed upon real-world objectives (Egan et al., 2016; Braga Rodrigues et al., 2020). As such, AR could be employed to inform aquaculture activities by their nature are highly variable and labor-intensive that are frequently influenced by species, location and aquaculture process (FAO, 2020; Yue and Shen, 2022). Connolly (2018) reported that the U.S.Navy uses Divers Augmented Vision Display (DAVD) that superimposes high-resolution sonar imagery on a diver's visual experience. AR can be used to improve efficiency of aquaculture production, monitor mortalities and welfare status of fish under a plethora of environmental conditions. This was also noted by Yue and Shen (2022) that the use of AR, in combination VR, for training and education as it pertained to fish welfare, disease prevention, escaping fish and dangerous working conditions. Yue and Shen (2022) highlighted the capability of AR to inform efficacy and economics of deploying underwater drones and robots that encompassed monitoring fish behaviour and mortality. Yue and Shen (2022) have reported on the use of AR with a cloud system to advance aquaculture to increase fish biomass, and to monitor fish health linked to water parameter determinants. Augment and Virtualh Reality in may be possible to review and evaluate appropriate locations across ca. 80,000 ha of peatland for both sustainable carbon cycles and deployment of aquaculture systems that includes risk mitigation.

3.7. Georeferencing and mapping

ArcGIS mapping can be used to inform restoration and rehabilitation of peatlands linked to ecology/biodiversity to inform carbon cycles (Rowan and Casey, 2021). ArcGIS mapping of the 80,000 ha of peatlands under the management of Ireland's Bord Na Mona (State Body) would enable profiling of peatlands to match locations for development of aquatic innovations in terms of desirable production sites balanced with environmental protection and ecology. ArcGIS mapping of peatlands, linked to ecology/biodiversity, ensures appropriate use of carbon cycles. Bord na Móna is rehabilitating and restoring bogs as part of its Peatlands Climate Action Scheme with the aim of reducing carbon emissions and the eventual creation of carbon sinks. This is complex as raised bog is very dependent on sphagnum moss activity that prefers acidic conditions; however, the ground water in cutaway bog from peat harvesting will have become alkaline. Thus, it is important to map the peatlands linked to physiochemical profiles that would be extremely challenging without using digital tools such as ArcGIS. For example, given differences in peatland acidity, solutions are more so focused not on bog restoration, but bog rehabilitation, which depends on the peatland providing a suite of habitat types, such as wetlands, fens, scrub and woodland that would benefit from end-to-end monitoring and use of cloud edge computing (Table 1). Bord na Móna, with Ireland's Economic and Social Research Institute (ESRI) has a trajectory to actively restore and rehabilitate 33,000 ha of peatlands. It uses ArcGIS to design the most appropriate rehabilitation measures and then implements a wide range of measures in real time; moreover, ArcGIS rapidly visualises the existing conditions across thousands of hectares of bogs using numerous datasets that informs design and implementation of the most appropriate rehabilitation measures to restore peatland function and deliver climate action benefits. For example, for each bog identified for rehabilitation, GIS specialists and ecologists use the desktop solution ArcGIS Pro and 3D spatial analysis tools to examine the ground level and create detailed, map-based rehabilitation plans.

Tahar et al. (2018a, 2018b, 2018c) reported on the use of ArcGIS to enable monitoring and mapping of emerging contaminants of concern in aquatic environments for subsequent risk mitigation and management decision making (Tahar et al., 2017). Effective risk assessment and prediction for deployment of appropriate interventions to mitigate pollutants in waste water is at best 'semi-quantitative' given the enormous number of contributory factors and variables to inform management decision making (Tahar et al., 2017). Tahar et al. (2018a, 2018b, 2018c) highlighted that occurrence and geodatabase mapping of contaminations of emerging concern onto appropriate river basin catchment management tools will inform predictive and simulated risk determinations to inform strategic investment in necessary mitigation infrastructure to protect rivers and economic activities that rely on clean water. The medium to longer term ambition would be to utilize relevant European software and models for the development of spatially explicit Geography-Referenced Regional Exposure Assessment Tool for Peatlands to manage these resources, similar to what is been achieved for European River Basins.

Digital transformation of data sets would enable real-time and improve reliability of water quality determinants for risk management and policy decision making. There is help identify key constraints, such as knowledge underpinning sensitivity of existing sophisticated analytical equipment to measure low-level pollutants in real time; therefore, the commensurate development of appropriate risk management models will also inform future intensification and diversification of aquatic industries including peatland-based innovation. For example, Tahar et al. (2017) developed a semi-quantitative risk assessment model for evaluating the environmental threat posed by three EU watch list pharmaceutials namely, diclofenac, 17-beta-estradiol, and 17 alpha-ethinyestradiol, to aquatic ecosystems using Irish data; this model adopts EPA's Source-Pathway-Receptor concept to define relevant parameters including low, medium and high risk score for each agglomeration of waste water treatment plants, including catchment, treatment, operational and management. It is envisaged that a similar type semi-quantitative RA approach may aid development of peatlands globally in terms of screening for potential risks where there is a need to measure or predict environmental pollutant concentrations and where hydrological data are available. This approach is semi-quantitative, as other factors such as climate change will need to be considered for estimating and predicting risks with new aquatic innovations. Nair and Domnic (2022) noted the influence of machine leaning in advancing many aspects of this industry'; specifically, these authors described a combined strategy including non-learning enhanced method and deep CNN (convolution neural networks) for picture reduction and reconstruction in underwater imagine in aquaculture. These authors suggested that this model outperforms existing methods in terms of picture enhanced, compression, and reconstruction quality.

3.8. Edge-internet of things (IoT) systems

Globalization has radically informed the development of sustaining and disruptive technologies (Schuelke-Leech, 2018), where traditional industries such as agriculture and aquaculture employ vanguard technologies to expand upon opportunities that has enabled smart farming and the agri-food industry 4.0 (Klerkz et al., 2019). Perez-Pons et al. (2021) highlighted pressing need to make farms more profitable and sustainable via the analysis of data envelopment analysis and the application of the Internet of things and Edge computing; this approach allows monitoring environmental conditions with real-time data from the different sensors installed on the farm; thus, minimizing costs and achieving robustness by way of transitioning important data to the cloud after edge computing. Essentially, the edge devices process the data and then decide either to send this data to the cloud for further processing or make decision locally at the edge (Table 1). Edge computing can also be applied to sensor fault diagnosis and data repair (Wang et al., 2021). Technology requirements are increasingly important for agri-food industry with particular emphasis on meeting challenges faced by producers along value chain that also reflects a diversity of types of farms such as crop-cultivating or mixed farms that grow crops and produce livestock. These also rely upon fragile water resources; moreover, Eurostat noted that that total irrigable are in the EU-28 was ca. 15.5 Mha (8.9% of the total) whereas only 10.2 Mha (5.9% of the total) was irrigated thus highlighting the opportunities for implementing low-cost technological solutions (Fleming et al., 2016). The Industrial Internet of Things (IIoT) potentially enables technologies focused on implementation of monitoring and resource management solutions across many Industry 4.0 applications that embraces cloud computing, big data, AI or distributed ledger technologies (such as blockchain) that will improve traceability and productivity of commercial processes (Yu et al., 2017).

Perez-Pons et al. (2021) noted that when transmitting data to the cloud, there remains several challenges including data privacy, energy consumption, or costs associated with cloud services. Essentially, service providers charge users relative to the amount of data transferred, stored or processed in the cloud. However, by using Edge Computing technologies, one can decrease the amount of data transferred between the IoT layer and the cloud that will also allow for deployment of machine learning models at the edge of the network reducing response time and enabling service provision even if communication with the cloud is interrupted (such as rural areas associated with peatlands) (Alonso et al., 2020). Perez-Pons et al. (2021) had also reflected on the findings of Pedra-Munoz et al. (2016) who reviewed years of improvements of applying technologies at family-farm level with sustainability, where the former reported that IoT and Edge computing can present a competitive advantage when measuring efficacy of decision making units. Perez-Pons et al. (2021) reported on different variables from the Environmental Performance Index with real-time sensors and the application of Edge-computing platforms that can reduce the data traffic to the cloud. In addition, 5G is a key enabler of edge computing, which provides low latency and high bandwidth communication services between sensors/edge devices and the cloud, and as well as direct device to device communication (Wang et al., 2021).

4. Pollination and ecosystem service management

Mount Lucas is an abundant source of heather and other peatland flowering plants, this provides a rich opportunity for honey production from nectar or from secretions from living part of plans by native bees; this can be addressed in on site living labs. The stressful environment created by the peatlands can influence emergence of novel bioactive properties produced in heather-honey. Shafiee et al. (2013) has previously reported on the use of machine learning to differentiate and classify polyfloral from monofloral honey where latter has a higher commercial value. There is a correlation between honey colour and its floral origin and some chemical parameters that can be discerned using image analysis and algorithms. Different monofloral honeys have distinctive flavour and colour due to variance in their main nectar sources (Escriche et al., 2011). Use of imagine analysis is an area of emerging importance that reflects a method that supports rapid, real-time, simple, selective and low-cost properties appropriate for honey characterization. Moreover, honey industry requires simple, non-invasive, fast and economic technologies for characterizations – other digital approaches include an electronic tongue and data fusion of electronic nose (Escriche et al., 2011) where there is good correlation evident by applying data fusion. The latter aids human panels in making decisions for application to honey quality evaluation that captures adulteration, classification of flora types along with their geographical sources. Image analysis can help discern honey colour that depends on a plethora of factors including phenolic and flavonoid contents, mineral contents and antioxidant activity (Dominiguez and Centurion, 2015). Machine learning as an innovation has been shown to enable objective assessment of visual attributes of food quality including colour. There are other multiple opportunities for machine learning for informing pollination; for example, Goblirsch et al. (2021) describe the potential of electron-beam for low-temperature treatment of pollen contaminated by complex bee parasites and viruses that may be used for commercial bumble bee purposes. The complexity of pollen contamination can be unravelled be potentially unravelled by use of flow cytometry using a suite of specific biomarkers in real time- where this non-invasive enumeration approach is potentially appropriate for machine learning and automation applications. The Irish company Apis Protect developed a digital platform using sensors and machine learning for monitoring hives; specifically, key parameters encompassing temperature, sound, humidity and temperature are recorded suing a wireless in-hive sensor device (Robb, 2021).

5. Waste water recirculation – nexus between monitoring, treatment and energy using a paludiculture framework

The Farm to Fork Strategy which is at the heart of the EU Green Deal is a key driver for efficiency within the nexus of food production, water and wastewater resources and treatment and broad sustainability issues. Indeed across the OECD Farm to Fork strategy reflects the requirements of food systems in terms of the “triple challenge” of food security and nutrition, livelihoods, and environmental sustainability (Rowan and Casey, 2021). While the concept of Industry 4.0 is now well established, when evaluating food production systems in terms of the use and reuse of resources such as water it is appropriate to consider the newer concept of Industry 5.0. Industry 5.0 sees digitisation as not just about productivity and growth; but is also part of a broader need for sustainable, human-centric and resilient industry. In the context of the positive transformation of peatland ecosystems, digitisation, applied to water resources can be seen in the context of Industry 4.0 and 5.0 concepts. The “Digital Water” programme within the International Water Association offers key lessons on how the water industry (or industry's where water is a key resource) can uptake and integrate next generation digital technologies. A series of white papers describe the various opportunities and challenges associated with the Digital Water Concept. Challenges with adoption include technical issues such as integrating smart actuators, sensors, and autonomous control systems in a sensible and transparent manner, cybersecurity issues, human resources issues and, crucially ensuring the need to have a clear value proposition.

Water management is key in paludiculture and should (i) maintain appropriate water levels for the activity in question and (ii) may be required to enable the supply of nutrients through the water inlet (Vroom et al., 2018). This may be required to address nitrogen losses after rewetting due to denitrification processes and anaerobic ammonium oxidation. Indeed this can provide an opportunity for local reuse of N rich agricultural wastewaters (Vroom et al., 2018). Recent work in the UK, analysed water management requirements through pumping of water to rivers when inputs to peatlands, due to rainfall, exceed evapotranspiration (Mulholland et al., 2020). Despite this there can be significant reductions in energy use, costs and associated greenhouse gas emissions for paludiculture when compared to arable activities on deep fen peat (Mulholland et al., 2020). Real time control of storm water control measures has been shown to have significant potential for urban water management (Xu et al., 2021) and reinforcement learning has also potential to mitigate flooding when compared to passive control and rule-based control systems (Bowes et al., 2021). Such innovation could be adapted for water management in paduciculture activities Furthermore, a digital transformation of how water and wastewater resources are managed, can impact both the use of water abstracted directly for paladiculture activities (e.g. for aquaculture) and the management from wastewaters resulting from such activities. Recent work in the water and wastewater treatment sectors can point the way forward in terms of digital adoption for efficient management of water resources in paludiculture. This can also help reduce concerns in terms of digital adoption through visibility of related case studies.

Artificial intelligence can be applied within the water sector under three headings namely (i) modelling, prediction and forecasting, (ii) decision support and operational management, and (iii) optimization. A broad digital transformation would also impact these areas but also a fourth, namely system and infrastructure design could be considered. There are lessons for paduliculture that can be gleaned from other sectors such as storm and flood management, wastewater treatment and the water treatment and distribution sectors. Table 2 summarises, in the context of paludiculture how a digital transformation could impact the sector. Developments in remote sensing could have significant implications for paludiculture. Weiss et al. (2020) presented a meta-review of remote sensing for agricultural applications. Technological improvements have meant that global, regional and local data on crop mapping, yield forecasting, biodiversity loss, water and soil impacts are, in many situations, readily available. Chawla et al. (2020) reviewed remote sensing products for analysis of water quality (e.g. surface water), water quantity (e.g. river or stream flow) and extremes (e.g. flooding and drought impacts). Remote sensing also provides an alternative for locations where in-situ sensing is problematic where satellite remote sensing can now monitor in near-real-time retrievals, most components of the terrestrial water cycle. Challenges remain relates to accuracy, data consistency, utility and also in retrieving data related to groundwater, water quality, surface water levels, and river flows and in relation to the products themselves (Chawla et al., 2020).

Table 2
Examples of impacts of digital transformation on water resources in paludiculture.

Modelling, prediction and forecasting	System and infrastructure design	Decision support and operational management	Optimization
• Scenario analysis to support design (e.g. robust design under varying conditions) • Links to process optimisation and potential for real--time process modelling using digital twins.	• Optimise design to enable future expansion and digitisation • Reduce life cycle costs through development of digital models and/or digital twins • Design to enable future expansion	• Management of water levels • Real-time control of waste-water treatment processes • Fault detection and diagnosis on water systems • Regulatory compliance	• Optimised pumping regimes for water level management • Minimise energy consumption • Optimised system maintenance (e.g. preventative maintenance) • Optimise on-site productivity

Data collection in the water sector has long been recognised as a key challenge. In many cases the may be collected from relatively harsh environments which results in added maintenance. Furthermore there can be concerns including (i) lack of trust in data veracity, (ii) poor data management systems and (iii) the use of systems that are over-complicated and unoperable for end-users. Therrien et al. (2020) also highlighted key steps and ways forward for ensuring the steps from adequate data collection to action can be completed. Corominas et al. (2018) conducted a comprehensive review of computer based techniques for data analysis to improve operation of wastewater treatment plants. The EU have led in terms of research in this area with the most cited techniques including artificial neural networks, principal component analysis, independent component analysis and partial least squares. However the review acknowledged a lack of objective comparison of techniques, the need for guidelines, the requirement for validation at full-scale, and the limited options for active optimization of data information content and quality. Clifford et al. (2017) proposed an approach balancing spatial resolution of data with the costs involved in collecting such data and It is clear the use of real-time monitoring and control systems has significant potential but further case-specific validation is necessary.

Newhart et al. (2019) comprehensively reviewed specific applications of various real-time control in wastewater treatment facilities and presented examples of on-site applications across various industrial and municipal sectors. While Newhart et al. (2019) pointed out the potential for such control to be more difficult to implement in decentralised wastewater treatment facilities, Fox et al. (2022) demonstrated how data driven real-time control of a decentralised wastewater treatment system (in this case a sequencing batch reactor) can be optimised to achieve regulatory compliance, reduce energy consumption and increase system throughput. Both standard statical approaches and more advanced approaches using neural networks and regression modelling (Fox et al., 2022) were implemented. Key to these approaches was their compatibility with standard (low-cost) programmable logic controllers and enabling the end-user optimise the control approach.

Fault detection and diagnosis, while common across various engineering sectors, has focused mainly on leak detection at a municipal water supply level rather than building or industrial settings (Seyoum et al., 2017; Hashim et al., 2020). Fault detection in these settings can reduce leaks but also enable efficient monitoring and preventative maintenance of equipment such as sensors, valves, pumps and motors used for water and wastewater management. There are various approaches that can be used to leverage data from water systems in industrial processes. Mulligan et al. (2021) developed a series of water distribution system performance assessment rules and demonstrated how these would result in significant energy and water savings and associated greenhouse gas emissions. Hashim et al. (2020) used principal component analysis and support vector machine techniques to enable accurate detection of various faults in a large public building and an industrial setting. The problem of false alarm moderation (false alarms can undermine user confidence) has also received recent attention using both modelled data (Chen, 2010) and using case-study data from industrial settings and large buildings (Hashim et al., 2020). Fault detection in wastewater treatment also requires further testing in full-scale facilities and a pathway forward of using hybrid models such as linking gaussian process regression, artificial neural networks with principal component analysis or reinforcement learning to challenges associated with issues around sensor accuracy and transient operational conditions (Sundui et al., 2021).

Nature based solutions (NBS) have been identified as key in addressing challenges in water management across urban, agricultural and ecological settings. In the agricultural landscape, NBS can be applied for soil health, carbon mitigation, downstream water quality protection, biodiversity benefits as well as assisting agricultural production and supply chains to achieve net-zero environmental emissions (Rowan and Casey, 2021). Evaluting the ecotoxicological safety of NBMS will also be importnat moving forward (Garvey et al., 2015). Examples of recent applications include wastewater treated using naturally occurring algae, bacterial and duckweed using IMTA process (O'Neill et al., 2020), use of earthworms based technology for composing and wastewater treatment applications (Cooney et al., 2021; Hylton et al., 2022; Arora and Saraswat, 2021), zooplankton for tertiary wastewater treatment to enable wastewater reuse (Pous et al., 2021). The INNOQUA (H2020) project presented reviewed and demonstrated various pathways for nature based treatment of wastewater and options for enabling wastewater reuse (Bumbac et al., 2021). The study reviewed constructed wetlands, waste stabilisation ponds, anaerobic treatment systems and vermifilters and presented details of performance, design and maintenance requirements and ability to meet various regulatory standards across a wide variety of applications. NBS technology can be underpinned by models and tools that support better land use, enable accurate nutrient flow modelling and support the development of sustainability metrics via life cycle assessment; moreover, while NBS are designed to minimise technological requirements, there are significant opportunities to further enhance their benefits and enable process flexibility through targeted real-time control (Basil et al., 2021).

6. Aquaculture and other aquatic systems

Peatlands presents an opportunity to establish new food production systems that can offset negative environmental consequences of resource constrained conventional terrestrial farming. Peatlands aquaculture can fulfil consumer needs by both intensifying and diversifying production of new freshwater areas and fish species. The emerging nature of the industry provides an opportunity to build in digital solutions that can enable high technological developments tailored to the specific needs of the production model. Technology interfaced with digital solutions can be used to address the challenges of low impact paludiculture (such as low-trophic IMTA, RAS, organic) and environmental services. Digital technologies can support efficient development of paludiculture products and can be used to develop climate-friendly, sustainable production systems generating high quality proteins and other products.

Essentially, Mount Lucas peatland demonstrator is ideal for establishing digital systems to allow digitalization and use of collected data across the full value chain to inform new eco-innovation balanced with environment protection. Digital tools such as Edge-cloud sensors, AI, machine learning and augmented reality can be used to build models from collected data and facilitate implementation of a circular strategy to produce biomass of high value fish (such as trout and perch). At the same time models that integrate biological constraints (microbiome, fish growth and health), system functioning, and effluent outputs can improve biomass productivity and represent a step towards precision aquaculture. Moreover, the integration of customized management systems throughout the supply chain will

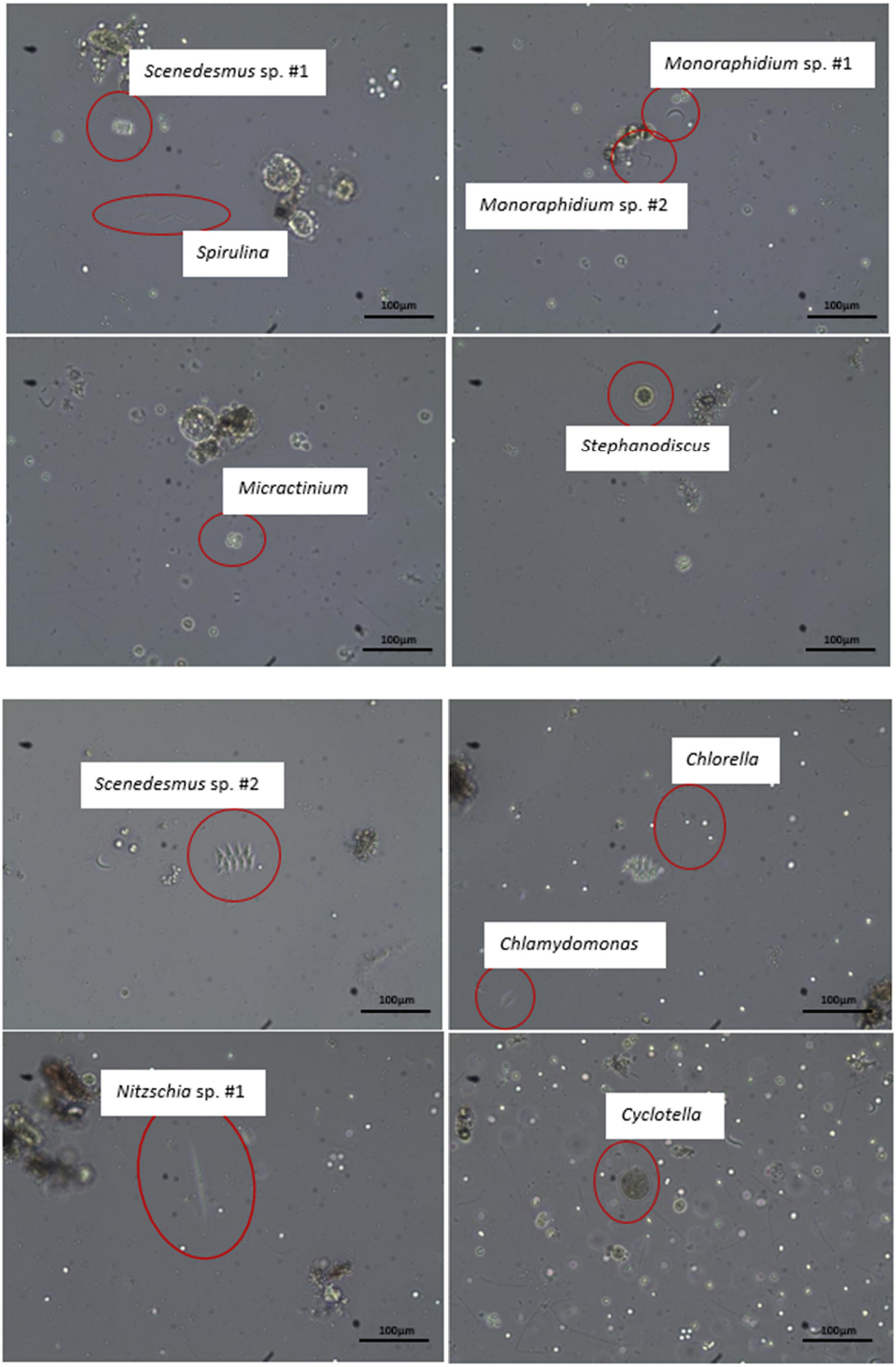

Fig. 2. Imagery of microalgae from the genera Scenedesmus, Nitzschia, Monoraphidium, Chlorella, Chlamydomonas and Cyclotella identified in Mount Lucas IMTA.

enable a well-managed, responsive and crisis proof system with improved traceability and authentication (Fig. 2). Such a digitally transformed, intelligent management system will enable development, testing and validation of optimised integrated multi-trophic aquaculture and recirculating aquaculture systems (IMTA/RAS) on the peatlands by integrating multi-sensing (heterogenous sensors), multifunctional real-time modelling for decision making with provision for climate resilience through full system monitoring (microbiome, water physicochemical parameters).

There is a pressing need to design, implement and deploy ICT technologies to provide end-to-end monitoring systems for aquatic-based foods produced in the peatlands (O'Neill et al., 2022). Integrated software, and establishment of smart sensors for real-time monitoring and remote data logging of production, is being implemented at the Mount Lucas peatland site. LCA, PCA, MFA models can contribute to green business models and the standardization of emerging peatland aquaculture and associated businesses globally. The latter also includes use of AI, machine learning and Edge – cloud to develop and evolve strategies to reduce waste and to consolidate gains achieved in aquaculture supply chain management. On a related point, Ruiz-Salmón et al. (2020) noted that the water-energy-food nexus allows assessment of the life cycle of seafood products that enables clustering and knowledge transferring to add value in the European Atlantic region. LCA can be applied to help understanding the benefits of ecolabelling and eco-design in aquculture under a circular economy approach (Ruiz-Salmón et al., 2020). Open knowledge sharing can also help advance paludiculture, such as software that integrates sensors (cameras, remote sensing), and predictive analysis (biomass estimation and forecasting, water quality monitoring) to enable improved operational decisions for optimised production balanced with environmental protection. Combined use of augmented reality and virtual reality can be used for training to promote human resource development, so it accompanies 4IR and becomes part of the digital transformation and Just Transition. ICT can be used to create a quality of experience (QoE) that enables specialist training in paludiculture on site and remote by linking to living labs. Hatch blue accelerator is gaining in popularity as a novel sustainable aquaculture and innovation programme offered globally for innovators that includes those converging disciplines (https://www.hatch.blue/accelerator).

Traditionally, there has been worldwide reliance upon 'end-of-pipe' engineering solutions for discharge wastewater control to safeguard water resources (Barrett et al., 2016; Tahar et al., 2017). This IMTA system of Mount Lucas will provide solutions and data for wastewater management and be a model system for social marketing and studies of consumer awareness and acceptance of aquatic paludiculture processes (Domegan, 2021) that may lead to disruptive innovation (Schuelke-Leech, 2018; Schuelke-Leech, 2021a, 2021b). Mount Lucas will also enable emerging innovations such as oral vaccine testing and the potential use of other safety indicators (Taufek, 2020; Usuldin et al., 2021; Wan-Mohtar et al., 2021). The digital transformation "Terrain-AI" project uses drones across the peatlands for monitoring carbon sequestration as a means for sustaining carbon sinks (SFI, 2021). ICT systems coupled to drones for data collection can provide real-time ecosystem management to promote and preserve pollinators across the peatlands by preserving and enhancing habitats, improving food sources through rewilding and decrease bee-disease through use of innovative technologies (Goblirsch et al., 2021).

The development of fully recirculated systems, such as this aforementioned IMTA system, that relies upon natural processes for remediating water quality, and do not discharge to receiving water presents a step change or potential disruptive sustainable solution. O'Neill et al. (2020) described the first IMTA system developed in the Irish peatlands that uses a balanced ecosystem of naturally occurring microalgae, bacteria and potentially duckweed that regulates waste and maintains water quality. An onsite wind turbine provide a renewable source of energy to operate aeration systems in the circulatory aquaculture ponds. However, global warming has created greater opportunities for extreme weather events that can influence vital food production, by way of droughts and flooding. The ability to monitor and predict the impact of extreme weather events through digitalization of the pilot IMTA processes will help future proof and protect food supplies globally. Naughton et al. (2020) highlighted the potential benefit of digital technologies for connecting 'in field' monitoring devices with living lab sophisticated equipment for real-time decision making in freshwater aquaculture.

Previous researchers have also highlighted that microalgae species that constitute a major proportion of the peatland aquatic-biome are excellence candidates for CO_2 bio-capture (Lopez-Pacheco et al., 2021; Wang et al., 2021); thus, use of end-to-end monitoring linked to sensors that will enhance efficacy will be important going forward. The microalgae in the aquaculture ponds constitute potentially thousands of species (O'Neill et al., 2022) where there is a pressing use machine learning with bioinformatics to unlock their real-time monitoring and occurrence. O'Neill et al. (2022) has also reported on using the occurrence of key microalgae in aquaculture ponds as potential biosensors for assessing the impact of climate change on IMTA process, which can be informed by using Cloud-edge computing. It is notable that microalgae represent a superior option for carbon fixation than terrestrial plants for higher growth and faster biomass production, doubling their biomass in less than 24 h for most species (Farrelly et al., 2013; Guo et al., 2017; Lopez-Pacheco et al., 2021). Fig. 2 illustrates the different microalgae represented of the genera *Chlorella, Raphidocelis, Scendesmus, Desmodesmus, Monaraphidium and Graesiella* that were isolated from Mount Lucas aquatic environment and were previously noted to exhibit CO_2 capture abilities (Lopez-Pacheco et al., 2021). Tabatabaei et al. (2011) noted that microalgae use carbon dioxide for energy conversion while producing approximately half of the atmospheric oxygen. While Zhao and Su (2020) estimated that microalgae can capture a maximum of 2.35 $GtCO_2$ in 100,000 km^2 culture area, which shows the potential of using these organisms that naturally occur in the peatlands for CO_2 capture (Ramaraj et al., 2014). Use of microalgae in this IMTA closed system have many advantages, including easy control, insufficient space required, high CO_2 sequestration rate, and no contamination risk, nearby all microalgae species may be cultivated, and high biomass density (Lopez-Pacheco et al., 2021). Lopez-Pacheco et al. (2021) also noted that through photosynthesis microalgae can fixate CO_2 by what is known as phyco-capture process. Thus, there is a pressing need to use digital tools to enable end-to-end monitoring and to optimise ponds systems to cultivate microalgae for CO_2 bio-capture.

7. European Digital Innovation Hubs – Quo Vadis

Digital Innovation Hubs (DIHs) are one-stop shops that help companies to become more competitive with regard to their business/production processes, products or services using digital technologies, while remaining environmentally sustainable and reducing greenhouse gas emissions. DIHs are based on technology infrastructure (Competence Centre) and provide access to the latest knowledge, expertise and technology to support their customers with piloting, testing and experimenting with digital innovations. DIHs also provide business and financing support to implement these activities, if needed across the value chain. As proximity is considered essential, DIH act as first regional point of contact; consequently, a DIH is a regional multi-partner corporation (RTOs, universities, industry associations, chambers of commerce, incubator/accelerators, regional development agencies, and potentially governments), and can also provide strong nexus with other service providers outside their region supporting companies with access to their services. The rationale behind this DIH initiative is to help European industry, small or large, high-tech or not, to grasp the digital opportunities. The EC will focus 500 M€ over the next 5 years from Horizon Europe budget to support the development of DIHs as the level of digitalisation remains uneven, depending on the sector, country and size of company: only 20% of SMEs in the EU are highly digitised. This challenge is particularly pertinent for the digital transformation of peatland eco-products and services. Key assets aligned with DIHs include (a) information on infrastructures; (b) expertise; (c) network contacts of key players and communities at large; (d) expertise in initiating robust collaborations of key stakeholders to meet specialist USP offerings; (e) access to financial capital; and (f) effective digital marking to ensure trustworthy brand that attracts stakeholders and ensures high quality delivery. Thus, digital transformation of a peatland-focused hub will enable real-time access to networks; upskill and satisfy R&D opportunities; track and communicate technical expertise and consultancy, enable seamless and managed access to facilities; and support the contribution to policy measures.

Currently, there are 706 DIHs registered on the Catalogue of Candidate European DIHs tool that are in following evolutionary stages; fully operational (413), in preparation (223), and potential new DIHs from H2020 (70) (https://europa.eu/!NX87WD). The purpose of this European catalogue is to support networking of DIHs and to provide an overview of the landscape of DIHs in Europe supported by regional, national and European initiatives for the digitization of the industry. European DIHs (EDIHs) will play a central role in the Digital Europe Programme to stimulate the broad uptake of AI, high performance computing (HPC) and cybersecurity, as well as other digital solutions/interoperability for the public sector. EDIHs will support companies, and the public sector organisations, in the use of digital technology to improve the sustainability of their processes and products, in particular with regard to energy consumption and reduction in carbon emissions. The 325 candidate EDIHs are the DIHs (existing or not) that are assigned by Member States to participate in the Call for Proposal of the EC to obtain funding to become European DIHs; a network of 200 EDIHs will be financed in Europe via the new Digital Programme 2021–2027. Currently, the EC is verifying all entries in the catalogue tool based on information provided by each DIH as to whether or not the comply with 4 criteria; (1) be part of a regional, national, or European policy initiative to digitise the industry; (2) be a non-profit organization; (3) have a physical presence in the region and present an updated website clearly explaining the DIHs' activities and services provided for the digital transformation of SMEs/Midcaps or industrial sectors currently insufficiently taking up digital technologies; and (4) have at least 3 examples of how the DIH has helped a company with their digital transformation, referring to publicly available information, identifying for: client profile, client need, and solution provided to meet the needs. Generally, the main functions of EDIHs include (1) Test before invest, (2) Skills and training, (3) Support to Find Investments, and (4) Innovation ecosystem and networking. EDIHs are embedded in a local economy; for example, if manufacturing is important, the hub will enable companies in adopting Industry 4.0 and circular economy methods. Traditional ICT method, such as simulation and supply chain integration, will take on an important role where these are becoming more AI and HPC orientated. In addition, by introducing digital manufacturing, cybersecurity becomes a prerequisite. .

It is likely that the applicability and digital maturity of entities supported by Digital Innovation Hubs alone or embedded in Quadruple Helix concepts will be profiled using the categories described in Table 3. Innovation Radar methodology is an approach adopted by the European Commission to assess the impact of “test before invest” and “support to find investments” services of EDIHs. Mount Lucas peatland HUB will support and enable ‘train the trainer’ developing ways to transfer knowledge generated in a HPC, AI and Cybersecurity through regular workshops. This will also enable community building for stakeholders that includes agriculture, horticulture, health, public administration and so forth. Other activities to be adopted, aligned with EDIH framework, digital matchmaking marketplace, InvestEU, short term training courses, engagement with regional and national policy makers, deploy effective media presence to highlight peatland activities across the network, and impact assessment of activities that includes analysis of indicators, and KPIs, developing targets, generating new knowledge including Open access provision to support benchmarking and policy recommendations.

8. Business modelling and sustainability for enabling accelerating Mount Lucas green innovation

Ziegler et al. (2021) highlighted that despite increasing sustaining or disruptive potential, it remains challenging for value propositions and value network for new paludiculture products and services remains to be hurdled, which presents a barrier for commercial applicability. Several authors with subject matter-expertise in peatland innovation have appropriately noted that digital transformation of paludiculture products and services will have limited utility in the absence of a robust and valid green business model that delivers scale. Ziegler et al. (2021) described paludiculture to be an emerging, science driven, and collaborative innovation that are rarely directly commercially viable, where the authors focused on fuel, fodder, horticulture substrate and construction material. These peatland products are currently not under development at Mount Lucas. Moreover, Ziegler et al. (2021) reported that paludiculture faces significant, adverse path-dependency due to subsidies and regulations that appear to preferentially support agriculture on drained peatlands. Paludiculture initiatives to date typically involve landowners and users where further economic models supporting experimentation and scaling up of paludiculture products and services are required (Ziegler et al., 2021). Zeigler (2020) also reported that paludiculture is the productive use of wet and rewetted peatlands and proposed a 3Ms-schema of mission, modes and making innovation as a device to create space for a wide and inclusive discussion of paludiculture. The reader is directed to the published work of Planko et al. (2016) for key processes for building up a technological innovation system (that includes paludiculture) and arguments supporting a system building model approach in strategic management.

Entrepreneurs and SMEs at Mount Lucas are supported and enabled through a quadruple helix hub approach under an Empower Eco sustainability framework, which connects stakeholders across the business ecosystem including academia, industry, government and society (end-users). This reflects that need to adopt far-reaching changes of the macro environment in order to implement innovative sustainable technologies (Planko et al., 2015; Planko et al., 2016). This Empower Eco holistic approach aligns with previous scholars who reported on the combined insights from the strategic management literature and the technological innovations system (TIS) literature in order to provide a strategy framework for entrepreneurs to collectively build a favourable environment for their sustainable technology (Planko et al., 2016). It is notable that insights from system-building literature originate mainly from the systems perspective (Musiolik et al., 2012) that had previously not considered specific subject-matter insights from the company perspective (Planko et al., 2016). The holistic system building approach, aligned strongly with Quadruple Helix Hub concept depicted by Empower Eco, connects actors across their ecosystem to collaborate strategically in order to shape their environment (Rowan and Casey, 2021). Planko et al. (2016) noted that term ‘system building’ originates from the TIS literature and is defined as the “deliberate creation or modification of broader institutional or organizational structures in a technological innovation system carried out by innovative actors” (Musiolik et al., 2012). While this system building approach harnesses the use of a diverse suite of assets, facilities and expert in collaborating universities for addressing broad ranging enterprise needs, this approach as supports entrepreneurs and start-ups in co-creation and testing of low cost green solutions (Table 4).

For example, Accelerate Green is the first Irish accelerator dedicated to scaling companies based in the peatlands with a particular focus on climate action and sustainability by developing eco-products and services based on green innovation with a base in Boora, which is adjacent to Mount Lucas (Rowan and Galanakis, 2020). Accelerate Green combines Bord Na Móna’s commercial expertise and Resolve Partners expertise in building innovative companies, and is an equity-free scaling accelerator designed to create step change in green innovation (Bord Na Móna, 2022). It delivers eight 2-day deep progamme sessions that action planning, offsite innovation, strategic and business planning along with working with a peer group of successful entrepreneurs or ‘green-change leaders'. Accelerate Green also provides an ‘invest and enable’ funding strategy with an initial focus on established scaling climate tech companies, high-growth SMEs pivoting to climate change economy, earlier stage innovative-driven enterprises, renewables/carbon reduction, waste/circular, and AgTech.

Use of this systems building approach has also supported UNIVIV OneHealth/Emerald SME partners to map a business canvas that includes the economic feasibility for commercially producing high value protein from duckweed (Fig. 3) harvested from the aquaculture ponds at Mount Lucas that includes scalability. Irish demand for plan protein in animal feeds is approximately 900,000 tons, where current protein rich native crops (peas and beans) provide approximately 52,000 tons on 10,000 ha. The National Protein Stakeholders Group aspires to increase this production to 120,000 on 20,000 ha. Notably, 3000 ha of rewetted peatland ponds will produce 5000 tons of protein concentrate with zero artificial inputs including fertiliser and pesticide. Some 5000 tons of duckweed protein concentrate would displace 50% of imported protein concentrate Irish organic salmon industry. Thirty thousand hectares of duckweed on marginal lands would produce 50,000 tons of 65% protein concentrate that is approximately equivalent to 20,000 ha of pea and bean protein at approximately 30% to 35% protein. The direct commercial value is in excess of €50 m; thus, potentially displacing €50 m of imports from an Irish feed production and security perspective. Thus, rewetting peatland is commercially feasible from a farmers' perspective, if duckweed is cultivated as an alternative sustainable crop. Topics that require attention include processing duckweed to produce animal feed, optimizing duckweed growth conditions, and identifying lands most suitable for rewetting and change of use. The Mount Lucas site is licensed for fish farming where the fish waste stream supports the linked commercial production of duckweed that can be potentially used in the animal feed industry (O'Neill et al., 2022). O'Neill et al. (2019) also reported that duckweed is important for waste aquaculture stream quality and recirculation at Mount Lucas peatland site where duckweed works in concert with algae and microbes for this purpose. De Beukelaar et al. (2018) reported that duckweed is considered to be a promising source of protein for human food products due to its high protein content and environmentally friendly production properties. Albeit not peatland focused, Bonomo et al. (1997) had previously described the use of a pilot duckweed as biological approach to produce reliable, simple and cost-effective small wastewater treatment system. In spite of the profitable characteristics of duckweed (high productivity, high protein content, wide geographic distribution, control of negative impacts from conventional wastewater treatment ponds), the results intimate that extensive use in Italy seems difficult due to the high requirement of land area and the ceasing of growth in winter months (at least in Northern Italy). However, the peatlands represents a large expansive area in many countries internationally, including Ireland. In temperate climates, a reasonable use of duckweed looks to be the production of good quality secondary effluents (BOD and SS removal) from small communities, especially in seasonal (summer) wastewater treatment plants. Duckweed is the smallest and fastest-growing aquatic plant, and has advantages including simple processing and the ability to grow high biomass in smaller areas. Therefore, duckweed could also be used as a new potential bioreactor for biological products such as vaccines, antibodies, pharmaceutical proteins, and industrial enzymes. Moreover, Yang et al. (2021a, 2021b) recently reported on plant bioreactors have flourished into an exciting area of synthetic biology due to their product safety, inexpensive production cost, and easy scale-up.

Currently, the commercial production of high value 'organic' cultured perch and trout at Mount Lucas is no likely to be commercially viable given the low fish biomass or tonnage on a 4 ha site, but this also provides an excellent innovation system for education, training and research given it's state-of-the-art IMTA system focus. Fish health/welfare and the linked microbiome profile in cultured pond water will also strongly contribute as indicators or tools for studying impact of climate change on sustainable food production systems (O'Neill and Rowan, 2022; O'Neill et al., 2022), where these activities will also support social enterprises (Rowan and Casey, 2021), and the development of digital technologies.

The EIDH smart specialisation strategy for structured support and development of peatland innovation includes provision for Entrepreneurial Discovery process using bottom up approach. Typically, this embraces five categories– (1) launching strategic initiatives; (2) re-entering existing programmes; (3) updating stakeholder strategic agencies; (4) aligning infrastructure; and (5) setting up strategic fora. Digitising Peatland activities to manage projects, networks, skills and training, tech transfer, consultancy and strategy; transnational connectivity and communication; profile and embed regional actors that can promote diffusion of best practices and knowledge transfer; expand project opportunities; facilitate learning, experimentation and capacity building; manage workshops, SAPs and supporting specialist modules for PhDs; promote and foster ad-hoc alliances to enable open innovation; broker/match make academia with industry; accelerate entrepreneurial activities; align interests to local industries and opportunities for converging these; connecting with complementary EIDH for information flow and sharing on EU topics; support trusted partners that will provide subject-matter expertise and complementary services; develop successful business models for collaborations; an efficient channel to other EIHs, regional and markets that includes access to capacities, best practices and skills.

Table 3
Categories used to describe common functions of European Digital Innovation Hubs.
Source: https://europa.eu/!NX87WD

Category	Description
INTELLIGENCE	are intelligent systems used for decision making that both understand and adjust to specific circumstances; these are systems than can predict or plan to improve quality and to optimise capacity
CONNECTIVITY	the ability to access data in a secure and real-time manner; appropriate systems and machine will exchange data that may also be an integrated part of the business process.
FLEXIBIITY	the ability to adapt and customise systems and business processes to specific needs so that personalized products can be produced at affordable, mass-production prices?
AUTOMATION	can repetitive task be automated in a reliable way.
SUSTAINABILITY	are natural resources used in a sustainable manner, whereby not wasting fragile resources, also ensuring that no harm is done to the environment nor quality of life of citizens. SERVICES – are new sustaining or disruptive business models used where products are offered as a service.
SOCIAL	are workers motivated, engaged and empowered to carry out their work in an autonomous manner when working within the new systems.

Mount Lucas has focused on development innovations to support primary production of freshwater fish and to improve ecological performance with future provision for secondary process and diversification towards reduced waste and improving shelf-life. Development of customized ICT solutions for production and supply chain management to improve safety, quality and awareness towards enabling transition to eco-friendly aquaculture and adjacent innovations. This will be achieved by digitally connecting the living labs with in field aquatic and adjacent innovation in the peatlands (Fig. 1). Mount Lucas will support multi-stakeholder engagement to stimulate creation of innovative and disruptive solutions for eco-friendly aquatic food systems. Met through generation, validation and application of new knowledge at both pilot-scale and commercially in order to sustainably improve performance by enabling knowledge and technology exchanges that considers Open innovation. Means to consolidate sustainability include establishing and deploying best practice, quality assurance and risk management that can be met by specialist training and infrastructure with partnering companies. Essential is the development of effective and appropriate ICT management and related innovative tools throughout the supply chain that will embrace traceability and safety.

Mount Lucas will rely upon digital tools to develop, optimise, automate and validate land-based IMTA-RAS (IMRAS) models that include high protein foods that have a low environmental footprint or impact. Peatland-focused models to satisfy a circularity approach to produce high-value fish (such as Perch and Trout) along with low trophic plant species, such as duckweed. Monitor and control physicochemical parameters of culture ponds to reflect optimised ratio of microalgae and bacteria with duckweed (*Lemna minor*) to produce biomass of fish along with using this natural ecosystem to regulate waste and maintain water quality through recirculation. Develop sensors that will respond to key performance indicators in the pond to match aquaculture effluent and biomass productivity, along with commercial production of duckweed that feeds of aquaculture waste stream.

Integrated digital (intelligent) management system for IMTA that includes provision for multi-sensing technologies aligned with multi-functional management platforms (advanced monitoring, modelling, data analytics, and decision making); this system should also measure and model variances in climate and other disruptive fluxes to system through real-time system monitoring (microbiome, water physicochemical parameters, toxic microalgae) and modelling.

Schuelke-Leech (2021a, 2021b) recently described disruptive innovation and how it applies to the changes proposed for the Green New Deal era, which is also highly relevant to digital transformation of the peatlands. This author noted that achieving the ambitions of the Green New Deal will require social, economic, and industrial revolutions, rarely experienced in our history. However, climate change is going to force monumental changes; the latter has already decoupled the end-to-end value chain at Mount Lucas where O'Neill et al. (2022) recently reported that IMTA production for trout and perch was affected by extreme weather events that lead to fish mortality. O'Neill and co-workers (2022) also reported also noted that the emergence of different species of microalgae in this IMTA peatland process can be used as an early warning tool for disruptive climate variance events. Schuelke-Leech (2021a, 2021b) reported that the Green New Deal offers a vision for controlling and directing society's transformation through the development of new green technologies and public policies that mitigate and support the transformation to a sustainable and just society. The reader is directed to the model of Schuelke-Leech (2018) for an understanding of magnitudes of disruptive technologies and applicability. Rowan (2019) also provided examples of potential disruptive technologies for disease mitigation that can be applied to safeguard peatlands aquatic products. A summary of potential key emerging innovative activities, models, products and services arising from the convergence of biological with digital domains over the next decade is illustrated in Fig. 4; it noticeable that some of these may lead to disruptive innovation.

Table 4
Digital transformation of the multi-actor ecosystem (Quadruple Helix Hub) along with commensurate infrastructure, supports and enterprise activities.

Concentrated single-access supports for industry, entrepreneurs, disruptors	Linked acceleration activities	Digitisation
Step-Change Physical Infrastructure & Systems Supports	R&D Collaborative Facilitation	End-to-end Edge computing AI, ARVR, QoE, blockchain, cyber-physical systems
Pre-start Ups	Design Maturation Activities	ARVR, QoE, AI.
Ideation & Design Thinking	Technical Maturation Activities	AI, machine learning, augment reality, IoT
Market Research	Financial Planning	Blockchain
-Early Needs Analysis	Legal Assistance	Blockchain
-Product Market Fit Analysis	Social and Digital Marketing (including informing customer behavioural change)	ARVR, IoT
Early Technical Validation	Networking	Edge – IoT systems
-Test the Tech	Dedicated Grant Writing/Reporting	End-to-end monitoring, Edge computing (sensors, robotics), photonics.
-Experimentation/Validation in Pre-Pilot -Scaled to Real-Life Setting	Connection to Academic Staff/Expertise and Equipment to support commercialisation	Edge computing, ARVR (QoE).
"Living lab" – specialist equipment usage for data generation (real-time analysis)	Test beds in the environment (traditional slow analysis and hand-held devices)	Big data, machine learning AI, ARVR.
Conduit to State Financial Supports/Agencies	Enable Social Enterprise - Outreach Functions	Blockchain, cyper-physical systems, AI.
Specialist training	Technical training - ecotourism	ARVR/QoE; digital twin

9. Conclusions

There is a strong trajectory towards development of wet peatland innovation for new green job creation where this novel aquatic ecosystem must balance economic, environmental and social sustainability. Peatlands represents an important carbon sink where it is commensurately imperative to protect the environment, ecology aligned with regulatory policies. Digital transformation has radically changed adjacent Agriculture 4.0 that has been mainly driven new business models focusing on local productivity. Green innovation and social enterprises across the peatlands value chain will be accelerated through digital transformation, which will be harnessed through EDIH model structure that is complementary to that of the quadruple helix hub (academic-industry-government-society) concept. This new paludiculture enterprise ecosystem will test-the-tech and digitally connect green-minded companies, stakeholders, enables and end-users. It is advocated that future strategic orientation of digital policies and plans will be aimed at ensuring and achieving international consensus and agreement on harmonization of processes. For example, digital tools for enabling future strategic development of this Irish Mount Lucas peatland demonstrate will include focusing on protecting biodiversity; monitoring and ensure sustaining carbon sink with net zero gas emissions; developing new aquatic green-innovations that includes high quality protein sources, fully

Fig. 3. Duckweed harvested from the IMTA peatland site at Mount Lucas in the Republic of Ireland.

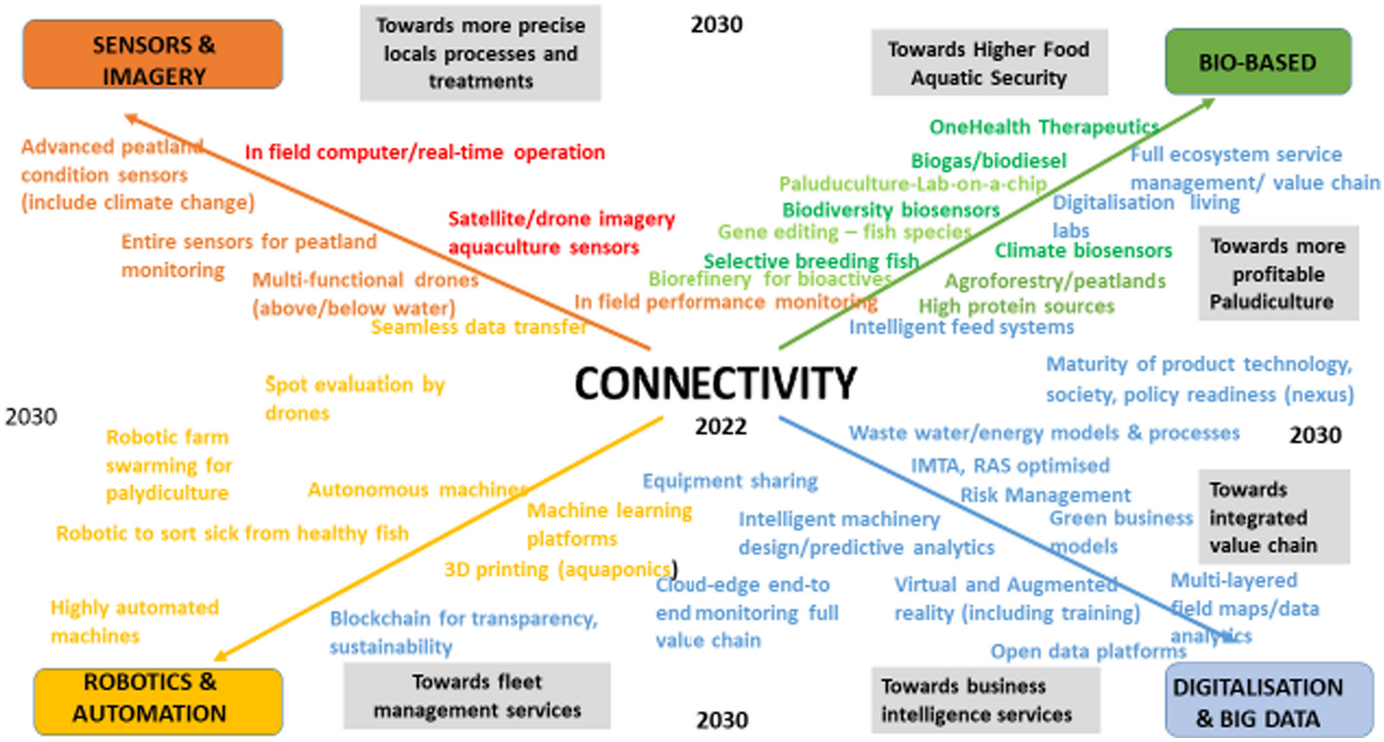

Fig. 4. Summary of potential key emerging innovative activities emerging from peatlands enabled by digital transformation over next decade.

recirculated waste water without need for end-of-pipe disease mitigation treatments, development of renewable energies, bioprospecting of bioactives from waste streams, in field testing of sensors and robotics, smart development of vertical farming and exotic mushrooms, agro-forestry, and pollination and ecosystem service management. Peatlands innovation will be advanced through digital solutions that address process automation, data analytics and processing, control and management systems; moreover, these activities reflect those applied to inform the 4th technological revolution under Industry 4.0 along with alignment with the main tenets of Industry 5.0 human-centric model, and with many of the UN's sustainable development goals. Digital transformation of paludiculture products and services as described herein will yield the next generation of multidisciplinary-trained researchers equipped with the necessary cross-cutting knowledge and skills to advance sustainability and climate action agendas for society with a global orientation. Funding instruments such as the European Just Transition, Interreg, and Horizon Europe will advance these opportunities by fostering and supporting key partnerships with stakeholders for the betterment of society.

9.1. Implications and recommendations

- There is much to be learnt by generating a deeper appreciation of the central role of key digital technologies supporting Agriculture 4.0 for unlocking adjacent and cross-cutting opportunities for the peatlands that will be met by more collaborate projects aligned with EIDH and Quadruple Helix Hub concepts. For example, this holistic approach should also focus on gaining a better understanding of the impacts of climate change for the intensive sustaining of peatland innovations at Mount Lucas (Ireland), which will potentially provide a useful blueprint to replicate across peatlands globally using an Open access knowledge-sharing model.
- There remains a lack of clear understanding as to what the concept of sustainability means for industries supporting paludiculture; therefore, it is envisaged that digital technologies will help meet this gap by way of promoting and implementing virtual training, management and creating greater awareness of these emerging eco-enterprises, products and services for end-users. Examples include using AI, machine learning, immersive technologies (AR/VR)
- Over the past 5 years there has been an accelerated transition from 'Brown to Green' that reflects what has become the paradigm shift away from harvesting peat as a fossil fuel to developing sustainable eco-innovations on the same peatlands. Therefore, there is a pressing need to understanding the roles of local government, industry and society in the management development of paludiculture innovations, which will inform new policies and job creation.
- It is important to create an awareness surrounding Peatlands innovations and to understanding how the digital transformation of such enterprises can powerful contributors to new business models and regional economies, which includes meeting several of the United Nations' sustainable development goals.
- Big data created from digital transformation of peatlands using drones will inform geo-referencing of sites with view to optimised usage balanced with protecting environment and biodiversity including ecosystem service management.
- There is a trend to develop new regional digital innovation hubs to meet community transitions to low carbon economy; however, there is a pressing need to provide clear guidance on the roles of each of the separate 706 DIHs across Europe so as to optimise cross-cutting usage by stakeholders that includes provision for integration trans-regionally.
- There are growing opportunities to support the swarm of new green start-ups companies that will be enabled through digitised living labs connected to environment test beds that will include AI/ML informed process automation, blockchain and cyber-physical systems for transparency, safety and security, IoT Cloud based approach to optimise sensors, drones and satellites for carbon sequestration and development of aquatic innovations ranging from aquaculture to vertical farming.
- Digital technologies will be enable Peatland enterprises to become more efficient through effective business models in real time; moreover, lessons learnt from Agriculture 4.0 suggests that key activities will include process automation and robotics, information systems and applications, cyber-physical systems, data analytics and logistics.
- Digital technologies will unlock societal challenges for rural and poor

regions as attested by the Irish peatland – midlands that will inform a fair and just transition across Europe.

- Digital technologies will help develop green innovation that will contribute to strategic management in order to mitigate against disruption in supply chains; this topic including mitigating against emerging risks including climate change, global conflict, and pandemics.
- Digital tools will help us appreciate key data outputs across several environmental test bed, such as use of LCA, PCA, MLF for generating data to help inform societal, political and technological readiness levels (or maturity) of green innovation across the aquatic peatlands ecosystem. Digital technologies will help define international standards for peatland innovation balanced with environmental protection including new policies, plans and licencing.
- Digital transformation can expedite the transition from 'brown to green'; for example, the trend away from peat harvesting as a fossil fuel to supporting and enabling the development of sustainable eco-innovations such as e-aquaculture, aquaponics, vertical farming, agroforestry and social enterprises such as honey production, exotic mushroom cultivation, pollination and ecosystem service management, eco- and darksky tourism.
- There is a need to reach an agreed consensus from stakeholders on the implementation of appropriate digital strategies to develop the peatlands including use of georeferencing, drones and satellites to map the peatlands matched with physiochemical parameters, carbon sink and biodiversity.
- Digital transformation to wettable peatlands products and services will also inform a new generation of researcher and promote job creation for rural areas that were strongly relient-upon peat harvesting as a means of producing fossil fuels for their livelihoods that disturbed carbon sink. Notably, the adjacent Agriculture and food sector are responsible for 19.29% of global gas emissions.
- Use of blockchain will help local farmers to directly reach customers in a secure and efficient manner.
- AI, virtual reality and augmented reality will enable a quality of experience for specialist training in the peatlands living laboratories (wet-labs, ecotoxicology, biodiversity) and provide a connected experience to the suite of environmental test beds that will showcase new eco-innovation, products and services; such as through Erasmsus +, MSCA RISE programmes.
- Digital transformation of peatland research and enterprise will inform new specific polices met through Horizon Europe, European Just Transition, European Green Deal, UN Sustainable Development Goals and so forth
- Digital transformation of peatlands will inform a fair and just transition of communities that are pivoting to low carbon economies along with enabling and accelerating green innovation.

CRediT authorship contribution statement

N. J. Rowan, Deborah Power: Conceptualization. E. A. O'Neill, Eoghan Clifford, Niall Murray, N.J. Rowan: Data Curation: N. J. Rowan, D. Barcelo, E. Clifford, Y. Qiao, D.M. Power, E. A. O'Neill: Data analysis; N. J. Rowan: Funding Acquisition; E.A. O'Neill, E. Clifford, N. J. Rowan; Investigation; N. Rowan; N. Murray, Y. Qiao, E. Clifford, D. Barcelo: methodology; E. A. O'Neill: Project Administration; N. Rowan, E. Clifford; D. Power: Resources; N. Murray, Y. Qiao; software; E.O'Neill, Y. Qiao, N. Rowan, N. Murray: validation; N. Rowan, N. Murray, Y. Qioa, D. Barcelo, E. Clifford, D. Power, E. O'Neill: roles/writing – original draft. N. Rowan, N. Murray, Y. Qioa, D. Barcelo, E. Clifford, D.M. Power, E.O'Neill: Writing – Review and Editing.

Declaration of competing interest

The authors declare that there are no competing interests or conflicts of interest with respect to the publication of this article.

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