Applying Paludiculture in Multifunctional Buffer Zones Between Agricultural Land and Nature to Improve Ecosystem Functioning

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Abstract

The growing population and the rising demand for food has led to land use changes, changes in water management and agricultural intensification, leading to environmental challenges. These challenges include eutrophication, peatland degradation, soil subsidence and greenhouse gas emissions. Research on paludiculture and buffer zones have often been conducted separately; however, in this review these are integrated to find out whether paludiculture can be applied in multifunctional buffer zones between agricultural land and nature to improve ecosystem functioning. Paludiculture can effectively reduce nutrient fluxes to surrounding areas through biomass production and harvest. The commercial production of “paludicrops”, crops grown under wet conditions, can encourage landowners to implement paludiculture in buffer zones. Different kinds of paludicrops could potentially be grown together, including natural vegetation, to increase the biodiversity and provide ecosystem services in buffer zones. This way paludiculture buffer zones can support water purification, peatland conservation, enhance biodiversity, reduce greenhouse gas emission, and act as water retention and storage areas.

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1.0 Introduction

The growing population and the rising demand for food has led to urbanization and land use changes to agricultural land (Karp et al., 2012). Additionally, land management has become more intensified, replacing smallholder farms (Hurni, Tato, & Zeleke, 2005; Karp et al., 2012). This includes higher stocking densities on pastures and intensified crop production (Muscutt, Harris, Bailey, & Davies, 1993). These changes have affected water management and hydrology. Agricultural intensification including the use of heavy machinery and drainage to keep the land dry has led to soil degradation, reducing soil infiltration rates and storage capacities, increasing the risk of flooding. Additionally, the water quality is decreasing, due to pollution runoff by fertilizer and pesticide use from agricultural land (Wheater & Evans, 2009). Intensified agriculture for crop production seeks to increase the productivity and yield per unit area by growing crops in a monoculture, adopting tillage and crop rotation practices, and using pesticides and fertilizer (Blumenthal & Mitchell, 2006; Chavarria et al., 2018; Tsiafouli et al., 2015). Unfortunately, this intensification comes with a cost. Monocultures lack a high biodiversity, reducing ecosystem services including pollination, soil nutrient enhancement and integrated pest control (Omer, Pascual, & Russell, 2007). Additionally, intensive use of pesticides strongly reduce the soil fertility (Chavarria et al., 2018). To enhance the nutrients in the soil and increase the productivity, synthetic inputs such as fertilizer are used. These fertilizers contain nutrients, such as nitrogen and phosphorus, which may lead to eutrophication (Jabłońska et al., 2020; Shi et al., 2016; Zak et al., 2019). Eutrophication of areas surrounding agricultural land leads to major environmental challenges. Such challenges include algal blooms and hypoxia in lakes, streams and estuaries, and biodiversity loss (Christen & Dalgaard, 2013; Zak et al., 2019).

1.1 Buffer zones

Buffer zones have been introduced in some European countries since the 1980s due to the multiple benefits they provide. Buffer zones may help transform heavy precipitation events into a smoother discharge curve, to mitigate flood risk (Ahmad, Liu, Günther, Couwenberg, & Lennartz, 2020). Additionally, buffer zones are implemented to act as a transition strip between dry and wet areas, to avoid significant changes in water table fluctuations in moisture-sensitive areas. Buffer zones may be implemented when drainage systems are used to keep agricultural land dry, but bordering nature areas should not be drained (Soutter & Musy, 1993). The water retention capacity is supported by vegetation growing in the buffer zone, that slows the surface flow. Due to the water retention capacity of buffer zones, they may protect biodiversity by providing suitable habitat for pollinators, birds, and amphibians, and create opportunities for recreation and education (Miettinen et al., 2012; Zak et al., 2019). Buffer zones with vegetation may also provide shade and regulate the temperature in stream habitats. Debris may help support fish and benthic invertebrate communities (Correll, 2005; Miettinen et al., 2012; Sood, Uniyal, Prasanna, & Ahluwalia, 2012). One of the main benefits of buffer zones is reducing nutrient fluxes from agricultural land to surrounding areas, which helps support a high biodiversity. These buffer zones help to protect areas from pollution, including pesticides and nutrients (Christen & Dalgaard, 2013; Geurts et al., 2020; Jabłońska et al., 2020; Syversen & Bechmann, 2004). Buffer zones capture and remove nutrients by biological, chemical, physical, and biochemical mechanisms, such as microbial denitrification and plant uptake (Jabłońska et al., 2020; Uusi-Kämppä, Turtola, Hartikainen, & Yläranta, 1996). This helps to optimize ecosystem functioning of areas surrounding nutrient rich areas by reducing nutrient loading (Christen & Dalgaard, 2013; Geurts et al., 2020; Jabłońska et al., 2020).

1.1.1 Biodiversity, and ecosystem functioning and services

A higher biodiversity is of great importance in supporting ecosystem functioning. A review by Tilman et al. (2014) found that numerous studies have shown that communities greater in biodiversity are approximately twice as productive as monocultures of the same species, due to trade-off-mechanisms allowing for long-term coexistence of competing species. Species traits and interactions help maintain the functioning and stability of ecosystems and biogeochemical cycles (Loreau et al., 2001). Eutrophication may lead to reduced biodiversity, due to a shift in competition from nutrients to light, in plants. This allows for the excessive growth of a few dominant species, reducing plant diversity (Hautier, Niklaus, & Hector, 2009). A reduction in plant diversity may negatively impact the biodiversity of species relying on specific primary producers. In a study by Root et al. (2016) specialist herbivore moth communities were in decline due to a reduction in plant diversity as a result of intensive forest management (Root et al., 2017). Eutrophication can therefore indirectly negatively impact ecosystem functioning, by reducing the biodiversity. A well functioning ecosystem supports the provision of ecosystem services, providing goods and services to the human population (Balvanera et al., 2006). One of these services includes the provision of clean (drinking) water through nutrient cycling (Fisher, Turner, & Morling, 2009). The loss of biodiversity and ecosystem functioning can compromise ecosystem service delivery (Balvanera et al., 2006). Therefore, to sustain these services to society, it is of great importance to maintain a well-functioning ecosystem with a high biodiversity.

1.2 Paludiculture

Often peatlands are drained to convert areas to agricultural land. The lowering of the water table causes peat oxidation and soil subsidence (Ahmad et al., 2020; Chang, Tsai, & Yang, 2019; Geurts et al., 2020; Geurts et al., 2019; Jabłońska et al., 2020; Schröder, Dahms, Paulitz, Wichtmann, & Wichmann, 2015). Soil subsidence brings the water table closer to the soil surface. A low-lying terrain is more susceptible to flood risk, as the water storage capacity depends amongst other things on the depth (Wang, Zhao, Xu, Wang, & Peng, 2013). Soil subsidence makes the area less suitable for agricultural practices, and action needs to be undertaken to stop the loss of this vulnerable land (Kandel, Karki, Elsgaard, Labouriau, & Lærke, 2020). In addition, these drained peatlands change from being a carbon sink to being a carbon source. In Europe, they are responsible for 80% of greenhouse gas emissions from agricultural areas despite covering only 10% of the land surface (Tanneberger, Moen, Joosten, & Nilsen, 2017).

Rewetting can be used to restore degraded peatlands. Rewetting helps to reduce peat oxidation, land degradation, and carbon dioxide (CO_2) emission (Wichmann, Krebs, Kumar, & Gaudig, 2020). This however may lead to the mobilization of nutrients, such as phosphorus, to surface waters. These nutrients decrease the water quality and may result in eutrophication (Jabłońska et al., 2020). Eutrophication can deteriorate the quality of aquatic habitats, and lower the aesthetic and recreational values (Miettinen et al., 2012). To prevent these effects, paludiculture may be implemented. This is the productive use of wet and rewetted peatlands to harvest biomass in combination with the provision of ecosystem services, (Geurts et al., 2019; Kandel et al., 2020; Lahtinen, Mattila, Myllyviita, Seppälä, & Vasander, 2022; Schröder et al., 2015; Wichmann et al., 2020). "Paludicrops" are crops grown under wet conditions (Geurts et al., 2019), and take up excessive nutrients from the water, and are harvested for biomass production (Geurts et al., 2020). This reduces the environmental impact, whilst utilizing these nutrient-rich areas (Ziegler, 2020).

1.2.1 Advantages and disadvantages

Paludiculture has many benefits, including peatland conservation, which is a cost-efficient way to reduce greenhouse gas emissions by reducing carbon dioxide emissions. Rewetting a peatland creates anaerobic conditions, increasing denitrification to dinitrogen gas (N_2), reducing the emission of nitrous oxide (N_2O), also a greenhouse gas (Geurts et al., 2019; Karki, Elsgaard, Audet, & Lærke, 2014; Lahtinen et al., 2022). On the other hand, methane (CH_4) emissions may increase. Methane has a higher radiative force compared to carbon dioxide, and may counteract the impact obtained from reduced carbon dioxide emissions (Kandel et al., 2020). Rewetting creates anaerobic conditions, favoring methanogenesis (Lyu, Shao, Akinyemi, & Whitman, 2018). Peatlands can furthermore help to prevent drought and flooding through acting as water retention and water storage areas, which can mitigate the effects of climate change and sea level rise. This natural flood management is of great importance, as more extreme rainfall and runoff events may take place due to climate change (Zak et al., 2019). Converting relatively small areas of drained peatland to paludiculture can already have great effects. Geurts et al. (2019) state that converting one hectare of drained peatland to paludiculture can be as effective as taking climate mitigation actions on ten to 100 hectare of soils used for food production (Geurts et al., 2019).

1.3 Main and sub-questions

The question is how paludiculture can be introduced to multifunctional buffer zones between agricultural land and nature to improve ecosystem functioning. It is hypothesized that paludiculture implemented in buffer zones can be an effective way support several ecosystem functions, such as reducing nutrient fluxes to surrounding areas, as there are quite a few paludicrops that can take up excess nutrients. A paludiculture buffer zone could be positioned between drained agricultural areas and wetland nature reserves, to prevent excess nutrients from agricultural areas reaching nutrient poor natural areas with a high biodiversity (Geurts et al., 2020). Apart from removing excess nutrients, applying paludiculture in buffer zones could help conserve peatlands and reduce greenhouse gas emissions, and act as a water retention area (Geurts et al., 2019; Karki et al., 2014; Lahtinen et al., 2022; Zak et al., 2019). In these changing times with a growing world population, food shortages, climate change and a future shortage of fossil fuels, renewable and long-lasting solutions are necessary. Paludicrops could be the solution to these problems through acting as bioenergy and food production landscapes and greenhouse gas mitigation (Christen & Dalgaard, 2013; Giannini et al., 2016). The production of biomass can provide a financial benefit, and therefore the implementation of paludiculture in buffer zones may be more attractive to the landowner. Instead of sacrificing valuable land only for ecosystem functioning, the landowner can grow paludicrops in the buffer zone (Geurts et al., 2020; Geurts et al., 2019; Jabłońska et al., 2020). A simplified visualization of what paludiculture in a multifunctional buffer zone between agricultural land and nature could potentially look like is shown in figure 1.

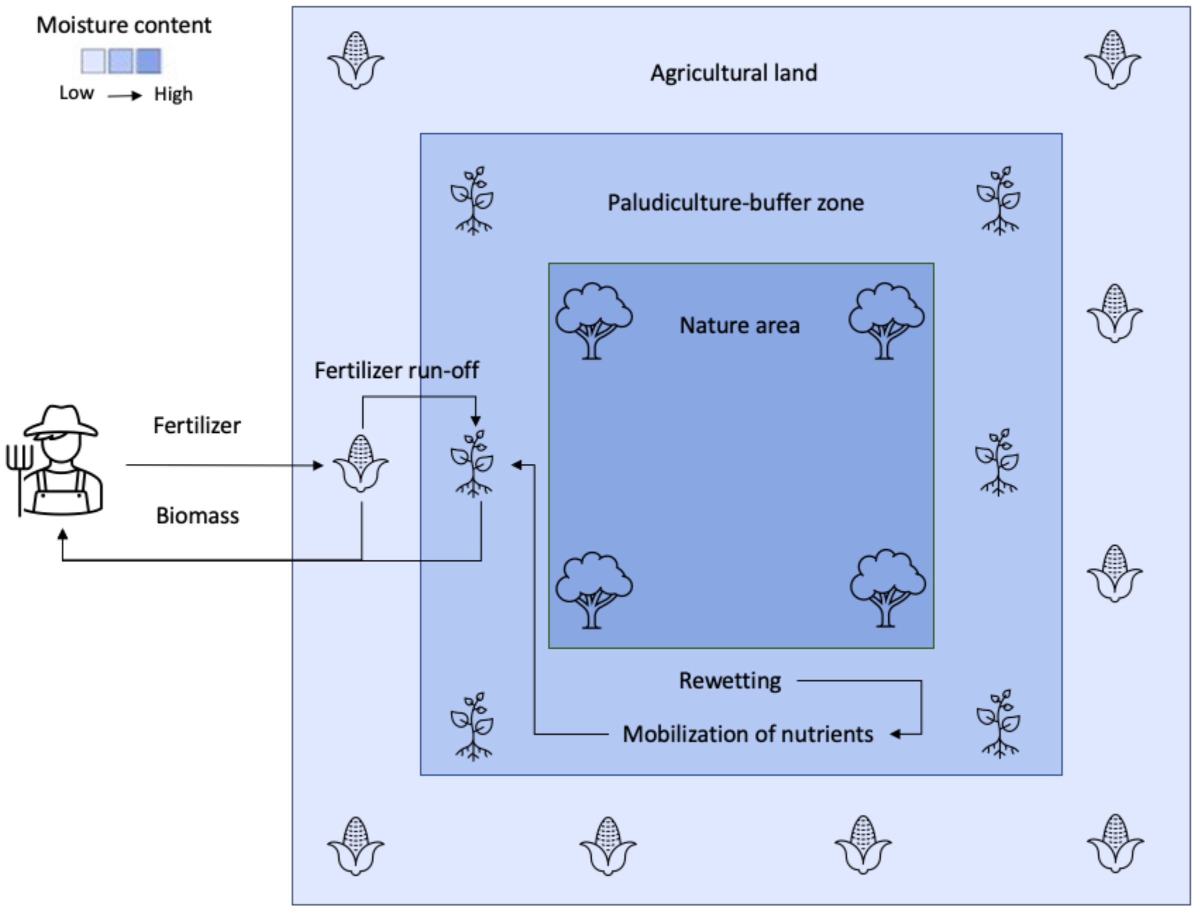

Figure 1 A simplified visualization of paludiculture in a multifunctional buffer zone between agricultural land and nature areas to improve ecosystem functioning by taking up excess nutrients from fertilizer runoff and producing valuable biomass that can be harvested.

Apart from the main question, there are several sub-questions that are answered in this review to help answer the main question. One of these questions is what requirements, including the hydrological conditions, nutrients and buffer zone size should be considered for these paludiculture buffer zones to function well. In case landowners would like to apply paludiculture in buffer zones, they could use this information as guidelines.

Once the conditions in the buffer zone are suitable, plant species can be introduced. It is the question which paludicrops should be introduced depending on their requirements and products. There are several plant species known to grow well on rewetted peatlands. To accommodate for the different requirements of each paludicrop, a heterogenous buffer zone design may be implemented. Apart from keeping nutrient concentrations low in nature areas, having a polyculture of multiple paludicrops and mixed natural vegetation could also increase biodiversity and benefit ecosystem functioning. Depending on the goal of the landowner, and the requirements of the intended paludicrops, different paludicrops could be grown in these buffer zones.

Lastly, it is of interest to explore how ecosystem functioning and services can be quantified and optimized in paludiculture buffer zones. It is also important to find out if there any disadvantages to applying paludiculture in buffer zones regarding their functions and services, or if there only are synergies. This may help landowners in making the decision whether to apply paludiculture in buffer zones, and how to optimize it.

1.4 Literature collection

To answer the question how paludiculture can be applied in multifunctional buffer zones between agricultural land and nature to improve ecosystem functioning, the scholarly online search engine Google Scholar was used. The keywords used to search for relevant literature differed depending on which of the questions were to be answered. To start off with prior reading, general keywords were used. For example, to search for literature on buffer zones surrounding agricultural land, the key words ‘buffer zone AND agriculture’ were used. To start off with paludiculture, simply the keyword ‘paludiculture’ was used. Ample (recent) literature covered the importance of paludiculture and specific paludicrops with the related products. This provided an indication of what paludicrops exist, what requirements they have and so forth. For the main question, the keywords ‘paludiculture’ AND ‘buffer zones’ AND ‘ecosystem functioning’ were used. It was however found that there was limited literature found on the combination of buffer zones and paludiculture. Therefore, the keywords paludiculture and buffer zones were mainly researched separately. To find out the ecosystem services paludiculture and buffer zones provide, the key words ‘buffer zone’ OR ‘paludiculture AND ‘ecosystem services’ were used. For the paragraph covering the terms used to indicate buffer zones, literature found during the buffer zone searches was used. This search seemed to cover all the different buffer zone terms. To find literature on paludiculture buffer zone size and hydrological conditions, the keywords ‘buffer zone’ OR ‘paludiculture’ AND ‘size’ and ‘buffer zone’ AND ‘hydrology’ OR ‘water level’ OR ‘conditions’, and ‘nutrients’ AND ‘paludiculture’ AND ‘deficiencies’ OR ‘excess’ were used.

In the original search for paludiculture, general information was found. Several species that occurred the most in the found literature were chosen to continue with more specific searches. For literature on *T. latifolia* and *P. australis,* the keywords ‘paludiculture’ OR ‘buffer zone’ AND ‘T. latifolia’ OR ‘cattail’ OR ‘P. australis’ OR ‘reed’ AND ‘applications’ OR ‘stand age’

OR ‘biomass production’ OR ‘nutrient removal efficiency’ OR ‘harvest’ OR ‘water level’ OR ‘maintenance’ was used. For natural vegetation, ‘paludiculture’ OR ‘buffer zone’ AND ‘natural vegetation’ AND ‘application’ OR ‘water level’ was searched for. For specific literature on *Alnus, Salix, Sphagnum and Azolla,* the following similar keywords were searched for ‘Alnus’ OR ‘alder’ AND ‘paludiculture’ OR ‘buffer zone’ AND ‘application’ OR ‘water level’ OR ‘harvest’ OR ‘nutrient removal efficiency’, with only a difference in species name, both the Latin and English name, per search.

To obtain literature on the residence time and flow rate, the searches included the keywords ‘buffer zone’ OR ‘paludiculture’ AND ‘residence time’ OR ‘flow rate’. However, limited literature was found for the residence time and flow rate specific to buffer zones or paludiculture. Therefore, the keywords ‘buffer zone’ OR ‘paludiculture’ were replaced with ‘constructed wetland’, as more literature used this term. The last literature search focused on finding the synergies and trade-offs related to paludiculture and used ‘paludiculture’ AND ‘disadvantages’ OR ‘challenges’ to conduct this search. This search provided general literature covering this topic. Additional searches were done to obtain additional useful information, such as how to quantify and optimize ecosystem functioning and services.

1.5 Terminology

In literature there are several terms used to describe a buffer zone. Jabłońska et al. (2020) used the term “wetland buffer zone” to describe wetlands as riparian areas acting as buffer zones through reducing nutrient loading between agricultural lands and a river (Jabłońska et al., 2020).

Walton et al. (2020) supported this definition, by adding additional water bodies to the definition, such as lakes. Walton et al. (2020) put emphasis on the land-water interface, and that peatlands are a type of wetland (Walton et al., 2020). There are two types of wetland buffer zones: the natural and constructed wetland buffer zones. Natural wetlands are ecosystems characterized by the presence of water, with water-saturated soils that are poorly aerated, supporting vegetation that survive these wet conditions, called hydrophytes (Ansola, Arroyo, & de Miera, 2014). Constructed wetlands are manmade or artificial, and imitate the abilities of natural wetlands through removing pollutants from water, but in a more controlled environment (Ansola et al., 2014; Mander, Tournebize, Tonderski, Verhoeven, & Mitsch, 2017).

There are additional terms used in the literature, such as “intelligent” or “integrated buffer zone” (IBZ), that are sometimes used interchangeably. However, the term “integrated buffer zone” was used more often in the found literature compared to “intelligent buffer zone”. IBZ’s are like the wetland buffer zone but differ in the sense that the IBZ is said to be more efficient in pollutant removal and are meant to improve wider ecosystem services. Zak et al. (2019) continues to describe IBZ’s as having two compartments, an aquatic part, and a planted infiltration zone. These two zones together provide the optimum environment for anaerobic microbial processes and plant uptake of nutrients (Zak et al., 2019).

The term “riparian buffer zone” is additionally a widely used term in the found literature. This however often refers to a zone along the banks of a river or stream, with its main function being determining the structure and function of the stream habitat (Barling & Moore, 1994). This does not seem to fit the overall meaning of the buffer zone described in this review, as it is specific to a zone along the banks of a river or stream. Therefore, literature focusing on riparian buffer zones has been read with caution.

The principles used to describe a buffer zone overlap greatly, apart from riparian buffer zones, and thus it was decided to simply refer to buffer zones. The main principles are that a buffer zone is a transition zone between dry and wet areas, to avoid significant changes in water table fluctuations in moisture sensitive areas, and to purify water to keep nutrient concentrations low to maintain a high biodiversity. The buffer zone type presented in this review is situated in the temperate and continental climatic regions, which are found in northern-central Europe, Canada, and northern USA (Walton et al., 2020). In this review, the possibility of applying paludiculture in these buffer zones will be discussed. The buffer zone is the place in the landscape, and paludiculture the practice of wet agriculture and forestry on peatlands (Geurts et al., 2019; Kandel et al., 2020; Lahtinen et al., 2022; Schröder et al., 2015; Wichmann et al., 2020). The simplified combined term for paludiculture implemented in buffer zones is called "paludiculture buffer zone".

2. What requirements should be considered for paludiculture buffer zones to function well?

One of the most important steps to take is to find a suitable location for a paludiculture buffer zone. In this review, the possibility of applying paludiculture in buffer zones between agricultural land and water bodies or natural areas is discussed. Paludiculture is the practice of wet agriculture and forestry on peatlands, and therefore locations with drained and degraded peatlands should be considered (Geurts et al., 2019; Kandel et al., 2020; Lahtinen et al., 2022; Schröder et al., 2015; Wichmann et al., 2020). These degraded peatlands may have been converted to agricultural land. Some of this land can be used as a paludiculture buffer zone, so that the buffer zone can reduce nutrient loading from the agricultural land to bordering water bodies or natural areas (Geurts et al., 2019).

2.1 Hydrology

The hydrology is of importance to support a well functioning paludiculture buffer zone.
To implement paludiculture and support carbon sequestration, the area must be rewetted, and the average water table must be present near the peat surface year-round (Giannini et al., 2016; Lupascu & Wijedasa, 2021; Perrochet & Musy, 1992). Walton et al. (2020) put emphasis on the difficulty of restoring the hydrology of long-term dehydrated peatlands, due to soil degradation and subsidence. Degraded peatland show a significant increase in hydrophobic groups compared to natural peatlands, making it more difficult to restore peatlands to their original state by rewetting (Maftu'ah, Fahmi, & Hayati, 2019). Furthermore, instead of relying on groundwater, these former peatlands are now fed by rainwater or are flooded by adjacent surface water bodies, as they became isolated from the natural groundwater flow. Rewetting a peatland for restoration purposes may create a new hydrological system; instead of being restored to its original hydrology (groundwater fed), these areas may be fed by a mixture of rainwater, groundwater, and surface water (Walton et al., 2020). Therefore, it is important to consider that these rewetted former peatlands will act differently than pristine peatlands. One of the methods to obtain and maintain a local suitable hydrology is by managing the water level in the buffer zone. The water

level can be tracked using water logger technology, such as piezometers and observational benchmarks. The blocking or opening up of waterways, or using water pumping techniques are methods to maintain the desired water level (Budiman et al., 2020; Karki et al., 2014). Managing the water level is important to maintain the optimal conditions for life in these paludiculture buffer zones. Geurts et al. (2020) support this idea by stating that managing the water level is not only important for the paludicrops growing in these wet anaerobic buffer zones, but also for supporting denitrifying microorganisms, and therefore increasing the nitrogen removal capacity. Buffer zones acting as water retention areas may have fluctuating or higher water levels during times with heavy precipitation. In times of drought, the water level may be lower. To account for these fluctuations, paludicrops that can withstand these fluctuations should be chosen. However, a balance between the optimal water level for the paludicrops and water retention capacity should be made to optimally utilize the obtained ecosystem services.

2.2 Nutrients

The conditions in a buffer zone must be balanced for optimal productivity and nutrient removal by paludicrops. Paludiculture is implemented in buffer zones to extract excess nutrients from nutrient mobilization after rewetting and fertilizer runoff. However, rewetting and harvesting activities can also lead to changes in nutrient availability. The limiting nutrient for the growth of paludicrops is often nitrogen. After rewetting, denitrification increases, and nitrogen will be lost to the atmosphere as N_2 (Walton et al., 2020). Nitrogen deficiencies limit biomass production and can therefore strongly decrease the ability to remove nutrients (Geurts et al., 2020; Hou, Chen, McGroddy, & Wen, 2012). This is not likely to take place in paludiculture buffer zones, as they will often be situated near agricultural land, with a lot of nitrogen runoff. In addition, some crops can fixate nitrogen themselves to prevent nitrogen limitation, such as *Typha latifolia* (cattail) (Biesboer, 1984). Especially *Azolla* (water fern) is an efficient nitrogen fixator (Talley, Talley, & Rains, 1977). Phosphorus will most likely not be a limiting factor, as phosphorus gets mobilized after rewetting of former agricultural peat soils and may also be present in farm runoff. Other nutrients, such as potassium are not affected by rewetting. However, summer harvesting could potentially lead to deficiencies (Geurts et al., 2020). Excess nutrients are more likely to cause problems than nutrient deficiencies. Excess nutrients can lead to eutrophication and algae growth, that can outcompete seedlings for light (Christen & Dalgaard, 2013; Geurts & Fritz, 2018; Zak et al., 2019). It is therefore important to keep a balance between nutrient input and output; excess nutrients can cause undesirable effects to the surrounding areas and may inhibit the growth of seedlings, but nutrient deficiency can negatively affect plant productivity and nutrient removal capacity. This could be solved by taking water samples regularly and calculating the total in and output. Based on these results, the landowner could choose to make changes to change the balance of nutrient input and output. Apart from nutrient availability, pH can also affect the growth of paludicrops in buffer zones. Many paludicrops, such as *T. latifolia* and *Phragmites australis* (common reed) can grow at a wide pH range. However, at a soil pH below 4 to 4.5 the growth and productivity will be negatively affected, as nutrient uptake and cation supply by the roots will be diminished. Especially *P. australis* is sensitive to a low soil pH, due to the accumulation of ammonium (Geurts & Fritz, 2018). Therefore, soil pH should be measured to make sure the pH does not drop too low, and plant productivity is maintained.

2.3 Size

Size is an important aspect to consider for these paludiculture buffer zones to function well. Quite some literature on riparian buffer zone size for rivers and streams was available, such as a review by Barling & Moore (1994). This review suggested a buffer zone size of 20 to 30 meters for rivers. However, riparian buffer zones for rivers tend to fulfill other roles than the buffer zones discussed in this paper, and therefore it is highly unlikely that the sizes presented in these papers will be accurate (Barling & Moore, 1994). Apart from riparian buffer zones for rivers, there was limited literature found covering buffer size. However, a paper by Miettinen et al. (2012) specifically focuses on buffer zones in the form of unharvested riparian zones between clear cut areas and receiving waterbodies, such as small streams, to reduce nutrient loading and increase biodiversity benefits. Miettinen et al. (2012) extended the traditional Faustmann (1849) rotation model by including biodiversity benefits and the effect of nutrient loading to watercourses to find out the optimal buffer zone size. For this model, they consider societal values (harvest revenue, water quality, and biodiversity). For the specific size of 4% of the total area they included both biodiversity benefits and reduction of nitrogen loading; if only nitrogen loading was considered, it was not worth having a buffer zone. Therefore, this paper highlights the importance of having multiple positive effects on deciding whether a buffer zone is worth having, when considering societal values. However, this paper focusses on forests providing timber and amenity services for society. This differs greatly from paludiculture in buffer zones, as in the paper by Miettinen et al. (2012), the creation of a buffer zone to meet the requirements concerning water quality and biodiversity decreases the harvest revenue, whereas paludiculture does generate revenues and acts as a buffer itself (Geurts et al., 2020; Geurts et al., 2019;

Jabłońska et al., 2020). Therefore, concerning their model, the buffer zone may be smaller than the stated 4% when including paludiculture and still fulfill the societal values, as revenues will be generated. On the other hand, the paludiculture buffer zone may be larger than the given 4%, as the biomass production in paludiculture buffer zones generates income and landowners may decide to dedicate more land to paludiculture. This however makes it difficult to determine what size a paludiculture buffer zone should ideally be, as the 4% most likely does not accurately describe the size of a paludiculture buffer zone.

Perrochet and Musy (1992) also tried to find out the optimal buffer zone size. The paper emphasized the importance of having a large enough buffer zone to prevent water levels in natural areas from being affected by drained agricultural land, but not using too much valuable agricultural land. However, instead of giving a single percentage or value for the optimal buffer zone size, they provided the reader with a formula. The final optimal buffer zone size depends on many factors, including rainfall, drainable porosity, soil profile, boundary conditions and so forth. However, they did not consider biodiversity benefits like the Miettinen et al. (2012) paper. As there is little literature covering the optimal buffer zone size, it is suggested that further research is needed to accurately describe the optimal buffer size, especially in combination with paludiculture. This kind of research, or model, would need to consider multiple aspects that Miettinen et al. (2012) and Perrochet and Musy (1992) included, but additionally other factors such as the revenue generated, the minimal and optimal buffer zone size for the growth and harvest (including the use of machines) of specific paludicrops and the filtering capacity of specific paludicrops.

3. What paludicrops should be grown in multifunctional buffer zones, depending on their requirements and products?

There is ample literature covering different types of paludicrops and their uses available. However, literature has not focused on applying polyculture in paludiculture buffer zones to benefit biodiversity and ecosystem functioning. To answer this question, different crops were compared to discover whether certain paludicrops could be grown in the same buffer zone simultaneously, depending on their individual treatment requirements and without diminishing their individual benefits. In addition, the benefits of a natural mixed vegetation will be discussed.

3.1 T. latifolia and P. australis

3.1.1 Applications and stand age

T. latifolia and *P. australis* have similar applications. This includes being used for insulation purposes and building material, extraction of protein, fibers and cellulose, and combustion (Geurts et al., 2019). *T. latifolia* and *P. australis* are particularly suitable for bioenergy, due to their high biomass production and high nutrient concentrations (Ren et al., 2019). The stand age for *P. australis* and *T. latifolia* is an important factor for biomass production, application, and nutrient buffering. Older stands of at least three years had a maximum aboveground biomass production and nutrient removal two to three times higher than younger stands of less than three years. Even older stands, of more than five years old, produced a higher aboveground biomass and removed more nutrients, including phosphate, nitrogen and potassium (Geurts et al., 2020).

3.1.1 Harvest period and frequency

Both species can be harvested throughout the year but depending on the harvest period and frequency, the biomass quality may vary, and different applications are possible for the paludicrops. This includes the nutrient removal efficiency and the vitality of the plant. Geurts et al. (2020) state that *P. australis* is sensitive to summer harvest and can reduce biomass production rates in later years. *P. australis* could therefore be harvested in October instead when nutrients have been transported to the rhizomes, preparing the plant for regrowth in the spring (Geurts et al., 2020). This contradicts the results obtained by other studies. An experiment conducted by Dragoni, Giannini, Ragaglini, Bonari and Silverstri (2017) states that a summer harvest of *P. australis* is the most feasible option (Dragoni, Giannini, Ragaglini, Bonari, & Silvestri, 2017). In addition, Giannini et al. (2016) states that later harvests do not improve the biomass quality (Giannini et al., 2016). However, these experiments were conducted in Italy. Giannini et al. (2016) state that harvests in northern Europe did show improved biomass quality. This may be due to the climatic conditions; in colder climates the nutrient content is reduced, which is not the case in milder and frost free winters in a Mediterranean climate (Giannini et al., 2016). In addition, Geurts et al. (2020) focus on vitality and biomass production in later years, whereas Giannini et al. (2016) puts emphasis on biomass quality. Depending on the aim of the paludicrop, different harvesting periods may be chosen. Considering this review focuses mainly on northwestern Europe, the results by Geurts et al. (2020) are considered most reliable.

Therefore, it is beneficial to harvest *P. australis* once a year in October to prevent lower production rates in subsequent years. An experiment by Toet, Bouwman, Cevaal and Verhoeven (2005) showed that the vitality of *T. latifolia* and *P. australis* was not affected by annual harvesting of the shoots in October over two years (Toet, Bouwman, Cevaal, & Verhoeven, 2005).

The final product is often an important factor for landowners. Depending on the objective of the paludiculture buffer zone a harvest period can be chosen. The summer biomass is suitable for biogas or fodder production and optimizes the biomass production and nutrient uptake for *T. latifolia. P. australis* biomass production remained stable until October (Geurts et al., 2020). A winter harvest of *P. australis* and *T. latifolia* after a frost period can provide biomass suitable for insultation and building purposes due to the low water content, and benefits biodiversity the most (Geurts & Fritz, 2018; Joosten, Gaudig, Tanneberger, Wichmann, & Wichtmann, 2016). Even though biomass production will be lowered 30 to 50% compared to a summer harvest, nutrient removal rates will remain reasonably high, particularly for *T. latifolia* (Geurts et al., 2020). Harvesting does not have to be limited to once a year. In case the nutrient availability is high and nutrient removal is the objective, harvesting can be done more often. However, a high degree of maintenance, such as harvesting multiple times a year, may limit regrowth and disturb the system. Geurts and Fritz (2018) found that harvesting the green biomass of *T. latifolia* three times in ten months negatively affected the regrowth in spring, which might limit carbon and nutrient transfer to their rhizomes. For ecosystem functioning purposes, harvesting may be limited, to allow for natural processes to take place. A paper by Wichtmann and Wichmann (2011) states that maintenance can destroy breeding habitats, and therefore harvesting may be limited to outside breeding seasons of species that are present in the paludiculture buffer zone (Wichtmann & Wichmann, 2011). Therefore, depending on the objective, landowners may decide to focus on biodiversity and harvest once during the winter. On the other hand, the focus may lie on nutrient removal, and in this case the harvest may take place multiple times a year, and/or during the summer months.

3.1.2 Maintenance

To maintain sustainable yields *P. australis* and *T. latifolia* should be harvested above the water table, to preserve oxygen flow to the roots and rhizomes to prevent the decay of the plants caused by anaerobic processes. After harvest, it must be made sure that any excess plant biomass is removed. Jabłońska et al. (2020) state that any plant biomass that is left to decompose may reduce the nutrient removal capacity due to increased decomposition, and recycling of plant-incorporated nutrients back to the paludiculture buffer zone (Jabłońska et al., 2020). However, not the entire plant should be removed. To preserve peat, the belowground biomass should be left intact to reduce soil disturbance (Geurts et al., 2019), to provide a surface to serve as substrate for microbes and to enhance belowground aerobic processes (Meng, Hu, Pei, Hou, & Ji, 2014). In addition, leaving a source of carbon is important to keep the microbial community active. Denitrifying bacteria need a source of carbon to support nitrogen removal from the system (Jabłońska et al., 2020; Zak et al., 2019). Therefore, leaving belowground biomass can both help in peat preservation and enhancing denitrification.

3.1.3 Nutrient uptake efficiency

Nutrient uptake efficiency was shown to be similar for *P. australis* and *T. latifolia.* These crops can take up substantial amounts of nitrogen and phosphorus, whilst sequestrating carbon. Parde et al. (2021) showed that *P. australis* and *T. latifolia* took up 70% of the nitrogen and phosphorus present in a constructed wetland (Parde et al., 2021). Tanner (1996) showed an uptake of 79 to 93% of the total phosphorus, and 65 to 92% of the total nitrogen, and showed a positive linear correlation with the biomass production. Geurts et al. (2019) also found that the nutrient uptake almost linearly increased with higher biomass production. However, they found that the removal of phosphorus and potassium, and biomass production slightly differed for *P. australis* and *T. latifolia*, with *T. latifolia* taking up more of these nutrients and showing a higher biomass production. This suggests that *T. latifolia* may be a more efficient paludicrop than *P. australis* regarding nutrient removal and biomass production (Geurts et al., 2020; Rezania et al., 2019). However, in a constructed wetland experiment by Meng et al. (2014) *P. australis* and *T. latifolia* removed a similar amount of nitrogen, but *P. australis* extracted more nitrogen than *T. latifolia*. Literature shows that the nutrient uptake efficiency seems to greatly vary in different studies, and therefore it may be difficult to determine which species is more efficient and may benefit water purification the most (Meng et al., 2014).

In a wetland mesocosm experiment by Tanner (1996), the efficiency of nutrient removal was investigated for several plant species, including *P. australis*. Tanner (1996) found that at higher nutrient concentrations, the efficiency in nutrient uptake and use in the form of biomass production decreased (Tanner, 1996). Therefore, depending on the nutrient concentration in the paludiculture buffer zone, the nutrient uptake and nutrient use of the paludicrops may differ. At locations or times when the nutrient availability is low, *P. australis* may be a more suitable candidate due to its higher nutrient use efficiency. In addition, *P. australis* is more suitable in the long term, as it will sequester more carbon and reduce greenhouse gas emission, due to its peat forming abilities, than *T. latifolia* in the long-term (Geurts et al., 2020).

3.2 Azolla

Azolla lives in symbiosis with a nitrogen fixating bacterium, like *Sphagnum*, allowing it to thrive even in nitrogen poor conditions (Costa, Santos, & Carrapiço, 2010; Shiomi & Kitoh, 1987). Higher biomass production is observed when phosphorus concentrations exceed nitrogen concentrations. In an experiment by Costa, Santos, Carrapiço, and Pereira (2009) *Azolla* removed 40 to 65% of the phosphorus in an urban wastewater treatment. Due to its nitrogen fixating ability the nitrogen absorption capacity of *Azolla* is lower than other paludicrops (Shiomi & Kitoh, 1987). *Azolla* has a wide variety of applications, such as green manure or fertilizer (Costa et al., 2010; Slagter, 2017). Due to its high protein and crude fat content, and low cellulose and lignin content it is suitable to be used as feed supplement for animals (Costa et al., 2010; Shiomi & Kitoh, 1987). *Azolla* is sensitive to high ammonium concentrations, which inhibits growth and nitrogen fixation (Costa, Santos, Carrapiço, & Pereira, 2009). Therefore, ammonium concentrations should be kept low to ensure optimum *Azolla* growth.

3.3 Sphagnum

Sphagnum (peat moss) is a fast growing plant that has a high nutrient removal capacity. *Sphagnum* biomass can be used as a high quality renewable substitute for fossil peat in horticulture growing media, therefore reducing peat extraction (Geurts & Fritz, 2018; Geurts et al., 2019; Joosten et al., 2016; Temmink et al., 2017; Vroom et al., 2020). The cultivated *Sphagnum* replaces the need to harvest slightly decomposed *Sphagnum*, or white peat, from peatlands (Günther et al., 2017; Wichmann et al., 2020). *Sphagnum* can be used to restore degraded peatlands and their hydrology, by effective sequestration of carbon and due to its water storage capacity. Carbon sequestration leads to lower greenhouse gas emissions. *Sphagnum* additionally supports ecosystem functioning through harboring characteristic fen plants and fungal species (Geurts & Fritz, 2018). Biomass can be harvested throughout the year (Joosten et al., 2016). *Sphagnum* can form a thick layer on former agricultural soil with nutrient rich fossil peat within 3.5 years (Riet, Elzen, Hogeweg, Smolders, & Lamers, 2017). However, harvest using heavy machinery may disturb the peatland community and limit *Spagnum* growth (Fenton & Bergeron, 2007), and therefore may limit ecosystem functioning (Geurts & Fritz, 2018).

3.4 Alnus and Salix

Alnus (alder), a tree species, may be planted in these buffer zones for timber production (Geurts et al., 2019; Joosten et al., 2016). *Alnus* has a high nutrient uptake efficiency. Due to its symbiotic relationship with arbuscular mycorrhizal fungi, this species is facilitated in acquiring nitrogen and phosphorus from its surroundings (Monzón & Azcón, 2001). Mander, Kuusemets, Lõhmus, and Mauring (1997) found that the nitrogen and phosphorus removal was 80 to 81% and 67 to 81% respectively. The trees are harvested at time intervals of approximately every ten to 15 years, with an optimum harvesting time during the winter frost (Joosten et al., 2016).

Salix (willow) is another tree species that could be implemented in the paludiculture buffer zone. This paludicrop provides timber, and can be used for combustion purposes (Giannini et al., 2016; Joosten et al., 2016). *Salix* can be harvested every four to five years, producing biomass for bioenergy production. *Salix* is an efficient paludicrop, that can take up substantial amounts of nitrogen and phosphorus, resulting in high biomass production (Perttu & Kowalik, 1997). In a study by Shi et al. (2016) *Salix* extracted 82 to 88% of the nitrogen and 57 to 66% of the phosphorus present in a phytoremediation wastewater study (Shi et al., 2016). *Alnus* and *Salix* are beneficial for biodiversity and improve ecosystem functioning in the buffer zone by nutrient uptake, providing shade and supporting stabilization of the buffer zone's bank. Furthermore, the growth of trees can help stimulate nutrient removal by supporting denitrifying microorganisms, by providing a carbon source used as electron donor (Zak et al., 2019).

3.5 Natural vegetation

Natural vegetation may spontaneously grow in the buffer zones, as some species can withstand high water levels, ranging from -30 to ten cm above the soil surface. Completely eradicating natural vegetation may be difficult due to their fast growth. Instead, the natural vegetation, such as various types of grasses, including *Phalaris arundinacea* (reed canary grass), may be left to grow in these buffer zones to reduce the cost and time dedicated to maintenance. The natural vegetation has relatively few applications, but could still be utilized as fodder for livestock, for combustion or biogas production (Geurts et al., 2019). Having more natural vegetation mixed in with the other paludicrops enhances the biodiversity of the buffer zone, and may improve ecosystem functioning (Balvanera et al., 2006).

3.4 paludiculture-buffer zone design and polyculture

Creating a heterogeneous design of the paludiculture-buffer zone can accommodate for the different required water depths and harvest methods or frequencies depending on the paludicrop. Creating different depths can help grow different paludicrops with different water depth requirements within the same paludiculture buffer zone. Depth can be created by digging deeper at some locations in the paludiculture buffer zone and keeping some parts shallower by leaving sediment. Keeping the paludicrops spatially separated can help overcome harvest difficulties or prevent interspecific competition.

3.4.1 T. latifolia and P. australis

T. latifolia can be grown in a wide range of water levels, ranging from zero to 20 cm above the soil surface. *P. australis* has a wider water level range of -20 to 20 cm above the soil surface (Geurts et al., 2019). This would mean that the optimum water level in a buffer zone containing both (adult) species would be between zero to 20 cm above the soil surface. Providing stable water levels within this range is essential for fast and healthy plant growth, to obtain a high density of *P. australis* and *T. latifolia*. Water saturation additionally supports anaerobic denitrifying microorganisms in the removal of nitrogen from the buffer zone by lowering the oxygen availability (Jabłońska et al., 2020). However, in case of extremely high water levels or drought, both species, and in particular *P. australis* can survive. Wet conditions are necessary for germination and to prevent peat oxidation, but water levels should not be above five cm above the soil surface for seedlings. Therefore, the water level may have to be regulated, depending on the age of the paludicrop, by using active irrigation and farming pumps (Geurts & Fritz, 2018).

3.4.2 Azolla

Azolla requires a water depth of five cm above the soil surface or more, but will survive for only a few days in dry conditions, and only grows when floating on water (Slagter, 2017). Regarding the required water level of five cm above the soil surface, *Azolla* could be grown together with the beforementioned paludicrops (Slagter, 2017). Due to its floating abilities, it can be quite easily harvested separately from the other standing paludicrops. The combination of *T. latifolia* and *Azolla* has been demonstrated by Vroom et al. (2018). *Azolla* production is beneficial, as *Azolla* can be harvested continuously to obtain high protein yields (Brouwer et al., 2018). *Azolla* doubles every two to five days, due to its very high growth rate (Hamdan & Houri, 2021). However, growing *Azolla* together with other paludicrops could reduce the growth rate of seedlings from other species, by reducing light availability. Further research needs to be conducted to support this statement.

3.4.3 Sphagnum

The optimum water level for *Sphagnum* is different to that of the other paludicrops, with the optimum water level for this species being -15 to -five cm in regards to the soil surface (Geurts et al., 2019). Furthermore, it is most likely difficult to implement *Sphagnum* with the beforementioned paludicrops. Large fast growing graminoids, such as *P. australis* and *T. latifolia* thrive on high nutrient availabilities and outcompete *Sphagnum.* At lower nutrient concentrations *Sphagnum* has a competitive advantage due to their efficient nutrient use, and nitrogen fixating abilities (Leppänen, Rissanen, & Tiirola, 2015), when the performance of vascular plants is reduced (Malmer, Albinsson, Svensson, & Wallén, 2003). However, *Sphagnum* may be shaded by the larger graminoids and may obtain less light energy necessary for photosynthesis, and therefore maintains a competitive disadvantage when grown together with *T. latifolia* and *P. australis*, especially when the nutrient availability is high. In addition, *Sphagnum* increases the acidity of its surroundings, limiting decomposition, reducing nutrient mineralization and nutrient availability for vascular plants (Malmer et al., 2003; Temmink et al., 2017). *Sphagnum* is a good ecosystem engineer, optimizing the environment for its own benefit, but also for other peatland species, and sequestrating carbon by increasing the peat accumulation rate (Malmer et al., 2003). It however reduces the optimal growing conditions for some other vascular plants, such as *P. australis* and *T. latifolia.* Additionally, a too high nitrogen input with limited phosphorus availability can result in internal ammonium poisoning in *Sphagnum*, as excess nitrogen cannot be utilized for growth (Temmink et al., 2017). Therefore, the high nutrient availability that increases biomass production in *P. australis* and *T. latifolia,* might negatively impact *Sphagnum* growth. To account for these difficulties, *Sphagnum* should be grown at a different height or water level at a separate location within the paludiculture buffer zone. This way, the different paludicrops will not outcompete each other, nor will they have to grow in a suboptimal water level.

3.4.4 Alnus and Salix

Alnus can withstand a wide range of water levels ranging from -40 to five cm above the soil surface (Geurts et al., 2019). However, this does indicate that compared to paludicrops such as *T. latifolia* and *P. australis* this tree species favors relatively drier conditions. Additionally, it provides different products and has a lower harvest frequency. This could complicate harvest if grown together with *T. latifolia* and *P. australis*. Therefore, *Alnus* should be grown at a different location with a different depth. The same goes for *Salix. Salix* prefers water levels to stay relatively low, as in an experiment by Geurts and Fritz (2018) *Salix* developed yellow leaves and grew less tall in higher water levels (Geurts & Fritz, 2018).

3.5 Density

Lastly, the density of the paludicrops in the paludiculture buffer zone must be considered. One problem that may occur with the consistent high water level is the development of floating algae beds due to nutrient runoff to the buffer zone, which may induce methane emissions. This particularly is the case in areas with low vegetation cover (Geurts & Fritz, 2018). Therefore, a solution may be to grow the paludicrops in a high density, to take up excess nutrients that could cause eutrophication.

3.6 Residence time and flow rate

Nutrient removal efficiency from wastewater wetlands, or buffer zones, depend among other things on the hydraulic residence time (Zahraeifard & Deng, 2011). In a field-based study in a constructed wetland in proximity to agricultural land by Ioannidou and Pearson (2019) the effects of flow rate on mixing characteristics was investigated using fluorometric measurements. This experiment showed that the residence time was affected by the flow rate. Higher flow rates caused a decline in the mean residence time. Plant growth can alter the flow velocity (Ioannidou & Pearson, 2019). However, in a dye tracer experiment by Holland et al. (2004) it was found that flow rates did not have significant effects on the residence time, but water level did instead. Therefore, when also including water level, this became a significant factor for residence time. This suggests that water level is not only important for plant requirements and denitrification, but also for influencing the residence time affecting nutrient removal efficiency (Holland et al., 2004; Zahraeifard & Deng, 2011). A decrease in the residence time negatively impacts nutrient utilization, as there is less of an opportunity to incorporate the nutrients (Uncles, Frickers, & Harris, 2003). In case we consider the results of Ioannidou and Pearson (2019), a higher flow rate decreases the residence time and therefore negatively affects nutrient uptake. In a hydroponics experiment the importance of flow rate for plant growth was investigated. An increase in flow rate benefitted plant growth by promoting ion absorption and root elongation due to physical stimulation. However, when the flow rate exceeded the ideal value, plant growth was hindered due to excessive physical stimulation (Baiyin et al., 2021). The ideal flow rate most likely varies for different species, and therefore, specific research will need to be conducted to find out the ideal flow rate for the paludicrops implemented in buffer zones.

4. How can ecosystem functions and services in buffer zones be quantified and optimized?

There are several factors that play a role in optimizing ecosystem functioning and services. To optimize ecosystem functioning and services, these factors should be quantified first.
The quantification and balancing of the functioning of a paludiculture buffer zone and the ecosystem services it provides could give landowners an indication if implementing multifunctional buffer zones is beneficial. Are there only synergies, or also trade-offs, when looking at the ecosystem functioning and services of a paludiculture buffer zone?

4.1 Nutrient removal capacity and water purification

One of the main functions of the multifunctional buffer zones is to remove pesticides and nutrients and prevent eutrophication of surrounding areas, to support a high biodiversity (Geurts et al., 2020). To measure the buffering, or nutrient removal capacity, nutrient concentrations in the soil could be measured in the agricultural land, the buffer zone with paludicrops and the nature areas (Gilley, Eghball, & Marx, 2007). The paludicrop used affects the nutrient removal capacity, as different species have different nutrient uptake efficiencies. The optimal nutrient uptake capacity should be quantified per paludicrop. Based on this information, the nutrient removal capacity can be optimized by choosing paludicrops with the greatest nutrient uptake capacity.

Additional factors including the residence time and flow rate, affect the nutrient removal capacity (Holland et al., 2004; Zahraeifard & Deng, 2011). A low flow rate increasing the residence time positively affects nutrient uptake, as plants have a greater opportunity to take up nutrients (Ioannidou & Pearson, 2019; Uncles et al., 2003). On the other hand, a higher flow rate physically stimulates roots which benefits plant growth, by increasing ion absorption and root elongation (Baiyin et al., 2021). To optimize the nutrient uptake, the balance between a high and low flow rate should be quantified.

4.2 Biodiversity

There are several types of biodiversity. Whereas alpha diversity is a measure of the local biodiversity in one habitat, beta diversity conveys the biodiversity of multiple habitats. Gamma diversity quantifies the overall diversity of different habitats in a region. Alpha diversity could be used as a measure for biodiversity in case only the biodiversity in the paludiculture buffer zone, agricultural land, or natural area or water body is measured. However, if trying to quantify the difference in the biodiversity across several habitats, beta diversity would be most suitable (Buckland, 2009).

To quantify biodiversity over time, monitor programmes could be set up. This may include taking samples in randomized plots and establishing trends (Buckland, 2009). For example, the biodiversity in surrounding agricultural land, the buffer zone and in the nature area or water body could be measured and compared. When measured before and after the implementation of the paludiculture buffer zone between agricultural land and nature areas or water body, the change in biodiversity can be measured. This would provide information on the biodiversity gain due to the implementing the paludiculture buffer zone.

Nutrient uptake reduces the risk of eutrophication and the growth of dominant fast growing species (Jabłońska et al., 2020; Shi et al., 2016; Zak et al., 2019), and thus may support a higher local biodiversity that can benefit ecosystem functioning and services (Christen & Dalgaard, 2013; Zak et al., 2019). Therefore, to optimize biodiversity, plants with a high nutrient uptake should be implemented at a high density to prevent an excess of nutrients. Additionally, the paludiculture buffer zones provide a water body that create suitable habitat for various species, including amphibians, birds, and insects (Miettinen et al., 2012; Zak et al., 2019). The paludicrops in the buffer zone provide debris, shade, and regulate the temperature to help support these populations (Correll, 2005; Miettinen et al., 2012; Sood et al., 2012). Heterogeneity in the buffer zone helps optimize biodiversity. Heterogeneity provides a greater diversity of niches for both plants and animals compared to homogeneous landscapes. This is because different species have varying requirements to thrive (Burnett, August, Brown, & Killingbeck, 1998). For example, some species may prefer a higher water level than other species. Therefore, several species of paludicrop should be grown in the same buffer zone at varying water levels, depending on their requirements.

4.3 Water storage and retention

Paludiculture buffer zones can store and retain water to help prevent drought and flood risk, and therefore help mitigate the effects of climate change and sea level rise (Zak et al., 2019).

Additionally, the buffer zone prevents significant water table fluctuations between areas of low and high moisture content. For example, the moisture content for agricultural land is usually kept low using drainage systems compared to nature areas and water bodies (Soutter & Musy, 1993).

Several factors influence the water storage and retention capacity. The water retention capacity is influenced by the soil texture, including the soil porosity, soil organic matter and silt content. The storage capacity is in turn influenced by the water retention properties of the soil and the profile thickness (Geroy et al., 2011). Furthermore, the height of the water table and deepness of the ditch affect the storage capacity (Wang et al., 2013). The water retention capacity can be quantified by taking core samples and based on this information and additional factors the water storage capacity may be quantified (Reeve, 1986).

Vegetation growing in the paludiculture buffer zone optimizes the water retention capacity, by slowing down the surface flow. Additionally, the greater the soil porosity, soil organic matter and silt content, the greater the water retention capacity (Geroy et al., 2011). Therefore, to optimize the water retention capacity, paludicrops should be planted in relatively high density to slow down the surface flow and increasing the soil organic matter. The root systems of the paludicrops additionally can increase the soil porosity (Udawatta, Anderson, Gantzer, & Garrett, 2006). To optimize the storage capacity a deeper buffer zone is suggested as there is more space for water to go to. This is because the water storage capacity of soil is influenced by its depth, and capacity to hold water (Wang et al., 2013).

4.4 Peat restoration and carbon sequestration

Low groundwater levels due to drainage practices to keep agricultural land dry had led to peat oxidation causing soil degradation (Ahmad et al., 2020; Chang et al., 2019; Geurts et al., 2020; Geurts et al., 2019; Jabłońska et al., 2020; Schröder et al., 2015). Subsequently, increased carbon dioxide and nitrous oxide emissions may occur (Querner, Jansen, van den Akker, & Kwakernaak, 2012). Quantifying these factors can help optimize peat restoration and carbon sequestration.

There are several techniques to quantify peat thickness. One involves manual probing using a metal pole, which ought to be pushed into the ground until the point of resistance. The second is the ground-penetrating radar (GPR) which is a geophysical technique that images the base of the peat (Parry, West, Holden, & Chapman, 2014). Khasanah and van Noordwijk (2019) estimated the annual rate of subsidence using metal rods. They indicated the initial point of measurement, and monitored peat subsidence over a few years. Negative values indicated an increase in peat thickness. Therefore, to find out whether peat is lost or conserved, the thickness can be measured using different techniques. Additionally, carbon dioxide emissions can be quantified to find out whether carbon dioxide is emitted or stored. Khasanah and van Noordwijk (2019) calculated carbon dioxide emissions by measuring subsidence, changes in bulk density and carbon organic content. The groundwater level, which affects both subsidence and carbon dioxide emissions can be monitored and quantified using PVC tubes (Khasanah & van Noordwijk, 2019).

Wet conditions are favorable to reduce peat oxidation and soil subsidence, and capture carbon. The groundwater levels can be raised using pumps. However, this does considerably raise the cost of maintenance. Therefore, groundwater levels may only be raised when necessary. This includes raising the water levels when a drier period is expected (Querner et al., 2012). In the paper by Querner et al. (2012), they set a water level target of ± two centimeters relative to the surface. They however decided on this level as agricultural practises took place at their location, and therefore the water level must be kept lower than for instance in a paludiculture buffer zone. For a paludiculture buffer zone the water level must depend on the optimal water level required by the paludicrops, and may therefore differ greatly compared to the results shown by Querner et al. (2012). This includes reestablishing a natural water table to restore the abiotic conditions necessary for paludicrops and peatland communities (Gorham & Rochefort, 2003). This also supports the reduction of carbon dioxide emissions, by creating anaerobic conditions (Geurts et al., 2019; Karki et al., 2014; Lahtinen et al., 2022). Additionally, the restoration of the biotic conditions, help restore ecosystem functioning in degraded peatlands (Moreno-Mateos, Power, Comín, & Yockteng, 2012). De Deyn, Cornelissen and Bardgett (2008) state that restoring conditions that slow down decomposition contributes to carbon sequestration and biomass accumulation. Furthermore, vegetation that can endure the physical conditions, such as paludicrops, can also contribute to carbon sequestration and biomass accumulation. However, variation exists depending on the plant specific traits (De Deyn, Cornelissen, & Bardgett, 2008). Therefore, to optimize peatland restoration and carbon sequestration, the water level should be restored to create anaerobic conditions reducing peat oxidation and slowing down decomposition. Paludicrops should be chosen based on their ability to endure the relatively harsh conditions and their ability to contribute to carbon sequestration and biomass accumulation.

4.5 Synergies

Paludiculture buffer zones may be profitable besides improving ecosystem functioning and providing services. Economically viability may encourage landowners to implement these buffer zones. Whether the paludiculture buffer zone is economically viable depends for one on the product obtained. A study by Wichmann (2017) found that the commercial viability of paludiculture depends on the different products obtained by the harvest of *P. australis*. Monte Carlo simulations predicted that *P. australis* harvest is most profitable when used for thatching compared to combustion or biogas production. In addition, the timing of the harvest played a role in profitability; *P. australis* for biogas production should be harvested in the summer, and in the winter for direct combustion. The paper concluded that to balance ecosystem services provided by paludiculture, subsidies are necessary (Wichmann, 2017). Wichmann et al. (2020) showed similar results, but for *Sphagnum*. Their five year field research concluded that *Sphagnum* cannot financially compete with peat to be used as growing media. However, in case it would be used for orchid cultivation at a medium to high productivity, then it would be economically viable. The most economically feasible option was to used *Sphagnum* shoots as seeding material. Wichmann, Krebs, Kumar, and Gaudig (2020) concluded that to cover the cost of replacing peat with *Sphagnum*, consumers should pay an additional fee of 10%. A large demand for renewable products, large scale implementation and setting climate targets can make *Sphagnum* farming more profitable (Wichmann et al., 2020). Therefore, depending on the final product, additional fees, subsidies, an increased market and implementation, profitability can be optimized whilst enhancing ecosystem functioning and providing services. This way, landowners do not have to sacrifice valuable land.

4.6 Trade-offs

Even though implementing paludiculture in buffer zones supports ecosystem functioning and provide services, there can also be disadvantages. Schröder et al. (2015) addressed this challenge. They found that wet soils have a limited bearing capacity, making it more difficult to use machinery in paludiculture. The bearing capacity depends on the vegetation composition and density, and the soil water content. Therefore, rewetted peat cannot hold conventional agricultural machinery. Some adaptations can be made, including using low pressure tires, smaller sized machinery or harvesting during winter (frost). However, these adaptations have disadvantages, such as reduced application for large scale harvests, being less cost efficient, and being limited by weather conditions (Schröder et al., 2015). The available machinery for the harvest may disturb peat formation, limiting the provision of ecosystem services (Geurts & Fritz, 2018). In addition, the machinery flattens the ground, reducing surface structure and soil porosity. This may alter the water storage capacity and the permeability of the soil, increasing the amplitude of water table fluctuations (Schröder et al., 2015).

Another challenge that arises when applying paludiculture buffer zones is the amount of land required. More research must be conducted on the exact buffer size necessary depending on the paludicrops grown and the prospects. Obtaining land poses an economical challenge (Kandel et al., 2020), as agriculture may provide a higher income per hectare than paludiculture, without subsidies. A survey by Ziegler et al. (2021) conveyed that the lack of economic viability forms a major barrier for the implementation of paludiculture. Dryland agriculture still outcompetes wet paludiculture (Tan, Lupascu, & Wijedasa, 2021; Ziegler et al., 2021). However, subsidies based on payments for ecosystem services arising from paludiculture could make the implementation of paludiculture buffer zones economically viable on the long term and stimulate landowners. Currently, most paludicrops do not have the status of agricultural crops and are therefore not eligible for the EU's Common Agricultural Policy (CAP) for agricultural payments. However, changes to this policy are being made, to support paludiculture implementations. Wetlands International (n.d.) states that the European Parliament and Council have recognized paludiculture as an agricultural activity and eligible hectares in the CAP. In addition, in the Netherlands ecosystem services are rewarded for some forms of nature inclusive agriculture. For paludiculture, this could include rewarding reduced greenhouse gas emissions (carbon credits), water purification and other ecosystem services (Geurts et al., 2019). Rising energy prices, progress in processing biomass and higher costs to prevent rising water tables will help paludiculture compete with conventional agriculture. However, policies and laws will ultimately determine the profitability of paludiculture (Wichtmann & Wichmann, 2011). Due to these limitations, ecosystem functioning, and services provided by paludiculture buffer zones may be hampered.

5. Conclusions and future perspectives

The main question focused on how paludiculture can be introduced to multifunctional buffer zones between agricultural land and nature to improve ecosystem functioning. Buffer zones can be positioned on degraded peatland between agricultural land and nature. The intended buffer zone can be rewetted and paludiculture can be implemented improving ecosystem functioning and services such as peatland restoration, carbon sequestration, removing excess nutrients, enhancing biodiversity, and acting as water storage and retention areas. Additionally, buffer zones are implemented to act as a transition strip between dry and wet areas, to avoid significant changes in water table fluctuations in moisture sensitive areas. Paludicrops can produce valuable biomass, and therefore may provide a financial benefit to the landowner.

Certain requirements, including hydrological conditions, nutrient levels and buffer zone size are important for a well functioning paludiculture buffer zone. The optimal water table must be near the peat surface year around, to keep the area wet for paludiculture, to sequestrate carbon and to maintain optimal conditions for denitrifying microbes. To balance between the optimal water level for paludicrops and the water retention capacity, water logging technology, drainage and opening waterways must be considered. However, fluctuations throughout the year are unavoidable and therefore paludicrops that can withstand these fluctuations should be chosen. Restoring the original hydrology may however be difficult, due to soil subsidence and peat degradation. The conditions in the buffer zone must be monitored and balanced for optimal productivity and nutrient removal by the paludicrops. There is limited literature about the required buffer zone size and additional research must be conducted to determine the optimal buffer zone size.

Depending on the objective of the landowner different paludicrops and practices may be implemented. The paludicrop and harvest period affect the product obtained from the paludiculture buffer zone. Frequent harvesting may increase the nutrient removal capacity but may limit regrowth and disturbs the system affecting ecosystem functioning. Maintenance is important to reduce decomposition and the recycling of nutrients back into the paludiculture buffer zone. On the other hand, belowground removal of biomass may disturb the system and removes carbon necessary for denitrifying bacteria.

There are various species of paludicrop, some of which can be grown together based on their requirements. Additionally, natural vegetation may spontaneously grow in the buffer zones, as some species can withstand high water levels. Completely eradicating natural vegetation may be difficult due to their fast growth. Instead, natural vegetation may be left to grow in these buffer zones to reduce the cost and time dedicated to maintenance, and to support ecosystem functioning. Creating a heterogeneous design of the paludiculture buffer zone can accommodate for the different required water depths, harvest methods or frequencies and to overcome interspecific competition. The heterogeneous design supports the implementation of a polyculture in the buffer zone, which increases the biodiversity and benefits ecosystem functioning. To investigate the practicality of a heterogeneous design and implementing a polyculture in buffer zones, field research must be conducted. The residence time and flow rate affect the nutrient removal efficiency and should be optimally balanced. The ideal flow rate most likely varies for different species, and therefore, specific research will need to be conducted to find out the ideal flow rate for the paludicrops implemented in buffer zones.

Finally, it was discussed how ecosystem functioning and services, including the nutrient removal capacity, biodiversity, water storage and retention, and peat restoration and carbon sequestration can be quantified and optimized. Quantification includes taking field samples and setting up monitoring programmes. Optimizing ecosystem functions and services may focus on choosing paludicrops based on nutrient uptake capacity, implementing a heterogeneous buffer zone design with a polyculture, planting paludicrops in a high density, and restoring and optimizing the (a)biotic conditions. Synergies and trade-offs were additionally discussed. Without subsidies, paludiculture is still less profitable than conventional agriculture, which may be a barrier to landowners. Changes in policies and laws, increased market demand, subsidies, payments for ecosystem services, product certificates, and additional fees can make paludiculture more profitable and lower the barrier to implementing paludiculture buffer zones.

For future perspectives, more specific details on the application and profitability are necessary to encourage landowners to implement paludiculture buffer zones between agricultural land and nature to improve ecosystem functioning. The quantification, optimalisation and changes in policies and laws to reduce trade-offs and benefit synergies may help landowners in their decision and implementation of paludiculture buffer zones. Therefore, more research needs to be conducted on this topic. Lastly, education on the societal benefits and how to implement a paludiculture buffer zone can encourage landowners.

6. Rebuttal

Comment and rebuttal: Several comments made by Jeroen Geurts were about the reference style. He mentioned that I should limit the number of names, e.g., using 'et al.' instead of + three names. However, I decided to not implement this comment as the style I used, APA 6, only abbreviates the author names to 'et al.' if the number of names is more than five. For papers with more than five authors, I did shorten it to 'et al.'. Additionally, APA 6 only mentions the five authors once; afterwards, it is shortened to 'et al.'.

Comment: "Je begint hier met losse soorten, dan een kopje maintenance, dan natural vegetation, dan trees en dan weer losse soorten. Als Maintenance bij T.latifolia en P.australis hoort, dan zou het een subparagraaf moeten worden. Kun je misschien met nummers werken, waardoor je dat duidelijker kan aangeven? Geldt ook voor de rest van de review. Dus verschillende niveaus: hoofdstuk 1, 2, 3, etc. sectie 1.1, 1.2, 1.3 etc en daaronder evt. 1.1.1. etc. (of kopjes zonder nummer). Dit komt de structuur ten goede denk ik."

Rebuttal: One of the biggest changes I have made after receiving the feedback is the structure and layout. I decided to include a table of contents and make use of sub paragraphs to improve the layout and I shifted and altered pieces of text to make them fit better and improve the structure.

Comment: "Zoals ik eerder opmerkte, miste ik dit toen je het over CO2 en N2O emissies na vernatten had. Past dit stuk daar dan niet beter? Ik vind het hier aan het eind in elk geval niet zo passen."

Rebuttal: Another change, which relates to structure, is removing the piece of text about methane from the last sub-question and moving this to the introduction, where I discuss greenhouse gasses. Jeroen Geurts mentioned that methane fits better in the introduction where carbon dioxide and nitrous oxide emissions are discussed, and I agree. This way, I thoroughly discuss each greenhouse gas in the same section, which is less confusing than discussing them in separate sections.

Comment: “Wat ik een beetje mis in je verhaal is dat je een bufferzone zo inricht dat je verschillende hoogtes creëert en dus verschillende waterhoogtes. Dan kun je deze bomen op de wat hogere stukken zetten bijvoorbeeld.”

Rebuttal: I decided to incorporate this comment by including a section on buffer zone design, which discusses the reason for creating a heterogeneous design to accommodate for the different required water depths and harvest methods or frequencies depending on the paludicrop.

Comment: “Schrijf eerst over hoe je de functies en diensten kwantificeert en daarna hoe je ze optimaliseert, waarbij je onderscheid maakt in synergies en trade-offs…verder ga je alleen (beperkt) in op het kwantificeren van nutrient removal, maar doe je dit niet voor water vasthouden, water bergen, biodiversiteit”

Rebuttal: I struggled quite a lot with answering the last sub-question, as I did not know how to tackle and structure this question. However, after the feedback I decided to first structure the text better and based on the new (sub-)headings I altered and restructured the text. After this, I went more into depth about how to quantify and optimize ecosystem functioning and services. I discussed additional factors of ecosystem functioning and services, such as water retention and storage capacity, and biodiversity.

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