

Review

Transitioning from Degraded Peat to Paludiculture: Evidence-Based Roadmap for Research and Practice

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Abstract

Paludiculture, the sustainable productive use of wet and rewetted peat soils, offers a dual solution for preserving soil carbon and reducing greenhouse gas emissions whilst offering a form of income for landowners/farmers. However, establishing best practices for the transition to wet agriculture production systems remains difficult due to the inherent variability of peatland sites. This study synthesises evidence from the peer-reviewed literature, grey literature, and stakeholder surveys to map current practices, concepts, knowledge gaps, and research priorities. The main gap is a lack of long-term studies tracking crops from establishment through multiple harvests. Practical knowledge is also geography-ically, limiting applicability without local environmental and policy context. Further critical gaps include crop species selection, upscaling, biodiversity impacts, specialised harvesting equipment, and evolving end-product markets, alongside country-specific legal and financial barriers. Key recommendations include establishing a robust initial site investigation as edaphic properties and previous land-use can inform crop establishment and potential operational hurdles. Furthermore, increased funding for long-term farm-based projects, technological innovation and prioritising producing data that supports finance models must be made available to offset the costs of transitioning and developing new, system-level agronomical tools. Ultimately, scaling paludiculture hinges on robust incentive frameworks, shared knowledge platforms, and standardised nomenclature to guarantee long-term environmental and economic sustainability.



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Keywords: land-use change; climate mitigation; rewetting; *Typha*; *Sphagnum*; biodiversity; water quality

1. Introduction

Societal demand is growing to rewet drained peatlands, a move essential for curbing greenhouse gas (GHG) emissions [1,2], halting peat mineralisation, and preventing land subsidence and water pollution [3,4]. Peatland drainage generates 4–5% of global anthropogenic GHG emissions through peat oxidation and elevated fire risk resulting in further carbon dioxide (CO₂) emissions and air pollution [5,6]. In addition, drained peatlands lead to soil subsidence [7,8], biodiversity loss [9], eutrophication and downstream pollution [3]. However, rewetting drained peatlands previously used for agriculture or peat extraction can help restore some of the essential ecosystem services [9,10]. Beyond these environmental safeguards, rewetting offers the chance to unlock landscape multifunctionality, providing a suite of ecosystem services that vary depending on how the land is managed post-rewetting.

Paludiculture, the productive land use of wet and rewetted peatlands, has emerged as a multifunctional system capable of harmonising ecological and climate targets with sustainable agricultural output [11]. By rewetting and maintaining elevated water tables in organic rich peat soils, paludiculture preserves carbon stocks and reduces CO₂ emissions and subsidence while yielding versatile biomass for bioenergy, sustainable building materials, horticulture, food (berries) and high-value biochemicals [12–14].

Beyond immediate environmental benefits, this transition can revitalise rural socio-cultural landscapes, supporting local employment, sustainable farming practices and nature-based tourism. Concurrently, it facilitates supply-chain decarbonisation aligning land-use practices with retail net-zero mandates. Transitioning to sustainable paludiculture requires, however, fundamentally different agronomic practices and management techniques compared to conventional drained systems [11,15]. In temperate and boreal contexts, challenges include inter alia complex regional water management permits, environmental permitting for hydrological modifications, and navigating agricultural subsidy alignments, alongside securing local stakeholder buy-in [15–19]. Existing studies often evaluate isolated components, such as specific crop yields or localised GHG fluxes, without integrating the broader hydro-agronomic, technical, and socio-ecological factors required for operational scaling.

Using an evidence synthesis approach coupled with stakeholder surveys, this study aimed to map the extent of available research and practitioner knowledge on temperate and boreal paludiculture to prevalent themes, critical knowledge gaps and emerging operational frameworks. Specifically, this review evaluates the practical options for the conversion of drained peat soils to paludiculture systems focussing on four key thematic domains:

- (a) Site characterisation: initial site investigations to inform site preparation, rewetting protocols and crop species;
- (b) Soil and hydrological management: water table control, irrigation/drainage infrastructure, edaphic properties and water supply and quality;
- (c) Environmental monitoring: parallel tracking of crop biomass, GHG fluxes and biodiversity indicators;
- (d) Agronomic variables: crop performance, health, nutrition, feedstock and extracts composition as well as low-impact harvesting techniques and yield management technologies.

Furthermore, an analysis of established paludiculture frameworks was undertaken to identify operational challenges and transferrable insights for temperate and boreal contexts.

Specifically, participants were asked to identify ambiguous terminology, causing confusion in the paludiculture sphere. Finally, this evidence synthesis provides an operational roadmap for paludiculture transition and outlines key priorities for future research.

2. Materials and Methods

2.1. Evidence Synthesis Search Strategy

A systematic evidence synthesis was conducted to address the methodological and geographic heterogeneity within the temperate and boreal paludiculture literature [20]. The review drew on three categories of data: (1) the peer-reviewed literature, (2) grey literature, and (3) recommendations from stakeholders via survey (Figure 1). This process legitimises multiple forms of knowledge, which is in line with recommendations from global assessments [21].

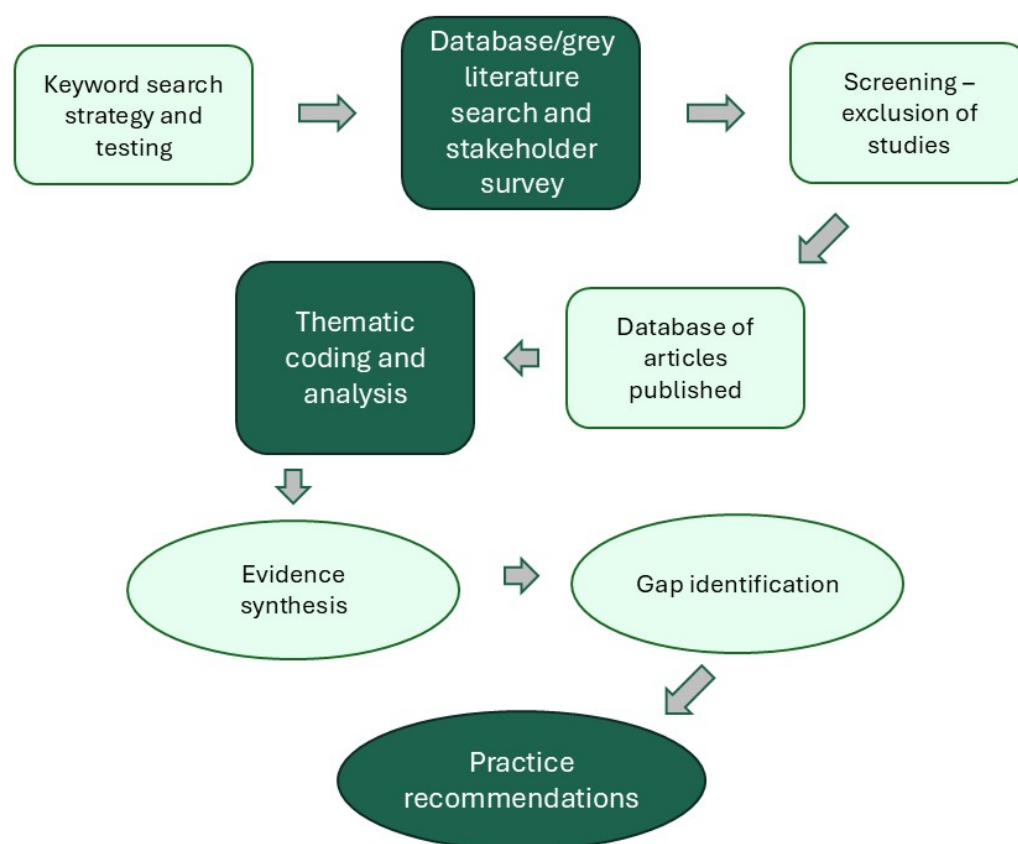


Figure 1. Overview of evidence synthesis methodology.

The literature search was conducted using Scopus/Web of Science as well as Google scholar as a source of both peer-reviewed and unpublished grey literature.

The Web of Science and Scopus databases were searched several times to refine the search strings for the study scope and aims, and a final search was conducted on 9 April 2026 using the keyword search strings detailed in Table 1. Different phrases and keyword strings were tested using Boolean searching (AND, OR, NOT) and the addition of various terms (e.g., biodiversity, Sphagnum, Typha) to the core search string, e.g., (paludiculture) AND (biodiversity). However, these variations yielded no additional value in the results. Results from these databases were combined, as Web of Science generally covers natural sciences and engineering, while Scopus includes the social sciences to a greater degree, so combining these data sources improved the quality and scope of the results [22]. Tropical peatlands were excluded from the search to limit the study to boreal and temperate peatlands, as

were any studies where yearly average water levels were lower than −50 cm. A summary of the keyword search strategy for each database is provided in Table 1.

Table 1. Sources of literature and keyword search.

Source	Keyword Search
Web of Science	(paludiculture) (Topic) (sphagnum farming) (Topic) (typha farming) (Topic) (wetter farming) AND (peat OR peatland OR bog OR fen) (Topic)
Scopus	TITLE-ABS-KEY (paludiculture) TITLE-ABS-KEY (sphagnum farming) (typha farming) (Topic) TITLE-ABS-KEY (wet farming) AND (peat OR peatland OR bog OR fen)
Google Scholar	Paludiculture Wetter farming
ProQuest theses Europe	paludiculture

Google Scholar was used to broaden the search scope and counter publication bias [23]; however, when ‘wet farming’ was added as a search parameter, it yielded few new resources. A search on ProQuest also yielded unpublished theses. These searches were combined using the bibliometrix package version 5.1.1 [24] in R version 4.5.0 [25], and additional manual work was needed to clean the data. This involved removing any duplicates, publications which were not carried out on peat soils, publications addressing tropical peatlands and studies where water table depth (WTD) was too low to be considered paludiculture (<−30 cm) or wetter farming (<−50 cm). The search was conducted for English language manuscripts only and any suggested literature from Germany and the Netherlands was translated using Gemini version 3.6 Flash model (Google, 2025). As a result of the stakeholder survey responses (see Section 2.2), the term ‘wetter farming’ was added to the literature search as it can give relevant insights into the transition from degraded peatlands to paludiculture systems in the context of rewetting and new wet-peat agronomical practices.

2.2. Researcher and Stakeholder Surveys

An online survey was conducted in September 2025 to elicit expert knowledge and stakeholder perspectives on current knowledge gaps and issues in paludiculture research. The survey targeted researchers/stakeholders within the Palus Demos project, researchers serving an advisory role to the Palus Demos project and Palus Demos sister projects (within the same Horizon EU funding). These participants include farmers, land managers, academics, industries, government agencies and NGOs. The survey questionnaire included 8 questions and collected a range of data, including on the disciplines represented, issues and knowledge gaps in the researcher’s field of study, and their understanding of paludiculture (Supplementary Materials Text S1: Survey questions). The survey also provided an opportunity to suggest key sources of other non-peer-reviewed literature including grey literature, NGO reports, etc. and to identify key definitions of terms that may be regionally specific.

2.3. Data Analysis

Each of the 455 entries (410 excluding policy) in the final database were coded according to the main themes identified for analysis (column titled “Theme” in the database;

Figure 2). Within each theme, topics were created to identify specific areas of interest as per the results of a workshop with Palus Demos researchers. Initial themes included cultivation/growth, GHG fluxes, crop species, policy and land-use (Supplementary Materials Table S1). Content analysis was operationalised through a structured review matrix in Microsoft Excel drawing on the approach in Flood et al. [26]. This matrix was used to extract key information from the literature and included the following categories: research practices; key findings relating to the theme; key research gaps; and future recommendations. Analysis of the evidence was carried out and summarised under key review themes, crops, paludiculture techniques, soil, water, carbon/climate, biodiversity, management, technology and policy. To maintain a complete database, we retained policy-only documents but excluded them from the content analysis as they did not address the study's aims.

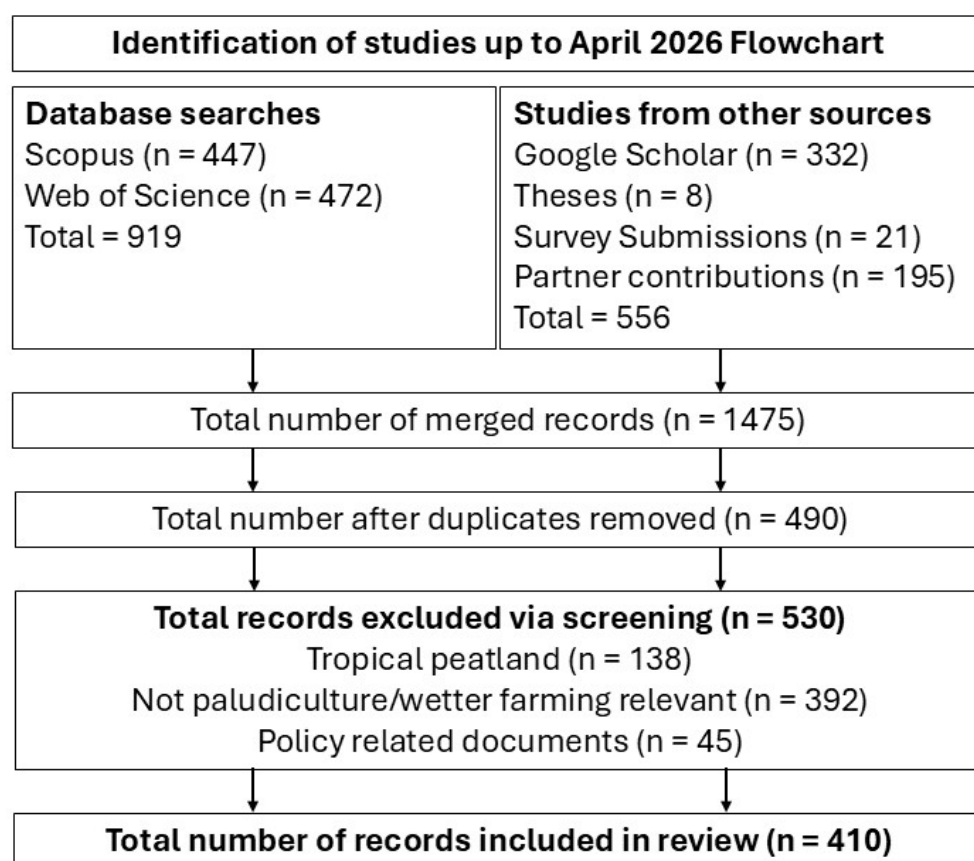


Figure 2. Flowchart indicating each phase in the evidence synthesis.

3. Results

3.1. Publication Patterns

The created database (https://palusdemos.org/wp-content/uploads/2026/07/Palus-Demos-WP2-Lit-Rev-Database_version-1.xlsx, 5 September 2026) provides details of information sources relevant to paludiculture activities in temperate peatlands and is available for download on the Palus Demos website (<https://palusdemos.org/>, 5 September 2026). The database is searchable by author, DOI/URL, title, theme, year of publication and topic. The database showed an increase in the number of publications throughout the years (Figure 3). The sources of data and corresponding number of records retrieved were as follows: Web of Science and Scopus (n = 214); ProQuest Thesis (n = 8); researcher submissions from survey (n = 21) and submissions from Palus Demos participants (n = 195); and manual/Google searches (n = 17) (Figure 2). Paludiculture research has increased dramatically in the last 10-years with 2025 yielding the most results with over 50 citations

(Figure 3). The countries where most studies originated were from northern and central Europe (Figure 4). The country with the greatest number of publications was Germany with 123 publications, which is more than twice as many publications than the next most cited country (the Netherlands with 56 publications; Figure 4).

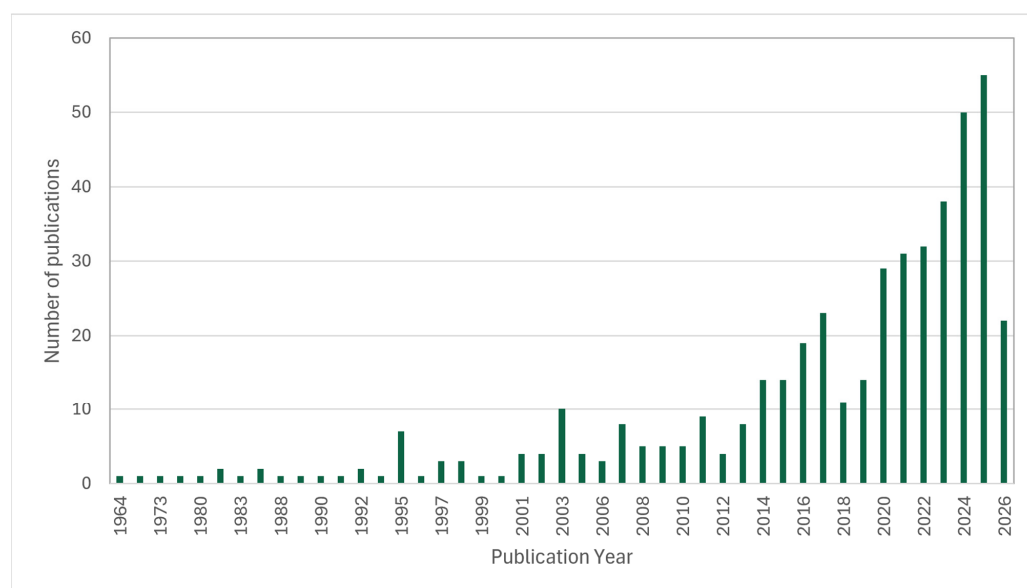


Figure 3. Number of publications per year from Web of Science, Scopus and Google Scholar literature search and grey literature acquired from the survey (search ended in April 2026).

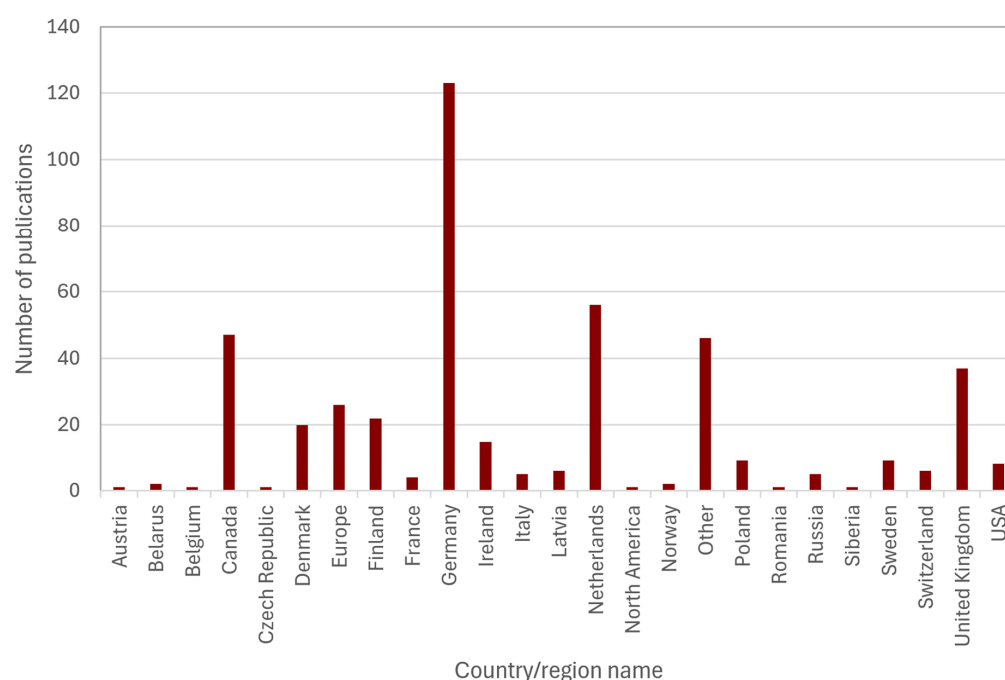


Figure 4. Number of publications per country from Web of Science, Scopus and Google Scholar literature search and grey literature acquired from the survey.

A map of European paludiculture sites was created from the analysed literature (Figure 5, site coordinates in Supplementary Materials Tables S2 and S3). This map further emphasises the geographical bias with European paludiculture sites being mostly researched in Germany and the Netherlands.

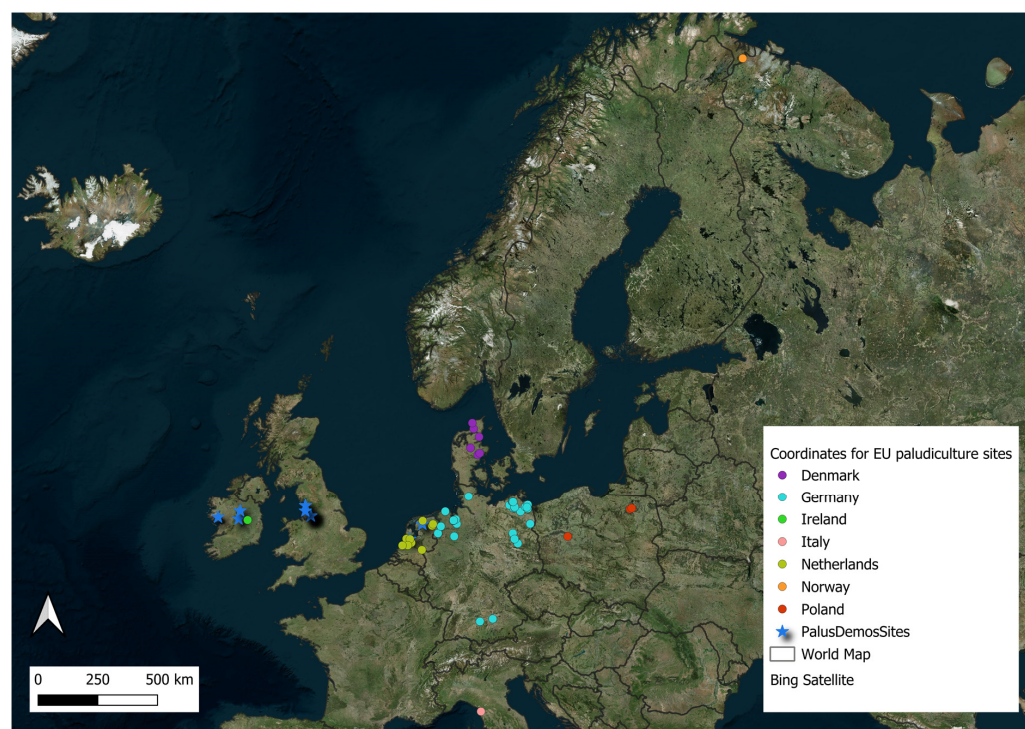


Figure 5. Map of European paludiculture sites sourced from the literature, indicated by different colours for different countries and Palus Demos paludiculture sites which are indicated by blue stars. All site coordinates and countries are presented in Supplementary Materials Tables S2 and S3.

Figure 6 details the thematic distribution of records from the database, highlighting the major gaps in the academic literature, while the number of publications found per topic under each theme is presented in Supplementary Materials Table S1. More than 82.7% of all studies were associated with six themes: GHG/carbon/climate (21.2%), paludiculture techniques (18.8%), soil (15.4%), crops (14.1%) and management (13.2%). Research on water (8.8%), biodiversity (4.9%) and technology (3.7%) was less established making up 17.2% of the research (Figure 6). Details of themes and topics within themes are detailed in Supplementary Materials Table S1.

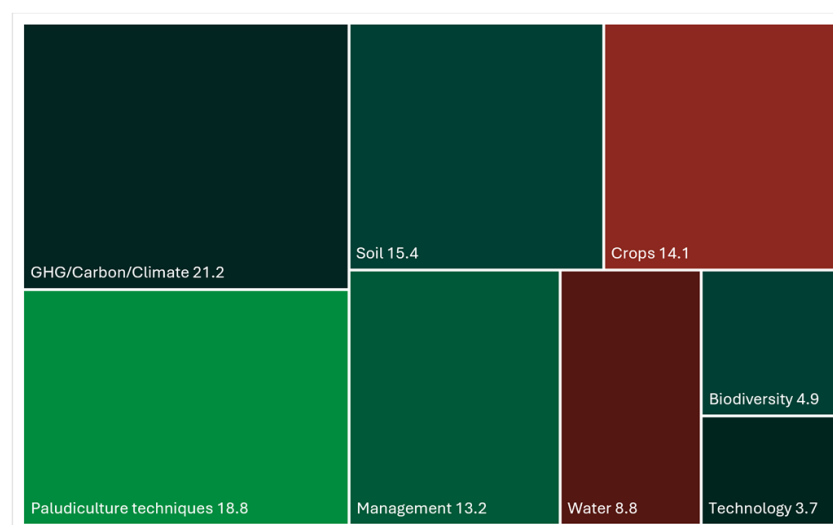


Figure 6. Thematic distribution and percentage of publications (April 2026).

3.2. Evidence Base Review by Theme

A summary of evidence by theme is presented in this section along with a summary of practices/recommendations and key knowledge gaps (Table 2).

Table 2. Thematic summary of trends, practices and research gaps.

Theme	Current Knowledge/Trends	Practices and Recommendations	Research Gaps and Future Research
Soil	Soil nutrients inhibit <i>Sphagnum</i> growth but aid <i>Typha</i> growth. Paludiculture is proven to reduce or halt soil subsidence [27].	Implement BACI (before, after, control, impact) experimental designs to monitor edaphic parameters and soil microbial communities across pre-conversion, establishment, and post-harvest stages.	Very few paludiculture-specific studies investigating soil, especially soil subsidence and mitigation measures [27]. Little is known about the microbiome or the fate of pharmaceutical compounds in peat soils [28]. There is a general lack of studies investigating microbes in rewetted peat soils under biomass production. Knowledge gap regarding long-term peat subsidence mitigation dynamics and rates [27].
Water	Transitioning from drainage to paludiculture can positively impact water quality with <i>Typha</i> and reeds acting as effective nutrient buffer [29].	Replicate the use of <i>Typha</i> and reed species to test nutrient removal for polluted water catchments. Implement rigorous water management in large-scale demonstration sites.	Spatial gap in the data for water quality and nutrients. Future research should focus on effective water management for a broader range of species (not just <i>Sphagnum</i> , <i>Typha</i> and reeds). Further research required for effective irrigation methods in paludiculture systems. Long-term water quality and water table monitoring should be routinely carried out, as should investigations into drivers of dissolved nutrients and carbon [30–32]. Significant knowledge gap regarding crop-specific evapotranspiration rates and overall water requirements in paludiculture systems. Gaps concerning the mobilisation of nutrients and heavy metals in water.
Crops	<i>Typha</i> , <i>Sphagnum</i> and reeds are considered high value paludiculture crops with the most extensive study history.	Prioritise investigations into species comparisons for optimum growth and the impact of nutrients on yield [33].	Lack of investigation into species like <i>Drosera</i> , <i>Aronia</i> , and <i>Myrica gale</i> . Gaps in harvesting technology, product development, and crop health. Lack of studies investigating food crops on wet peat soils [34]. Long-term studies and upscaling also have significant gaps.
Paludiculture Techniques	<i>Sphagnum</i> cultivation is a mature research area, while <i>Typha</i> and reed cultivation are more recent focus areas.	<i>Sphagnum</i> —WTD 10cm below the capitula; monitor soil moisture levels as WTD may not reflect soil moisture levels; use of straw, mesh, cotton grasses or Ericoids for cover/better establishment [35]; consistent monitoring for weeds [35–37]; reestablishment slow (5–10 years). <i>Typha</i> —WTD at or above the surface for optimum growth (although CH ₄ should be carefully monitored); winter harvesting in northern climates [38,39]; rapid cultivation—annual or bi-annual harvesting is possible. Reeds—WTD at or above the surface; winter harvesting in northern climates. <i>Drosera</i> —cultivation in greenhouse for optimum growth [38]. Generally, avoid fertilisation where possible to mitigate any nutrient loading impacts on paludiculture systems.	Further research is needed on the role of herbivory (mostly birds) on paludiculture crops. For <i>Drosera</i> , future research investigating medicinal properties and potential products required [38]. Research and development for machinery that harvests without impacting the peat and associated C stocks [40]. Further research on irrigation techniques which are affordable and easily implemented [41]. Paludiculture techniques for species other than <i>Sphagnum</i> , <i>Typha</i> and reeds are lacking. Weed management techniques are currently challenging and a consensus on terms used for weed management should be further discussed.

Table 2. Cont.

Theme	Current Knowledge/Trends	Practices and Recommendations	Research Gaps and Future Research
Management	Topsoil removal to reduce surface nutrient levels; it is cautiously recommended for species which favour lower nutrient levels. Transitioning from BAU to paludiculture yields significant biodiversity enhancements, GHG flux mitigation, and reduced peat subsidence.	5–10 cm of topsoil removal was recommended for successful establishment and can significantly reduce GHG emissions in <i>Sphagnum</i> farms [42], although there is a trade-off of reduced soil C.	Much of the literature is regionally specific and may not reflect needs of all sites [42–44]. Uncertainty in C dynamics in paludiculture sites [45]. Many studies mentioned issues with lack of funding and market gaps [46–48], as well as policies which support paludiculture implementation [49,50]. Long-term monitoring following the initial land-use change is essential [42]. Monitoring for BACI is important for impacts of management changes.
Carbon/Climate	Paludiculture decreases GHG emissions in general but is also striving for C neutrality.	BACI are the recommended monitoring practices for new projects. The paludiculture system as a whole needs to be monitored (access ways; harvesting; donor sites; fluvial C fluxes) to ensure the paludiculture goal of peat preservation [45,51]. Monitoring of N ₂ O fluxes if paludiculture site is fertilised or has high soil/water nutrient levels.	Long-term monitoring of GHGs and fluvial C fluxes, including harvesting [52]. Spatial gaps in the data—most temperate and boreal research is in northern and central Europe and Canada. Further research should involve fluvial C fluxes and C losses with harvesting [53]. Lack of data on N ₂ O fluxes from paludiculture systems.
Biodiversity	Paludiculture increases biodiversity compared to business as usual [54–56].	Comparison to semi-natural and business-as-usual sites	Impact of harvesting on biodiversity remains understudied [57]. Need for longer-term monitoring and studies on deeper peat layers [58]. Monitoring of <i>Sphagnum</i> donor sites [57]. Biodiversity research in the context of paludiculture remains constrained to a narrow range of taxonomic groups.
Technology	This is a rapidly growing area of research.	Upscale of techniques and integration of multi-spectral data. Integration of AI, predictive modelling and machine learning into paludiculture research, for improved monitoring of paludiculture sites. Funding for machinery innovation which allows for harvesting of materials with little/no soil disturbance is essential for sustainable paludiculture [38,59].	Improvements to model, mapping and machine learning accuracy is essential for representative results [60]. Funding opportunities for technology advancement are lacking [61]. The full environmental impacts of building regionally adapted machinery capable of traversing peatlands, planting, irrigating or harvesting, need to be appraised

3.2.1. Soil

Peat Subsidence

One of the main goals of rewetting and establishing paludiculture is to reduce peat soil subsidence. In certain regions (e.g., The Netherlands), this is directly linked to the reducing the risk of flooding [62].

To date, research on reducing peat soil subsidence remains mostly fragmented, focusing on localised case studies that evaluate a limited range of technical or land-use options. It was demonstrated that implementing a controlled rewetting regime not only reduced soil subsidence but actually reversed vertical land loss, achieving accretion rates of 70–90 mm y^{−1} [27,63].

Paludiculture is predicted to reduce land subsidence mainly through higher surface water levels [27,62,64]. However, several factors such as peat type, depth, and density as well as climate factors including soil temperature also affect subsidence rates and remained under-studied in paludiculture systems [62].

Peat Accumulation/Litter Decay

Paludiculture generates plant biomass and litter, providing the organic material necessary for future peat formation once submerged in water-saturated layers. *Sphagnum* growth and decay dynamics are critical in producing material that can serve as both an alternative growing medium component and donor material for peatland restoration. Only two studies over the last 13 years have explicitly addressed litter decay in paludiculture contexts [65,66] while pre-2016 research focused predominantly on *Sphagnum* decomposition in restoration sites [67–72]. Across all studies, plant community composition governed litter decay rates, directly influencing both harvestable biomass yields and long-term peat accumulation potential [70,72,73].

Nutrients

Despite the naturally oligotrophic status of most intact peatlands, historical drainage, resource extraction, agriculture, and silviculture frequently result in nutrient enrichment. “Soil nutrient” studies which focussed on *Sphagnum* and nutrient additions found that typically higher nutrient levels inhibited growth [74,75], and therefore these areas are not recommended for *Sphagnum* paludiculture without prior mitigation measures. The legacy of past drainage activities can alter soil quality even after rewetting, with on-going carbon content reduction and secondary soil transformation [76,77]. Furthermore, rewetting peat soils for restoration or paludiculture purposes can also increase stores of nutrients such as phosphorus (P) and nitrogen (N) [78–81], reducing run-off into neighbouring systems.

Topsoil Removal

Cautionary application of topsoil removal may serve as an effective preparatory measure for *Sphagnum* paludiculture, particularly on sites with legacy agricultural nutrient loading or within multifunctional constructed wetlands aiming for simultaneous crop yield and nutrient mitigation [42,82–85]. Research into the use of this technique for *Sphagnum* has shown that removal of just 5–10 cm of surface soil can increase the likelihood of vegetation establishment and mitigate adverse effects of rewetting former agricultural peatlands by reducing CH₄ emissions and avoiding nutrient release in surrounding areas [42,83,84]. However, this can result in substantial removal of carbon from the system, especially in largescale sites and has implications for carbon offsetting schemes. Therefore, topsoil removal should only be used when the soil is polluted or when there is a risk to crop value, with growth of crops such as *Typha* and reeds for nutrient uptake preferable.

For *Typha* and *Phragmites*, topsoil removal can negatively impact growth due to nutrient removal which can limit long-term productivity [86]. Initial comparable information on site-specific nutrient levels and the objectives of the paludiculture endeavour need to be considered prior to transitioning.

3.2.2. Water Management

Water management for paludiculture generally involves raising water tables through ditch blocking and bunding, or sustaining high water levels via distribution channels from storage areas, alongside trials of overhead irrigation. Stop-log gates are typically deployed to regulate water inflow and discharge excess water to mitigate flooding. In the Netherlands, hydrological management operates at a landscape scale under the authority of regional water boards, whereas in other regions, governance remains divided with drainage managed broadly by drainage boards and paludiculture hydrology addressed primarily at the local farm level.

Water management was most commonly associated with optimised growth and reduced GHG emissions. The most common species investigated were *Typha* [87] and *Sphagnum* [88–90]. For *Sphagnum*, studies found that stable water levels around 10 cm below the capitula are optimum for growth [88,90]. *Typha* grew best with water levels above soil level [87,89], though *Typha* is resilient to fluctuating water levels between drought and inundation.

Water Quality and Supply

Rewetted peat soils provide many valuable ecosystem services including acting as buffers against eutrophication and acidification for downstream waters [3]. However, in regions where paludiculture is adopted on former agricultural land, high nutrient levels in on-site and/or irrigation waters can affect growth of certain paludiculture crops [87–89,91]. For instance, *Sphagnum* is known to be sensitive to elevated nutrient levels with high concentrations of some nutrients suppressing *Sphagnum* growth [89], while *Typha* thrives in environments with higher nutrient contents [87,89]. A few studies focused specifically on water deficit and impact on hydro-physical properties of peat in the context of *Sphagnum* growth [92–97].

A key consideration for paludiculture is that rewetting agricultural sites can mobilise phosphorus and drive downstream eutrophication [47]. Risk models must integrate pH, alkalinity, calcium, iron, and sorption capacity [78].

3.2.3. Crops

Paludiculture Crop Species

Crop selection is a critical component of paludiculture establishment and must be evaluated prior to implementation, as species suitability is primarily dictated by pre-existing site conditions. The theme “crops” encompasses information relating to species investigations, crop health and biomass assessment (Supplementary Materials Table S1). While the most common crops investigated were *Sphagnum*, *Typha*, and reed species (such as *Phragmites australis*, *Carex* spp. and *Phalaris arundinacea*), other species including berries (*Vaccinium* spp.) and medicinal plants (*Drosera*) have been researched although to a lesser extent (Table 3; [98,99]). Most of the studies date from 2016 and after, highlighting a switch in the literature from restoration-based plant studies to potential crops for rewetting and paludiculture systems. While initial work including productivity was extensively reviewed by Tanneberger [100], the majority of the paludiculture crop studies concerned the effects of nutrients on growth [33,101–105], resulting in a lower number of high value species being investigated. For example, a German study investigated nutrient dynamics in 12 species of *Sphagnum* to find the most appropriate species for paludiculture, with *S. denticulatum*, *S. fallax*, *S. riparium*, *S. fimbriatum*, and *S. squarrosum* identified as fast-growing species [33]. One of the most extensively researched fen crops is reed canary grass (*Phalaris arundinacea*), which has been evaluated under contrasting water table and shallow drainage regimes to determine their effects on biomass productivity and methane (CH₄) emissions in agricultural fen peatlands [106,107].

Beyond these well-known paludiculture species, researchers have trialled a wide range of crops on rewetted and cultivated peat soils with high WTD, from biomass grasses to woody and high-value species. Sundew (*Drosera* spp.) cultivation has been investigated alongside *Sphagnum* species [108], though empirical evidence indicates optimal yields occur under controlled greenhouse conditions rather than in natural or semi-natural environments [38]. Additionally, hybrid Napier grass (*Pennisetum purpureum* Schumacher × *P. americanum* cv. ‘Pakchong1’) and giant reed (*Arundo donax*) from Thailand were also tested for paludiculture suitability in Denmark [109], where both showed good potential even

in northern climates. Evidence from short-rotation coppice willow (*Salix* spp.) cultivated on severely degraded agricultural peatlands indicates that elevating water tables can yield relatively favourable GHG balances compared to conventional forage grass systems; however, re-establishing a net peat carbon sink remains challenging on such sites [110]. Field studies evaluating mixed forage swards and set-aside vegetation as reference or alternative paludiculture systems reveal that under similar hydrological conditions, these grass-dominated communities are more susceptible to carbon loss than woody crops [110]. Widmer et al. [111] even trialled paddy rice in organic peat soils in Switzerland which resulted in reduced GHG emissions compared to drained management.

Collectively, the experiments demonstrate that paludiculture research has ceased to be so narrowly focused on mosses, reeds and Typha and is now in the business of testing various functional groups of crops (woody, graminoid, and moss).

In addition, crops imply intensive management of water, nutrient levels, weed species, etc., which are the focus of high intensity agriculture. However, there is also research associated with “low intensity paludiculture”, involving extensive use, low impact harvesting or grazing of semi-natural, rewetted peatlands requiring minimal intervention [112,113]. Under high water table regimes, extensive livestock grazing (e.g., regulated via virtual fencing) and summer silage harvesting on wet peatlands are being investigated as viable paludiculture options [114].

Research is also exploring “wetter farming,” maintaining intermediate water tables (−50 to −30 cm) to accommodate commercial crops that tolerate high water levels without full saturation [110,115–117]. In almost all cases, the higher the water level, the less productive the site was for food crops [115–117], highlighting that if rewetting is the goal, these food crops may not be a profitable option. However, some studies have already demonstrated no reduction in productivity of lettuces and radishes with higher water levels [34,117].

Table 3. Potential plant species for paludiculture implementation in northern temperate regions [98,99].

Latin Name	Common Name	Plant Type	Product	Material Harvested
<i>Alnus glutinosa</i>	Black alder	Tree	Wood; biofuel	Wood
<i>Aronia melanocarpa</i>	Chokeberry	Shrub	Food	Fruit
<i>Arundo donax</i>	Giant reed	Graminoid	Bio-energy crop	Aboveground biomass
<i>Azolla filiculoides</i>	Duckweed	Fern	Fodder; feed; fertiliser	Whole plant
<i>Carex riparia</i> and other species	Great pond sedge and other sedges	Graminoid	Fodder; biofuel; paper	Aboveground biomass
<i>Drosera rotundifolia</i>	Round leaved sundew	Forb	Medicinal uses	Aboveground biomass
<i>Glyceria maxima</i>	Reed manna/sweet grass	Graminoid	Fodder; biogas	Aboveground biomass
	Low intensity grassland	Grasses	Grazing land	Aboveground biomass
<i>Mentha aquatica</i>	Water mint	Herb	Tea leaves	Leaves
<i>Myrica gale</i>	Bog myrtle	Shrub	Hops for beer; medicinal uses	Leaves
Paddy rice	Rice	Grain	Food for human consumption	Endosperm
<i>Pennisetum purpureum</i> <i>Schumacher</i> × <i>P. americanum</i> (L.) Leeke cv. Pakchong1	Hybrid Napier grass	Graminoid	Bio-energy crop	Aboveground biomass

Table 3. Cont.

Latin Name	Common Name	Plant Type	Product	Material Harvested
<i>Phragmites australis</i>	Reed	Graminoid	Thatching; biofuel; construction material; insulation; fodder;	Aboveground biomass
<i>Phalaris arundinacea</i>	Reed canary grass	Graminoid	Fodder; biofuel; packaging	Aboveground biomass
<i>Rubus chamaemorus</i>	Cloudberry	Shrub	Food	Fruit
<i>Salix</i> spp.	Willow	Tree	Fuel; weaving material; fodder	Aboveground biomass
<i>Sphagnum</i> spp.	Peat moss	Moss	Horticultural growing media; material for restoration; orchid cultivation	Aboveground biomass
<i>Typha</i> spp.	Cattail	Graminoid	Construction material; biofuel; insulation material; fodder; packaging; horticultural growing media	Aboveground biomass
<i>Vaccinium oxycoccus</i> ; <i>Vaccinium macrocarpon</i>	Cranberry	Shrub	Food	Fruit

Biomass

In order to entice land managers/farmers to paludiculture adoption, biomass harvesting and establishing the potential yield and properties of paludiculture crops is essential. “Biomass” studies were almost exclusively conducted on reeds (*Phragmites australis*, *Carex* spp. and *Phalaris arundinacea*) and *Typha* species [12,14,39,118–120], most likely due to their fast-growing nature. Biomass yield estimates remain scarce and localised, with few studies offering multi-year averages necessary to contextualise inter-annual variability. On-going UK trials reported *Typha* biomass harvests from young plantations between 1.5 and 2.5 tonnes per hectare and similar figures for seed heads harvest (Mike Longen, Pers. Comm). Harvest time was frequently discussed in the literature with winter harvesting recommended in more northern climates [39,120]. *Typha* and reed biomass were tested for suitability and met requirements for combustion biomass [39,118] and as effective building materials [12–14]. Restoration studies have also investigated several strategies to optimise *Sphagnum* yields, including selecting species based on productivity and decay resistance, which can be applied to paludiculture systems [65].

3.2.4. Paludiculture Techniques

Cultivation/Growth

Cultivation and growth of paludiculture crops can be challenging and is a relatively new area of research (last 15 years). Growth of peatland vegetation with paludiculture in mind requires techniques which focus on quick establishment of crops and optimised growth of desired plant components. *Sphagnum* cultivation and growth have proved challenging due to the specific conditions needed for optimised growth. For optimised *Sphagnum* establishment, cover in the form of straw mulch, artificial mesh or nurse species is needed for quick establishment; however, excessive vascular plant cover can impede *Sphagnum* growth [121–124]. Straw and artificial mesh have been successfully used to retain moisture by reducing evapotranspiration rates which protect *Sphagnum* plants. Research has demonstrated that planting of nurse crops such as Ericoids and Bog cotton (*Eriopho-*

rum spp.) can increase successful *Sphagnum* establishment and is essential for hummock maintenance; however, this may not be suitable for growing media where a purer crop is desired [125,126]. The use of bioreactors for *Sphagnum* cultivation is a new and promising area which could optimise the cultivation process [127,128]. Meanwhile, BeadaMoss® plugs grown on cutover peatlands with surface irrigation resulted in high growth rates in dry matter and volume [129], with plugs performing better (higher photosynthesis and nutrient content) than wild *Sphagnum*, which is consistent with observations from restoration trials [130].

Cultivation/growth of *Typha* spp. and common reed (*Phragmites australis*) remain sparsely investigated due to fewer agronomic constraints, with existing studies addressing propagation only as a secondary focus. The main recommendations are to maintain water levels at or above the surface, and to ensure sufficient nutrient supply [29,41,131,132]. Techniques for planting such as seeding and planting by machinery or by hand are most common [41,131], however, drone-assisted planting has been successfully utilised in the Netherlands [133].

Fertilisation

Fertilisation in rewetted peatlands should be avoided to ensure water quality. However, certain crops can benefit from fertiliser application such as *Typha* and reeds. This review found a limited number of studies which investigated fertilisation, which were mostly interested in the effect of fertiliser application on GHG emissions [132,134]. These studies found reduced CH₄ emissions with nitrogen (N) treatment in both *Phragmites* and *Typha*, and negligible N₂O fluxes [132,134], pointing to an efficient use of nutrients in these crops which does not result in increased GHG emissions.

Irrigation

Sustaining high summer water tables poses a major hurdle for paludiculture, yet targeted research on irrigation solutions remains scarce despite widespread acknowledgments. While rewetting peat soils have been found to decrease evaporative flux from the system, the delay in covering the bare peat with vegetation (when cultivating *Sphagnum* for example) means that it cannot yet regulate soil moisture conditions [135]. A study from Germany found that evapotranspiration rates were indeed higher from paludiculture systems than natural bogs, pointing to a need for a constant water supply [136]. They highlighted that compensating for the 1993–2013 average water deficit would require an estimated 160 mm of water annually, which is a conservative estimate [136]. Based on long term figures from UK trials, it has been estimated that c. 15,000–20,000 m³ per ha per day would be required in a normal year during summer periods (May to early August).

Techniques for irrigation were mostly through use of automatic pumps from storage or ditch water [113,131,136]; however, overhead irrigation has been trialled with mixed results. *Sphagnum* farming pilots in the UK have used overhead irrigation, comparing spray and drip feed irrigation to simulate rainfall [129]. In these trials, irrigation was used to optimise moisture conditions for *Sphagnum* growth, with spray irrigation producing the strongest results for both *Sphagnum* growth and reduction in GHG emissions [129]. Although the water table was not actively raised before planting, expanding *Sphagnum* cover stabilised water levels near the surface and retained peat moisture [129]. However, research in Germany found irrigation via sprinklers can have a negative impact on *Sphagnum* farming as it induced high levels of DOC in the peat water [113,131]. Additionally, implementation of these techniques can be costly and may not be easily applied to larger sites.

Weed Management Techniques

As mentioned above, weed management is essential for ensuring a pure crop which can be readily utilised in the market. Topping is a traditional agricultural method which involves the cutting of the taller parts of a plant to promote dominance of the desired crop and reduce the growth of unwanted species [131,137]. For example, this method can be used for *Typha* to promote growth while simultaneously reducing the presence of unwanted species such as *Juncus* spp. Topping would also be a successful weed management technique for other paludiculture systems on wet meadows and pastures [41,131]. This is not to be confused with the commonly used term “mowing” which mainly refers to the mechanical control of vascular plants before or during paludiculture establishment which may be outcompeting *Sphagnum* in paludiculture systems [36,121,131,138].

It is important to identify what constitutes a “weed” in the context of paludiculture projects and their objectives. For *Sphagnum* farming, weed management of species such as *Juncus* spp. is critical for high yields and quality of the potential growing media product [121]. Yet management of *Eriophorum angustifolium* is unnecessary in *Sphagnum* cultivation [121] and was found to have no negative effects on *Sphagnum* growth, possibly due to low levels of litter accumulation [35]. Growth of other vascular plants does require mowing and was considered extremely important for *Sphagnum* cultivation in trials in Germany [36,121,136,139]. Extensive research from the Greifswald Mire Centre highlights the nuanced role of vascular plant cover in *Sphagnum* weed management; while complete absence of vascular plants negatively affects moss growth, excessive vascular cover induces shading and competitive stress that suppresses *Sphagnum* productivity [36,121,138]. Specialist German equipment ranges from brush cutters and triple-tyred single-axle mowers to long-reach, causeway-based excavators fitted with specialised mowing buckets (see Figure 6 in [36]). Straw mulch is considered a viable weed management option for *Sphagnum* protection from excessive vascular plant growth but may be difficult to manage in windy regions or not welcomed in the context of growing media products.

Harvesting

Topic harvesting received limited focus across peer-reviewed and the grey literature, reflecting the relative novelty of paludiculture research and a predominance of early-stage trials. Reeds and *Typha* were the most common plants investigated under topic harvesting, with winter harvesting suggested for high yields in northern climates [39,120,140], whilst Autumn harvesting was reported as optimum for more southern European climates [141]. *Sphagnum* harvesting had varied results for optimum harvest times with 5-year cycles suggested in Germany [36], 7–10 years recommended in Canada [142], and work in the UK examining 3 year crop cycles (Beadamoss® pers. com.).

3.2.5. Management/Land-Use

Transitioning from degraded peat to paludiculture (Business as usual (BAU) vs. paludiculture vs. “natural” peatland) can be challenging and expensive and was frequently studied, with special interest in C balances and species establishment. This again highlights the early stages of paludiculture-related research, where a focus on establishment has dominated. So far, the literature indicates that paludiculture does not diminish peat C stocks or peat forming potential when compared to rewetted (non-productive) sites [37,47,64,143–145]. While being a recommended sustainable practice, grazing on rewetted peat remains a risk factor for soil disturbance and potential C losses; although, this can be site-specific [146]. Prior to 2007, the body of literature regarding land-use was predominantly comprised of *Sphagnum* restoration studies. These investigations primar-

ily prioritised optimal vegetation establishment, a metric subsequently identified as a fundamental prerequisite for *Sphagnum* paludiculture [147–151].

3.2.6. Greenhouse Gas, Carbon and Climate

Greenhouse Gas Fluxes

Wetland GHG fluxes have emerged as a primary focus in recent land-use and climate literature, with extensive evidence demonstrating that transitioning degraded peatlands (e.g., cutaway and former agricultural soils) to paludiculture effectively reduces GHG emissions [34,55,90,152]. Paludiculture ‘carbon’ studies are increasingly being evaluated for future inclusion in voluntary carbon markets and national funding framework such as the UK Peatland Code and Ireland’s Peatland Standard, as a mechanism to monetise avoided GHG emissions in rewetted peat soils [153,154]. Of the studies investigating GHG fluxes, few investigated full net ecosystem carbon budgets [153–157], with most studies focussing on atmospheric GHG fluxes, mainly in the form of CH₄ and CO₂. Similar to findings from restoration works, water level is particularly important for GHG flux reduction, with levels close to the soil surface favourable for reducing emissions [34,45,90,152,158–161] with Evans et al. [162] finding that for every 10 centimetres of reduction in effective water table depth, net warming emissions reduce by approximately 3 t CO₂e ha^{−1} yr^{−1} (CH₄ and CO₂ fluxes combined). More specifically, transition to paludiculture was predicted to have some of the highest carbon sequestration rate of >1000 kg C ha^{−1} y^{−1} above rewetted forests, open fens and bogs [163]. Vegetation communities can impact CH₄ fluxes, with *Sphagnum*-dominated sites producing negligible CH₄ in comparison to other non-*Sphagnum* peatland vegetation [164,165], corroborating earlier general rewetting studies [2]. When measuring GHG fluxes from a paludiculture site, it is important to include drains, ditches, irrigation water and access ways [45,51], as it has been estimated that these areas could contribute 3.5 Tg CH₄ yr^{−1} (0.6–10.5 Tg CH₄ yr^{−1}), which is equivalent to 0.2–3% of global anthropogenic CH₄ emissions [166]. Harvesting is another important aspect to consider when measuring GHGs, with previous studies finding significant C depletion even with raised water levels [51,152,155,158,167,168].

Little is known about nitrous oxide (N₂O) emissions from paludiculture systems. However, from the few studies which did investigate N₂O fluxes, an increase in fluxes can occur [106,169,170], especially on former agricultural lands where nutrient levels in soils and water can be high. Considering N₂O is such a potent GHG with a global warming potential 263 times that of CO₂ over a 100-year period [171], it is essential to establish the magnitude of N₂O fluxes from eutrophic paludiculture sites.

Typha and reed are known for high productivity although they can emit large amounts of CH₄, a potent GHG with a global warming potential 32 times that of CO₂ over a 100-year period [171]. Some plants can act as conduits to CH₄, allowing for gas transport directly from roots to shoots through aerenchyma. Although highly productive, *Typha* and reeds risk significant methane emissions (a GHG 32-fold more potent than CO₂ over a century) by venting gas directly through root-to-shoot aerenchyma [171]. Other plants such as *Sphagnum* spp. produce negligible CH₄ fluxes [164,165], and can even oxidise CH₄, mitigating the gas transport seen in other species [172]. If GHG mitigation is the goal of a paludiculture project (carbon farming), crop selection should be carefully considered. Additionally, use of biochar and sulphate addition has also been tested as a method for enhanced carbon sequestration and GHG mitigation in wet farming [34,173], although it is yet to be tested in the context of paludiculture.

Warming Climate and Extreme Events

Predicting crop responses to climate warming and extreme events is critical for designing effective climate change mitigation strategies. Studies investigating the effect of warming on paludiculture crops was limited and has so far focussed on how warming may affect decomposition and microbial activity [174–176]. Open-top chambers are commonly employed for climate manipulation, but because they often warm the canopy while cooling the peat profile [174,176], supplemental soil heating is required to simulate realistic future climate conditions. Nonetheless, these studies offer critical insights into the differential effects of warming across two *Sphagnum* microhabitats, revealing that warming triggered an increase in dark septate endophyte root colonisation and a decrease in peroxidase activities within hummocks, whereas these metrics remained stable in lawns. This demonstrates that rising temperatures disproportionately impact drier hummock microhabitats, while lawns remain buffered against such changes [175]. In contrast, increasing temperatures in *Sphagnum* lawn species resulted in gains in competitive strength whereas hummock species are likely to become dominant in cases where increased temperatures coincide with decreased precipitation [177]. While this is a positive sign for paludiculture systems which rely mostly on *Sphagnum* lawns, it is unclear if the presence of microtopography could contribute to a buffering effect. The ‘wetter farming’ experiments will also help inform the effects of climate change on paludiculture systems, with emphasis on water management systems that ensure higher water table depths (−50 to −30 cm compared to −100 cm for BAU) during dry periods [178].

3.2.7. Biodiversity

Rewetting degraded peat soils has the potential to re-instate ecosystem services including enhanced biodiversity value, but challenges exist due to historical land use as well as environmental and management variables [179]. Limited empirical evidence indicates that paludiculture improves site-level biodiversity compared to business-as-usual agricultural drainage, though community composition remains below that of near-natural reference peatlands [54,55,57,58,180–182]. It has also been ascertained in the literature that drainage ditches can be a significant habitat type for aquatic invertebrates. In the Netherlands, water bodies in peatland agricultural areas can contain a diverse invertebrate fauna, similar to that of water bodies in nearby nature reserves [183]. Nonetheless, the paucity of biodiversity-related research within paludiculture systems is evident and may partially be caused by a methodological challenge. For instance, assessing biodiversity uplifts in paludiculture using UK Biodiversity Net Gain (BNG) metrics is constrained by misalignments between paludiculture habitats and standard classification schemes (UKHab), making both baseline establishment and uplift characterisation difficult [184]. To address this limitation, several other methodologies are being tested including the Wallacea Trust framework which could be integrated into unified carbon and biodiversity credits [185,186].

3.2.8. Technology

The transition to paludiculture relies heavily on technological innovations, ranging from specialised machinery to remote sensing (UAV and satellite systems) and machine learning. These technologies enhance site characterisation, operational harvesting, and the monitoring and modelling of GHG fluxes. Despite its rapid growth, this thematic area remained the least represented in the systematic literature review. Most of the studies focussed on mapping/remote sensing through use of hyperspectral data [60], spatial assessment tools [61], spectral indices [187] and multispectral data [188].

3.3. Terminology

Defining terminology is important to limit confusion and misrepresentation of findings. The survey conducted as part of this literature review aimed to identify phrases which may have different meanings in different countries/regions (Supplementary Materials Text S1).

- Paludiculture definition:

A primary conceptual challenge in implementing paludiculture transitions lies in the ambiguity and evolving definitions of paludiculture within scientific and policy frameworks. The term was originally presented by Joosten [189] as an innovative alternative to drainage-based peatland agri- and silviculture by cultivating biomass directly on wet or rewetted peatlands. Since then, paludiculture definitions have become more specific with not only rewetting and crop management in mind, but newer concepts such as carbon and biodiversity farming. While Joosten et al. [190] defined paludiculture as “The productive use of wet or rewetted peatlands”, current EU Horizon’s projects expanded the definition adding “..with water levels close to the surface, i.e., conditions under which peat is preserved” (Paludi4all.eu) or “that preserves the peat soil and thereby minimises CO₂ emissions and subsidence” (Palusdemos.org). These more specific definitions of paludiculture offer a new perspective past a simple land-use strategy to more nature-positive language aiming to appeal to farmers and land managers hoping to achieve a just transition from drained peat agriculture to “thriving paludiculture landscapes” (Paluwise.eu). In all cases, paludiculture involves wet or rewetted soils, i.e., saturated by water (of note, all organic soils are assumed to have originally been wet and therefore a drained organic soil needs rewetting to become a wet soil).

Ultimately, synthesising stakeholder objectives into a unified definition of paludiculture is constrained by regional governance, institutional priorities, and differing socio-political frameworks (e.g., The Uks DEFRA Roadmap [191]). It is therefore highly recommended that the term ‘paludiculture’ should always be defined within its context.

- “Wetter farming” on peat soils spans a continuum from paludiculture to partial rewetting, defining management regimes where water levels are elevated above drained baselines yet remain below complete saturation. In this context, two drainage classes typically apply: ‘shallow drained’ (mean annual WTD 10–30 cm below the surface) and ‘deep drained’ (mean annual WTD 30–50 cm). In practice, wet farming on peat typically involves adapting existing field drainage infrastructure (e.g., retrofitting control structures, adjustable sluices, or subirrigation pipe networks) to raise and actively regulate water table depths, rather than installing conventional deep-drainage systems. Wetter farming experiments are very informative not only in terms of managing the water table, crop productivity and adapted agronomical techniques but also GHG fluxes under ‘wetter conditions.’ However, there are few studies investigating these transition areas. As with paludiculture, there remains a large amount of uncertainty regarding large-scale operations and viability over multiple harvesting cycles. While operational retrofitting incurs capital costs and requires site-specific water management permissions, detailed financial incentives, subsidy mechanisms, and regulatory approval pathways are highly region-dependent and fall outside the scope of this review. Nonetheless, wetter farming is key in helping to adapt techniques to wetter soils as well as potentially acting as a management strategy for a ‘transition period’ or for ‘buffer area’ supporting actual paludiculture sites.
- Mowing/Topping/Cutting and Weed Management: As discerned from the literature search, mowing can have two meanings; control of unwanted vascular plants in *Sphagnum* farming [124], and low intensity grass-land use where pastures are mown for their biomass for feedstock [47]. This can cause confusion as both terms are widely

used. Additionally, topping is a traditional agricultural method which involves the cutting of the taller parts of a plant to promote dominance of the desired crop and reduce the growth of unwanted species [137]. Use of the term ‘weed management’ is suggested as the primary term when referring to control of unwanted species that may impact the growth of the desired crop.

4. Discussion: Translating Evidence into Practice

This literature review has evaluated the peer reviewed and grey literature that is relevant to the establishment of paludiculture practices in temperate and boreal climates. The main barrier to paludiculture establishment, which was present in scientific peer reviewed literature and grey literature alike, was the lack of policies which allow for funding schemes for paludiculture establishment and associated monitoring [43,46,112,192,193]. This is a major hurdle for land managers and farmers as transitioning from dry to wet agriculture on peat soils can be very expensive. Additionally, lack of funding for long-term projects which span from rewetting to harvesting are minimal and do not demonstrate the long-term potential of paludiculture to land managers/farmers [30,43,52,194–198]. Moreover, there is a noticeable spatial data bias which remains in the literature. Most existing studies are regionally constrained to North-Central Europe (Figure 4). Consequently, practitioners must prioritise localised evidence over the direct adoption of external protocol, with a necessity for context-contingent methodologies to ensure success in diverse landscapes.

The results from this review have identified 11 key recommendations for effective paludiculture establishment in temperate degraded peatlands (Table 4). These recommendations could help inform paludiculture establishment in many regions and are transformed into a conceptual diagram in Figure 7.

Table 4. Techniques to transition from dry to wet agriculture on peat soils and monitoring protocols based off the current peer reviewed and grey literature. For more in-depth and crop-specific instructions see [113,131].

Aims		Paludiculture Establishment Techniques Currently Utilised
Initial site investigations	Establishing what can be cultivated on-site based off the site’s history	• Edaphic conditions such as peat type, peat depth, nutrient status are important to inform what can be grown on-site (high nutrients would prevent cultivation of nutrient-sensitive species such as <i>Sphagnum</i>). • Mapping out the site’s history can inform crop selection. For example, if a site is formerly agricultural land where fertilisation was used, this can impact the success of crops grown on-site.
Site preparation	Pre-planting site management with the main objective being raising the water table	• Blocking of ditches, drains or dams to maintain a near or above-surface water level. • Topsoil removal: recommended for peat moss (<i>Sphagnum</i>) in polluted sites only to remove nutrient-rich topsoil; not generally recommended for reeds or <i>Typha</i> as nutrient removal can limit long-term productivity unless soil is highly polluted. • Construction of access ways to avoid crop and soil disturbance: especially important for <i>Sphagnum</i>. • Site levelling: can promote growth and result in more consistent crops. • Infrastructure for water management—drainage during flooding or irrigation during dry spells.

Table 4. Cont.

Aims		Paludiculture Establishment Techniques Currently Utilised
Environmental practices	Use local materials, avoid excessive topsoil removal and limit fertilisation	• Use of local materials will reduce the overall C footprint of paludiculture while supporting local businesses. • Topsoil removal can reduce nutrients in paludiculture systems but can also result in increased C losses and should only be used in cases of extreme eutrophication. • Limit fertilisation to maintain water and soil quality.
Soil monitoring	Soil analysis to inform what paludiculture establishment solves for soil C, nutrients and subsidence	• One of the main objectives of paludiculture is to reduce soil subsidence and preserve soil C. Therefore, BACI for carbon content in soils is recommended. • Nutrient accumulation in soils should be monitored as this can impact crop health. • Track elevation gains to monitor any switches from subsidence to accretion.
Water management	Maintaining high water levels and avoiding flooding	• Irrigation ditches for maintaining high water levels to avoid soil erosion with oxygen exposure. • Drains for removal of excess water. Closed basins can result in flooding, especially in winter months.
Water quality monitoring	Establish nutrient/heavy metal contents in water sources, basins and dams	• Water should be monitored at three locations: the source, basin and dams (if present). • Use of peatland plants such as <i>Typha</i> and reeds can remove excess nutrients and is a sustainable way to remove nutrients with regular harvesting. • More frequent monitoring in the summer months and following any storm or extreme weather events.
Crop planting/establishment	Successful establishment: survival, fast early growth, vigour and soil cover/canopy closure, recruitment	• <i>Typha</i>—Planting using seeding, manually by hand or mechanical planting with vegetable or forestry planting machinery. • Reeds (<i>Phragmites australis</i>, and <i>Carex</i> spp.)—Planting manually by hand or mechanical planting with vegetable or forestry planting machinery. • <i>Sphagnum</i>—moss cuttings can be spread at high density (70–80%); plugs of <i>Sphagnum</i> can be planted at high density (9 plugs per m² recommended by Beadamoss® for carbon farming and could be doubled for sphagnum farming); BeadaGel® spread using tanks is still under development. • To keep moisture in and protect it, straw or mulch can be spread with the <i>Sphagnum</i>. • Berries—manual planting.
Crop assessment	Methods which focus on ensuring crop health	• Monitor growth rates at least twice a year, before and after the growing season. • Regular site visits to monitor and deal with any weeds or unwanted grazers. • Brush wire/stakes in ground for monitoring growth in height [199]. • Monitor densities of crops.

Table 4. Cont.

Aims		Paludiculture Establishment Techniques Currently Utilised
Greenhouse gas monitoring	GHG emission reduction via water table management and paludiculture implementation.	- Regular GHG monitoring should be carried out to determine any reductions in emissions compared to business as usual. - The eddy covariance and chamber-based methods are most common for GHG monitoring. - Rewetting of peatlands can result in increased CH₄, although emissions reductions from CO₂ with rewetting result in reduced GHG emissions overall. - Little is known about N₂O fluxes from paludiculture sites.
Biodiversity monitoring	Monitoring of any changes to biodiversity compared to BAU	- BACI for any groups of interest. - All the studies which investigated paludiculture and biodiversity saw increased biodiversity with a switch to paludiculture compared to business as usual.
Harvesting	Methods which focus on optimising yields and reducing soil disturbance	- Harvest timing can be important for reeds and <i>Typha</i> and may differ regionally. - Allowing <i>Sphagnum</i> enough time to form large mats prior to harvesting is important for growing media production. - Innovation of machinery which does not disturb peat soil is essential to preserve stored carbon.

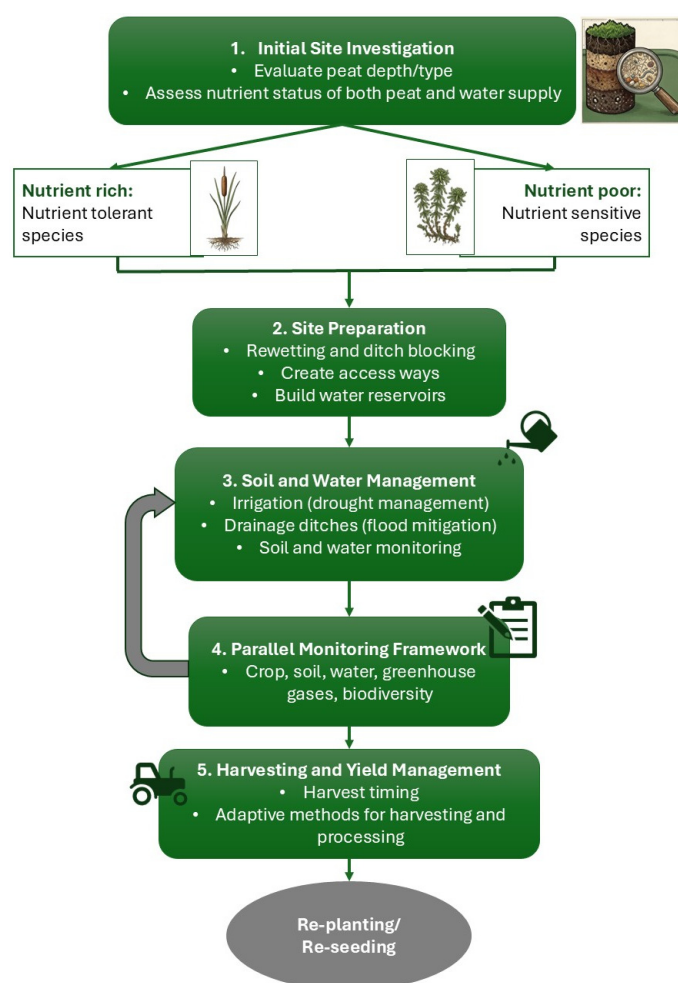


Figure 7. Key steps and decision nodes for paludiculture establishment derived from the recommendations detailed in Table 4.

4.1. Challenges and Lessons Learned for Effective Paludiculture Establishment by Country

4.1.1. Germany

Germany had by far the most paludiculture publications of any country and is a pioneer country for paludiculture establishment (Figure 4). Paludiculture techniques represented the predominant research theme originating from Germany, where the majority of biodiversity investigations were also conducted, underscoring the country's leading role in paludiculture research. Most *Sphagnum* paludiculture research originates in Germany where a high coverage of *Sphagnum* fragments (70% or more) is usually spread from a donor site with straw which allows for moisture retention and cover [36,124,138]. Other species which were the focus of German research were crops such as *Typha*, *Phalaris* and *Carex*, although these crops mostly investigated GHG dynamics [155,169,194], growth [55,61,87,200,201] and harvesting (biogas potential, optimal harvest timing and biomass) [39,99,118,202–204]. Rarer species such as *Drosera* were also investigated for cultivation potential [38,108,205].

4.1.2. The Netherlands

The theme “water” was investigated in the Netherlands more than in any other countries. This outcome is likely driven by highly artificial hydrological regimes and compromised water quality in the Netherlands, where EU Water Framework Directive metrics indicated that only 1.4% of surface waters met good status criteria in 2022 [206]. High nutrient levels were favourable for *Typha* and reed cultivation [83,104,132,134,207,208], whereas high nutrient content in Dutch waters means that *Sphagnum* cultivation is very challenging, due to the detrimental effects of high nutrient levels on *Sphagnum* growth [89,91]. This has resulted in most recent Dutch studies favouring *Typha* and reed species investigations over *Sphagnum*. However, in the Netherlands, proposed alterations to water management regimes are governed by stringent regulatory frameworks that require site-specific approvals for localised land parcels. This regulatory burden represents a major operational barrier that compounds pre-existing negative farmer perceptions regarding peatland rewetting. A lack of species diversity was also present in the Netherlands with most publications investigating *Typha* [29,53,83,84,89,101,104,132,134,140,207–210], and to a lesser extent *Sphagnum*, of which most studies were addressing restoration of peatlands rather than paludiculture per se [30,47,72,89,91,97,102,211–215].

4.1.3. Canada

The literature obtained from Canada yielded results primarily from *Sphagnum* cultivation sites and not paludiculture sites per se. However, the methods used in the earlier cultivation experiments have influenced many countries' approaches to *Sphagnum* farming establishment [216–218]. Research into more paludiculture-based systems is lacking in Canada with more focus on *Sphagnum* restoration in the country.

4.1.4. The United Kingdom

Soil was the most common theme from the UK. These studies focussed mostly on *Sphagnum* [67,195,219] and in the context of overall restoration of a suitable vegetation cover to help with downstream water quality. In the UK, approximately 85% of drinking water is provided directly from peatlands, highlighting their importance in water security in the region [220], and is a significant driver for rewetting in the country. However, transitioning from agricultural practices to paludiculture holds many challenges in the UK with land managers being hampered by systemic barriers involving regulatory complexity, financial uncertainty, and legal risks [221,222], making the transition a daunting prospect for farmers. Mulholland et al. [223] discussed the potential for paludiculture in England and Wales citing issues with water management in the UK. These ranged from recommendations

for avoiding conflict with neighbours by creating hydrologically isolated sites from adjacent drained farmland, to challenges with maintaining high soil water levels, especially recommending designing systems for water resilience [223]. Reconciling the competing demands of food security and GHG emissions from agricultural peatlands necessitates the development of innovative, multi-functional land-use strategies which “wet farming” and “paludiculture” should be part of [34].

4.1.5. Finland

Despite peatlands covering 30% of Finland, this literature search found little published research into paludiculture-related studies (Figure 4). The majority of Finnish studies focused on GHG dynamics, carbon cycling, and climate mitigation, consistently reporting net reductions in GHG emissions following vegetation establishment and regeneration [110,158,224–226]. *Sphagnum* was the focus of most of the studies conducted in Finland [158,227–231]; however, investigations into *Typha* [232], *Salix* [110], *Drosera* [233] and *Carex* [224] also occurred. Finland’s focus on *Sphagnum* cultivation has illuminated critical empirical gaps, notably regarding the net GHG flux impacts associated with biomass harvesting [158]. Furthermore, current frameworks often assume that all abandoned organic croplands are suitable for paludiculture conversion, a premise that may fail to account for site-specific hydrological and edaphic constraints [225].

4.1.6. Denmark

Denmark has focussed on a wide range of species for paludiculture research, mainly *Phalaris arundinacea*, although investigations into *Typha* spp., *Phragmites australis*, *Arundo donax* *Festuca* spp. and *Pennisetum purpureum* Schumacher × *P. americanum* (L.) Leeke cv. Pakchong1 also occurred. Similar to the overall results of the literature search, themes of GHG/Carbon/Climate dominated, comprising more than 50% of the Danish studies and are relatively recent, with the oldest studies dating from 2014.

4.1.7. Ireland

In Ireland, state-sponsored, large-scale peat extraction for fuel and electricity production has ceased, leaving many areas of bare industrial peat soils ripe for paludiculture establishment [26]. Peat extraction currently operates within an uncertain regulatory climate, driving the sector to seek “just transition” pathways that enable continued, sustainable management of peatland assets. Studies from Ireland show a very new and disparate research associated with small-scale rewetting of cutaway peatlands ranging from plant parasitic nematodes [234], use of fish cultivation waste for production of duckweed and/or microalgae biomass [193,235–237] and a review of the digital transformation of paludiculture-based eco-innovation [238]. Irish studies pertaining to rewetting of cutaway peatlands and plant-mediated GHG emissions [2] as well as the effects of water level fluctuations on *Sphagnum* performance provide critical additional information for paludiculture projects [239].

4.2. Future Research

Despite paludiculture being in its infancy, it has demonstrated potential as a viable option for land managers to remain productive while maintaining important carbon, biodiversity and climate goals [124,131,157,240,241]. The knowledge gaps presented above in Table 2 highlight the growing need for information which will entice farmers, land managers and policy makers to adopt paludiculture as viable for future economic and climate goals. Long-term monitoring is constrained by typical funding cycles of 3–5-years, which are frequently insufficient to span the full timeline from initial site establishment to biomass harvesting in paludiculture systems [30,43,52,124,152,194–197]. Additionally,

farmers who may contemplate paludiculture are typically unwilling to join these short-term projects as they do not guarantee long-term financial stability (pers. coms. Jeroen Vrolijk; [222,242]). Therefore, longer term funding will allow for collection of this critical data and may entice more farmers/land managers to attempt paludiculture adoption.

To date, the current body of literature on paludiculture remains heavily reliant on small-scale demonstrator or pilot sites, limiting insights into large-scale viability as well as landscape effects. Practitioners will resist transitioning to paludiculture unless commercial-scale projects verify not only saleable products opportunities but income levels comparable to traditional, drained agricultural peat soils. Furthermore, research findings from the ‘pioneer countries’ in paludiculture should be adapted to regions of high peatland cover where paludiculture is a viable option. The findings from these ‘pioneer countries’ should be used in a strategic roadmap, which will account for regional climate, peat type, land-use history and cultural aspects. The socio-cultural aspect of paludiculture also warrants further investigation, specifically emphasising methods which will reduce the risk of damage to archaeological artefacts which may be preserved in peat soils [26].

The literature review has also highlighted the species bias in the current available data. A handful of crops have been investigated in a range of countries; however, certain crops are highly under-investigated such as berries, sundew and woody species, all of which could be important paludiculture crops (especially woody species for tropical peatlands in south-east Asia). These processes need to be upscaled as little is known about the viability of these under-investigated species as paludiculture crops [38,108,205]. Evaluating wet pasture grazing represents a key future research priority, offering a lower-barrier paludiculture adoption route for livestock farmers hesitant to shift toward bio-economy crop systems [27]. Similarly, farmers currently cultivating food crops may be hesitant to switch to non-food products cultivation such as reed, *Typha* or *Sphagnum*; hence, further investigations into berries and other food crops should be a priority.

Currently, paludiculture systems are constrained by highly labour-intensive operations as conventional agricultural machinery was engineered exclusively for trafficability on drained soils rather than saturated, rewetted peat soils. In addition, pioneer paludiculture operations in Germany would have benefited from a cold winter climate that permitted trafficability on frozen ground (such conditions are absent in Western Europe). Technology such as drone planting and harvesting is being trialled [243]; however, this is yet to be tested on larger sites, and drone technologies may not currently be suitable for certain crops.

4.3. Limitations

A notable limitation of this review is the exclusion of subtropical peatland research and a lack of research on temperates outside of Europe and North America. While tropical East Asian peatlands face well-documented degradation and present significant opportunities for paludiculture adoption [244–246], studies examining wet agriculture or peatland management in non-tropical Asian contexts remain vastly underrepresented in the global literature. Beyond the intentional scope boundary set on temperate and boreal systems, the relevant regional literature often goes uncaught in standardised search strings because the explicit term “paludiculture” is not widely adopted in these non-European/North American contexts.

For instance, Wang et al. [247] investigate the differential impacts of agricultural conversion on flood-fed mineral floodplains compared to highly sensitive rain-fed peatlands. While their findings directly inform sustainable wetland management, the study was excluded from automated search protocols due to the absence of key terms like “paludiculture” or “wet farming”. Consequently, the lack of studies in this review reflects both a genuine scarcity of temperate/subtropical Asian paludiculture trials in English-

language literature and a methodological barrier caused by regional differences in terminology. Expanding future reviews to include translated non-English databases and localised agricultural nomenclature will be crucial for capturing the full scope of Asian wetland management strategies.

5. Conclusions

Transitioning from dry to wet agriculture on peat soils can be summarised as the action of reversing drainage-induced peat degradation by re-establishing high water tables. This enables the introduction of hydrophytic crops managed under water-level-controlled, low-input regimes that preserve peat integrity from site preparation through harvest. In short, it represents a complex, multi-dimensional and multi-adaptive decision framework involving hydrological, agronomical, technical and socio-economical components. Using an evidence synthesis approach, this review mapped the extent of available research across the first three pillars to understand the existing techniques, protocols and challenges. Despite the research and literature outputs being fragmented and imbalanced (spatially and species-wise), the outlines of a roadmap for paludiculture projects are beginning to emerge. Initial site investigations are crucial to understanding cultivation success and can predict site preparation needs (rewetting methods and water management needs). Parallel long-term monitoring of crops, soil, water quality, greenhouse gases and biodiversity are essential for future projects as reliable data which will inform viability and incentivise future paludiculture funding. This will include upscaling of demonstrator sites to prove viability of paludiculture both practically and financially. Harvesting techniques and yield management require further funding and innovation focussing on low-impact technologies and affordable options for farmers. This includes harvesting techniques with a low carbon footprint which verify net greenhouse gas mitigation across the entire lifecycle.

Further investigations into the viability of wet pastures for grazing is needed, especially for regions with a strong history of livestock farming where a transition to crop-based paludiculture may be unpopular. Additionally, policy frameworks must address regulatory permitting complexities, not just financial incentives. Finally, the need for long-term funding will require restructuring institutional grant timelines to match long-term ecological and harvest lifecycles. Ultimately the success of transitioning to wet agriculture on peat soils will hinge on the establishment of appropriate incentive frameworks that provide clear operational procedures that deliver sustainable outcomes, supporting long-term environmental benefits.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/land15091676/s1>. Text S1: Survey questions sent to Palus Demos partners and advisers. Table S1: Themes and topics, with the number of topics per theme. Table S2: Palus Demos sites. Table S3: European paludiculture sites shown in Figure 5.

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