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Testing the potential use of UK wetland plant species in paludiculture using examples from the Somerset Levels

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Abstract

The trade-off between economic benefits and environmental sustainability results in the unsustainable use of wetlands through conversion to agricultural land. As a result, causing peat degradation, reducing the ecosystem's capacity to provide ecosystem services. Paludiculture, the concept of cultivating wetland plant species in rewetted conditions that can be converted and utilised commercially, presents an opportunity to harmonise economic stability and environmental protection. However, most research into paludiculture has been conducted in continental Europe; there is a knowledge gap regarding paludiculture in the UK. In this research, seven UK wetland plant species were harvested from the Somerset Levels, a low-lying wetland area with high agricultural presence and nutrient contamination. Samples were harvested as close to a monoculture as possible using a 0.25m^2 quadrat, freeze-dried to enable the dry biomass production to be calculated, milled, and then passed through an X-ray Fluorescence (XRF) and Carbon, Hydrogen, and Nitrogen (CHN) analyser to determine the nutrient removal capacity of each plant species. Statistical analysis, including a one-way ANOVA test, identified a significant difference between the dry biomass production of the plant species; *Typha latifolia* produced the greatest dry biomass yield of 50.32 t ha-1-yr-1, followed by *Phragmites australis*; *Glyceria maxima* produced the smallest dry biomass yield of 3.35 t ha-1-yr-1. Furthermore, *T.latifolia* demonstrates a significantly greater nutrient removal capacity, potentially removing 21.8 t ha-1-yr-1 of carbon and 3.12 t ha-1-yr-1 of phosphorus per yield, followed by *P.australis*. These findings show that *T.latifolia* and *P.australis* have the greatest potential for paludiculture within the UK to remediate nutrient contamination and restore the wetlands whilst maintaining land productivity. Although this study has demonstrated the potential of paludiculture on the Somerset Levels and Moors (SLM) the individual conditions of alternative locations in the UK, such as soil pH and water table depth, should be revised to determine the suitability for paludiculture.

Keywords: Paludiculture, Wetlands, Sustainable agriculture, Ecosystem services, Peat degradation.

Introduction

Wetlands are transition zones between terrestrial and aquatic environments, characterised by land areas where the water table lays near or just above the land surface permanently or seasonally (Hatvany, 2009). This water saturation is a determining factor in the soil development and the species of flora and fauna that inhabit the area (U.S. Geological Survey, 2022). Peatlands are a type of wetland covering only 3% of the world's land area yet are the most significant carbon terrestrial sink in the world, holding more than 550 gigatonnes of carbon (International Union of Conservation of Nature, 2022). Peatlands are sensitive systems with limited ecological boundaries, comprised of layers of decaying organic matter within anoxic conditions making complete decomposition impossible (Jeglum & Rydin, 2013). Wetlands provide many essential benefits to society, known as ecosystem services (Christie *et al*., 2011). These include but are not limited to, climate change and greenhouse gas (GHG) mitigation, flood risk mitigation, water purification, and biodiversity conservation (Christie *et al*., 2011).

Wetlands face anthropogenic threats through agriculture, peat extraction, forestry, global warming, and infrastructural developments, contributing to a 25% reduction of mires globally (Nieminen *et al*., 2017; Parish *et al*., 2008). Improper land-use upon peatland, such as conversion to agricultural land, typically exceeds the ecological boundaries of which peat flourish within, causing soil degradation, peat oxidisation and GHG emissions, which reduces the capacity of peatlands to provide vital ecosystem services (Olsson *et al*., 2022; Royal Society for the Protection of Birds, 2011; Lahtinen *et al*., 2022). Within the agricultural sector, there is a trade-off between environmental objectives and the necessity for agricultural production; this creates challenges when restoring peat (Lahtinen *et al*., 2022; Alewell *et al*., 2021). Paludiculture offers an opportunity to reduce GHG emissions from degraded peatlands whilst maintaining land productivity (Lahtinen *et al*., 2022). This practice refers to the cultivation of wetland plant species in wetland conditions to encourage peat accumulation and produce a commercial crop. This biomass can be harvested and utilised productively, potentially mitigating any loss of agricultural productivity that peatland restoration could cause (Gummer *et al*., 2018). Therefore, this has potential to provide economic incentives for stakeholders to conserve peatlands (Natural England, 2022; Abdel-Aziz *et al*., 2020).

The ecosystem benefits of paludiculture have been recognised amongst scientists as a strategy to tackle issues, such as climate change, sustainably and naturally (Borst *et al.,* 2022; Aavola *et al.,* 2011; Kreuter & Teague, 2020). The United Nations Framework Convention on Climate Change highlight peatland's crucial role in achieving Sustainable Development Goals (SDG) (De Klein *et al*., 2019). Paludiculture presents an opportunity to advance towards several SDGs, such as SGD 9: Industry, Innovation and Infrastructure, SDG 12: Responsible Consumption and Productive, SDG 6: Clean Water and Sanitation, SDG 13: Climate Action, and SDG 15: Life on Land (United Nations, 2023).

Methodology

Site description

Sample collection was carried out at two wetland sites: Greylake and Moorlinch, situated on the SLM, UK (figure 1). Sample collection took place in late June 2022. The site is lowland wet grassland containing low-lying basin peat with some raised bogs, bordered by alluvial silt and clay (IUCN, 2022a). SLM was declared a Royal Society for the Protection of Birds site (RSPB), Sites of Special Scientific Interest (SSSIs), and a Special Protection Area (SPA) due to the abundance of waterfowl during the winter period, and a Ramsar site for the inhabiting invertebrates (Natural England, 2021). 79% of the SLM is used for agricultural practices which has contributed to the sites' condition being declared 'unfavourable declining' by Natural England (2021) (Deane, 2016). This site was selected due to the excessive phosphorus concentrations, which highlights the need for alternative sustainable land-use management (NE, 2021). Six of the seven sampling sites were located within Moorlinch, a SSSI site, and one was in Greylake Nature Reserve (figure 1).

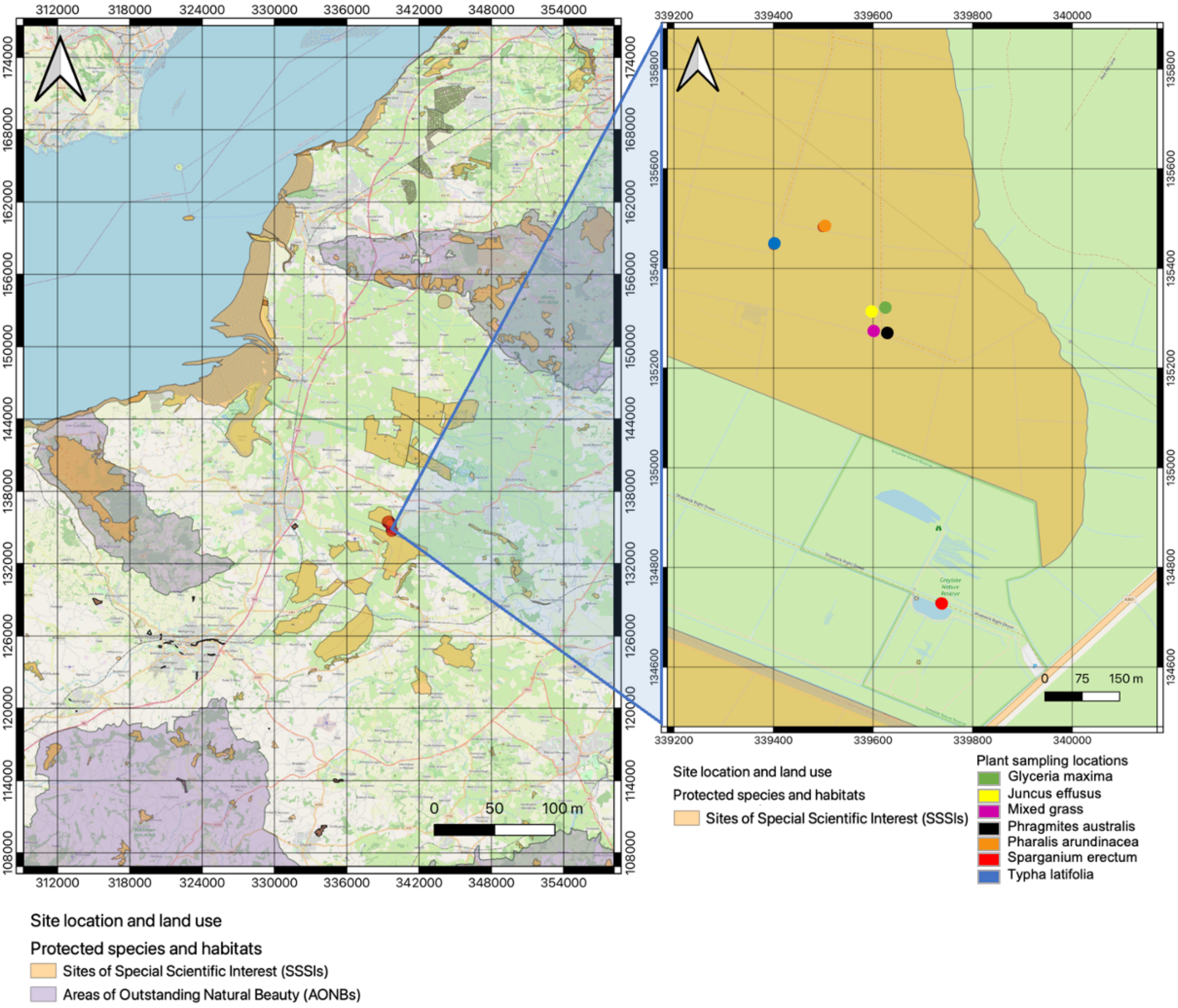

Figure 1: The sampling locations of the seven wetland species where data was collected in Moorlinch and Greylake, Somerset, UK, showing the location of Sites of Special Scientific Interest (Natural England, 2022a). Created in QGIS using OpenStreetMap basemapping.

Field work and collection

Seven wetland plant species were harvested within Moorlinch and Greylake. Locations were identified by previous field sampling carried out the year before, by the research team, where species were found as close to a monoculture as possible; this was important as it meant a year's worth of growth was being collected. Wetland plant species harvested were *Glyceria maxima, Juncus effusus, Mixed grass, Phragmites australis, Phalaris arundinacea, Sparaganium erectum, Typha latifolia* (table 1).

Table 1: A description of the characteristic of the species of interest within this study and their uses within commercial production.

Species	Common name	Characteristics	Utilisation
Typha latifolia	Cattail	Recognised by its cigarshaped head; growing naturally in areas submerged with water and has a high biomass making it a suitable paludicrop (Joosten *et al*., 2016).	Typically used for insulation plates; it has mould resistant properties, good hygrothermal performance and the ability to regulate air quality (Joosten *et al*., 2016; De Jong *et al*., 2021). Literature has shown that annual harvested biomass ranges between 3.58 t ha^{-1} and 22.10 t ha^{-1} (AbdelAziz *et al.,* 2020).
Mixed grass	Mixed grass	Mixed grass is a monocotyledon, typically inhibiting drier areas near gullies (McNamara *et al*., 2008).	Mixed grass compromises some 80% of productive agricultural land due its importance for livestock grazing (McNamara *et al*., 2008; Boval & Dixon., 2012).
Juncus effusus	Common Rush	According to Abdel-Aziz *et al.* (2020), the presence of *Juncus effusus* suggests wet, poor quality agricultural soil. Because of these circumstances, vegetation is often short and thick stemmed. However, research has shown that with enough nutrients and space, thin tall stems can grow.	Used in Japan for the construction of tatami mats, a type of flooring (AbdelAziz *et al*., 2020).
Glyceria maxima	Reed Sweet Grass	This is a rhizomatous perennial grass which inhabits aquatic environments up to 15cm deep, growing up to 1m tall (RHS, 2023).	Abdel-Aziz *et al.* (2020) identifies this species as a good fodder paludicrop, however it has lower forage quality.
Phalaris arundinacea	Reed Canary Grass	This species is a perennial rhizomatous genotype, that inhabits sites which are rarely flooded but mineral rich (Royal Botanic Gardens., 2023, Schulz *et al*., 2011).	It is utilised for animal food, paper, medicine due to its medicinal properties and as poison (Royal Botanic Gardens., 2023; Wichtmann *et al.,* 2010).
Sparganium erectum	Branched Bur Reed	This species is an aquatic perennial that inhabits shallow mesotrophic or eutrophic freshwater (Plant Atlas, 2023). Stands to 1.5m tall with a branched inflorescence and unstalked flowers (NatureSpot, 2023).	This plant species has many medicinal properties and has previously been used for chills, chest pains and abdominal pains (Moerman, 1998; Yeung, 1995).
Phragmites australis	Common Reed	This is a cosmopolitan graminoid species which grows in conditions ranging from damp ground to water deeper than 1m, making them suitable to wetlands (Abdel-Aziz *et al.,* 2020). Graminoid species are effective for filtration, restoration, and repopulating areas with vegetation (CNP, 2019).	Joosten *et al.* (2016) identified *Phragmites Australis* as a favourable crop for paludiculture use due to its high biomass. This species as traditional used as a thatching material, specifically used for thatched roofing due to its durability and long-life cycle (Gellerich *et al*., 2016).

Species identification

Due to the high presence of grassland on SLM, mixed grass has been used within this study as a comparison against paludicrops to compare whether paludiculture has the potential to enhance ecosystem service production compared to current land-use.

At each monoculture location, a 0.25m^2 quadrat was placed and the identified species inside the quadrat was harvested (multiplied by 4 to represent 1m^2). Species were harvested just above the root to allow regrowth. Soil samples were collected in small pots directly below where the vegetation was harvested. Onsite, directly after harvesting, samples were bundled using string and weighted using a hanging scale; this ensured a true wet weight was obtained. Wet weight was recorded, and each sample was bagged according to species. Then, the vegetation and soil samples were transported back to the University of Plymouth and were stored in the freezer.

Sample drying

Vegetation and soil samples were held in the freezer due to the expected length of time between fieldwork and laboratory work. Each sample was reweighed (to 3 decimal places) before beginning the freezer-drier process, ensuring each sample bag or pot was wiped down using a paper towel to remove condensation, as this could give inaccurate weight readings. A freeze drier was used to dry out the samples to measure the water content within each species. This method was applied to three samples of each species so three values could be obtained per species for analysis. The pressure was set to 62 mbar and the temperature was -49°C. The transition between removing each sample from the freezer, to weighing and then in the freeze drier had to be done quickly to reduce the risk of samples defrosting. Once in the freezer drier, samples were removed after 48 hours and weighed, then replaced in the freeze drier until there had been no fluctuation in weight for 24 hours to ensure the samples were dry. After this time, absolute dry weights were recorded for each plant species and soil sample.

Soil sample preparation

A mortar and Pestle were used to hand grind the sample down to <63 microns as this size was essential for nutrient analysis. Sediment was passed through a 1mm and then 63 micrometre sieves to ensure sample was small enough, this was then transferred into clearly labelled sample bags. This method was applied to three samples of each species so three values could be obtained per species for analysis.

Vegetation sample preparation

Initially, this process began using a grinder to help break down the vegetation for the next step. After the sample size had reduced, samples were placed in the oven at 30°C for 12 hours to remove any moisture obtained through grinding in preparation for further grinding. This method was applied to three samples of each species so three values could be obtained per species for analysis.

Further vegetation sample preparation for XRF (X-ray Fluorescence)

Milling was carried out using a Fritsch Planetary Mill (Pulverisette 5). 4g of sample material was weighed (to 3dp), placed in synthetic silica bowls with 5 steel balls inside and were milled at 300 revolutions per minute for 8 mins, then a further 3 minutes with 1g of ceridust, this acts as a binding agent to form the pellets. Each sample could then be stored in clearly labelled sampling bags and stored in the oven at 30°C to ensure samples maintained dry. This method was applied to three samples of each species so three values could be obtained per species for analysis.

XRF analysis

The milled vegetation sample containing ceridust was spooned into compressible aluminium briquetting cups until sample was in line with the top of the dish, ensuring material was pressed into the corners to remove air spaces. Using a XFR press, the briquettes were pressed at a pressure of 150kN to form pellets with a 32mm diameter and passed through the XRF analyser (see appendix 1). Three pellets were produced for each species and passed through the XRF analyser. XRF analysis is a non-destructive technique to establish the elemental composition of the samples using “wavelength-dispersive spectroscopic principles”; phosphorus was the key element studied (XRF scientific, 2023; Reiche & Chalmin, 2014).

CHN analysis (Carbon, Hydrogen, Nitrogen)

CHN analyser was used to determine the carbon, hydrogen, and nitrogen content within each sample. This process requires high temperature combustion, oxidation, and reduction (Thompson, 2008). For CHN analysis, tin foil capsules were filled with 8-12mg of sample, using forceps to avoid contamination, and weighed. Once the correct weight was obtained, the capsules were crushed into a ball to seal. To ensure no sample had leaked out, capsules were reweighted to ensure there was no fluctuation in weight prior to crushing. Using forceps, each individual ball was transferred into the sample tray, which would be passed through the CHN analysis to generate results obtained in a spreadsheet. This method was conducted three times for each species so three values could be obtained per species for analysis.

Results

Biomass yield

The freeze-drying process enabled the percentage of dry weight per sample to be obtained which could be compared to the wet weight per gram of each sample to calculate the dry weight per gram. This value was then scaled up to tonnes per hectare to obtain the dry biomass per t ha-1-yr-1 for each species. Implications during the freeze-drying of *Glyceria maxima* samples resulted in incorrect dry weight values, therefore unpublished data generated by the research team was used during biomass analysis for this plant species. Standard deviation and standard error were calculated for each species, and a box plot was produced (figure 2). Standard error was calculated by dividing the standard deviation by the square root of the sample size.

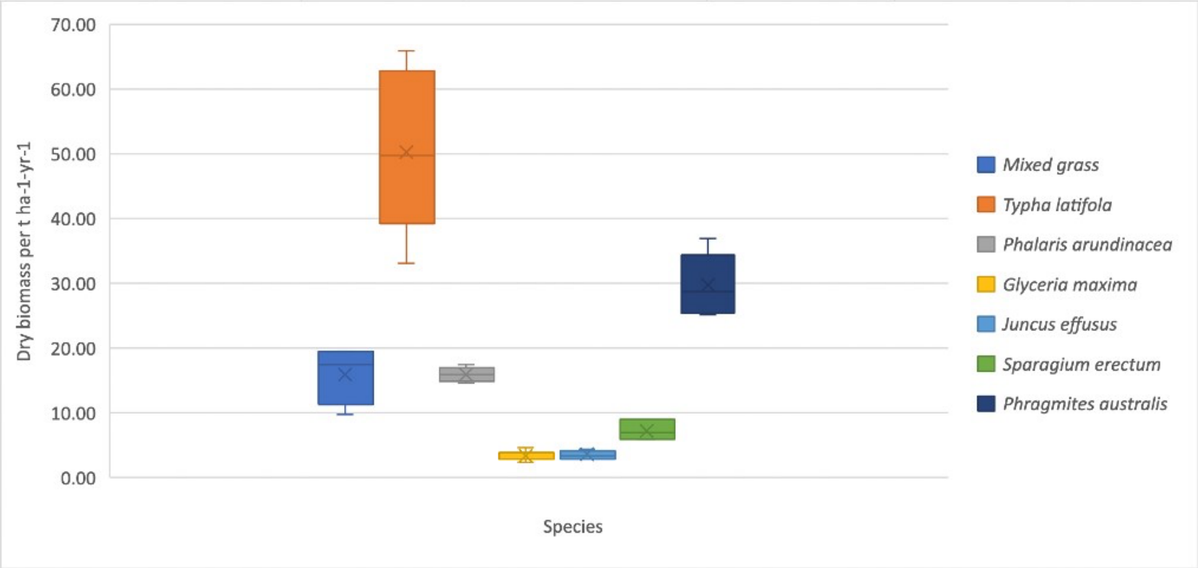

Figure 2: Box and Whisker plot of the dry biomass per t ha-1-yr-1 of each of the seven species harvested on the Somerset levels. ‘x’ on the box and whisker plot represents the mean, the top and bottom of the box represents the upper and lower quartile. The top and bottom line represent the maximum and minimum value in the data sets.

Table 2 - Grouping information of the seven plant species obtained through a post hoc Tukey test, with 95% confidence, to determine which species have a statistically significant difference in their dry biomass yields. Means which do not share a letter are significantly different meaning there is a significant difference between data sets. A statistically significant difference is identified between: *Mixed grass – G.maxima, P.arundinacea – G.maxima, P.australis – G.maxima, T.latifolia – G.maxima, P.arundinacea – J.effusus, P.australis – J.effusus, T.latifolia – J.effusus, P.australis – Mixed grass, T.latifolia – Mixed grass, T.latifolia – P.arundinacea, S.erectum – P.australis, T.latifolia – P.australis, T.latifolia – S.erectum.*

Species	**N**	**Mean**	**Grouping**
Typha latifolia	6	50.32	A
Phragmites australis	6	29.88	B
Mixed grass	4	16.11	C
Phalaris arundinacea	6	16.08	C
Sparagium erectum	3	7.35	C D
Juncus effusus	4	3.59	D
Glyceria maxima	11	3.35	D

Using R studio version 4.2.2 (R Core Team, 2022), a Shapiro-Wilk test determined the dry biomass per t ha-1-yr-1 of each species to be normally distributed. A parametric one-way ANOVA test was used to identify whether the dry biomass between species was statistically significantly different (SSD), this produced a P-value of 4E-16. This is less than the critical value (CV) of 0.05, therefore the null hypothesis can be rejected, showing there is a SSD between at least one pair of data. A post hoc Tukey test identified which pairings are SSD. Output grouping information shows which species are SSD (table 2)(visual representation available in appendix 3).

Nutrient removal capacity

Phosphorus

1. Phosphorus content (%) of species.

The XRF analysis revealed the phosphorus content as a percentage for each species (figure 3). From this, the mean and standard deviation was calculated.

To test for a SSD in the phosphorus content (%) between species, a Kruskal-Wallis test was carried out in excel. A non-parametric test was used as data was assumed non-normally distributed due to the small sample size. The P-value of 0.058 (see appendix 4) is greater than the CV of 0.05, the null hypothesis is accepted. However, it should not be concluded that the null hypothesis is true, instead it should be considered as a possibility as more a larger sample size is required to reject it.

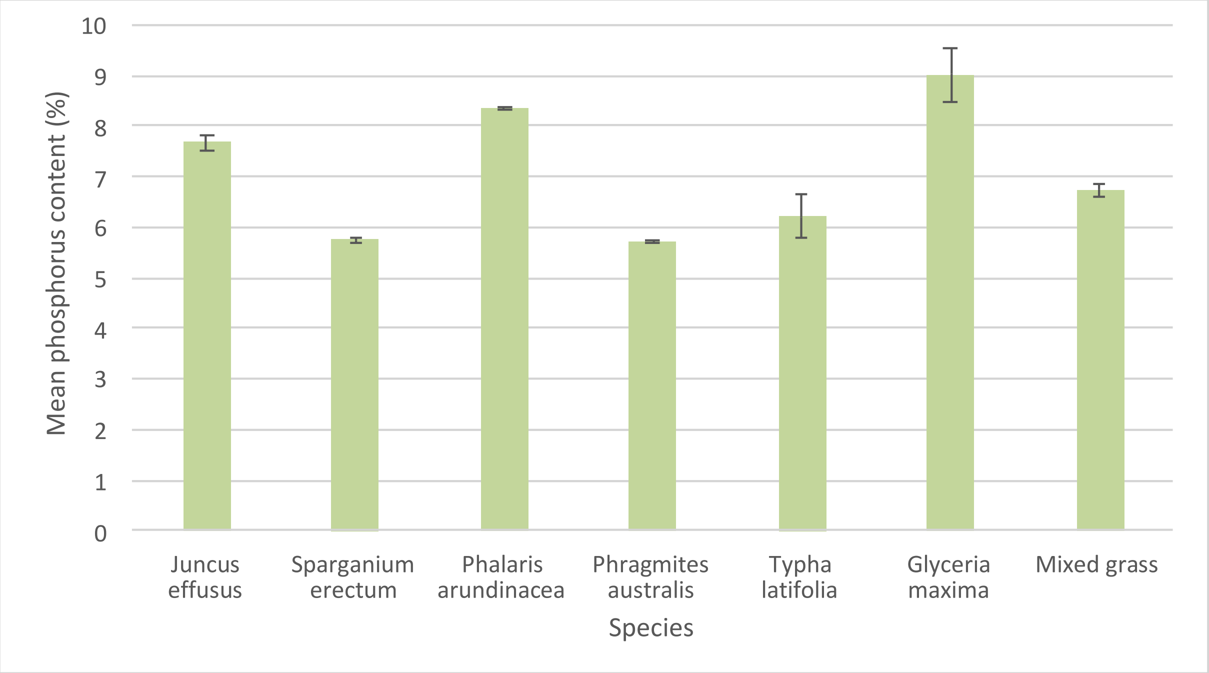

Figure 3: Bar chart showing the phosphorus content (%) for each wetland plant species harvested on the Somerset levels (± standard deviation).

2. Phosphorus removal capacity of each plant species

To determine the phosphorus removal capacity of each species per t ha-1-yr-1, the phosphorus content (%) per species was compared to the mean dry biomass yields. This was achieved by calculating the phosphorus content (%) as a percentage of the dry biomass yield which produced the phosphorus removal capacity t ha-1-yr-1 for each species (figure 4). A separate table including the means was produced as the mean values will be used when comparing against other variables (table 3). For example, *P.australis* had a mean dry biomass of 8.978 t ha-1-yr-1, the mean phosphorus content was 5.737%, therefore the calculated mean phosphorus content per t ha-1-yr-1 of dry biomass is 1.662.

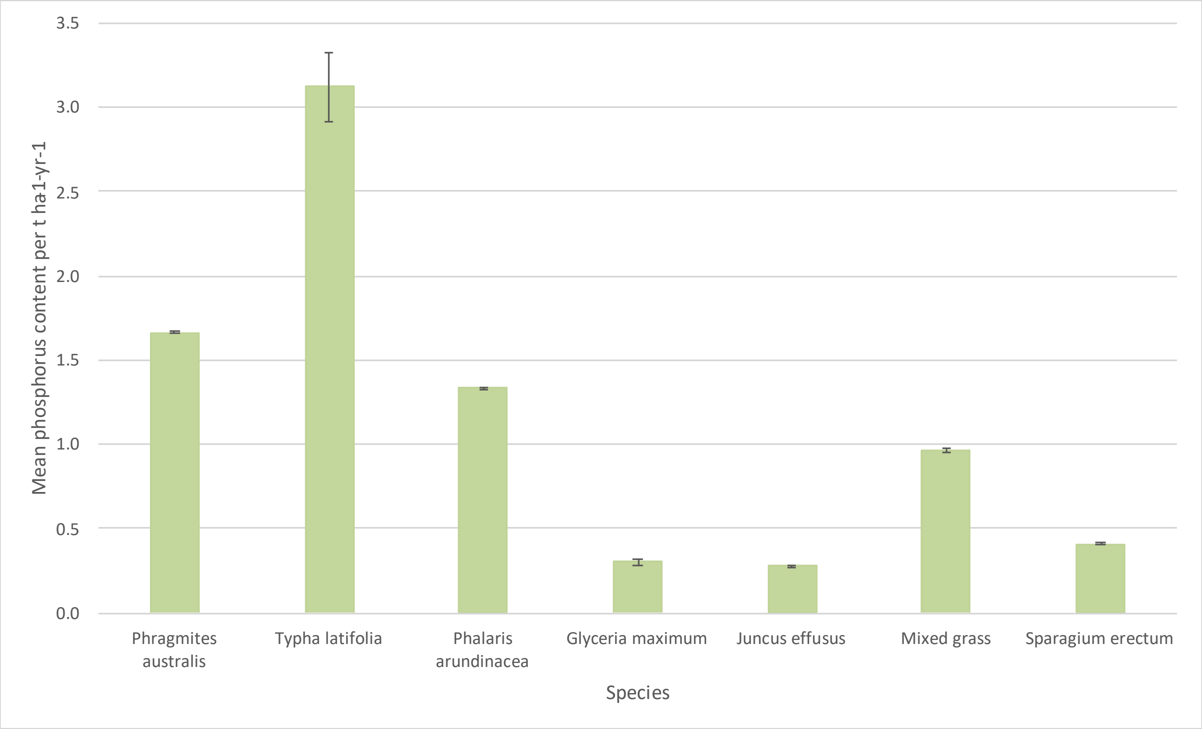

Figure 4: Bar chart showing the mean phosphorus content per t ha-1-yr-1 of each wetland plant species harvested on the Somerset levels (± standard deviation).

Table 3: The mean phosphorus removal capacity per t ha-1-yr-1 dry biomass of wetland plant species harvested on the Somerset levels (per t ha-1-yr-1).

Species	**Mean phosphorus removal capacity per t ha-1-yr-1 dry biomass**
Phragmites australis	1.662
Typha latifolia	3.121
Phalaris arundinacea	1.338
Juncus effusus	0.275
Mixed grass	0.964
Sparagium erectum	0.409
Glyceria maxima	0.302

To identify which species had the greatest phosphorus removal capacity, a Kruskal Wallis test was used to determine if there was a SSD between species. Non-normal distribution was assumed due to the data sample size; therefore, a non-parametric test must be used. The P-value of 0.046 (see appendix 5), is less than the CV of

0.05, therefore the null hypothesis can be rejected, and the alternative hypothesis accepted. This shows that there is a SSD between at least one pair of data sets. A post-hoc Mann-Whitney U test identified no SSD between any pairings. The small data sample size may limit the accuracy and precision of the data analysis; therefore, additional research should be carried out to obtain a larger data set before conclusive answers can be drawn.

Carbon

1. Carbon content (%) of species.

The CHN analysis revealed the carbon content as a percentage for each plant species (figure 5). From this, the mean, standard deviation, and standard error were calculated.

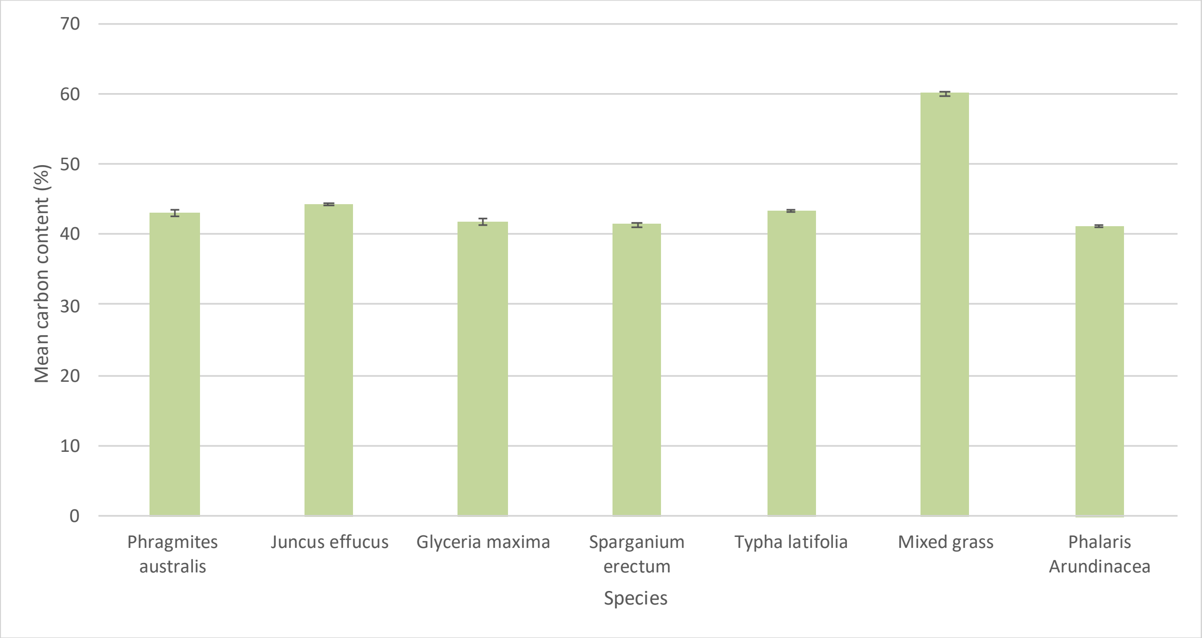

Figure 5: Bar chart showing the carbon content (%) for each plant species harvested on the Somerset levels (± standard error).

A Shapiro-Wilk test determined the data for the carbon content (%) of 6/7 species to be normally distributed, *T. latifolia* followed a non-normal distribution. To test for a SSD in the carbon content (%) between all seven species, a non-parametric KruskalWallis test was conducted in excel. This produced a P-value of 0.007; less than the CV, therefore the null hypothesis is rejected. The alternative hypothesis can be accepted, concluding that there is a SSD between species' carbon content. To identify where this differentiation between species occurs, a Mann-Whitney U test was conducted. The outcome identified no SSD between the carbon content (%) of the species.

A one-way ANOVA test is more powerful; therefore, a one-way ANOVA test was carried out between the six species data which followed a normal distribution. The

Pvalue was 4.488E-13, less than the CV (see appendix 6). Therefore, the null hypothesis is rejected, and the alternative hypothesis is accepted, this shows that at least one pair of data sets show a SSD. A post hoc Tukey test was carried out which produced output grouping information showing which species are SSD (table 4) (visual representation available in appendix 7).

Table 4: Grouping information of the seven species obtained through a post hoc Tukey test, with 95% confidence, to determine which species have a statistically significant difference in the carbon content (%). Means which do not share a letter are significantly different meaning there is a significant difference between data sets. A statistically significant difference is identified between: *Mixed grass – P. australis, J. effusus – G.maxima, Mixed grass – G.maxima, Mixed grass – J.effusus, P.arundinacea – J.effusus, S.erectum – J.effusus, P.arundinacea – Mixed grass, S.erectum – Mixed grass.*

Species	**N**	**Mean**	**Grouping**			
Mixed grass	3	59.94	A			
Juncus effusus	3	44.28		B		
Phragmites australis	3	43.10		B	C	
Glyceria maxima	3	41.66			C	D
Sparagium erectum	3	41.35				D
Phalaris arundinacea	3	41.27				D

2. Carbon storage capacity of each species

To determine the carbon storage capacity per yield for each species, the carbon content (%) per plant species was compared to the mean annual dry biomass yields. This was achieved by calculating the carbon content (%) as a percentage of the annual dry biomass yield which produced the carbon content per t ha-1-yr-1 of dry biomass for each species (figure 6). A separate table including the means was produced, as the mean values will be used when comparing against other variables (table 7). For example, *P.australis* had 29.88 t ha-1-yr-1 of dry biomass, the carbon content was 43.1%, therefore the calculated carbon content per t ha-1-yr-1 of dry biomass is 12.88.

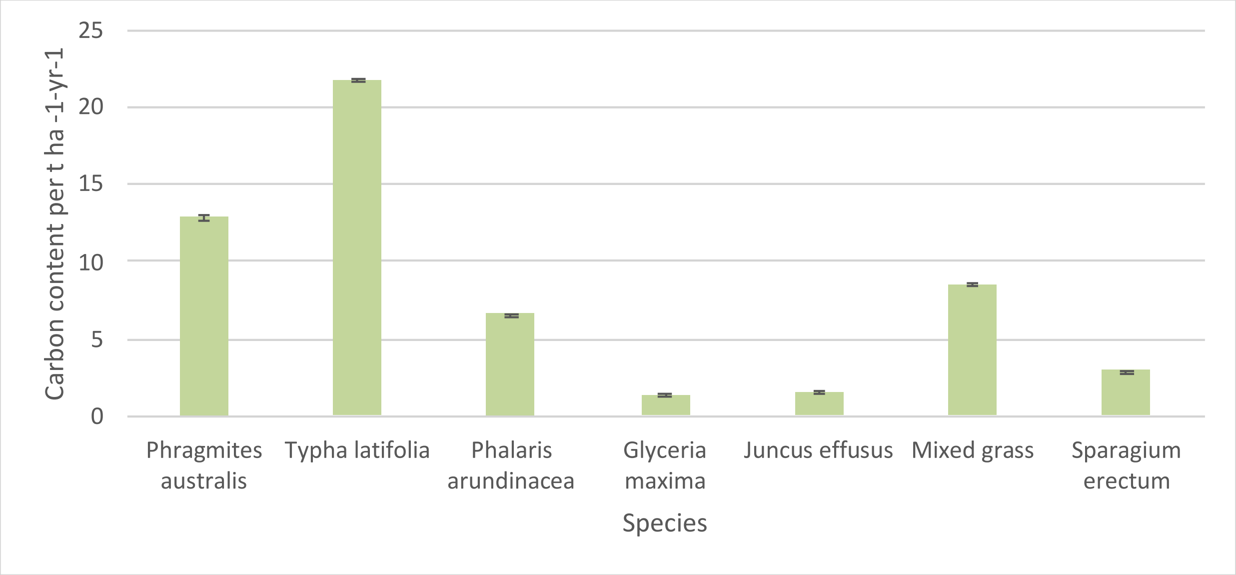

Figure 6: Bar chart showing the mean carbon storage capacity per t ha-1-yr-1 of each plant species harvested on the Somerset levels (± standard error).

Table 5: The mean carbon storage capacity in dry biomass per plant species harvested on the Somerset levels (t ha-1-yr-1).

Species	**Mean carbon storage capacity per t ha-1-yr-1 dry biomass**
Phragmites australis	12.88
Typha latifolia	21.80
Phalaris arundinacea	6.60
Juncus effusus	1.59
Mixed grass	8.58
Sparagium erectum	2.94
Glyceria maxima	1.40

A Shapiro-Wilk test determined the data for the carbon storage capacity of 5/7 species to be normally distributed, *T.latifolia* and *J.effusus* followed a non-normal distribution. To test for a SSD in the carbon storage capacity between all seven species, a nonparametric Kruskal-Wallis test was conducted in excel. This produced a P-value of 0.003; less than the CV of 0.05, therefore the null hypothesis should be rejected, concluding that there is a SSD between the species carbon storage capacity. A posthoc Mann-Whitney U showed no SSD between species.

Due to the reduced efficiency of non-parametric tests, a parametric one-way ANOVA test was carried out between the five species data which followed a normal distribution. The P-value was 7E-16, less than the CV. Therefore, the null hypothesis is rejected, and the alternative hypothesis accepted, this shows that at least one pair of data sets show a SSD. To identify which species have a SDD, a post hoc Tukey test was carried out. Output grouping information shows which species are SSD (table 6) (visual representation available in appendix 8).

Table 6: Grouping information of the seven species obtained through a post hoc Tukey test, with 95% confidence, to determine which species have a statistically significant difference in their carbon storage capacity. Means which do not share a letter are significantly different meaning there is a significant difference between data sets. This shows that there is a statistically significant difference between all pairings of data; all species have a statistically significant difference in their carbon storage capacity (t ha-1-yr-1).

Species	N	Mean	Grouping				
Phragmites australis	3	12.49	A				
Mixed grass	3	8.58		B			
Phalaris arundinacea	3	6.60			C		
Sparagium erectum	3	2.94				D	
Glyceria maxima	3	1.40					E

Association between variables.

Scatter plots identified a linear relationship between phosphorus content and mean dry biomass per t ha-1-yr-1 of species, carbon content and mean dry biomass per t ha-1-yr-1 of species and carbon content and phosphorus content of species per t ha1-yr-1. To measure the strength and association of these relationships, a spearman rank order correlation was used. A strong positive relationship can be identified between all measured variables (table 7).

Table 7: Spearman rank-order correlation R-value output for 3 tested associations using phosphorus content, carbon content and dry biomass (per t ha-1-yr-1) of the wetland plant species harvested on the Somerset levels.

Correlation	R-value
Phosphorus content (%) and mean dry biomass per t ha-1-yr-1 of species.	0.93
Carbon content (%) and mean dry biomass per t ha-1-yr-1 of species.	1
Carbon content (%) and phosphorus content (%) of species per t ha-1-yr-1.	0.93

Discussion

Agriculture is a major driver of eutrophication and GHG emissions; therefore, with increasing pressure from climate change, sustainable agricultural alternatives are required to ensure compliance with UK environmental and climate targets (Withers *et al*., 2014; Mitsch *et al*., 2012; DEFRA, 2023). Paludiculture can offer a solution to adhere to both environmental objectives and agricultural productivity within the UK (Borst *et al*., 2022). However, additional research relating to UK wetland plant species focusing on nutrient content and bulk dry weight assessments is required (Tanneberger *et al*., 2022; Vroom *et al*., 2018).

Dry biomass production

Identifying which wetland plant species produces the greatest dry weight (per t ha-1-yr-1) was necessary concerning the commercial viability of paludiculture. Species with a higher dry biomass production have a greater nutrient removal and storage capacity, as identified using Spearman rank-order correlation (table 7), demonstrating opportunities to rectify nutrient contamination and mitigate climate change. In addition, paludicrops with higher cultivated biomass can substitute greater quantities of emission-intensive materials, further reducing carbon emissions (Moorwissen, 2009). The dry biomass production of *T.latifolia* and *P.australis* was significantly higher than other species with an average estimated yield of 50.32 and 29.88 (t ha-1-yr-1).

These paludicrops are identified as the most viable option for paludiculture throughout previous literature (Wichmann, 2017; Vroom *et al*., 2018; Brix *et al*, 2020). McNaughton (1974) found a significant positive correlation between the net productivity of *T.latifolia* and leaf elongation, demonstrating that leaf tissue differentiation controls productivity rather than intrinsic variations in the metabolic properties of the plant. This makes this species an effective paludicrop as this rapid canopy growth produces high biomass yields. However, the observed dry biomass production (per t ha-1-yr-1) values collected in this study are considerably higher than previous research (Joosten *et al*., 2016). A comparative assessment by Abdel-Aziz *et al.* (2020) found the 'potential biomass production' (t ha-1-yr-1) to be between 3.72-12.60 for *P.australis* and 3.58-22.10 for *T.latifolia*, significantly less than the biomass production values produced within this study. However, Kuhlman *et al*. (2013) found that adding nutrient-rich water into cultivation sites could increase yields by 25 (t ha-1-yr-1). Therefore, excessive nutrient concentrations upon SLM could provide an explanation supporting the higher dry biomass production within this study. Furthermore, Borst *et al*. (2022) found that nitrogen-rich soils stimulate biomass production; this further supports this explanation. This observation can add to existing evidence on the relationship between high nutrient concentrations and biomass production.

Alternatively, the unintentional collection of some of the previous year's annual growth within the quadrat, rather than the intended collection of solely this year's annual growth, could be a partial explanation. Also, the collection of other species during harvest could be contributing, although the research team carry out this methodology annually at the site and has previously found this to be a limitation; therefore, careful consideration was taken when harvesting species to mitigate this issue. As a result, this may only have a minimal impact on biomass yield.

Nutrient removal capacity

The increased use of fertilizers contributes to the leakage of phosphorus and nitrogen into surrounding water bodies, causing eutrophication (Tilman, 1999). Furthermore, drainage-based agricultural practices on wetlands reduce the soil's capacity to store carbon; instead, GHG emissions are released, contributing to global warming (Lahtinen *et al.,* 2022). Therefore, the remediation of wetlands is essential to avoid additional environmental harm (Withers *et al*., 2014). For this reason, this research aimed to measure the phosphorus removal capacity and carbon storage capacity of seven native wetland plant species to assess their effectiveness for potential use in paludiculture within the UK to mitigate the issues currently faced.

The findings indicate that *Glyceria maxima* has the greatest phosphorus content (%); however, this species' mean phosphorus removal capacity (t ha-1-yr-1) was low due to its insignificant dry biomass production. Steinbachová & Tylová (2008) found a reduction of soluble carbohydrates in the roots of *G.maxima* in response to NH4+-N, suggesting that the soil acidity of the SLM could have adverse effects on *G.maxima* growth (Wang *et al*., 2022). However, this could not be confirmed without examining membrane NH4+ fluxes, root energy status and soil pH (Steinbachová & Tylová, 2008). For the same reason, although Mixed grass had the greatest carbon content (%), the mean carbon storage capacity (t ha-1-yr-1) was low.

It was important to identify which wetland plant species had the greatest phosphorus removal capacity potential per yield to mitigate contamination on the SLM and which the greatest carbon storage capacity potential per yield to maximise climate change mitigation. The observed differences within the findings indicate that *T.latifolia* had the greatest carbon storage (21.80 t ha-1-yr-1) and phosphorus removal capacity (3.1 t ha-1-yr-1), followed by *P.australis*. These results were consistent across literature and built on existing evidence of the ecosystem service potential paludiculture can create (Brix *et al*.,2020). Furthermore, the high nutrient removal capacity of both *T.latifolia* and *P.austalis* shows their high water purification capacity, presenting a promising opportunity to rectify current nutrient levels on SLM while encouraging carbon sequestration and long-term storage in the converted materials (Brix *et al*., 2020). These results follow suit to a study conducted by Brix *et al*. (2020), who concluded that *T.latifolia* presents as the most viable option for "nutrient removal schemes" and "ecosystem service payments". This is an essential consideration for the economic viability of this major land-use change, as paludiculture is currently restricted by its economic uncertainties (Wichmann, 2017).

However, the strong nutrient removal capabilities may make the ecosystem nutrient deficient; research has shown that this may limit paludicrop growth (Borst *et al*., 2022). Brix *et al*. (2020) found that nitrogen has a stronger limitation capacity for *T.latifolia* than *P.australis*; this suggests that *P.australis* has a "higher nutrient-use efficiency". For this reason, *P.australis* could be a viable and sustainable option for future paludiculture if soil fertility continues decreasing in line with current trends (Brix *et al*., 2020).

Although there is a need for more consistent significance across tests within the data analysis of phosphorus content between species, it would be incorrect to claim there is no difference. Observed differences in the phosphorus removal capacity between species are identifiable. However, it is recommended that further research replicating this study's methodology should be undertaken to obtain more accurate and precise results. For this reason, these observed differences must be taken provisionally when recommending which paludicrops present the most viable option for paludiculture regarding species' phosphorus removal capacity.

Commercial viability

The commercial viability of paludicrops is an important consideration in the transition to paludiculture. Research has demonstrated the environmental benefits of such practices in the form of ecosystem services (Borst et al., 2022). The transformation of harvested biomass into functional materials prevents nutrient recycling in the wetland ecosystem through decay (Jeke et al., 2015). However, this process's effectiveness depends on the harvest time. Harvest must occur before the plant matures and translocate nutrients into below-ground biomass, which above-ground harvesting would not effectively remove. Martin and Fernandez (1992) found that 70% of nutrients could be removed during a late September harvest. Within this study, biomass was harvested in late June, so this study may not represent these plant species' optimal nutrient removal capacity.

In the 21st century, land use and cover are the greatest threat to wetland ecosystems; climate change exacerbates the impact of wetland conversion, which in turn accelerates climate change through peat degradation and GHG emission production (Clark & Tilman, 2017). Research has found that T.latifolia and P.australis have a high plastic physiological and morphological response, allowing reeds to adapt to pressures climate change creates (Caplan et al., 2015; Brix & Eller, 2012). This is a crucial consideration for the sustainability of future agriculture in the UK; these paludicrops could provide stable economic and environmental benefits when current agricultural practices are no longer feasible (Brix et al., 2001).

In the UK, up to 85% of the thatched roofing material consumption (P.australis) is imported, demonstrating the economic potential and national demand for P.australis cultivation (Becker et al., 2020; ThatchAdviceCentre, 2023). This form of paludiculture could allow the UK to reduce this reliance and become self-sufficient. Similarly, the UK also imports large quantities of fibreboard. T.latifolia is extensively used for insulation boards; therefore, there are opportunities for the commercial market of T.latifolia to substitute fibreboard for Typhaboard. Additionally, the US is utilising T.latifolia within biodegradable food packing, demonstrating this crop's versatility and the potential paludiculture has within innovation (Fens For The Future, 2023). However, this transition away from drainage-based practices on wetlands requires a top-down approach; this land management change is only economically viable with the recognition of paludiculture within agricultural schemes, stakeholder collaboration or financial support for land-owners (IUCN, 2022).

Conclusions

This research aimed to identify which native wetland plant species are the most viable option for paludiculture in the UK, using examples from the SLM. Based on a quantitative analysis of seven wetland plant species, paludiculture presents a promising opportunity to mitigate nutrient pollution and restore UK wetlands without compromising land productivity. The results indicate that *T.latifolia* is the most viable options due to its high biomass production of 50.32 t ha-1-yr-1 and high nutrient removal capacity of potentially 21.8 t ha-1-yr-1 of carbon and 3.12 t ha-1-yr-1 of phosphorus per yield. *P.australis* was another viable solution with a high biomass production and nutrient removal capacity. In summary, *T.latifolia* and *P.australis* cultivation have the greatest potential to address nutrient contamination in the UK and restore wetland production, all while sustaining land productivity. The findings support existing research carried out predominately in Europe; however, this research extends the knowledge by providing insight into the environmental benefits paludiculture could provide for UK wetland ecosystems.

Evidently, without the acknowledgement of paludiculture within current agricultural subsidy schemes and legislation, the transition to paludiculture from current drainage-based practices is not economically viable. Therefore, multi-stakeholder engagement is essential to make this transition feasible. Furthermore, this research has demonstrated the nutrient removal capacity of *T.latifolia* and *P.australis*, displaying an opportunity to establish nutrient removal schemes and ecosystem service payments within the UK agricultural sector, which would reward and encourage landowners to manage wetlands sustainably. While the small sample size limits the generalisability of the results, this study provides a greater understanding of the effectiveness of paludicrops in providing ecosystem services compared to the current land-cover of mixed grass. To understand the implications of these results, future studies should carry out this methodology over three-years to obtain greater data sets. In addition, measuring the water table depth and pH could help understand the influence these variables play on productivity and to identify suitable locations for paludiculture within the UK to maximise efficiency, effectiveness, and productivity.

Future work

This study's aims and objectives have helped bridge gaps within the knowledge regarding nutrient content and dry weight of seven native wetland plant species for potential use in paludiculture in the UK. This study has contributed to the science, as Natural England is utilising the data generated by the research team to assess how paludiculture could be a solution to reducing the excessive phosphorus concentrations present on the SLM and restoring the peatland. Natural England is conducting paludiculture trials this year on Greylake, and this study has contributed to baseline data on which species would be most effective to use.

Although this study has demonstrated the potential use of these species within paludiculture on the SLM, individual conditions of alternative locations in the UK may need to be revised to ensure how effective paludiculture could be. Literature on paludiculture has identified that pH is a limiting factor in the effectiveness of paludiculture together with water management (Gaudig *et al*., 2017; Borst *et al.,* 2022). Therefore, future research should assess the suitability of the land for specific paludicrops by considering pH alongside the long-term management of water levels to maintain optimal ranges for paludicrops; this is species-specific (Gaudig *et al*., 2017; Borst *et al*., 2022).

Furthermore, most research is based on the suitability of species for paludiculture; there needs to be more knowledge regarding the costs and revenue of this practice, which creates challenges for the transition towards paludiculture within the UK. There is a requirement for more information on site conditions, such as land suitability, size, soil characteristics, and biomass yields, to overcome the implications of determining machinery type and labour input needed (Tanneberger *et al.,* 2022).

For future research, carrying out this methodology in the exact location over a three-year timeframe would enable additional data to be collected, strengthening data analysis, and ruling out the potential influence of external variables. In addition, other variables, such as soil pH and water table depth, could be measured to test the association for effective paludiculture growth to maximise the potential of future paludiculture projects. Finally, comparing nutrient levels during the recommended harvest season of late September would also be beneficial.

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