Technical Report:

Overcoming financial barriers for paludiculture with biochar integration

Paludiculture Exploration Fund

UK Centre for Ecology & Hydrology, Bangor University, Scotland's Rural College, RSK ADAS, Lapwing Energy and the University of Nottingham.

Version history

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About the project

This project examined how integrating biochar into rewetted peatland systems could help overcome financial barriers to paludiculture. It focused on the potential for biochar to enhance the environmental performance and economic resilience of farming on wet peat soils. The work considered policy, practice, and market contexts to identify where barriers lie and what opportunities exist. The outcomes offer practical recommendations for supporting land use change that works for both people and climate.

The work is funded by Natural England and led and managed by UKCEH. It comprises five separately managed work packages covering four consecutive stages of work: Integration of Biochar Application Methods with Minimal Impact (WP1), Identifying Cost-Effective Biochar for Enhanced C Financing (WP2); Maximising C Finance, Mitigating Methane, and Assessing Agronomic Benefits (WP3); Identifying Addressing Policy Barriers for Biochar Integration with Paludiculture (WP4); and Economic Analysis of Biochar Carbon Markets and Credit Stacking (WP5).

The project partners are UK Centre for Ecology & Hydrology (UKCEH), Bangor University, Scotland's Rural College (SRUC), RSK ADAS, Lapwing Energy and the University of Nottingham.

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Acronyms Used

AES	Agri-Environment Scheme
BAU	Business-as-usual
C	Carbon
CDR	Carbon Dioxide Removal
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DOC	Dissolved Organic Carbon
EU	European Union
GGR	Greenhouse Gas Removal
GHG	Greenhouse Gas
GIS	Geographic Information System
GPP	Gross Primary Productivity
GWT	Ground Water Table
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for the Conservation of Nature
LCA	Lifcycle Assessment
NEE	Net Ecosystem Exchange
NGO	Non-Governmental Organisation
N_2O	Nitrous Oxide
NIR	National Inventory Report
NOBV	Dutch Research Programme on Greenhouse Gas Dynamics in Peatlands and Organic Soils
MRV	Monitoring, Reporting and Verification
OC / OC%	Organic Carbon / Organic Carbon percentage
PAR	Photosynthetically active radiation
REA	Rapid Evidence Assessment
Reco	Ecosystem Respiration
SDG	Sustainable Development Goals
SFI	Sustainable Farming Incentive
SOC	Soil organic carbon
SOM	Soil organic matter
UNEP	United Nations Environment Programme
UNFAO	United Nations Food and Agriculture Organisation
UNFCCC	United Nations Framework Convention on Climate Change
WP	Work package

Contents

1. Introduction

Paludiculture offers significant opportunities to reduce carbon emissions from inherently high emitting areas of previously drained peat. However, these systems are not yet financially viable at scale. The high upfront investment costs of rewetting infrastructure and the relatively low market value of wetland crops present significant economic barriers. Moreover, concerns remain over potential trade-offs with methane (CH_4) and nitrous oxide (N_2O) emissions, and the complexities of establishing new markets and policies that support alternative land uses.

Biochar, a carbon-rich, stable product of biomass pyrolysis, is widely recognised for its potential in carbon capture and its additional soil and agronomic benefits. When applied to soil, biochar may support multiple ecosystem services, including long-term carbon storage and possibly suppression of CH_4 emissions. However, its integration in rewetted peat systems is not well understood, and uncertainties remain around its stability, environmental impacts, and effects on crop productivity and water quality under paludiculture conditions.

This report presents findings from the Natural England-funded project "Overcoming Financial Barriers for Paludiculture with Biochar Integration," delivered by UKCEH in partnership with Bangor University, Scotland's Rural College, RSK ADAS, Lapwing Energy and the University of Nottingham. The project evaluated how biochar can contribute to a financially viable, environmentally sustainable model of paludiculture on lowland peat.

Report Structure

The report is structured around five interconnected work packages (WPs), each addressing a key barrier to biochar integration in paludiculture systems:

Section 2 explores the scientific basis for using biochar in rewetted peat soils. It brings together theoretical modelling, a national-scale litterbag experiment, field experiments including the Winmarleigh Sphagnum Carbon Farm trial, and mesocosm studies to understand the behaviour of biochar under paludiculture conditions.

Section 3 identifies opportunities and barriers within existing policy frameworks. Using a structured policy diagnostic approach, this Section evaluates the policy landscape around paludiculture and biochar in the UK and internationally.

Section 4 synthesises evidence from stakeholder engagement, including biochar suppliers and farmers, to assess perceptions, practical considerations, and barriers to adoption.

Section 5 presents the results of economic modelling comparing the financial viability and climate mitigation potential of different paludiculture business models with and without biochar.

Section 6 provides a concise policy brief, drawing on findings from across the work packages to make recommendations for policymakers, industry stakeholders, and land managers.

Together, these Sections provide a holistic assessment of the viability of biochar as a lever to support the transition to low-emission, economically viable farming on rewetted peatlands.

2. Exploring Biochar Use in Paludiculture

Integrating Modelling, Experimental, and Field Approaches

Authors: UKCEH– Jenny Rhymes, Christopher Evans, Niall McNamara, Caio Fernandez, Rosie Broyd, Lily McGuinness.

This Section explores the role of biochar in rewetted peat soils through a multi-scale approach, combining theoretical modelling with laboratory and field-based experimentation. The following complementary components are included:

1. **Theoretical modelling:** A model was developed to estimate decomposition rates of biochars with varying stabilities under saturated peat conditions, providing a framework to predict long-term carbon persistence.
2. **Litterbag experiment:** Biochars of different stabilities were deployed in litterbags to paludiculture sites across the UK to empirically assess decomposition rates.
3. **Field experiment at Winmarleigh:** Automated chamber systems were deployed at a paludiculture site to measure in situ GHG fluxes at high temporal resolution in response to different biochar applications.
4. **Mesocosm experiment (data not yet included; water quality summary included):** Controlled experiments examined the effects of biochar on GHG emissions and its interaction with gypsum. An additional component, funded by the Environment Agency, assessed the implications of these treatments on water quality.
5. **Ongoing agronomic field trial (data not yet included):** A separate in situ study is currently evaluating the agronomic impacts of biochar on willow and miscanthus crops

grown under paludiculture conditions, alongside ongoing soil respiration measurements. Results from this trial will be included in the next project report, due in March 2026.

Together, these approaches offer insights into how biochar behaves in rewetted peat, its potential for carbon removal, and its influence on greenhouse gas emissions under paludiculture management. The work focuses on comparing the carbon removal potential of low- and high-stability biochars, and evaluating whether biochar, gypsum, or their combination can effectively suppress methane emissions. These measurements are critical for assessing the viability of biochar integration in paludiculture systems, not only to maximise carbon credit income through enhanced carbon removals, but also to ensure that potential agronomic or environmental trade-offs (e.g. reduced crop yields or water quality risks) do not undermine the economic sustainability of these systems.

2.1 Executive Summary

This Section examines the role of biochar in rewetted peat soils under paludiculture, using a combination of modelling, mesocosm studies, and early-stage field experiments to investigate its potential benefits and trade-offs. The primary aim is to assess whether integrating biochar can enhance carbon dioxide removal (CDR) under paludiculture management, and in doing so, increase access to carbon finance as a means of overcoming key economic barriers to adoption. The work focuses on how biochar stability, environmental conditions, application methods, and co-amendments influence carbon dynamics, greenhouse gas emissions, and water quality. While some findings are preliminary, together they begin to build a more complete picture of how biochar might support both climate mitigation and the financial viability of rewetted peatland systems.

Theoretical modelling provided an initial assessment of whether rewetted peat conditions could enhance the persistence of lower stability biochars, which are typically excluded from carbon markets due to faster decomposition rates. Under saturated conditions, the model predicted up to a 40 percent increase in carbon retention over 100 years for low stability biochars compared to well-aerated mineral soils. This resulted in a 33 percent increase in overall CDR efficiency when biochar yield was also considered. These findings suggest that rewetted peatlands may offer a pathway to scale up biochar use while reducing biomass demand, provided that permanence and stability can be demonstrated.

To test this, a national litterbag experiment was conducted across 13 peatland sites representing both paludiculture and business-as-usual (BAU) conditions. Rewetting significantly reduced decomposition of labile organic matter (e.g. wood and tea), while biochar treatments showed consistently low mass loss across all sites, regardless of water management. Since mass loss indicates carbon loss, these results suggest high biochar stability. Interestingly, the high-stability biochar showed more mass loss than lower stability biochars, likely due to leaching differences influenced by the size of the biochar . This highlights the influence of physical properties on early-stage decomposition and the need for longer-term monitoring to assess biochar persistence under rewetted conditions.

At the Winmarleigh field site, a rewetted lowland peatland managed as a Sphagnum-based paludiculture carbon farm, automated chamber systems were used to measure high-frequency CO_2 fluxes in response to surface-applied biochar. Both high- and low-stability biochars initially suppressed Gross Primary Productivity (GPP) and increased Net Ecosystem Exchange (NEE), likely due to shading of the low-growing moss vegetation. Vegetation recovered over the growing season, particularly in plots treated with high-stability biochar. Low-stability biochar reduced ecosystem respiration (Reco) throughout the season, suggesting possible microbial suppression. Soil temperatures were consistently lower in biochar-treated plots, likely due to shading and the insulating effect of the biochar. These results highlight the importance of application method and short-term trade-offs, particularly where biomass yield or rapid vegetation establishment are key economic drivers in paludiculture systems.

In addition to carbon fluxes, the potential water quality implications of biochar and gypsum amendments were assessed through a controlled mesocosm experiment funded by the Environment Agency. Biochar alone had no significant effect on solute concentrations compared to controls, although nitrate levels were elevated in some replicates during the early stages, with occasional exceedances of drinking water thresholds. This may reflect a temporary increase in soil oxygen availability following amendment, potentially enhancing nitrification.

Gypsum, tested for its potential to suppress methane emissions, showed clearer effects on water chemistry. While the 1 t/ha application rate had negligible impacts, the 10 t/ha rate significantly increased sulfate concentrations, with some values exceeding ecological and drinking water thresholds by factors of two to six. These increases were accompanied by reductions in dissolved organic carbon (DOC) and ammonium, and occasional increases in bromide. This suggests that high application risks may poses concerns for water quality.

Together, these findings illustrate both the promise and the complexity of integrating biochar into paludiculture systems. Theoretical modelling suggests that rewetted peat conditions could enhance the long-term carbon retention of lower stability biochars, offering the potential to reduce production costs and increase scalability. If supported by empirical evidence, this could make lower stability biochars more financially attractive for use in carbon credit schemes, provided that permanence, co-benefits and low environmental risks can be demonstrated.

2.2 Theoretical Modelling

Unlocking Carbon Removal Potential through Low-Stability Biochars

Introduction

Biochar is increasingly recognised for its potential to support carbon dioxide removal (CDR) due to its relative stability in soil systems. However, current CDR standards and carbon markets favour highly stable biochars produced at high pyrolysis temperatures, often above 600°C. While these biochars resist decomposition, their production sacrifices significant amounts of the original feedstock carbon and intensifies competition for biomass.

This creates a fundamental trade-off: greater biochar stability comes at the expense of lower carbon yield. Lower stability biochars, which are cheaper and more energy-efficient to produce, are typically excluded from CDR pathways due to concerns over decomposition. This modelling study explores whether rewetted peatlands, where saturated conditions suppress microbial activity, offer a viable environment for deploying lower stability biochars while maintaining or even improving long-term carbon retention.

Rationale

Rewetted peatlands are characterised by low oxygen availability, which limits microbial decomposition. If these conditions also suppress biochar degradation, then the need to rely exclusively on highly stable (and low-yield) biochars may be reduced. This could open the door to more scalable and cost-effective CDR pathways, provided the permanence of stored carbon can be demonstrated.

Key questions addressed in this study

- Can rewetted peat conditions increase the stability of biochars with inherently lower recalcitrance?
- How does the overall CDR potential compare between low- and high-stability biochars when deployed in saturated (representative of paludiculture conditions) vs. optimal decomposition environments?

Modelling Approach

We estimated 100-year biochar carbon retention (Fperm) across a range of biochar stabilities, defined by H/Corg molar ratios (a proxy for pyrolysis temperature). Data were extracted from Rodrigues et al. (2023), and decomposition rate modifiers from three biogeochemical models (ECOSSE, Daycent, and StandCarb) were applied to adjust these values to reflect saturated (rewetted) peatland conditions.

Decay rate constants (k) were then used to simulate exponential decay trajectories over 100 years, comparing retention of high-stability (H/Corg 0.1–0.2) and low-stability (H/Corg 0.6–0.7) biochars under rewetted vs. optimal conditions.

Additionally, we calculated CDR potential by incorporating both carbon retention and biochar yield (i.e. the proportion of feedstock carbon retained in the biochar). This allowed us to compare overall system efficiency.

Results

Figure 1 shows that rewetted peat conditions increased carbon retention by approximately 5% for highly stable biochars, and by up to 40% for lower stability biochars.

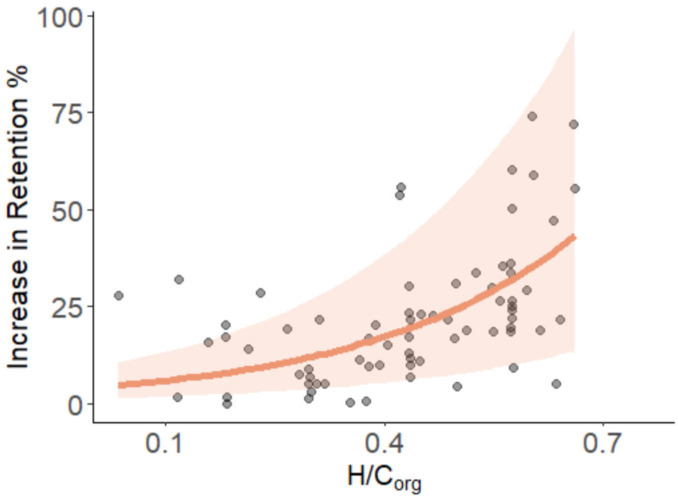

Figure 1: *Relationship between biochar H/C molar ratio (a proxy for biochar stability, high stability to the left and lower stability to the right) and the increase in biochar carbon retention over a 100-year period when applied to rewetted peat soils, compared to soils with optimal decomposition rates. The fitted exponential model (solid line) represents the predicted increase in retention, while the shaded area indicates the 95% confidence interval derived from bootstrapped model estimates.*

Figure 2 illustrates how decay trajectories diverge over time. Low stability biochars showed substantial losses in typical soil conditions but retained a significantly greater fraction of carbon when applied to rewetted peat.

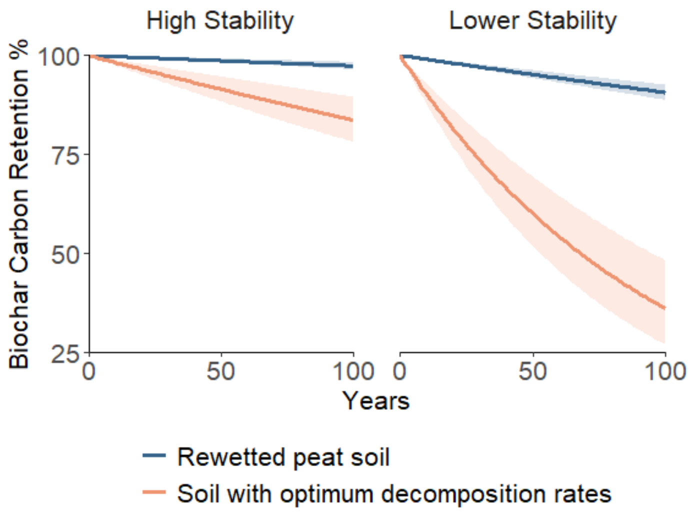

Figure 2*: Modelled decay of biochar carbon retention over 100 years in rewetted peat soils (blue) and soils with optimal decomposition rates (orange). The decay curves represent the fraction of biochar carbon retained over time with separate panels for biochars of high stability (H/C_{org} = 0.1-0.2) and lower stability (H/C_{org} = 0.6-0.7). Solid lines indicate the mean decay trajectory, while the shaded regions represent the 95% confidence intervals derived from the standard error of decay rates.*

Figure 3 demonstrates that the overall CDR potential was highest for low stability biochars applied to rewetted peatlands. In this scenario, a 33% increase in CDR efficiency was observed compared to deployment in well-aerated mineral soils.

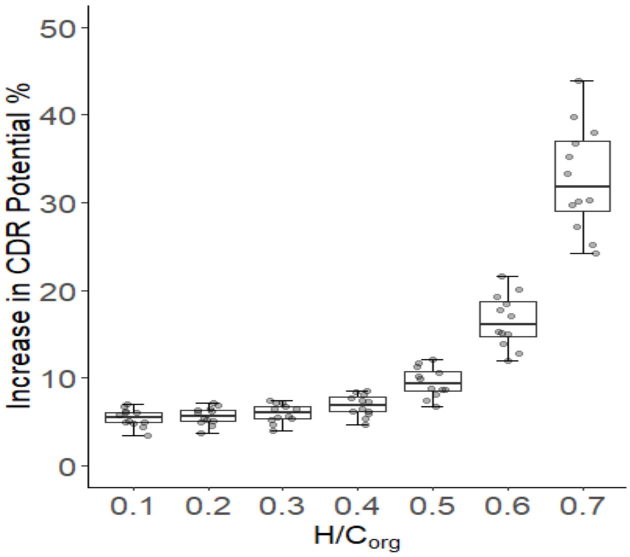

***Figure 3:** Increase in CDR potential (%) in rewetted peat soils relative to soils with optimal decomposition rates for a range of biochar H/C_{org} molar ratio categories. Boxplots illustrate the effective enhancement in biochar CDR. Each box represents the interquartile range (25th to 75th percentile), with the horizontal line inside the box indicating the median value. The error bars represent the 10th and 90th percentiles. Points represent individual data observations to demonstrate distributions.*

Conclusion

This modelling study suggests that rewetted peatlands offer a unique opportunity to deploy lower stability biochars in a way that enhances long-term carbon storage. By leveraging saturated conditions to suppress decomposition, this approach can improve the overall CDR efficiency of biochar while reducing biomass demand. This work has been prepared as a manuscript and is available upon request.

2.3 National Scale Litterbags Experiment

To better understand how biochar behaves under paludiculture conditions, a national-scale litterbag experiment was established across a diverse set of UK peatland sites. The aim was to assess how different types of biochar and organic materials decompose when applied to rewetted peat soils. This experiment provided insights into the persistence of biochar in saturated environments and its interactions with existing soil organic matter. By including both paludiculture and business-as-usual (drained) sites, the study captured variation in management practices that could influence decomposition. Results help to inform how biochars of different stabilities could contribute to long-term carbon storage when applied to soils under paludiculture.

Figure 4: Map of the sites used for the national litterbag experiment. Blue dots represent paludiculture sites only, and green dots represent paludiculture paired with business-as-usual site (drained peat).

Methods

To evaluate decomposition rates of biochar and organic matter in rewetted peat soils under different land management regimes, we conducted a litterbag experiment across 13 field sites representing a range of paludiculture and business-as-usual (BAU) conditions (Fig. 1). Of these, nine sites were under paludiculture only, while four also included adjacent BAU plots, site descriptions are available in the Appendix 1. Decomposition was assessed using mesh litterbags filled with biochar or organic material and buried in the topsoil.

Each bag was constructed from a fine mesh, folded in half and sealed on two sides by stitching and on the third side using adhesive. Final bag dimensions were 10 cm × 10 cm. Bags were oven-dried at 80 °C for 24 hours and weighed to four decimal places prior to burial.

Five treatments were tested: three types of biochar (low-, medium-, and high-grade) and two organic controls—loose-leaf tea and wood. Material particle sizes were <10 mm for tea, 5–10 mm for medium- and high-grade biochar, and 10–30 mm for low-grade biochar and wood. Each litterbag was tagged with a colour-coded zip tie to facilitate recovery in the field.

At each site, seven replicates per treatment were installed to enable destructive harvesting at multiple time points. Because litterbags cannot be reused once sampled, this allowed for sequential retrieval at four intervals (3, 6, 12, and 18 months) to assess mass loss over time as a proxy for decomposition. Litterbags were randomly buried horizontally at a depth of 10 cm and spaced 15 cm apart.

Additional litterbags for each treatment were prepared and retained to account for material losses during handling and transport. These reference bags were not buried but subjected to the same drying and weighing protocol, and average mass loss from these was incorporated into final calculations to correct for handling-related losses.

Following retrieval, litterbags were stored at 4 °C for up to one week, washed gently to remove debris, then dried at 80 °C for 24 hours and reweighed. In cases where root intrusion was observed, contents were emptied and roots manually removed prior to drying and weighing.

Mass loss was calculated as the difference between the initial dry weight and the final dry weight at each retrieval time point, with adjustments made for handling and transport loss based on the reference litterbags.

Site Environmental Conditions

To characterise environmental conditions that can influence decomposition, we continuously monitored soil and air temperature, soil volumetric water content, and water table depth at each site.

TOMST TMS-4 loggers (Wild et al., 2019) were installed at each site to measure soil temperature (10 cm below soil surface), volumetric soil moisture content and air temperature (15 cm above soil surface) Loggers were installed vertically in the topsoil following manufacturer guidelines to ensure consistent positioning across sites. Measurements were recorded at 15-minute intervals and downloaded periodically for processing. Raw data were cleaned and summarised using R package myClim (Man et al., 2023), , applying the peatland-specific calibration to estimate volumetric water content.

Water table depth was recorded using HOBO U20L-04 ® water level loggers installed within slotted PVC piezometers at each site. Loggers were deployed at least 50 cm below ground level and set to record pressure at hourly intervals. Barometric pressure data were required to correct water level readings for atmospheric effects. Where available, this was obtained from the UK Met Office or UKCEH flux towers located near the field sites.

Barometric compensation and water level calibration were performed using HOBOware® software. Final water table depths were calculated as the difference between the logger-recorded pressure and the corrected barometric pressure, relative to the ground surface.

Statistical Analysis

Statistical analyses were conducted in R (R version 4.4.2; (R Core Team, 2024). To evaluate the effects of peatland land use on the percentage mass loss of different litter types over time (biochars and orgaic materials), we fitted a mixed-effects model using the lme() function from the nlme package (Bates et al., 2018). Fixed effects included peatland land use (BAU vs Paludiculture), litter type, and their interaction, along with residence time as a covariate. A random intercept for site was included to account for repeated measures.

At present, site-level environmental data are incomplete and have not been included in the model. However, we plan to incorporate these variables in future analyses to better account for environmental variation across sites and to more robustly isolate treatment effects.

Because decomposition typically follows a non-linear decay curve, characterised by rapid initial mass loss followed by a slower phase, we applied a logarithmic transformation to the time variable (residence time in days). This transformation helped to linearise the relationship between residence time and mass loss, allowing the non-linear decay dynamics to be captured within a linear model framework.

Predicted values with confidence intervals were generated from the fitted mixed-effects model using the predictSE() function from the merTools package (Frederick, 2019). Predictions were made for the original dataset to visualise fitted mass loss trajectories across litter types and land use types over time. Confidence intervals (±1.96 × SE) were calculated to represent the 95% uncertainty bounds around the predicted means. These predictions were plotted alongside the observed data to visually assess model fit and treatment effects

Model assumptions were verified through graphical inspection of residuals (residuals vs fitted values, Q–Q plots) and assessment of leverage and influence using Cook's distance. Fixed effect significance was assessed using Type III ANOVA. To aid interpretation of interaction effects, estimated marginal means were calculated using the emmeans package (Lenth R, 2025). Pairwise comparisons were conducted (1) between biochar types within each land use, and (2) between land use within each biochar types. Bonferroni-adjusted p-values were also reported for sensitivity analysis. All statistical summaries and visualisations were produced using flextable (Gohel D, 2024) and ggplot2 (Wickham H, 2016).

Results

The linear mixed model revealed significant main effects of land use ($F = 10.97$, $p = 0.0011$), litter type ($F = 154.92$, $p < 0.001$), and their interaction ($F = 4.32$, $p = 0.0022$; Table 1). These results indicate that the response to land use (BAU vs Paludiculture) varies depending on litter type, which is supported by both the statistical comparisons and the visual trends shown in Figure 1.

Figure 5 illustrates the predicted and observed mass loss over time for each litter type under BAU and paludiculture conditions. Biochar treatments (Low, Medium, and High Stability) generally exhibited low overall mass loss with no significant difference between land use type (Figure 1 and Table 1). In contrast, Tea and Wood litters had much higher mass loss, with visibly greater losses under BAU than paludiculture conditions. These trends are statistically supported by the pairwise comparisons between land use within each litter type, which showed significant differences for Wood ($p = 0.0005$) and Tea ($p = 0.0002$) only (Table 3).

Furthermore, comparisons within each land use showed a consistent hierarchy among litter types. Tea litter consistently exhibited the highest mass loss under both BAU and paludiculture conditions ($p < 0.001$), followed by Wood, and then the biochar-based litters. Among the biochar treatments, the high stability biochar generally exhibited greater mass loss than both the medium and low stability types, although these differences were not always statistically significant (Table 1). Notably, differences between low and high stability biochars were observed under both BAU and paludiculture conditions, while differences between medium and high stability biochars were evident under paludiculture alone.

*Table 1. Results of Type III ANOVA from the linear mixed-effects model evaluating the effects of land use (BAU vs. Paludiculture), litter type, and their interaction on percentage mass loss. The model includes log-transformed residence time as a covariate and a random intercept for site. Significant effects are indicated by p-values and significance codes (p < 0.05 = *, p < 0.01 = **, p < 0.001 = ***).*

Effect	DF	Error term	F-value	p-value	Significance
(Intercept)	1	228	154	0.0000	***
Land use	1	228	11	0.0011	**
Litter type	4	228	155	0.0000	***
Log Days	1	228	58	0.0000	***
Land use X Litter type	4	228	4	0.0022	**

Table 2: Estimated marginal means (EMMs) for each litter type under BAU and Paludi management systems. EMMs are model-derived means with associated standard errors and 95% confidence intervals, providing a numerical summary of the interaction effects.

Land Use	Litter Type	emmean	SE	df	lower.CL	upper.CL
BAU	Low Stability	4.75	2.54	8	-1.11	10.61
Paludi		5.77	1.90	8	1.38	10.15
BAU	Medium Stability	9.67	2.43	8	4.07	15.26
Paludi		6.86	1.85	8	2.60	11.12
BAU	High Stability	14.43	2.43	8	8.84	20.03
Paludi		15.51	1.85	8	11.25	19.77
BAU	Wood	20.99	2.38	8	15.51	26.48
Paludi		12.31	1.85	8	8.04	16.58
BAU	Tea	46.90	2.43	8	41.30	52.49
Paludi		37.57	1.83	8	33.34	41.79

*Table 3: Pairwise comparisons of estimated marginal means between BAU and Paludi land use within each litter type. Values are based on linear mixed model contrasts, including estimates, standard errors, t-ratios, and p-values. Significance levels are indicated as follows: ***p < 0.001, **p < 0.01, p < 0.05.*

Contrast	Litter Type	estimate	SE	df	t.ratio	p.value	Significance
BAU - Paludi	Low Stability	-1.02	2.64	228	-0.39	0.7005	
BAU - Paludi	Medium Stability	2.81	2.48	228	1.13	0.2597	
BAU - Paludi	High Stability	-1.08	2.49	228	-0.43	0.6656	
BAU - Paludi	Wood	8.68	2.46	228	3.53	0.0005	***
BAU - Paludi	Tea	9.33	2.48	228	3.77	0.0002	***

Table 4: Pairwise comparisons of estimated marginal means between litter types within each land use. Values are based on linear mixed model contrasts, including estimates, standard errors, t-ratios, and p-values. Significance levels are indicated as follows: ***p < 0.001, **p < 0.01, p < 0.05.

Contrast	Land Use	estimate	SE	df	t.ratio	p.value	Significance
Low Stability - Medium Stability	BAU	-4.92	2.91	228	-1.69	0.4430	
Low Stability - High Stability	BAU	-9.68	2.91	228	-3.32	0.0091	**
Low Stability - Wood	BAU	-16.24	2.87	228	-5.65	0.0000	***
Low Stability - Tea	BAU	-42.15	2.91	228	-14.47	0.0000	***
Medium Stability - High Stability	BAU	-4.76	2.81	228	-1.69	0.4398	
Medium Stability - Wood	BAU	-11.32	2.77	228	-4.09	0.0006	***
Medium Stability - Tea	BAU	-37.23	2.81	228	-13.24	0.0000	***
High Stability - Wood	BAU	-6.56	2.77	228	-2.37	0.1284	
High Stability - Tea	BAU	-32.46	2.81	228	-11.54	0.0000	***
Wood - Tea	BAU	-25.90	2.77	228	-9.34	0.0000	***
Low Stability - Medium Stability	Paludi	-1.09	1.98	228	-0.55	0.9815	
Low Stability - High Stability	Paludi	-9.74	1.98	228	-4.92	0.0000	***
Low Stability - Wood	Paludi	-6.55	2.00	228	-3.28	0.0106	*
Low Stability - Tea	Paludi	-31.80	1.97	228	-16.18	0.0000	***
Medium Stability - High Stability	Paludi	-8.65	1.93	228	-4.48	0.0001	***
Medium Stability - Wood	Paludi	-5.45	1.94	228	-2.81	0.0424	*
Medium Stability - Tea	Paludi	-30.71	1.92	228	-16.01	0.0000	***
High Stability - Wood	Paludi	3.20	1.94	228	1.65	0.4674	
High Stability - Tea	Paludi	-22.06	1.92	228	-11.51	0.0000	***
Wood - Tea	Paludi	-25.25	1.92	228	-13.12	0.0000	***

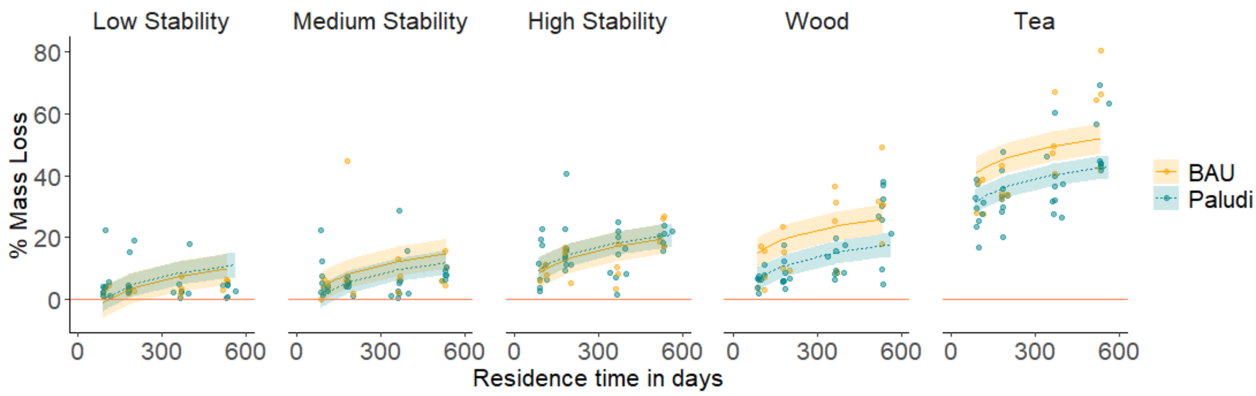

Figure 5: Predicted and observed percentage mass loss of litter types over time under business-as-usual (BAU) and paludiculture conditions for each litter type treatment. Lines represent modelled predictions with 95% confidence intervals (shaded areas), while points show observed values. Low, medium and high stability treatments refer to biochar.

Discussion

This study set out to assess how biochar and organic materials decompose in rewetted peatland systems compared with drained, business-as-usual (BAU) conditions. Our main goal was to determine whether lower-grade biochars could achieve similar persistence to higher-stability biochars under paludiculture, potentially expanding the range of viable materials that offer higher net carbon removals.

1. Decomposition is strongly influenced by land use

   As expected, decomposition rates were consistently higher in BAU (drained) plots compared to paludiculture (rewetted) sites for the labile litters, wood and tea. These results reinforce the established understanding that rewetting inhibits peat loss through oxidative decomposition.

2. Biochar stability did not differ by land use—though long-term effects of rewetting may still emerge

   Across all three biochars, mass loss did not differ significantly between BAU and paludiculture sites. This suggests that, at least within the first 18 months, rewetting alone did not confer additional stability to the biochars.

   However, the marked reduction in decomposition rates for tea and wood confirms that rewetting is suppressing decay processes. Given that biochars decompose more slowly than labile organic matter, it is plausible that the stabilising effect of rewetting simply has not yet had time to influence detectable differences in mass loss. In this context, the lack of divergence between land uses for biochar does not undermine the potential of paludiculture to enhance biochar persistence. It suggests instead that longer-term monitoring is needed to detect any such effect.

Biochar type strongly influenced mass loss, with high-stability biochar unexpectedly losing more mass

While differences between land uses were minimal, differences between biochar types were more pronounced. In both BAU and paludiculture plots, the high-stability biochar generally exhibited greater mass loss than the low- and medium-stability types. This was unexpected given its higher fixed carbon content and lower H/C ratio.

One explanation may lie in the physical properties of the high-stability biochar. Its finer particle size and higher dust content may have increased its vulnerability to loss through leaching or handling, despite corrections using reference bags. This highlights the importance of considering not just chemical stability but also physical form when selecting biochars for field applications. A new experiment has commenced to test the impact of volume-to-surface-area

2.4 Winmarleigh – Sphagnum Carbon Farm

Executive Summary

This study evaluated the short-term effects of surface-applied biochar on carbon dynamics in a rewetted lowland peatland managed under paludiculture. Biochar, produced at either high or low pyrolysis temperatures, was applied to peat soils under sphagnum paludiculture farming previously drained for agriculture.

Key findings

Vegetation Response: Immediately following application, both high and low stability biochar suppressed carbon uptake, likely due to shading of the moss layer inhibiting the plant's ability to photosynthesise. Vegetation began to recover within months, particularly in plots with high stability biochar.

Carbon Fluxes: Surface-applied biochar initially reduced carbon uptake, with both high and low stability biochars significantly suppressing Gross Primary Productivity (GPP) in the early growing season. This likely reflects physical shading of the moss layer, which limited photosynthesis. Low stability biochar also reduced ecosystem respiration (Reco), indicating short-term microbial suppression, while Reco later increased under high stability biochar, possibly due to delayed microbial activity. Although Net Ecosystem Exchange (NEE) showed reduced carbon uptake shortly after application, it recovered within 6 months. This suggests that short-term reductions in CO_2 uptake may be balanced by the long-term carbon storage introduced through biochar application.

Soil Microclimate: Biochar lowered soil temperatures, likely due to surface shading and the insulating effect of porous biochar materials.

Management Implications: While biochar can contribute to long-term carbon storage, surface application may temporarily reduce productivity in low-growing vegetation. Application methods should be carefully considered in paludiculture systems to avoid short-term trade-offs.

These results provide early insights into the interactions between biochar, vegetation, and carbon cycling in rewetted peatlands, supporting more informed decision-making around its use in paludiculture and carbon paludiculture and carbon removals.

Methodology

Study Site Description

Winmarleigh is a lowland raised peat bog that was drained and converted to farmland in the 1970s, located in the North West of England . In 2020, the site was rewetted to transition from conventional grassland for grazing to a paludiculture-based carbon farming model planted with *Sphagnum* to restore peat-forming vegetation (Figure 6).

Figure 6. Rewetted paludiculture site at Winmarleigh Carbon Farm (link).

Experimental design

The experiment took place in a hydrologically controlled cell which were dominated by *Polytrichum* mosses. We used a randomised split-plot design to assess the impacts of biochar on a rewetted peatland, examining both potential ecosystem responses and biochar stability over time. The experiment consisted of four replicate blocks, each containing three treatments: control (no biochar application; n=4), high stability biochar (20 t ha^{-1} of wood feedstock combusted above 600°C; n=4) and lower stability biochar (20 t ha^{-1} of wood feedstock produced at <500°C; n=4). Each plot measured 1.5m X 1.5 and was established in January 2024, with a 1 m buffer separating adjacent plots within a block. Biochar was carefully surface applied by hand to the peat surface on March 11th, 2024, at a rate of 20t ha for each biochar type. Automated Eosense chambers were installed at the centre of each plot to allow for greenhouse gas measurements of CO_2 and CH_4 (Figure 7).

Figure 7: Automated Eosense chambers used to measure CO_2 and CH_4 fluxes.

Flux measurements

Surface CO_2 soil fluxes were continuously measured using an automated chamber system. This system comprised twelve transparent automated gas flux chambers (eosAC-LT, Eosense, Dartmouth, NS, Canada) connected to a multiplexer (eosMX, Eosense, Dartmouth, NS, Canada), which allowed sequential chamber sampling for analysis via a wavelength-scanned cavity ring-down spectrometer (Picarro G4301, Santa Clara, CA, USA).

Gross Primary Productivity (GPP), Ecosystem Respiration (Reco), and Net Ecosystem Exchange (NEE) were modelled using high-frequency CO_2 flux measurements. Briefly, Reco represents the total CO_2 efflux coming from both autotrophic and heterotrophic respiration processes, NEE is the net CO_2 flux of respiration processes and photosynthetic uptakes between the ecosystem and the atmosphere (i.e. the observed measured CO_2 fluxes), while GPP reflects the gross CO_2 assimilation by photosynthetic organisms.

To estimate Reco and GPP, high-frequency CO_2 flux data were aligned with environmental variables, including air temperature and photosynthetic active radiation (PAR). Sunrise and sunset times were computed based on the study site's geographical coordinates (latitude: 53.924081, longitude: -2.850314) in order to facilitate the classification of data into daytime and nighttime periods, essential for the accurate partitioning of NEE into its component fluxes.

On this basis, to estimate Reco nighttime CO_2 fluxes, the data were first filtered to nighttime periods only as photosynthetic activity ceases in the absence of light and thus ensuring that only respiration is considered. Nighttime periods were identified based on solar position, specifically considering times when PAR was zero or negligible. Only CO_2 flux measurements above 0.04 mg CO_2 m^{-2} h^{-1} were selected in this step to ensure data quality. Reco was estimated with the Lloyd Taylor function (Lloyd & Taylor, 1994):

$$Reco = R_{10} \times \exp\left((E_o \times \left(\frac{1}{T_{ref} - T_o} - \frac{1}{T - T_o}\right)\right)$$

where R_{10} is the respiration rate at the reference temperature T_{ref} (10 ºC), E_o is an activation energy parameter, T_o is a constant (-46.02 ºC), and T represents the ambient air temperature.

The Reco model was fitted separately for each treatment to account for potential differences in respiration responses. The same model was also employed to predict daytime Reco using corresponding air temperatures and under the assumption that the temperature dependence of respiration is consistent across diurnal cycles.

The NEE is basically represented by our directly measured CO_2 fluxes, where positive values indicate net CO_2 release to the atmosphere, and negative values indicate net uptake by the ecosystem. In this sense, GPP was finally calculated as the difference between Reco and NEE.

$$GPP = Reco - NEE$$

Additional site measurements

To enable gas flux calculations and to ensure that paludiculture conditions were maintained throughout the experiment, environmental variables were monitored continuously. These included photosynthetically active radiation (PAR), soil temperature, soil volumetric water content, and water level. The site remained consistently wet over the measurement period, with an average water level of -0.19 ± 0.01 (mean daily mean ± s.e.) relative to the soil surface from 7 March to 31 December 2024.

Statistical analyses

For CO_2 fluxes, prior to any modelling analyses, the data was assessed for normality using visual inspection of histograms, Q-Q plots, and formal tests, including the Shapiro-Wilk and Kolmogorov-Smirnov tests. Temporal autocorrelation and heterogeneity were also tested through the autocorrelation function (ACF) and via a likelihood ratio test (LRT) comparing the null model (an intercept-only model) and the additional, nested model containing a random effect associated with Block/Plot. Since both (temporal autocorrelation and heterogeneity) were confirmed, linear mixed-effects models (LME) were fitted on CO_2 fluxes using the nlme package and correlation structure functions (Pinheiro. et al., 2018). The data were either logarithmic or square root transformed and subsequently used for further analyses when data were found to be not normally distributed.

To evaluate the effects of treatment (Control – No Biochar; High Stability Biochar; Low Stability Biochar), season (Early Growing Season *vs*. Late Growing Season), Time (i.e. changes over time), potential environmental variables (Water Table Depth and Soil Moisture), as well as relevant interactions, on CO_2 fluxes, a series of candidate models were first constructed to compare different fixed-effect structures. For all model structures random effects were always specified as a nested structure (Block/Plot) to account for repeated measures within blocks and individual chambers. Model comparisons were fitted using maximum likelihood (ML) estimation to allow for model comparisons. To account for temporal autocorrelation in repeated measures, models incorporating an autoregressive correlation structure (corAR1) and an exponential correlation structure (corExp) were also formally tested. Model selection was based on Akaike Information Criterion (AIC), LRT tests, and assessment of residual diagnostics. Among the candidate models, those including temporal autocorrelation (corAR1 and corExp) improved model fit compared to models without correlation structures, highlighting the need for accounting for temporal autocorrelation.

The final best selected model for CO_2 fluxes included Treatment, Season, Time, and their interactions, as fixed effects, a random intercept for Block/Plot, and an exponential correlation structure for temporal autocorrelation. Model assumptions were verified by inspecting Q-Q plots and residual histograms for normality, as well as residual-vs-fitted plots for homoscedasticity. Final model validation was performed through autocorrelation function (ACF) plots to confirm adequate handling of temporal dependency.

For environmental data specifically, Generalised Additive Mixed Models (GAMMs) were used with repeated measures using *mgcv* (Wood, 2023). Hourly means were calculated for PAR, soil temperature, and soil moisture. For each environmental variable, Julian day of year and time of day were included as a non-linear random factor (spline). To determine if biochar application affected soil temperature and moisture, repeated measures GAMMs also included biochar treatment as a fixed effect. To determine if there were differences in water level between block, repeated measures GAMMs also included block as a fixed effect.

All statistical analyses were conducted in R programming language version 4.4.1 (R Core Team, 2024) and the additional packages, lme4 (Bates et al., 2015), MuMIn (Barton, 2019), car (Fox & Weisberg, 2019), emmeans (Lenth, 2021), ggplot2 (Wickham, 2009), myClim (Man et al., 2023), and mgcv (Wood, 2023) using an alpha level of 0.05 for significance determination.

Results

Vegetation cover

Surface application of biochar initially covered the vegetation in the biochar treated plots. *Polytrichum* mosses and vascular plants colonised and grew through the biochar over the course of growing season ~ 6 months (Figure 8; observation). The images show a series of chambers used for gas flux measurements in the experiment. From a visual assessment, it is possible to observe varying degrees of moss cover under different biochar treatments. In general, chambers without biochar (top left and bottom left) appear to support a more uniform and dense moss cover, with minimal disturbance to the natural vegetation. In contrast, chambers with biochar amendments (middle and right columns) show a clear difference in vegetation growth. The mosses in these plots are growing alongside biochar particles, with some areas displaying limited moss growth compared to the untreated control. In particular, the plots with biochar appear to have a more heterogeneous distribution of moss cover, with some areas where moss has grown up and around the biochar, while in other areas the substrate is still exposed. This could suggest that biochar application initially altered the microenvironment, potentially affecting moss establishment or growth. Moss cover did not change in low stability biochar plots between June and October 2024 ($t(18) = -1.05$, $p = 0.895$). While moss cover increased in high stability biochar treated plots over the same period ($t(18) = -5.28$, $p = 0.001$) from mean cover of 18.5% to 52.5%. However, these figures do not reflect changes from the time of biochar application, when moss cover was visually absent across all treatments. The observed increase suggests that mosses were growing up through the biochar-amended soil, indicating adaptation to the altered conditions over time.

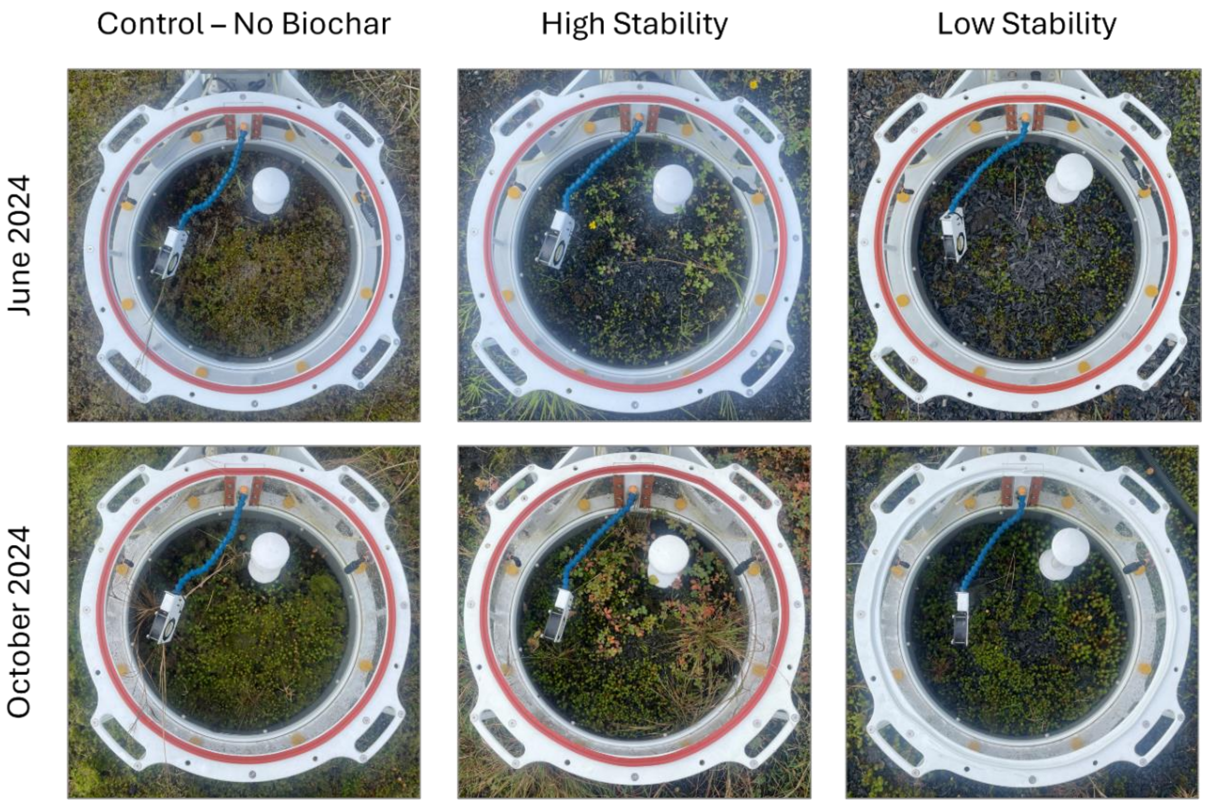

Figure 8: *Vegetation communities in chambers on 11 June 2024 and 17 October 2024.*

CO_2 fluxes

Calculated GPP showed distinctive seasonal and treatment-dependent patterns (Figures 9 and 10). In the early growing season, following biochar application (dashed vertical line; Figure 9) in the biochar treatment plots, the control (no-biochar) treatment displayed a marked and consistent increase in GPP, while both high and low biochar stability treatments showed lower and relatively stable GPP levels (Figure 9). In contrast, in the late growing season, all treatments showed greater variability in GPP, and the observed treatment differences became less evident (Figure 9). In general, Linear mixed-effects modelling confirmed that both high and low biochar stability treatments significantly reduced GPP relative to the control (LRT = 16.71; p = 0.01), by approximately 20% and 36%, respectively, over the entire measurement period. Additionally, the GPP was significantly higher in the late growing season by approximately 11% compared to the early growing season (LRT = 55.57; p = <0.01). The statistical analysis also revealed a strong interactive effect between treatment and season (LRT = 105.33; p = <0.01) indicating that the treatment effect on GPP is season dependent (Figure 10). Specifically, the control treatment (i.e. no biochar application) showed a significant ~72% decrease in GPP from the early to late growing season, whereas the biochar treatments showed increases of 68% (high stability) and 52% (low stability). This pattern was largely an artefact of the reduced GPP following treatment application in the early growing season. The shift was particularly evident in the high stability biochar treatment, which showed the greatest increase in GPP from the early to late season (68%, Figure 10). In line with this, the significant temporal effect suggested a slight but consistent decline trend in GPP over time under control treatment, while biochar treatments show a slight increase in GPP (LRT = 41.82; p = <0.01, Figures 9 and 10).

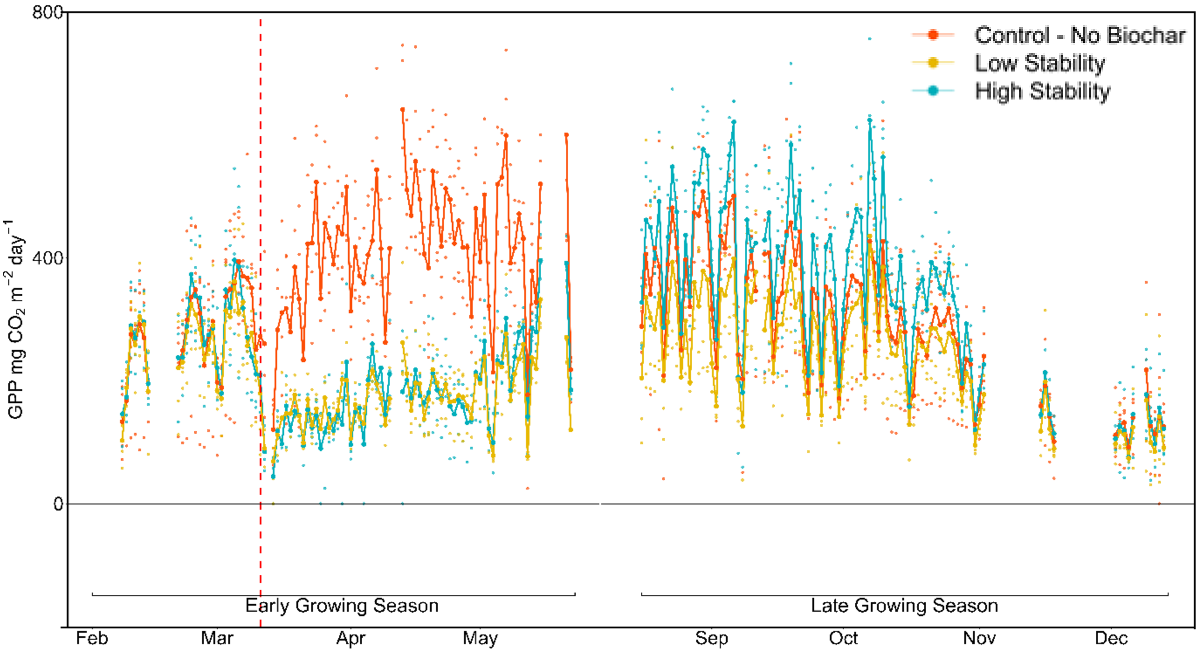

Figure 9: Seasonal variations in Gross Primary Productivity (GPP) under different biochar treatments over time. The red, blue, and yellow points and lines represent the control (no-biochar), high stability biochar, and low stability biochar treatments, respectively. Points show daily mean calculated GPP values per block (n=4 for each treatment per day), while lines represent the mean GPP per day for each treatment. The dashed vertical red line indicates the day of biochar application in the treated plots (March 11, 2024). For clarity, the y-axis is truncated at 800 mg CO_2 m^{-2} day^{-1}, with few extreme values above this threshold excluded.

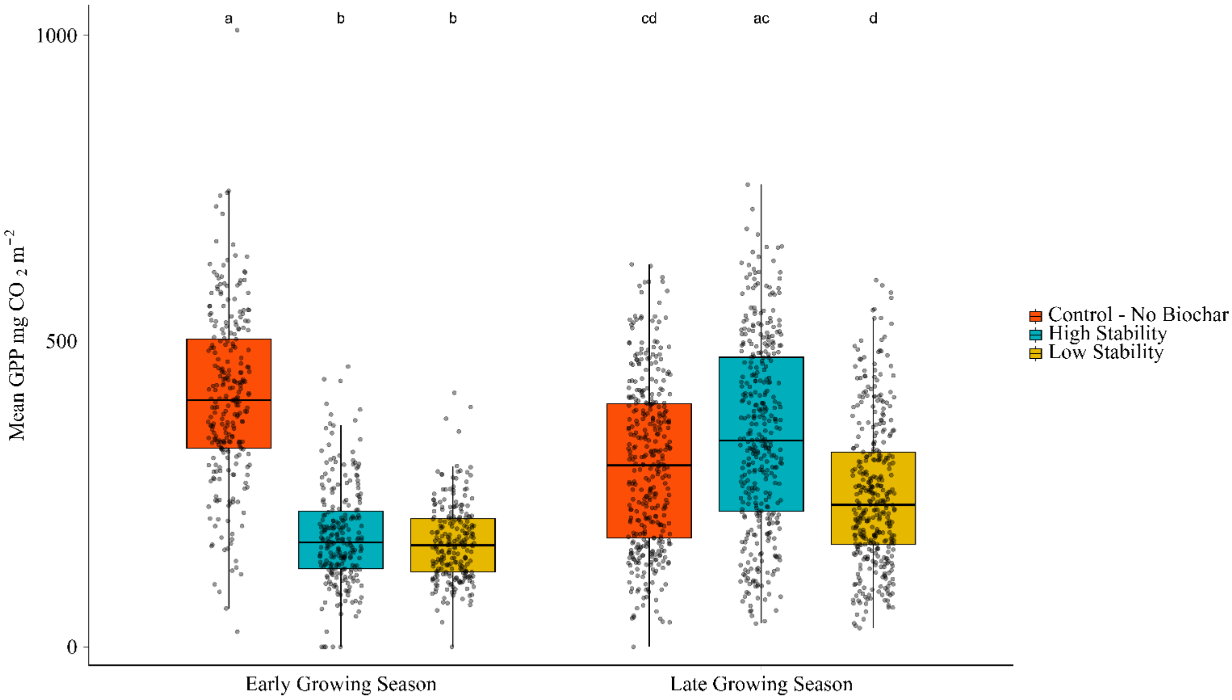

***Figure 10**: Effect of biochar treatment (no-biochar, high stability biochar and low stability biochar) and season (early growing season vs. late growing season) on Gross Primary Productivity (GPP). Boxplots* show the distribution of GPP (mg CO_2 m^{-2}) for each treatment and season. Points represent individual daily mean measured values, and letters above boxplots indicate statistical significance (P<0.05).

As observed for GPP, the modelled Reco results also showed a distinctive seasonal and treatment-dependent pattern (Figures 11 and 12). In general, during the early growing season, Reco increased gradually across all treatments, with a clear treatment effect particularly emerging towards the end of the season. The late growing season was characterised by a higher initial Reco across all treatments compared to the end of the early growing season, followed by a declining trend toward the end of the measurement period (Figure 11). Despite these observed patterns, and in contrast to the GPP results, no significant interaction was detected between treatment and season (LRT = 1.79; p = 0.41). However, linear mixed-effects modelling, confirmed significant main effects of treatment (LRT = 8.89; p = 0.02), season (LRT = 46.97; p <0.01), and time (LRT = 28.42; p <0.01) on Reco. Specifically, in the early growing season, the low stability biochar treatment significantly reduced Reco by 21% relative to the control, whereas the high stability biochar treatment did not differ significantly from the control (Figure 12). In the late growing season, the high stability biochar treatment showed a marginally significant increase in Reco (11%) compared to the control (p = 0.04), while the low stability biochar treatment showed no significant difference relative to the control (p = 0.26, Figure 12). Similar to the GPP results, Reco was significantly higher in the late growing season, increasing by 11% Reco compared to the early growing season. However, in this case, the seasonal effect was further influenced by time (Season × Time: LRT = 250.23; p < 0.01), highlighting the declining trend in Reco over time during the late growing season (Figure 12).

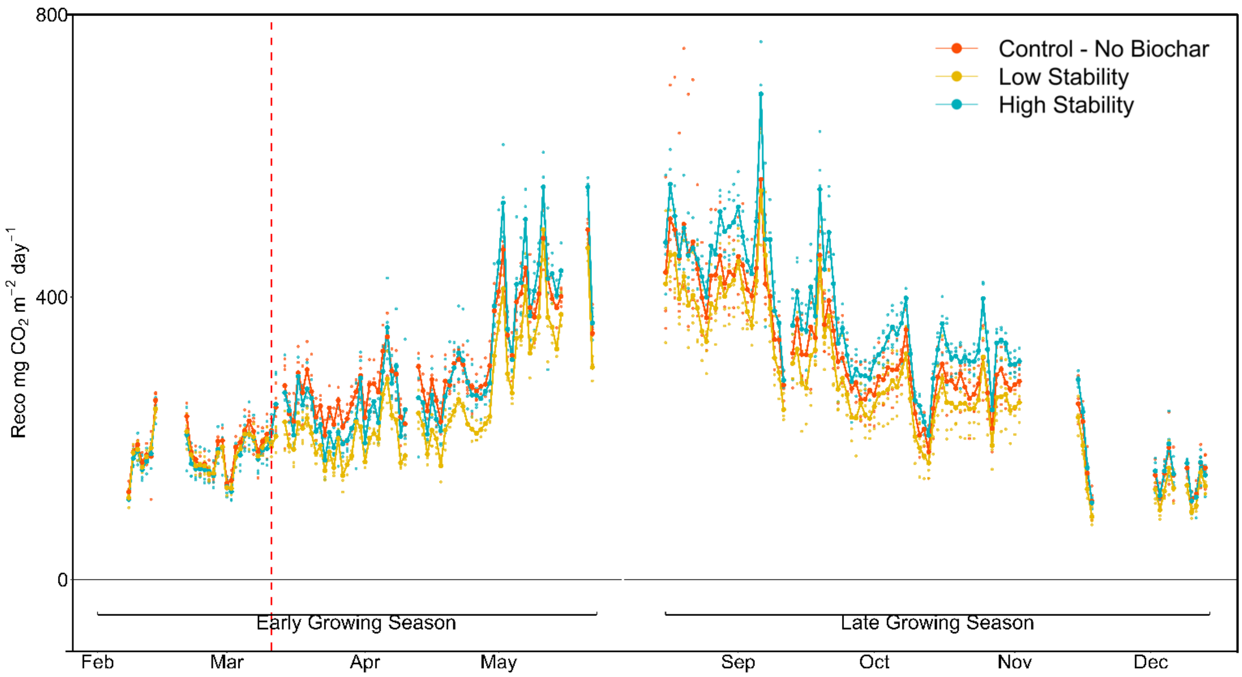

Figure 11: Seasonal variations in Ecosystem Respiration (Reco) under different biochar treatments over time. The red, blue, and yellow points and lines represent the control (no-biochar), high stability biochar, and low stability biochar treatments, respectively. Points show daily mean modelled Reco values per block (n=4 for each treatment per day), while lines represent the mean Reco per day for each treatment. The dashed vertical red line indicates the day of biochar application in the treated plots (March 11, 2024).

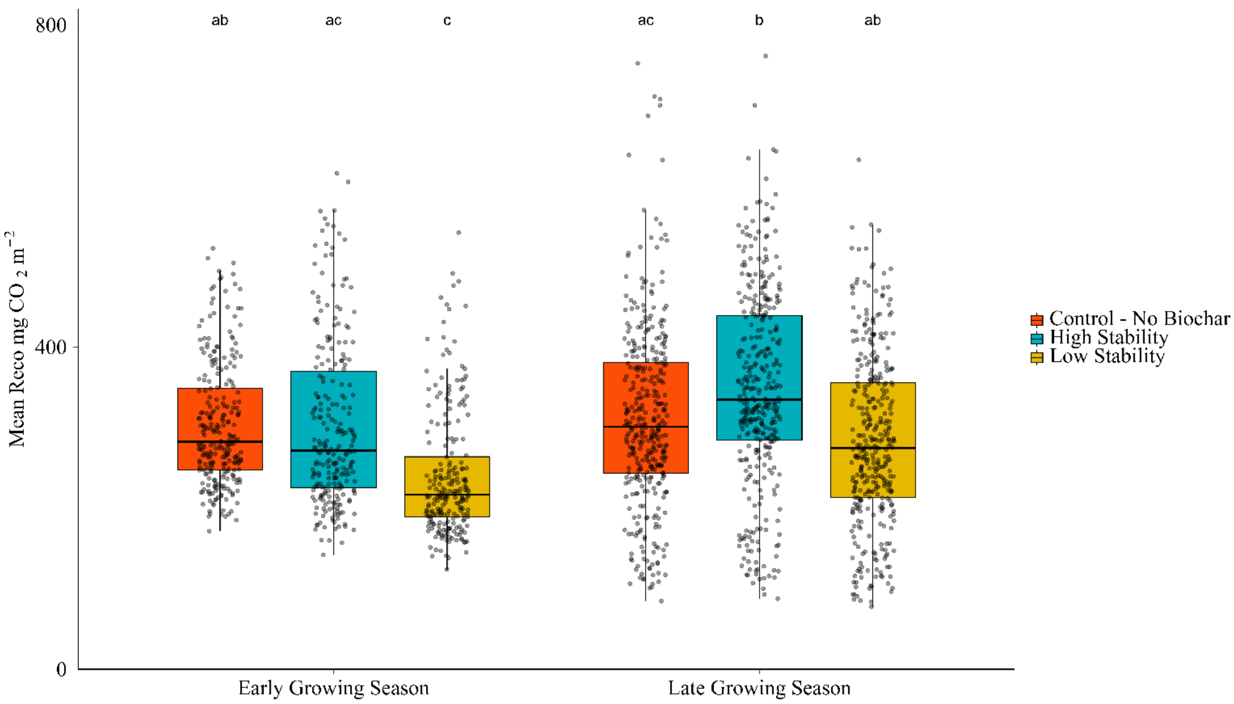

Figure 12: Effect of biochar treatment (no-biochar, high stability biochar and low stability biochar) and season (early growing season vs. late growing season) on Ecosystem Respiration (Reco). Boxplots show the distribution of Reco (mg CO_2 m $^{-2}$) for each treatment and season. Points represent individual daily mean measured values, and letters above boxplots indicate statistical significance ($P<0.05$).

Regarding NEE, statistical findings revealed a strong main effect of treatment on NEE (LRT = 16.06; p = <0.01) and a marginal effect of time (LRT = 3.73; p = 0.05), whereas the overall difference between early and late growing seasons was not significant (LRT = 1.88; p = 0.17). However, significant interaction effects were observed between treatment and season (LRT = 38.37; p = <0.01), and between treatment and time (LRT = 56.59; p = <0.01), suggesting that the influence of biochar on NEE was highly dynamic and dependent on biochar application along with seasonal and temporal contexts (Figure 14). By late season, the control's NEE increased by ~102%, shifting NEE from -105.50 to 1.94 mg CO_2 m^{-2}, while the high stability treatment's NEE declined by ~100%, dropping from 119.59 to 0.29 mg CO_2 m^{-2}. The low stability treatment's NEE remained relatively stable, despite an observed ~40% decrease from 59.61 to 35.85 mg CO_2 m^{-2} between the early and late growing seasons Figure 14. This pattern reflects the artefactual influence of GPP responses immediately following application (Figure 9). Additionally, *Figure 13* also indicates a slight decline in NEE over time for both high and low stability treatments, whereas the control's NEE consistently increased.

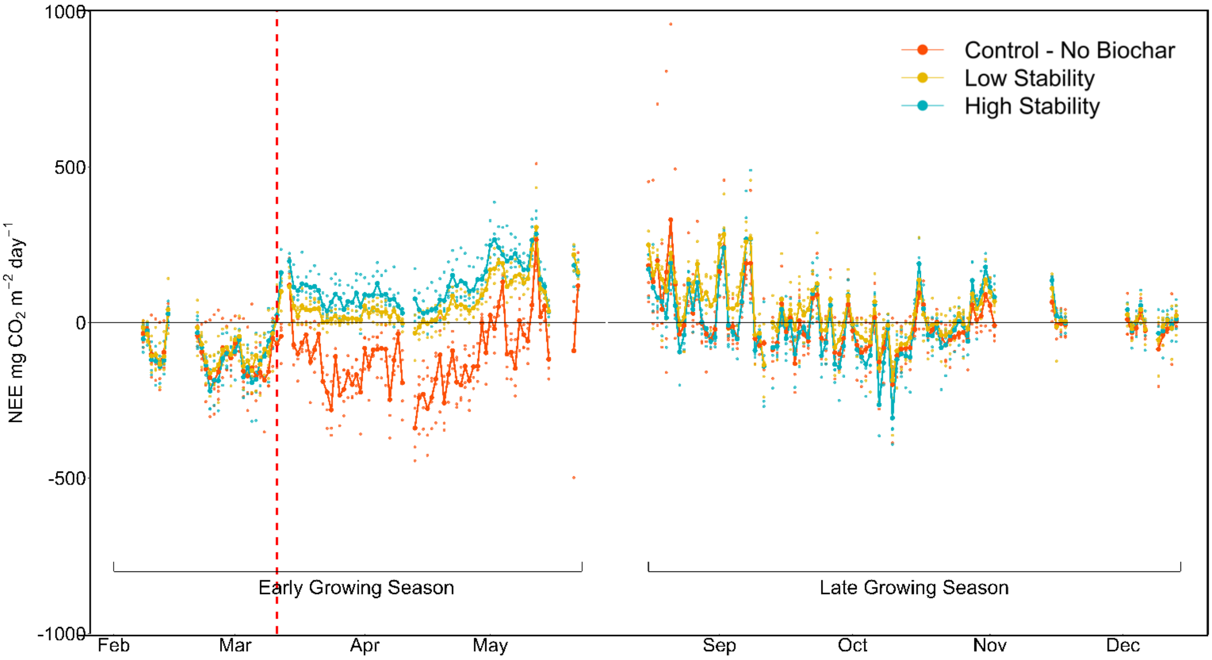

Figure 13: *Seasonal variations on mean measured Net Ecosystem Exchange (NEE) under different biochar treatments over time. The red, blue, and yellow points and lines represent the control (no-biochar), high stability biochar, and low stability biochar treatments, respectively. Points show daily mean measured NEE values per block (n=4 for each treatment per day), while lines represent the mean Reco per day for each treatment. The dashed vertical red line indicates the day of biochar application in the treated plots (March 11, 2024).*

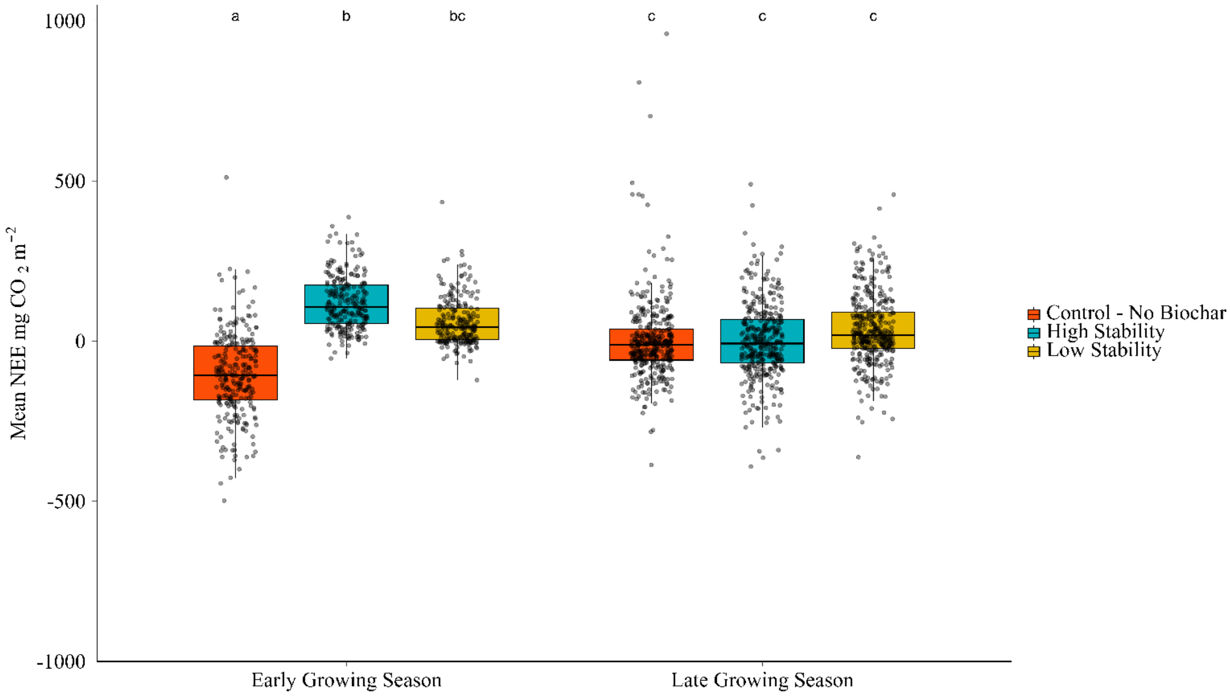

Figure 14: *Effect of biochar treatment (no-biochar, high stability biochar and low stability biochar) and season (early growing season vs. late growing season) on mean measured Net Ecosystem Exchange (NEE). Boxplots show the distribution of NEE (mg CO_2 m^{-2}) for each treatment and season. Points represent individual daily mean measured values, and letters above boxplots indicate statistical significance ($P<0.05$).*

Soil Properties

Soil temperature varied with date and time; soil temperature increased during the summer (Figure 15; $F = 63255$, $p < 0.001$) and afternoon ($F = 890.6$, $p < 0.001$). Soil temperature was marginally greater under the control treatment than either high or low biochar stability treatments ($F = 373.7$, $p < 0.001$).

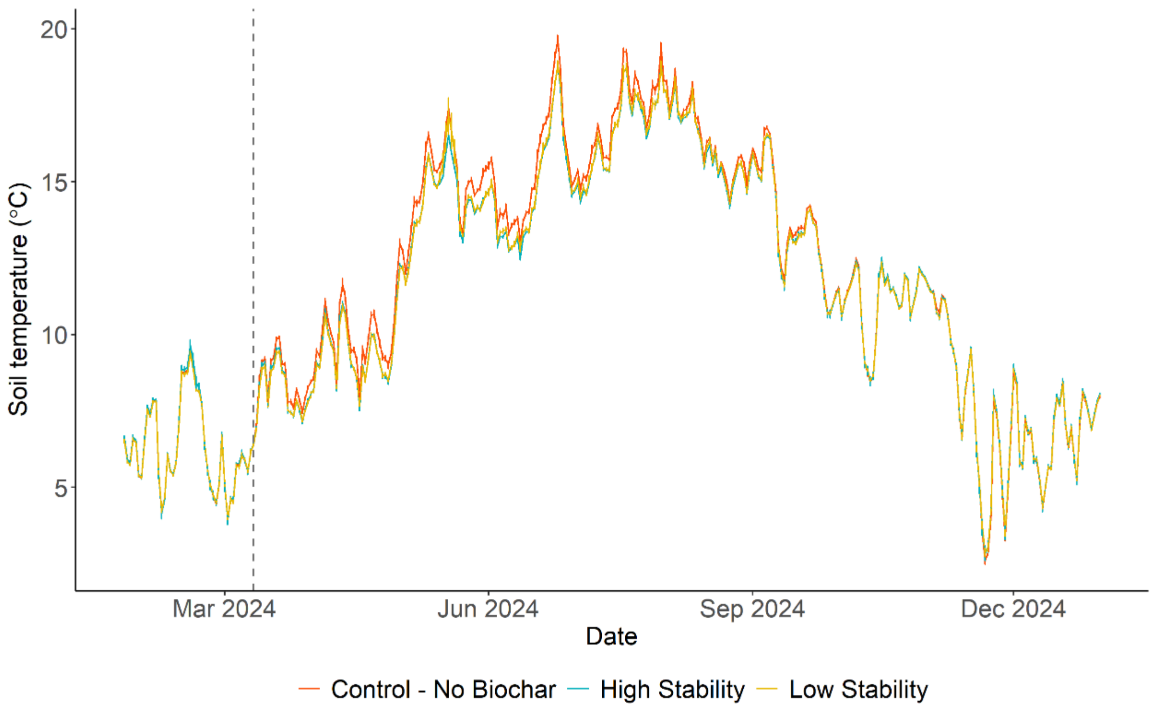

Figure 15: *Soil temperature at 8 cm depth. Data show control - no biochar application (red), high stability biochar application (blue), and low stability biochar application (yellow) plots. Vertical dashed line represents the biochar application on 11 March 20*

Discussion

This study set out to assess how surface-applied biochar influences carbon dynamics and soil properties in a rewetted lowland peatland under paludiculture management. By comparing high and low grade biochars, which differ in pyrolysis temperature and presumed stability, we aimed to understand whether their properties differentially affected CO_2 fluxes, particularly gross primary productivity (GPP), ecosystem respiration (Reco), and net ecosystem exchange (NEE). While the experiment also served as an initial test of the hypothesis that low grade biochar may remain stable under saturated, oxygen-limited conditions, the design was primarily intended to evaluate short-term impacts on carbon dynamics, the soil microclimate and effects on the vegetation. Methane emissions were also measured, they will be reported in the next iteration of this report.

Biochar impacts on vegetation and carbon dynamics

Our findings indicate that surface application of biochar can strongly influence short-term carbon dynamics in rewetted peatland systems, particularly those managed for *Sphagnum* based paludiculture. In the early growing season, both high and low stability biochar treatments showed reduced gross primary productivity (GPP) and more positive net ecosystem exchange (NEE) compared to control plots, indicating a suppression of carbon uptake. This likely reflects the physical effect of the surface-applied biochar, which appeared to reduce light availability for photosynthesis by covering the moss layer. The effect was particularly evident in the weeks following application, suggesting that light limitation, rather than soil chemical changes, was the dominant driver for this response.

Additionally, Moss recovery was more pronounced in the high stability biochar plots, which may be due to differences in particle size. The high stability biochar had a finer structure (approximately 0.4 cm), potentially allowing mosses to grow up through the gaps more easily. In contrast, the low stability biochar had larger, coarser fragments (2–3 cm wide) that may have physically impeded moss growth.

Although not quantified in this study, this suppression of GPP may have implications on crop yields. However, signs of recovery in GPP later in the growing season across both biochar treatments indicate that vegetation was able to recolonise the biochar-covered areas over time, despite lower moss cover in the lower stability plots. This resilience is encouraging, but it raises important questions about the timing and method of biochar application, particularly where rapid vegetation establishment is a key management goal.

Ecosystem respiration (Reco) was lower in the low stability biochar treatment compared to the control during the early growing season. This suppression may indicate a short-term reduction in microbial activity, potentially due to sorption of labile organic compounds or initial disturbance effects following application. However, this effect diminished over time, and by the late growing season, Reco in the low stability treatment had recovered to levels comparable to the control. In contrast, Reco increased in the high stability biochar plots later in the season, suggesting a delayed stimulatory effect. This may reflect changes in microbial community composition over time or increased availability of carbon substrates for microbial decomposition. It is important to note that our approach does not distinguish between heterotrophic respiration of native soil organic matter and decomposition of the biochar itself. However, increased carbon losses observed in the litterbag experiment suggest that the high stability biochar may have leached more labile material into the soil, potentially fuelling microbial respiration.

Effects of biochar on soil properties

Soil temperatures were lower in the biochar-treated plots compared to the control plots, which may be partly due to how the biochar interacted with incoming solar radiation. By covering the soil surface, the biochar reduced direct exposure to sunlight, limiting the amount of heat absorbed by the soil. It may also have acted as an insulating layer, with air trapped in its porous structure slowing the transfer of heat into the soil. This insulating effect can vary depending on the porosity of the biochar (Weber and Quicker, 2018). These factors may have contributed to the cooler conditions observed.

Implications for Paludiculture

1. Surface application may inhibit low growing vegetation productivity.
   Our findings suggest that surface-spread biochar can temporarily suppress photosynthesis in low-growing vegetation by reducing light availability to the moss layer. This led to lower GPP in the weeks following application. Such impacts on early-stage vegetation establishment may reduce productivity and could have knock-on economic consequences in paludiculture systems, particularly where income is tied to biomass yield or carbon credit schemes reliant on vegetation-based removals.
2. Appropriate application methods need to be considered.
   The observed shading effect indicates that standard surface application methods may not be the most appropriate for low growing vegetation. Alternative approaches such as using biochar plugs or incorporating biochar during groundworks may help deliver the benefits of biochar while avoiding negative effects on vegetation.
3. Carbon stocks from biochar may balance early reductions in uptake.
   While biochar application reduced photosynthetic CO_2 uptake by the vegetation in the short term, the carbon introduced into the system through biochar amendments contributes to long-term carbon sequestration. This highlights the importance of integrated carbon accounting that considers both ecosystem carbon dynamic and stocks.

Limitations

- The study was conducted over a single growing season, limiting our ability to assess long-term effects of biochar persistence, weathering, and interactions with vegetation.
- While methane (CH_4) was measured, results are not included in this report and will be analysed in a subsequent phase, meaning current conclusions focus solely on CO_2 dynamics.

2.5 Mesocosm Experiment

This study addresses uncertainties regarding potential water quality impacts of biochar amendments to lowland peat soils under raised water table management. Using an ex-situ mesocosm approach with a water table depth aligned with paludiculture conditions, we assess temporal changes in lowland peat porewater responses to biochar amendment (low and high stability) with and without gypsum amendment (at two application rates).

The rationale for testing gypsum amendments lies in its potential to suppress methane emissions. Gypsum promotes the growth of sulfate-reducing bacteria, which compete with methanogens for available carbon, thereby reducing methane production.

Relative to unamended controls, no statistically significant differences were found for low or high stability biochar on the suite of solutes examined, nor evidence for biochar-gypsum interactions (Table R1). Across all treatments and unamended controls, several water quality parameters did not exhibit levels of concern for water quality (notably, phosphate, pH, biological oxygen demand, DOC). However, this was not universally the case for nitrate, ammonia and sulphate.

Table R1. Summary of statistically significant treatment effects relative to controls.

	Biochar		Gypsum	
	HSB 10 t ha^{-1}	LSB 10 t ha^{-1}	1 t ha^{-1}	10 t ha^{-1}
Nitrate	↔	↔	↔	↔
Phosphate	↔	↔	↔	↔
Ammonium	↔	↔	↔	↔
pH	↔	↔	↔	↓
Conductivity	↔	↔	↔	↑
Sulfate	↔	↔	↑	↑
Chloride	↔	↔	↔	↔
Fluoride	↔	↔	↔	↓
Bromide	↔	↔	↔	↑
DOC	↔	↔	↔	↓
Slope Ratio	↔	↔	↔	↑
$SUVA_{254}$	↔	↔	↔	↓
BOD_5	↔	↔	na	↔

↑	*increase relative to control*
↓	*decrease relative to control*
↔	*no difference to control*

Nitrate responses to biochar amendments exhibit the most uncertainty, nitrate levels were elevated relative to controls in several, but not all, mesocosm replicates during the first weeks of the experiment, resulting in no overall statistically significant treatment effect. Nonetheless, high levels exceeding the drinking water standard of 50mg NO3/L were observed. These coincided with lower ammonium concentrations, suggesting more pronounced nitrification, which would be consistent with more aerobic conditions owing to reduced soil moisture. The implies that biochar amendments may have accommodated increased soil oxygen availability, albeit only for the first weeks of the experiment. This mechanism remains speculatory, but if upheld, it could indicate a risk of significant nitrate mobilisation shortly after amendment. These aspects are worth further study.

Statistically significant effects on porewater solutes were largely limited to the 10 t/ha rate gypsum amendment, and overall, no conclusive impacts were determined for the 1 t/ha gypsum rate. Sulfate concentrations increased significantly with gypsum amendment rate, and for 10 t/ha amendment, reached concentrations exceeding drinking water and ecological water quality criteria by factors of 2-6 (>250-1000 mg/L). Where applied, gypsum additions were the predominant control of conductivity, resulting in increases and decreases in certain ions relative to controls, indicative of soil complexation processes, and solubility controls. For example, 10t/ha gypsum suppressed Fluoride and DOC concentrations, but also increased Bromide concentrations on occasion relative to controls. DOC suppression at 10 t/ha gypsum was consistent with impacts on solubility owing to increased ionic strength (viz. conductivity) and was reflected in DOC quality metrics that indicate suppression of more aromatic fractions. However, these DOC responses are not considered of concern for water quality.

Ammonium concentrations remained below 2.5 mg N/L in mesocosms amended with 10t/ha of gypsum, whereas controls and biochar treatments exhibited several values in the range of 2.5–6mgN/L. Overall the sum of nitrate and ammonium N was somewhat lower at 10 t/ha. Evidence suggests a range of inhibitory effects on microbial nitrogen cycling in soils at high sulfate concentrations, with implications for soil microbial communities and biogeochemical cycling under long term gypsum amendment. There is thus a need to establish the balance in terms of amendment rates in regard to associated benefits for suppressing methane emissions and impacts on water quality. While the levels of ammonium were generally not of concern for water quality, associated estimates of free ammonia exceed recent threshold concentration criteria for both long- and short-term ecological impacts. Here it is worth stressing that porewaters are not necessarily strictly indicative of the quality of water ultimately exported to waterbodies due to a range of potentially attenuating processes including dilution. This facet is common to all parameters and underscores a need for improved understanding of hydrological dynamics and solute export in lowland peat soils and landscapes.

Knowledge gaps

The results regarding biochar and nitrate suggest it is worth examining the nature of moisture and oxygen conditions in soil horizons amended with biochar in relation to biochar particle size and initial moisture content, combined with further qualification of inorganic nitrogen concentrations, toward informing best practices to reduce the risk of environmental impacts.

There are a range of uncertainties regarding solute mobilisation and export that are underpinned by incomplete understanding of the hydrological dynamics of lowland peatlands. As such, it would be worth extending studies to greater, more environmentally representative spatial scales (in-situ plot / field scales) to permit further qualification and improve process understanding.

Only dissolved parameters have been examined herein. While particulate matter fluxes may be less significant in lowland environments where slopes are low, these remain source of uncertainty.

High sulfate concentrations with the 10 t/ha gypsum treatment are of concern for ecological and drinking water quality and with uncertain implications for soil biogeochemical functioning. If the 1 t/ha gypsum rate (without water quality impacts) is not associated with reduced methane emissions, then higher rates may be required but would need to be balanced against potentially negative impacts on water quality.

3. Policy Opportunities and Barriers

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3.1 Executive Summary

Background and context

Paludiculture offers significant opportunities to reduce carbon (C) emissions from inherently high emitting areas of previously drained peat. However, models exploring the financial viability of paludiculture suggest that the revenues generated by cultivated paludiculture crops, are lower than high value cropping on drained peat. This economic picture makes paludiculture an unattractive business model to adopt. To be considered as a viable alternative, paludiculture business models will need to rely on new and/or alternative revenue streams (i.e. new product markets).

By enabling access to the emerging voluntary carbon markets, biochar incorporation could help to enhance the revenue potential of paludiculture. However, these revenue streams are still in their infancy and may not have the revenue generating potential to offset the considerable opportunity costs associated with switching from grassland, arable or horticultural production to paludiculture. Therefore, irrespective of whether or not biochar forms part of the system, direct governmental support is likely to continue to be needed (at least in the short to medium term) to make paludiculture profitable.

Methodological approach

This report presents the outcome of a comprehensive analysis of all of the opportunities and barriers associated with the policy framework surrounding paludiculture and biochar use. Evidence for this analysis was gathered using a Rapid Evidence Assessment (REA) of academic and grey literature from both national and international sources and was evaluated using a policy diagnostic approach (Morestin and Castonguay, 2013). This comprehensive evaluative process incorporates a causal model with embedded logic chains. Causal models help to establish the wider policy framework within which specific policies sit, whilst the logic chain approach enables an assessment of the efficacy of individual policies. The development of the logic chains also enables a detailed exploration of the dependencies, assumptions and conditions associated with each policy and the wider framework.

Results

The REA returned minimal results for policies specific to paludiculture or biochar, therefore links with these research areas were explored through indirect, but related, policy areas (e.g. policies associated with peatland). Although at an early stage of development within the UK, the returns from the literature search highlighted how paludiculture practices are well established internationally. To reflect these findings, the policy frameworks of Germany, the Netherlands, Latvia, Switzerland and Indonesia were identified as suitable international locations to evaluate alongside the UK. These case studies provided a wider geographical and geopolitical evidence base for the report.

The creation of the causal models associated with both the UK and international policy frameworks enabled the identification of a wide variety of policies which could be indirectly linked to paludiculture and/or biochar. The main policies and their interactions (from a UK perspective) are displayed within Figure 16 (Section 3.3); within this infographic the policies are grouped into four main categories:

- Climate change: through soil C sequestration the objectives associated with climate change policies are indirectly linked to both biochar and paludiculture.
- Habitat quality and biodiversity: environmental improvements associated with re-wetted peatland systems create an indirect link between paludiculture, habitat and biodiversity policies.
- Food security: studies concerning the negative impact of paludiculture on domestic food production highlights linkages with food security related policies.
- Water and waste management: there are concerns that raising water tables could create flood risk in winter and unsustainable irrigation requirements in summer. This provides a consequential link between paludiculture and water management policies. Biochar is currently directly regulated in the UK by waste management policies, which need to be considered when planning its incorporation into paludiculture.

Logic chains were created to evaluate the specific policies and interventions associated with these key policy areas. Engagement with stakeholders is often key to logic chain development, but as this was beyond the scope of the research, the data gathered via the peer reviewed literature was expanded to include input from grey literature. This included published case studies, non-governmental organisations (NGOs) and best practice documents.

The outputs from the logic chains (Appendix 3) highlighted that availability of investment capital, stakeholder buy-in and public sector support systems (e.g. agri-environment schemes (AES)), were often key dependencies or conditions for effective policy implementation. Consequently, the opportunities for paludiculture identified within the logic chains included those that relate to carbon credits and associated income diversification opportunities. Soil preservation and diversification of crops, (linked to food related policies but dependent upon consumer awareness and acceptability to the farming community), and national/international targets for peatland restoration were also identified as opportunities within the current policy frameworks.

The main barriers to greater uptake of paludiculture practices within the current policy context were associated with high initial capital investment and large opportunity costs. The latter barrier was strongly linked to the undeveloped supply chain for paludiculture products, limited product marketability and limited public sector support for transition to paludiculture.

For biochar the main opportunities were similar to those of paludiculture. This included opportunities associated with C sequestration and soil improvement. In addition, its potential to be created from waste allows it to function within the principles of a circular economy; with the heat created as a byproduct having the potential to be repurposed for use in heat networks. The main barriers to a greater uptake of biochar were linked to both the practicalities of implementation (e.g. challenges of producing biochar on farm, the new technology and techniques required and sourcing of feedstock) and the wider policy and research context, (e.g. waste regulation and a lack of scientific consensus on the long-term environmental impacts).

Conclusions
The main outcome of this research is that there are currently no international or national level policy frameworks focused specifically on paludiculture or biochar. The main opportunities for paludiculture and biochar currently only exist in-directly through policies associated with climate change mitigation, habitat and biodiversity. The absence of a specific policy framework is in itself a policy barrier with current policies in-directly impeding uptake. For paludiculture these primarily relate to water management and food security policies, with waste and biomass policies presenting as barriers to biochar uptake.

To enable the development of the policy framework, for both paludiculture and biochar, further research is required to address a number of key evidence gaps. This includes research to evidence how water could be managed effectively to mitigate the barriers posed by planning regulations; the revenue and production potential associated with paludiculture crops; the financial returns generated by C credits focussed on paludiculture systems; and the long-term environmental effects and revenue generation potential of biochar incorporation.

3.2 Introduction

Background and context

Paludiculture
Paludiculture is a relatively new land management practise for the UK. It describes farming and agroforestry systems suited or adapted to wetland habitats (IUCN, 2023). The Michael Succow Foundation et al. (2021), stated that it is “the productive land use of wet and rewetted peatlands that preserves the peat soil and thereby minimizes CO_2emissions and subsidence”.

Drainage of peatland for agriculture has led to considerable peat degradation, resulting in the release of C as dissolved organic carbon (DOC). DOC predominantly enters the atmosphere as carbon dioxide (CO_2); therefore, making England’s lowland peat soils amongst the largest sources of greenhouse gas (GHG) emissions (compared to other land uses in the UK) (Evans et al., 2016).

Therefore, in areas where the peat soils have not yet been completely lost to drainage, paludiculture offers a potential opportunity to reduce GHG emissions, conserve the existing peat and potentially sequester more C into the soil. Currently, UK paludiculture discussions have been predominantly focused on drained, agricultural, lowland peatlands, in areas such as the East Anglian fens, Somerset Levels, and the Lancashire mosses. Paludiculture could also be practiced in the uplands, however, at present we are unable to find any case studies on upland paludiculture projects. Therefore, the ideas and practices being developed provide opportunities for paludiculture which could be applied across all peat areas within the UK’s devolved nations (IUCN, 2023).

One of the biggest challenges for paludiculture adoption is economic barriers. Models exploring the financial viability of paludiculture, suggest that revenues generated by cultivating crops using a paludiculture approach are lower than high value cropping on drained peat. Jong et al. demonstrated this in 2021 with research which compared Typha production in a paludiculture system to current dairy production on drained peatlands. Jong et al. (2021) concluded that Typha paludiculture cannot compete with Dutch dairy farming due to high investment, cultivation costs, loss of land value and low market commodity prices for Typha biomass.

This highlights the considerable opportunity costs which can significantly limit the uptake of paludiculture, when switching from grassland, arable or horticultural production. To offset this, paludiculture business models rely on new and/or alternative revenue streams, such as new product markets, carbon credits, direct support from subsidies or public sector financing (Caudwell, 2022, Jong et al., 2021). The incorporation of biochar within paludiculture could help to overcome these financial barriers.

Biochar

Biochar is a charcoal-like product created through low oxygen pyrolysis of biomass feedstocks. Given its high carbon content and stable structure, biochar has been recognised as a tool for long term carbon capture when added to soils (Jeffery et al., 2015). Additionally, it has potential to improve further soil functions, such as water holding capacity and could therefore deliver additional agronomic benefits (Meyer, 2017, Jeffery, 2015).

The application of biochar to land managed for paludiculture could improve its carbon storage performance, relative to its application in conventional agricultural settings (Caudwell, 2022). This enhanced capability could help to maximise finance revenues through carbon financing. Consequently, generating a viable income stream alongside the production of the agricultural commodity being grown.

Scope and objectives

Policy and legislation can create barriers which prevent development of new industries; because of this, the policy framework surrounding both paludiculture and biochar is an important factor for the project to consider. Policy and legislation can also create opportunities, for example, offering a service which contributes towards targets set within a global, legally binding agreement could improve the marketability of that service. In a UK context, both paludiculture and biochar are still in their infancy, therefore it is likely that large gaps exist within the current policy framework. This would need to be rectified to facilitate the development of paludiculture.

RSK ADAS were commissioned to identify policy barriers and opportunities for biochar integration with paludiculture. To achieve this a rapid evidence assessment (REA) of literature was used to identify the policies (and their associated levers) which effect (directly and indirectly) the viability of a paludiculture business model, alongside any synergies and conflicts with the integration of biochar. The information generated by the review was assessed using a policy diagnostic approach. This involved the development of logic chains and causal models to assess the wider context of the policy. The methodological approach taken for both the REA and policy diagnostic are detailed in Section 3.3.

Objectives
The objectives of this research were to:

- Develop an understanding of the potential interactions between the policies associated with paludiculture and biochar through the construction of a causal map of the policy framework, (internationally, nationally and at a regional/farm level)
- Explore the evidence on the efficacy of these policies through the creation of logic chains for paludiculture and biochar
- Identify the gaps in the evidence base which could represent both a barrier and an opportunity for the integration of biochar and paludiculture

3.3 Evaluation Framework

Rapid Evidence Assessment (REA)

Rapid evidence assessment (REA) offers a systematic and transparent basis to identify, critically appraise, and synthesise evidence that reduces the potential for bias. The approach uses a structured, stepwise methodology (Figure 16), following an a priori protocol to comprehensively collate, critically appraise and synthesise existing research evidence (Dicks et al., 2017).

For this evaluation, the REA methodology was used to identify and review academic and grey literature on the policy context and associated evidence of efficacy from the UK and across the globe. Given the weight of the literature, in addition to the UK, the policy diagnostic approach was expanded to include 5 countries. These included:

Germany and the Netherlands, as they are geographically close to the UK, and paludiculture studies (particularly in the case of Germany), were frequent within the literature.

- Switzerland, as is similar to the UK, their lowland peat is used extensively for horticultural production. It was also an early adopter of biochar application to agricultural soil (Meyer et al., 2017).
- Latvia, as it has a well-developed peat extraction industry and the associated policy framework to address the environmental impacts.
- Indonesia, as it has had considerable experience of peatland restoration to combat peatland fires and to cut down on land-use C emissions.

Evidence was identified using key search terms through academic search engines (including Science Direct and Google Scholar). Further academic and grey literature was found through citation tracing, Google searches and relevant websites.

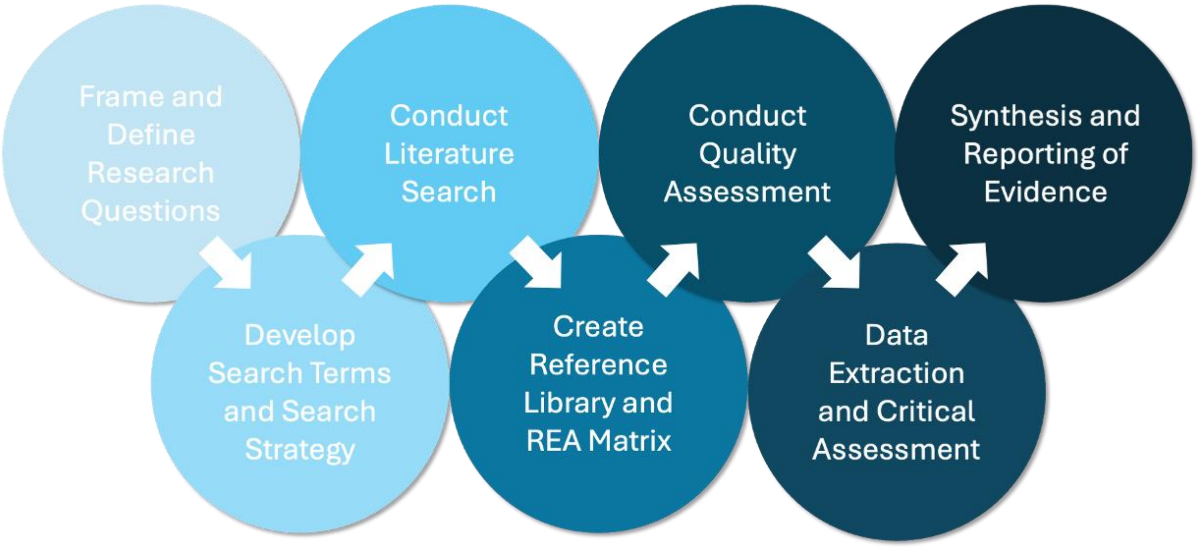

Figure 16: *REA stepwise process*

Search terms were developed from the key aims outlined in Section 3.1 and are detailed in Appendix 2. The evidence assessment was substantial, assessing the first 100 papers identified by each of the search terms.

Using Excel, the evidence was organised into review summary matrices, with supporting evidence tables. This provides clear, fully referenced outputs, as well as a transparent and audited record of where information was sourced. This document is included as Supplementary Attachments: PDC Matrix.

The review was conducted between December 2023 and July 2024. The full REA protocol is included in Appendix 2.

Policy Diagnostic

The policy diagnostic approach chosen for this evaluation, is a structured framework approach developed by Morestin and Castonguay (2013). This approach was chosen because it incorporates the creation of a Causal Model to define the wider policy framework within which the paludiculture related policies sit; as well as a more detailed theory of change focussed logic model to interrogate specific policies. A third step in the process, policy dimensions, was not completed as part of the research. This step relies on stakeholder feedback on the evidence in the literature. Following discussions with the project team, it was agreed that the insights from stakeholders was better focussed in subsequent work led by ADAS for this project. The policy dimensions element provides value by supplying a basis for comprehensive analysis, both of the key components of policy effects, and policy implementation. Should this research be continued in the future, we recommend that the policy dimensions element is included within the policy diagnostic approach, as it will aid in the understanding of the likely uptake of both current and future policy interventions (see Appendix 2).

Causal Models

The causal model is designed to encompass wider elements which could impact on the efficacy of a policy such as external factors, (that may run counter to the policy being studied or, conversely, amplify its effects); contingencies (the contextual conditions which might cause one outcome to occur as opposed to another (Weiss, 1998)); and unintended effects that a policy may inadvertently trigger. The causal models contained in Appendices 2 and 3 are a broad and shallow analysis of the wider policy framework, from global to farm-gate level drivers; within which the specific paludiculture, biochar and peatland restoration related policies sit. Due to paludiculture being a relatively new practice, there are no policies which directly target its actions or uptake. Consequently, and where possible, tangential links with policies which could create a barrier or opportunity to its development have been included.

In Appendix 2, we have presented the full causal models moving from left to right, with the farm business positioned at the centre of the model. This demonstrates how levers from both ends of the supply chain may act upon the primary producer. A causal model was completed for all five of the countries included in this review (Appendix 2).

Logic chains

A logic model sets out the conditional stages of a policy in addressing a problem and is focused on effectiveness. At each stage, a set of conditions or assumptions need to apply in order for the next stage to be realised. This logic chain approach is widely used in European policy evaluation and is well established (EENRD, 2014). A limitation of logic models is that they, (necessarily) represent an often-complex problem in a simple, linear analysis. As such, they do not identify all the possible causes of a given problem (this is the value of the inclusion of the causal model). Further they are focused on intended outcomes and do not identify all the effects of a public policy, notably unintended effects.

Making a logic chain meaningful, and being able to test its robustness to complex situations requires:

- Explaining at each step why a policy lever (input) would lead to realisation of future policy objectives (outcomes);
- explicit statement of underlying assumptions and dependencies; and
- expert knowledge of the context for policy implementation.

The logic chain also sets out the basis for measurement of input/output (what represents success). This measurement is in the form of SMART indicators of success and where the evidence might come from (e.g. national statistics, grower surveys etc).

The development of these models, via this framework, enabled us to determine the efficacy of the existing policies, as well as gain an insight into how these policies work in practice. The full logic chains have been reproduced in Appendix 2.

3.4 Evaluation Findings

Causal models

Peatlands cover only ~3% of the earth's land area and store the equivalent of 75% of our atmospheric carbon (IPS, 2018). Consequently, they are globally recognised as a tool for climate change mitigation. At the UNEP COP in 2019 it was acknowledged that good peatland management can create effective C sinks, whilst also creating an important habitat for many, including rare, species. The rewetting of drained, degraded peatlands used within conventional agriculture could contribute towards both international climate and habitat restoration goals. However, the current economic returns are marginal. Incorporation of biochar as part of the paludiculture practises has the potential to accelerate C sequestration (Štrubelj, 2022).

Although frequently referenced in international policy, currently there is no legislation at an international or national level which is specifically targeted at paludiculture. Our evaluation of the literature has therefore focussed on the structure of the international policy framework surrounding peatland, highlighting potential opportunities and barriers within these policies for development of paludiculture practice, and where possible, the integration of biochar. A simplified version of framework this is presented in Figure 17. For a full causal model please refer to Appendix 2.

Due to the lack of policy on paludiculture, there is currently disparity between terminology used within different policies, meaning there is no agreed definition for the terms paludiculture, wetter-farming and restoration. In addition, management practices (including required water table depth) vary between policies. In this research we identify paludiculture as an agricultural practice which uses a water table depth of 10 – 30 cm below field height.

Within Figure 17, we display the main policies (both legally binding and non-binding), which our research has identified to have a potential effect on the development of paludiculture. The outline causal model is then segmented into four categories, three of which are: climate mitigation, habitat/biodiversity and food security. For these three categories, the international organisations responsible for the creation of the policies are included. The arrows display where policies come from, and how they interact. The text within the purple boxes summarises the main opportunities or barriers to the development of paludiculture within each policy. A narrative evaluation of the international policies within these three categories is presented in Section 3.3.

Water/Waste Management is the final category in Figure 17, for which no separate, relevant international policy was found through our evidence review. Therefore, this category is not included in Section 3.1.1. However, as per the other categories the arrows illustrate connection between UK policies, organisations and/or programmes. The UK elements of the wider framework for all four categories are also discussed within Section 3.3.

There are very few policies related to biochar. It has therefore been included in Figure 17 as a separate category and, where possible, woven into the paludiculture framework. Within the infographic, the central bubble contains the UK peatland policy framework; these programmes, codes, plans and strategies have evolved because of the wider framework. The UK peatland policies are also reviewed in Section 3.3 and detailed further within Table 5.

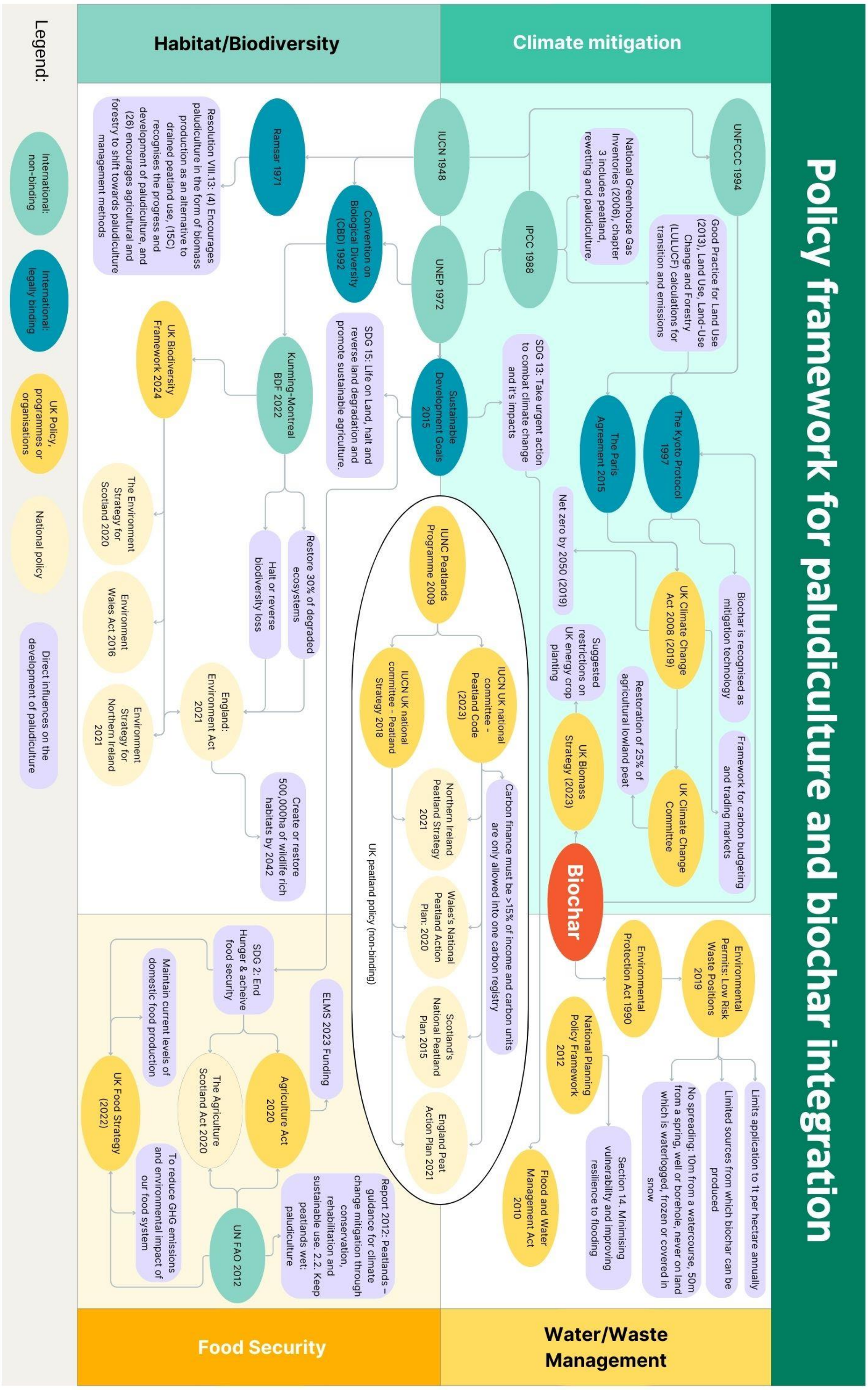

Figure 17: *Outline causal model of the international and national policy framework which impact paludiculture, and the integration of biochar into paludiculture practices.*

Summary of opportunities and barriers within international policy
This section introduces all of the international policies which influence the development of UK policy surrounding paludiculture and biochar. It also highlights British commitments to international agreements which paludiculture and biochar have the potential to contribute towards.

Climate mitigation
The 2013 amendment to the IPCC (2006) defines rewetting as "the deliberate action of raising the water table on drained soils to re-establish water saturated conditions, e.g. by blocking drainage ditches or disabling pumping facilities". The guidelines recognise that rewetting can be used in several management practices, including paludiculture. It provides the framework and equations to calculate the emissions or removals of CO_2 from rewetted organic soils. Allowing the GHG flux associated with C sinks to be quantified whilst considering a range of factors; these include time since rewetting, soil type, climate zone, vegetation cover and land use.

The IPCC (2013) provides the main elements to consider when quantifying the C sequestration potential of paludiculture. Firstly, recognition that the water table height has a significant effect on biological processes which initiate GHG fluxes. Secondly it highlights the need for vegetative cover to re-instate a C sink, which ultimately leads to soil C sequestration. The requirement for vegetative cover could restrict paludiculture crops to those which maintain groundcover, for example coppiced woodland. Finally, the IPCC states that rewetting generally reduces CO_2 emissions when compared to drained conditions, but the timescale for a site to transition from a CO_2 source to a CO_2 sink can vary, and soil C can be lost to the atmosphere from rewetted organic soils in the form of DOC. These factors show very particular management is required to create a C sink using paludiculture management practices. Therefore, this may affect the potential for paludiculture to gain funding through C credits. Further research on the potential of paludiculture to sequester C may be required, and the use of biochar could be included within this research.

Further calculations for GHG emissions from peatland and wetlands can be found within the IPCC's Good Practice for Land Use, Land-Use Change and Forestry (LULUCF). The LULUCF provides guidance on how to calculate land area; to prevent over-looking land, or land appearing in more than one land use category. In 2013, wetland drainage and rewetting were added an elective activity under article 3.4, which provides guidelines for how to calculate GHG emissions whilst transitioning from traditional lowland peat agriculture to paludiculture.

In 1997, the UN Framework Convention on Climate Change (UNFCCC) created the Kyoto Protocol to reduce GHG emissions, with the aim of mitigating global warming. The Kyoto Protocol allows reporting and accounting of LULUCF activities within its guidelines for GHG emissions trading; stating that parties may account for anthropogenic greenhouse gas emissions resulting from wetland drainage and rewetting. Their definition for wetland drainage and rewetting is: "a system of practices for draining and rewetting on land with organic soil that covers a minimum area of 1 hectare". The Kyoto Protocol also recognises that biochar is a climate change mitigation technology, as it improves carbon sequestration in soils. This recognition means that the Kyoto Protocol is one of the few policies providing guidance on both biochar and paludiculture.

The Paris agreement (2015) has since superseded the Kyoto Protocol, with the primary aim of maintaining global average temperatures well below 2°C above pre-industrial levels. Although the Paris Agreement does not directly address peatlands or paludiculture, the Kyoto protocol provides evidence that good peatland management can contribute towards the aims of the Paris agreement. Sustainable Development Goal (SDG) 13 overlaps with the goals of the Kyoto Protocol and Paris Agreement, through its request for urgent action to mitigate climate change. Therefore, presenting another policy avenue by which paludiculture could be incentivised.

Habitat restoration

The Kunming-Montreal Global Biodiversity Framework (GBF) 2022 is a global agreement adopted by 196 countries. One of its goals is to restore 30% of degraded ecosystems globally, a second is halting or reversing biodiversity loss. Although agricultural practices will not return a habitat back to its natural state, which means conservation restoration will always have more significant gains; improvements in habitat quality on agricultural land can be made. Therefore, the GBF recognises that agri-food sectors directly contribute to over 50% of its targets, and indirectly to all of its targets. Target 10 from the GBF is specifically focussed on agriculture, committing countries to manage agricultural areas sustainably, with application of biodiversity friendly practices. In the context of paludiculture, Caudwell (2022) highlighted that drained peatland agriculture degrades peat soils and can cause subsidence, whereas peatland rewetting offers improvement in many measures of ecosystem health, including biodiversity, soil enrichment, water and air quality (Tunneberger, 2021b). Additionally, Martens et al. (2023) stated that rewetting peatlands has been shown to support higher biodiversity and species quality than drained peatland. In an alignment with GBF, the SDG15 also aims to halt and reverse land degradation and promote sustainable agriculture.

Ramsar 2018 addresses the protection of wetlands of international importance, including guidance on both peatland and paludiculture. Resolution VIII.13: (4) Encourages paludiculture in the form of biomass production as an alternative to drained peatland use, (15C) recognises the progress and development of paludiculture, and (26) encourages agricultural and forestry to shift towards paludiculture management methods. However, there is a caveat in the same resolution in Ramsar 2018 (Section 27), which states paludiculture must take place where it is deemed the best land use for climate change mitigation, and where biodiversity values are not compromised.

Rewetting for paludiculture could therefore protect peat soils which are otherwise degraded due to draining the land. Consequently, paludiculture practises (in the right place) could help to achieve goals associated with both GBF, SDG15 and Ramsar 2018 by helping to prevent land degradation and improving ecosystem health.

Food security

The Paris Agreement (2015) article 2(b) states that all means to adapt to climate change and reduce GHG emissions, must not threaten food production. This presents a potential barrier to UK paludiculture as there are a limited number of food crops that can tolerate paludiculture conditions; if a transition towards construction and biomass crops occurred food security could be impacted. Alongside a potential contravention of the Paris agreement, SDG2: “End hunger, achieve food security and improved nutrition and promote sustainable agriculture” also highlights the importance of sufficient production levels to meet global requirements.

The UN Food and Agriculture Organisation (FAO) wrote a report in 2012, offering guidance for climate change mitigation through conservation, rehabilitation and sustainable use. Section 3.2 covered the importance of keeping peatlands wet. This section also referenced paludiculture, evidencing that within the food and agricultural industries, the shift to more sustainable agricultural practises promotes a drive for greater use of paludiculture.

Summary of international policy

There is currently no legally binding policy for either paludiculture or the use of biochar at an international level. However, international policies do acknowledge (even if indirectly), how paludiculture can contribute towards international goals for climate mitigation, habitat restoration and biodiversity. Biochar is also given recognition within international policy as a climate mitigation tool, however there is little guidance available for its application, and no guidance available for application on wetted soils. The guidelines and calculations for C trading standards on peatland also provide an opportunity for paludiculture practises to form part of the C sequestration offer. This could improve the financial viability of paludiculture if these practises were incorporated into C finance development.

The primary international policy barrier for paludiculture is food security. If paludiculture within the UK was practised more widely, it could potentially result in reduction in food productivity. This potential contravention of international food security targets would need to be balanced against the climate change and habitat restoration opportunities. However, a potential alternative solution is the displacement of crops which are not for human consumption. This could create available land for paludiculture without effecting food security; this will be discussed further within section 3.3.

Opportunities and barriers within UK policy

Although the increased profile of paludiculture is evident within the UK, a national policy for rewetted lowland peat agriculture is yet to be developed.

In 2009 the IUCN UK Peatland Programme was established to promote peatland restoration at a national scale, which included developing wet agriculture and paludiculture. In 2018, the UK Peatland Programme wrote the UK Peatland Strategy. However, each devolved nation also has its own peatland plan or strategy (refer to Figure 17 and Table 5). The UK Peatland Strategy, however, is designed to drive and coordinate these national peatland plans, whilst monitoring and assessing the UK's progress towards international commitments for climate and habitat restoration goals.

The UK Peatland Strategy target is to achieve two million hectares of good condition, restored or sustainably managed peatland by 2040. The primary climate and biodiversity goals associated with each of the devolved nations policies are outlined in Table 1 along with details of any associated funding.

Table 5: A summary of peatland strategies or plans for England, Scotland, Wales & Northern Ireland

National Plans	Policy aims and funding options		
	Paludiculture/lowland peat agriculture aims	Peatland	Funding

England Peat Action Plan 2021	Develop sustainability for lowland agricultural peatlands (LAPTF), by 2022	Restore 35,000ha by 2025 Develop England peat map by 2024	Nature for Climate Fund and SFI
Northern Ireland Peatland Strategy 2021	Develop and publish a strategic peatland policy including strengthening of agricultural policy	Restoration of degraded peatland habitats by 2030 Sustainable peatland management/conservation by 2040	Funding to be developed
Scotland's National Peatland Plan 2015	*NA*	Healthy and resilient peatlands by 2030	Peat Action and Scottish Rural Development Fund (through NatureScot), and the Heritage Lottery Fund
Wales: National Peatland Action Programme 2020	Establish field-scale trials (feasibility & viability) for wet agriculture and paludiculture techniques	Restoration action on 600-800ha of peatland annually Capture and store carbon Maintain biodiversity	Peatland restoration/ development grants, Nature Networks Fund and Resilient Communities' Fund

Climate mitigation

The IUCN UK Peatland Programme has also written the UK Peatland Code, which is a voluntary standard for natural capital financing, using emissions reductions created by UK peatland projects. It offers transparency and assurance through independent verification to investors. The UK Peatland Code states that peatland restoration projects must demonstrate (through financial analysis), that a maximum of 85% of the project costs are covered through income (including public grant or private), with a minimum of 15% coming from carbon finance. Project costs do not include validation, verification, provision of facilities for recreation or access, land acquisition, loss of land value or income forgone from previous agricultural income. This could present a barrier to paludiculture, as food crops produced on drained peatland offer higher profits than crops tolerant to rewetted soils. Additionally, the minimum project duration is 30 years, which may also have an impact on uptake when the peatlands involved are associated with high value commodities soils.

The IUCN UK Peatland Programme are trialling paludiculture for potential future inclusion in the UK Peatland Code. This includes an exploration of stacking carbon credits with other ecosystem service payments. If the stacking of environmental benefits was approved the financial barriers of the current code may be resolved. The latest revision of the code (2.1) also includes fenland projects, providing further opportunity for paludiculture in wetlands.

In 2019, the Office of National Statistics (ONS) report concluded that restoring all UK peatlands to a near natural condition, would cost between £8.4 to £21.3 billion, however they would provide £109 billion in carbon benefits alone. This would equate to a five or ten to one return on investment (ONS, 2019). The UK Committee on Climate Change (CCC) has also highlighted the value of peatlands and has published one of the only targets for paludiculture practices in the UK. The CCC suggested that restoration of 25% of cropland on lowland peat is required by 2050 to meet Net Zero (CCC, 2020).

In response to these assessments and advice, the Department for Environment, Food and Rural Affairs (Defra) established a Lowland Agricultural Peat Task Force (LAPTF) in 2021. The LAPTF aims to determine how good management of lowland, agricultural peatlands can contribute to the UKs goal of Net Zero by 2050. It provides a long-term road map on how to achieve commercially viable paludiculture, recognising that systematic changes of policy, funding, science and innovation are required. Since publication of the LAPTF Chair's report (2022) a £6.6M lowland peatlands research and development programme and a £5.6M Paludiculture Exploration Fund were confirmed by the UK government (Coffey, 2023).

The potential to reduce GHG emissions by raising the water table is greatly affected by the water table depth. Due to this, the latest Environmental Land Management Scheme (ELMS) payments have two payment rates for lowland peat, which change according to water table depth. The ELMS scheme has three main pillars, one of which is the Countryside Stewardship (CS) scheme, which contains location specific actions which are focused on specific habitats or features. The CS scheme now contains two actions for lowland peat: action code SW17 which is for cropped or arable land on peat soils, and action code SW18 for grassland on peat soils.

Within ELMS a water table height of 10 to 30 cm below the field surface offers a payment of £1,409 per ha in SW17, and £1,381 in SW18. The payment significantly reduces for both actions for a water table depth of 31 to 50 cm below the field surface, to £892 per ha in SW17 and £840 in SW18. The higher rewards for water table depths between 10 cm and 30 cm are likely aimed at rewarding optimal GHG emission reductions, as shown in Figure 18; in which Evans et al. (2021) display the effects of water table depth on GHG emissions. The payments offered by the ELMS are beneficial to paludiculture, for which a 10 to 30 cm water depth is optimal, allowing paludiculture farmers to claim the highest value subsidies.

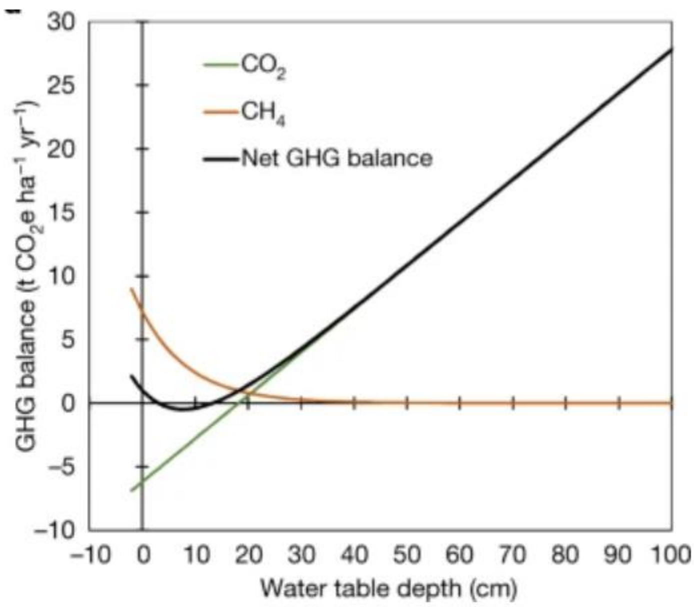

***Figure 18:** Annual mean values of carbon dioxide and methane flux versus mean water table depth (Evans et al., 2021)*

Habitat Restoration

The inclusion of water level management within the UK's Agricultural Act (2020), (implemented through the CS scheme), will also be beneficial for improving wetland habitats. Paludiculture will never return a habitat back to its natural state, but it can produce improvements in habitat quality in comparison to drained agriculture. However, the criteria for SW17/18 highlight the complexities of water management within the UK by requesting that each site is individually designed, with a feasibility study and a Water Level Implementation Plan. Consultation and consent from the Environment Agency, Internal Drainage Board or Local Authority must also first be sought before implementation of these actions. This is to ensure there are no negative impacts on adjacent land, flood management water resources or fish migration. In addition, land drainage consent and/or planning permission may be required if changes to infrastructure are needed, (e.g. removal of a flood defence structure or installation of water control structures).

SW17 also highlights that there is no current, accurate map of lowland peat soils in the UK. Therefore, landowners are required to contact Natural England to confirm if their land is appropriate for these actions. Creating this map is one of the tasks which the England Peat Action Plan has planned to complete. ELMS also require consideration for priority or protected species and historic or archaeological features, when designing the high-water level agreement.

The complex paperwork, communication with multiple organisations, water management requirements and land status issues, could create a barrier for landowners and farmers to engage with ELMS. Arguably, in addition to the costs of infrastructure and machinery needed to begin paludiculture practices, receiving SW17/18 payments may be seen as not financially viable, due to the time commitment to meet this myriad of requirements. Further research on stakeholder opinions is required to quantify how the complexities of current policy are affecting uptake of paludiculture. Attempting to address the practical requirements of biochar integration with any agricultural system using stakeholder surveys and a workshop, revealed that farmers wanted more evidence on financial returns. Therefore, further research on finances may be required before accurate stakeholder opinion can be provided (Personal communication, 2024). In addition, further research into what 'paludiculture' means to farmers, conservationists and policy makers could assist in resolving the disparity in perception between different stakeholder groups.

Planning regulations (which are reflected in the ELM requirements) and the regulations for water use in times of water scarcity (included in the Flood and Water Management Act (2010), could also serve as barrier to the implementation of paludiculture practises. Section 14 of the National Planning Policy Framework (2012) commits to minimising vulnerability and improving resilience to flooding. Johnson (2018), Liu (2923) and Tanneberger et al., (2021a) believed wetter farming could help mitigate flooding as it reduces soil degradation and subsidence. Further research is required to generate the evidence needed to avoid such regulations acting as a barrier; possibly preventing the development of retaining and draining infrastructure which is essential for paludiculture.

Food security

The UK's Agriculture Act (2020), and the UK Food Strategy (2022) both present potential barriers to the uptake of paludiculture practises. Both Acts commit to maintaining current levels of UK food production, as well as reducing the emissions and environmental impact of our food system. The shift to paludiculture practises (at least in the short term), may create reductions in crop yield and production of certain food products. As explained within the summary of international food security.

However, research completed within the UK by Rhymes et al. (2023b), (commissioned by the World Wildlife Trust), calculated that the CCC's target of restoring 25% of lowland peat and introducing some form of wetter farming practices on a further 50%, can be reached without reducing food production. This is because crops which are not for human consumption utilise a substantial proportion of lowland peat; including fodder crops for livestock and feedstocks for anaerobic digestion. Further research by Evans et al. in 2024 highlight the resent increase in biogas feedstock, estimating a threefold increase in maize grown for biogas on peat soils between 2015 and 2021. Rhymes et al. (2023b) suggested that incentivising the growth of crops for human consumption, (particularly vegetables), on peatland alongside relocation of other crops which are not for human consumption, would maintain food security whilst freeing up land for restoration or wetter farming.

The UK Biomass Strategy (UKBS) 2023 provides guidance on crops grown for biofuels. It highlights that there is a limited supply of land, and that ideally biofuels should be sourced from waste products, rather than removing land from food production. This could create a barrier for paludiculture in the UK, because many biomass crops are well suited to temperate, wetted land conditions. However, when following the advice of Rhymes et al. (2023b) detailed above, this could be advantageous for paludiculture by helping to displace biomass crops, therefore making land available for food crops.

Currently, restricted levels of domestic energy crop planting are suggested; however, the regulations and the limits are not yet established. The government is funding a Net Zero land use research and development programme, which will deliver a sustainable approach to land use which considers net zero, environmental recovery and maintaining food security (UKBS, 2023). Until this framework in established, future markets for paludiculture crops are hard to predict, creating a barrier to uptake for landowners.

Therefore, food security currently presents a potential barrier to development of paludiculture. However, further research into displacement of crops which are not for human consumption, and incentives for human food crops could provide a solution to these challenges. Whilst movements to make agriculture more sustainable, could provide further support for the development of paludiculture.

Biochar

The main policy relating to biochar is found within the waste management regulations implemented through the Environmental Protection Act 1990. Within their environmental permits, low risk waste positions 60 and 61 limit biochar's source material, its usage to one tonne per hectare and prevents it from being spread on waterlogged soil within 10m of a stream or 50m of a spring. This presents a significant barrier to the integration of biochar within paludiculture practices.

Current research into biochar is based on short term laboratory data with the results varying according to feedstock, pyrolysis conditions, soil conditions, climate and application rates (UKBS, 2023). This presents an issue for regulators as it is currently not possible to create a framework suitable for all types of biochar. To overcome this hurdle, further research is required to generate an evidence base and provide reassurance that biochar will not harm the environment over the long term. The UK Research and Innovation (UKRI) is funding a £30 million research project to assess the stability of biochar; its C sequestration potential; and impact on environmental health and soil ecosystems. Natural England are also funding £18M of biochar research through their GGR innovation competition. If this research returns favourable results, some of the barriers for biochar integration with paludiculture may be removed.

Causal Model for Germany, the Netherlands, Latvia, Switzerland, and Indonesia

Temperate peatlands across Europe, much like the peatlands of the UK, have been drained or had their peat extracted for agricultural or other resource and land use purposes. Tropical peatlands in Indonesia have a different set of issues, including being used for palm oil and pulpwood plantations.

Similar to the UK model, Appendix 2 showcases the policy barriers and enablers regarding biochar, paludiculture and peatland restoration in Germany, the Netherlands, Latvia, Switzerland, and Indonesia. All of the European countries mentioned, bar Switzerland, are among those with the largest emissions from peatlands in the EU (Wichtmann, Joosten and Schröder, 2016). Indonesia's peatlands are estimated to have degraded areas totalling around 13Mha (Yuwati et al., 2021,). In the interest of creating a broad picture of related policies, information under each country is not as detailed as the Causal Model for the UK. Since the high-level/international drivers and consumer/social attitudes are broadly consistent with those in the UK, those columns have been replaced by one that focuses on continental or regional influences, and one that provides a little context regarding peatland use in the respective countries.

While not highlighted in the structure of the Causal Models, there is also extensive interaction and knowledge transfer between countries with regards to peatland restoration and paludiculture. One example of this would be funds and other resources from the EU to Indonesia to reduce C emissions from peatland . Another example is the Care-Peat project, which includes the UK and the Netherlands, whose aims include developing methods of C measurement. The Netherlands' Delta Programme has also collaborated with Indonesia for knowledge-building purposes related to peat rewetting (MIE, 2013).

Logic chains

Using policies identified in the outline causal model presented in Section 3.3, the logic chains discussed in this section provide a more detailed theory of change, focussed on the interrogation of specific policies. The conditional stages of the policies are identified, problems are addressed, and their effectiveness evaluated.

UK logic chain

The policies found through the review of literature and presented in the causal models are largely composed of drivers, incentives and markets to carry out peatland restoration, but few, if any, act as a direct catalyst for the uptake of paludiculture. Similarly, policies related to biochar are either restrictive or prescriptive, with the only incentives being provided by private markets to suppliers. Therefore, there is currently little incentive for application (for biochar's primarily for carbon storage) unless the same party are also producing it. This is partly due to the relative novelty of both these innovations, with legal guidelines and clear markets yet to be defined.

To construct a meaningful logic chain which enables a qualified evaluation of possible future developments and likely structural barriers; we have extrapolated from the policies related to peatland rewetting. The regulations on peatland rewetting included restoration, existing carbon markets, and the allocation of public research funding. Beyond the UK context, the logic chains based in Indonesia and Germany illustrate the challenges related to increasing the uptake of paludiculture.

Drained lowland peat accounts for 85% of the GHG emissions from peatland in England (Rhymes et al., 2023b). Most restoration efforts thus far have been targeted towards upland peat, and wetter farming and restoration options offered by AES are likely to appeal to those who have limited or no production on their peatland. A large portion of vegetables grown in the UK are grown on lowland peat, and rewetting targets would necessitate a change in the present system of land use in the UK (Rhymes et al., 2023b). As such, the development of alternative production methods, such as paludiculture, on these lowland peat soils which allows for similar economic returns is key. Mulholland et al. (2020) find that "although there is considerable potential, paludiculture does not yet offer an economically viable, large-scale or immediately implementable solution to the challenge of high GHG emissions from cultivated lowland peats".

The benefits and costs of paludiculture implementation will likely diverge from the ONS estimate for rewetting peatland in the UK, (£8.4-21.3b and £109b respectively), due to the need for additional infrastructure and machinery to accommodate harvesting on wet peat soils (Office for National Statistics, 2019, Defra, 2022). With regards to the alternative crops that could be grown in a paludiculture system, 88 potential native crops have been identified on the UK Paludiculture Live List, including biomass for bioenergy, sphagnum as a peat-replacing growing media, and reed (University of Leicester et al., 2021, LAPTF, 2022). The revenue potential of these alternative crops would also need to be taken into consideration when assessing the costs and benefits of a paludiculture system.

The biochar industry in the UK does not presently have "direct public policy support for biochar production and deployment" (Price and Morris, 2024). The development of biochar primarily for GGR use would likely include the utilisation of government resources, to amplify initial demand and establish a regulatory framework (Zhou et al., 2022). There is ongoing research on the development of how biochar can be deployed in the UK; including development of local heat networks, which distribute the heat generated within biochar production .

The UK logic chain (Appendix 2) uses the expansion of the existing UK Peatland Code to include paludiculture as its central policy, including carbon credits from biochar, and payments for other ecosystem services. As both paludiculture and biochar require further research (covering both scientific and socio-economic implications); there is unlikely to be sufficient evidence to support regulatory change of the scale required to make it economically outperform current drainage-based farming practices, without a source of funding. There is a high opportunity cost to land use change from drainage-based agriculture to paludiculture. Therefore, the impact that funding will have on stakeholder actions, and how that impact is likely to be distributed should be considered.

As the UK Peatland Code is a voluntary standard and not a requirement, its direct effects will be limited to those who choose to engage with it. However, the UK Peatland Code has the potential for further unintended effects, such as impact on land price, landscape, infrastructure and community resource distribution.

There is a related prior example of the expansion of a voluntary code, with the German MoorFutures scheme integrating other ecosystem services (Bonn et al., 2014). Payment for a multitude of ecosystem services sits comfortably alongside existing government policy of agricultural subsidies for environmental protection and action against climate change, although issues of double-counted environmental benefits may arise.

Presently, the UK Peatland Code connects restoration projects with those who wish to buy C units or pending issuance units. There are currently 267 projects covering 34,310 ha; however, none have been running for long enough to be verified thus far. Within the summary provided by the peatland code on these projects, the vast majority are in the uplands, making it unlikely that they are practicing any form of paludiculture. Adapting or expanding the UK Peatland Code from the existing framework and mechanisms would likely ensure collaboration with established structures and finance in this sphere.

UK limitations

Biochar and paludiculture are both methods of C capture and storage that have significant potential. However, both also sit between several policy areas and competing interests. These include environmental protection, climate action, waste management, food security and related resource management. Significantly, agricultural and environmental policy is presently in a state of flux due to the changes associated with the UK's agricultural transition post Brexit. As such, it is difficult to predict with certainty whether emissions from peatland will be given significant focus and resources over the long term.

Related to this, is the lack of enabling regulation regarding biochar. Stakeholders in research completed by Price and Morris (2024), suggest small-scale biochar production in the UK context has many benefits. However, the science around biochar's various properties, risks and potential is not settled (Jeffrey et al., 2013). This uncertainty makes it difficult to establish a one-size-fits-all regulatory framework that works for varied localised circumstances. Similarly, a better understanding of peatland emissions during rewetting in lowland ecosystems would also be a key part of better understanding the risks and benefits.

The causal model and logic chain (Appendix 2) for the UK illustrate that there are currently no regulatory penalties or major economic drawbacks (apart from the increasing cost of drainage), for continuing with the present system of cultivation on lowland peat. Expansion of the UK Peatland Code, while acting as an emerging incentive, does not guarantee interest and uptake of the relevant practices. In addition to this, consumer appetite for the bundled ecosystem services may not be guaranteed over the long term. A shift from this structure of contractual arrangements may necessitate separate contracts for C credits, water quality and biodiversity; which have both beneficial and detrimental consequences for financial viability.

There are also other influences that have not been included, due to having no clear measure of the degree of their importance within policy. This includes the influence of international bodies and associated agendas (i.e. United Nations Decade for Ecosystem Restoration, the International Mire Conservation Group, and the Global Peatlands Initiative).

Indonesia logic chain – Updated measurement reporting and verification (MRV) system
Existing Indonesian policy recognises the importance of peatland restoration and maintenance at the national and international level; in part due to the threat of peat fires and haze (Giesen and Sari, 2018). Therefore, Indonesia has established targets for restoration and preservation of peatland, being 2 Mha and 24 Mha respectively (Astuti, 2021). There is significant interest in reforestation and biodiversity protection measures in Indonesia, and large-scale peatland restoration projects generating C credits are underway . Paludiculture is also “legislatively supported in Indonesia by Government Regulation No.57/2016 on the Protection and Management of Peatland Ecosystems” (Miller, 2022), and has been promoted “Over the past decade… to rehabilitate degraded peatlands by providing an income to local farmers and reducing the negative environmental impacts of drained peatland systems” (van der Meer et al., 2021).

However, a common theme in the academic literature regarding restoration measures was querying the long-term nature of current efforts (Uda, Schouten and Hein, 2020; Yuwati et al., 2021). In addition to this, while there is ongoing scientific and commercial exploration of certain paludiculture crops (Miller, 2022;), dilution of paludiculture practices has occurred in order to achieve sufficient returns (Budiman et al., 2020), and prevent significant setbacks in the form of ”inadequate funding, ecological knowledge deficits, and bureaucratic inertia” (Miller, 2022). Existing attempts at paludiculture face the problem of regulatory restrictions on non-timber forest products (NTFP) being cultivated, and a lack of strong markets for the products (Giesen and Sari, 2018).

The costs of restoration can range from approximately $400-25,000 /ha (Uda, Schouten and Adventa, 2020). While the costs of damage from fires and the risks posed by subsidence in the long term are large (Giesen and Sari, 2018), there is a need to provide equal economic opportunities and alternatives for the ten million people who rely on peatlands and cannot otherwise maintain/restore them (Miller, 2022; Yuwati et al., 2021). Restoration efforts also have to contend with the interests of oil palm and pulpwood companies, and the livelihoods of their workers (Astuti, 2021). Approximately 1.4 Mha of the area of peatland that is required to be restored is on company concessions and would have to be restored by those private actors (Wicaksono and Zainal, 2022).

The proposed policy for Indonesia’s Logic Chain (Appendix 2) is the establishment of an independent MRV mechanism to certify peatland restoration and paludiculture projects. This is partly based on the guidelines for the Roundtable on Sustainable Palm Oil (RSPO, 2018), with added criteria to meet for raising the water level and reducing emissions. In this scenario, biochar may be used as a soil amendment, and potentially represent an alternate income stream from voluntary carbon markets. The overarching aim is the development of markets for paludiculture products through creating trust in the environmental/ecosystem services provided through their cultivation, as opposed to a business-as-usual scenario of C emissions. This could, alongside the diversification of income through C credits, be aimed towards benefitting smallholders.

Indonesia - limitations

Indonesia's peatlands have received significant focus as a means of combating climate change, and several promising policies have been enacted. However, the present status of restoration measures, both in terms of the extent of rewetting and the proper restoration of rewetted areas, is in question. Paludiculture and biochar provide theoretically beneficial opportunities in the long-term, through sustainable land-use and increased soil fertility respectively but would have to contend with several barriers.

While pulpwood and palm oil plantations are significant creators of carbon emissions from peatland use, reducing palm oil production may lead to C leakage; which could occur through the increased production of other vegetable oils with less efficient land-use (Ritchie, 2021). The relative benefits and cost to the environment from draining peatland for palm oil, against clearing land for the cultivation of other vegetable oils is a factor that needs to be better understood.

Germany logic chain – support tool for land-use decisions

Degraded peatlands are a significant problem and a source of agricultural carbon emissions for Germany, responsible for "37% of the agricultural GHG emissions" (Tanneberger et al., 2020). Of the country's peatlands, 92% have been drained, while degraded areas were estimated to emit 53 Mt CO_2 in 2020 (BMUV, 2023). A large portion of peatlands in the country which are under agricultural use are permanent grassland (Tanneberger et al., 2020). Peat extraction is another significant activity; however, "most areas currently under peat extraction are required by law to be rewetted for nature conservation" (Tanneberger et al., 2021b).

There is ongoing exploration and funding of paludiculture projects in Germany; and interest in the preservation of peatland "for nature conservation purposes" (Schlattmann and Rode, 2019). The review of literature found that there was significant interest in developing viable paludiculture models in Germany, particularly at the level of peatland-rich federal states. Wichmann (2017) modelled the economic returns on harvesting reeds through paludiculture, and found that cultivating reeds for thatching was, theoretically, a viable business model. There are also trials for harvesting Sphagnum in Lower Saxony . Outcomes from these trials bear significance for the UK context, as the paludiculture crops in focus are similar.

However, the academic literature also frequently points to contradictions in policy between wetland habitat protection and agricultural subsidies. As outlined in the Causal Model in Appendix 2, control over peat within Germany is devolved to the level of state governments; while many of the policies and legislation affecting biochar and paludiculture in Germany are primarily those at the level of the European Union. This includes restrictions on which crops are eligible for the common agricultural policy (CAP) subsidies, potentially locking some paludiculture crops out of that avenue of funding and acting as a potential conflict between the objectives of the CAP pillars (Wichmann, 2018). Another influence is the waste directive, and its application to the production of biochar in the EU (Štrubelj, 2022). Wichmann and Nordt (2024), in an examination of the major barriers to paludiculture in Germany, found that the legislative architecture around the process of rewetting requires significant time and resources to meet water and nature conservation requirements.

The policy in the logic chain for Germany (Appendix 2) is the development of a paludiculture viability map, based on existing academic and policy work identifying land-use options. This includes Schlattmann and Rode's (2019) development of a spatial assessment tool for particular paludiculture crops, covering legal, habitat requirements, potential economic benefit and GHG mitigation potential. As well as Mecklenburg-Vorpommen's paludiculture strategy creating a paludiculture land classification system (Tanneberger et al., 2020). The overall aim is to develop a tool that can be updated and used to inform decision-making by identifying areas where paludiculture is possible and suitable on a practical level, as well as legally and economically sound.

Germany - limitations

The main limitation to the policy proposed in the logic chain is its limited influence on actual uptake of paludiculture. For significant numbers of farmers and land managers to be willing to invest, the development of market pathways for paludiculture products would have to be made clearer (e.g. creation of standards, labelling and greater consumer awareness). Changes may also be required of existing mechanisms, especially the CAP, which would require a wider consensus than one among the German government at the federal level. For example, CAP introduced a minimum standard for maintaining good agricultural and environmental conditions (GAEC 2), however, how it is nationally implemented controls its effectiveness. Currently, Germany allows arable use of peatlands to continue and minimum water levels are not addressed. Alteration to draining infrastructure to allow deeper draining requires permissions from local nature conservation agencies and water authorities, but it is not forbidden (Wichmann & Nordt, 2024).

3.5 Discussion

There are examples, both in the UK and across the world, of paludiculture and biochar being tested and trialled. Peatland rewetting has been extensively documented in the legislative/policy process, while biochar has a strong presence as an option in CO_2 removal markets. However, this review has not found examples of a policy framework designed to incentivise the widespread and economically successful integration of the two.

To summarise the key opportunities and barriers within all areas of paludiculture and biochar arising from our research (and extrapolating insights from the international examples) we have created Figure 19 for paludiculture , Figure 20 for biochar. This Section analyses the hypothetical policy put forward in the UK logic chain, using Morestin's (2012) six dimensions for public policy analysis. This addresses the policy in terms of effectiveness, unintended effects and equity, as well as the implementation aspects of costs, feasibility and acceptability.

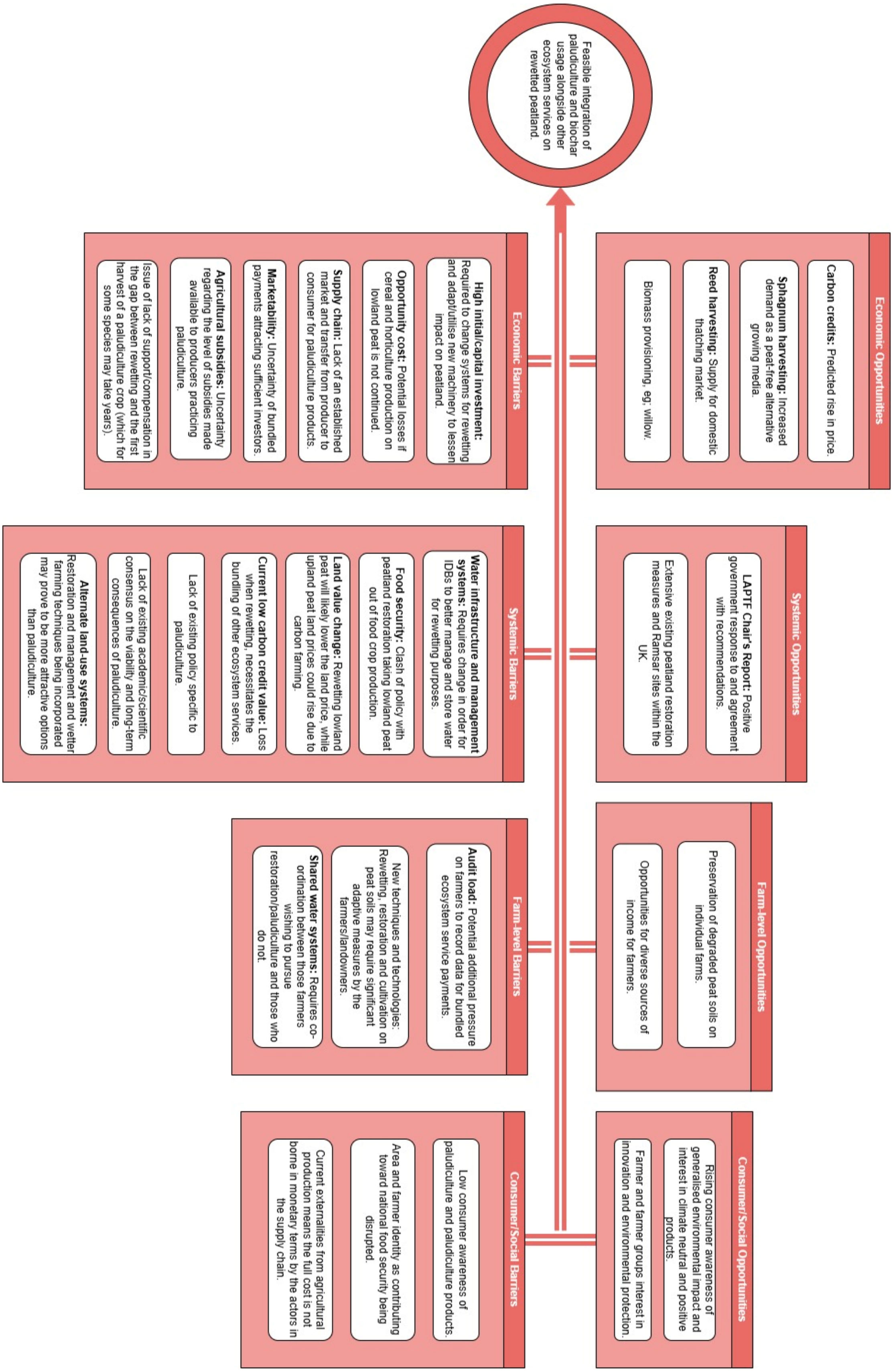

Figure 19: Barriers and opportunities relating to paludiculture.

Note: Opportunities are above the central line, while barriers are below. Some elements, such as C credits, may appear on both sides as they are currently acting as an impediment but are predicted to have a more positive influence in the future.

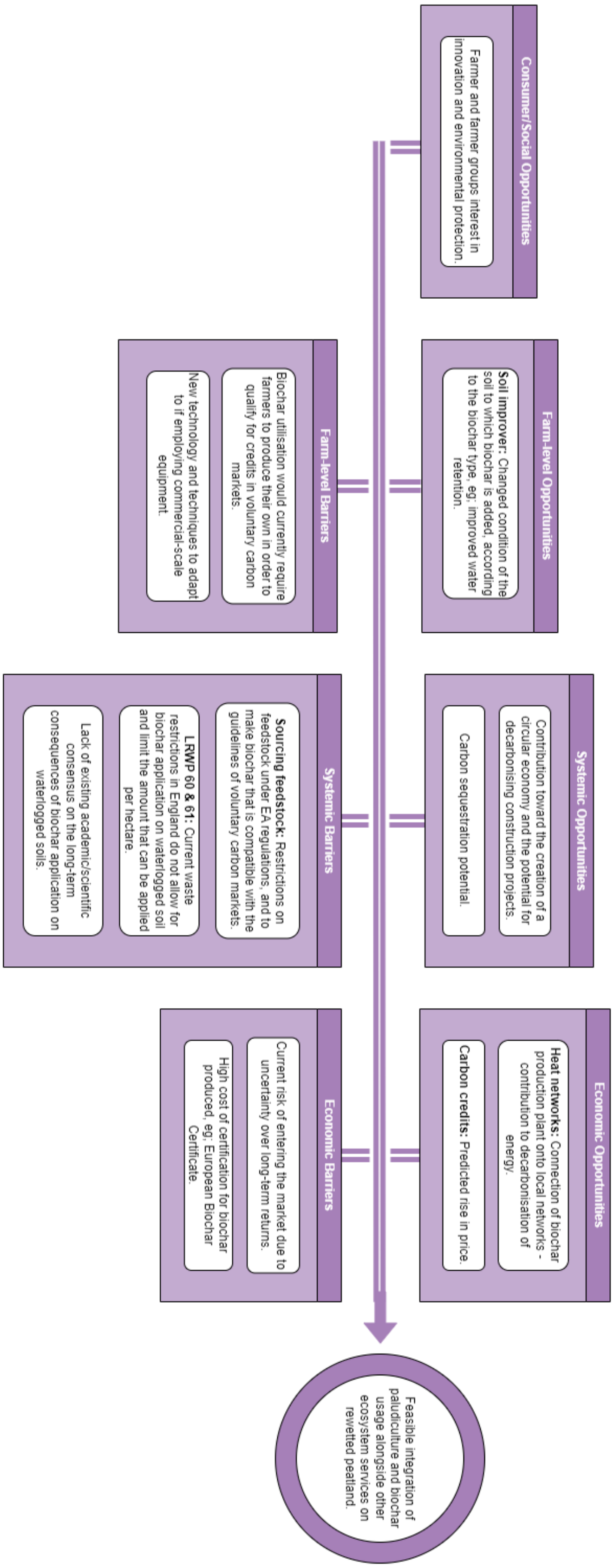

Figure 20: *Barriers and opportunities relating to biochar.*

Effectiveness

Although the predominant objective of paludiculture is to enable the continuation of agricultural activities on rewetted peatland; the evidence from the literature indicates that incidental benefits (e.g. biodiversity and flood water management) typically associated with peatland restoration may also occur (Mulholland et al., 2020). These wider benefits have been shown in the latest revision (2.1) of the UK Peatland Code, which now includes options for fens. However further exploration could be beneficial, especially for upland areas.

Unintended effects

Unintended effects of the inclusion of Paludiculture in the UK Peatland Code however could include any major impacts on the food crops grown in the UK. As per the discussion in Section 3.3 with regards palm oil production in Indonesia, this may result in carbon leakage with food having to be imported from other parts of the world. There is also the potential for a double counting of climate benefits to occur, through the existing AESs and the UK Peatland Code, which would have to be accounted for through the verification process (DEHSt, 2018). Finally, biochar deployment in peatland may also have pose risks to health when proper techniques for application to the peat soils are not followed (PHST, 2010).

Equity, acceptability and cost

With regards to equity and acceptability, it is essential that no farmer should be financially penalised for following a paludiculture or wetter farming strategy to reduce emissions. Unless the business case can prove that the financial viability of paludiculture, they cannot be expected to adopt it. This makes the business case fundamental to the widespread adoption of paludiculture (Tanneberger et al., 2020; Stuart et al., 2023). One common theme found across regions and countries is that the profitability of drainage-based agriculture on peatland is presently high (regardless of what is being cultivated, e.g. livestock, horticulture, pulpwood, etc.), and disincentivises a switch to wetter farming or paludiculture (Johnson and Land, 2019; Liu et al., 2023; Uda, Schouten and Hein, 2020). With the recent introduction of remuneration through the countryside stewardship scheme, this financial support may help to balance this difference.

Feasibility

Despite the logic chains for Indonesia and Germany being influenced by those countries' specific contexts and existing policies, they help illustrate the range of action required to establish paludiculture as a viable land-use option. Although there is evidence of people practicing paludiculture in Indonesia over the last 100 years, the term 'paludiculture' was unknown until recently (Giesen and Sari, 2018). Therefore, it is mostly a novel method of cultivation that must contend with an existing subsidy and regulatory environment which incentivises drainage-based agriculture.

3.6 Conclusions and recommendations

There is currently no international or national policy framework for paludiculture or for the use of biochar. However, both are individually gaining global recognition; evidenced by the number of policies and reports within which they are referenced (albeit indirectly). For paludiculture the primary opportunities in policy are associated with objectives related to climate change, habitat restoration and biodiversity targets. Barriers to the implementation of paludiculture practises however are for those policy objectives associated with water management and food security.

Research is required to evidence whether water quantity management practises put in place to enable paludiculture can be implemented to mitigate flood risk and minimise water requirements in times of drought. Further research also needs to be conducted into the food crops suitable for wetted land, as well as the potential for displacement of crops not for human consumption; this research is required to prove that paludiculture will not reduce domestic food production. However, biomass crops utilised for both energy and construction are well suited to paludiculture and may offer more potential within C markets, representing another opportunity by which the financial viability of paludiculture could be enhanced.

Biochar's primary opportunity sits within policy objectives associated with climate mitigation technology, whilst the barriers in policy are associated with waste and biomass. Further research in this area is required to demonstrate tangible benefits for GHG emissions and C sequestration alongside an exploration of the environmental concerns which currently limit biochar's usage.

No policies exist to prevent the integration of biochar with paludiculture practises, however nor are there any explicit incentives. To enable integration, a framework for C credits needs to first be established. To ensure financial viability of paludiculture, this should consider allowing stacking C credits gained with payments from other environmental benefits.

A number of these gaps in evidence are currently being explored through both this and other projects funded via Natural England's Paludiculture Exploration Fund. If the evidence generated by this research addresses the challenges outlined above, the guidance provided by the LAPTF, UK Peatland Code and UK Peatland Strategy, as well as lesson learnt from international examples, could help develop a comprehensive policy for enabling the financial viability of paludiculture in the UK.

4. Barriers and Enablers for Biochar Application in Paludiculture

Insights from Stakeholder Engagement

Authors: *ADAS– Natasha Alons, Liz Reddy and Jenny Rhymes.*

4.1 Executive Summary

This report summarises the findings from stakeholder engagement as part of answering 'can existing infrastructure and machinery support biochar integration'. Stakeholder engagement was undertaken by RSK ADAS Ltd and aimed to assess:

1. Whether biochar application to paludiculture soils requires distinct practical approaches compared to conventional farming on drier soils,
2. whether farmers with land suitable for paludiculture have the existing infrastructure and equipment required for biochar application or whether new investment is necessary, and
3. The attitudes of stakeholders towards biochar application in paludiculture.

Engagement with both biochar suppliers and farmers revealed common perspectives on biochar application methods and the challenges associated with its use in paludiculture. Both sets of stakeholders agreed that conventional machinery, such as compost and manure spreaders, could be adapted for biochar application with minimal additional investment. However, significant challenges arose when considering paludiculture, where the wet conditions hinder machinery access and raise concerns about soil compaction. Both farmers and suppliers emphasised the need for specialised, lightweight equipment to ensure effective biochar application in these waterlogged environments. There was also some uncertainty about whether existing equipment would be compatible, which could potentially lead to high investment costs.

It is important to note that these challenges stem not only from biochar application but from the broader transition from conventional to paludiculture farming. Such equipment is also necessary for other critical farm operations, such as planting and harvesting, and thus, the investment needs extend beyond biochar application alone.

Farmers identified a potential workaround by temporarily drying the paludiculture fields to allow conventional machinery to access the land. While this could help address machinery limitations, it likely comes with significant trade-offs. For instance, draining the land would increase emissions, potentially undermining the environmental benefits of the practice. Additionally, managing the water by storing it during the drying phase and re-wetting the fields later would require considerable effort and resources, further complicating the process.

Despite shared concerns over infrastructure needs and application techniques, both stakeholder groups recognised the potential of biochar in paludiculture, particularly if underpinned by financial

incentives. However, there was noticeable resistance to paludiculture as a mainstream farming model. Many farmers viewed it more as a conservation-focused practice rather than a viable commercial farming approach. They expressed apprehensions about land access, potential impacts on food security, and the uncertainty surrounding financial returns, all of which contributed to hesitance in adopting paludiculture on a wider scale.

A key regulatory concern raised during the engagement was that carbon credits for biochar application are currently awarded only to the producer of the biochar, not the end user (the farmer). While this is not the case for all carbon credit markets, it is a significant limitation in the more established markets operating in the UK. This disconnect presents a major barrier, as farmers bear the costs and logistical challenges of applying biochar but are unable to directly benefit from the associated carbon credits. Addressing this imbalance could strengthen incentives for farmers to adopt biochar, both in paludiculture and conventional agricultural systems.

Moving forward, clarity on policy, financial support, and infrastructure investment will be key to overcoming these barriers and ensuring that biochar can play a meaningful role in paludiculture systems.

In conclusion, while biochar is seen as a promising addition to conventional farming practices, greater research and practical demonstrations are needed to address challenges related to its application in paludiculture, alongside the development of clear regulatory frameworks and financial incentives to support its integration.

4.2 Introduction

Paludiculture offers significant opportunities to reduce carbon emissions from inherently high emitting areas of previously drained peat. However, there is a high level of uncertainty as to its economic viability. Current business models are heavily reliant on new and/or alternative revenue streams, such as new product markets, carbon financing or subsidies. The incorporation of biochar into the paludiculture system, and associated links with carbon financing, could improve financial viability. Biochar for agricultural use is relatively new in the UK, as such ADAS and UKCEH undertook exploratory research to understand the initial types of infrastructure investment requirements might be necessary for co utilising biochar under a paludiculture farming model.

In September 2023, stakeholder engagement was undertaken to assess current biochar usage in the UK, explore its feasibility within conventional farming models, and determine whether existing machinery and practices can be universally applied under paludiculture conditions. This culminated in a workshop in Ely, Cambridgeshire on 5th December 2023 with stakeholders invited by Fenland Soils. An informal e-mail questionnaire and online interview (referred to as the ‘supplier questionnaire’ for the purposes of this report) was conducted with three UK-based biochar suppliers.

Scope and objectives

The aim of the primary research with stakeholders was to garner the practical requirements to facilitate biochar application such as, storage facilities, machinery and equipment. Questions focussed on determining: i) whether existing infrastructure and/or machinery from farmers that are candidates for paludiculture adoption (e.g, farming on drained lowland peat) can support biochar integration with paludiculture; and ii) what adaptation or investment costs would be required to allow for paludiculture with biochar integration.

This report outlines the methods and high-level findings from both the biochar supplier questionnaire and workshop with Fenland Soil in Ely. The aim of the questionnaire was to gain a general understanding of the potential barriers and enablers individuals applying biochar to agricultural land might experience regardless of farming model. These findings aided in developing the workshop questions, the objective of which was to collect opinions on the practicalities of applying biochar to agricultural land.

4.3 Literature review: Biochar use in agriculture

To explore how biochar could be integrated into paludiculture farming models, we first examined its current use within conventional agriculture. This assessment helped determine whether existing practices can be directly applied or if adaptations are needed to accommodate biochar use under wet peat soil conditions.

Methodology

To gain an understanding of the evidence surrounding the use of biochar on agricultural land or in the UK more generally, a brief, high level literature review was undertaken. The review focussed on current policies and barriers to application, with the key findings incorporated into a subsequent stakeholder questionnaire f. Google Scholar and Internet search engines were utilised to find literature, articles and media relevant to biochar application in the UK and Europe. For this exploratory phase, search terms included; “Biochar+paludiculture”, “Biochar application”, “Biochar spreading”, “Biochar+agriculture”, “Biochar policies UK”, “Biochar policies Europe”, “Biochar barriers”, “Biochar support”, “Biochar machinery”, “Biochar infrastructure”, “Biochar suppliers”, “Biochar stakeholders”.

Regulation

The majority of the identified literature focussed on current policies and regulations. For example, Meyer *et al.,* (2017) review biochar regulation for several European countries. However, they focussed more on components and the process of making biochar, rather than its use or application. Fawzy *et al., (*2021) also noted that the production of biochar for a particular requirement requires *“extensive knowledge”* and in the EU, a European Biochar Certificate (EBC). Further detail about biochar regulations can be found in Section 3.

Biochar Application on Agricultural Land

Motivations and perceived benefits of applying biochar on agricultural land

While biochar has many uses, traditionally it has been utilised as a soil improver due to its perceived agronomic benefits. It must be noted that benefits can substantially vary between soil types, crops grown and geophysical differences in biochar properties associated with feedstock type and pyrolysis conditions. In some cases biochars have not provided any benefits at all (Ye et al. 2020).

Application rates of biochar on agricultural land

Typically, biochar tends to be applied to agricultural land before the planting season, and can be applied alongside organic and mineral fertilisers (Joseph *et al.,* 2021). Major (2010) states that *"In conventional field cropping systems, biochar should ideally be managed using traditional farm machinery and incorporated into routine field operations"*. Thus, biochar would be applied when a farmer or landowner ploughs, plants or harvests.

Methods of biochar application

Typically, biochar is either applied to agricultural land through surface spreading or by incorporating it into the soil. As to which method is used will largely depend on routine field operations. For example, grasslands are re-seeded every 3-5 years providing an opportunity to incorporate biochar into the soil when the soil is tilled. However, during the periods in which the land is in pasture, surface spreading is the only practical approach for biochar application.

It is typical for biochar to be applied to agricultural soils by utilising existing farmyard machinery and equipment. For example, farmers use lime spreaders for biochar application.

Gelardi *et al.,* (2019) suggest other methods of integrating biochar in the soil such as pelletising and the use of slurry tankers with manure slurry mixed in with the biochar. The authors note, however, that the machinery in the latter case would have to be monitored for damage. Pellets may overcome a spreading health and safety risk as it has also been noted that dust emission can be a challenge when spreading biochar as a powder (Xie *et al.,* 2021; Gelardi *et al.,* 2019).

This includes traditional banding (a band of fertiliser alongside planted seeds), as a method that causes minimal soil disruption. Soil application methods are heavily influenced by the type of farming system, labour availability, and power machinery available (Graves *et al.,* 2013). There was little information in the media, nor the academic or grey literature regarding whether contractors or farmers themselves would be better suited to applying the biochar to the farmland.

More research is needed to understand potential challenges to the widespread use of biochar such as *larger* industrial-scale biochar carbon storage creating environmental impacts and costs (Hansen *et al.,* 2017). Therefore, "tailor-made" biochars may need to be developed for particular soils and crops to achieve specific outcomes (Ramos *et al.,* 2017). In the context of paludiculture, these factors could be important in understanding the practicalities and behaviour for biochar application to these soils.

4.4 Biochar Supplier Perceptions

Background

This exploratory research aimed to identify the barriers and enablers for biochar storage and application on agricultural land in the UK, with a particular focus on its use in paludiculture. As no commercial examples of biochar use in paludiculture currently exist in the UK, the research focussed on stakeholder perceptions of the incorporation of biochar into other soil types.

The research involved three biochar suppliers and utilised an informal data collection approach through e-mail questionnaires and one online interview. Given the nascent stage of biochar use in the UK, the suppliers expressed reluctance to participate in formal interviews, leading to the decision to use a questionnaire to maintain open communication. This initial phase helped shape the research direction and inform questions for the future workshop with farmer stakeholders.

Methodology

Data on the current and required capabilities for biochar application were gathered from three UK-based biochar suppliers, each of whom were provided with nine questions (Appendix 4) via e-mail and an interview. The data collection was exploratory, aimed at gaining insights into biochar usage in agriculture and identifying future trends. The suppliers were selected from contacts within the project research team. These stakeholders were reluctant to participate in a formal interview, as they perceived the biochar industry in the UK to be nascent and felt the information they had to share was more anecdotal than definitive. To encourage participation, a questionnaire was used for data collection, providing a more informal way to engage with suppliers and facilitate open discussion via e-mail. While all suppliers were UK-based, the online interview was conducted with an organisation that has a more established international presence. The remaining data was collected by e-mailing the questions to the other suppliers.

Key Findings

Through an exploratory questionnaire and interview with three UK-based biochar suppliers, the following key findings were identified, we provide further detail in the Appendices (Section 8).

Biochar Role in Agriculture

The UK-based biochar suppliers primarily emphasised biochar's role as a soil improver particularly with regards to enhancing soil structure, water retention and nutrient availability for agricultural applications like tree planting, high-value crops, and grassland. Suppliers were uncertain about the widespread adoption of biochar among UK farmers, though some were aware of farmers participating in carbon finance markets.

Application Methods

The machinery typically used for biochar application includes rear discharge manure spreaders, lime spreaders, and fertiliser spinners. Suppliers reported that biochar could be added to organic materials like compost or farmyard manure (FYM) and spread with standard agricultural equipment. The addition of biochar to these mixtures can enhance microbial activity in the soil, contributing to improved soil health and plant growth. No additional capital or labour costs were anticipated for a typical farm, as existing equipment could be adapted for biochar application.

Biochar Storage and Handling

Proper storage of biochar is essential to prevent combustion risks and maintain product quality. Suppliers highlighted the importance of moisture control, with some recommending pelletised biochar for easier storage and handling. However, concerns were raised that compression into pellets may reduce biochar's surface area, potentially limiting its microbial benefits. Additionally, it was noted that pelletisation could impact biochar's overall life cycle benefits, though it was unclear whether this referred to economic viability or carbon performance.

Blending biochar with organic materials such as compost or slurry was identified as a practical solution for minimising dust, reducing handling challenges, and improving safety on farms.

Challenges in Paludiculture

Existing biochar application methods may not be directly transferable to waterlogged peat soils due to access constraints and machinery limitations. Suppliers and stakeholders highlighted the need for lightweight equipment or alternative delivery systems to avoid compaction risks and ensure even application. Additionally, concerns were raised about biochar mobility in wet conditions, with suggestions that application timing and water table management should be considered to maximise its effectiveness in paludiculture systems.

Regulatory Considerations

While biochar suppliers were not opposed to regulation, they suggested that third-party auditors could verify biochar products for use in agricultural systems, rather than creating a new UK regulatory body. Suppliers acknowledged the importance of existing standards like the Biochar for Sustainable Soils initiative, which could serve as useful models for regulating biochar in agriculture and paludiculture.

4.5 Peatland Farmer Perceptions

This section presents the key themes from a workshop held in partnership with Fenland Soil on 5th December 2023 in Ely. The workshop was structured into two parts: the first focused on discussion questions related to biochar, while the second explored biochar integrated with paludiculture (Appendix 7).

Seven participants attended, representing a mix of farmers, advisors, researchers, and a city council representative. In addition, three members from Fenland Soil participated in discussions.

The three-hour workshop began with a presentation from UKCEH outlining the project. Attendees then engaged in three themed discussions at designated 'stations' around the room, where biochar samples were available for hands-on interaction. Discussions were informed by findings from the supplier questionnaire, which explored general awareness and perceptions of biochar and integrating biochar with paludiculture. Building on supplier insights, the workshop provided an opportunity to further examine perspectives on paludiculture, particularly in relation to policy and the role of biochar in improving its financial viability.

The following sections summarise the main themes from these discussions, including insights from both structured and informal conversations held during the event.

Stakeholder perceptions on evidence gaps

During the Q&A session the farmers raised questions that demonstrated a mix of curiosity, scepticism, and practical concerns regarding biochar application in agriculture. Overall, the questions raised highlighted that while farmers recognise biochar's potential, they need more evidence, clear policy guidance, and practical demonstrations before committing to widespread adoption. The key themes raised included:

Scientific Understanding & Long-Term Carbon Storage

Farmers were interested in the gases produced from production, the long-term carbon sequestration potential, soil nutrient retention (NPK), and biochar water absorption qualities. Comparisons to Anaerobic Digestors (AD) suggest they value circular nutrient management.

Sustainability

Farmers were concerned about the sustainable sourcing of feedstock to produce biochar, including the types of wood used and the longevity of biochar in soil. Questions around whether certain biochar types would break down too quickly and how their application fits into sustainable land management practices highlighted the desire for clear guidance.

Regulatory & Policy

Questions were asked around the 1-tonne regulatory application limit (dry vs. wet weight) and its rationale. This highlighted the uncertainty about compliance and potential limitations. There were queries as to whether this could be integrated with agri-environment schemes like Sustainable Farming Incentive (SFI), reinforcing the message that farmers were open to the idea but required further information/guidance to influence uptake.

Economic & Market Considerations

Questions on carbon content per tonne of biochar, the balance between food and fuel production, and payments to farmers revealed economic and national food supply concerns. The comparison with anaerobic digestion also suggests a need to understand whether biochar application (and creation) represented a sufficiently competitive economic opportunity.

Proposed Practical Application Methods

Methods for conventional lowland peat farming

Discussions initially centred on biochar application within conventional agriculture. Participants unanimously agreed that they already possessed the necessary equipment for application, suggesting the use of compost/fertiliser spreaders, waste/manure spreaders, or lime spreaders.

The rate of application was perceived as dependent on multiple factors, including soil impact, cost, and anticipated benefits. Participants emphasised that application rates should be guided by the need to maintain optimal soil health and structure. A key challenge identified was the particle size and density of biochar, which could affect application efficiency. However, practical experience in this area was limited, and participants suggested that trials would be necessary to establish best practices.

There was little general awareness of regulatory restrictions on biochar application. When researchers informed participants about the Environment Agency's 1 t/ha application limit, some suggested that staggered applications could help maintain microbial activity over time. This response indicated an underlying interest in the potential microbial benefits of biochar application.

Methods for paludiculture farming on lowland peat

The discussion then shifted to biochar application under paludiculture conditions. Participants generally expressed negative perceptions toward paludiculture as a farming model, citing several key concerns:

- Difficulty with land access - The wet conditions of paludiculture farming were seen as a barrier to basic farm operations, including machinery use.
- Food security concerns – Farmers worried that converting land to paludiculture would reduce food production whilst also offshoring the high emission problem elsewhere given this will likely increase the need to rely on imports.
- Financial viability – Poor financial returns from paludiculture were seen as a major limitation.

Despite these reservations, when prompted to consider biochar application under a hypothetical paludiculture farming model, participants proposed integrating application with planting or harvesting. This approach was seen as practical, as land would likely need to be temporarily drained for machinery access, providing an opportunity to apply biochar at the same time.

Specialist machinery was also discussed, with concerns raised about high costs, particularly for attachments that might not be compatible with existing equipment. Alternative solutions were suggested, including:

- Low-ground-pressure vehicles similar to those used for lime spreading.
- Machinery adapted from other sectors, such as equipment used in snow-covered environments (e.g., ski slopes) or forestry.
- Drones, which could mitigate soil structure damage from heavy machinery. However, participants noted that drone application would need to be evaluated in a full Lifecycle Analysis (LCA) to assess feasibility.

There was a general perception that land would need to be drained before biochar could be applied, reinforcing concerns about the practicality of application in persistently waterlogged conditions.

If financial support were available for paludiculture, farmers expressed a preference for using contractors to spread biochar. Some suggested that biochar suppliers could act as contractors, leveraging their expertise to ensure proper application.

Motivations for biochar use

Farmers were primarily motivated to apply biochar for its potential to improve soil health, enhance carbon sequestration, and provide financial benefits, with key drivers including financial returns, net-zero targets, and a better understanding of its scientific and agronomic advantages.

Landowners identified two primary incentives for biochar application within a paludiculture system:

- Earning carbon credits – Using biochar for carbon credits to generate revenue.
- Enhancing their own carbon balance – by offsetting emissions.

Participants were presented with an example of a commercial circular farming model on lowland peat that incorporated paludiculture, food production and biochar (Lapwing Energy, Reverse Coal Project). This model is defined by the Reverse Coal Project as the following:

'We rewet lowland peat and establish short rotation coppice willow. The biomass is then harvested and fed through pyrolysis to produce biochar and generate renewable energy. We then bury the biochar, locking carbon back in the ground. The high grade heat and power will be used to power controlled environment agriculture for more sustainable food production.'

Following this, participants highlighted that financial incentives could also include energy savings or selling through energy production during the pyrolysis process. They highlighted that the biochar infrastructure could resemble that of anaerobic digesters, where energy could be sold to the grid as well as used by the producer. However, it was noted that the grid might be saturated, especially if there is poor infrastructure. Currently, the National Grid lacks sufficient capacity, and smaller sub-plants may not be large enough to make a meaningful impact. Alternatively, it was suggested that funding support could come from the SFI or forestry grants.

Challenges and Reservations for Paludiculture Integrated with Biochar

While there was no significant pushback against the concept of biochar itself, concerns were raised regarding its implementation and, more notably, the broader shift toward paludiculture. Participants expressed hesitation about biochar use primarily in relation to cost, the lack of measurable benefits for soil health, potential interference with crop production or harvesting, and uncertainty around financial returns.

More significant resistance emerged regarding paludiculture. Many participants perceived it as a practice primarily for conservation rather than commercial farming, leading to expectations that it would require substantial subsidies to remain financially viable. Paludiculture was viewed as a niche approach, relevant only to deep peat or low-lying areas prone to flooding. Given that only parts of a farm might initially be suitable for paludiculture, participants questioned whether the necessary investments could be justified when considering the overall farm system. This suggests that financial and logistical concerns, rather than outright opposition to the concept, were key barriers to adoption.

One of the most significant perceived challenges was water management, particularly concerns about whether sufficient water would be available to sustain paludiculture effectively. Was also noted that with climate change increasing the likelihood of extreme weather events, participants questioned how paludiculture would handle excess water during storms, particularly given its reliance on maintaining a high-water tables.

Participants felt that the largest investment required for paludiculture would be in drainage infrastructure, with terraced drainage suggested as a potential solution. As paludiculture has the potential to reshape landscapes, cooperation among multiple landowners was seen as essential for success. The need for collective action may present a barrier, as individual farmers may be reluctant to invest in a system that depends on broader regional adoption. Additionally, concerns were raised about the potential for methane fluctuations in flooded conditions and suggested that emissions trade-offs should be considered.

The practicality of biochar application within a paludiculture system was also questioned. Given the current regulatory limit of 1 t/ha, some participants felt that applying biochar to peatland would require significant effort for relatively little gain. Financial considerations were central to these discussions, with participants calculating that biochar production could generate an income of approximately £5,000/ha, assuming a gross margin of £2,850/ha before storage and haulage costs. However, annual maintenance costs could significantly impact profitability, reinforcing concerns about financial viability.

Another major issue was the limitations of current voluntary carbon credit markets, such as PuroEarth, which in some cases only provide payments to farmers if they produce the biochar themselves, rather than for its application. This was seen as a major disincentive for biochar application, as farmers who do not have the capacity to produce biochar would not receive financial support for using it. However, participants did acknowledge that biochar could offer an opportunity to improve their own carbon balance, particularly through Scope 3 emissions reductions. Some saw potential for biochar to serve as an "inset" rather than an "offset" in farm-level carbon accounting, allowing farmers to reduce their own emissions rather than purchasing external carbon credits. However, it was noted that this might require substantial tree planting to produce sufficient biomass for biochar.

More generally, participants emphasised the need for further evidence on the agronomic benefits of biochar production and storage within a paludiculture setting and how these elements could be used to improve overall economic viability.

Beyond agronomic and financial concerns, some participants felt external pressure related to broader agricultural policy shifts. There was a perception that farmers are being pushed towards land-use changes that may not align with their priorities, particularly when food security is a concern. This scepticism was reinforced by past controversies, such as media criticism of farmers growing maize for bioenergy instead of food production. These concerns suggest that any large-scale adoption of paludiculture and biochar would need to be carefully framed within broader agricultural and environmental policies to ensure farmer buy-in.

4.6 Conclusions

The workshop provided valuable insights into farmers' perspectives on the use of biochar in both conventional farming and paludiculture. While farmers generally viewed biochar positively, recognising its potential benefits for soil health, carbon sequestration, and financial returns, their primary reservations were related to the broader concept of transitioning to paludiculture.

For conventional farming, there was clear interest in using biochar, with farmers expressing a readiness to incorporate it into their existing practices. Practical concerns such as application methods, regulatory limitations, and cost-effectiveness were raised, but these were seen as challenges that could be addressed through further research and trials, rather than insurmountable barriers.

When it came to paludiculture, the response was notably different. The idea of converting conventional vegetable production land to paludiculture was met with more resistance, primarily because it was perceived as a land-use shift toward conservation rather than commercial farming. Farmers raised concerns about the impact on food security, financial viability, and the practicality of managing wetland conditions. While some expressed interest in integrating biochar into paludiculture under certain conditions, the overarching reluctance to embrace paludiculture as a viable farming model was the main barrier. The need for significant infrastructure investments and doubts about the long-term economic returns made the concept less appealing.

In terms of investment costs for biochar, farmers acknowledged that they currently possess the necessary machinery for biochar application within conventional farming models, such as compost/fertiliser spreaders and manure spreaders. However, it was noted that within the context of paludiculture, equipment requirements (and investment costs) may differ due to the waterlogged conditions. If the land is temporarily dried to allow machinery access, then existing equipment can be used for biochar application.

Supplier perceptions aligned with farmers as to the types of machinery required for biochar application, indicating that both groups identified similar infrastructure needs. However, while farmers were more attuned to the potential of carbon credit markets, suppliers focused primarily on the agronomic benefits of biochar as a soil improver. This difference in focus could be attributed to the way carbon credits are currently structured in some of the more developed voluntary carbon markets, where the carbon credits are owned by biochar producers or suppliers, rather than those that apply to it land (e. g. farmers). This structure means suppliers have a financial incentive to sell biochar with the associated carbon credits, but it doesn't directly increase the revenue for farmers unless they produce the biochar themselves. As such, the potential financial benefit from carbon credits is not typically highlighted by suppliers when marketing biochar as these benefits have already been utilised by the biochar producer.

In conclusion, while farmers are generally open to the potential of biochar in conventional farming, the shift toward paludiculture remains a contentious issue. For biochar to gain broader acceptance, particularly in paludiculture systems, there needs to be greater clarity on its practical application, financial incentives, and long-term benefits. Additionally, the move toward paludiculture must carefully consider wider economic and policy frameworks to ensure it aligns with farmers' (and policy makers) priorities, including food security, financial viability, and farm-level sustainability goals. The integration of biochar, therefore, is less about its direct application and more about how it fits within the wider context of land use, policy incentives, and farm infrastructure, with particular attention paid to the investments required for transitioning to a paludiculture model.

5. Economic Analysis of Paludiculture Farming Models with Biochar Integration

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5.1 Executive Summary

This Section evaluates the financial and environmental viability of a range of paludiculture business models for lowland peat soils, including scenarios with and without biochar production. Paludiculture refers to the cultivation of wetland crops on rewetted peatlands, offering a nature-based solution to reduce greenhouse gas emissions and restore degraded soils. This study assesses how integrating biochar, produced from harvested paludiculture biomass, can enhance both climate benefits and farm-level returns. The analysis draws on life cycle assessment (LCA), techno-economic analysis (TEA), and farm-level financial modelling to explore four scenarios:

Key Findings

- Paludiculture based solely on crop sales is not currently competitive with conventional arable or horticultural cropping when relying solely on crop sales. However, when combined with agri-environment payments and carbon credit income (e.g. from the Peatland Carbon Code), it can become a viable land use alternative on deep peat soils.

- Integrating biochar production with paludiculture improves both environmental and financial performance, only when farmers produce their own harvested biomass for biochar production. This avoids high purchase costs and enables direct access to biochar carbon credits. Buying in biochar, by contrast, is not financially viable under current carbon credit prices.

- Among the three crops assessed, reed and miscanthus show the most promising performance, offering stronger financial returns and carbon savings compared to willow. Reeds deliver the highest return per unit of labour, while miscanthus demonstrates strong carbon removal potential when converted to biochar.

- Integrated paludiculture business models that 'stack' income from crop sales, government payments (e.g. ELMs), and carbon credits offer the highest potential returns. However, current market and policy constraints, such as restrictions on stacking payments and credit ownership, limit uptake. Flexibility in these rules would significantly improve paludiculture adoption potential.

Policy and Practice Implications

- Policy adaptations are needed to allow stacking of agri-environmental payments and carbon credit income, and to enable farmers to retain credits from biochar produced off-site.
- Investment in regional pyrolysis infrastructure would improve scalability for biochar integration and access to carbon markets for land managers.
- Biochar credit schemes should consider rewetted conditions when assessing permanence and carbon removal potential, as these environments enhance the long-term stability of even low-grade biochars.

Conclusions

Paludiculture, particularly when paired with integrated biochar systems, shows promising potential as a climate-smart land use strategy for lowland peat soils. While biochar integration can enhance both financial and environmental outcomes, many of the benefits, particularly around the stability of low-grade biochar in rewetted conditions, remain theoretical and requires further empirical validation. Nonetheless, the modelling suggests that, under the right conditions and with appropriate policy support, these systems could offer viable alternatives to conventional farming while delivering meaningful greenhouse gas reductions.

5.2 Introduction

Paludiculture, the cultivation of wet-adapted crops on rewetted peat soils, is increasingly recognised as a land use strategy that can deliver both climate and environmental benefits. By raising the water table on drained agricultural peatlands, paludiculture has the potential to significantly reduce greenhouse gas emissions while maintaining productive use of the land. However, uptake remains limited due to financial uncertainty and a lack of clear evidence on viable business models for farmers and landowners.

This report assesses the financial and environmental viability of several paludiculture cropping systems, including those that incorporate biochar production. Through a combination of life cycle assessment, techno-economic analysis, and farm-scale financial modelling, the study evaluates the costs, benefits, and trade-offs associated with producing biochar from paludiculture crops and applying it to land as a means of generating carbon credits.

The analysis also compares a range of income sources, including crop sales, agri-environment payments, and carbon credits from rewetting and biochar, to identify the conditions under which paludiculture can provide a financially attractive and climate-positive alternative to conventional farming on lowland peat soils.

5.3 Methods

This study evaluates the financial and environmental performance of paludiculture business models on deep peat, including the integration of biochar. The methods are split into three interconnected parts:

Part 1: Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) of biochar production pathways, led by the University of Nottingham.

Part 2: Farm-level financial modelling and scenario analysis of land use transitions to paludiculture, led by Bangor University.

Part 3: Spatial optimisation of biochar infrastructure within lowland peat areas, led by the University of Nottingham.

The outputs from Part 1. including the cost of biochar production, transport and estimates of carbon removals and carbon stability feed directly into Part 2, where they are incorporated into financial models to assess the viability and scalability of different management options.

Part 1: Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA)

The system boundary encompasses feedstock transport, drying, and pyrolysis. We analysed two primary production scenarios covering potential options for producing biochar from paludiculture crops grown on peat:

- Farm-scale production using batch pyrolysis without heat generation for low- and high-grade biochar.
- Commercial-scale production using continuous pyrolysis with heat generation for low- and high-grade biochar.

Both scenarios were assessed through life cycle assessment (LCA) and tecno-economic analysis (TEA) to determine their environmental and economic viability of both scenarios.

The system boundary is illustrated in Figure 21 and the functional unit is defined as 1 tonne of biochar produced. Inventory data considerations are detailed in Appendix 8.

Biochar is categorised into high-grade and low-grade types based on production temperature, atomic H/C ratio, and carbon stability. We used European Biochar Certificate (EBC, 2023) guidelines for production temperature and H/C ratio, defining high-grade biochar as produced at temperatures above 500 °C with an atomic H/C ratio between 0.2–0.7, and low-grade biochar as produced at temperatures below 500 °C with H/C ratios above 0.7. However, carbon stability values were not assumed based on conventional approaches. Instead, we estimated 100-year carbon retention using H/C_org ratios extracted from Rodrigues et al. (2023), adjusted for rewetted conditions using soil moisture modifiers from three biogeochemical models—ECOSSE, DayCent, and StandCarb. The final100-year carbon retention value was the mean of the three model-adjusted estimates. For further detail please see Section 2.2.

For farm-scale production, a transportation distance of 2 km was assumed, as biochar production occurs on-site. In contrast, a 50 km transportation distance was considered for commercial-scale production, accounting for potential transport to external facilities.

The data for this analysis were sourced from lab-scale analyses conducted within the GGR Biochar Demonstrator project and peer-reviewed literature.

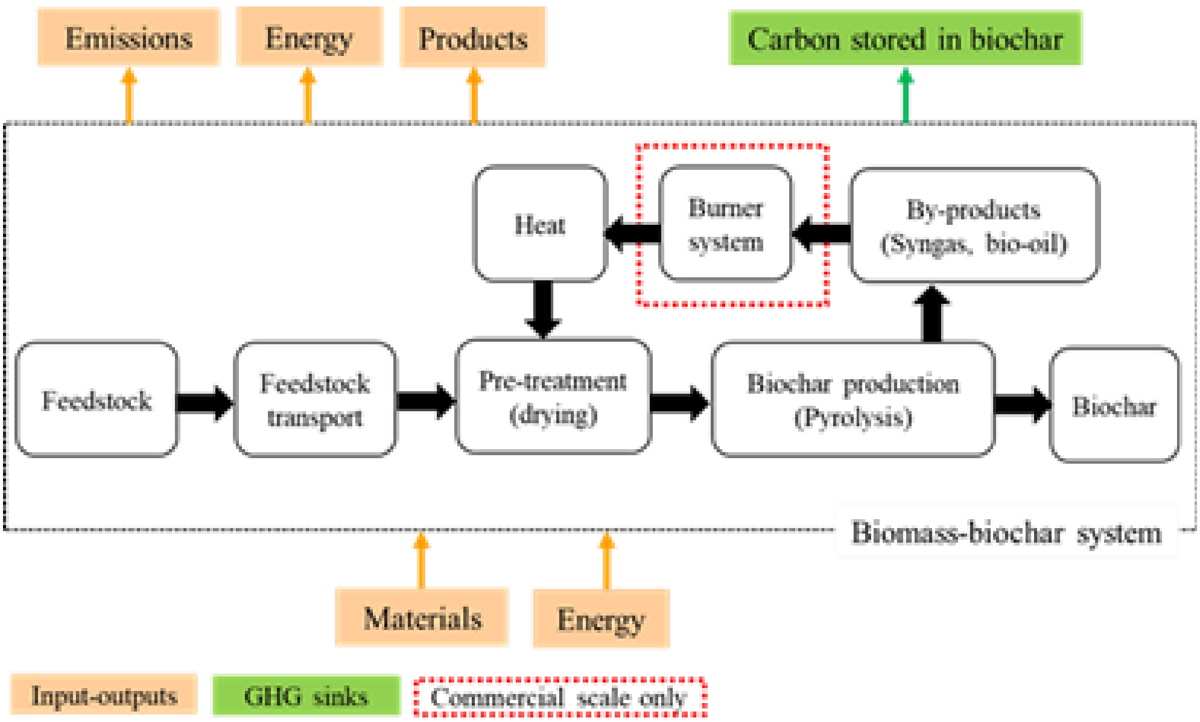

Figure 21: Biochar production system boundary.

Part 2: Farm-level financial modelling

We constructed a Microsoft Excel© based tool to compare 'alternative' paludiculture management systems to indicative business-as-usual management scenarios based on:

- Environmental performance (GHG emissions reduction)
- Financial performance (long term financial returns)
- Cost-effectiveness (GHG savings per pound of operating costs)

The modelling tool used in this project is a development of the approach taken in the Lowland Peat 2 (LP2) Project (Evans et al., 2023). Much of the data within the model is drawn from work packages within the LP2 project and supplemented with actual farm data, other industry sources (e.g., John Nix Pocketbook for Farm Management) and peer reviewed literature. The original model was built on look-up tables of GHG emissions factors for different water table depths, allowing users to alter WTD depths and estimate the impacts on GHG emissions and financial returns. For this project the model was developed further to include additional capability to estimate the amount of carbon credits that could be generated from rewetting, carbon credits from Biochar production and investment appraisal of land use transitions to paludiculture (over a 30-year horizon). We incorporated the UK (Fen) Peatland Carbon Calculator V2 (Evans et al., 2023) into the model and look up tables of results from the LCA/TEA modelling carried out in Part 1 to estimate the costs of biochar production and carbon credit generation.

The model can be parameterised with farm specific data relating to cultivation, inputs and costs to suit a range of different situations.

Crop options and scenarios

We used our Excel© based tool to model the financial and environmental outcomes of five cropping options across four business model scenarios (describing different combination of income streams, governmental payments and carbon credit scheme rules). All of these crop options and scenarios were modelled based on 'deep' peat soils (assuming a depth of > 100 cm). Table 6 outlines the crop options considered in this analysis.

Table 6: Modelled crop options.

Option	Name	Water table depth (cm)	Description
Crop option 1	Wheat (BAU)	100	Based on winter wheat assuming average yielding system.
Crop option 2	Lettuces (BAU)	50	Based on cropping with lettuces harvesting twice a year.
Crop option 3	Miscanthus	20	Based on miscanthus (*Miscanthus x giganteus*) with a 20-year crop lifetime.
Crop option 4	Willow	20	Based on willow (*Salix spp.*) short rotation coppice with a 22-year crop lifetime.
Crop option 5	Reed	10	Based on common reeds (*phragmites australis*) with a six-year crop lifetime.

Wheat (BAU) and Lettuces (BAU) reflect examples of prevailing agricultural management of deep peat soils (i.e., arable cropping on deeply drained soils and high value horticulture on soils where perhaps the water table is higher yet still drained). Miscanthus, willow and reed reflect alternative options suitable for paludiculture that could be implemented on deep peat soils with significantly raised water table depths.

Financial performance

Within our Excel© based tool we used a range of financial metrics to compare the financial performance of the different crop options and a range of integrated business models. To calculate all of the financial metrics, we took general agricultural management (including fertiliser requirements and cultivations) and budgeting data (including income, variable costs and fixed costs) from the *John Nix Pocketbook for Farm Management* (Redman, 2022). We took operational data for high value horticulture with lettuces from a range of sources in the literature (Bartzas et al., 2015; Canals et al., 2008; NSW DPI, 2013). We took costs for paludiculture establishment from specialist online information (Crops for energy, 2025).

Gross and net margin

We used gross and net margins to compare potential annual returns of the five cropping options. We calculated the gross margin of each cropping options as:

Gross margin (£ ha^{-1}) = income – variable costs

Variable costs included establishment (e.g., seed, plugs or rhizomes), fertiliser and sprays. We calculated the net margin of each cropping option as:

Net margin (£ ha^{-1}) = income – (variable costs + fixed costs)

Fixed costs included labour, machinery costs (fuel, repairs, depreciation, and insurance), cultivations and assignable farm overheads (maintenance, utilities, and general overheads). For the agriculture options (wheat and lettuces) these are based on annual costs and incomes, for miscanthus and reed these are based on annual incomes and costs annualised over the lifetime of the crop (20 years for miscanthus and 6 years for reeds). For willow these are based on costs annualised over the lifetime for the crop (22 years) and annualised returns (based on harvest every three years)

The gross and net margin figures were calculated to compare:

1. the returns of each of the cropping options (two agriculture and two paludiculture) based on incomes from crop sales alone.
2. the returns of the three paludiculture crops based on crop sales and biochar carbon credits assuming biochar (low- and high-grade wood) was bought in and applied to the crop.

Capital budgeting and integrated business models

The modelling in Evans et al., (2023) suggested that based on direct incomes alone from crop sales that paludiculture couldn't compete with conventional arable or horticultural cropping on deep peats. Hence, in this project we explored how several business model scenarios, including different combinations of income, government payments, biochar production (from harvested crops) and generation of carbon credits, impact the financial viability of paludiculture as a management option. Table 7 outlines the integrated business models considered in this analysis.

In scenario 1 income is generated from the sale of paludiculture crops into established markets (bioenergy for miscanthus and willow and thatching for reeds) and payments for ELMS SW17 *Raise water levels in cropped or arable peat soils.* In scenario 2, carbon credits sales from the peatland carbon code are stacked on top of incomes from sales and additional government payments as above. In scenario 3, paludiculture crops are diverted into production of low-grade biochar using a farm-scale mobile kiln and applied back to the soil, allowing the farmer to generate and sell biochar carbon credits on top of the peatland carbon code credits and ELMS payments. Scenario 4 is the same as scenario 3, except that the farmer pays for use of a commercial pyrolysis set up to produce the low-grade biochar to generate and then sell biochar carbon credits. Scenarios 1 and 2 push the boundaries of the rules of stacking carbon credit incomes and governmental payments. Scenarios 3 and 4 push the boundaries of biochar carbon credit schemes.

Table 7: *Integrated business model scenarios:*

Business model Scenario	Biochar application?	Incomes				Biochar carbon credits destination
		Direct incomes (sales)	Government payments	Peatland code carbon credits	Biochar carbon code carbon credits	
Scenario 1	Without biochar application	☑	☑			
Scenario 2	Without biochar application	☑	☑	☑		
Scenario 3	With biochar application		☑	☑	☑	Farmer produces low grade biochar in mobile unit (biochar credits to farmer)
Scenario 4	With biochar application		☑	☑	☑	Farmer produces low grade biochar in commercial unit (biochar credits to farmer)

To account for the longer-term additional income streams (through governmental payments and carbon credits) and different time horizons of the alternative cropping options we used capital budgeting techniques (based on two different types of discounted cash flow forecasting). We used:

- Net present value (NPV) and annual equivalent value (AEV) is a measure of the absolute value of the investment by calculating the present value of all future cash flows. The NPV and AEV figure is as an indicator of long-term financial returns at a given discount rate (i.e., the overall increase in 'wealth' from investment in that option).
- Internal rate of return (IRR) provides a standardised measure of profitability, allowing for direct comparison of options with varying costs, revenues and time horizons. The IRR figure provides a measure of the relative financial returns.

We calculated the NPV as:

$$NPV = \sum_{n=1}^{N} \left(\frac{CF_n}{(1+i)^t} \right)$$

where CF_n is the cash flow in year n, t is the time period (number of years into the future), N is the time horizon, i is the discount rate.

We calculated the AEV to convert the NPV to an annual 'payment', this allows comparison of long-term investments with agriculture (i.e., yearly incomes). We calculated the AEV as:

$$AEV = \left(\frac{i(NPV)}{1-(1+i)^{-N}} \right)$$

where *N* is the time horizon and *i* is the discount rate. Both the NPV and AEV were initially calculated over a 30-year time horizon and at a discount rate of 5%. We also carried out a sensitivity analysis recalculating these at 3, 4, 6 and 7%.

To calculate the IRR we used the following formula:

$$NPV = 0 = \sum_{n=1}^{N} \frac{CF_n}{(1 + IRR)^n}$$

where CF_n is the cash flow in year *n*, *n* is a single period between 0 and N*,* *N* is the time horizon and *IRR* is the Internal Rate of Return (i.e., the discount rate where NPV = 0).

We calculated the NPV, AEV and IRR metrics for both of the business-as-usual cropping options (wheat and lettuces) and for the three paludiculture cropping options across the four business model scenarios. The calculated for the three paludiculture options across the four business model scenarios was repeated twice assuming the farmer had either started with wheat (and a WTD of 100cm) or lettuces (and a WTD of 50cm), this was important as the original starting crop (and WTD) had a big impact on carbon credit generation and hence financial returns. This part of the modelling drew in data from the TEA and LCA modelling carried out in part 1.

Returns to labour

Returns to labour is an important financial metric that helps evaluate the profitability and efficiency of labour input into an agricultural enterprise. Returns to labour assess how much value is generated per unit of labour input, showing whether workers are being used efficiently. High returns indicate labour is producing significant value relative to its cost. To calculate this, we divided the annual equivalent value of the cropping options by their annual labour requirements (determined by the enterprise inputs in the Excel© model and standard labour requirements for agricultural operations in the John Nix Pocketbook for farm management).

Environmental performance

To assess the environmental performance of the different management options we used a carbon footprinting approach. The carbon footprints calculated using our Excel© based tool were based on CO_2, N_2O emissions (both direct and indirect) and CH_4 emissions (all expressed as CO_2e) up to 'the farm gate'. CO_2 emissions included direct emissions from organic soils, diesel use and lime and Indirect emissions from fertiliser use and agrochemical use. N_2O emissions from included direct emissions from organic soils, fertilisers, crop residues returned to soils and indirect emissions from volatilisation and leaching and runoff. CH_4 emissions included only those from organic soils due to our management scenarios not involving any livestock.

We followed the *IPCC Guidelines for National Greenhouse Gas Inventories Volume 4 AFOLU* (IPCC, 2019) for calculating indirect CO_2 emissions from fertiliser, direct N_2O emissions from fertilisers and crop residues returned to soils, and indirect N_2O emissions from volatilisation and leaching and runoff. We used emissions factors for direct CO_2 , N_2O and CH_4 emissions from organic soils from peer reviewed literature (Evans et al., 2021). We took all other emissions factors from the IPCC emissions factor database (IPCC, 2021). We took additional operational data used to calculate the carbon footprints relating to machinery diesel use from *SAC Farm management handbook* (SAC Consulting, 2022), fertiliser application rates from the *John Nix Pocketbook for Farm Management* (Redman, 2022) and Pesticide application rates from Pesticide Usage survey reports (Ridley et al., 2021a, 2021b, 2020).

In the carbon footprint estimates, carbon removal from the crop is not considered in this calculation. If carbon removal is to be included in the footprint assessment, the fate of the harvested product must be accounted for. The potential for long-term carbon storage depends on its end use. For instance, incorporation into construction materials may sequester carbon for decades, whereas use as animal bedding or other rapidly decomposing applications will result in quicker CO2 release back to the atmosphere. Long-term carbon storage from biochar incorporation is accounted for in the carbon footprint estimates, this is based on the estimates of the total carbon removal through biochar production derived from part 1 methods.

Cost-effectiveness

Using the carbon footprints and financial costings modelled using our Excel© based tool we calculated the cost effectiveness of each of the alternative paludiculture cropping options as a GHG mitigation option.

We calculated the costs-effectiveness of each of the management scenarios as the reduction in GHG emissions per £1 of annual operational costs using the following formula:

Cost-effectiveness (kg CO_2e £$^{-1}$) = CO_2e emissions reduction/(variable + fixed costs)

The CO_2e emissions reduction was calculated as:

CO_2e reduction = CO_2e emissions of the BAU scenario - CO_2e emissions of the alternative scenario

Part 3: Optimising Biochar Infrastructure for Scalable Deployment

To support the scalability of biochar integration into land use transitions on lowland peat, we developed a spatial optimisation model within the Biochar Demonstrator project to identify cost-effective locations for commercial-scale biochar production facilities and their respective feedstock supply networks. This modelling aimed to minimise overall production and transportation costs while maximising feedstock utilisation and carbon removal potential. Actual road transport distances were estimated using the Python OpenRoute service module.

5.4 Results

Paludiculture – without biochar application

This section presents the baseline financial performance of five crop options on lowland peat soils, based solely on income from crop sales. The analysis includes two conventional business-as-usual

(BAU) crops (wheat and lettuces) and three alternative paludiculture crops (miscanthus, willow, and reeds).

Table 8 compares the gross and net margins of the five crop options based solely on income from crop sales, excluding any government support payments or carbon credits. The results clearly illustrate the economic dominance of conventional cropping systems under current market conditions. Arable cropping with wheat yields a gross margin of £1,642 and a net margin of £959 per hectare per year, while high-value horticulture such as lettuces far exceeds this, with annual net margins over £47,000 per hectare. These figures reflect the high turnover and intensive inputs typical of horticultural systems, which can be extremely profitable, especially in peri-urban areas or where multiple harvests are possible.

In contrast, none of the paludiculture options miscanthus, willow, or reeds—come close to matching the financial returns of conventional cropping when relying on crop sales alone. Miscanthus performs the best among the three, with a net margin of £278 ha^{-1} yr^{-1}, but this is still less than one-third of the returns from wheat and only a fraction of those from lettuces. Willow and reeds perform even less favourably, returning just £118 and £70 per hectare per year respectively. These low margins highlight the current financial barriers for paludiculture if assessed on crop revenue alone.

Table 8: *Gross and net margin (£ ha^{-1}) of the five crop options. The gross and net margins include only income from sale of the crops and not any additional incomes from governmental support payments or carbon credits.*

Crop Option	Gross Margin (£ $ha^{-1} yr^{-1}$)	Net Margin (£ $ha^{-1} yr^{-1}$)
Wheat (BAU)	1,642	959
Lettuces (BAU)	58,663	47,268
Miscanthus	517	278
Willow	358	118
Reeds	239	70

Paludiculture with Biochar Integration

This section explores the potential to enhance the financial and environmental performance of paludiculture systems through the integration of biochar. Building on the baseline analysis of paludiculture without biochar, we assess the implications of applying biochar either as an externally sourced input or through on-site production from paludiculture biomass. The analysis includes a comparison of biochar production pathways (low-grade vs high-grade; farm-scale vs commercial-scale) and assessment of fully integrated paludiculture-biochar systems. These scenarios are then compared against conventional cropping systems to evaluate their potential as scalable, financially viable and climate-positive land management models for lowland peat.

Comparing Biochar Production Approaches

To inform the integration of biochar into paludiculture systems, it is essential to understand how different biochar production methods perform in terms of carbon removal and cost-effectiveness. This section compares low- and high-grade biochar produced from three feedstocks (wood, miscanthus, and willow) at two different scales: farm-scale batch pyrolysis and commercial-scale continuous pyrolysis.

A key aspect of this analysis is the distinction between stable carbon and total carbon. Stable carbon refers to the fraction of biochar that is highly resistant to decomposition and is commonly used in carbon crediting and long-term sequestration accounting. Total carbon includes both stable and labile carbon, the latter of which is typically assumed to be lost to decomposition in aerobic conditions. However, under rewetted peatland conditions, where soils are anaerobic, a significant portion of the labile fraction may persist over long timescales (see Section 2.2).

Biochar Production Pathways: Carbon Sequestration and Cost at Point of Production

Figure 22 illustrates net GHG emissions (tCO_2eq) per tonne of biochar and per tonne of dry feedstock across production types. While emissions per tonne of biochar provide useful insight into the efficiency of the pyrolysis process, evaluating emissions per tonne of feedstock offers a more accurate reflection of the true carbon removal potential, since it captures how effectively each tonne of harvested biomass is converted into carbon. This feedstock-based perspective is essential when comparing the climate mitigation value of different cropping and biochar systems at scale.

- Low-grade biochar results in a higher biochar yield per tonne of feedstock. As a result, it shows greater net total carbon sequestration potential per tonne of feedstock.
- High-grade biochar, produced at higher pyrolysis temperatures, has a lower yield but a higher proportion of stable carbon, making it more robust under conventional carbon accounting methodologies.
- Farm-scale systems, while accessible and lower in capital cost, have higher emissions and lower energy efficiency, particularly due to fossil fuel use in the pyrolysis process.
- Commercial-scale systems use recycled syngas for heat, resulting in lower production emissions and marginally higher net sequestration per tonne of biochar and feedstock versus farm-scale production systems.

Transportation emissions remain a modest but important contributor, especially for commercial-scale systems where feedstock must be hauled to centralised facilities.

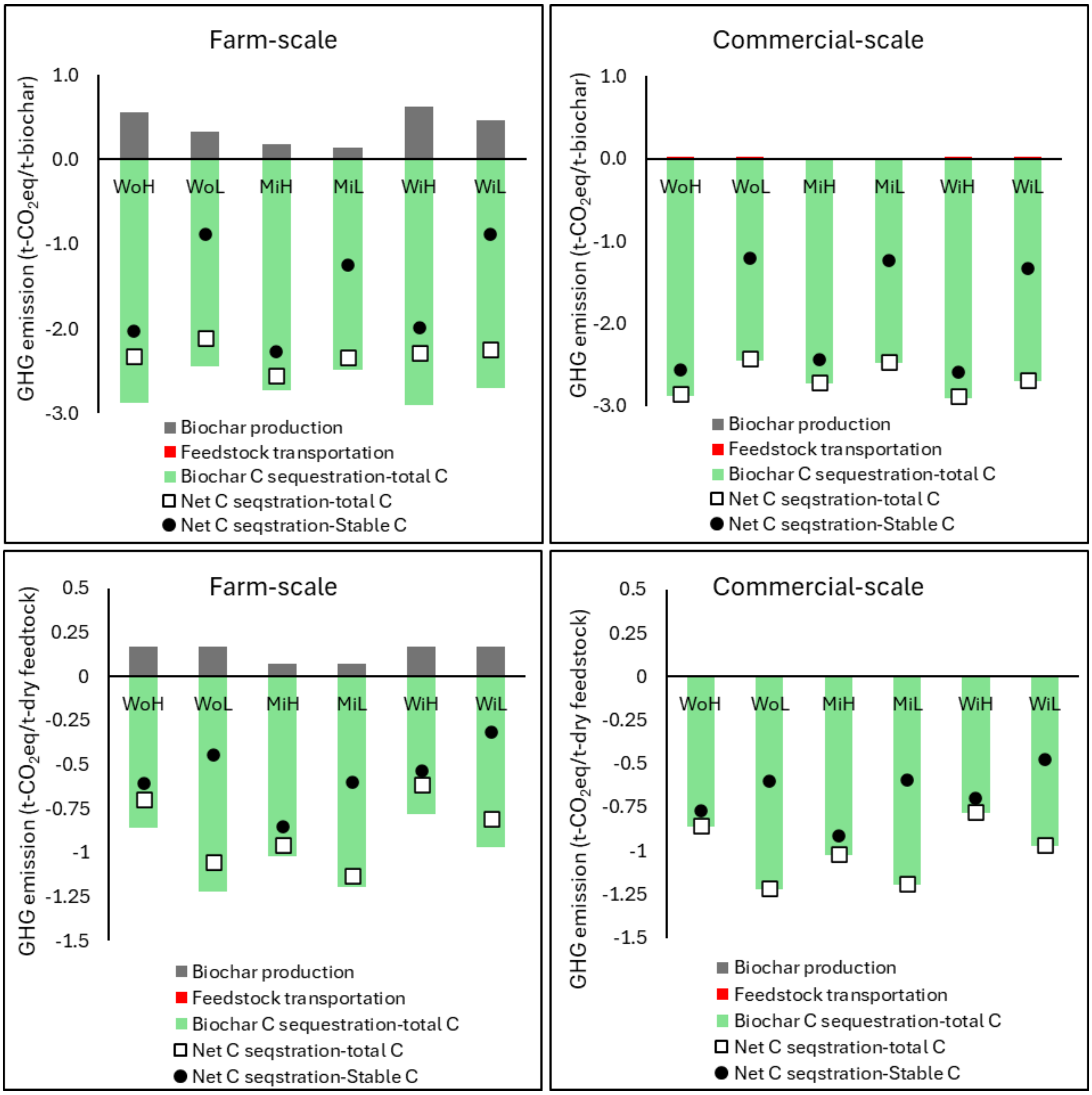

Figure 22: GHG emissions of farm- and commercial-scale production of low- and high-grade biochar. This analysis includes only emissions from biochar production and excludes any soil-related emissions (WoH:Wood high-grade, WoL: Wood low-grade, MiH: Miscanthus high-grade, MiL: Miscanthus low-grade, WiH: Willow high-grade, WiL: Willow low-grade).

Figure 23 presents the cost of CO_2eq removal (£/tCO_2) for each biochar production pathway, broken down by key cost components including feedstock, transport, operational (OPEX), and capital expenditure (CAPEX).

- Farm-scale production incurs higher removal costs across all feedstocks due to lower efficiency, smaller throughput, and greater labour input. However, it offers a flexible and decentralised option for landowners.
- Commercial-scale systems benefit from economies of scale and process integration, making them more cost-effective for biochar production.

- When considering total carbon content (i.e., including both stable and labile fractions), low-grade biochar becomes significantly more competitive, with removal costs dropping substantially across all feedstocks.

Importantly, results based on total carbon offer a more realistic reflection of carbon removal potential in rewetted peatland systems, where waterlogged, anaerobic conditions are likely to suppress microbial decomposition. In these conditions, a significant portion of the labile carbon fraction is expected to persist over the long term. As such, total carbon-based estimates may provide a truer indication of biochar's carbon removal performance in these specific land management contexts.

Nevertheless, we include the stable carbon-based costs as a conservative benchmark and are relevant for applications in drier, more aerobic environments, where decomposition rates are higher, and the labile fraction is more likely to be lost (e.g. drained peat).

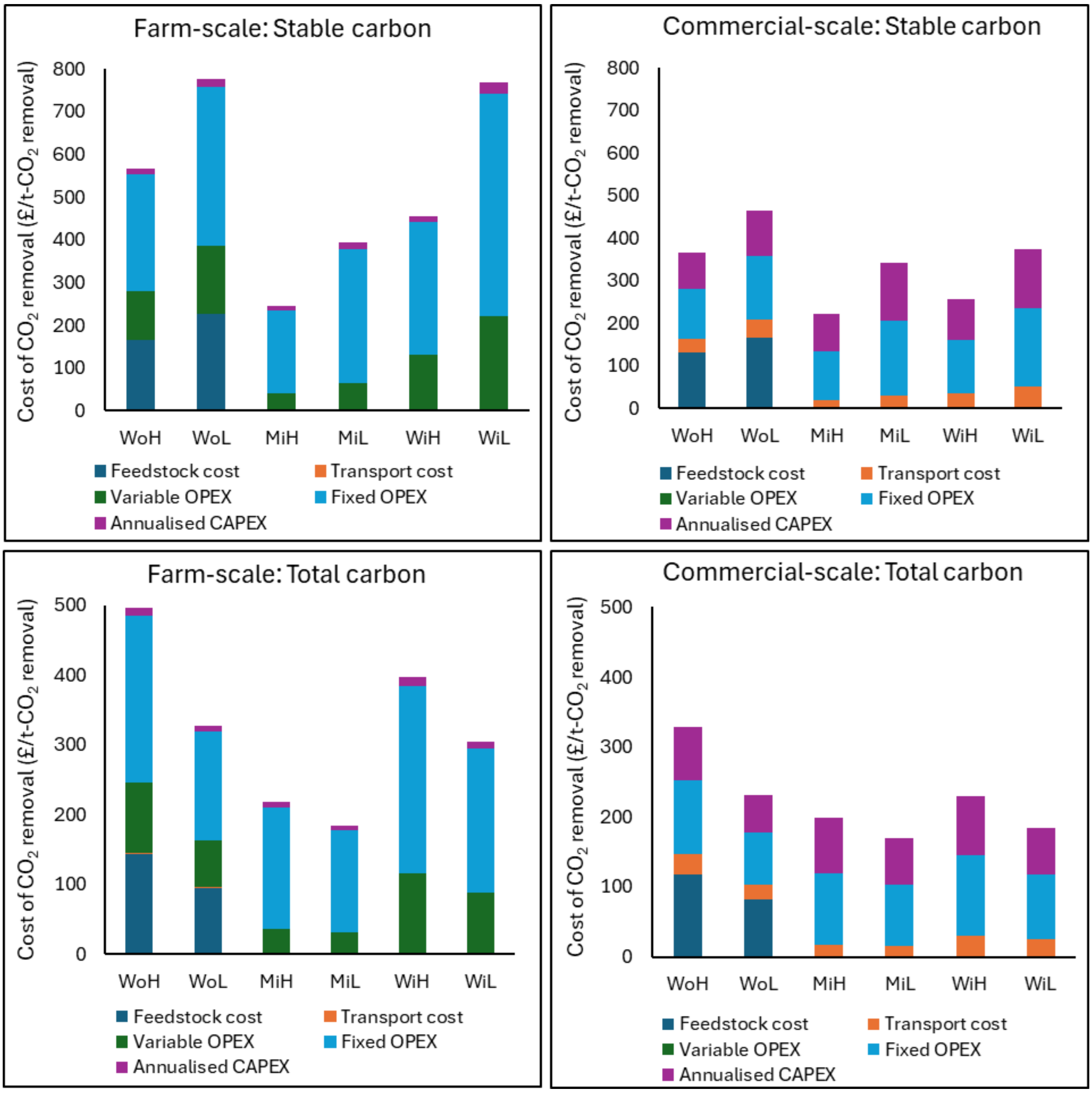

Figure 23: *Cost of carbon removal in farm- and commercial-scale production of low- and high-grade biochar considering the total carbon and stable carbon fraction in biochar (WoH:Wood high-grade, WoL: Wood low-grade, MiH: Miscanthus high-grade, MiL: Miscanthus low-grade, WiH: Willow high-grade, WiL: Willow low-grade, CAPEX-capital expenditure, OPEX-operational expenditure).*

Adjusted Carbon Removal and Cost Under Paludiculture Conditions

Building on the findings presented above, Figure 24 applies the same production pathways to a paludiculture context, modelling net GHG removal and cost-effectiveness over a 100-year period. This adjusted analysis incorporates carbon retention rates specific to rewetted peatland environments, as detailed in Section 2.2.

Key implications of this adjusted scenario include:

- The advantages of low-grade biochar become more pronounced, particularly for miscanthus and willow feedstocks, as the higher yield combined with improved labile carbon retention enhances overall GHG removal per tonne of feedstock.
- Commercial-scale systems maintain their advantage over farm-scale production, offering greater carbon removal and lower cost per tonne of CO_2eq, consistent with earlier findings.
- Cost-effectiveness improves substantially under rewetted conditions, with GHG removal costs falling across all pathways when accounting for higher biochar stability under paludiculture conditions.
- Among all pathways, commercial-scale production of low-grade miscanthus biochar emerges as a leading option, combining high removal potential with low cost under paludiculture conditions.

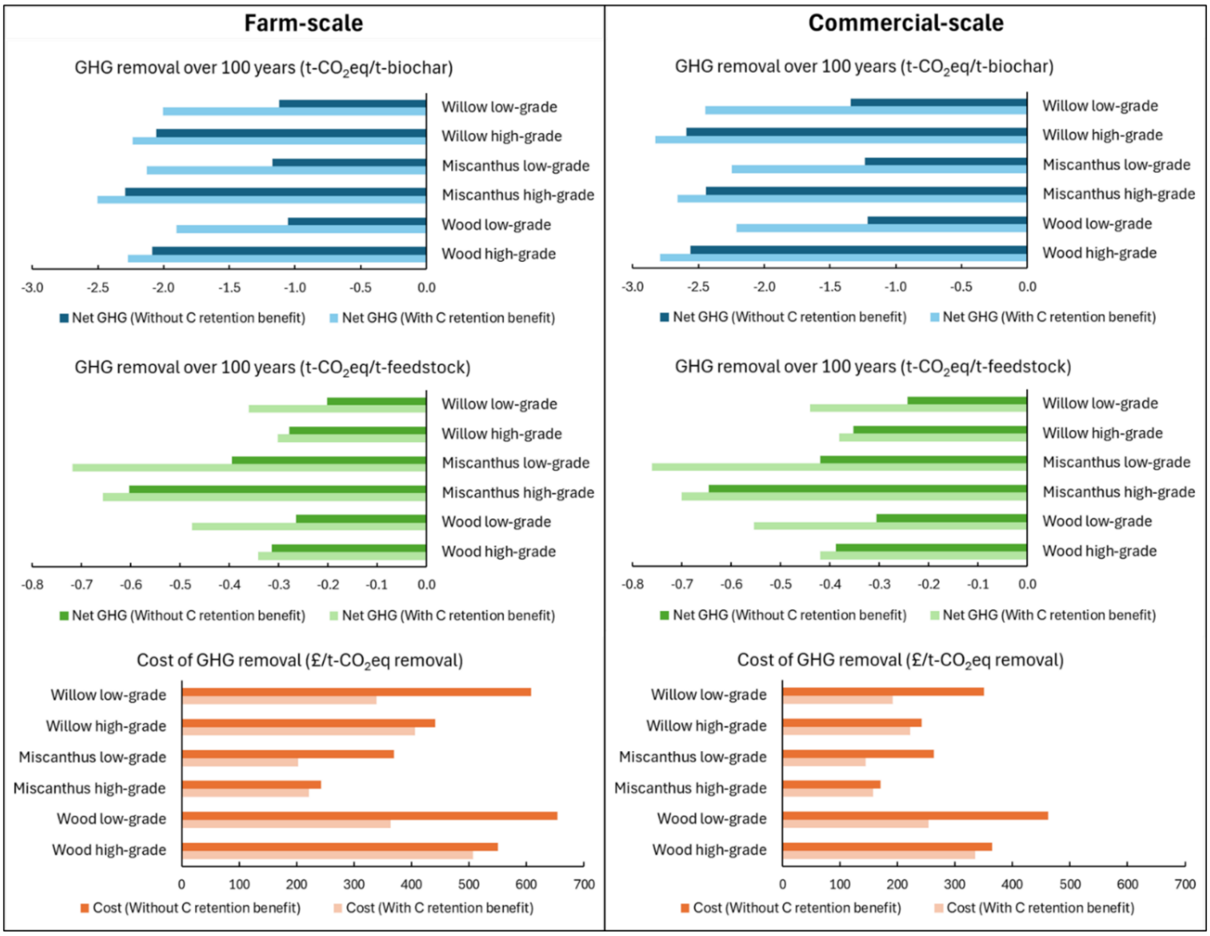

Figure 24: *Net GHG removal over 100-year period and cost considering farm and commercial-scale biochar production and application in rewetted peatlands. Without carbon retention refers to stable carbon only and represents costs associated with applting to a drier environment, whilst with C retention accounts for improved retention of the labile fraction when applied to a paludiculture system, based on figures from the Section 2.2.*

Externally Sourced Biochar for Paludiculture

Does it make financial sense to buy in biochar solely for the purpose of generating carbon credits? Based on our findings this is not the case, at least not under current market conditions.

The results presented in Table 9 highlights a fundamental challenge for integrating biochar into paludiculture systems via external sourcing: the economics simply do not stack up under current carbon credit market conditions. Even though biochar offers measurable carbon removal benefits, with net carbon removal rates of 2.42 and 2.83 tonnes CO_2e per tonne for low- and high-grade biochar respectively, the cost of purchasing and applying biochar significantly exceeds the revenue generated through carbon credits at current market rates.

Assuming a 30% profit margin from the supplier, the application of wood-derived low-grade biochar results in a net loss of approximately £497 per hectare, while high-grade biochar leads to a higher loss of around £946 per hectare. As it currently stands, farmers cannot justify buying in biochar purely for the purpose of generating carbon credits.

Table 9: Summary of costs, carbon benefits, and financial returns from applying externally sourced wood-derived biochar (low- and high-grade) to paludiculture crops. The table presents net carbon removal per tonne of biochar, estimated income from biochar carbon credits at £100 per tonne CO_2e, long-term carbon storage potential in rewetted peat soils, and the cost of purchasing and applying biochar per hectare assuming an application rate of one tonne ha^{-1}. Profit or loss is calculated based on two pricing scenarios: production cost only, and production cost plus a 30% profit margin.

Biochar type	Net carbon removals[a] (tonnes CO_2e tonne biochar^{-1})	Income from biochar carbon credits[b] (£ ha^{-1})	Long-term carbon storage in rewetted peat[c] (tonnes CO2e ha-1)	Cost to buy in biochar including purchase and application (£ ha^{-1})		Profit/loss of buying in and applying biochar(£ ha^{-1})	
				Purchase price based on costs of production only[d]	Purchase price based on costs of production plus 30% profit margin[d]	Purchase price based on costs of production only	Purchase price based on costs of production plus 30% profit margin
Wood Low Grade	2.42	242	2.27	569.97	738.97	-327.97	-496.97
Wood High Grade	2.83	283	2.24	943.97	1,228.97	-660.97	-945.97

Notes
a based on LCA data from part 1 of the analysis (see figure 22).
b based on prevailing price of £100 tonne-1 for biochar carbon credits.
c based on theoretical model in Section 2.2.
d based on £730 per tonne for low grade wood biochar (production cost of £561 per tonne plus 30% profit margin for producer) and £1,220 per tonne for high grade wood biochar (production cost of £935 per tonne plus 30% profit margin for producer) and £8.97 per hectare to apply biochar to field.
e based production cost of £561 per tonne) for low grade wood biochar and £935 per tonne for high grade wood biochar) and £8.97 per hectare to apply biochar to field.

While the Table 9 focuses on the cost-benefit balance of biochar application alone, Table 10 extends the analysis to show how buying in and applying biochar would affect the gross and net margins of within our model paludiculture farming systems miscanthus, willow and reeds. Here, we combine income from crop sales with income from biochar carbon credits and subtract the cost of externally sourced biochar (both low- and high-grade). This provides a more integrated view of how external biochar inputs would impact profits from these paludiculture models.

Across all three paludiculture crops, miscanthus, willow, and reeds net margins become negative when biochar is externally sourced for application. For example, miscanthus shows a net loss of £219 per hectare with low-grade biochar, increasing to £668 per hectare with high-grade biochar. These results reinforce the earlier conclusion that purchasing and applying externally sourced biochar is not financially viable under current carbon credit pricing.

Table 10 shows the gross and net margins of the three paludiculture crop options based on incomes from crop sales and from biochar carbon credits assuming either low- or high-grade wood biochar is bought in and applied. These results suggest that buying in biochar and applying it to the paludiculture crops is not a profitable approach. The current market price of biochar carbon credits at £100 per tonne is too low to make this a profitable model.

Table 10: Gross and net margin (£ ha^{-1}) of the three paludiculture crop options. The gross and net margins of the three paludiculture crops (outlined above) are adjusted to include cost of buying in biochar and applying to the crop and revenue from additional sale of biochar carbon credits.

Crop Option	Biochar type	Cost to buy in biochar including purchase and application[a] (£ ha^{-1})	Net carbon sequestration [b] (tonnes CO_2e tonne $biochar^{-1}$)	Revenue from biochar carbon credits[c] (£ ha^{-1})	Gross Margin (£ $ha^{-1} yr^{-1}$)	Net Margin (£ $ha^{-1} yr^{-1}$)
Miscanthus	Wood low grade	738.97	2.42	242	20.03	-218.97
	Wood high grade	1,228.97	2.83	283	-428.97	-667.97
Willow	Wood low grade	738.97	2.42	242	-138.97	-378.97
	Wood high grade	1,228.97	2.83	283	-587.97	-827.97
Reeds	*Wood low grade*	*738.97*	*2.42*	*242*	*-257.97*	*-426.97*
	Wood high grade	*1,228.97*	*2.83*	*283*	*-706.97*	*-875.97*

Notes
a based on £730 per tonne for low grade wood biochar (production cost of £561 per tonne plus 30% profit margin for producer) and £1,220 per tonne for high grade wood biochar (production cost of £935 per tonne plus 30% profit margin for producer) and £8.97 per hectare to apply biochar to field.
b based on LCA data from part 1 of the analysis (see figure 22).
c based on prevailing price of £100 tonne-1 for biochar carbon credits.

Integrated Paludiculture-Biochar Systems

An integrated paludiculture system refers to a land use model in which paludiculture crops are cultivated on rewetted peat, then harvested and converted into biochar on-site or via localised pyrolysis infrastructure. The resulting biochar is returned to the same or nearby land. This approach enables farmers to retain the full value of biochar carbon credits, reduce input costs, and improve the long-term financial and environmental performance of the system.

A key consideration in assessing the viability of this system is estimating the maximum potential biochar yield, which is directly influenced by the biomass productivity of the paludiculture crop in question. These yields determine feasible biochar application rates and, ultimately, the potential for carbon dioxide removal (CDR) (Table 11).

Among the crops assessed, miscanthus shows the highest potential, producing up to 5.2 tonnes per hectare per year (t ha^{-1} yr^{-1}) of low-grade biochar—equivalent to an estimated XX t CO_2e ha^{-1} yr^{-1} removed. Reeds provide a moderate yield of 3.2 t ha^{-1} yr^{-1} of low-grade biochar, corresponding to approximately X t CO_2e ha^{-1} yr^{-1}. Willow, while capable of producing 4.17 t ha^{-1} yr^{-1} of low-grade biochar, offers the lowest overall carbon removal potential (1.95–2.54 t CO_2e ha^{-1} yr^{-1}), largely due to lower biomass yields.

Table 11: *Estimated annual biochar yields and associated carbon removal potential for selected paludiculture crops grown on rewetted peat soils. Values are shown for high-grade and low-grade biochars, based on assumed pyrolysis efficiencies and carbon stability.*

Paludiculture crop	Biomass yield (tonnes ha^{-1})	High grade biochar		Low grade biochar	
		Potential biochar Yield (tonnes ha^{-1} yr^{-1})[a]	Total carbon removal (tonnes CO_2e ha^{-1} yr^{-1})[b]	Potential biochar Yield (tonnes ha^{-1} yr^{-1})[a]	Total carbon removal (tonnes CO_2e ha^{-1} yr^{-1})[b]
Miscanthus	13	4.55	12.21	5.2	12.79
Willow	8.33	2.499	7.14	4.165	9.32
Reeds	8	2.8	7.52	3.2	7.88

Notes
[a] *based on average biochar yields for specific pyrolysis conditions*
[b] *based on theoretical model in Section 2.2.*

Comparative Performance of Paludiculture Business Models

This section compares the financial and environmental performance of conventional (business-as-usual, or BAU) cropping systems on deep peat with alternative paludiculture models integrated with biochar production. The paludiculture scenarios incorporate a range of potential revenue streams, including crop sales, agri-environment payments (ELMs), carbon credits via the Peatland Carbon Code, and the use of low-grade biochar for carbon removal.

We focus specifically on low-grade biochar in this analysis, as it is less costly to produce and offers higher carbon returns than high-grade biochar. The analysis explores not only overall profitability across different business models, but also labour efficiency, greenhouse gas (GHG) mitigation potential, and the cost-effectiveness of emissions reductions per unit of operating cost.

Table 12 outlines the financial performance of two typical business-as-usual (BAU) cropping systems on deep peat, wheat and lettuces, providing the baseline against which all paludiculture and integrated models are assessed further below. At a discount rate of 5% over a 30-year period, wheat generates an NPV of £14,737 and an AEV of £959 ha^{-1} yr^{-1}. Lettuces deliver substantially higher returns, with an NPV exceeding £726,000 and AEV of £47,268 ha^{-1} yr^{-1}. These values highlight the high profitability of intensive horticulture, particularly in terms of absolute returns per hectare, though this comes with significant labour costs.

Table 12: *Net present value (£ ha^{-1}), annual equivalent value (£ ha^{-1} $year^{-1}$) and returns to labour (£ hr^{-1} ha^{-1} yr^{-1}) of the two business as usual agricultural crop options across the four scenarios. The NPV and AEV figures include additional incomes from governmental support payments or carbon credits (see Appendix 8 for full outline of scenarios). NPV and AEV calculated over 30 years at a discount rate of 5%.*

Crop Option	Net Present Value (£ ha^{-1})	Annual Equivalent Value (£ ha^{-1} $year^{-1}$)	Returns to Labour (£ hr^{-1} ha^{-1} $year^{-1}$)
Wheat (BAU)	14,737	959	170
Lettuces (Lettuces	726,619	47,268	155

Table 13 presents the results for three paludiculture crops (miscanthus, willow, and reeds) under four business model scenarios:

- Scenario 1: Crop sales + ELMs payments
- Scenario 2: Crop sales + ELMs + Peatland Carbon Code credits
- Scenario 3: ELMs + Peatland Carbon Code + biochar carbon credits (farm-scale production)
- Scenario 4: ELMs + Peatland Carbon Code + biochar carbon credits (commercial-scale production)

All of the paludiculture options are potentially financially viable (i.e., generate positive returns) across the four integrated business model scenarios (where there are additional incomes above crop sales). Generally, absolute returns are potentially higher when the original cropping was wheat rather than lettuces, this is due to higher potential peatland carbon code incomes from rewetting. Of the three paludiculture options cropping with reeds could generate the highest potential returns over 30 years at a discount rate of 5% (>£20,000 when wheat was the original crop and >£16,000 when lettuces was the original crop).

Miscanthus and reeds provide better financial returns than wheat in two scenarios: (1) when revenue comes from crop sales, ELMS payments, and Peatland Carbon Code credits (scenario two), or (2) when revenue is generated from ELMS payments, Peatland Carbon Code credits, and biochar carbon credits (scenarios three and four). Willow, however, is only likely to outperform wheat when revenue includes crop sales, ELMS payments, and Peatland Carbon Code credits (scenario two). When crop sales are replaced with biochar production (scenarios three and four), willow may perform worse than wheat. The results in Table 13 suggest that none of the crop options or business models can generate higher absolute returns than lettuces but are still financially viable when lettuces were the original crop. Appendix 8 shows the sensitivity of the NPV estimates to changes in discount rate ranging from 3-7%, all options remain financially viable across these discount rates.

6. Policy Brief

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6.1 Introduction

The problem

Lowland peats represent one of the most significant sources of peatland greenhouse gas emissions, largely because they have been drained for arable or horticultural production for many decades. Once the water table is lowered, peat decomposes rapidly, releasing carbon dioxide to the atmosphere. It is now recognised that simply raising the water table can help avert these ongoing losses, whether partially under existing crops or fully under wetland agriculture ("paludiculture", e.g., reeds). However, cultural barriers and the costs of maintaining higher water tables (including lost revenues where this impacts yields) have prevented large-scale adoption of interventions that could reduce emissions in this way. Moreover, these approaches do nothing to replace the carbon that has been lost since the sites were first drained.

The opportunity

Markets are now emerging for active emissions reductions from agricultural peat soils, where water tables can be raised, via the Peatland Code. Biochar carbon markets are also gaining traction internationally, although nascent in the UK. This project therefore sought to explore the potential for biochar application to build back lost carbon in degraded agricultural peats, generating new revenue streams that could make the switch to more sustainable management practices more financially viable.

Why biochar?

Biochar is of particular interest because of its stability and potential for carbon dioxide removal. In theory, placing biochar in soil is intended to "lock away" carbon, but in practice, the longevity of that carbon depends on both the characteristics of the material and the environment in which it is placed. Greater pyrolysis temperatures produce more stable forms of biochar that remain in mineral soils longer but generate lower yields of final product and require higher energy inputs. Lower stability biochars offer improved production efficiency and are less expensive to produce but, under typical drained conditions, can lose their carbon to the atmosphere very quickly.

6.2 Our Research

Methods

The research employed a mixed-methods design structured around multiple work packages, each targeting a different aspect of lowland peat rewetting and biochar integration:

- In one strand, researchers conducted field- and lab-based experiments to assess biochar decomposition rates, greenhouse gas fluxes, and potential crop yields under rewetted conditions. This involved establishing trial plots on drained agricultural peatlands that were subsequently rewetted, measuring changes in water table depth and collecting gas samples with automated chambers to quantify carbon dioxide and methane fluxes.
- Laboratory analyses further characterised the stability of various biochar types produced at different pyrolysis temperatures, while a suite of techno-economic and life cycle assessments estimated both financial feasibility and net carbon removal over time.
- Alongside the field and modelling work, a rapid evidence assessment of relevant policies and literature was carried out, enabling the team to locate barriers and opportunities in current regulations.
- Inputs from farmers and biochar suppliers added a practical perspective on the costs, equipment needs, and logistical constraints associated with integrating biochar in wet peat soils;
- Finally, an economic modelling tool was used to compare the profitability and greenhouse gas performance of paludiculture systems with and without biochar application against existing agricultural practices.

6.3 Key Findings

- Effective rewetting of lowland peat soils can significantly lower greenhouse gas emissions previously exacerbated by drainage and oxidation and can also create new opportunities for carbon sequestration and farm revenues when combined with biochar application.
- Although high-stability biochar is highly resistant to decomposition under most soil conditions, its higher production costs continue to hinder extensive use on agricultural land.
- When applied to rewetted peat, emerging evidence suggests lower-stability biochar often achieves greater long-term carbon retention than it would in dry mineral soils, creating opportunities in a peatland context for using a wider variety of feedstocks and from a range of pyrolysis techniques.
- By integrating lowland peat restoration and biochar use, this approach could convert degraded peat from a major emissions source into a long-term carbon sink, contingent on favourable policies, supportive carbon markets, and accessible technical know-how for land managers.

Barriers

- Current regulations limit how much biochar can be applied each year, thereby restricting carbon gains. Regulations also restrict application onto waterlogged soils, a likely barrier for paludiculture.
- Low-stability biochar is not currently eligible in biochar carbon markets, which overlook how biochar behaves in waterlogged peat soils.

- There is uncertainty about whether the land manager or the biochar producer should receive the financial benefit from carbon credits, given that each party plays a distinct role in creating the climate benefit.
- Farm-level trials highlight that the primary barrier is not biochar application itself, but the broader challenge of operating in saturated paludiculture conditions. While conventional tractors and spreaders (commonly used for compost or manure) can be adapted for biochar, they are often unsuitable for waterlogged fields. Crucially, the need for specialised, lightweight equipment extends beyond biochar—it is also essential for other core farming activities such as planting and harvesting. Once this machinery is in place, applying biochar is a relatively straightforward adjustment.

Limitations and future research

- Although theoretical models suggest that rewetted peatlands could enhance long-term biochar carbon retention, the actual decomposition rate of biochar in these environments remains uncertain due to limited empirical data that are also over short time scales.
- Traditional biochar MRV methods may not be suitable, especially when dealing with lower stability biochar. Developing peatland-specific protocols would be necessary to accurately quantify carbon sequestration. This could be achieved through water level monitoring, similar to the MRV approaches used in the Peatland Code.
- The impact of biochar on water quality in paludiculture remains uncertain. A preliminary study found limited effects, but only two biochar types were tested. Variability in biochar properties could pose risks to nutrient leaching.
- Evidence on biochar's impact on biodiversity remains limited. Alterations in water chemistry and peat structure may affect key invertebrate groups and soil microbial communities, but further research is needed to assess long-term effects on species diversity. This is especially important for paludiculture models that depend on biodiversity credits.

6.4 Recommendations

Policy options and market actions

The following recommendations seek to address the barriers identified in the project, to increase the likelihood that biochar application in paludiculture becomes a viable proposition for cultivated lowland peats. In addition to policy options, there are a number opportunities to influence existing international and emerging UK markets, based on the evidence from this research.

Increase allowable biochar application rates and permit use in paludiculture systems. Existing rules cap biochar additions to around one tonne per hectare per year, which is too low to achieve meaningful emissions reductions or carbon removals at scale. Furthermore, applications are not permitted on waterlogged soils. Raising this threshold and allowing for application on paludiculture soils, provided environmental safeguards are in place, would enable application to paludiculture soils and at higher-impact applications.

Include lower-stability biochar in carbon markets when used on wet peat soils. Current carbon credit systems reward only highly recalcitrant forms of biochar, despite growing evidence that low-stability biochar remains stable when applied in waterlogged peat conditions. Creating a special category that recognises the long-term carbon storage achievable in rewetted peatlands would align carbon credits with the latest evidence.

Use biochar for ditch blocking and bunding in rewetted peat systems. Placing biochar at depth when constructing peatland water-control structures capitalises on the strongly anaerobic environment. This approach could be explicitly integrated into peatland restoration grants and codes, with carbon gains measured and verified over time.

Work with biochar markets to more fairly allocate rewards between producers and farmers. Although biochar producers play an important role, it is the land manager who bears many of the costs and risks, especially if they re-wet productive peat fields. An equitable system that shares or transfers credits would enhance farmer participation and boost uptake, significantly expanding the supply of biochar credits to these markets.

Expand the Peatland Code to include rewetted peat with biochar. At present, the Peatland Code includes options to partially or fully rewet agricultural peat soils under existing agricultural practices, paludiculture or semi-natural habitats. Future versions of the Code could include the option to integrate biochar as an explicit bundle, or stacked with peatland carbon for sale to different buyers. The Peatland Code is in the process of developing the necessary architecture to issue biodiversity units as part of an explicit bundle with peatland carbon, and is developing stacking functionality in collaboration with the UK Land Carbon Registry. The development of biochar units within the Code would make biochar carbon significantly more accessible to farmers and project developers who would only need to develop a single Project Design Document rather than having to engage with two separate market mechanisms. It would also bring in a new revenue stream to the Peatland Code, which is currently investigating new business models to sustain its operations.

Ensure future BSI standards for peatland carbon markets include the option to integrate biochar. Building on the launch of BSI Flex 703 on the Supply of Nature-Based Carbon Credits, additional appendices or linked standards are planned to specify MRV and other requirements specific to particular land uses and habitats, with plans for one on peatland carbon. Based on the evidence from this research, this should include requirements and guidance to ensure competitors to the Peatland Code generate high-integrity carbon units from low-stability biochar applications to rewetted peat soils.

Adapt market requirements and guidelines to manage short-term methane flux. Waterlogged soils can increase methane production in the short-term, but the net climate benefit remains positive when properly managed. Markets should provide guidance on the management of water-levels and co-application of methane-suppressing amendments, to help maintain a consistently low methane profile.

Incorporate biochar into standard farm greenhouse gas calculators. Most models used to estimate on-farm emissions do not yet factor in biochar, and those that do rarely include options for lowland peat soils. Integrating biochar usage in rewetted peat soils would highlight the potential climate benefits and ensure consistent reporting across agricultural holdings.

Provide targeted financial and technical support for paludiculture. Although the practice can outperform drained arable cropping in climate terms and even in net returns if carbon prices are sufficiently high, high-value horticulture remains more profitable in many cases. Grants, capital allowances for specialised equipment, and guaranteed purchase agreements for wetland crops could help farmers take the initial step toward rewetting.

Use on-farm pyrolysis to unlock new feedstock options. Growing wet-tolerant species such as miscanthus and willow offers steady biomass supply that can be converted to biochar directly on-site, reducing transport costs. By capturing carbon credits for both rewetting and biochar application, producers may be able to diversify income streams and partly offset capital expenses for pyrolysis units.

Address supply chain gaps for wetland-derived raw materials. Encouraging greater uptake of reeds or other paludiculture feedstocks requires a stable market for these products. Linking these biomass materials with pyrolysis for biochar or for combined heat and power generation could incentivise local supply chains that valorise rewetted peat.

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Appendix

Appendix 1: National Litterbag Experiment

Table i. Characterisation (proximate analysis, ultimate analysis, and H/C ratio) of the biochars used to produce the litter bags.

Sample		Proximate analysis (Wt.%)					Ultimate Analysis (Wt.%)			**H/C Ratio (calculated)**
		Moisture	Volatiles	Fixed carbon	Ash		Carbon	Hydrogen	Nitrogen	
Low Stability	wet basis (as received)	4.0±0.4	60.6±1.6	32.4±1.2	3.0±0.9		57.4±1.0	5.6±0.1	0.34±0.02	1.17±0.02
	dry basis	**-**	**63.1±1.5**	**33.8±1.3**	**3.1±0.9**		**59.8±1.1**	**5.4±0.2**	**0.35±0.02**	**1.09±0.01**
	dry ash-free basis	-	65.1±1.4	34.9±1.4	-		61.7±1.1	5.6±0.2	0.37±0.02	1.09±0.02
Medium Stability	wet basis (as received)	4.1±0.7	34.1±1.4	61.2±1.3	0.7±0.1		71.5±1.6	4.4±0.1	0.27±0.02	0.72±0.01
	dry basis	**-**	**35.5±1.4**	**63.7±1.4**	**0.8±0.1**		**74.6±1.7**	**4.1±0.1**	**0.29±0.02**	**0.64±0.01**
	dry ash-free basis	-	35.8±1.4	64.2±1.4	-		75.1±1.7	4.2±0.1	0.29±0.02	0.64±0.01
High Stability	wet basis (as received)	9.4±0.6	16.5±2.4	66.3±2.1	7.8±0.2		74.7±0.6	2.1±0.1	0.88±0.04	0.34±0.02
	dry basis	**-**	**18.2±2.6**	**73.2±2.4**	**8.6±0.3**		**82.4±0.7**	**1.2±0.1**	**0.97±0.04**	**0.18±0.02**
	dry ash-free basis	-	19.9±2.8	80.1±2.8	-		90.2±0.7	1.3±0.2	1.06±0.05	0.18±0.02

Table ii. – Site information.

Site Number, Name and Location.	**Paludiculture (P) or Business as Usual (BAU)**	**Land characteristics**	**Crops or livestock present, and fertiliser application.**	**Historical land-use**	**Current management regime**	**Challenges to water regime e.g. any major fluctuations**
(1) Winmarleigh (53.92526, -2.84908)	Paludi	Lowland raised bog.	*Sphagnum* farm planted Dec 2020	First drained and farmed in 1970s with additional drainage in 1990s.	Drainage ditch, shared with the adjacent SSSI, has been blocked to raise the water table.	
(1) Winmarleigh (53.02802, -2.85185)	BAU	Lowland raised bog.				N/A
(2) Wright Farm (53.68847, -2.86669)	Paludi	Lowland peatland.	Iceberg lettuce (2020/21) – 988kg/ha fertiliser. Fallow (2022) Spring barley (2023)	Salad production for 40+ years.	Drains every 7m that feed into header main and a pump chamber. Land is pumped continuously via electric pumps.	Although not re-wetted the weather conditions since the trial have overwhelmed the pumps and there has been considerable surface water.

Site Number, Name and Location.	Paludiculture (P) or Business as Usual (BAU)	Land characteristics	Crops or livestock present, and fertiliser application.	Historical land-use	Current management regime	Challenges to water regime e.g. any major fluctuations
			Sphagnum moss/PEF trial (2024) to be irrigated from above *not* via re-wetting.			
(3) Rindle Farm (53.46648, -2.45159)	Paludi	Lowland peatbog.	Celery Planted 2022-2024	First drained and farmed >100 years ago as a potato field.	Drainage ditches blocked and bunds installed to maintain WTD at varying depths between surface level and 50cm below.	
(4) Horsey (52.75188, 1.62640)	Paludi	Lowland fen.	*Typha angustifolia* (lesser reedmace), *Typha latifolia* (reedmace), and *Phragmites australis* (common reed).	Grazing marsh on a high water table. Drained in the 1940s.	Re-wet in spring 2021. Water is brought in from the adjacent Waxham Cut watercourse. During re-wetting polders were created	Varying heights within reed bed compartments (+/- 100mm), due to limiting the amount of peaty soil that could be removed, means channels have formed around high points and polders are not evenly wet.
(5) Great Fen (52.48915, -0.18895)	Paludi	Low-lying /lowland fen first drained in the 1850s.	*Typha latifolia,* Planted in summer 2023. Aberdeen Angus cattle present next to test bed.		Not re-wetted yet, still subject to standard IDB drainage and test beds are pumped.	Drought periods.
(5) Great Fen (52.46001, -0.18477)	BAU	Lowland fen.	Barley.		Standard IDB drainage.	N/A
(6) Pollybell (53.45874, -0.91397)	Paludi	Lowland peatland.	Wet grass, converted to willow planted May 2024	Grass/Arable		
(6) Pollybell (53.45946, -0.90493)	BAU	Lowland peatland.	Wheat			N/A
(7) Chippenham (52.29942, 0.41478)	Paludi		Natural vegetation.	NNR since the 1960s. Failed drainage system 200 years ago but land	45 permanent collar dams installed in October 2024 using	Too early to tell.

Site Number, Name and Location.	Paludiculture (P) or Business as Usual (BAU)	Land characteristics	Crops or livestock present, and fertiliser application.	Historical land-use	Current management regime	Challenges to water regime e.g. any major fluctuations
				has tended to be summer wet/winter dry allowing the peat to dry out.	plastic piling to hold more water on-site in the summer.	
(8) Greylake (51.10887, -2.86120)	Paludi	Lowland fen.	*Typha latifolia, Phragmites australis,* and *Phalaris arundinacea* (reed canary grass) trials. Cattle graze with exclusion fencing to keep them off the trial and monitoring plots.	Re-wetted prior to trial with the same water management regime.	To allow for paludiculture planting surface vegetation and the roof mat was removed. This lowered land levels. Water levels significantly above field level through winter/spring and close to field surface through summer/autumn.	Vegetation stripping has meant water depth is significant in winter/spring.
(8) Greylake (51.10804, -2.86419)	BAU	Lowland fen.	Cattle graze with exclusion fencing to keep them off the trial and monitoring plots.	Arable for 30 years. Deep-drained and ploughed regularly it has lost approx. 50cm height.	Water at field level through winter/spring then naturally drop through summer/autumn with the only intervention being to keep surrounding ditches within 30cm of the field surface.	N/A

Appendix 2: REA method

Process and evidence

The key search terms resulted in the identification of 64 relevant papers. A further 77 referenced were found through other sources. The project timeframe provided limitations for further backwards and forwards citation tracing typical of a full systematic review (which has timeframes extending beyond six months).

The selection and evaluation of literature for the REA was undertaken as follows:

1. **Scientific information sources.** Science Direct and Google Scholar were used to retrieve peer-reviewed articles, scientific reports and conference proceedings.
2. **Further Information and citation tracing.** Grey literature was found through websites of government, relevant companies and media. With particular focus on policy and scientific trials based on climate change mitigation, water management, agriculture, biochar production and peatland restoration. Additionally, citation tracing was used to source further literature.
3. **Chronological selection.** The majority of all literature sourced was from 2018 to 2024. Additional references which were recommended by project partners were also included.
4. **Preliminary scoping review.** An initial search was undertaken using the search terms in Table iii in different combinations. The preliminary literature search returned 109 article hits based on key search terms.

Table iii.: Keywords and search strings used in preliminary scoping review of literature.

Preliminary Search Terms
Paludiculture AND "regulation" AND "biochar"
Indonesia AND paludiculture AND biochar
Paludiculture AND "regulation"
Paludiculture AND "policy"
Paludiculture AND "policy" AND UK
Netherlands AND "paludiculture"
Paludiculture AND carbon capture
Paludiculture AND agri-environmental schemes
Paludiculture AND agri-environmental schemes AND "UK"
Paludiculture AND policy AND "Europe"
Peatland carbon storage AND policy
Paludiculture AND "regulation" AND "biochar"
Paludiculture AND "policy" AND UK
"Paludiculture" AND "regulation" AND "Germany"
Paludiculture regulation and policies
Indonesia AND paludiculture AND regulation AND policy
Paludiculture AND "policy" AND "Germany"
Paludiculture AND "policy" AND "Netherlands"

5. **Refinement of literature.** From the preliminary search the literature selection was refined to ensure it focused on the research objectives. When search terms returned over 100 results, only the first 100 were used within the refinement process.

6. **Further literature.** 26 papers which were found through other sources and citation tracing were also used in this report.

Appendix 3: Causal models and logic chains

Table iv. Drivers and barriers for peatland restoration, paludiculture, and biochar usage.

Drivers and barriers for peatland restoration, paludiculture, and biochar usage.				
High- level/International	National level	Mechanisms	Farm business	Consumer/social attitudes
COP21 agreement: Global commitment to reducing carbon emissions and to limit a rise in average global temperatures, with state or multi-state actors setting out their plans in all sectors, including land use and agriculture through Nationally Determined Contribution plans[1]. Kyoto Protocol: Recognition and accounting of wetland emissions impact on climate change effects and action[2].	United Kingdom Climate Change Act 2008 (2050 Target Amendment) Order 2019: Net zero target of 2050[8].UK Peatland Strategy 2018: Co-ordinating influence on peatland restoration strategy, control over which is devolved. Target of 2Mha "in good condition, under restoration or being sustainably managed by 2040"[9].England The Environmental Improvement Plan 2023[10] (updated 25 YP) commits to the restoration of 35,000 ha of peatland by 2025, supported and funded by the Nature for Climate Peatland Grant Scheme[11].	Verra Verified Carbon Standard Program: GHG crediting programme, that has developed methodologies to measure the impact of rewetting temperate peatland[19] and biochar utilisation[20]. Puro: "... carbon crediting programme focused on carbon removals"[21]. Suppliers of biochar can sell or use the credits to generate offsets for	Environmental Land Management: Payments for actions such as cultivation of Sphagnum moss, both for carbon capture and water management value. Future financial support for peatland restoration schemes[26]. Countryside Stewardship: Payments for actions such as the creation of fen and	• Low consumer awareness of paludiculture and some of its products. • Rising demand for more climate neutral and positive products, as well as for general action on climate change effects. • Paludiculture presently perceived

[1] Secretary of State for Business, Energy, and Industrial Strategy, (2022) "United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution" Implications for peat restoration, pgs. 13, 14 and 28. Available at: United Kingdom of Great Britain and Northern Ireland's Nationally Determined Contribution

[2] O'Sullivan *et al.,* (2012)

[8] Climate Change Act 2008: https://www.legislation.gov.uk/ukpga/2008/27/contents.
Climate Change Act 2008 (2050 Target Amendment) Order 2019: https://www.legislation.gov.uk/uksi/2019/1056/contents/made.

[9] IUCN, (2018), pg. 12.

[10] Environmental Improvement Plan: https://assets.publishing.service.gov.uk/media/64a6d9c1c531eb000c64fffa/environmental-improvement-plan-2023.pdf. Pgs. 196-200.

[11] Nature for Climate Peatland Grant Scheme: https://www.gov.uk/guidance/nature-for-climate-peatland-grant-scheme

[19] Methodology for Rewetting Drained Temperate Peatlands:
https://verra.org/methodologies/vm0036-methodology-for-rewetting-drained-temperate-peatlands-v1-0/#overview.

[20] Methodologies for biochar application: https://verra.org/methodologies/vm0044-methodology-for-biochar-utilization-in-soil-and-non-soil-applications/.

[21] FAQs: https://puro.earth/faqs

[26] Environmental Land Management (ELM) update: how government will pay for land-based environment and climate goods and services: https://www.gov.uk/government/publications/environmental-land-management-update-how-government-will-pay-for-land-based-environment-and-climate-goods-and-services/environmental-land-management-elm-update-how-government-will-pay-for-land-based-environment-and-climate-goods-and-services#wetland-habitats-1.

Ramsar Convention on Wetlands: International treaty, to which all countries in this Model are party to, for the conservation of wetlands. The UK has 175 Ramsar Sites[3], or almost 7% of the world's Sites[4]. Global Environment Facility: Co-financing option for the restoration and conservation of peatlands[5]. Global Biodiversity Framework 30/30 target: Target for the conservation of 30% of land, waters and seas, "especially areas of particular importance for biodiversity and	England Peat Action Plan: Measures to protect peatland include restrictions on managed burning, the creation of an updated peat map, and the introduction of measures to restore peatland across the SFI and CS[12]. LRWP 60 & 61: Environment Agency guidance that limits the use of biochar and states it cannot be spread on land that is waterlogged[13]. Northern Ireland Northern Ireland Peatland Strategy 2022-2040: Aims "to ensure that peatlands in Northern Ireland are conserved or under restoration management to become healthy, functioning ecosystems before 2040"[14]. Scotland	other activities. The biochar must meet Puro production standards, and the use of the biochar must maintain the carbon captured over the long term[22]. Peatland Code: Voluntary standard (backed by the UK government) for rewetting peatland. Provides assurance "that the climate benefits being sold are real, quantifiable, additional and permanent"[23]. Biochar Quality Mandate: UK voluntary certification for	raised water levels on peat soils[27]. Local Nature Recovery: Pays for peatland restoration and management[28]. Scotland's Agri-Environment Climate Scheme includes payments for ditch-blocking[29]. The Sustainable Farming Scheme includes managing heavily modified peatlands (UA6) to prevent further degradation[30].	as impractical by some lowland peat farmers[33]. • Agriculture-based externalities mean that the full environmental cost of agricultural production is not currently borne by consumers. • Potential mismatch between regional or professional identity tied to food

[3] Ramsar country page: https://www.ramsar.org/country-profile/united-kingdom-great-britain-and-northern-ireland https://www.ramsar.org/country-profile/united-kingdom-great-britain-and-northern-ireland

[4] Ramsar Sites Information Service: https://rsis.org/?language=en

[5] O'Sullivan *et al.*, (2012)

[12] England Peat Action Plan, 2021.

[13] LWRP 60: https://www.gov.uk/government/publications/low-risk-waste-positions-miscellaneous/storing-and-treating-waste-to-make-biochar-lrwp-60.
LWRP 61: https://www.gov.uk/government/publications/low-risk-waste-positions-landspreading/storing-and-spreading-biochar-to-benefit-land-lrwp-61

[14] Northern Ireland Peatland Strategy 2022-2040: https://www.daera-ni.gov.uk/sites/default/files/consultations/daera/NI%20Peatland%20Strategy%20-%20Copy%20for%20EQIA%20Consultation.%20%208-8-2022.%20PDF_0.PDF., p. 7.

[22] Puro Standard Biochar Methodology: https://7518557.fs1.hubspotusercontent-na1.net/hubfs/7518557/Supplier%20Documents/Puro.earth%20Biochar%20Methodology.pdf.
Many more trading platforms for carbon credits exist; Puro and Verra were chosen for this causal model due to the large scale and additional certification for rewetting peatland, respectively

[23] How It Works - Peatland Code: https://www.iucn-uk-peatlandprogramme.org/peatland-code/how-it-works.

[27] Note: More actions are detailed in the ELM update under the 'Moorland and Upland Peat' and 'Lowland Peat' sections. https://www.gov.uk/countryside-stewardship-grants/sw18-raised-water-levels-on-grassland-on-peat-soils.

[28] Local Nature Recovery: more information on how the scheme will work: https://www.gov.uk/government/publications/local-nature-recovery-more-information-on-how-the-scheme-will-work/local-nature-recovery-more-information-on-how-the-scheme-will-work.

[29] Lowland Bog Management: https://www.ruralpayments.org/topics/all-schemes/agri-environment-climate-scheme/management-options-and-capital-items/lowland-bog-management/.

[30] Sustainable Farming Scheme: https://www.gov.wales/sites/default/files/consultations/2023-12/sustainable-farming-scheme-consultation-document_0.pdf. Pgs. 25-26.

[33] Rhymes *et al.*, 2023, p. 10.

ecosystem functions and services", by 2030[6]. Voluntary Carbon Markets: International markets that allow for the sale of verified carbon credits through the restoration and management of drained peatland, as well as through biochar creation[7].	Scotland's National Peatland Plan: Published in 2015, aims to restore peatlands to a healthy state by 2030[15]. Support of the Scottish Rural Development Plan in the past. Peatland ACTION: Scottish Government funding for peatland restoration, with a restoration target of 250,000 ha by 2030[16]. <u>Wales</u> National Peatland Action Plan: Running from 2020-2025, the programme seeks to restore/manage "all peatlands with semi-natural vegetation" and restore "a minimum of 25% of the most modified areas of peatland"[17]. Welsh Peatlands Project - Sustainable Management Scheme: Range of measures including PES strategy for sustainable management from 2014-2020, co-funding by RDP and EARFD[18].	biochar production and use. Includes guidelines on appropriate feedstock, change to end-of-waste status, and the production process, among other factors[24]. United Utilities SCaMP: Water company investing in improving water quality in moorland, paid for by increase in water bills and AES[25].	The Environmental Farming Scheme also supports management of peatlands[31]. DAC-GGR Phase 2: Projects aimed at establishing technologies to remove and capture carbon; including biochar innovations[32].	production, and the switch to paludiculture crops which may not be a food source.

[6] 2030 Targets (with Guidance Notes): https://www.cbd.int/gbf/targets.
[7] A list of suppliers, purchasers and facilitators of carbon capture and storage credits can be found at https://www.cdr.fyi/. A significant portion of the credits are generated through biochar creation.
[15] Scotland's National Peatland Plan: Working for our future: https://www.nature.scot/doc/scotlands-national-peatland-plan-working-our-future.
[16] Peatland ACTION - What we have achieved: https://www.nature.scot/climate-change/nature-based-solutions/peatland-action/peatland-action-what-we-have-achieved.
[17] National Peatland Action Programme, 2020-2025: https://cdn.cyfoethnaturiol.cymru/media/692545/national-peatlands-action-programme.pdf. P.13.
[18] Welsh Peatlands Project (Sustainable Management Scheme): https://www.iucn-uk-peatlandprogramme.org/projects/welsh-peatlands-project-sustainable-management-scheme-0.
[24] Biochar Quality Mandate (BQM) version 1.0: https://www.research.ed.ac.uk/files/17910590/BQM_V1.0.pdf.
[25] Wichmann, 2017. Pg. 31.
[31] IUCN Peatland Conference Country Update: Northern Ireland: https://www.iucn-uk-peatlandprogramme.org/sites/default/files/header-images/Conf%2022%20Speaker%20PWRPTs/DF_22.pdf.
[32] Projects selected for Phase 2 of the Direct air capture and greenhouse gas removal programme: https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-2-of-the-direct-air-capture-and-greenhouse-gas-removal-programme.

Table v. *Drivers and barriers for peatland restoration, paludiculture, and biochar usage.*

Drivers and barriers for peatland restoration, paludiculture, and biochar usage				
Country	Continent/regional level	National level	Mechanisms	Farm business
Germany Peatlands cover approximately of the country, with 95% being degraded. Portion of peatlands used for growing biogas and maize fodder[34].	Common Agricultural Policy: GAEC2 standard for the protection of peatlands. Also continues to subsidize drainage-based agriculture[35]. European Green Deal: Net zero emission of GHGs by 2050. 55% less GHG emissions by 2030[36].Includes the Farm to Fork Strategy, dedicated to sustainable agriculture. Biodiversity Strategy for 2030: Also, a subsidiary of the EGD, that among other targets, aims to "reverse the degradation of ecosystems"[37]. EU Habitats Directive: Protection of peatland habitats, including bogs, mires, and fens[38].	Climate Action Plan 2050: Peatland rewetting mentioned as one of the avenues for CDR[41]. Also stated that the government," *will examine the possibility of consistent, permanent funding for paludiculture*"[42], among other measures. National Peatland Protection Strategy 2022: Includes protection of peatland belonging to the federal government[43]. Peat Use Reduction Strategy: Aims to substitute peat use with alternate growing media and phase out usage in the hobby horticultural sector[44].	MoorFutures: Voluntary standard and carbon credits from rewetting peatland [45]. Price range of €35-67/tCO2-eq, and possible future updates to include water management and biodiversity options[46]. Funding of paludiculture projects by the German Environment Ministry[47].	

[34] Tanneberger *et al*., 2020.
[35] Wichmann and Nordt, 2024.
[36] The European Green Deal: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.
[37] Biodiversity strategy for 2030: https://environment.ec.europa.eu/strategy/biodiversity-strategy-2030_en#timeline.
[38] Wichmann and Nordt, 2024, p. 8.
[41] Borchers *et al*., 2023, p. 5.
[42] https://ec.europa.eu/clima/sites/lts/lts_de_en.pdf, pg. 71.
[43] BMUV, 2023
[44] BMEL, 2022
[45] The MoorFutures standard: https://www.moorfutures.de/konzept/moorfutures-standard/
[46] Wichmann, 2018, p. 20.
[47] Global Peatlands Initiative: https://globalpeatlands.org/germany-has-published-its-first-ever-national-peatland-protection-strategy

Netherlands Peatlands cover approximately 9% of the country's area[48]. Significant area of the country's peat meadows used for dairy farming[49]. Particularly concerned with the issue of soil subsidence.	European Biochar Certificate: Voluntary biochar standard created in 201139. Fertilising Product Regulation 2019: Change of the status of biochar from being legally uncertain and complex, to the possibility of being granted end-of-waste status40.	Climate Act 2019: Goal of 95% reduction of GHG emissions by 2050[50]. National Climate Agreement 2019: Aim of reducing 1Mt of emissions from peat meadow areas; €100M for reducing activity, changing technology and a 'voluntary cessation scheme' (among other measures), and €176M for related measures until 2030[51].	Valuta voor Veen: Voluntary market compensating farmers for increasing the water level on their peatland to reduce carbon emissions[52].	As mentioned before, payments for farmers on peat meadow areas to adapt and reduce carbon emissions. SNL Nature & Landscape: Subsidies for management of different peatland types, compensation for rewetted land, and water management[53].
Latvia		Latvia's Territorial Just Transition Plan: Includes peatland restoration and restriction of using peat for energy[56].	Mandated restoration of peat extraction sites; this does not necessarily mean that the	

[48] Veenweidegebied, The Netherlands: https://www.recare-hub.eu/case-studies/veenweidegebied-the-netherlands.
[49] National Climate Agreement - The Netherlands: https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands.
[39] Meyer *et al.*, 2017.
[40] Štrubelj, 2022.
[50] Climate Policy: https://www.government.nl/topics/climate-change/climate-policy.
[51] National Climate Agreement - The Netherlands: https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/national-climate-agreement-the-netherlands, pp. 143-145.
[52] Currency for Veen – Friesland: https://valutavoorveen.nl/.
[53] Wichmann, 2018, p. 23-24.
[56] Assessment of Latvia's Territorial Just Transition Plan: https://www.just-transition.info/wp-content/uploads/2023/02/2023-02-22_Assessment-of-Latvias-TJTP.pdf, p. 2.

Peatlands cover approximately 10-12% of the country's area[54]. Latvia has a significant peat export industry, primarily for use in horticulture[55].		The Just Transitional Fund will supply €192M for restoration and stopping peat-based energy generation[57]. Strategy of Sustainable Use of Peat Resources 2020-2030[58]. Implementation of the Sustainable Development Goals – 2022: Construction of a wind farm on an old peat extraction site[59].	peatland is restored or paludiculture is practiced[60]. EU LIFE project Sustainable and responsible management and re-use of degraded peatlands in Latvia: Objectives include making a peatland inventory and a tool for land-use planning[61].	
Switzerland Peatland is "less than 1% of the total country area and 2% of the agricultural land"[62]. Major portion of Swiss peatland is used for horticultural production.	Trading of credits based on biochar allowed under the Swiss Emissions Trading System. Swiss ETS is now linked with the EU's.	Climate and Innovation Act 2023: Sets the target of net zero by 2050[63]. Rothenthurm Initiative 1987: Protection of raised moors[64]. Ban on peat extraction[65].	European Biochar Certificate: Qualification of EBC premium biochar for use in agriculture as a soil amendment[66].	Max.moor (2015-2033): Mechanism created by the WSL[67] for 'ex-ante' compensation for raising water levels on bogs

[54] Ozola *et al*. 2023, p. 2.

[55] Peatland Management and Conservation in Latvia: https://www.iucn-uk-peatlandprogramme.org/news/peatland-management-and-conservation-latvia.

[57] EU Cohesion Policy: €4.6 billion for Latvia to support a green and fair economy and society in 2021-2027: https://ec.europa.eu/commission/presscorner/detail/en/ip_22_6249.

[58] Latvia's Eight National Communication and Fifth Biennial Report under the United Nations Framework Convention on Climate Change: https://unfccc.int/sites/default/files/resource/LATVIA_NC8_BR5_Final.pdf, pgs. 87-88.

VARAM develop "Guidelines for the sustainable use of peat 2020-2030": https://www.varam.gov.lv/en/article/varam-develop-guidelines-sustainable-use-peat-2020-2030.

[59] Cabinet of Ministers Republic of Latvia: https://pkc.gov.lv/sites/default/files/inline-files/Latvia%202nd%20VNR_2022_2pg%20%281%29.pdf, pg. 65.

[60] Ozola *et al*. 2023, p. 14.

Stivrins *et al*. 2024, p. 7.

[61] Nature Conservation agency carries out project on sustainable and responsible management of degraded peatlands: https://restore.daba.gov.lv/public/eng/about_the_project/.

[62] Ferré *et al*., 2019, p. 2.

[63] 2050 net-zero target: https://www.bafu.admin.ch/bafu/en/home/topics/climate/info-specialists/emission-reduction/reduction-targets/2050-target.html.

[64] Climate protection through raised bog protection - CO2 compensation through raised bog restoration in Switzerland: https://www.wsl.ch/de/projekte/klimaschutz-durch-hochmoorschutz-1/.

[65] Participants join forces to reduce peat use: https://www.bafu.admin.ch/bafu/en/home/topics/economy-consumption/info-specialists/peat-exit-plan.html.

[66] Meyer *et al*. 2017, p. 180.

[67] Conservation bogs – protect the climate: https://www.wsl.ch/en/news/conserve-bogs-protect-the-climate/

				and cutting down carbon emissions[68].
Indonesia The country has one of the world's largest areas of tropical peatland[69]. Peatland fires are a major threat, and cause harm through haze pollution, as well as through increasing carbon emissions from peatland[70].	ASEAN Strategy for Carbon Neutrality 2023: Includes a focus on biofuel production, including palm oil[71]. ASEAN Peatland Management Strategy 2023-2030: Covers existing threats to tropical peatland and sets out priorities for mitigating present adverse effects[72]. ASEAN Agreement on Transboundary Haze Pollution: Monitoring and mitigating the haze pollution caused through fires, including peatland fires[73].	Enhanced NDC 2022: Includes a peatland restoration target of 2Mha by 2030[74]. National Net Zero Target of 2060. Permanent moratorium on clearing 66Mha of forest and peatland[75]. Presidential Instruction 8/2018: Moratorium on palm oil plantation licenses being issued[76]. Range of regulatory measures aimed to support degraded peatland, including restoration guidelines, and encouragement of paludiculture[77].	Peatland and Mangrove Restoration Agency (BRMG): Organisation in charge of coordinating peatland restoration efforts. Works with Regional Peat Restoration Teams at the Province level[78]. Roundtable on Sustainable Palm Oil & Indonesian Sustainable Palm Oil: Certification schemes with a tangential impact on peatland protection.	RKMs: Community-based Peatland Action Plans are used to carry out rewetting of peatland and paludiculture practices, alongside peatland water management[79]. Desa Mandiri Peduli Gambut: Programme for peatland restoration and fire prevention

[68] Project Klimaschutz: https://www.wsl.ch/de/projekte/klimaschutz-durch-hochmoorschutz-1/.

[69] Restoring Indonesian Peatlands: https://www.wsl.ch/de/projekte/klimaschutz-durch-hochmoorschutz-1/.

[70] Nature for Climate Peatland Grant Scheme: https://www.gov.uk/guidance/nature-for-climate-peatland-grant-scheme

[71] ASEAN Strategy for Carbon Neutrality: https://asean.org/wp-content/uploads/2023/08/Brochure-ASEAN-Strategy-for-Carbon-Neutrality-Public-Summary-1.pdf, p. 8.

[72] ASEAN Peatland Management Strategy 2023-2030: https://asean.org/book/strategy-and-action-plan-for-sustainable-management-of-peatlands-in-asean-member-states-2023-2030/.

[73] ASEAN Agreement on transboundary haze pollution: https://asean.org/wp-content/uploads/2021/01/ASEANAgreementonTransboundaryHazePollution-1.pdf.

[74] Climate Promise – Indonesia: https://climatepromise.undp.org/what-we-do/where-we-work/indonesia.
Enhanced Nationally Determined Contribution - Republic of Indonesia: https://unfccc.int/sites/default/files/NDC/2022-09/ENDC%20Indonesia.pdf, pg. 28.

[75] Indonesia president makes moratorium on forest clearance permanent: https://www.reuters.com/article/world/indonesia-president-makes-moratorium-on-forest-clearance-permanent-idUSKCN1UY142/.

[76] President Jokowi Imposes Moratorium on New Palm Oil Plantations: https://setkab.go.id/en/president-jokowi-imposes-moratorium-on-new-palm-oil-plantations/.

[77] Government Regulation (PP) No. 71/2014 on the Protection and Management of the Peatland Ecosystems - Uda, Schouten and Hein, 2020, p. 3.

[78] Yuwati *et al*. 2021.

[79] Corrective action on peatland management in Indonesia: http://pkgppkl.menlhk.go.id/v0/wp-content/uploads/2022/01/CORRECTIVE-ACTION-ON-PEATLAND-PROTECTION-AND-MANAGEMENT-IN-INDONESIA-06des_.pdf

				efforts at the village level.

__Table vi.__ Logic Chain for UK peatland code expansion in the UK.

Policy Driver	Logic Chain	Assumptions	Dependencies
What is the policy lever employed?	INPUT: Expansion of the Peatland Code to include carbon units captured and stored through biochar creation and usage, as well as paludiculture and its associated ecosystem services (biodiversity, flood mitigation, soil and water management)[80].	• Expansion of awareness of biochar and paludiculture[81]. • Continued interest of the private sector in the ecosystem services and carbon credits provided through peatland restoration and biochar respectively[82]. • Continued interest in the development of paludiculture practices through public sector funding, in the form of scientific trials as well as incentives through AES.	• Peatland Code interest and capability to incorporate paludiculture[83]. • Peatland Code interest and capability to incorporate other ecosystem services[84].
What is the mechanism for implementation? Regulatory, voluntary, or incentive? Is it at the international, continental, or domestic level?	ACTION: Voluntary mechanism, with the incentive of payments for additional carbon capture through the use of biochar and sale of paludiculture products. In terms of practical implementation, machinery adapted to peatland conditions is required, and water management and storage would be key to rewetting and managing peatland.	• Expansion of Peatland Code from upland[85] to lowland agricultural peat areas remain close to current restoration costs of £5,000-15,000/ha[86]. • Income from non-carbon ES ranges from £550-2,000/ha/year[87].	• Investment in water management infrastructure[88]to make rewetting feasible for individual farmers without community disruption. • Uptake by farmers when drainage and soil subsidence present as problems. • Continuation of small-scale biochar production, and expansion of knowledge-sharing networks.

[80] LAPFT, 2022, pg. 19.
[81] 'Supporting people, partnerships and economies', https://www.gov.uk/government/publications/lowland-agricultural-peat-task-force-chairs-report-government-response/lowland-agricultural-peat-task-force-chairs-report-government-response.
[82] Dyer, S., House, J., Lynch, J., Ghaleigh, S., Strubelj, L. and Butnar, I. (2023, November 23). "GGR Biochar Regulations Workshop" [Workshop Presentation]. Biochar Demonstrator, University of Nottingham.
[83] Paludiculture call for evidence for Peatland Code: https://www.iucn-uk-peatlandprogramme.org/news/paludiculture-call-evidence-peatland-code.
[84] Peatland Code public consultation - potential for inclusion of biodiversity credits, https://www.iucn-uk-peatlandprogramme.org/news/peatland-code-public-consultation.
[85] Current projects concentrated in upland peat areas. Peatland Code Projects Summary: https://www.iucn-uk-peatlandprogramme.org/peatland-code/peatland-code-projects-summary.
[86] Financing mechanisms in Europe for restoring peatlands: https://vb.nweurope.eu/media/19450/financing-mechanisms-for-rewetting-peatlands_vf.pdf.
[87] Johnson and Land, 2019, p. 9.
[88] Lowland agricultural peat: water for peat pilots: https://www.gov.uk/government/publications/lowland-agricultural-peat-water-for-peat-pilots/lowland-agricultural-peat-water-for-peat-pilots#lowland-agricultural-peat-water-discovery-pilot-lapwdp.

	The inclusion of paludiculture within the Code is likely to be most relevant for lowland peat areas, but applicable beyond them.		
How is this policy engaged with? What are the processes of knowledge transfer and exchange within the industry? Does information dissemination rely on support from other policy levers or is it reliant on a more informal mechanism of KT? How is participation audited?	PARTICIPATION: Existing awareness of the pathway of restoration/management of peatlands through AES. Some existing knowledge of biochar as a soil amendment. Predominantly science-driven knowledge transfer regarding paludiculture[89].	• Increased relevance of Sphagnum moss as a growing media alongside the voluntary phasing out of peat extraction, including in the horticultural sector[90]. • Opportunities for entering markets for thatching and insulation through paludiculture crops.	• Development of a standard for valuing the prevention of carbon emissions/the capture of carbon emissions through paludiculture and biochar, with higher value over time in line with inflationary pressures. • Development of a consensus on MRV systems for paludiculture and biochar.
What is the short-term impact of the policy, and does it have the desired impact?	REACTION: Unlikely to have significant impact on the UK agricultural sector in the short-term while the specifics of biochar trade-offs and peatland rewetting techniques to minimise emissions are studied.	• Current Defra policy regarding food production limits the extent to which farmland can be turned over to support ecosystem services or carbon capture. Several paludiculture crops not contributing to food production may limit its spread.	• Potential qualification of land on which paludiculture is carried out to qualify for inheritance tax relief[91]. • Uptake may be improved by stakeholders' interest in diversified income in the future.
Is there a feedback mechanism to measure impact in order to inform the design, implementation, and improve the effectiveness of the policy? Are the impacts of this policy visible elsewhere in the relevant sectors? Does it require policy levers/funded support?	CHANGES IN KNOWLEDGE, APPROACHES AND SKILLS: Feedback mechanism includes the health of the integrated carbon credit markets evaluated through demand for and the prices of the relevant ecosystem and carbon credits. The market mechanism would have to be reinforced by a robust monitoring and evaluation system (like that implemented by the Woodland Carbon Code). Impact would also be seen through prices and demand for paludiculture products, and their stability over time.	• Adaptation of existing calculation for rewetting peatland by the Peatland Code to include captured emissions through paludiculture and additional missions in the rewetting (particularly methane) and cultivation process.	• Possible change in land price - alteration of Agricultural Land Classification system for peatland to ensure that the economic value is not reduced when rewetting or paludiculture is carried out.

[89] Ziegler *et al.*, 2022.
[90] Plans to phase out the use of peat in the amateur horticulture sector: https://www.gov.uk/government/news/plans-to-phase-out-the-use-of-peat-in-the-amateur-horticulture-sector.
[91] Spring Budget 2024 — Overview of tax legislation and rates (OOTLAR): https://www.gov.uk/government/publications/spring-budget-2024-overview-of-tax-legislation-and-rates-ootlar/spring-budget-2024-overview-of-tax-legislation-and-rates-ootlar#Section2.

Will the policy lever have a long term and fundamental impact on the sector for which it was designed, or does it require continuous regulatory and financial mechanisms to maintain?	CHANGES IN BEHAVIOUR AND ACTIVITIES: Tests for permanence carried out prior to the rewetting projects, and long-term contracts for maintaining raised water levels[92].	• Change in subsidy scheme for drained agricultural land that disincentivises re-drainage for cultivation in the long term. • Trust in institutions and organisations which support the scheme financially.	• Possibility of paludiculture crops not proving to be self-sustaining alongside AES, long-term mechanisms would need to be developed to support it. • 60% of lowland peat which is presently utilised for horticultural and cereal production would have the potential to undertake rewetting and paludiculture. Depending on uptake, potential impact on horticultural and cereal production in the UK would require a plan for alternate sources that does not export emissions[93].
Will the policy lever have a long term and fundamental impact on the uptake of paludiculture practices?	FINAL OUTCOME: Provided sufficient numbers of farmers/growers have adequate incentive to be involved, the policy could contribute to reducing carbon emissions from drained peatland.		• Development of markets for paludiculture products and biochar by-products, including food crops, insulation material, growing media, and heating.

Table vii. *Logic chain for MRV system for peatland restoration/paludiculture in Indonesia*

Policy Driver	Logic Chain	Assumptions	Dependencies
What is the policy lever employed?	INPUT: Creation of an MRV (Measurement, Reporting and Verification) system, along the lines of the RSPO[94], to track peatland rewetting targets set by the Indonesian government (blocking of canals, water levels over time, species diversity) and to certify paludiculture projects.	• The three R's (rewetting, revegetation, and revitalisation of livelihoods) remain key to Indonesia's peatland restoration policy[95]. • Continued operation of existing peatland restoration work carried out by the BRG and collaboration with NGO's and international actors (such as the Peat Care Village (DPG) programme).	• Government and public pressure on companies that have not implemented legally required restoration measures. • Better implementation of existing laws regarding peatland restoration.
What is the mechanism for implementation? Regulatory, voluntary or	ACTION: Public-third-sector partnership led by the BRG collaborating with an independent organisation for auditing purposes.	• Collaboration with organisations such as WRI Indonesia and HRW to monitor and document potential violations (both climate	• Development of a system that allows land rights disputes[96].to be settled,

[92] Bonn *et al.*, 2014, p. 61.
[93] LAPFT, 2022, pg. 4
[94] RSPO has voted to not grant certification to palm oil on peatland. Astuti, 2021.
[95] Yuwati *et al.*, 2021.
[96] Miller, 2022, p. 81.

incentive? Is it at the international, continental or domestic level?	Government resources leveraged to identify peatland areas of high priority, and monitoring organisation to provide certification to products grown through paludiculture.	and labour/exploitation based), continued updating of standards, similar to the RSPO model.	including acknowledgement of plasma, and transmigration issues[97].
How is this policy engaged with? What are the processes of knowledge transfer and exchange within the industry? Does information dissemination rely on support from other policy levers or is it reliant on a more informal mechanism of KT? How is participation audited?	PARTICIPATION: Two-way flow of information for the MRV system; information regarding rewetting and paludiculture projects flowing from volunteers and auditors/verifiers to the central government through the BRG, and funds and paludiculture KT and equipment flowing from the government to communities/companies engaged in the practice.	• Knowledge base from communities regarding what crops have historically been cultivated on peatland without drainage to be effectively utilised and to form an evidence base through trials[98]. • One-Map policy[99], among other mapping efforts[100] leads to consistent data across government departments and at the local level to meet sustainability targets.	• Government involvement in ensuring the food security needs of local communities are met without the need for significant clearing of peatland. • Payments/subsidies to the individuals involved in the restoration work, through the allocation of funds for environmental schemes. • Trust in the government/relevant organisations' administration of MRV system by the local communities and village-level government.
What is the short-term impact of the policy, and does it have the desired impact?	REACTIONS: The MRV system is unlikely to significantly increase the uptake of rewetting and paludiculture in the short term, being based on previous BRG schemes and the RSPO, but has the potential to make an impact on markets at the local level. Potential disruption to the monoculture model, due to risk of relying on one paludiculture crop in an underdeveloped market.	• Continued pressure from anti-haze campaigning organizations as well as international partners to continue fire prevention activities alongside monitoring of existing rewetted peatland.	• Potential development of markets for paludiculture products, with MRV certification acting as endorsement of carbon neutral/negative products. • Relaxing of regulations around NTFP in the case of paludiculture origin of the products[101]. • Potential development of carbon credit model for smallholders to diversify income streams.

[97] Miller, 2022, p. 81.
[98] Giesen and Sari, 2018
[99] Uda, Schouten and Hein, 2020, p. 5.
[100] Astuti, 2021
[101] Giesen and Sari, 2018.

Is there a feedback mechanism to measure impact in order to inform the design, implementation, and improve the effectiveness of the policy? Are the impacts of this policy visible elsewhere in the relevant sectors? Does it require policy levers/funded support?	CHANGE IN KNOWLEDGE, APPROACHES AND SKILLS: The MRV system would include (like the RSPO) a built-in feedback mechanism, so that concerns can be brought to attention beyond the local level. Integration with a knowledge-sharing platform, so that paludiculture trials and knowledge of yield, equipment required, growing times, existing market avenues and overall rate of return for differing types of peatlands can be communicated (making use of existing BRG connections and programmes).	• BRG and the auditing organisation have the personnel and resources to carry out audits over several years.	• Strong alternative avenue for issues with the MRV system/auditing process to be raised.
Will the policy lever have a long term and fundamental impact on the sector for which it was designed or does it require continuous regulatory and financial mechanisms to maintain?	CHANGES IN BEHAVIOUR AND ACTIVITIES: The MRV system as a policy lever requires continuous resources in the form of qualified personnel to conduct audits, long-term trials to establish best practice in paludiculture and payments for paludiculture in addition to existing agricultural subsidies.	• Potential reduction in the use of fire to farm.	• Scaling up of current paludiculture projects, interspersed with cash crop cultivation (coffee, pineapples) in order to sufficiently cover the costs of labour going into maintaining water levels after rewetting.
Will the policy lever have a long term and fundamental impact on the uptake of paludiculture practices?	FINAL OUTCOME: Actual extent of emissions reduction and paludiculture uptake is uncertain, but it provides an incentive through diversified income and help with market establishment.	• Strong existing laws regarding peatland use and immediate health drawbacks from fires keep the issue relevant and on the agenda nationally, even when affected areas are marginal.	• Mechanisms for promoting paludiculture products in a wider market are put in place, and prices provide a satisfactory economic return102.

[102] Salminah *et al.*, 2021.

Table viii. Logic chain for land-use support tool in Germany.

Policy Driver	Logic Chain	Assumptions	Dependencies
What is the policy lever employed?	INPUT: Development of a paludiculture viability map, that includes elements such as peat type and depth, suitability for particular paludiculture crops (and applicable subsidies), local water management, and existing nature protection areas to develop a picture of factors operating on peatland.	• Continued interest from the federal government in paludiculture as an option for lowering carbon emissions.	• Government funding for undertaking the social and scientific research required for developing a representative map.
What is the mechanism for implementation? Regulatory, voluntary or incentive? Is it at the international, continental or domestic level?	ACTION: Responsibility for the creation of the viability map distributed between the federal and state governments (peat use is in the states' remit).	• Collaboration at the state level, and particular involvement of the state of Mecklenburg-Vorpommen, with existing paludiculture strategy and map.	• Existing mechanisms for the collaborative knowledge-gathering of different states on a shared topic.
How is this policy engaged with? What are the processes of knowledge transfer and exchange within the industry? Does information dissemination rely on support from other policy levers or is it reliant on a more informal mechanism of KT? How is participation audited?	PARTICIPATION: Requires the engagement of state and federal actors, peatland farmers, local communities, and the scientific and actors who are already involved with paludiculture and rewetting. KT takes place locally to nationally to capture the local characteristics of the peatland and its circumstances. At the state and national level, the information is compiled and augmented with additional knowledge gathering exercises (eg. peat surveys) where necessary.		• Willingness of farmers and other people making a living on drained peatland to engage with the process and give their insights.
What is the short-term impact of the policy, and does it have the desired impact?	REACTIONS: Unlikely to lead to a direct increase in paludiculture and biochar projects. Primary role is to develop areas of interest in paludiculture and outline the various barriers (economic, regulatory, systemic, social, practical).	• The tool developed will be promoted at the local, state and federal level for use in making land-use decisions but is not legally binding[103].	
Is there a feedback mechanism to measure impact in order to inform the design, implementation, and improve	CHANGE IN KNOWLEDGE, APPROACHES AND SKILLS: Direct mechanism for feedback through interviews, surveys and workshops with local communities and those most likely to be affected by a change in land use. Direct impacts of the policy	• Identification of “deeply drained peatland” to best target areas where rewetting will make the most impact on emissions[104].	

[103] Tanneberger *et al.*, 2020, p. 231.

[104] Tanneberger *et al.*, 2022, p. 69.

the effectiveness of the policy? Are the impacts of this policy visible elsewhere in the relevant sectors? Does it require policy levers/funded support?	are uncertain, but continued government interest in the topic of paludiculture may make some interested. Requires funding for carrying out peat surveys, ecological assessments, interviews and workshops.		
Will the policy lever have a long term and fundamental impact on the sector for which it was designed or does it require continuous regulatory and financial mechanisms to maintain?	CHANGES IN BEHAVIOUR AND ACTIVITIES: Continuous resources to maintain in terms of continued monitoring of peat conditions (or a representative sample). No foreseeable fundamental impact, due to the existing regulatory, economic and practical challenges to paludiculture, both at the German and EU level.		• Recognition of existing contradictory policy and restrictive legislation.
Will the policy lever have a long term and fundamental impact on the uptake of paludiculture practices?	FINAL OUTCOME: A viability map has the potential to focus resources on relevant areas and illustrate the conditions of a particular area to those stakeholders interested in a restoration/wetter farming/paludiculture pathway.		

Appendix 4: Social research interview questions.

Questions asked via e-mail and online interview to UK-based biochar suppliers.

Please state which farming system you are answering these questions to;

- Grasslands (e.g., dairy, beef, sheep and/or mixed)
- Arable
- Both

If you answered with both and feel that the answers to the questions below would differ depending on farming system, please provide separate answers for each farming system.

1. Why are farmers applying biochar to their soils (e.g., to improve soil organic matter content)?
2. What do you think are the benefits of applying biochar to agricultural soils?
3. Are there any risks or challenges associated with biochar application to agricultural soils?
4. When would you incorporate biochar to an agricultural soil and why?

5. What application methods are used to incorporate biochar on agricultural land?

Please detail machinery and equipment used (if this is dependent as to when it is incorporated then please identify these differences) and is this in combination with other farm activities (e.g., ploughing).

1. What are typical application rates and do these differ depending on application methods or time of application?
2. Who would you expect to spread biochar onto agricultural soils (e.g., contractor or farmer)?
3. *"Paludiculture is the practice of crop production on wet or rewetted peatlands that preserves the peat soil and thereby minimises* CO_2 *emissions and subsidence".*
4. Do you foresee any issues with using biochar within a paludiculture farming system (e.g., practicality)?

Appendix 5: Biochar Supplier Findings

Perceived biochar role in agriculture

Currently, suppliers implied that biochar is primarily used in the UK as an organic soil amendment for tree planting, orchards, tomatoes, strawberries, high-value crops, aquaculture, and grassland. Its perceived benefits include acting as an organic fertiliser and improving water retention, particularly in dry conditions.

UK-based biochar suppliers highlighted biochar's role in enhancing plant-soil interactions. They reported that biochar promotes symbiosis between plant roots, particularly nitrogen-fixing legumes such as red and white clover and soil microbes. This, in turn, increases microbial biomass, especially fungal mycorrhizae. The symbiosis increases the living organic matter in the soil which assists in the break-down of dead and dying organic matter as well as enhancing the atmospheric nitrogen fixing capability. Greater nitrogen retention within the soil biome may also improve plant resistance to pests and diseases.

When applied in an activated form—such as mixed with slurry or compost—biochar is believed to serve as an excellent nutrient carrier. It functions as a slow-release fertiliser, enhances soil microbial activity, improves root structure, reduces nutrient leaching, conditions the soil, and integrates well with poultry manure or farmyard manure (FYM), increasing micronutrient availability.

Growers working with these suppliers have reported positive results. Biochar application has extended the growing season in both spring and summer, with notable yield increases compared to previous years. One organic farmer observed that yields were as high, if not higher, than when using artificial fertilisers. Additionally, improved pasture quality has led to better livestock health, lower veterinary costs, and enhanced herd performance.

One supplier, who is also a farmer, noted that in the previous winter, fresh-calved cows required less silage because they were gaining weight more efficiently. They attributed this to improved pasture grazing, driven by enhanced soil microbial activity and increased dung decomposition by dung beetles and earthworms. As a result, a larger grazing area was utilised without additional costs.

However, suppliers were uncertain about the widespread adoption of biochar among UK farmers, though some were aware of farmers participating in carbon finance markets.

Biochar application methods

It is believed that applying biochar to agricultural soils could be similar to the current practice of liming, with a lime spreader. For instance, it could be applied at the start of the growing season or incorporated directly into the soil during planting. However, since arable land is managed differently from grassland, biochar can also be applied to organic matter, where it will help create an ecosystem within the root zone.

The suppliers noted that prior to application to the soil biochar must be altered. For example, hydroseeding biochar which mixes it with mulch to aquafy it. Thus, a farmer could buy a retail bucket of biochar, then add it to compost and then add it to ground. Although, according to the suppliers, some farmers do not incorporate biochar in the soil. Instead, they spread biochar on top of land, as part of normal organic fertiliser application.

One livestock farm is known to apply once a year in early October, to allow the soil and microbial colony to be fully fertilised as it strives to be ready for Spring growth. The nitrogen and other nutrients overwinter in the clovers and soil microbes and are thus protected against leaching. Yet, on a wet farm it is not possible to spread organic manure in the Spring early enough to activate the soil microbes in time for the spring growth. Hence, applying in October supports the red clover to overwinter which retains the clover in the sward.

Suppliers explained that worms and natural soil movement take the biochar and organic material into the soil. In one farm example, after three years of surface application, some biochar had penetrated to a depth of 70mm.

For those farms who are using biochar they typically apply it to grassland with a rear discharge manure spreader, exactly the same as traditional FYM or compost. The mix includes 20% biochar arboriculture chip, straw-based FYM, broiler poultry litter or often a mix of all three. One farmer added some previous composted blend to seed the correct microbes, which is then composted for at least two months to allow the microbes to fully develop. This then acts as a microbe injection to the soil as well as the inherent NPK and trace element values.

The suppliers added that biochar must be added as part of an organic manure/compost mix. Currently only 5% in a mix is used as it is too expensive to include more. The suppliers postulated that bigger effects will likely show on more nutrient depleted land (e.g. USA).

It was suggested that the application of biochar could be done similar as to how lime spreading is done at the back of tractor. Pellets (which would be peletised before pyrolysis) can be stored in bags, however, they crack easily, hence are utilised more in garden centres. There was little concern about spreading and it was suggested that biochar could be included in a fertiliser spinner, which most farmers will have. Therefore, there was no perceived extra capital or labour costs required.

Due to the fire risk, proper storage is essential. By aquafying the biochar, the combustion risk is reduced as it then contains a low calorific value, because the energy has been used.

The biochar suppliers are spreading within the Environment Agency's (EA) Low Risk Waste Pollution (LREP) 61 egulation1 of one tonne of biochar per hectare over any twelve-month period. One supplier stated that they are currently working with the EA on the current spreading rate for the poultry sector chicken manure as the current tonnage per hectare results in high phosphate levels which leaches into river ecosystems. Another example of application rates, a supplier uses was 2-4 tonnes of mix per acre. This contains approximately 250-400kg of dry weight biochar. Additionally, it was found by a stakeholder that after the second cut, they apply a smaller amount, of approximately 2 tonnes, with the sole aim of feeding the microbes.

When asked who would spread biochar, the suppliers stated that application would be whoever currently spreads FYM or compost. Furthermore, it would be similar to the liming industry that it will be a mix of farmers and contractors.

Risks or challenges associated with biochar application to agricultural soil

It was suggested that pyrolysis can immobilise heavy metals, microplastics (PFAs etc.) and feedstock from waste. However, there is research reporting plants mutating, causing an increased risk of black grass and diseases from herbicide. Suppliers suggested to avoid a fire hazard, the biochar can be suppressed at the end of the process, so that the material is stackable, rather than liquid.

Supplier perception towards biochar integrated with paludiculture

Paludiculture is the practice of crop production on wet or rewetted peatlands that preserves the peat soil and thereby minimises CO2 emissions and subsidence2. Soil stability to carry the weight of typical machinery for biochar application (e.g., lime spreader), was deemed by the suppliers to be the biggest barrier to incorporating biochar into paludiculture practises.

Farmers identified that spreading could be relatively achievable at the end of summer when the water table is traditionally at its lowest. Although, a warning was given that if the land is too wet, the compaction of the wet soil would kill the microbes.

For storing biochar before its application, the ideas shared were sub-surface storage, such as rhizome or bracken, to avoid disturbing under the peat. Pellets were suggested by suppliers, this was due to them being smaller in size making them easier for storage. This was proposed for any type of agriculture, rather than specific to paludiculture. Although one proposed that the press energy to make biochar pellets would diminish the lifecycle benefits. Furthermore, the compressed nature would not allow much space for microbes, which was a perceived benefit of biochar, rather than an awareness of its application to paludiculture. For biochar to be utilised in agriculture, it was expected that it would act as a soil improver, such as providing microbes, there was no mention of carbon credits or its role in paludiculture by participants.

Regulation

The suppliers were not opposed to regulation and suggested that third party auditors could verify biochar, rather than have a UK regulatory body involvement. The material should be demonstrated against the EA's LRWP603 and LR614. Suppliers were aware of Iceland having accredited material via the International Biochar Initiative (IBI). New Zealand/Australia also have an accreditation scheme. A scheme would need to include surveys, in order to determine land type as application on softer ground may affect the soil structure and result in leaching. Lastly, it was suggested to review the Biochar for Sustainable Soils (funded by The Global Environment Facility and implemented by the United Nations Environment Programme) international guide which recommends that a reactor to contain and control chemical reactions, such as pyrolysis.

Appendix 6: Farmer Perception Findings

Questions raised by farmers

- What gases are produced?
- What is the long-term carbon stability – how many years?
- What is the source of the wood chip used to produce the biochar?
- How does it tie into agri-environment schemes, such as SFI?
- How much carbon is in a tonne of biochar?
- Would type of wood could be used to make biochar? An example in Michigan, USA, was shared where a farm is using large woodchip in replacement for gravel (which the UK uses). It was noted that soft wood would break down much faster.
- For what reasons would you apply biochar to paludiculture?
- In what circumstances chose biochar for your land as opposed to other means?
- Does biochar absorb water? This could mean that it is easier for crops to grow and machinery to work and retain water to minimise greenhouse gases.
- Is the 1 tonne regulatory quota related to dry or wet weight?
- What is the rationale to the regulatory quota?
- There is a land for food versus fuel debate, which will farmers get paid more for?
- Where will food come from, exports?
- Presently, it is only known that carbon is being locked up. What happens to NPK? Anaerobic Digestors (AD) do not lose any elements, there is no loss of nutrition as the material is returned to the soil with AD

Appendix 7: Farmer workshop materials.

Table ix. Workshop agenda and discussion questions.

Time	Topic	Actions	Activity	Resources
12:00	Introduction	Present Powerpoint slides with an explanation of the background to the project, plan for the workshop and definition of biochar. <u>Question to ask participants:</u> Who is aware of biochar? (Are you aware of biochar for agricultural land?)	Facilitator talking and show of hands for the participant question.	
PART 1: Biochar				
12:10	Biochar	Participants move from their table to assigned station and then rotate to answer all the questions on the wall/flipchart. <u>Questions to ask participants:</u> How would you apply biochar to fields? Would you apply it on the farm's least productive land or high-end or both? Why would you apply biochar? Do you have any hesitations about applying biochar?	Participants write on post-its and put on wall under each question.	Post-its Pens Flipchart Biochar sample station
PART 2: Paludiculture				
12:35	Paludiculture presentation	Present Powerpoint slides about paludiculture including the definition and any examples.	Facilitator presentation.	
12:30	Paludiculture	Smaller groups at each table with facilitators joining or rotating to other tables to probe and ask prompting questions. <u>Questions to ask participants:</u> Who has considered implementing paludiculture on their land? What reasons would you apply biochar to paludiculture? How would you physically apply biochar to paludiculture on your land?	Table-based discussions with facilitation and note-taking.	Questions handed out for each table.
12:45	Paludiculture & Policy	Explain the requirements for biochar application (e.g. develop on farm for carbon credits).	Facilitator explanation.	
12:50	Paludiculture & biochar policy	Now you have heard the policy requirements of biochar, how would you apply biochar to paludiculture?	Can be one large group or small table-based.	Keep Powerpoint slide showing the requirements.
12:55	Close	Facilitator answers any questions and closes the workshop.		

Appendix 8: Economic Analysis

Table x. Inventory data considered in biochar production.

Feedstock characteristics	%	Moisture %	Volatile Matter %	Ash %	Fixed Carbon %

Wood (Biochar demo data)	wet	50.00	37.12	3.24	9.64
	dry	0.00	74.24	6.49	19.27
Miscanthus (Mimmo *et al.*, 2014; Eibisch *et al.*, 2015; Rasse *et al.*, 2017)	wet	25.00	58.50	6.38	10.13
	dry	0.00	78.00	8.50	13.50
Willow (Wang *et al.*, 2014; Ferraro *et al.*, 2024)	wet	55.00	36.63	0.54	7.83
	dry	0.00	81.40	1.20	17.40
Working hours (Continuous)	8000	hrs p.a.			
Working hours (Batch, full time)	8	hrs per day			
Grid electricity (DESNZ, 2023)	0.18	£ per kWh			
	0.146	$kgCO_2/kWh$			
NG (DESNZ, 2023)	0.047	£/kWh			
	0.183	$kgCO_2/kWh$			
Discount rate of return	0.05	5%			
plant life	20	years			
Biochar properties	Stability (%)	Biochar yield (wt%)			
		Wood (Rosas *et al.*, 2015; Sessa, Veeyee and Canu, 2021; Jamal and Fletcher, 2023)	Miscanthus (Mimmo *et al.*, 2014; Janus *et al.*, 2015; Singh *et al.*, 2021)	Willow (Hamedani *et al.*, 2019; Leppäkoski *et al.*, 2021; Ferraro *et al.*, 2024)	
High-grade (>500 °C)	90	30	35	30	
Low-grade (<500 °C)	50	50	45	40	
Feedstock transport					
Distance for farm-scale	2	km			
Distance for commercial-scale	50	km			
Articulated >3.5-33t - 100% laden (100% loaded-full truck) (DESNZ, 2024)			0.91726	kg CO2-Eq/km	
Articulated >3.5-33t - 0% laden (0% loaded-empty truck) (DESNZ, 2024)			0.61558	kg CO2-Eq/km	
Transport cost parameter (Gamaralalage *et al.*, 2025)			0.22	£/tn.km	
Transport cost haulage parameter (Road Haulage Services Ltd, 2024)			0.94	£/km	
Feedstock cost					
Wood (Forest Research, 2024)	50	£/t			
Miscanthus	0	£/t			

Willow	0	£/t
Labour salary (SalaryExpert, 2024)	30000	£ p.a.
Farm-scale pyrolysis unit cost (Heinrich *et al.*, 2023)	0.05	M£

Table xi. Net present value (£ ha^{-1}) of the two business as usual agriculture crop options across the four scenarios comparing the sensitivity of the NPV figures to changes in discount rate. NPV and AEV calculated over 30 years at a discount rate of 3, 4, 5 6 and 7%.

Crop option	£ ha^{-1}				
	3.00%	4.00%	5.00%	6.00%	7.00%
Wheat (BAU)	18,790	16,577	14,737	13,196	11,896
Lettuces (BAU)	926,466	817,353	726,619	650,631	586,546

Table xii. Net present value(£ ha^{-1}) of the three paludiculture crop options across the four scenarios comparing the sensitivity of the NPV figures to changes in discount rate. NPV calculated over 30 years at a discount rate of 3, 4, 5 6 and 7%.

Crop option	Scenario	£ ha^{-1}									
		Wheat as original cropping					Lettuces as original cropping				
		3.00%	4.00%	5.00%	6.00%	7.00%	3.00%	4.00%	5.00%	6.00%	7.00%
Miscanthus	Scenario 1	12,083	11,141	10,295	9,531	8,840	12,083	11,141	10,295	9,531	8,840
	Scenario 2	29,458	25,875	22,891	20,385	18,262	19,646	17,534	15,742	14,208	12,885
	Scenario 3	29,243	25,687	22,725	20,237	18,130	19,431	17,346	15,575	14,060	12,752
	Scenario 4	29,652	26,045	23,041	20,518	18,382	19,840	17,704	15,892	14,341	13,004
Willow	Scenario 1	7,726	7,223	6,745	6,290	5,860	7,726	7,223	6,745	6,290	5,860
	Scenario 2	25,101	14,737	14,737	14,737	14,737	15,289	13,616	12,192	10,967	9,905
	Scenario 3	14,159	12,395	10,920	9,674	8,612	4,347	4,054	3,770	3,497	3,234
	Scenario 4	18,678	16,356	14,418	12,784	11,395	8,866	8,015	7,268	6,607	6,017
Reeds	Scenario 1	14,357	13,283	12,330	11,480	10,718	14,357	13,283	12,330	11,480	10,718
	Scenario 2	32,718	28,855	25,645	22,954	20,680	22,906	20,514	18,495	16,777	15,302
	Scenario 3	30,296	26,732	23,770	21,287	19,189	20,484	18,391	16,621	15,110	13,811
	Scenario 4	30,747	27,127	24,119	21,597	19,466	20,935	18,786	16,970	15,420	14,089

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