A Literature Review: More Sustainable Farming Practices Within Cropping Systems On Drained Lowland Peatlands

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Foreword

UK lowland drained peatlands, such as those found in the Fens of East Anglia and parts of Lancashire and Yorkshire, represent some of the most fertile and intensively farmed landscapes in the country. These areas have been drained over centuries to support high-value agricultural production, including the production of salad crops, root vegetables (such as carrots and onions), and potatoes. The combination of deep, organic-rich soils and intensive land use has made these regions central to the UK's fresh produce sector. The East Anglian Fens alone support approximately 40% of the nation's vegetable production (NFU East Anglia, 2019).

However, drainage coupled with intensive agricultural practices have resulted in the rapid oxidation of organic soils, leading to high greenhouse gas (GHG) emissions from the peat as it decomposes, soil subsidence, and biodiversity loss. In England, 85% of total peatland GHG emissions originate from lowland peatlands that have been drained for agriculture. Vegetable production on drained lowland peat presents a particularly acute 'triple challenge' – with the need to balance climate mitigation, food security, and environmental stewardship. While fully rewetting peat is the most effective intervention for halting carbon (C) loss and restoring peat integrity, its feasibility needs to be carefully considered at landscape scale and a mosaic land use approach is most likely to be needed. (WWF, 2023). With nearly half of fresh vegetables and 85% of fruit already imported, displacing production from lowland peat could increase the UK's reliance on imports and offshore environmental impacts to regions already facing water and soil stress (DEFRA, 2024). To maintain the UK's capacity for domestic vegetable production, it is likely that drained peatland landscapes will continue to produce some vegetable crops.

It is in this context that WWF-UK and Fenland SOIL have partnered to co-develop principles for sustainable lowland peat farming. This literature review outlines existing research on lowland peat farming and forms the scientific basis for the discussion paper "Principles for more sustainable cropped farming on drained lowland peat – A framework for practice, research and policy". The framework was developed in close consultation with agronomists, farmers, and scientists. It provides guidance to farmers and other supply chain actors on how to minimise climate and environmental impacts, while sustaining food production on select lowland peat soils. Much is still unknown about peat soils, and this paper is published with a list of recommendations for further research. It should therefore be seen as a conversation starter rather than a definitive list of farming practices for lowland peatlands.

A significant proportion of peatlands will have to be restored or re-wetted if the UK is to keep to its climate commitments (The Climate Change Committee's Seventh Budget recommends that 55% of all peatlands are put back to natural or re-wetted status by 2040). But where this is not feasible or advisable, adapting farming practices to protect the peat we have in this country can play a significant role in reducing their degradation and C emissions. Developing these principles for farming on lowland peat is therefore a key building block in solving the triple challenge lowland peat present us with.

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Executive Summary

Lowland peatlands are among the most carbon-rich ecosystems on Earth, yet many UK sites have been severely degraded by agricultural drainage, leading to high GHG emissions and erosion. These landscapes, vital for climate regulation and food production, especially in the East Anglian Fens, face the dual challenge of sustaining agriculture while reducing environmental harm.

This literature review evaluates more sustainable farming practices to mitigate peat oxidation, focusing on preserving soil moisture, managing hydrology and nutrients, minimising oxidative risks, and trialling experimental interventions. Synthesising current research and practice, this paper informed more sustainable farming principles for UK lowland peat, co-created by Fenland SOIL, WWF UK, and an expert panel of farmers and agronomists.

The review focuses on:

1. Preservation of Soil Moisture Content (SMC)
2. Hydrological and Nutrient Management
3. Oxidative Risks to Lowland Peatlands
4. Experimental Applications

Preservation of Soil Moisture Content

Maintaining SMC is critical for C storage, structural integrity, and ecological balance. Loss of moisture accelerates oxidation, turning lowland peatlands into net C sources. Climate-induced drought exacerbates this, particularly in drier UK regions like the Fens (Page et al., 2020). Drainage causes peat shrinkage and subsidence, increasing flood risks and infrastructure damage (Freeman et al., 2022).

Wind erosion significantly accelerates peat loss yet remains under-researched (Freeman, 2024). As peat dries, it becomes more vulnerable to erosion, creating a feedback loop of degradation (Evans et al., 2019; Bain et al., 2011). This undermines agricultural productivity and the long-term viability of peat-based farming systems (IUCN, 2020; Natural England, 2021).

Perennial wetland species such as sedges (Carex spp.), rushes (Juncus spp.), and reeds (Phragmites australis) reduce evaporation, stabilise peat, and mitigate subsidence (Limpens et al., 2008; Evans et al., 2020). Their reintroduction within a land management mosaic can slow subsidence and C loss.

Mulching enhances soil moisture retention, reduces wind erosion, and promotes vegetation establishment (Price et al., 1998; Salonen, 1987). Cover crops and organic mulches improve soil organic carbon (SOC) and nutrient cycling, though their impacts on GHG emissions remain underexplored (Wen et al., 2019; Abdalla et al., 2019).

Reducing soil disturbance through no-till practices and controlled traffic systems can preserve SMC and limit erosion (Freeman, 2024). Tillage exacerbates oxidation and subsidence, while compaction from

machinery impairs root function and soil structure (Schothorst, 1977; Raper, 2005). Sustainable peatland management must focus on reducing mechanical disturbance and optimising land use to enhance resilience.

Hydrological and Nutrient Management

Degradation of UK histosols has led to subsidence, increased flood risk, and long-term soil degradation through compaction and oxidation (Page et al., 2020; Freeman, 2024). Addressing these challenges requires balancing hydrological management, nutrient retention, and soil conservation.

Controlled drainage (CD) reduces water loss, improves nutrient retention, and enhances soil stability and water quality (Skaggs et al., 2010). The strategic use of low-grade weirs and drainage modifications can help mitigate oxidation, subsidence, and downstream eutrophication (Kröger et al., 2011). However, CD alone may be insufficient and needs complementing with riparian buffer zones (RBZs), which enhance nutrient filtration, bank stabilisation, and biodiversity (Mander and Kimmel, 2007).

Integrating CD with riparian buffer zones (RBZs) and tailored vegetation management, in a “mosaic approach” (Hudson and Stockdale, 2024), offers the most effective strategy for mitigating peatland degradation. Without such integration, piecemeal solutions risk treating symptoms rather than causes. A coordinated, landscape-scale strategy aligning hydrology, nutrient management, and soil conservation is essential for long-term sustainability.

Oxidative Risks to Lowland Peatlands

Lowland peatlands, critical C stores, are highly vulnerable to degradation through intensive agriculture. Lowering water tables and increasing aeration accelerate oxidation, causing C loss, land subsidence, and biodiversity decline. Crops requiring bare soil, deep roots, or with high evapotranspiration exacerbate these impacts.

Sustainable agricultural methods such as low-impact agriculture (LIA), controlled grazing, and cover cropping help maintain soil moisture, reduce disturbance, and protect peat from oxidation. Intercropping and the use of allelopathic species offer further potential to enhance productivity while reducing chemical inputs.

Agroforestry systems (silvoarable and silvopastoral) integrate trees with crops or grazing, supporting biodiversity and C sequestration while maintaining agricultural value. However, economic viability and concerns about tree planting shifting C from stable to reactive pools must be carefully considered.

Research gaps include the impact of different irrigation regimes on GHG emissions, and risks posed by crops like maize, which may increase oxidation and erosion on peat soils. Trials on crop-irrigation combinations and further exploration of intercropping and allelopathy are essential.

Experimental Applications

Chemical amendments offer potential to restore agricultural peatlands but require careful application. Copper suppresses microbial decomposition and fungal pathogens, reducing subsidence, but risks toxicity and nutrient cycle disruption at high concentrations. Soil coagulants like polyacrylamides can improve structure and reduce erosion but may degrade into harmful compounds. Mineral applications such as calcium and silicates can enhance nutrient availability and resilience but can also cause imbalances or leaching. Long-term ecological impacts must be evaluated through site-specific trials.

Organic amendments, including phenolic compounds, engineered biochar, and coarse woodchip, show promise for improving soil health, boosting C sequestration, and restoring degraded peatlands. However, their effectiveness is highly site-specific, depending on soil pH, moisture, microbial composition, and amendment type.

Biological inoculations offer an alternative to chemical treatments by enhancing microbial activity and soil health. Root exudates influence rhizosphere microbiology, supporting C and nitrogen (N) cycling. While individual microbial inputs show promise, diverse microbial communities like Johnson-Su compost may be more effective, promoting greater resilience and mimicking natural systems. Current literature focuses mainly on single-species inoculants due to ease of quantification, but greater benefits may stem from multi-species approaches.

Research Recommendations

Key priorities for more sustainable peatland agriculture include:

- Developing irrigation regimes (precision, subsurface) that maintain soil moisture and reduce GHG emissions, and comparing intermittent vs. continuous flooding.
- Researching maize under reduced-disturbance systems, with cover crops and impacts on soil microbial dynamics.
- Expanding studies into intercropping and polyculture strategies for biodiversity, nutrient cycling, and C sequestration.
- Exploring allelochemical alternatives to synthetic herbicides, ensuring their ecological safety.
- Evaluating RBZs and CD for nutrient retention, biodiversity, and emissions reduction.
- Testing the impacts of mulch, biochar, woodchips, minerals, phenolic compounds, and copper (Cu) on soil health, microbial activity, and GHG fluxes.
- Investigating rhizosphere dynamics and microbial inoculants (e.g., Arbuscular Mycorrhizal Fungi (AMF), Actinobacteria, Rhizobia, Johnson-Su compost) under variable hydrological conditions.
- Scaling up native wetland species reintroduction to stabilise hydrology, enhance nutrient cycling, and support restoration.

Introduction

Lowland Peatlands are amongst the most carbon-rich ecosystems on Earth, storing vast amounts of organic C accumulated over millennia under a high-water table, which retards mineralisation and humification of soil organic matter (SOM) (Mathur and Levesque; 1987; Rydin and Jeglum, 2013). These ecosystems play a crucial role in mitigating climate change by sequestering C, maintaining high biodiversity, and regulating water systems. Equally, these ecosystems have become the nexus of agriculture in the UK, creating a polarising issue which requires a multidisciplinary approach to address. Anthropogenic activities, including agriculture, drainage and land conversion have significantly degraded many lowland peatlands, driving oxidation and substantial GHG emissions (Cris *et al.,* 2014). Approximately two thirds of UK lowland peatlands are now identified as 'wasted' (Morris *et al.,* 2010) and whilst policy seeks to protect these environments, which is essential, the pertinence of UK food production must not be forgotten. The East Anglian Fens in the UK produce "33% of England's fresh vegetables, and 7% of the total agricultural output in England" (NFU, 2019).

Oxidation is one of the primary threats to agricultural peatlands, driven by drainage, land-use change and soil moisture loss. Lowland peatland oxidation converts these environments from C sinks to substantial C sources, as soil aeration accelerates aerobic mineralisation of SOM. Carlson *et al.,* (2017) indicate that peatland agriculture globally is responsible for 32% cropland GHG emissions, which is exacerbating peatland shrinkage and subsidence. Sustainable management practices are essential to mitigate peat degradation while balancing land use and economic activities.

This literature review seeks to critically evaluate sustainable practices that can mitigate peat oxidation and degradation within lowland peatlands. The focus areas include:

1. Preservation of Soil Moisture Content

2. Hydrological and Nutrient Management

3. Oxidative Risks to Lowland Peatlands

4. Experimental Applications

Through the examination of these practices, this review aims to identify effective potential methods and highlight areas where further research is required.

This review is structured into four major sections, each addressing a critical aspect of sustainable peatland management. Each section shall begin with an introduction to the challenge, such as 'Preservation of Soil Moisture Content', subsequently followed by potential solutions to this challenge, where these practices shall then be explored. The first section discusses methods to preserve SMC, including vegetation cover strategies, soil disturbance reduction techniques and moisture retention technologies. The subsequent section focuses on minimising drainage of peatlands, evaluating buffer zones and drainage reduction as various methods. The third examines land management techniques such as low-impact agriculture, vegetation management, agroforestry and monitoring or a combination of the above to prevent peat oxidation. Lastly, experimental applications to lowland peatlands are discussed in section 4, presenting alternative solutions to mitigate against the degradation of intensive agricultural lowland peatlands. The synthesis and discussion section of this review shall compare these approaches, identify research gaps and seeks to explore potential practical applications within lowland peatlands, which can assist in mitigating global temperature forcing and preserve lowland peatlands.

This literature review served as background for the development of sustainable farming principles for cropped farming on lowland agricultural peat. Using the existing research as a departure point, Fenland SOIL and WWF-UK convened an expert panel consisting of agronomists, farmers and soil experts to develop practicable principles. These were subsequently tested with a focus group of farmers. The group also identified areas of future research.

1. An Introduction to the Preservation of Soil Moisture Content

Soil moisture content is crucial within lowland peat due to the influence soil moisture has on C storage, soil integrity and ecological balance within these fragile ecosystems. Soil moisture helps preserve anaerobic conditions, protecting extensive organic C within peat, thus acting as a C sink. In the absence of soil moisture, the soil profile can become oxygenated, increasing microbial activity and decomposition, transforming these lowland peatlands into C sources. As climate change exacerbates global temperature rise, the effects of drought and water scarcity threaten agriculture, society, nature, and biodiversity, especially in dry regions of the UK such as the Fens (Jenkins *et al.,* 2024). Additionally, the structural integrity of peat is severely affected by soil moisture, with drained peat prone to shrinkage and subsidence which enhance flood risk and significantly damage infrastructure (Page *et al.,* 2020). The shrinkage of organic matter under aerobic conditions and the compaction of lowland peatland pore spaces results in subsidence and increases the vulnerability of soil erosion (Freeman *et al.,* 2022). The profound subsidence of lowland peat is exhibited in Holme Fen. In 1851, the Holme post, was installed level to the soil surface, and is now exposed (Fig. 1.), highlighting the effect of drainage.

It is essential to recognise the profound difference between organic C within peat (long-term C) and contemporary C, introduced to the soils as part of a short-term cycle.

Organic C in peat (Long-term C) is sequestered within peat due to anaerobic conditions, however draining of peat facilitates the release of this C, through oxidation and decomposition. Consequently, the integrity of lowland peatlands as C sinks is threatened by lowland peat degradation.

Contemporary C however, is short-term C, largely from biological activity which cycles rapidly though photosynthesis and respiration. This C exists in various form, such as leaf litter, root exudates and living plants and is readily available and easily utilised. Whilst this C contributes to the overall C present in lowland peatlands, it does not constitute any of the C which is sequestered, due to its rapid cycling.

Figure 1: The Holme post at Holme Fen, Cambridgeshire. Driven into the peat in 1851, the posts' top marked the ground level, 4m higher than present day. (Photo - Page, S) (Page et al., 2020)

"The severity of wind erosion events on cultivated peatlands has long been recognised, yet measurements of their magnitude and dynamics remain extremely rare" (Thompson, 1957a; Freeman, 2024). The only published study quantifying soil erosion rates that was identified during this review is Warburton (2007). Wind erosion is closely linked to SMC; as peat dries, its structural integrity weakens, making it more susceptible to wind-driven particle loss (Evans *et al.,* 2019). This depletion of surface material not only exacerbates the decline in soil moisture, further exposing desiccated layers to the elements, which accelerates peat degradation, leading to a positive feedback loop of erosion and drying (Bain *et al.,* 2011).

A structural decline in peat reduces its agricultural productivity, posing a significant threat to UK agriculture, which is heavily reliant on peatland-based food production (IUCN, 2020). While some studies suggest that wheat yields may show short-term improvements on degraded lowland peatlands, the long-term sustainability of such systems is questionable. Degraded peatlands become increasingly incapable of supporting high-value vegetable and salad crops, either entirely or at the same scale as healthier peat soils (Natural England, 2021).

Beyond agricultural concerns, the drainage and subsequent drying of peatlands also have severe ecological consequences. Numerous species rely on the saturated conditions of lowland peatlands, and their desiccation results in biodiversity loss and habitat degradation (Crump, 2017). As the paleo and contemporary genetic reservoir of peatlands diminishes, so too does the resilience of these ecosystems to further environmental stressors. Addressing wind erosion and soil moisture decline is therefore critical not only for agricultural sustainability but for the broader conservation of peatland biodiversity.

1.1 Potential Solutions for Soil Moisture

1.1.1 Vegetation reintroduction

Vegetation plays a fundamental role in maintaining soil moisture levels in lowland peatlands by providing shade, reducing evaporation, and stabilising the peat. Native and perennial plant species, such as sedges (*Carex* spp.), rushes (*Juncus* spp.), and reeds (*Phragmites australis*), have been shown to significantly decrease moisture loss by minimising surface exposure, and enhancing water retention in the peat profile (Limpens *et al.,* 2008; Evans *et al.,* 2020). The integration of these into field margins could prove instrumental in reducing wind erosion of soil and improving the hydrology of lowland peatlands.

A key case study from the East Anglian Fens highlights the effectiveness of reed planting in reducing moisture loss. Multiple studies demonstrated that *Phragmites australis* establishment not only conserves soil moisture but reinforces habitat integrity by promoting hydrological stability and reducing aeolian erosion – locally termed ‘fen blow’ in East Anglia (Price *et al.,* 1998; Evans *et al.,* 2020). Similarly, Armstrong *et al.,* (2015) found that reed-dominated peatland sites exhibited lower subsidence rates and improved resilience to desiccation compared to degraded, unvegetated areas.

Comparable research from the Netherlands indicates that sedge reintroduction can effectively reduce peat subsidence in drained agricultural peatlands. Guo *et al.,* reported that *Carex* species enhance water retention, thereby slowing peat oxidation and C loss. These findings align with those of Joosten *et al.,* (2012) who emphasised the role of perennial wetland vegetation in maintaining peatland hydrology. The successful implementation of sedge reintroduction in the Netherlands suggests that integrating similar strategies in the UK’s fenland regions could complement existing reed-planting efforts. Future research should focus on comparing the hydrological benefits of different plant species under varying lowland peatland management conditions.

1.1.2 Mulching

The application of mulch on lowland agricultural peat holds promise for ameliorating soil moisture retention and moderating temperature fluctuations, while also offering protection against aeolian erosion. Exposed peat surfaces are particularly susceptible to crust formation, which, when combined with erosion, inhibits the establishment of plant propagules, and prevents surface vegetation establishment (Salonen, 1987). Consequently, bare soils remain sites of wastage without ground cover application, as conditions do not facilitate natural establishment, which would prevent soil erosion. By shielding the soil, mulch can mitigate these erosive processes, fostering surface stability, SMC increases, and potentially reducing GHG emissions.

In agricultural peatlands, mulches present a possible alternative to cover crops, both serving to reduce wind erosion, enhance nutrient cycling, and contribute to soil organic carbon (SOC) accumulation. Whilst the interactions between cover crops and soil nutrients are well-documented, the implications of mulch application on lowland peat – particularly regarding its influence on GHG fluxes – remain understudied (Wen *et al.,* 2019; Abdalla *et al.,* 2019). The incorporation of organic materials, whether as mulch or cover crops, may initially trigger a spike in GHG emissions, due to soil disturbance and the introduction of labile C to the upper soil horizons. This is evidenced by Guo and Liu (2022), who indicated that soil mulching resulted in a 21.62% increase in carbon dioxide (CO_2) emissions and a 1.73% increase in nitrous oxide (N_2O) emissions. However, comparative analyses between mulched, cover-cropped, and exposed peat fields could provide critical insights into the long-term C and N fluxes associated with these practices. A more comprehensive understanding of these dynamics would help determine whether mulch applications can contribute to climate change mitigation on agricultural peatlands and, if so, at what scale they would be effective in influencing global temperature forcing.

1.1.3 Reduced soil disturbance approaches – tillage minimisation

A reduction in soil disturbance is critical in reducing aeolian erosion of soil, which is strongly associated with soil physiochemical properties and vegetation cover. Aggregate size distribution, moisture content, SOM content and particle density, are suggested by Freeman (2024) as potential factors which mitigate soil losses from wind erosion within lowland agricultural peatlands. Vegetation is a mediating factor, with tree presence producing significant reductions in wind speed and thus soil erosion, but equally low-lying vegetation cover demonstrates similar mitigative effects against soil erosion (Funk and Engel, 2015; Chang *et al.,* 2021; Jiang *et al.,* 2024). Widespread agricultural practices demand exposed soil and sparse vegetation cover which exacerbate soil erosion, especially during spring, where erosive climatic conditions peak (Skidmore, 2017; Newman, 2022). Such practices identified by Bartkowski *et al* (2023) indicate vegetation cover reduction and tillage as potential drivers in soil erosion. Tillage reduces soil aggregate size through disturbance, and indirectly decreases SOM, increasing erodible material present when compared to no-till practices (Hevia *et al.,* 2007).

Significant effects of tillage, include increased oxidation of soil and a decline in SMC, which can have significant impacts on decomposition rates. Soil aeration creates optimal environmental conditions for the aerobic mineralisation of SOM – which is the driving force for subsidence along with drainage (Schothorst, 1977; Dawson *et al..,* 2010). Ball *et al,* (1999) indicate that tillage disrupts soil microsites, potentially lowering methane (CH_4) diffusion from the atmosphere into soils, decreasing the efficacy of lowland peatlands to sequester CH_4. Such subsidence can be worsened by compaction causing dramatic change to pedogenic properties of lowland peat, which may negatively affect productivity as soil hydrology alters, causing reductions to pore space and SMC.

In addition to tillage, vehicular impacts on soil are significant, with compaction, and erosion through turbulence, both results of traffic (Kuhns *et al.,* 2010). Compaction has strong negative effects on SMC, reducing pore space, increasing bulk density of soils, severely impacting plant roots via decreased oxygen and water availability; the implications for plant productivity are vast due to the reliance on these agri-environments for copious quantities of produce (Raper, 2005). Additionally, erosion through turbulence from vehicles causes soil losses, and whilst vehicular elimination is impossible in crop production, methods can be used to reduce the impact of trafficking on crops and soil erosion. Such methods include a reduction in trafficking, implementation of controlled trafficking systems, vehicle size reduction, minimising the tractive element of vehicles and/or subsoiling.

2. An Introduction to Hydrological and Nutrient Management

Histosols have been degraded through intense drainage within the UK, historically via gravitational drainage which was superseded by pumping. These actions have reversed the previous conditions, in which impeded drainage produced the waterlogged conditions necessary for peatland formation (Sly, 2010). Visible impacts of drainage such as subsidence can easily be identified within the fens, causing profound damage to infrastructure and enhancing flood risk (Fig. 1). Subsidence occurs through shrinkage, as drainage removes water from soil pores reducing its volume and causing the compaction of peat, which is highly compressible, alongside the oxidation of peat which increases microbial mineralisation of SOM (Page *et al.,* 2020; Freeman, 2024). Consequently, minimising drainage is essential to reduce subsidence and other negative pedogenic effects without requiring complete reintervention in the form of water table management within lowland peatlands.

Agricultural landscapes with high fertiliser inputs face mounting challenges related to nutrient management, soil degradation, and hydrological instability. These intensively managed systems are characterised by high agricultural productivity, but suffer from the unintended consequences of nutrient runoff, soil depletion, and increased flood risk. The widespread use of N and phosphorus (P) fertilisers in such regions has significantly altered nutrient cycles, leading to pervasive leaching into watercourses. This has profound implications for freshwater ecosystems, contributing to eutrophication, biodiversity loss, and the deterioration of water quality (Craswell, 2021). The Fens, with their extensive network of drainage ditches, streams, and rivers, are particularly vulnerable to this process, as agricultural runoff readily enters watercourses, accelerating nutrient loading (Vanek, 1992). The interplay between hydrological modification and nutrient export is further exacerbated by the degradation of peatlands, where drainage-induced subsidence and oxidation release stored P and C, compounding the effects of fertiliser application. This creates a reinforcing cycle of nutrient mobilisation, soil loss, and declining water quality, necessitating a landscape-scale response that integrates both water and nutrient management.

Effective mitigation requires a shift from conventional drainage and fertilisation practices toward a mosaic approach that interlinks hydrological control, soil conservation, and targeted nutrient retention strategies. Controlled drainage offers a means to regulate water tables while simultaneously reducing nutrient leaching, enhancing both agronomic productivity and environmental stability (Skaggs *et al.,* 2010). Similarly, RBZs serve as critical nutrient sinks, capturing excess N and P before they enter surface waters, thereby reducing eutrophication risk while stabilising soil structure and improving habitat connectivity (Mander and Kimmel, 2007). The integration of these strategies into a cohesive land management framework presents an opportunity to mitigate the environmental impacts of intensive agriculture without undermining productivity.

Addressing these challenges requires a nuanced understanding of the complex interactions between drainage, soil processes, and nutrient fluxes in agricultural landscapes. The degradation of histosols in the Fens exemplifies the broader tension between intensive agronomy and the natural environment, underscoring the need for adaptive management strategies that restore balance to nutrient cycles whilst maintaining food security. By interweaving hydro-ecological interventions, a sustainable mosaic model can be produced which preserves the long-term viability of lowland peatlands and enhances the resilience of agroecosystems in the face of climate and land-use pressures.

2.1 Potential Solutions for Hydrological and Nutrient Management

2.1.1 Methods for Drainage Minimisation

Controlled drainage involves the management of drainage systems to conserve water and reduces nutrient losses to surface waters, which could be employed within lowland peatlands to decrease water table depth and reduce drainage rates when rigorous drainage is unnecessary (Skaggs *et al.,* 2010). Practices may include blocking drains which are unnecessary, or partial drain blocking, through the installation of low-grade weirs, which can improve nutrient conservation and water management. Biological transformation, immobilisation and mitigation of pollutants and nutrients are discussed by Kröger *et al.,* (2011) as ditch processes, enhanced by increasing residence times of nutrients and pollutants in weired systems, mitigating their occurrence in excessive concentrations downstream. Water management is critical in the responsible management of lowland peatlands, of which CD could prove an important part. Whilst CD alone cannot be considered sustainable management, as decomposition will persist in aerated layers of peat, it would be a significant improvement from the status quo in lowland peatlands (Freeman, 2024).

Supplementary to CD, reducing drainage intensity involves implementing shallower drainage facilitating the increase in water table. This would assist in maximising the saturation of peat, whilst maintaining agronomic productivity, simultaneously reducing emissions from lowland peatlands and decreasing peatland oxidation, microbiological decomposition, and subsidence (Ingram, 1978; Driehuyzen; 1987; Freeman, 2024). The reduction of subsidence is of obvious significance, decreasing damage to infrastructure, reducing the need to increase drain depth, reducing soil compaction and soil pore space collapse. The mitigation against subsidence will assist in the preservation of productive histosols within agri-environments near impossible without an element of change to hydrological management.

2.1.2 Riparian Buffer Zones

Lowland peat soils, particularly when drained for agriculture, are highly vulnerable to nutrient loss, erosion, and GHG emissions. Riparian buffer zones offer important mitigation potential in these systems. The P absorbing qualities of forested buffer strips can be especially effective in agricultural peatlands, where peat releases P when saturated (Vanek, 1992). Preventing excess N from entering watercourses is similarly critical in intensively farmed areas like the Fens, where fertiliser use results in pervasive nutrient runoff and leaching into drainage ditches (Craswell, 2021).

In addition to nutrient management, RBZs play a key role in reducing C losses from lowland peat ditches. Vegetated buffers stabilise banks, trap particulate organic C (peat fragments) from eroded soils, and reduce the need for dredging (Cooper et al., 1987). Acting as windbreaks, particularly when composed of tall vegetation like trees, RBZs also reduce wind-driven erosion of dry, friable peat – a major risk on exposed drained peatlands. Furthermore, increasing vegetation and tree cover along ditch margins enhances shading, which cools water temperatures and suppresses microbial activity, thus helping limit GHG emissions from peat-derived organic matter.

Riparian buffer zones also offer multiple benefits across soil types. They can significantly improve stream water quality by removing nutrients from flowing water and enhancing biodiversity in agri-environments (Mander and Kimmel, 2007). Wooded buffer strips lining stream or dyke banks are particularly effective at P removal between sedge fens and streams, while grasslands facilitate denitrification in wet meadows (Lowrance et al., 1997; Kuusemets et al., 2001). When combined, these elements form the "ideal structure of riparian buffer communities" (Mander and Kimmel, 2007), removing excess nutrients and reducing inputs into recipient waters. These riparian biotopes also "create more connectivity in landscapes" (Mander et al., 1997) by providing habitat networks and supporting biodiversity.

Vegetation composition, water residence time, and flooding frequency all affect nutrient uptake in RBZs (Liu et al., 2017). A carefully curated mix of native trees, shrubs, and grasses – including perennial sedges, rushes, common reeds, clovers, Willow, and Alder – can improve landscape connectivity, habitat diversity, and soil stability, while promoting nutrient retention. These buffer systems also contribute to sediment trapping and bank reinforcement, reducing erosion from overland flow (Tjaden and Weber, 1997). Through their influence on microtopography, vegetation can further shape hydrology and pedogenic physiochemistry, promoting a more resilient agroecosystem (Moser et al., 2009)

3. An Introduction to Oxidative Risks of Lowland Peatlands

The exposure of peat to oxygen accelerates humification, and aerobic mineralisation of SOM, leading to C loss, land subsidence, and biodiversity decline (Oleszczuk *et al.,* 2008). Crops that require bare soil or lead to prolonged periods of soil exposure remove protective organic material, allowing oxidation to proceed unimpeded. Similarly, crops with extensive rooting structures can physically disrupt peat matrices, introducing oxygen into deeper layers and accelerating microbial activity responsible for C loss. The cumulative impact of these practices has profound consequences for C sequestration, land stability, and GHG emissions.

Overgrazing is an undesirable effect of unmanaged livestock on peatlands, driving oxidation through compaction of peat by livestock, and the removal of surface vegetation, producing bare soils (Lunt *et al.,* 2010). On drained peats these processes are exacerbated, with a lack of saturation in the upper peat layers making compaction more devastating for lowland agricultural peatlands. Livestock are not a popular choice on peat due to the highly productive land being better suited to growing high value vegetable crops.

3.1 Potential Solutions to Mitigate Oxidative Risk

3.1.1 Crop Selection

Specific agronomic practices are extremely damaging to agri-environments, enhancing oxidation, peat degradation and subsidence. Irrigation practices can significantly impact the magnitude of GHG emissions through their controlling effect on SMC, which modulates microbial activity and pedogenic physiochemistry (Sapkota *et al.,* 2020). Therefore, non-irrigated crops might exhibit greater GHG emission levels compared to irrigated cropping, however, more research surrounding the impact of different irrigation regimes on lowland peat, is essential to understand the effect of various irrigation methods on GHG release. Current literature indicates contrasting findings regarding irrigation regimes and does not focus on organic soils, making a trial pertinent to discover the positives or negatives of various methodologies used in the current agronomic landscape (Kallenbach *et al.,* 2010; Edwards *et al.,* 2018; Franco-Luesma *et al.,* 2019; Sapkota *et al.,* 2020).

Row crops and tubers are not recommended on organic soils, due to deep cultivation, bare soil exposure and/or low-level water table maintenance. The low-water table reduces soil-moisture which facilitates oxidation of lowland peat, exacerbated by deep ploughing and soil exposure, aerating greater quantities of peat. This significantly enhances emissions from lowland peatlands through mineralisation, CH_4 oxidation, denitrification, and aerobic decomposition (Freibauer *et al.,* 2004; Oleszczuk *et al.,* 2008). Maize also creates bare soil exposure due to the timing of maize drilling, making it a high-risk crop for soil erosion and oxidation – exposing soil during spring where aeolian erosion risk is greatest. The risk posed by maize for oxidation could significantly degrade lowland peatlands due to long-term exposure, which Jenkins (2023) indicates is possible to mitigate against with cover crops. However, this occurred on clay loam soils, which behave very differently to peat soil. Therefore, research into the relationship between maize, oxidation and soil erosion is required on peat soils, alongside any potential mitigation strategies. Without this, maize remains a significant risk crop, exacerbating two major negatives in soil erosion and oxidation both driving lowland peatland subsidence.

In addition to row crops and tubers, high evapotranspiration (ET) rate crops may pose significant risk to lowland agricultural peatlands, increase water loss from soils exponentially. Evidence is required to substantiate this, with research surrounding ET essential for understanding the impact of high ET crops on lowland peat. Complementary to this, crops with extensive rooting systems, which may disrupt the peat matrix, facilitating significant aeration of agricultural peat, exacerbating oxidation and soil moisture losses.

3.1.2 Low-Impact Agriculture

Low-impact agriculture integrates ecological principles into land management to foster productive, resilient, and biodiverse farming systems. Unlike conventional approaches – which prioritise monoculture, intensive cultivation, and chemical inputs – LIA works in harmony with ecological processes. In the UK, unsustainable agricultural practices have been a major driver of environmental degradation, contributing to the country's status as the most ecologically depleted nation in Europe (Baines, 2025). Low-impact agriculture is particularly relevant in peatland contexts, where sensitive hydrology and soil structures are vulnerable to disturbance.

Rotational Cropping

Rotational cropping is prominent within agronomy, with UK farmers mostly making use of crop rotations to build soil, fix nutrients and grow cash crops, whilst also mitigating pest and disease residency risks – with each crop bringing benefit, be it ecological, or economic. However, the knowledge behind rotational cropping is developed within inter-cropping systems, with combinations of crops having mutual benefits, including allelopathy, and nutrient fixation. Inter-cropping was historically typically perceived as negative, with more plants in the same area promoting competition for resources, but the benefits of these cropping systems are now being realised (Mahmood *et al.,* 2013; Haider *et al.,* 2015). Evidence states that allelochemicals released from certain plants may have significant positive impacts for agricultural management and crop yields (Cheng and Cheng, 2015). The interaction of these chemicals can be exploited within agronomy to promote growth and development through polyculture, benefitting agroecosystems profoundly through productivity enhancements and the reduced need for chemical applications (Macais *et al.,* 2003; Han *et al.,* 2013). Allelochemical applications present the potential to reduce the need for harsh broad-spectrum pesticides such as glyphosate, either through cover cropping or potential development and use as sprays, but this would require experimental research to uncover the potential impacts of these.

Polyculture and Allelopathy

In drained peat systems, polyculture can help maintain year-round vegetative cover, reducing surface desiccation and slowing oxidative loss. Allelopathic interactions have been shown to reduce weed pressure and support crop development, with potential to reduce reliance on herbicides like glyphosate (Cheng and Cheng, 2015; Macais et al., 2003; Han et al., 2013). These systems could be trialled on lowland peat systems to identify the success of polycultures and the commercial viability of these. The potential to control weed burdens on peats could be very appealing, and ties into the idea of minimising chemical inputs.

Rotational Grazing

On peat soils, rotational grazing prevents overgrazing and compaction, which are key drivers of peat degradation. Controlled livestock movement allows vegetation recovery, maintains ground cover, and reduces mechanical pressure that can displace or compact peat, facilitating better hydrological function and reducing oxygen ingress (Lunt et al., 2010). When implemented effectively, rotational grazing enhances pasture productivity, distributes nutrients more evenly through manure, and supports a more diverse grassland flora. It also contributes to diversified farm income and improved livestock health (Carvalho et al., 2010).

3.1.3 Afforestation and Agroforestry

The application of afforestation can have many positive effects on mineral soils; however, the International Union for Conservation of Nature (IUCN) does not recommend it on peatlands, outlining significant concerns of forest planting due to C translocation from significant C sinks (lowland peatlands) to more reactive sources (trees).

Potential afforestation as a restorative technique through the incorporation of carr woodlands (wetland forests dominated by tree species like willow (Salix spp.) and alder (Alnus glutinosa)), could be utilised on peatlands as part of a mosaic landscape approach, due to its existence in previous lowland peat landscapes. Historically prevalent in the UK, carr woodlands thrive in waterlogged conditions typical of peatlands and play a crucial role in maintaining hydrological stability and preventing peat oxidation, a major source of

GHG emissions (Rotherham, 2011). Establishing carr woodlands on degraded peatlands can aid in rewetting efforts, reduce subsidence, and enhance ecosystem resilience – which could form part of a mosaic approach to peatland management.

Agroforestry – the intentional integration of trees with crops or livestock – offers a multifaceted approach to more sustainable peatland management, enhancing biodiversity, improving soil health, and providing potential economic resilience. Silvoarable systems, which combine agricultural or horticultural crops with long-term tree cultivation, enable farmers to secure annual income while trees mature, thereby balancing short-term profitability with long-term ecological benefits. Furthermore, these systems can integrate polyculture into arable land, reduce soil erosion due to the trees and varying layers of crops protecting the soil surface, and promote a productive yet diverse agri-environments. Other agroforestry practices, such as silvopastoral systems (integrating trees with livestock grazing), meadow orchards (fruit trees interspersed in grasslands), and riparian buffers (vegetated areas alongside waterways), contribute to ecosystem restoration and productivity. These systems have been shown to enhance C sequestration, reduce soil erosion, and improve water management in agricultural landscapes (Jose, 2009). It is possible that within lowland peat systems that agroforestry would promote greater diversity, demonstrated at Whitehall Farm by Stephen Briggs, which in turn benefits soil health, protects the soil and shows a method to preserve farming on lowland peatlands. Whitehall Farm is pertinent as a net-zero system, integrating tree cover and perennial vegetation through agroforestry practices can provide alternative land-use options that avoid deep drainage, thereby preserving peat integrity and supporting biodiversity (Lawson *et al.,* 2014). Or alternatively, the integration of these vegetations as RBZs could be highly effective within field margins and managed ditches. Despite its potential, economic viability of agroforestry remains a challenge, as transitioning from conventional farming to agroforestry systems involves longer investment horizons. However, diversified income streams from timber, non-timber forest products, and ecosystem services payments can offset initial financial barriers (Graves *et al.,* 2007). Policy incentives, such as agri-environment schemes, could further encourage adoption, although current IUCN framework indicate a direction of tree felling on peat, as opposed to planting (IUCN, 2020). As climate change and soil degradation pressures intensify, agroforestry presents a nature-based solution for lowland peatlands, balancing agricultural productivity with ecological preservation, however the economics behind this system currently do not provide any incentive for long-term investments of benefit to farmers.

To develop effective mitigation strategies, continuous monitoring and assessment of peatland conditions are essential. Remote sensing technologies, such as satellite imagery and LiDAR, provide valuable insights into hydrological fluctuations and vegetation cover changes over time. Hydrological modelling can predict the impacts of different land-use scenarios on water table dynamics, aiding in the design of sustainable agricultural interventions. Soil C assessments, including direct measurement of peat decomposition rates and GHG emissions, allow for evidence-based decision-making in land management policies. Integrating these monitoring tools into conservation frameworks is critical for ensuring that peatland ecosystems remain viable C sinks under changing agricultural pressures.

4. Experimental Applications

Experimental applications of various amendments, including Cu, soil coagulants, minerals, and phenols, have been investigated to improve soil stability, nutrient availability, and overall peatland resilience.

Copper applications are being explored for their ability to manage microbial communities and control soil-borne pathogens, although concerns over toxicity and long-term accumulation remain. Soil coagulants, such as polyacrylamides, offer a potential solution to reduce soil erosion and improve aggregate stability, yet their environmental impact requires further scrutiny. Mineral amendments, including calcium and silicates, have been investigated for their role in mitigating acidification and enhancing soil structure. Additionally, phenol applications have shown promise in slowing organic matter decomposition, thereby reducing C loss. Biological inoculations have emerged as an innovative approach to peatland restoration by enhancing microbial diversity and promoting effective microbiomes which protect soil health, which seeks to improve C sequestration and soil resilience. Woodchip applications present potential for improving the hydrology and microbial balance within lowland peatlands, although research must focus on mitigating drawbacks such as N immobilisation and maximising efficacy. While these experimental applications hold potential, further research is necessary to evaluate their long-term effectiveness and ecological implications in lowland peatlands.

4.1 Chemical Applications

4.1.1 Copper Applications

Copper has been widely studied for its antimicrobial properties and its potential influence on soil microbial communities in lowland agricultural peatlands. As an essential micronutrient, Cu plays a critical role in enzymatic functions and plant health, particularly in processes such as photosynthesis, respiration, and lignin synthesis (Kabata-Pendias & Pendias, 2001). However, excessive Cu concentrations can lead to toxicity, negatively affecting microbial diversity and plant growth (Giller *et al.,* 1998). Experimental applications of Cu aim to assess its ability to suppress pathogenic microorganisms and reduce decomposition rates while maintaining beneficial microbial populations that contribute to soil fertility. Studies have shown that copper-based amendments can reduce fungal pathogens in agricultural soils, thereby improving crop resilience (Graham *et al.,* 2011). Furthermore, "the decomposition and resultant subsidence of all organic soils can be reduced to less than 1cm per year with applications of Cu" (Mathur & Farnham, 1985). However, concerns regarding Cu accumulation, leaching, and long-term ecological impacts necessitate careful evaluation of its use as a soil amendment in peatland agriculture. The risk of Cu binding to organic matter and becoming immobile, leading to potential deficiencies in crops, must also be considered (Alloway, 2013).

Field trials in Canada have provided valuable insights into the effects of Cu applications on peatland soils. Research by Mathur and Levesque (1983) examined the role of Cu amendments in mitigating microbial decomposition rates in organic soils, particularly in intensive agricultural settings. Their findings suggested that while Cu applications significantly reduced microbial respiration rates, leading to decreased CO_2 emissions, they also altered microbial community structures, favouring populations that were more resistant to metal toxicity. Additionally, Mathur and Levesque (1985) demonstrated that controlled applications of Cu sulphate could effectively suppress fungal root pathogens, improving crop yields in lowland peatland farms. These studies highlight the dual role of Cu as both a suppressor of harmful pathogens and a potential modulator of soil microbial dynamics, necessitating balanced application strategies to optimise agricultural benefits while minimising environmental risks.

Further studies have explored the potential of Cu amendments in addressing subsidence issues in managed peatlands. Research in Quebec and Ontario has examined the long-term impacts of copper-treated soils, particularly concerning nutrient cycling and SOM preservation (Mathur and Sanderson, 1978, Levesque & Mathur, 1986). These trials indicated that while Cu application effectively slowed peat decomposition, excessive concentrations could lead to reduced N mineralisation, impacting plant-available nutrients. This underscores the importance of site-specific Cu dosing to prevent unintended consequences, such as nutrient imbalances or soil acidification. However, continued research is required to refine application guidelines, ensuring that Cu is used efficiently without contributing to long-term soil contamination or toxicity concerns. Whilst a plethora of evidence exists for Cu applications as an agronomic practice, the implications for GHG balancing remain under researched.

4.1.2 Soil Coagulants

Soil coagulants, such as polyacrylamides and other binding agents, have been explored for their potential to improve peatland soil structure and reduce erosion. These substances work by enhancing soil aggregation, minimising particulate loss, and increasing water retention capacity (Sojka *et al.,* 2007). In lowland peatlands, where subsidence and compaction are major concerns, coagulants may help stabilise the soil matrix and improve resilience to waterlogging and desiccation (Holden *et al.,* 2004). Research has shown that polyacrylamides can reduce soil erosion by improving aggregate stability and limiting the transport of fine particles (Levy & Warrington, 2015). However, the long-term efficacy and environmental compatibility of soil coagulants require further investigation. Potential risks include altered hydrological properties and interactions with SOM that may impact microbial activity and nutrient dynamics (Guzman *et al.,* 2020). Additionally, concerns exist over the breakdown products of synthetic coagulants, some of which may have unforeseen ecological effects on wetland environments (Xu *et al.,* 2018).

The ecological impacts of soil coagulants are a growing concern, particularly in sensitive environments such as peatlands. While these substances can enhance soil stability and reduce erosion, they may also disrupt natural hydrological and biochemical cycles. Coagulants, particularly synthetic polymers, have been shown to influence microbial communities by altering nutrient availability and organic matter decomposition rates. Changes in microbial composition can have cascading effects on soil fertility, plant growth, and overall ecosystem function (Guzman *et al.,* 2020). Furthermore, the introduction of coagulants into wetland environments raises concerns about their persistence and potential to accumulate in sediments, potentially affecting aquatic organisms and disrupting food web interactions. Some studies suggest that prolonged exposure to these substances may lead to shifts in wetland vegetation patterns, reducing biodiversity and altering habitat conditions for peatland-dependent species (Xu *et al.,* 2018).

Beyond ecological concerns, potential carcinogenic effects of soil coagulants on humans and animals warrant further scrutiny. Some synthetic coagulants, particularly polyacrylamides, degrade into acrylamide, a known neurotoxin and probable human carcinogen (WHO, 2011). Exposure to acrylamide through contaminated water or soil may pose risks to agricultural workers, livestock, and wildlife inhabiting treated areas. Studies have indicated that chronic exposure to acrylamide can lead to neurological damage, reproductive issues, and increased cancer risk in both humans and animals (Dearfield *et al.,* 1995). The potential for bioaccumulation in plant tissues raises additional concerns, particularly for crops grown in coagulant-treated soils that could introduce these compounds into the food chain. Given these risks, regulatory frameworks should aim to restrict such applications to prevent potential widespread damage to ecological health and societal health because of acrylamide bioaccumulation and ingestion.

4.1.3 Mineral applications

The application of minerals, such as calcium, silicates, and other essential nutrients, have been investigated as a strategy to enhance soil fertility and counteract peat degradation in agricultural lowland peatlands. These amendments can help mitigate soil acidification, improve cation exchange capacity, and support plant growth in nutrient-deficient peat soils (Bragazza *et al.,* 2004). Calcium, for instance, plays a key role in aggregate formation, root development, and overall nutrient availability, making it particularly valuable for improving soil structure and stability in degraded peatlands (Rowell, 1994). Similarly, silicate amendments have been linked to enhanced plant resilience by strengthening cell walls, thereby increasing resistance to both biotic stressors, such as pests and pathogens, and abiotic challenges, including drought and nutrient imbalances (Epstein, 1999). Given the fragile nature of agricultural lowland peat, where drainage and intensive land use accelerate degradation, mineral applications offer a potentially sustainable approach to maintaining soil health and productivity.

Mineral applications can also influence microbial community composition and activity, which are critical for nutrient cycling and peatland resilience. Research has shown that calcium and silicate additions can enhance microbial functions by providing essential elements that support enzymatic processes involved in organic matter decomposition and nutrient transformation (Hinsinger *et al.,* 2003). However, while promising, the application of minerals in agricultural lowland peatlands presents several research gaps. The long-term impacts of these amendments on peat stability, C sequestration, and microbial interactions remain underexplored, particularly concerning the potential for nutrient leaching and shifts in soil chemistry. Additionally, the effectiveness of these applications varies significantly depending on soil composition, drainage conditions, and long-term nutrient availability, necessitating site-specific trials to optimise their use (Waddington *et al.,* 2010). Over-application could lead to unintended consequences, such as nutrient imbalances or altered microbial community dynamics, which may further accelerate peat degradation rather than mitigate it. Future research should aim to develop tailored application strategies that consider the unique characteristics of agricultural peatlands, ensuring that mineral amendments contribute to both short-term productivity and long-term soil sustainability.

4.2 Organic Applications

4.2.1 Phenol Applications

Phenolic compounds play a crucial role in soil dynamics, particularly in peatland ecosystems, where they act as natural inhibitors of microbial decomposition. These compounds influence soil C cycling by suppressing oxidative enzymes, thereby slowing down the breakdown of organic matter and enhancing C sequestration potential (Freeman, Ostle & Kang, 2001). The enzymatic "latch" hypothesis suggests that the accumulation of phenols limits the activity of phenol oxidase, an enzyme responsible for decomposing organic matter, leading to increased C storage in peat soils (Fenner & Freeman, 2011). However, while natural phenolic accumulation contributes to peatland stability, the potential for artificial applications of phenols to enhance C retention is still under investigation. Experimental studies have explored whether controlled phenol amendments could reinforce C storage while maintaining ecosystem functions, though results remain highly context-dependent, influenced by soil pH, hydrological conditions, and microbial community composition (Jassey et al., 2018). Furthermore, the interactions between phenols and other soil amendments, such as biochar and mineral applications, remain unclear, highlighting a gap in research concerning multi-faceted soil restoration strategies (Bragazza et al., 2006).

Despite their potential benefits in C retention, phenolic compounds pose significant ecological challenges and risks. Research indicates that excessive phenol concentrations can disrupt microbial community balance, leading to altered nutrient cycling and suppressed microbial diversity (Pind, Freeman & Lock, 1994). This disruption can have cascading effects on soil health, as microbial communities play a vital role in N and P availability, which are critical for plant growth and ecosystem function (Hättenschwiler & Vitousek, 2000). Additionally, some phenolic compounds exhibit phytotoxic effects, inhibiting seed germination and root elongation, which could have long-term implications for vegetation dynamics in peatland and agricultural systems (Zakharova, Stepulak & Michalak, 2014). Given that phenols interact with SOM and minerals, their long-term persistence and bioavailability require further study to assess their potential accumulation in terrestrial and aquatic environments (Hernes *et al.,* 2017).

Some synthetic phenols and their derivatives, such as bisphenol A and chlorophenols, have been classified as endocrine-disrupting chemicals with potential carcinogenic effects (Dou *et al.,* 2021). These compounds can leach into water sources, contaminating drinking water supplies and affecting aquatic ecosystems (Rodríguez-Rodríguez, Marco-Urrea & Caminal, 2011). High concentrations of phenols in wastewater have been linked to toxicity in aquatic organisms, leading to bioaccumulation and potential disruptions in trophic interactions (Vega-Loyo *et al.,* 2012). Furthermore, phenols have been associated with soil and groundwater contamination in industrial and agricultural settings, raising concerns about their environmental persistence and degradation pathways. Future research should prioritise the development of safe application thresholds (if any), monitoring of long-term ecological impacts, and investigation into sustainable methods for mitigating potential phenol-related risks in soil and water systems. A balanced approach is essential to harness the benefits of phenolic compounds while safeguarding ecosystem health and human well-being.

4.2.2 Biochar incorporation

Biochar, a carbon-rich byproduct of pyrolysis, has garnered attention for its potential role in peatland restoration, particularly in addressing soil instability and GHG emissions. One of its primary benefits in drained lowland peatlands is its ability to enhance soil structure by improving aeration and increasing water-holding capacity. These properties can help mitigate subsidence, a major issue in degraded peatlands that contributes to C loss and further ecosystem degradation (Page & Baird, 2016). Additionally, biochar amendments have been found to enhance soil aggregation, which in turn reduces erosion and promotes long-term C sequestration (Lehmann & Joseph, 2015). Given the vulnerability of lowland peatlands to degradation due to drainage and land-use change, the application of biochar presents a promising avenue for improving soil stability and resilience.

Aside from its physical benefits, biochar also plays a significant role in regulating biogeochemical processes within peat soils, particularly in mitigating GHG emissions. Studies have shown that biochar can suppress CH_4 emissions by altering microbial community dynamics. This occurs through a reduction in methanogenic archaea populations while concurrently promoting methanotrophic bacteria, which oxidise CH_4 before it is released into the atmosphere (Sheng *et al.,* 2018). Moreover, biochar's ability to retain nutrients, such as N and P, further enhances soil fertility, reducing nutrient leaching and promoting plant productivity in degraded peatlands (Hussain *et al.,* 2021). However, the effectiveness of biochar is highly dependent on factors such as feedstock type, pyrolysis conditions, and application rate. Variability in these parameters influences its stability, porosity, and adsorption capacity, thereby necessitating further field-based research to optimise biochar formulations for peatland restoration (Brassard *et al.,* 2016). As such, while biochar holds promise as a sustainable soil amendment, its large-scale application in peatland management requires careful assessment of environmental and site-specific factors.

4.2.3 Woodchip amendments

Woodchip amendments have been experimentally tested in lowland peatlands as a strategy for improving soil structure, enhancing water retention, and mitigating peat degradation. The incorporation of woodchips has been shown to increase soil porosity and improve aeration, thereby reducing soil compaction and promoting root penetration (Evans *et al.,* 2021). In drained peatlands, maintaining higher soil moisture levels is crucial for slowing peat decomposition and minimising C loss, and woodchip additions have demonstrated potential in preserving wetter conditions (Cooper *et al.,* 2019). Additionally, woodchips serve as an organic substrate that enhances microbial activity, particularly within denitrifying bacterial communities, which can contribute to the reduction of nitrate leaching into adjacent water bodies (Zak *et al.,* 2018). This aspect is particularly relevant in agricultural peatlands where excessive nutrient runoff can lead to eutrophication of freshwater systems.

Beyond their hydrological and microbial benefits, woodchip applications have been explored for their role in ecosystem restoration. When used as a surface mulch, woodchips can help retain moisture, moderate soil temperature fluctuations, and suppress the establishment of invasive plant species, thus creating more favourable conditions for native peatland vegetation (Andersen *et al.,* 2020). In re-wetted peatland systems, organic amendments such as woodchips may also contribute to peat formation by fostering conditions conducive to Sphagnum moss growth, a key driver of peat accumulation (Strack *et al.,* 2022). However, potential trade-offs exist, particularly concerning nutrient dynamics. The high C:N ratio of woodchips can result in temporary N immobilisation, as microbial communities consume available N to break down the added organic material (Edmondson *et al.,* 2021). This can lead to short-term nutrient deficiencies for plants, requiring careful management to balance decomposition rates with plant nutrient requirements. Additionally, the long-term stability of woodchip amendments in peatlands remains an area requiring further study, particularly in relation to decomposition rates, changes in microbial composition, and potential interactions with other soil amendments such as biochar or compost (Glendell *et al.,* 2023).

Future research should focus on optimising woodchip application methods to maximise benefits while mitigating potential drawbacks. Field trials investigating the influence of different woodchip types, particle sizes, and application rates on peatland restoration outcomes could provide valuable insights into best management practices. Furthermore, studies exploring the interactions between woodchips and other organic amendments, such as biochar or compost, could help refine multi-faceted restoration strategies aimed at enhancing peatland resilience and C sequestration. Addressing these knowledge gaps will be essential in determining the feasibility of scaling up woodchip-based restoration approaches for more sustainable peatland management and climate change mitigation.

4.3 An Introduction to Biological Inoculations

Hiltner (1904) observed microbe presence was greater within the rhizosphere than the rest of the soil for the first time, which was later understood to be linked to root exudates. Root exudates are a rhizodeposition process, and a significant source of labile organic C released by plants (Nguyen, 2003), containing various compounds, which act as repellents and signallers for various microorganisms. Root exudates have been theorised to impact C and N cycling, with el Zahar Haichar *et al.,* (2014) suggesting root exudates "exhibit a priming effect on the rhizosphere". This is supported by Girkin *et al.,* (2016) who indicate that within tropical peat, increased C fluxes and microbial activity are associated with root exudate additions and C mineralisation.

"Within the plant rhizosphere, saprophytic microflora can be both deleterious and beneficial to plant growth and crop yields deleterious" (Strap, 2011), which broadbrush pesticide spraying completely controls, by eradicating large proportions of soil microbiology. Biological inoculations could act as bio-controls which are beneficial to agricultural yield and crop growth, overcoming agri-environmental issues surrounding soil health, ecological degradation, nutrient cycling and pathogens, whilst reducing chemical inputs (Kloepper *et al.,* 2004). The complexities and nuances of interaction within the rhizosphere are understudied, largely due to an "inability to accurately quantify and identify the microbial inhabitants" (Strap, 2011).

4.3.1 Arbuscular Mycorrhizal Fungi

Arbuscular mycorrhizal fungi are critical symbiotic organisms that establish mutualistic relationships with the roots of over 80% of terrestrial plant species, enhancing nutrient uptake – particularly P – and improving plant resilience to abiotic stress (Smith & Read, 2008). In degraded or agriculturally drained peatland systems, AMF contribute to ecological restoration by restoring nutrient cycling, supporting plant recolonisation, and promoting the development of structurally stable soils. The hyphal networks of AMF increase the effective root surface area, facilitating P and micronutrient acquisition in oligotrophic peat soils, which is essential for re-vegetation and long-term soil recovery (van der Heijden *et al*., 2015). However, scientific opinion is divided surrounding AMF inoculant success and consistency within cropping systems (Ryan and Graham, 2018).

Recent studies have highlighted the role of AMF in stabilising soil aggregates and reducing erosion, particularly in re-wetted or restored peatlands transitioning from agricultural use (Leifheit *et al*., 2014). Their role in glomalin production – an AMF-derived glycoprotein – has been linked to enhanced C storage and soil structure improvement, which are vital for mitigating CO_2 emissions in carbon-rich peat soils (Rillig *et al*., 2001; Jeffries *et al.,* 2003). However, hydrological fluctuations may influence AMF colonisation success, with AMF promoting drought resistance in plants – unnecessary within lowland agricultural peatlands, which may limit AMF's success (Kalamulla *et al.,* 2022). Additionally, concerns surrounding mass production and shelf-life of AMF are causes for concern regarding AMF use as a commercial inoculation (O'Callaghan, Ballard and Wright, 2021). Furthermore, Hart *et al.,* (2017) identify AMF as difficult to monitor and potential threats to soil and plant diversity if they are invasive.

4.3.2 Actinobacteria

Actinobacteria (AB) are renowned for their role in the decomposition of complex organic compounds such as lignin – abundant in peat forming vegetation. In disturbed peat soils, AB contribute to the restructuring of microbial communities by breaking down recalcitrant organic matter and producing extracellular enzymes that facilitate humification processes (Goodfellow & Williams, 1983). Their secondary metabolites also contribute to plant disease suppression, enhancing the resilience of restoration plantings in compromised peat systems (Barka *et al*., 2016). The application of AB inoculation within lowland agricultural peat systems, could be disease oriented; however, the synergistic ability of AB to function with AMF and N fixers – makes them valuable components of microbial consortia, in restoring soil health and a functional microbiome. Further research into the interrelationships between AB and AMF could prove invaluable regarding microbial resilience, disease control and long-term C stability within lowland agricultural peatlands, especially under changing hydrological regimes.

4.3.3 Rhizobia

Rhizobia are nitrogen-fixing bacteria that form symbiotic associations with leguminous plants, producing nodules in which atmospheric N is converted into plant-available ammonia. This biological N fixation (BNF) is especially valuable in nutrient-depleted peatlands, where synthetic fertiliser use can exacerbate eutrophication and C loss (Graham & Vance, 2000). Legume–Rhizobium partnerships have been tested in paludiculture systems and rewetted fens to supply essential N while minimising GHG emissions from inorganic N inputs (Tiemann *et al*., 2015). However, it should be noted that lowland peatland environments possess high N content, so the specific incorporation of N fixers may prove essential within severely degraded peatland skirt, where N content may be a greater concern.

4.3.4 Johnson-Su

The Johnson-Su composting bioreactor method has gained increasing attention for its potential to enhance soil health and promote C sequestration in degraded peatlands. Unlike conventional composting methods, which often produce thermophilic, bacteria-dominated composts, the Johnson-Su system generates a fungal-dominated, microbially diverse compost that supports long-term SOM (Su & Johnson, 2019). This shift in microbial composition is particularly significant for peatlands, where fungal networks play a critical role in organic matter decomposition and C cycling. Experimental applications in lowland peatlands of the UK have explored whether Johnson-Su compost can enhance peat stability by increasing microbial biomass, improving nutrient cycling, and strengthening soil structure. Research suggests that these compost amendments can promote peatland resilience by fostering beneficial fungal communities that enhance nutrient transport and stabilise organic matter, leading to reduced C losses from peat soils (Lehmann *et al.,* 2020). Additionally, the slow-release nature of nutrients in fungal-dominated composts may help prevent rapid microbial mineralisation, which often contributes to CO_2 and CH_4 emissions in peatland environments (Cotrufo *et al.,* 2019). A complete lack of GHG emissions data regarding Johnson-Su application, presents a significant research gap, which requires fulfilment to affirm or disprove the efficacy of its application.

Johnson-Su compost has been shown to support plant growth, root development, and water retention, which are essential for mitigating peat degradation and improving ecosystem function. Studies indicate that the high humic content and balanced nutrient profile of this compost can improve soil aggregation and water-holding capacity, reducing vulnerability to erosion and subsidence in drained peatlands (Brown *et al.,* 2021). Furthermore, compost-derived humic substances have been found to influence root exudation, promoting beneficial plant-microbe interactions that contribute to peatland restoration (Martinez *et al.,* 2020). However, the successful integration of Johnson-Su compost into large-scale peatland management strategies presents logistical and practical challenges. Factors such as compost application rates, seasonal variability, and soil moisture conditions require careful management to optimise microbial activity while preventing unintended nutrient leaching or shifts in soil chemistry (Liang *et al.,* 2021). Additionally, the long-term persistence of microbial communities introduced through compost amendments remains an open research question, particularly in intensively managed agricultural peatlands where soil disturbance and drainage significantly alter microbial dynamics.

Further research is needed to explore the long-term ecological impacts of Johnson-Su compost applications on peatland ecosystems, particularly in the context of sustainable agriculture and climate change mitigation strategies. While initial studies suggest promising outcomes for C sequestration and peatland restoration, more extensive field trials are necessary to assess compost stability under varying environmental conditions. Moreover, understanding the interactions between Johnson-Su compost, native peat microbial communities, and GHG emissions is essential for developing optimised composting protocols tailored to peatland conservation (Harris *et al.,* 2022). Addressing these knowledge gaps will be crucial in determining whether this method can be effectively scaled up for widespread use in agricultural and conservation contexts, contributing to more sustainable land management practices for lowland peatlands.

5. Discussion

Lowland peatlands, serve as vital C sinks but are increasingly threatened by both environmental and anthropogenic pressures, including agricultural practices, climate change, and land management decisions. The degradation of these ecosystems, driven by oxidative processes and drainage, has profound consequences for both C storage and broader ecosystem services. The stability and functionality of peatlands are closely tied to SMC, which plays a critical role in maintaining their C sequestration potential and structural integrity. Historically, the drainage of peatlands for agriculture has disrupted natural hydrological regimes, leading to C loss, increased subsidence, and greater susceptibility to erosion. These changes undermine the long-term viability of peatland soils and contribute to wider environmental challenges, including GHG and biodiversity loss. To address these challenges, a multifaceted approach is necessary, one that integrates soil moisture management, vegetation restoration, and sustainable agricultural strategies. Rewetting initiatives have been widely advocated to restore hydrological balance and mitigate C loss, but they are not sufficient on their own. A more dynamic, integrative solution requires a paradigm shift to transform the agricultural status quo on lowland peatlands, through a mosaic approach; essential in the preservation of lowland peatland agroecosystems.

The mosaic approach to peatland management, combines diverse strategies tailored to local conditions, offering a holistic and flexible framework for addressing the complex challenges facing lowland peatlands.

Continued research and monitoring are essential to refine these methods and ensure the long-term resilience of agroecological lowland peatlands. The role of lowland peatlands as both C sinks and agricultural landscapes is increasingly recognised, and future strategies should aim to balance ecological restoration with sustainable land use to promote both environmental and economic sustainability in these regions.

5.1 Research recommendations:

Irrigation regimes:

One critical research area is the development of optimised irrigation regimes that maintain soil moisture while minimising peat oxidation and GHG emissions. Automated and precision-controlled irrigation techniques should be explored to enhance peatland hydrology. Additionally, subsurface irrigation methods that reduce water loss and retain soil moisture could be compared to traditional surface irrigation techniques. Research could also focus on the effects of intermittent versus continuous flooding on peat decomposition rates and crop yields, as well as how irrigation impacts microbial communities that influence GHG fluxes and nutrient cycling. These research areas, would assist in producing more functional and effective irrigation systems, designed to maximise efficiency and minimise GHG emissions.

Maize Longevity on Peat:

Maize cultivation on peatlands requires careful management to prevent soil subsidence and nutrient depletion. Research should examine drilling techniques that minimise soil disturbance while ensuring optimal germination and yield. Additionally, integrating cover crops with maize cultivation could improve SOM levels, reduce erosion and GHG emissions. Long-term studies are needed to assess the sustainability of maize monocultures on peatlands, particularly their effects on soil structure, microbial activity, and C flux. Understanding the role of maize root exudates in altering microbial communities and nutrient dynamics will also be crucial for sustainable maize production on peatlands.

Intercropping:

Intercropping and allelochemistry offer potential solutions for improving peatland agriculture by enhancing biodiversity and reducing chemical inputs. Research should explore crop combinations that optimise N fixation and stabilise peat soils. Investigating the interactions between allelochemicals and soil microbial communities will provide insights into their potential to suppress weeds naturally and influence nutrient cycling. Furthermore, research should assess how root exudates from intercropped species impact GHG fluxes and overall C dynamics in peatlands. Long-term studies are needed to evaluate the sustainability and yield trade-offs of intercropping systems compared to monocultures.

Allelochemical sprays:

The development of allelochemical sprays represents a promising alternative to synthetic herbicides for peatland agriculture. Studies should focus on extracting and refining allelochemicals from native peatland species, followed by field trials assessing their effectiveness in controlling invasive species. Further research should explore the interactions between allelochemical sprays and soil microbial communities to determine their broader ecological impacts. Additionally, the potential for these sprays to alter GHG emissions and nutrient availability should be investigated to ensure they contribute to sustainable peatland management.

Polyculture:

Polyculture systems offer another avenue for improving the sustainability of peatland agriculture. Research should evaluate different crop combinations to determine their efficacy in maximising biomass production and conserving peatland ecosystems. Carbon sequestration potential in polyculture systems should be compared to that of monocultures to understand their role in mitigating climate change. Furthermore, economic analyses should assess the viability and market potential of polyculture-based farming in peatlands. The impact of polyculture on soil microbial diversity and its potential to reduce disease incidence may also be explored to understand its broader agricultural benefits.

Species Reintroduction:

The reintroduction of native wetland plants such as reeds, sedges, and rushes is a crucial strategy for peatland restoration. Research should identify optimal species for C sequestration and soil stabilisation while examining hydrological management techniques that support successful re-vegetation. Studies could also investigate the impact of reintroduced vegetation on nutrient cycling and peat formation. Scaling up plant-based restoration efforts requires further research into cost-effective and practical strategies for large-scale implementation.

Riparian Buffer Zones:

Riparian buffer zones play a key role in mitigating nutrient runoff and enhancing biodiversity in peatland landscapes. Research should assess their effectiveness in reducing N and P leaching from agricultural land and identify plant species best suited for nutrient uptake in riparian buffers. Additionally, studies should investigate how buffer zones influence GHG emissions and contribute to peatland C sequestration. Long-term ecological and hydrological monitoring will be necessary to quantify the benefits of riparian zone management for peatland conservation.

Controlled drainage:

Controlled drainage presents an appealing approach to deal with lowland peat emissions whilst maintaining productivity, but quantification of the impact of different water table heights on GHG ditch and field fluxes and long-term peatland stability. Studies could also investigate the effectiveness of CD in minimising nutrient losses while maintaining soil fertility, and if this impacts crop yields. Furthermore, considerations around management during high rainfall events is essential, an exploring this is a critical consideration. Biodiversity opportunity is also vast with this project, but research is needed to assess how different water management strategies influence wetland species and ecosystem services. Lastly, scope for focus on policy is an important consideration, making this sort of scheme more appealing for farmers, especially as a collaborative effort across hydrological systems.

Agroforestry Systems:

Identifying the most suitable tree species for peatlands is a key research priority, along with understanding the long-term impacts on soil properties and farm productivity. Comparative studies between agroforestry and conventional farming are essential to assess its effectiveness in GHG reduction and overall sustainability.

Mulching:

Mulching is another important strategy for reducing GHG emissions and improving soil health in peatlands. Research should compare different types of mulch, including organic and synthetic options, to determine their effects on CO_2, CH_4, and nitrous oxide fluxes. Studies assessing how mulching influences soil moisture retention, microbial activity, and overall peatland stability may also be of significant value. Understanding the decomposition rates of organic mulches and their contributions to SOM will be critical for developing effective mulching strategies that balance productivity and climate mitigation.

Copper Applications:

Copper influences on nutrient cycling, microbial activity, and SOM decomposition are all of interest within research, but GHG emission prevention, sits as a field with a considerable lack of research. Additionally, safe application thresholds must be determined to prevent heavy metal accumulation, which could negatively affect both soil health and water quality. Exploring its interactions with other soil amendments will also be crucial for perfecting its use in sustainable peatland agriculture.

Mineral Applications:

Tailored mineral applications can enhance soil health and productivity in peatlands, but further research is required to examine the effects of different mineral amendments on peat decomposition rates, nutrient availability, and plant uptake efficiency. Investigating how these amendments interact with soil microbial communities will provide insights into their potential to support more sustainable peatland agriculture. Research into whether certain mineral applications enhance C sequestration without accelerating peat oxidation could make these very appealing.

Phenol Applications:

The use of phenolic compounds to slow peat decomposition and enhance C storage is an emerging area of interest. Future studies focusing on identifying effective phenol sources and evaluating their impact on peat soil ecosystems would provide a better understanding of any potential applications for phenols in farming. Additionally, determining the best application techniques and dosage levels will be critical to balancing environmental benefits with agricultural feasibility.

Biochar Applications:

The addition of biochar to lowland peat soils could improve soil structure, enhance water retention, and stabilise C. However, further research is needed to understand how biochar interacts with peatland hydrology and microbial communities. Studies examining its ability to reduce GHG emissions and nutrient leaching while supporting crop productivity would be extremely valuable. To ensure practical implementation, research determining the most effective biochar application rates, and methods tailored to different peatland conditions would confirm its widespread efficacy.

Woodchip Applications:

Woodchip applications offer another potential amendment for peatland soils. Research should focus on decomposition rates and their impact on C cycling, soil aeration, and microbial activity. Investigating the potential of woodchip applications to reduce peat subsidence and enhance soil stability will be crucial for determining their viability as a soil management strategy. Using woodchip amendments in existing peatland farming systems could contribute to long-term sustainability, making this another choice for research.

Rhizosphere Dynamics and Biological Inoculants:

Future research should investigate the functional complexity of microbial interactions within the rhizosphere, particularly the role of root exudates in driving microbial community dynamics and influencing C and N cycling. Advanced molecular tools, such as metagenomics and metabolomics, could help resolve current limitations in identifying and quantifying rhizosphere microbiota. Emphasis should be placed on understanding the balance between beneficial and pathogenic saprophytic species, as well as the long-term effects of biological inoculants on soil health and crop performance. Comparative studies evaluating inoculant effectiveness under different peatland management regimes – including organic versus conventional systems – could clarify their potential as more sustainable alternatives to chemical pesticides and fertilisers.

Arbuscular Mycorrhizal Fungi Inoculations:

Research is needed to evaluate the efficacy of AMF inoculants in the unique conditions of lowland agricultural peatlands, particularly under fluctuating water tables and high baseline fertility levels. Studies should explore the interactions between AMF and native peatland vegetation to determine inoculant compatibility and potential unintended ecological impacts. Field trials assessing glomalin production and its influence on C sequestration could offer insights into AMF's role in peat soil stabilisation. Furthermore, addressing practical challenges – such as inoculant shelf life, mass production, and colonisation consistency – would support more widespread application in peatland restoration. Finally, research into potential invasiveness or biodiversity impacts of commercial AMF strains is needed to safeguard native soil communities.

Actinobacteria Inoculations:

Targeted studies should explore the potential for Actinobacteria to accelerate organic matter transformation and enhance humification in rewetted or degraded peat soils. Research should investigate how these microbes interact with other beneficial organisms such as AMF and nitrogen-fixing bacteria in shaping microbial consortia that support soil function and plant health. Emphasis should be placed on understanding Actinobacteria's role in disease suppression and their metabolic versatility under waterlogged or nutrient-deficient conditions. Field-scale applications should test AB inoculants across a range of peatland soil types, evaluating their influence on C cycling, microbial resilience, and vegetation re-establishment under both restored and drained scenarios.

Rhizobia Inoculations:

Future research should examine the effectiveness of Rhizobia inoculation in degraded and nutrient-depleted peatland margins, particularly in tandem with leguminous species suited to paludiculture. Long-term studies should quantify N fixation rates under varying hydrological and soil nutrient conditions to determine the feasibility of substituting synthetic fertilisers with biological inputs. Investigations should also assess the contribution of Rhizobia to GHG mitigation, particularly in terms of reducing N_2O emissions linked to conventional fertilisation. Understanding symbiotic efficiency in high-N peat environments and how inoculated Rhizobia perform compared to native strains could inform more targeted and ecologically safe applications in restoration and low-input agriculture.

Johnson-Su Applications:

The use of Johnson-Su bioreactor compost represents an emerging strategy for improving soil microbial health in peatlands. Exploring the effects of fungal-dominant compost on peatland microbial ecology, nutrient cycling, and soil structure stability through field-scale trials could evaluate the impact of Johnson-Su compost on crop yields and GHG emissions. Understanding its long-term effects on peatland C sequestration will also be essential for assessing its role in more sustainable land management and potential for widespread application

Glossary of Terms

Abiotic
Non-living physical and chemical components of an ecosystem, such as sunlight, temperature, soil, and water, which influence living organisms.

Acidification
The process by which soils, or water bodies become more acidic, often due to acid rain or agricultural practices, leading to potential ecological harm.

Acrylamide
A potentially carcinogenic chemical formed during high-temperature cooking and industrial processes; also found in some soil conditioning agents.

Aggregate
A cluster of soil particles bound together more strongly than to adjacent particles, playing a key role in soil structure, aeration, and water retention.

Agri-environments
Landscapes managed for both agricultural productivity and biodiversity conservation, often supported by subsidy schemes or policies.

Agroecosystems
Ecosystems that are used for agriculture, including the crops, livestock, and the environmental components that interact with them.

Agroforestry
A land-use system that combines trees with crops or livestock, enhancing biodiversity, soil health, and economic resilience.

Agronomic
Relating to the science and technology of producing and using plants for food, fuel, fibre, and land reclamation.

Allelochemicals
Biochemicals produced by plants that influence the growth, survival, or reproduction of other organisms, often used in natural weed suppression.

Allelochemistry
The study of chemical interactions between plants and other organisms through the release of allelochemicals.

Anaerobic
Describes processes or organisms that occur or live in the absence of oxygen, often resulting in slower decomposition and methane production.

Anthropogenic
Originating from human activity; often used to describe pollution, land-use change, and climate change impacts.

Antimicrobial
Substances that kill or inhibit the growth of microorganisms, used in agriculture to control disease but potentially leading to resistance.

Bioaccumulation
The accumulation of substances, such as pesticides or heavy metals, in an organism over time, often magnifying up the food chain.

Biochar
A carbon-rich product derived from the pyrolysis of organic material, used to enhance soil health and sequester carbon.

Biotic stressors
Living factors that negatively affect plant health, such as pests, diseases, and invasive species.

Biotopes
Small, uniform areas of habitat with specific environmental conditions and associated organisms.

Carcinogenic
Having the potential to cause cancer in living tissue.

Carr woodlands
Wet woodland ecosystems typically dominated by alder and willow, found in waterlogged or peatland areas.

Cation exchange capacity
A measure of a soil's ability to hold and exchange positively charged ions (cations), essential for nutrient availability and pH regulation.

Coagulant
A substance that promotes the clumping of particles, used in water treatment and sometimes in soil remediation.

Composting bioreactor
A contained system designed to optimise the microbial breakdown of organic waste into compost.

Controlled drainage
A water management practice that regulates the flow of water through subsurface drains to improve crop yields and reduce nutrient loss.

Denitrification
The microbial conversion of nitrate to nitrogen gas, a key process in the nitrogen cycle that reduces soil fertility and contributes to greenhouse gas emissions.

Desiccation
Severe drying or dehydration, which can affect soils, plants, and microbial activity.

Ecological balance
A stable state in an ecosystem where biotic and abiotic factors are in equilibrium, supporting biodiversity and sustainability.

Endocrine disrupting chemicals
Substances that interfere with hormonal systems, potentially causing adverse health effects in humans and wildlife.

Eutrophication
The enrichment of water bodies with nutrients, leading to excessive plant growth, oxygen depletion, and loss of aquatic life.

Evapotranspiration
The combined process of water evaporation from soil and plant surfaces and transpiration from plant leaves.

Fast carbon
Carbon stored in short-lived biomass that cycles rapidly through ecosystems.

Glycoprotein
A molecule composed of a protein linked to carbohydrate chains; in soil, glycoproteins can be involved in microbial adhesion, signalling, or structural stability.

Habitat connectivity
The degree to which landscapes allow organisms to move and interact, essential for biodiversity and ecological resilience.

Histosol
A soil type rich in organic matter, often found in wetlands and peatlands, with low mineral content and high carbon storage capacity.

Holistic approach
A systems-based perspective that considers ecological, social, and economic factors in environmental management.

Humic content
The portion of organic matter in soil derived from decomposed plant and animal material, contributing to fertility and structure.

Humification
The process of organic matter decomposition into humus, a stable component of soil organic matter.

Intercropping
A farming practice of growing two or more crops in proximity for benefits such as pest control, soil fertility, and resource use efficiency.

Labile carbon
Easily decomposable forms of organic carbon in the soil, such as sugars and amino acids, that are readily used by microorganisms for energy and growth.

Leaching
The loss of soluble nutrients or contaminants from soil as water moves through, potentially causing groundwater pollution.

Lignin synthesis
The production of lignin, a complex organic polymer in plant cell walls that provides structural support and resistance to decay.

Metabolic byproducts
Products produced because of metabolism; in this context these are greenhouse gas emissions (CO_2, CH_4, and N_2O).

Metabolomics
The comprehensive study of the complete set of metabolites – small molecules like sugars, amino acids, organic acids, and lipids – present within a biological sample (e.g., a cell, tissue, organism, or environmental matrix) at a given time.

Metagenomics
The study of genetic material recovered directly from environmental samples – such as soil, water, or the human gut – without the need to culture organisms in the lab.

Methanogenic archaea
Microorganisms that produce methane as a metabolic byproduct in anaerobic environments like peatlands or waterlogged soils.

Methanotrophic
Organisms that consume methane, often playing a role in reducing greenhouse gas emissions in soils and wetlands.

Microbial consortia
A group of different microorganisms that live together and interact in a shared environment, often working synergistically to carry out complex processes like nutrient cycling or organic matter decomposition.

Micronutrient
Essential elements required in small amounts for plant and animal growth, such as zinc, iron, and manganese.

Microtopography
Small-scale variations in land surface elevation that influence water distribution, vegetation patterns, and soil processes.

Mineralisation
The microbial breakdown of organic matter into inorganic nutrients that plants can absorb.

Monoculture
The agricultural practice of growing a single crop species over a large area, often linked to reduced biodiversity and soil health.

Mosaic approach
A landscape management strategy that combines different land uses and habitats to enhance ecological diversity and resilience – whilst maintaining productivity simultaneously.

Neurotoxin
A toxic substance that affects the nervous system of organisms, sometimes found in pesticides or naturally produced by certain plants or fungi.

Nitrification
The microbial conversion of ammonium to nitrate in soils, an important step in the nitrogen cycle.

Nutrient cycling
The movement and exchange of nutrients within ecosystems through processes like decomposition, uptake, and leaching.

Nutrient fixation
The conversion of atmospheric nutrients, particularly nitrogen, into forms usable by plants, typically via microbial symbiosis.

Oligotrophic
Refers to organisms or environments that thrive in low-nutrient conditions; oligotrophic microbes are typically slow-growing and efficient at using limited resources.

Overgrazing
Excessive grazing by livestock that depletes vegetation, degrades soil, and leads to erosion and biodiversity loss.

Oxidation
A chemical reaction involving the loss of electrons, often leading to changes in soil chemistry or contaminant transformation.

Oxidative risk
The potential for oxidative stress caused by reactive oxygen species, affecting soil organisms or plants.

Pedogenic
Relating to soil formation processes influenced by biological, climatic, and geological factors.

Pesticides
Chemicals used to kill or control pests, including herbicides, insecticides, and fungicides, which can impact non-target organisms.

Phenolic compounds
Organic molecules with phenol groups, common in plant defence, decomposition resistance, and sometimes allelopathic activity.

Phenols
A type of aromatic organic compound often derived from plants, contributing to antimicrobial and antioxidant properties.

Photosynthesis
The process by which green plants use sunlight to convert carbon dioxide and water into glucose and oxygen.

Physiochemistry
The study of physical and chemical interactions, particularly in soils, such as pH, salinity, and nutrient availability.

Phytotoxicity
The toxic effects of substances (e.g., herbicides, heavy metals) on plant growth and health.

Polyacrylamides
Synthetic polymers used in soil conditioning and erosion control, with environmental concerns due to potential acrylamide residues.

Polyculture
An agricultural system where multiple crop species are grown together, promoting biodiversity and resilience.

Polymers
Large molecules made up of repeating subunits, used in various agricultural applications such as soil conditioners or controlled-release fertilisers.

Priming effect
A phenomenon where the addition of fresh organic matter (like root exudates) stimulates microbial activity, leading to increased decomposition of existing soil organic matter.

Propagules
Plant parts (e.g., seeds, spores, cuttings) capable of developing into a new plant, crucial for species dispersal and regeneration.

Pyrolysis
Thermal decomposition of organic material in the absence of oxygen, used to produce biochar, syngas, and bio-oil.

Recalcitrant
Describes organic compounds that are resistant to decomposition due to their complex or stable chemical structure (e.g., lignin), often contributing to long-term carbon storage in soils.

Residence
The length of time a substance (e.g., water, carbon) remains within a particular system or location.

Rhizodeposition
The release of organic compounds from plant roots into the surrounding soil, including mucilage, sloughed cells, and root exudates, which serve as energy sources for soil microbes.

Rhizosphere
The narrow zone of soil directly influenced by root secretions and associated microbial activity; it is a hotspot for biological and chemical interactions between plants and soil organisms.

Riparian
Relating to the interface between land and a river or stream, often important for ecosystem services and water quality.

Root exudates
Soluble organic compounds secreted by plant roots (e.g., sugars, amino acids, organic acids) that influence microbial communities and nutrient availability in the rhizosphere.

Rotational cropping
The practice of alternating crop species in a field across seasons or years to improve soil health and reduce pests.

Rotational grazing
A livestock management system where animals are moved between pastures to allow vegetation recovery and improve soil conditions.

Saprophytic
Describes organisms, especially fungi and bacteria, that obtain nutrients by decomposing dead or decaying organic matter.

Sequestration
The process of capturing and storing carbon or other substances to mitigate climate change or pollution.

Silvoarable
An agroforestry system combining trees with arable (crop) farming on the same land.

Silvopastoral
An agroforestry system integrating trees with pasture and livestock.

Slow carbon
Carbon stored in long-term parts of the carbon cycle (e.g. peat, coal), contributing to long-term sequestration.

Soil matrix
The solid part of the soil consisting of mineral and organic particles, forming the physical framework of soil.

Soil resilience
The soil’s capacity to recover structure and function after disturbance, critical for long-term ecosystem productivity.

Subsidence
The gradual sinking of land, often caused by the drainage of peatlands or extraction of groundwater.

Toxicity
The degree to which a substance can harm organisms, depending on dose, exposure, and sensitivity.

Trophic interaction
Relationships among organisms based on feeding and energy transfer, such as predator-prey or herbivore-plant dynamics.

Trophic levels
The hierarchical levels in a food web, from primary producers to apex predators, representing energy flow through ecosystems

Appendices

Lowland Peat Practice Tables.xlsx

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