Comparing pond creation and restoration for biodiversity conservation in a British agricultural landscape

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BA/BSc Geography

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Abstract

There is a growing recognition that pond conservation is extremely valuable for preserving freshwater biodiversity across lowland agricultural regions. However, there is much debate about the most effective way to manage ponds to maximise landscape-scale biodiversity. The dominant approach in the UK is to create new ponds and allow old ponds to be lost to terrestrialisation. However, a method which has been subject to more study in recent years is pond restoration, which involves de-shading and de-silting old ponds to reset succession. At present, the relative merits of both management strategies are little known, including their effectiveness over longer timescales across lowland agricultural regions. This study takes place across Broad Oak Farm, Brights Farm, Earlsway Farm, Wyken Hall Farm, Black Bourne Valley Nature Reserve and Ilketshall St Andrews Commons, which are all located in Suffolk, England. These regions have a high density of ponds that have been rotationally managed by the Suffolk Wildlife Trust using both pond creation and restoration. To determine the consequences of created and restored ponds on biodiversity, macrophytes for both types of ponds were surveyed across three 'time since management categories': 1-2 years, 3-7 years and 8-12 years. The results show that created and restored ponds each give rise to different aquatic plant communities across each time period, suggesting that both types of management can enhance landscape biodiversity. However, restored ponds contributed considerably more species to the landscape as well as more rare and unique macrophytes. This was likely influenced by long-lived seed banks in the sediment of the old restored ponds which can bring back many rare aquatic plants that had colonised prior to terrestrialisation. This suggests that although pond creation is important, pond restoration should certainly not be neglected and deserves greater recognition with the UK conservation agenda.

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Preface

The main reason I was drawn to a geography degree was because of my keen interest in biodiversity conservation which had stemmed from my love of nature and visiting national parks. Therefore, during my time at UCL I particularly enjoyed learning about ecology and biodiversity in modules such as ‘Ecological Patterns and Processes’ and ‘Global Environmental Change’. However, I was struck by a common theme during my learning which was the impact of anthropogenic change on the environment and how biodiversity is being lost across the globe. Therefore, I was motivated to undertake a project for my undergraduate dissertation related to biodiversity conservation, as I knew I wanted to play a part in helping to prevent species loss.

When I met Carl Sayer, who eventually became my supervisor for this project, I was immediately drawn to his work on freshwater conservation. I learnt how freshwater ecosystems are some of the most threatened regions on earth due to anthropogenic activities such as pollution, habitat loss and introduction of alien species. I was particularly fascinated by Carl’s work on pond conservation and the huge biodiversity potential of these small waterbodies in agricultural regions. When discussing pond conservation with Carl, he told me how for many years he had been fighting to get pond restoration to be given greater priority within agricultural conservation agenda in the UK. Pond restoration is a management strategy which involves removing the organic matter and overgrown trees from old terrestrialised ponds in order to reset succession. At present, the work conducted by the Norfolk Ponds Project and UCL Pond Restoration Research Group has shown the great potential of pond restoration to give rise to a large diversity of aquatic, semi-aquatic and terrestrial species across lowland agricultural regions. Given that there is a huge number of terrestrialised ponds within farmland regions due to the neglect they faced following agricultural intensification, restoration seems like a very efficient way to preserve biodiversity. However, at present the most common method for managing ponds in the UK is to allow old ponds to undergo succession and dig new ponds to replace them. Therefore, we decided that it would be interesting to compare both these methods of pond management, pond creation and restoration, to assess how their compare in terms of practicality, efficiency and effectiveness when it comes to conserving biodiversity. There are no studies comparing these two management strategies so I hope my research in this area could help to better inform pond management.

I was fortunate thanks to Juliet Hawkins and the Suffolk Wildlife Trust to be able to undertake this research across the Suffolk countryside, the region where I grew up and call home. Having a personal connection to my field location has really helped me to understand how biodiversity can be improved across the agricultural landscapes in my local area and appreciate the importance of freshwater management for wildlife.

1. Introduction

1.1. Freshwater biodiversity

Freshwater ecosystems are some of the most biodiverse regions that exist, supporting over 10% of all species on earth, despite only accounting for around 0.8% of the worlds surface (Strayer and Dudgeon 2010). These systems contain an extraordinary array of aquatic life, whilst also providing important ecosystem services to human societies (Dudgeon *et al.* 2006). However, over the last century freshwaters have become some of the most endangered ecosystems in the world with recorded declines in biodiversity on a scale far greater than observed for marine and terrestrial systems (Sala *et al.* 2000). The scale of the problem has been identified across many national contexts such as in Britain, where 90% of wetland habitats have declined, placing over 10% freshwater species at risk of extinction (The Wildlife Trusts 2021). The main threats to freshwater biodiversity in the UK have come from the anthropogenic alternations of natural landscapes through habitat degradation, overexploitation and water pollution (Williams *et al.* 2010). This damage has been acknowledged in UK conservation legislation, such as the Water and Resources Act 1991 and more recently The Water Environment Regulations 2003, that aims to improve the quality of freshwaters. Although declines in biodiversity have been recorded across the whole aquatic landscape, these legislative frameworks are almost exclusively focused on the protection of larger waterbodies such as lakes and rivers, and much less so on small waters such as ponds, ditches and springs (Mainstone 2017).

1.2. Conservation value of ponds

There has been a great interest in protecting larger waterbodies in both the scientific literature and environmental protection, which has meant the biodiversity potential of smaller freshwaters has often been overlooked or assumed to be inferior to their larger equivalents (Davies *et al.* 2008). This is likely due to the greater perceived socio-economic value of rivers and lakes resulting from their different uses such as food and water supply, drainage, navigation and recreational activities (Boix *et al.* 2012). Although there has been less research on smaller waterbodies, recent studies suggest that they could provide a disproportionately large contribution to aquatic biodiversity compared to larger freshwaters, particularly ponds which have shown a high between-site variability in their species composition (Williams *et al.* 2004). The high biodiversity of ponds is largely due to the greater heterogeneity in the physio-chemical and habitat characteristics between these small waterbodies which often results in them having a higher species richness per area than larger freshwaters (**Fig. 1**) (Williams *et al.* 2004). Consequently, ponds can make a significant contribution to regional biodiversity, and in the UK they have been shown to support over two-thirds of all native aquatic plants and animals, including many which are rare and of high conservation priority (Williams *et al.* 1997). Therefore, over the last decade the number of published studies on pond conservation has risen rapidly, suggesting ponds could be part of the solution to declining freshwater biodiversity, although one which has not yet been fully exploited (Janssen *et al.* 2018).

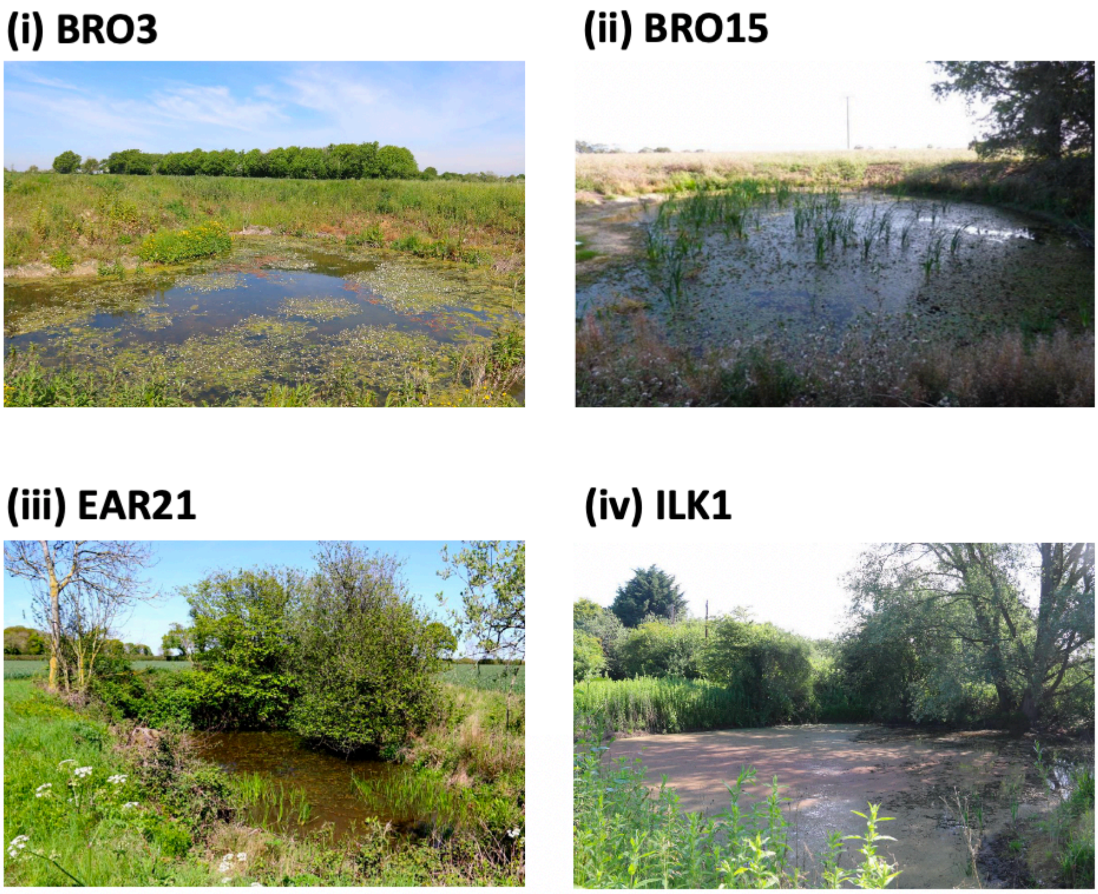


Figure 1. Showing the heterogeneity in the habitat characteristics and surroundings of four ponds that were used in this Suffolk ponds study (Photo credits ©Juliet Hawkins).

Ponds are small bodies of freshwater which can range in size from 1 m^2 to 2 ha, that can be ephemeral or permanent, and can have various origins (Biggs *et al.* 2005). Many ponds can occur naturally in the environment, such as 'kettle holes' which date back many millennia to when they were formed following the previous glaciation (Lischeid *et al.* 2018). Typically, these ponds are small and shallow, unconnected to a stream network and are commonly found in high densities across upland regions (Goldyn *et al.* 2015). Ponds can also be man-made, although many were not originally created for conservation. These include bomb-crater ponds, which have been created by military activities over the last century and occur all over the world (Vad *et al.* 2017). As wartime scars, these ponds have typically been subject to infilling and grassland rehabilitation measures, although given their potentially high biodiversity value more recent efforts have focused on their conservation (Vad *et al.* 2017). More commonly, man-made ponds are found across the lowlands of Europe, particularly in Britain, where historically they have had various uses in agriculture (Prince 1962). Many of these ponds in lowland England originated as marl pits (that subsequently became ponds), dug between the 17th to the early 20th century to extract marl, a valuable soil improving agent that was spread on nearby fields (Prince 1962). These ponds also had various other uses in villages from field drainage and water storage to cattle watering and stocking with fish (Upex 2004). Marl-pit ponds existed on the rural landscape at a time before widespread mechanisation and the intensification of agriculture, where farmers fields comprised of species rich grasslands and wildflower meadows that were grown to feed livestock (Riley 2005). These small man-made ponds can therefore be found in dense networks in current and former farmland areas and on common land across Britain.

In species poor environments, such as intensively cultivated agricultural landscapes, ponds could be particularly important to enhancing the diversity of aquatic and terrestrial communities (Declerck *et al.* 2006). Dense networks of open canopy ponds have shown to be important in farmlands for increasing the connectivity of metapopulations of rare aquatic species (Clauzel *et al.* 2015). For example, regional-scale restoration of agricultural ponds in south-eastern Estonia showed an increase in the threatened pond-breeding amphibian populations such as *Pelobates fuscus* (common spadefoot toad) and *Triturus cristatus* (great crested newt) which rose by 6.5 and 2.3 times respectively (Rannap *et al.* 2009). This was largely the result of restoring and creating clusters of ponds to increase the density of pond habitats as well as varying the morphology and habitat surroundings of each pond to attract a wider diversity of amphibians (Rannap *et al.* 2009). Ponds can not only improve the connectivity of aquatic species but have also been shown to provide important resources which can benefit terrestrial organisms (Davies *et al.* 2016; Walton *et al.* 2020). For example, recent restoration of farmland ponds can increase the abundance and richness of pollinators through improvements in the diversity of pollen and floral nectar resources (Walton *et al.* 2020). Furthermore, restoring ponds to macrophyte-dominated conditions has been shown to help reverse the decline in farmland bird populations by providing a vital source of food through increasing the availability of emergent aquatic insects (**Fig. 2**) (Davies *et al.* 2016). An additional benefit to conserving smaller water bodies in farmlands is that it is arguably a very efficient method of preserving biodiversity given that ponds are relatively easy to create and restore without interfering with agricultural productivity (Williams *et al.* 2010). However, despite the socio-economic and ecological benefits of farmland ponds, in recent decades these habitats have become increasingly threatened (Angélibert *et al.* 2004).

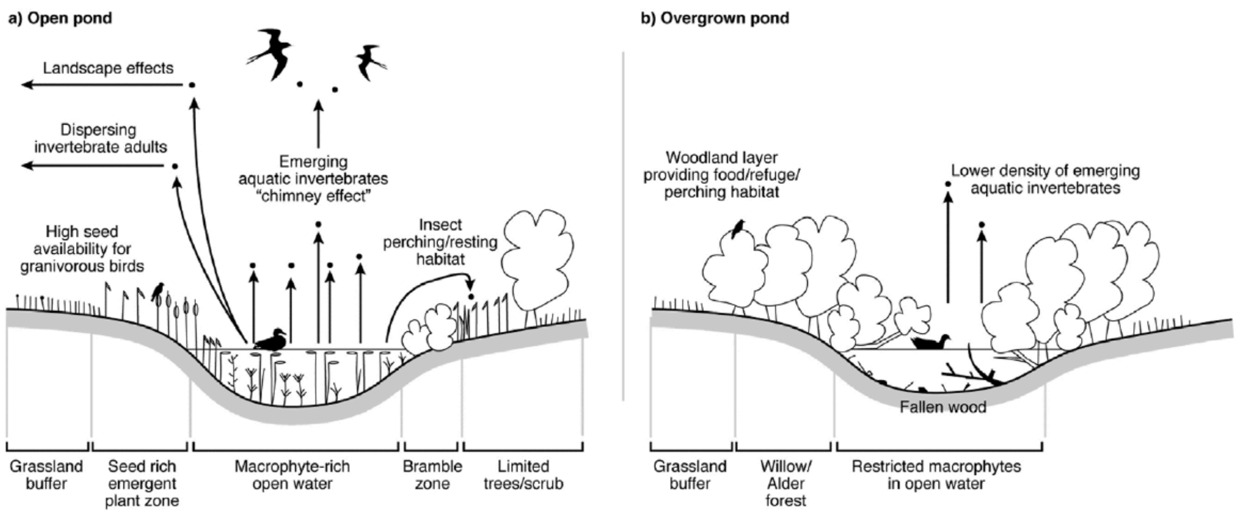


Figure 2. Diagram showing the differences in the habitat characteristics and food resources available for birds at (a) open-canopy restored ponds and (b) unmanaged terrestrialised ponds (Davies *et al.* 2016).

1.3. Threats to pond biodiversity

Due to their small volume, ponds can be particularly susceptible to various forms of habitat degradation (Brooks 2009). Over the last century, it has been estimated that pond loss across European countries has exceeded 50%, with the greatest declines in regions caused by the fading utility of ponds following the mechanisation of agriculture and urbanisation (Wood *et al.* 2003). This is also the case in the UK where ponds are thought to have declined by around 75% over the last century (**Fig. 3**) (Hassall 2014). This degradation can largely be attributed to the intensification of agricultural production following World War II and the active infilling and elimination of ponds to make space for more crops (Boothby *et al.* 1995). Furthermore, changes to other agricultural practices in the UK including livestock production and water abstraction, which have increasingly taken place indoors, means many rural ponds have become neglected (Wood *et al.* 2003; Sayer and Greaves 2020). However, past and on-going pond conservation projects over the last few decades have meant that the number of ponds in the UK have risen by around 12.5% (1998 – 2007), although numbers are still much lower than 150 years ago (Hassall 2014). Ponds are also still widely seen as having little use value to farmers and current UK conservation policies offer small waterbodies minimal legal protection (Boothby 2003). Therefore, farmland ponds are still likely to be subject to the commercial interests of farmers and landowners, placing many ponds under threat from physical destruction (Boothby *et al.* 1995).

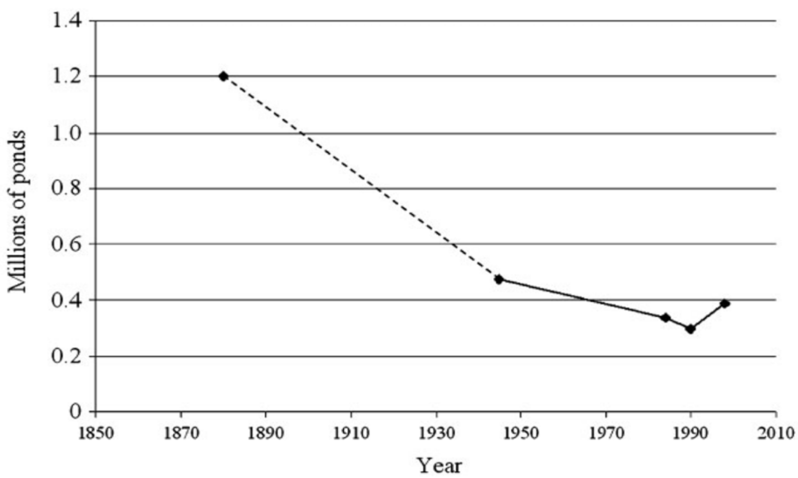


Figure 3. Changes in the number of ponds in Great Britain from 1880-2000 (Biggs *et al.* 2005).

Agricultural practices have also contributed to declines in the water quality of UK farmland ponds which can negatively impact aquatic biota (Williams *et al.* 2010). Nutrients from fertilisers are some of the most problematic pollutants to enter ponds alongside animal health by-products and waste from pastoral farming. These chemicals can enter ponds through a multitude of pathways that can drain broad areas of land, causing eutrophication (Peltzer *et al.* 2008). Methods to control the concentration of pollutants entering ponds, from the deintensification of catchment areas (e.g. grass buffers) to the source control of chemical loads, have been shown to go some way towards mitigating agricultural pollution (Yates *et al.* 2006). But the diffuse nature of these pollutants can still make it challenging to control meaning nutrient interception and land management remain important to protecting freshwater biodiversity (Davies *et al.* 2008).

Non-native aquatic plants can also have detrimental effects on freshwater biodiversity by out-competing native species. There are eleven non-native invasive species which have been identified as a major threat to UK ponds including *Azolla filiculoides, Elodea canadensis* and *Myriophyllum aquaticum* (Pond Life Project 2000). One of the most problematic invasive plants, which was recently (post-1956) introduced from New Zealand, is *Crassula helmsii* (Smith and Buckley 2020). These invasive species are a persistent problem in ponds and are difficult to remove due to a combination of factors, including resistance to chemicals, fast growth, rapid reproduction and high dispersal ability (Stiers *et al.* 2011).

One of the most pressing threats to farmland ponds, which has only come to the fore more recently, has been the threat of pond abandonment and terrestrialisation (Janssen *et al.* 2018; Sayer and Greaves 2020). Following the intensification and mechanisation of agriculture following World War 2, the utility of ponds began to decline and so were often filled in or neglected (Wood *et al.* 2003). Furthermore, having fewer people employed to work on the land (e.g. to clean ponds) combined with the loss of livestock meant there was less disturbance of open canopy farmland ponds that was capable of resetting succession. Consequently, in many agricultural lowland regions this led to mass terrestrialisation, with the landscape dominated by overgrown late-successional ponds which were dry and full of organic matter (**Fig. 4**) (Sayer *et al.* 2013). This lack of management over many decades has led to a decline in the heterogeneity of farmland landscapes resulting in a loss of high-quality aquatic habitats and wildlife (Janssen *et al.* 2018).

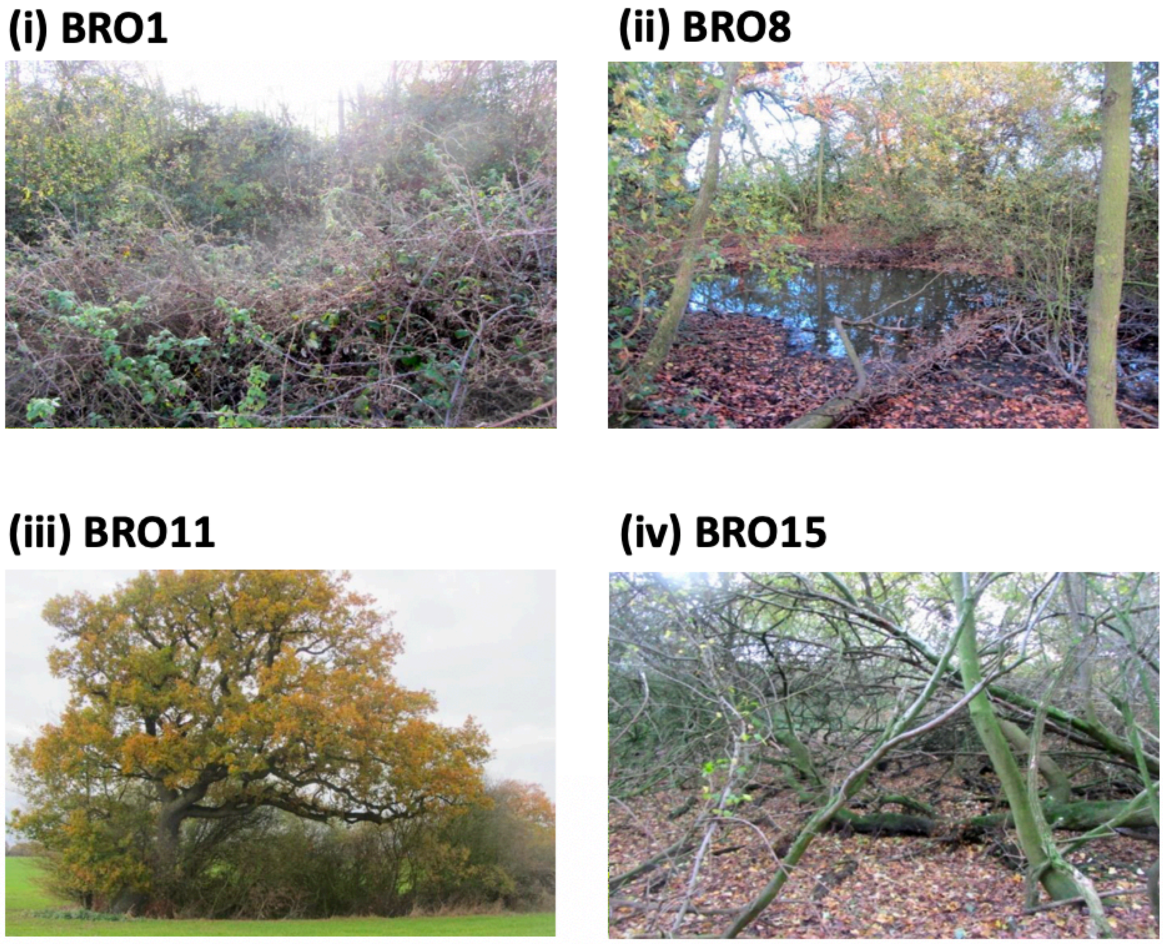
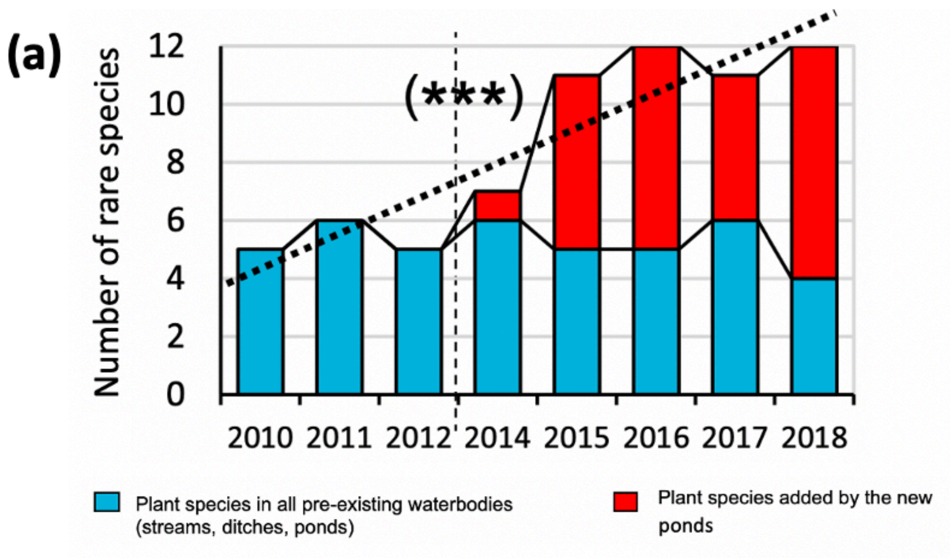


Figure 4. Examples of four overgrown, unmanaged ponds, that were used in this Suffolk ponds study, prior to restoration (Photo credits ©Juliet Hawkins).

1.4. Pond conservation management

Over the last decade, in order to counter the threats of pond loss and the decline in the quality of remaining pond habitats, pond management has emerged as an important method of conservation (Williams *et al.* 2010). There is a general consensus that to reverse the declines in freshwater biodiversity, there is a need to improve landscape heterogeneity and replace ponds that were lost to terrestrialisation (Bigg *et al.* 1994; Sayer and Greaves 2020). Therefore, the main aim of pond management is to increase the number of open-canopy ponds giving rise to early-mid successional aquatic communities in order to improve landscape biodiversity (Sayer *et al.* 2012; Janssen *et al.* 2018).

The dominant approach to pond management over the last few decades in the UK has been pond creation. In more recent years, this approach has been largely advocated by the 'Million Ponds Project' run by the Freshwater Habitat Trust, which aims to build a million new clean water ponds to replace old ponds that have undergone succession (Freshwater Habitats Trust 2021c). Their main rationale for promoting pond creation over other types of management is that it allows ponds to be dug in the most convenient locations allowing ponds to remain unpolluted throughout their lifetime (Freshwater Habitats Trust 2021a). Furthermore, the creation of new ponds also allows greater control over their design and underwater topography meaning that pond complexes can be created to include pools of various shapes, sizes and depths with different habitat surroundings (Williams *et al.* 1997). Therefore, newly created ponds could increase the diversity of aquatic microhabitats, potentially increasing the variety of wildlife that could colonise a site. For example, adding new ponds to the agricultural catchment of the River Soar and River Welland in Leicestershire was shown to increase plant species richness and rarity by 26% and 181%, respectively (**Fig. 5**) (Williams *et al.* 2020). It has been suggested that this is likely because newly excavated ponds can provide competitor-free zones and nutrient poor substrates which can benefit many rare earlier coloniser plants, such as the charophytes (Lambert and Davy 2011; Williams *et al.* 2020).



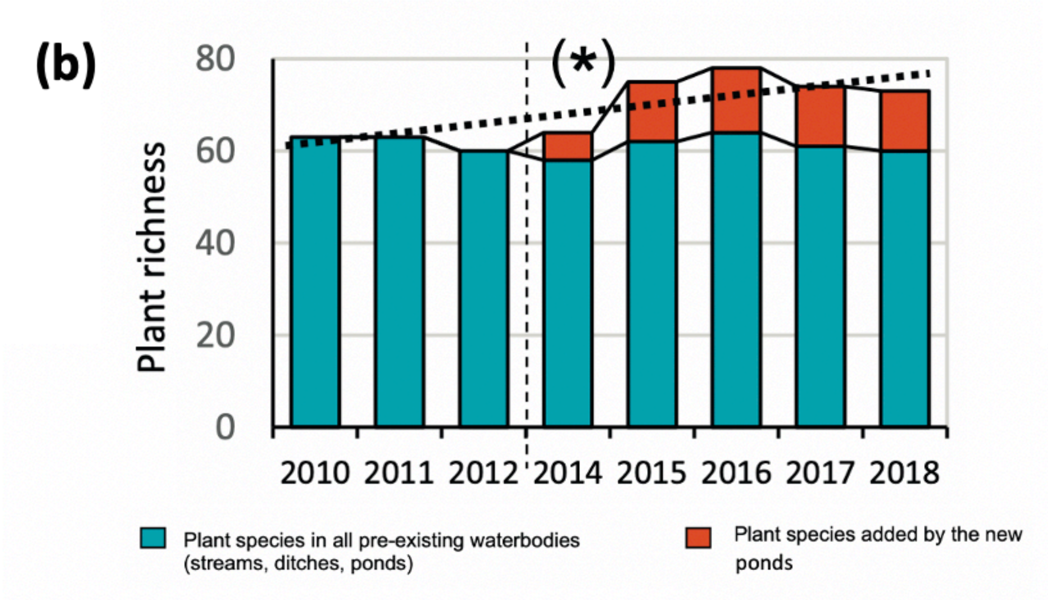


Figure 5. Showing the change in the gamma (a) rarity and (b) richness from adding clean water ponds to the Stonton catchment. The dashed line represents the period where the new ponds were added. The linear regression for overall plant richness/rarity is represented by the dotted line. The statistical significance of the regression line is denoted by the asterix where p = < 0.5 (*), <0.01 (**), <0.001(***) (Williams *et al.* 2020).

A newer approach to pond management has been the restoration of 'ghost ponds.' This has involved the excavation of previously infilled ponds in intensively cultivated agricultural fields, which have then been left to fill with water and colonise naturally (Alderton *et al.* 2017). These resurrected ponds have been shown to colonise very rapidly, giving rise to a high diversity of macrophytes within a year following management (Alderton *et al.* 2017). The speed of colonisation could largely be attributed to the germination of long-lived viable seed banks buried beneath agricultural fields in the soil of these previously aquatic habitats (Alderton *et al.* 2017). Studies of wetland restorations have shown decadal to centennial-scale survival of the propagules of many aquatic plants, which are able to bring rare or extinct species back onto the landscape (Scott *et al.* 2012; Kaplan *et al.* 2014). Therefore, ghost ponds could provide a key source of macrophytes especially where other mechanisms of seed dispersal (e.g. wind, animal) could be hampered by the more fragmented nature of modern-day farmland settings.

A more common method of management which has been subject to a lot of study in recent years is pond restoration. This involves de-shading and de-silting degraded ponds to return them to an earlier stage of succession (Walton *et al.* 2021). Restoration also involves maintaining the original shape, size and bathymetry of old ponds, with the aim of maintaining physical pond diversity in the landscape. The results of restoration on pond biodiversity are relatively well established, showing rises in the richness and diversity of macrophytes, invertebrates, pollinators and birds at restored sites (Sayer *et al.* 2012; Davies *et al.* 2016; Walton *et al.* 2020). Similar to the ghost ponds, early colonisation of macrophytes at restored ponds is very rapid due to the exposure of seed banks following the removal of organic matter (Sayer *et al.* 2012). Given that many restored ponds were originally dug as marl pits, they are mostly found in arable fields (Prince 1962). This means restored ponds could be more susceptible to long-term problems such as eutrophication if not appropriately managed with grass buffers (Davies *et al.* 2008). On the other hand, created ponds which are commonly dug in less polluted farmland settings, such as meadows, have a further benefit of requiring less management due to livestock being able to keep back encroaching scrub (Declerck *et al.* 2006). However, the main advantage of pond restoration is that given the strong influence of seed banks, restored ponds could provide species rich habitats in arable fields where biodiversity is the lowest.

Pond conservation can help to create a high-quality network of pond habitats, known as pondscapes, which allow for greater species dispersal and connectivity at the regional scale (Boothby 1997). It has been suggested that one of the best ways to manage lowland agricultural pondscapes is through rotational management (Sayer *et al.* 2012; Walton *et al.* 2020). This creates ponds at different successional stages, providing a wider diversity of physico-chemical conditions and microhabitats which could be exploited by more species (Hassall *et al.* 2012). At present, evidence suggests that pond creation, restoration and ghost ponds are all very good for biodiversity (Sayer *et al.* 2012; Alderton *et al.* 2017; Williams *et al.* 2020). However, there is a lack of understanding as to which methods may be the most appropriate or effective when used rotationally in lowland agricultural regions. Additionally, most research is focused on the shorter-term outcomes of pond management, with longer-term outcomes little known, particularly the patterns of colonisation in relation to the type of management. Although this is an untested theory, it has been suggested that restored ponds may flourish quickly but may then decline rapidly given the faster dominance of more competitive species from seed banks (Freshwater Habitats Trust 2021a).

Alternatively, created ponds mainly rely on animals and wind for seed dispersal which means they may take longer to colonise (Williams *et al.* 2008). Overall, there seems to be a greater need for understanding the relative biodiversity value of different forms of pond management to inform the best conservation methods in agricultural regions.

1.5. Present study

This study, situated in Suffolk, will explore the biodiversity value of using both pond creation and restoration across an agricultural setting. The ponds in this study are located across Bramfield Farm, Brights Farm, Earlsway Farm, Wyken Hall Farm, Black Bourn Valley Nature Reserve and Ilketshall St Andrews commons. All of the localities have been the focus of pond conservation projects organised by Suffolk Wildlife Trust. The approach to conservation in these regions has involved a combination of pond creation and restoration across arable fields, meadows and woodlands, which have been rotationally managed to create a mosaic of ponds at various successional stages (Suffolk Wildlife Trust (SWT) 2020). This has produced a diversity of well-connected heterogenous habitats shown to support a broad range of aquatic plants, invertebrates and amphibians, many which are locally rare or listed as priority conservation species under the UK Biodiversity Action Plan or Red Data Book (SWT 2020). Most notably, the SWT pond management has helped to restore populations of *T. cristatus* (great crested newt), a nationally and internationally important species protected under the EU Habitats and Species Directive (92/43/EEC), as well as various rare stoneworts such as *Nitella capillaris*, *Tolypella intricata* and *Tolypella glomerata* (SWT 2020) To date, no comprehensive scientific analysis of these sites have been undertaken to assess how pond creation and restoration contribute to the biodiversity value of the region. Understanding the colonisation of these different types of ponds could help to identify whether there is 'best' form of management or if a combination of both is more ecologically beneficial across different spatial and temporal scales.

1.6. Study aims and objectives

This study exploits the unique opportunity by the Suffolk Wildlife Trust pond conservation work, to compare pond creation and restoration and assess their relative merits in terms of conservation outcomes for wetland plants. Macrophytes are the focus of this study because they provide important food and nesting resources for different fauna, so are often an effective surrogate taxon for indicating potential biodiversity (Gioria *et al.* 2010). This study will be the first of its kind to understand the distinct contributions of newly created and restored ponds to alpha and gamma diversity on an agricultural landscape over time. This will be addressed using the following objectives:

1. Assess the differences in the habitat characteristics of restored and created ponds.
2. Understand how macrophyte richness of created and restored ponds varies in the time following management.
3. Determine how species communities change over time in response to the type of management.
4. Assess the biodiversity value of the created and restored ponds based on their rare and unique species.

Based on the unique life histories of newly created and restored ponds it is likely that the type of management will influence the species communities. Firstly, I hypothesise given the strong role of seed banks, restored ponds may initially give rise to a wider diversity of macrophytes including more unique and rare species, than the created ponds. Secondly, I predict over time given the greater probability of the dispersal of propagules between both types of ponds and nearby wetland regions, this may result in a wider range of aquatic plant communities at the landscape. As newly created ponds are normally designed for the purposes of conservation with more favourable habitat conditions, collectively they may be able to sustain more species over time without further management. However, as restored ponds are likely to be located in arable fields, I would expect the species richness of these ponds to decline more quickly than the created ponds due to the faster increase in canopy shading and accumulation of organic matter.

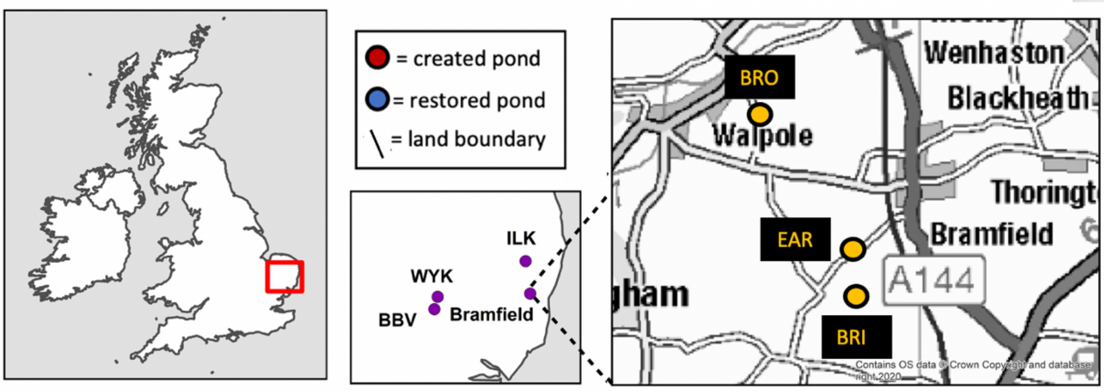
2. Study site

2.1. Climate and geology of field sites

This study was undertaken across six locations that focuses on ponds in Suffolk, eastern England (**Fig. 6**). These were Broad Oak Farm (BRO), Earlsway Farm (EAR), Brights Farm (BRI), Wyken Hall Farm (WYK), Black Bourne Valley Nature Reserve (BBV) and Ilketshall St Andrews commons (ILK). As a lowland agricultural region, Suffolk is approximately 112 ft above sea level (Maplogs 2021). The study sites experience higher than average summer (22°C) and winter (7°C) temperatures, although lower annual rainfall (600-700 mm) compared to the whole of the UK (summer 16°C, winter 6°C, 885 mm annual rainfall) (Weather and Climate 2021). Most ponds across the locations are permanent and supplied by a combination of surface and groundwater with fluctuating water levels influenced by seasonal variations in temperature (SWT 2014).

The geology of the sites is largely comprised of a rolling chalk plain overlain by post-cretaceous deposits consisting of Neogene clays, gravels and sand (Woods *et al.* 2012). The chalk is thickest towards the east of Suffolk, across the farms located in Bramfield as well as Ilketshall St Andrews Commons, but the oldest strata are more exposed towards the west near Wyken Hall farm and Black Bourn Valley Nature reserve (Woods *et al.* 2012). The soils are loamy and well drained, and the surface geology of the ponds are mostly chalky boulder clay (Hawkins 2019; Cranfield University 2021).

(a)



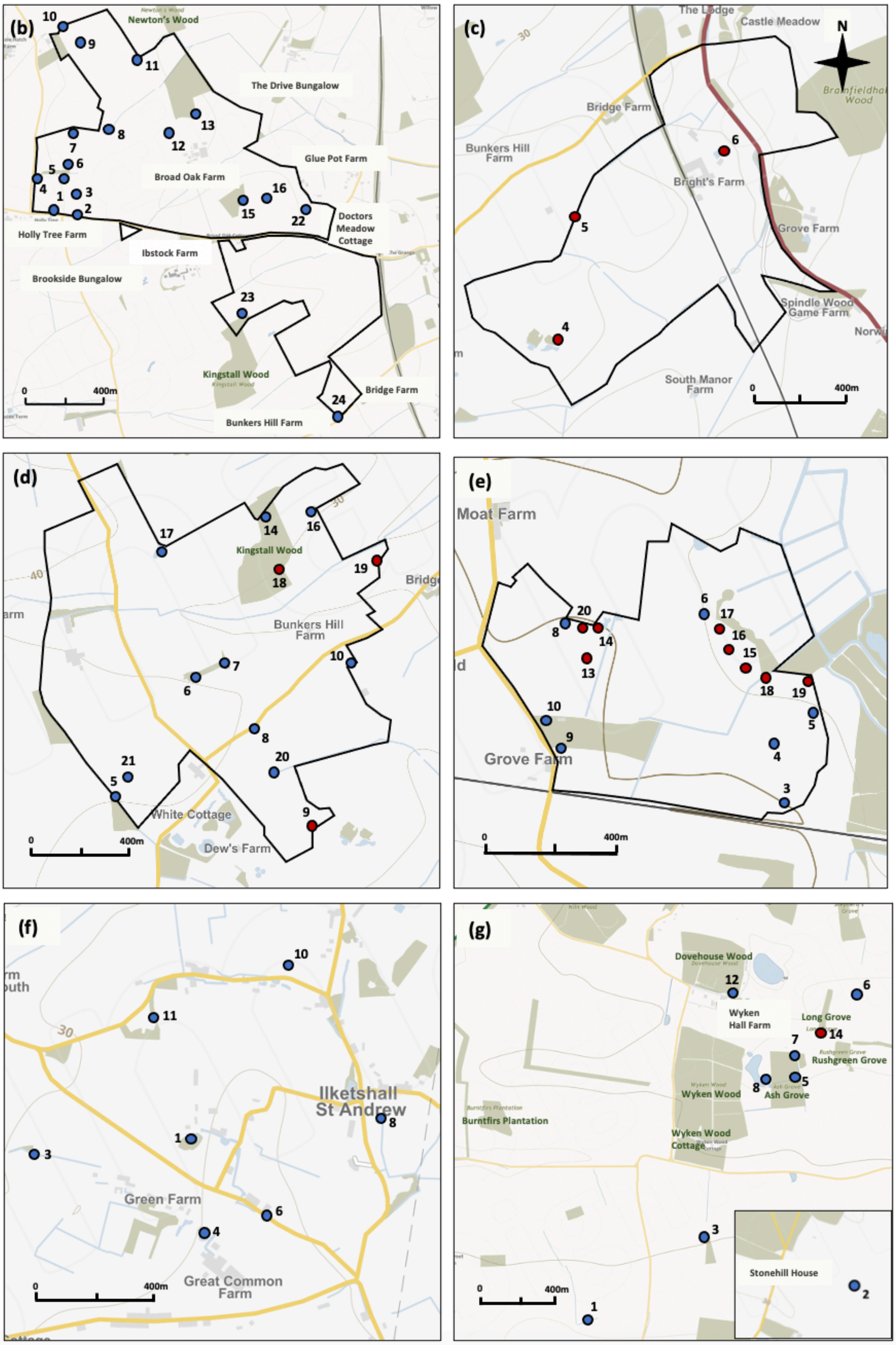


Figure 6. The six study locations and all ponds: (a) UK context, (b) Broad Oak Farm, (c) Brights Farm, (d) Earlsway Farm, (e) Black Bourn Valley Nature Reserve, (f) Ilketshall St Andrews commons, (g) Wyken Hall Farm (Source: EDINA Digimap 2021).

2.2. Pond management

The six field locations have a combined area of 1059 hectares, containing 98 ponds that are mostly located in agricultural settings (**Table 1**). The crops grown across Bramfield Farm, Brights Farm, Earlsway Farm and Wyken Hall farm vary yearly and include winter cereals (wheat, barley), field beans, oil seed rape, linseed and rotational legume-rich leys. Black Bourn Valley is currently a nature reserve but was formerly an arable farmland until 2017 (SWT 2021). Ilkeshall St Andrews is an area of common land which allows usage of the land by locals for animal grazing (Ilketshall Commons 2021).

Table 1. Site information for the six locations in this study.

Location name	Area (hectares)	Site use	Pond density of local parishes (km2) (English Nature 1999)	Number of ponds monitored by the SWT	Number of created ponds used in this study	Number of restored ponds used in this study
Brights Farm	101	Agricultural	12.3	8	3	0
Black Bourne Valley Nature Reserve	88	Agricultural (-2017), Nature reserve (2017-present)	9.6	20	8	7
Broad Oak Farm	142	Agricultural	7.3 - 13.7	24	0	18
Earlsway Farm	162	Agricultural	12.3	21	3	10
Ilketshall St Andrews Commons	80	Common land	14.2	11	0	7
Wyken Hall farm	486	Agricultural	3.9	14	1	8

The SWT has rotationally managed ponds across these high density pondscapes over the last two decades, having restored 50 ponds and created 17 new ponds, to create a mosaic of ponds at various successional stages. The aim of pond conservation in Suffolk has been to reverse the declining biodiversity of rural and farmland regions to create what Natural England define as 'ponds of high value', which are high-quality pond habitats that support diverse aquatic communities (Natural England 2010; SWT 2020). This has included the conservation of metapopulations of rare and unique species that rely on the connectivity between pond clusters, such as Great Crested Newt *T. cristatus*, the Norfolk Hawker dragonfly *Anaciaeschna isosceles* and numerous Suffolk priority water beetle species such as *Hydrophilus piceus*, *Berosus affinis* and *Enochrus testaceus* (SWT 2020).

Macrophyte survey data from 65 ponds across this rural Suffolk landscape was used in this study. This includes 50 restored and 15 created ponds selected based on the availability of macrophyte survey data from SWT surveys (**Appendix 1, 2**). Although, both types of ponds were found in arable and meadow surroundings, due to differences in their origins, more restored than newly created ponds were found in arable settings (**Fig. 7, 8**). Since management has taken place, most of the arable ponds are well buffered with at least 6m grass margins. The created ponds, which are predominantly located in meadows, are disturbed by roaming cattle, which could shape vegetative communities through poaching emergent plant growth and influencing underwater and marginal pond microhabitats.

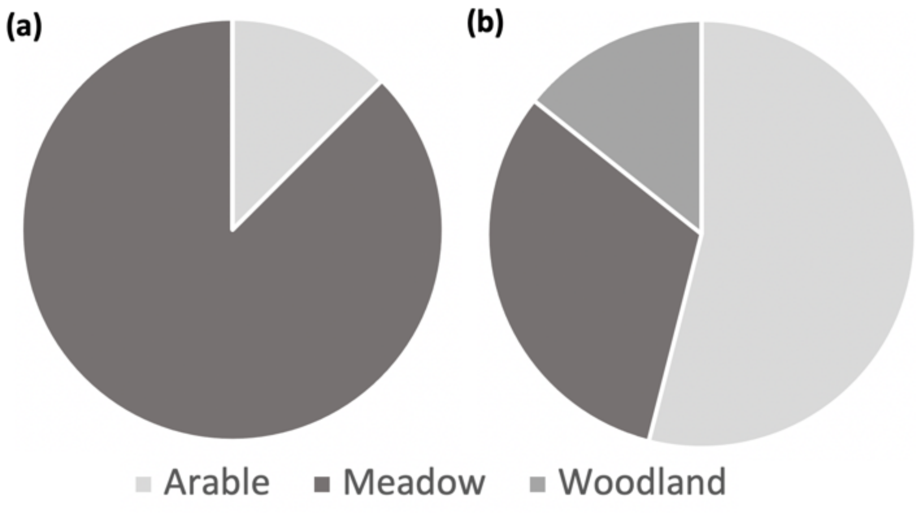


Figure 7. Proportion of (a) newly created and (b) restored ponds found in arable, meadow and woodland settings.

(a) Arable

(i) EAR9 - *Newly created*

(ii) BRO4 - *Restored*

(b) Meadow

(i) BRI4 - *Newly created*

(ii) ILK3 - *Restored*

(c) Woodland

(i) BBV10 - *Restored*

(ii) WYK7 - *Restored*

Figure 8. Examples of the three different land use surroundings across the six field sites (All photo credits © Juliet Hawkins, except for BBV10 ©John Lord).

3. Methodology

3.1. Macrophyte sampling

Pond macrophyte data for restored and created ponds across the six study sites has been collected by the SWT since 2005. The main surveyor was Juliet Hawkins, farm conservation advisor for the Suffolk Wildlife Trust. For each pond, the sampling carried out was part of a broader survey, mainly targeted at *T. cristatus* conservation and normally took place in the years following pond management (**Appendix 3**). Macrophyte data was collected by visually observing the presence of emergent and floating plants within each pond, with a grappling tool used to assist the identification of some submerged aquatic species, especially stoneworts (Characeae). Most plants were identified on site with the aid of a 10x hand lens and various identification guides which included ‘Polish Charophytes’ (Urbaniak and Gąbka 2014), ‘Red Data Book of British and Irish Stoneworts’ (Stewart and Church 1992) and Botanical Society of Britain and Ireland (BSBI) handbooks (Moore 1986; Preston 1995). Stonewort identifications were confirmed by UK charophyte recorder Nick Stewart. The presence of various amphibians and invertebrates were also recorded during pond surveys, as well as wildfowl disturbances and indications of water quality (see **Appendix 3**). Field sketches and photographs for each pond were taken to record the distribution and location of vegetation. This methodology was fairly consistent between all surveyed ponds to ensure they were comparable across sites and years. All data collected was submitted to Suffolk Biological Information Service (SBIS).

3.2. Data collation

3.2.1. Macrophyte data

Pond macrophyte data for the restored and created ponds at each of the six locations was acquired from the SBIS and Juliet Hawkins’ work as a private consultant. The data received comprised of plant species lists (presence/absence data) for all years that each pond was surveyed between 2005-2020. For each pond, the year management had taken place was ascertained from the SWT pond monitoring reports. Non-aquatic plant species were deleted from the records as well as any partial plant surveys as determined by consultation with Juliet Hawkins. In some instances, where macrophytes were only identified to genus level, some of these were kept in the dataset due to their high abundance or ability to deduce the likely species from SWT monitoring reports or SWT wetland plant surveys (**Table 2**). Alternatively, other genus-level records with very few recordings were deleted from the dataset as this was unlikely to skew the findings.

Table 2. How decisions were made to either keep or delete genus-level records in this study.

Action taken	Justification for action	Genus-level records affected
Kept	Kept in the records at genus level due to high abundance across pond surveys.	*Chara* spp.
	Was able to identify these to the species level based on site photographs or the SWT pond monitoring reports.	*Glyceria* spp. *Typha* spp. *Veronica* spp.
	Was able to infer species based on species-level records of these genus found in the same pond survey, suggesting most of these genus-level records are likely to be duplicate recordings.	*Carex* spp. *Eleocharis* spp. *Juncus* spp. *Lemna* spp. *Myriophyllum* spp. *Potamogeton* spp. *Ranunculus* spp.
Deleted	Very few records so deletion is unlikely to greatly skew findings.	*Carex* spp. *Rorippa* spp.

3.2.2. Physical habitat characteristics

A range of physical variables were chosen for inclusion in this study based on aspects of the created and restored ponds which could influence biodiversity (Williams *et al.* 1997; Sayer *et al.* 2012). As both types of ponds were originally designed for different purposes, understanding their morphological characteristics could be important to explaining macrophyte richness. Pond area was calculated using OS maps and the shape of each pond was graded on a scale of 1-10 using photographs to assess pond marginal complexity (**Appendix 4**) (Pond Action 1998). Furthermore, differences in the geographical location of created and restored ponds could influence propagule dispersal and resulting species communities (Hinden *et al.* 2005). Therefore, aerial maps and SWT pond monitoring reports were used to identify the intensity of agricultural and other human activities taking place within the proximity of each pond. Canopy shading, which is known to be an important factor in ponds, was estimated using site photographs (Hassall *et al.* 2012).

3.3. Data analysis

3.3.1. Species richness and habitat characteristics

The patterns of biodiversity and habitat characteristics of the created and restored ponds were compared in this study. Pond surveys were categorised into three groups, 1-2 years, to highlight early pond succession, as well as 3-7 years and 8-12 years, to assess how created and restored ponds colonised over time. An independent t-test was used to calculate significance between the area of the created and restored ponds. Mann Whitney U tests were used to test significance between the marginal complexity, percentage shading and species richness of the created and restored ponds, including their changes over time. Spearman's rank was also used to test the correlation of the species richness and shading data. The alpha level for these analyses were pre-determined at $p<0.05$, a set standard for ecological analysis (Shaw and Wheeler 1998).

3.3.2. Biodiversity calculations and rare and unique species estimates

Regionally rare wetland plant species are an important indication of the biodiversity value of pond management. In this study, following the approach undertaken by Williams *et al.* (2020), a plant was classified as rare if it occurred in fewer than 10% of 100 x 100km grid squares across Suffolk. This was calculated using the post-2000 BSBI distributions database (BSBI maps 2021). Comparing the biodiversity value between the restored and created ponds was likely to be affected by the large difference in the number of surveys between the restored ponds (72 surveys) and created ponds (38 surveys). Therefore, the number of rare or unique species per pond was calculated for these analyses to reduce bias. The overall effects of pond creation and restoration on species richness were calculated using Shinozaki rarefaction curves for each time since management category. This was processed using Past 4.04.

3.3.3. Multivariate analysis

Principal Components Analysis (PCA) was selected for the multivariate analysis given the species data was nominal (presence/absence). This was undertaken using CANOCO 5 (ter Braak and Smilauer 2012) to compare the responses of aquatic plant communities to pond creation and restoration across the different time since management categories.

4. Results

4.1. Pond habitat characteristics

There were some important differences in the habitat characteristics of restored and created ponds which may be important to explaining macrophyte richness and diversity. Firstly, there was some slight variation in the sizes of the ponds between both categories (**Fig. 9**). Although an independent t-test showed that the differences in area between restored and created ponds were not significantly different (P = 0.935), the created ponds had a lower median area and inter-quartile range (IQR) indicating that they were generally smaller (Median: C = 150 m^2, R = 183 m^2; IQR: C = 119 m^2, R = 159 m^2). There were also three outliers amongst the restored ponds which were larger than other sites in the dataset: BRO5 (547 m^2), WYK7 (582 m^2) and ILK4 (919.8 m^2). For the created ponds, the largest area measured was 1412 m^2 at BRI6, which is used as an irrigation reservoir.

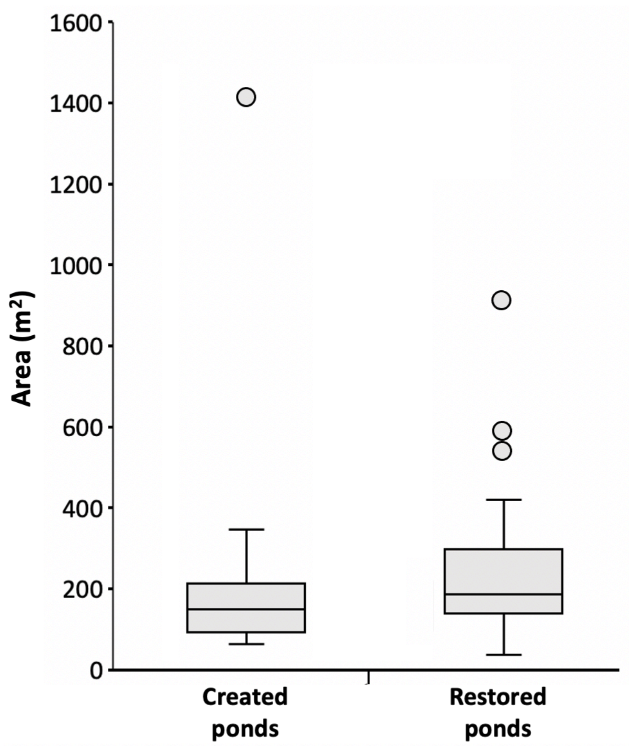


Figure 9. Comparison of the area of newly created and restored ponds. Boxes show median, upper and lower quartiles. Whiskers shows minimum value and maximum value. Difference between upper and lower quartiles represent the inter-quartile range. Difference between minimum and maximum value represents the range. Circles represent outliers.

Marginal complexity scores of ponds in both management categories (**Fig. 10**) ranged from 1 – 8 showing that the pond margins of both created and restored ponds varied from circular to convoluted shapes. The median marginal complexities of the created (MC = 4) and restored ponds (MC = 3) were fairly similar, suggesting that the Suffolk pondscapes are dominated by oval shaped ponds. Although a Mann Whitney U test showed no significant difference in the marginal complexity scores between both management categories (P = 0.106), comparison of the IQR's suggested greater variety in terms of shape complexity for ponds that had been newly created (IQR: C = 4; R = 2). This likely reflects the efforts of the SWT to maximise the number of aquatic habitats available to attract more species.

There were some distinct differences in the percentage shading of the created and restored ponds in the years following management. In each of the three time since management categories, there were significant differences in shading between the created and restored ponds, with restored ponds having an average of 20% more canopy cover (P < 0.0001 for 1-2, 3-7, 8-12 years) (**Fig. 11**). In the years following management, there appears to be a slight increase in the percentage shading of the created and restored ponds, suggesting that woody vegetation starts to develop around these small waterbodies in a short amount of time. Between 1-2 years and 3-7 years after management, there was no shading amongst any of the created ponds. However, at 8-12 years there is some evidence of marginal tree growth across a few of the created ponds, raising the maximum percentage shading of ponds in this category to 5%. Across the restored ponds the median shading in each time since management category was 20%, with large IQR's, suggesting that most restored ponds surveyed had some degree of canopy cover (IQR: 1-2 years = 28.75, 3-7 years = 25, 8-12 years = 30). However, canopy cover of the restored ponds was shown to increase more rapidly over time compared to the created ponds, with an increase in the lower and upper quartiles between 1-2 and 3-7 years, and a further rise in the minimum value, upper quartile and maximum value at 8-12 years.

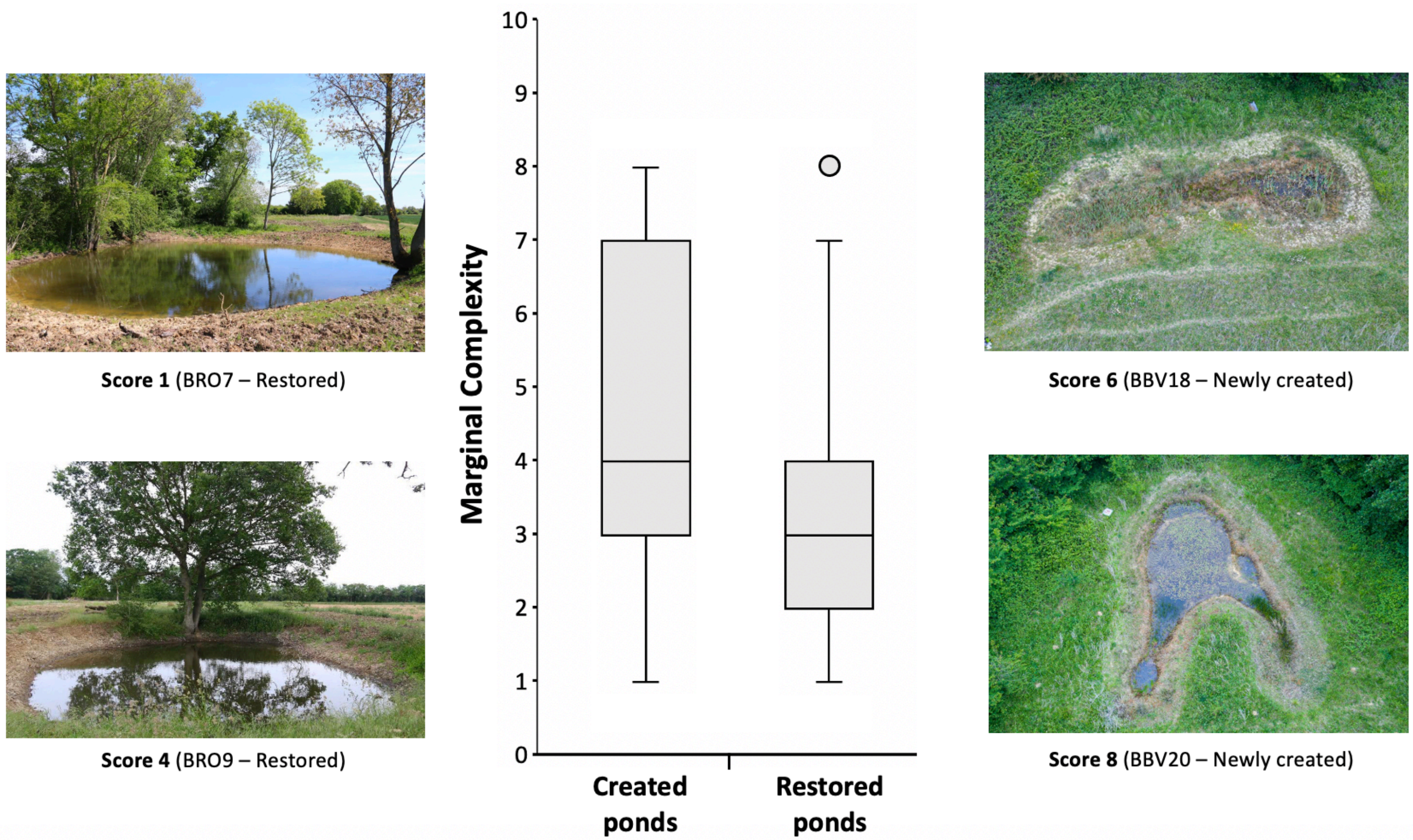


Figure 10. Comparison of the marginal complexity scores of the newly created and restored ponds (Photo credits: BRO7 & BR09 © Juliet Hawkins, BBV18 and BBV20 © John Lord). Boxes show median, upper and lower quartiles. Whiskers shows minimum value and maximum value. Difference between upper and lower quartiles represent the inter-quartile range. Difference between minimum and maximum value represents the range. Circles represent outliers.

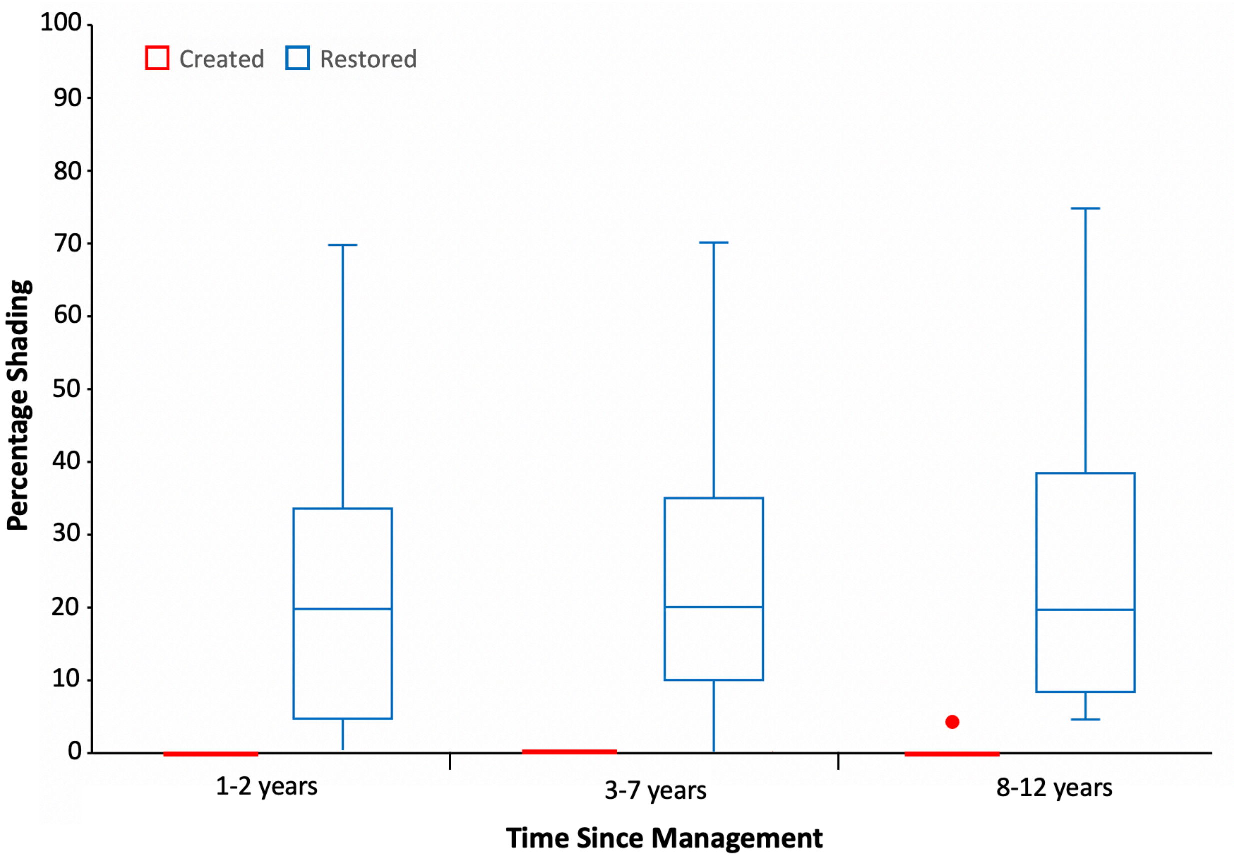


Figure 11. Changes in percentage shading of the created and restored ponds in the years following management. Boxes show median, upper and lower quartiles. Whiskers shows minimum value and maximum value. Difference between upper and lower quartiles represent the inter-quartile range. Difference between minimum and maximum value represents the range. Circles represent outliers.

4.2. Macrophyte richness

A total of 80 macrophytes were recorded across the 110 surveys of the 65 Suffolk ponds as undertaken between 2005-2020 (**Appendix 5**). 75 wetland plant species were found in restored ponds and 43 were found in created ponds over this time period. However, it is important to note that there were 72 surveys carried out for the restored ponds, compared to only 38 surveys for the created ponds with this likely explaining this large difference in species richness across the two pond categories. Across all surveyed ponds, the top ten most abundant species were *Agrostis stolonifera* (71 surveys), *Juncus inflexus* (68 surveys), *Potamogeton natans* (64 surveys), *Alisma plantago-aquatica* (52 surveys), *Epilobium hirsutum* (51 surveys), *Typha latifolia* (44 surveys), *Chara vulgaris* (42 surveys), *Juncus articulatus* (40 surveys), *Ranunculus aquatilis* (38 surveys) and *Solanum dulcamara* (36 surveys).

There appears to be little relationship between the percentage shading of the created and restored ponds with macrophyte richness (**Fig. 12**). This is confirmed by the statistically significant Spearman's rank correlation coefficient of 0.315 (P = 0.001). Although the shading of the created ponds only ranged from 0-5%, they contained anywhere between 1-23 macrophytes. Restored ponds between 0-35% shading also had quite varied macrophyte richness ranging from 4-25 species. However, ponds with higher than 40% shading, which were all restored, had a lower species richness more generally, ranging from 5-14 wetland plant species. This suggests that, at least for the restored ponds, species richness may decrease slightly with increased shade.

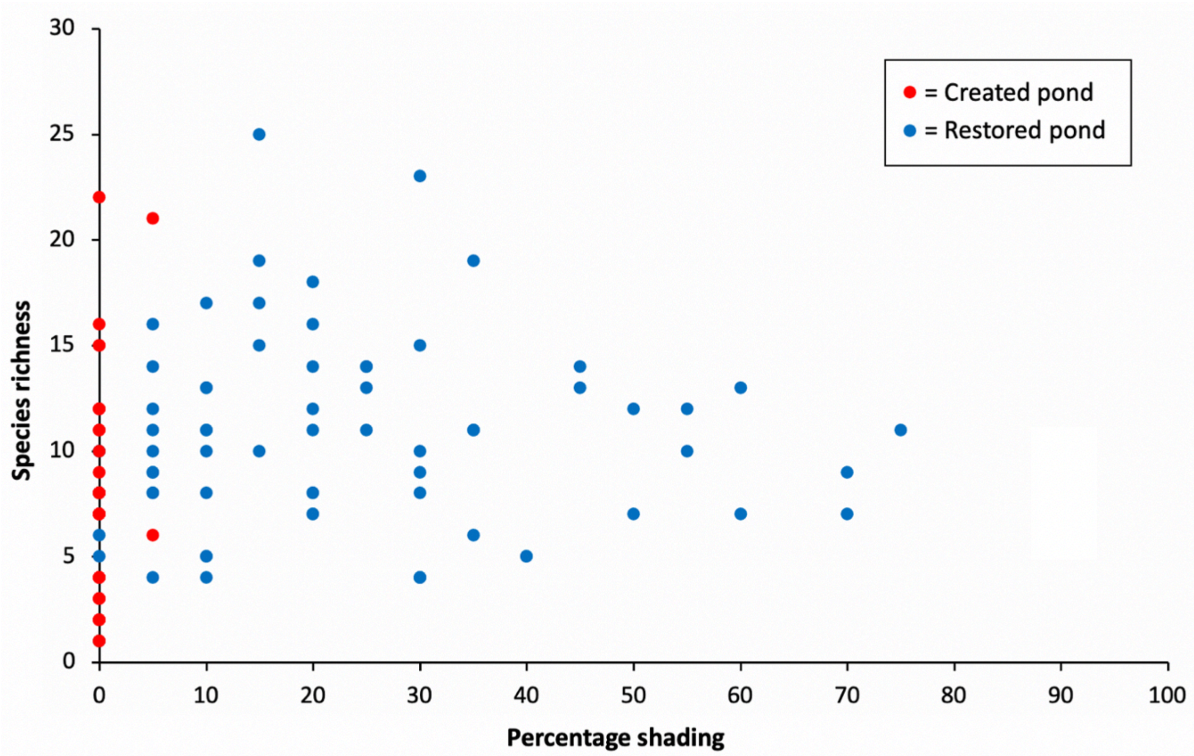


Figure 12. Relationship between percentage shading and species richness between restored and created ponds.

There were more distinct changes in patterns of species richness between created and restored ponds following management (**Fig. 13**). After 1-2 years, median species richness of the created ponds was much lower than for restored ponds. This difference was statistically significant (P < 0.0001), suggesting restored ponds colonise with wetland plants much more quickly than created ponds (**Table 3**). At 3-7 years, the number of species in the created ponds increased to a median richness of 7, whereas a more moderate rise in macrophyte richness (median 11 species) was evident for the restored ponds. At 8-12 years, the median number of species in the created ponds continued to rise to 9.5 macrophytes, whereas median species richness of the restored ponds decreased to 10 wetland plant species. This indicates that the species richness of these late successional restored ponds was overall declining after 8+ years. There was no significant difference between the created and restored ponds at 3-7 years or 8-12 years, as was the case for restored ponds across all time since-management categories. However, the difference in species richness between the created ponds across all time periods was significantly different, indicating that the most rapid increase in species richness for these ponds took place in later years.

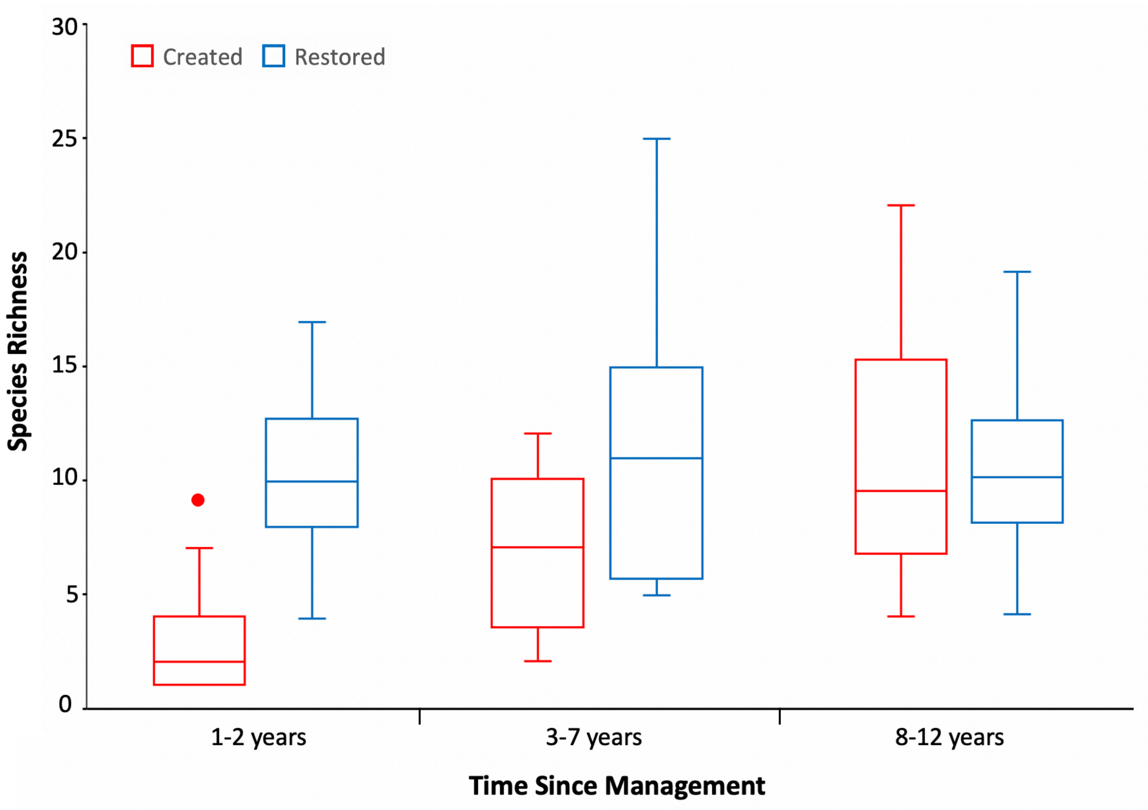


Figure 13. Species richness of the created and restored ponds in the years following management. Boxes show median, upper and lower quartiles. Whiskers shows minimum value and maximum value. Difference between upper and lower quartiles represent the inter-quartile range. Difference between minimum and maximum value represents the range. Circles represent outliers.

Table 3. Results of Mann Whitney U testing for macrophytes between restored (R) and created (C) pond time categories (*indicates significance at 0.05 level).

(a)

C + R comparison		
C	**R**	**p – value**
1 – 2	1 – 2	0.000*
3 – 7	3 – 7	0.055
8 – 12	8 – 12	0.969

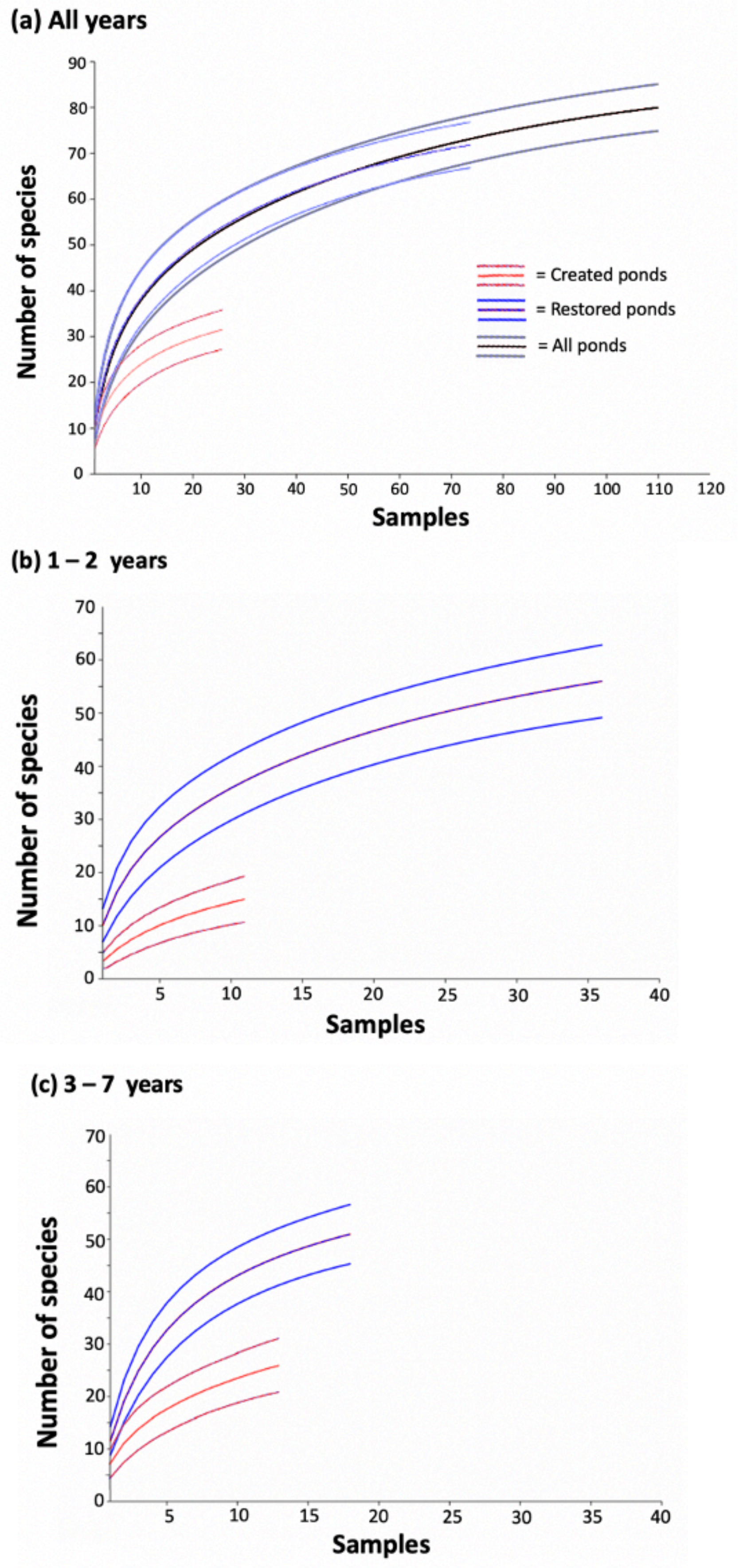
(b)

C + C comparison		
C	**C**	**p – value**
1 – 2	3 – 7	0.007*
1 – 2	8 – 12	0.000*
3 – 7	8 – 12	0.048*

(c)

R + R comparison		
R	**R**	**p – value**
1 – 2	3 – 7	0.469
1 – 2	8 – 12	0.875
3 – 7	8 – 12	0.937

At the landscape scale, the difference in species richness between the created and restored ponds varies quite significantly over time. Some 80 macrophytes were recorded across 110 pond surveys and given that the rarefaction curve for all ponds is nearing asymptote, it seems likely that the surveys captured a large proportion of all wetland plant species present in the study region (**Fig. 14a**). Across all years, restored ponds contributed considerably more species to the landscape than created ponds and in each separate time category, the rarefaction curves for the restored ponds are always steeper than for created ponds. The rarefaction curves at 1-2 years showed the greatest difference in the number of species collected, with restored ponds contributing around 40 more species to the landscape than the created (**Fig. 14b**). At 3-7 years, the rarefaction curves of the created and restored ponds steepen, suggesting more species were recorded per survey in both pond categories (**Fig. 14c**). This steepening of both the created and restored ponds continues at 8-12 years, although across all time categories rarefaction curves for the created ponds show the biggest difference (**Fig. 14d**). This suggests that the number of species newly created ponds contribute to the landscape increases the most as time progresses. However, the rarefaction curves for the restored ponds are consistently steep, showing they contribute a large number of species to the landscape across all time periods.


(a) All years
Number of species
Samples
= Created ponds
= Restored ponds
= All ponds
(b) 1 – 2 years
Number of species
Samples
(c) 3 – 7 years
Number of species
Samples

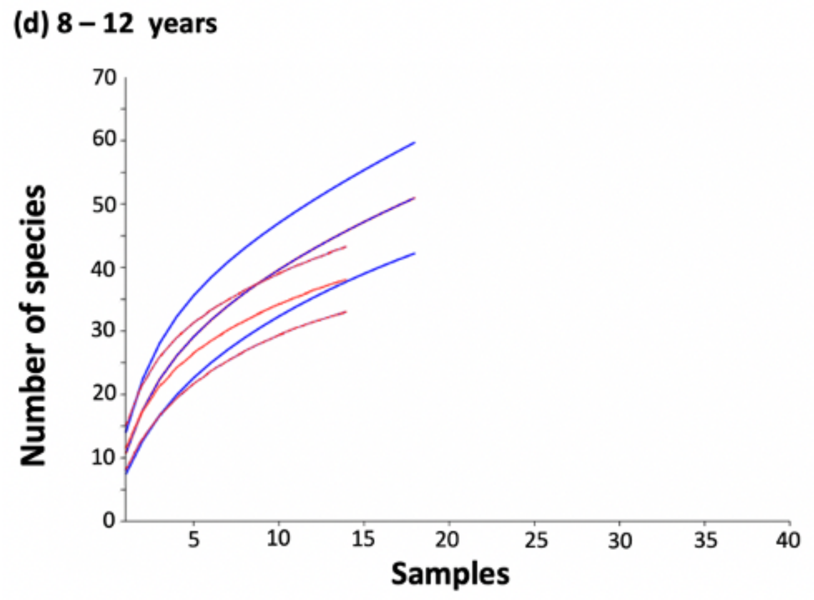


Figure 14. Rarefaction curves of macrophyte richness for restored and created ponds for (a) All years, (b) 1-2 years, (c) 3-7 years and (d) 8-12 years.

The overall species richness for all managed ponds seems to show a slight increase across the three time categories (**Fig. 15**). A Mann Whitney U test showed no significant difference in the species richness across the years (**Table 4**). However, the median species richness of all managed ponds rises from 9 to 10 between the earliest to the latest time category. There is also a gradual increase in the minimum value, lower quartile and upper quartile over the three time periods, suggesting a subtle increase in the macrophyte richness over time.

4.3. Rare and unique species

There was a large difference in the number of species that were unique or rare to the type of pond management that had taken place. Across all time periods, restored ponds (0.5 species/pond) gave rise to more than three times as many unique species than created ponds (0.13 species/pond) (**Fig. 16**). Of the unique species occurring in restored ponds, six were regionally rare: *Callitriche obtusangula* (BBV6), *Chara hispida* (WYK8), *N. capillaris* (BRO4, EAR6), *Oenanthe fistulosa* (ILK4), *Potamogeton trichoides* (ILK3, ILK4, WYK3), *T. intricata* (BBV5, BRO4, BRO5). By contrast, only one regionally rare macrophyte, *Schoenoplectus tabernaemontani* (BRI4, BRI5), was unique to the created ponds. Both the created and restored ponds gave rise to one unique invasive species each. For the created ponds this was *C. helmsii* (1 survey), and for the restored it was *A. filiculoides* (1 survey).

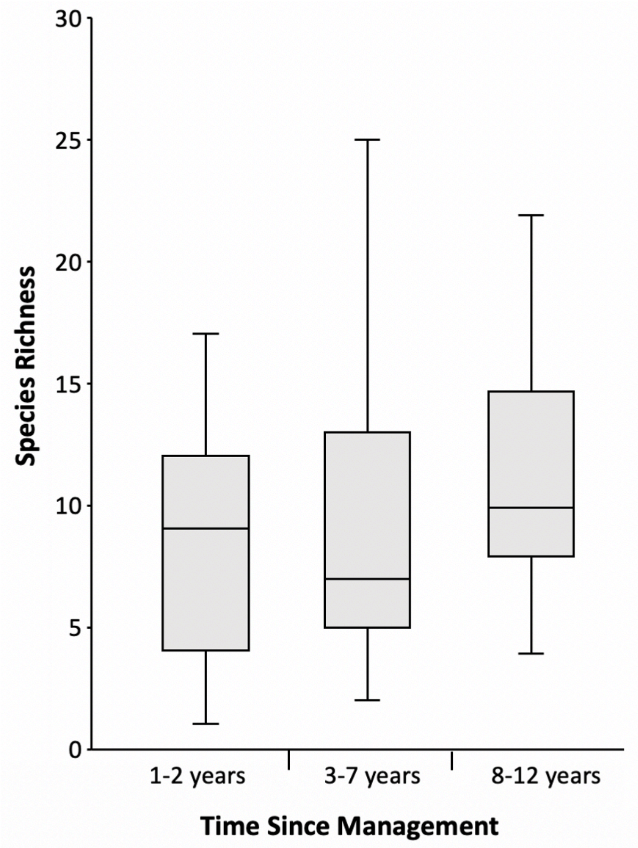


Figure 15. Species richness of all restored and created ponds combined in the years following management. Boxes show median, upper and lower quartiles. Whiskers shows minimum value and maximum value. Difference between upper and lower quartiles represent the inter-quartile range. Difference between minimum and maximum value represents the range. Circles represent outliers.

Table 4. Results of Mann Whitney U testing for all restored and created ponds combined across the three time categories (* indicates significance at 0.05 level).

Time period	Time period	p – value
1 – 2	3 – 7	0.469
1 – 2	8 – 12	0.875
3 – 7	8 – 12	0.937

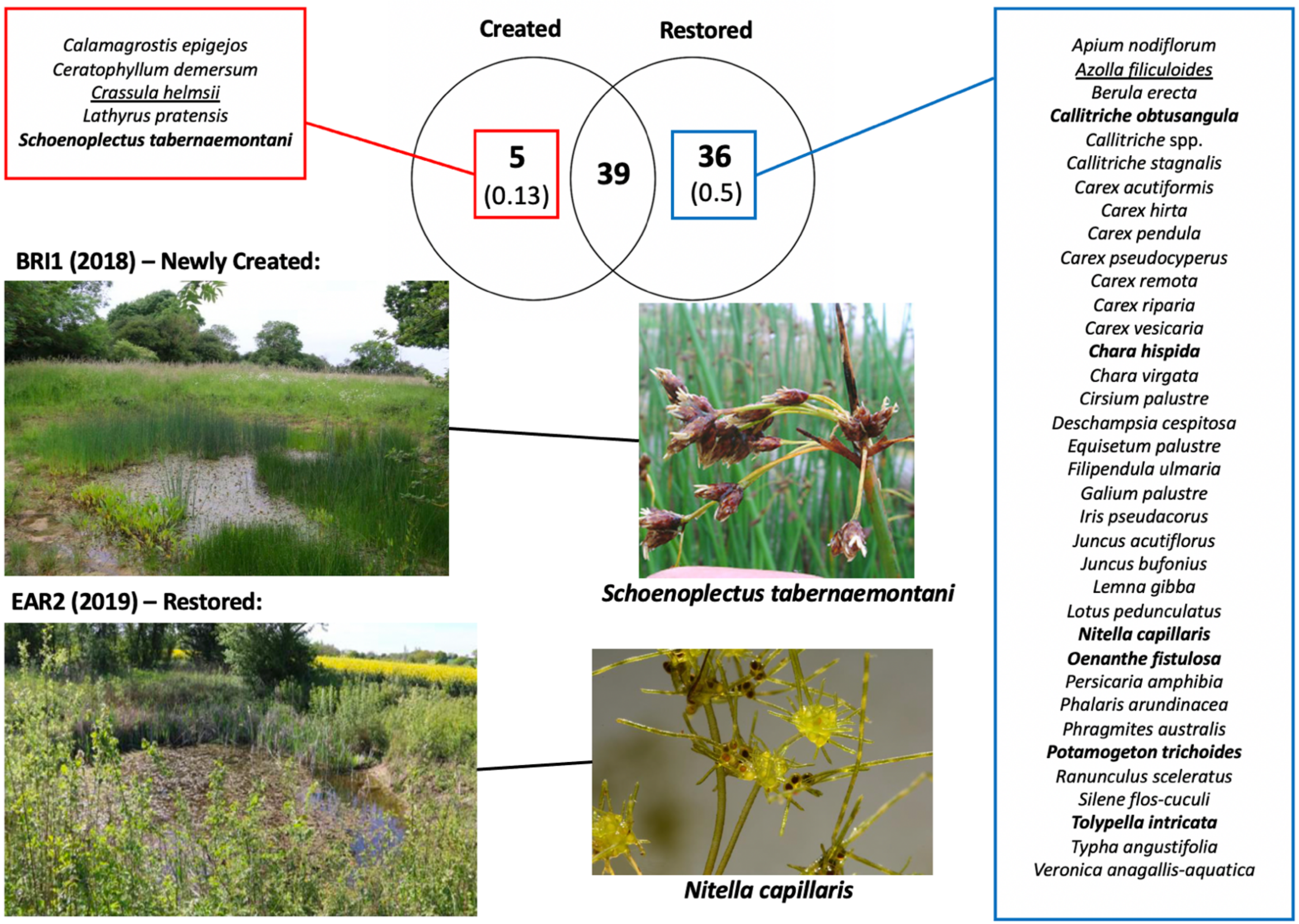


Figure 16. Venn diagram showing the number of unique species occurring in the created and restored ponds with number of unique species per created/restored pond in brackets (Key: Rare species = bold; Invasive species = underlined). Photo credits: BRI1 & BR2 © Juliet Hawkins, *Schoenoplectus tabernaemontani* (Go Botany 2021), *Nitella capillaris* (Biopix 2021).

Within each time category, there were considerably more unique species per pond in the restored ponds than the newly created (**Table 5**). For the created ponds, there was a rise in unique species as the time since management increased, with the greatest jump occurring between 3-7 (0.15 species/pond) and 8-12 years (0.71 species/pond). For the restored ponds, the number of species unique to the time period increased between 1-2 years (1.19 species/pond) and 3-7 years (1.44 species/pond), but then declined slightly at 8-12 years (1.28 species/pond). Of these species that were unique to restored and created ponds in each time period, the number of macrophytes which were regionally rare rose as time since management increased (**Table 6**). However, restored ponds still contained more unique rare species than the created ponds. In each time category the unique rare species were different between the restored and created ponds suggesting that both types of management provide a unique biodiversity value to the Suffolk pondscape.

Table 5. Number of unique species in the created and restored ponds for each time since management category with the number of unique species per created/restored pond in brackets.

	Created	Restored
1-2 years	0 (0)	43 (1.19)
3-7 years	2 (0.15)	26 (1.44)
8-12 years	10 (0.71)	23 (1.28)

Table 6. Rare species unique to each time category for created and restored ponds.

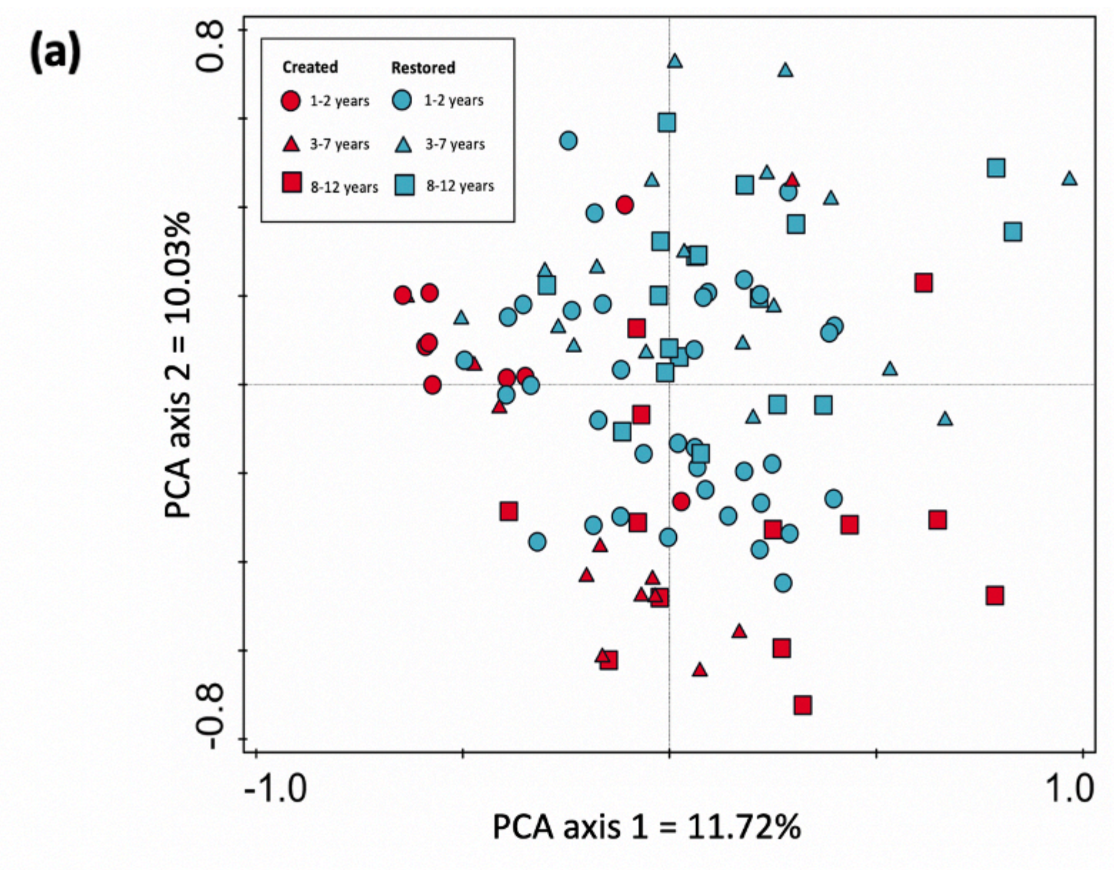
Time since management	Created	Restored
All time periods	*Schoenoplectus tabernaemontani*	*Callitriche obtusangula* *Chara hispida* *Nitella capillaris* *Oenanthe fistulosa* *Potamogeton trichoides* *Tolypella intricata*

1-2 years	(none)	*Chara globularis* *Nitella capillaris* *Tolypella glomerata* *Tolypella intricata*
3-7 years	*Tolypella glomerata*	*Oenanthe fistulosa* *Potamogeton trichoides* *Ranunculus peltatus*
8-12 years	*Ranunculus peltatus* *Schoenoplectus tabernaemontani* *Tolypella glomerata*	*Callitriche obtusangula* *Chara hispida* *Oenanthe fistulosa* *Potamogeton trichoides* *Tolypella intricata*

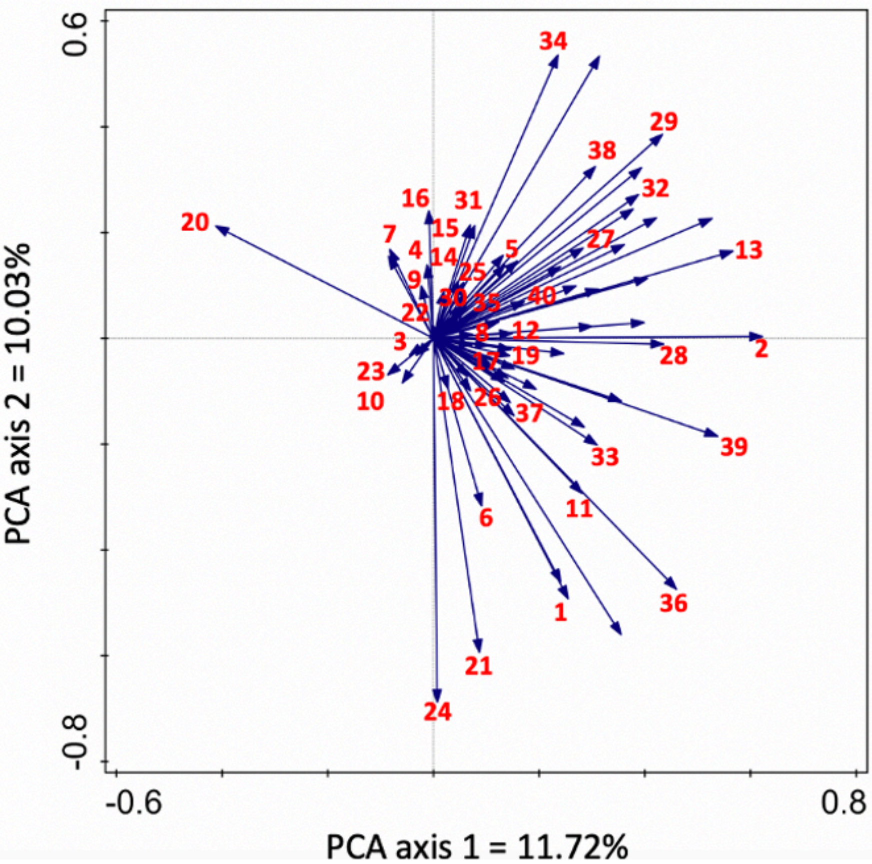
4.4. Community composition

The PCA output shows that the community composition of the restored and created ponds is largely influenced by the type of pond management and the time it took place (**Fig. 17**). Axis 1 explains 11.72% of the variation in the data, whereas axis 2 explains 10.03%. For newly created ponds, the pond surveys taken in the early - mid years after creation is associated with distinct clusters. The species communities of the ponds 1-2 years after creation are mostly placed at the far left of Axis 1, with *Agrostis stolonifera, Chara* spp. and *Juncus inflexus,* characterising this cluster. At 3-7 years, the species assemblages of the created ponds are clustered towards the bottom of axis 2 which are mostly influenced by *A. stolonifera*, *Chara globularis, Chara vulgaris, J. articulatus, J. inflexus* and *P. natans*. However, the pond survey taken 8-12 years after creation are more spread out, but remain largely in the bottom quadrants, suggesting that community composition of these ponds encompasses a wider variety of macrophytes. These species include *A. stolonifera, A. plantago-aquatica, Carex flacca, C. vulgaris, Eleocharis palustris, J. articulatus, J. inflexus, P. natans* and *Pulicaria dysenterica*.

The restored ponds show clear changes in species communities following management, although the patterns are less distinct than observed for created ponds. The ponds 1-2 years following restoration are loosely clustered in the bottom quadrants close to axis 2 or in the lower part of the top quadrants. The species that dominate these communities are *A. stolonifera, A. plantago-aquatica, C. vulgaris, E. hirsutum, J. inflexus, P. natans, R. aquatilis, Ranunculus sceleratus, S. dulcamara* and *T. latifolia*. The restored ponds that were surveyed 3-7- and 8-12-years following management are widely interspersed amongst each other in the middle to top region of the upper quadrants. There are a number of macrophytes that are important to influencing both these communities which include *A. stolonifera, A. plantago-aquatica, Carex otrubae, E. hirsutum, Juncus effusus, J. inflexus, Lycopus europaeus* and *P. natans*. Other wetland plants which drive species composition 3-7 years following restoration are *Mentha aquatica* and *R. aquatilis*. Whereas at 8-12 years *S. dulcamara* also has a significant influence on macrophyte assemblages. These results show that having created and restored ponds at different stages post management can add to the biodiversity of the landscape.



(b)


0.6
-0.8
-0.6
0.8
PCA axis 2 = 10.03%
PCA axis 1 = 11.72%

(c)

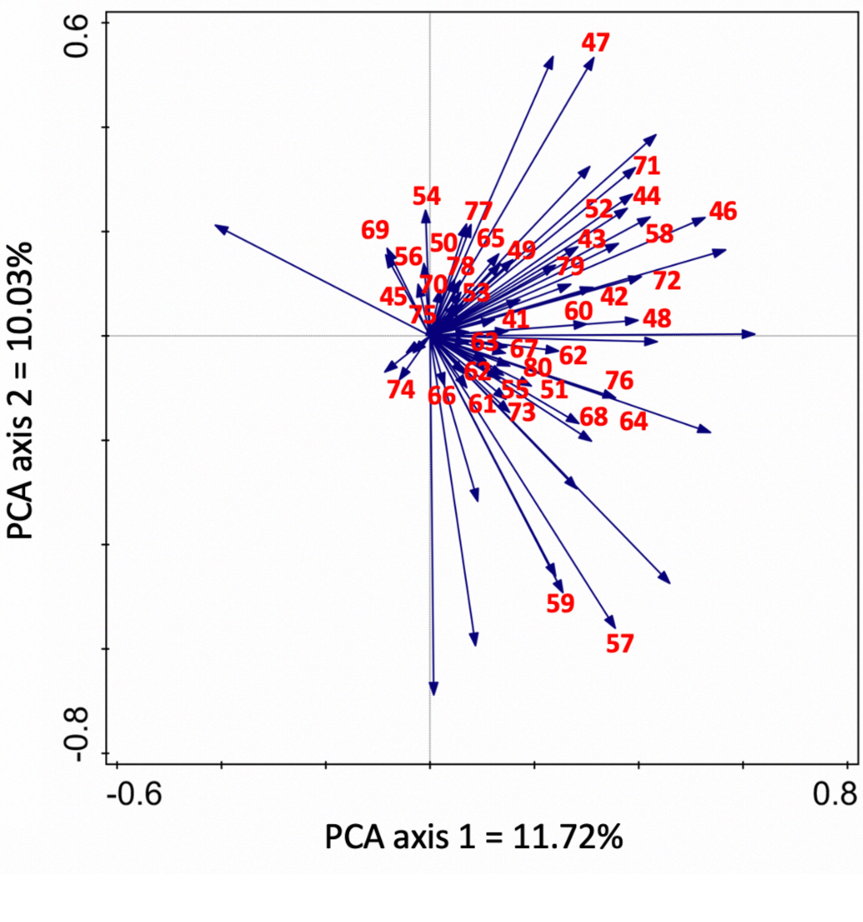

0.6
-0.8
-0.6
0.8
PCA axis 2 = 10.03%
PCA axis 1 = 11.72%

Figure 17. PCA analysis showing the (a) species composition of the restored and created ponds across the different time since management categories and (b + c) the species responsible for these differences (Key: 1= *Agrostis stolonifera*; 2= *Alisma plantago-aquatica*; 3= *Apium nodiflorum*; 4= *Azolla filiculoides*; 5= *Berula erecta*; 6= *Calamagrostis epigejos*; 7= *Callitriche* spp.; 8= *Callitriche obtusangula*; 9= *Callitriche stagnalis*; 10= *Carex acutiformis*; 11= *Carex flacca*; 12= *Carex hirta*; 13= *Carex otrubae*; 14= *Carex pendula*; 15= *Carex pseudocyperus*; 16= *Carex remota*; 17= *Carex riparia*; 18= *Carex vesicaria*; 19= *Ceratophyllum demersum*; 20= *Chara* spp.; 21= *Chara globularis*; 22= *Chara hispida*; 23= *Chara virgata*; 24= *Chara vulgaris*; 25= *Cirsium palustre*; 26= *Crassula helmsii*; 27= *Deschampsia cespitosa*; 28= *Eleocharis palustris*; 29= *Epilobium hirsutum*; 30= *Equisetum palustre*; 31= *Filipendula ulmaria*; 32= *Galium palustre*; 33= *Glyceria fluitans*; 34= *Iris pseudacorus*; 35= *Juncus acutiflorus*; 36= *Juncus articulates*; 37= *Juncus bufonius*; 38= *Juncus effusus*; 39= *Juncus inflexus*; 40= *Lathyrus pratensis*; 41= *Lemna gibba*; 42= *Lemna minor*; 43= *Lemna minuta*; 44= *Lemna trisulca*; 45= *Lotus pedunculatus*; 46= *Lycopus europaeus*; 47= *Mentha aquatica*; 48= *Myosotis scorpioides*; 49= *Myriophyllum spicatum*; 50= *Nitella capillaris*; 51= *Oenanthe aquatica*; 52= *Oenanthe fistulosa*; 53= *Persicaria amphibia*; 54= *Phalaris arundinacea*; 55= *Phragmites australis*; 56= *Potamogeton crispus*; 57= *Potamogeton natans*; 58= *Potamogeton trichoides*; 59= *Pulicaria dysenterica*; 60= *Ranunculus aquatilis*; 61= *Ranunculus flammula*; 62= *Ranunculus peltatus*; 63= *Ranunculus sceleratus*; 64= *Ranunculus trichophyllus*; 65= *Rorippa nasturtium-aquaticum*; 66= *Rumex crispus*; 67= *Schoenoplectus lacustris*; 68= *Schoenoplectus tabernaemontani*; 69= *Scrophularia auriculata*; 70= *Silene flos-cuculi*; 71= *Solanum dulcamara*; 72= *Sparganium erectum*; 73= *Tolypella glomerata*; 74= *Tolypella intricata*; 75= *Typha angustifolia*; 76= *Typha latifolia*; 77= *Veronica anagallis-aquatica*; 78= *Veronica beccabunga*; 79= *Veronica catenata*; 80= *Zannichellia palustris*).

5. Discussion

This section seeks to understand the differences in the alpha and gamma diversity between the created and restored ponds, which will be explored by comparing the habitat characteristics and colonisation patterns of both types of ponds over different timescales. These findings can have important implications for conservation across agricultural regions, which can help guide best practice to pond management.

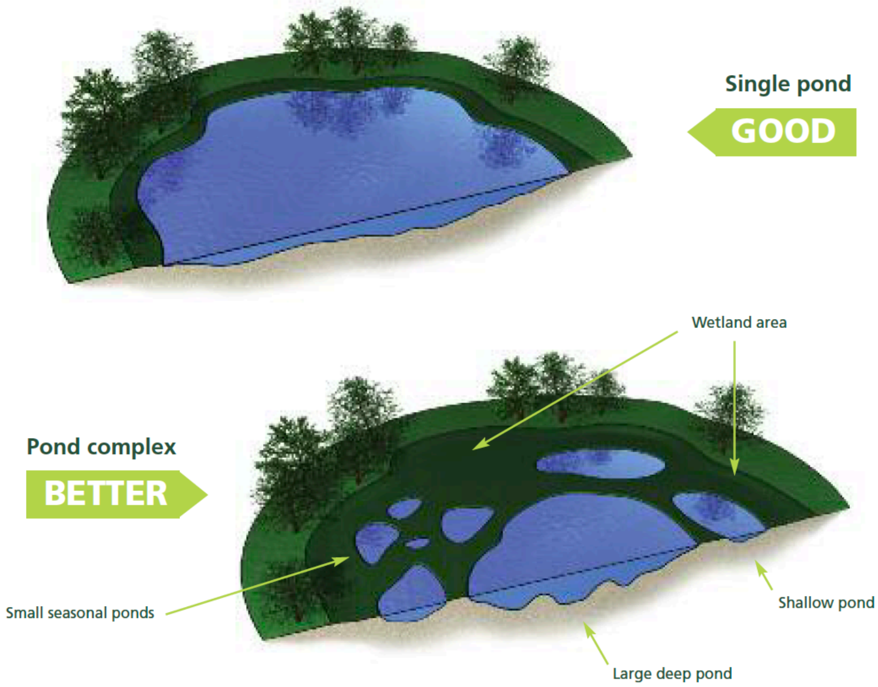
5.1. Morphological and environmental differences between created and restored ponds

There were some clear morphological differences between the newly created and restored ponds which could be explained by the differences in their origins. Although the difference in area and marginal complexity between the created and restored ponds was not statistically significant, the restored ponds were still slightly larger and less complex in shape (**Fig. 9, 10**). Like many old agricultural ponds in the UK, many of the restored ponds in this Suffolk study were likely dug as clay pits during the medieval period in order to extract clay for construction materials (e.g. clay lump, wattle and daub buildings) (Prince 1962). As the purpose of these ponds was to extract marl, they were likely dug deeper than the created ponds, which has resulted in a lot of these old agricultural ponds being large and steep sided (Prince 1962; Sayer *et al.* 2013). Many of the restored ponds in this study also tended to have at least one gently sloping side. This was probably used to create a gentle gradient so that an ox/horse-pulled cart to enter the pit and load the clay for ease of transporting material (SWT 2020). Furthermore, when these ponds came to be used later for other purposes such as drinking water, these gentle gradients were likely used to enter and clean out the ponds of organic matter (SWT 2020). Therefore, having a less complex shape to these old marl-pit ponds would make it easier to carry out these historic uses. At the Bramfield sites, pond BRO5, BRO10, BRO22 and EAR17 have been noted as particularly large and deep and it is suspected they may have been used for flax-retting (SWT 2019; SWT 2020). This is a process whereby bundles of flax or hemp were weighed down under water to separate the fibres for weaving linen (Higham 1989). Suffolk was an important centre for sailcloth manufacture during the 1600 and 1700’s and under the Act of Parliament by Henry VIII, retting could not take place in rivers but only in the ground or in pits (Fordham 2005;

Halesworth 2021). Furthermore, given the Acts of Parliament of 1533 and 1563 required that a quarter of an acre of hemp or flax should be grown on farms that were over sixty acres, it may be that some of the restored ponds were originally large retting pools which could explain why they were slightly bigger than the created ponds (Halesworth 2021).

The created ponds that have been dug across these agricultural regions tend to be smaller with more complex margins (**Fig. 9, 10**). On one hand, this is surprising considering most man-made ponds which are dug for various cultural and everyday purposes are often circular in shape. For example, garden fishponds are often circular as it is advised they have smooth simple margins to maintain water circulation (Any Pond 2021). However, the ponds created by the SWT have been deliberately designed for the purposes of conservation to maximise opportunities for wildlife. In particular, there has been an emphasis on creating ponds with varying shapes, depths and uneven underwater profiles to create various microhabitats that could give rise to different species communities (**Fig. 18**) (SWT 2014; SWT 2019; Freshwater Habitats Trust 2021c). There is also some consensus that lots of small ponds could give rise to more species than one large pond with a similar total area, meaning that the slightly smaller size of newly created ponds in Suffolk should benefit biodiversity (Gee *et al.* 1997; Oertli *et al.* 2002).

(a)



(b)

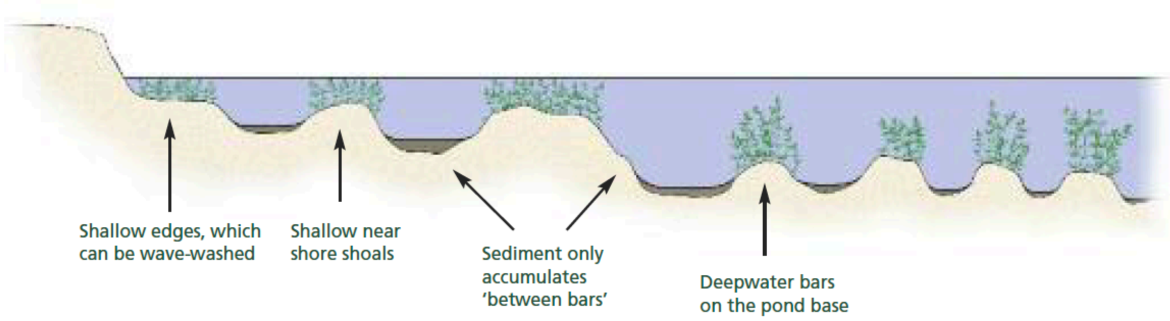


Figure 18. Showing the ideal ways of designing new ponds to create more habitats for wildlife which inspired the ways ponds were created by the Suffolk Wildlife Trust: (a) creating pond complexes and (b) varying underwater topography (Freshwater Habitats Trust 2021c).

There is also evidence that the morphology of the restored and created ponds have influenced the resulting species communities, especially the rare macrophytes. When the restored ponds underwent management, micro-topographical differences were created on the pond floor whilst still maintaining the historic integrity of their banks and margins (SWT 2020). Consequently, following patch-treatment of restored pond BRO6, *N. capillaris* was able to establish on exposed substrate on a shallow underwater shelf (0-40 cm) on the pond edge (**Fig. 19**) (SWT 2019). It has been suggested that these sorts of raised platforms such as underwater bars and shoals prevent the accumulation of organic matter, allowing substrate to fall off these high areas into the deeper water (Freshwater Habitats Trust 2021c). This keeps bare substates exposed which are often ideal for stonewort growth (Freshwater Habitats Trust 2021c). However, many of the created ponds in this study also had similar uneven and shallow underwater topographies, but none gave rise to *N. capillaris*. Given the history of these old restored ponds and their existence in previously species rich farming landscapes, *N. capillaris* was likely established in BRO6 due to seed bank disturbance. This suggests that although pond morphology could be important to the establishment of certain macrophytes, the type of species that colonise ultimately depend on seed availability.

Figure 19. Location of *Nitella capillaris* in BRO6, May 2019 (photo and caption credits © Juliet Hawkins).

One of the most important environmental variables which likely influenced the resulting pond communities was shading. Over the three time periods studied, shading of the restored ponds was on average 20%, whereas for the created ponds it was 0% (**Fig. 11**). Some level of canopy cover can be important for ponds as it can provide different habitat conditions, allowing species with various shade tolerances to colonise (Joye *et al.* 2006; Hassall *et al.* 2011). Although chemical variables were not recorded in this study, shading often results in a higher input of organic matter and reduced dissolved oxygen levels in ponds (Bronmark and Hansson 2005). As a result, species known to be more tolerant of shade and higher nutrient conditions, such as *Lemna minor*, *Lemna minuta, S. dulcamara* and *Persicaria amphibia*, were far more abundant in the restored ponds than the created ponds (Thompson *et al.* 1984; Moss 2002; Williams *et al.* 2020). This shows how differences in the canopy cover related to the type of managed pond could provide more heterogeneous conditions in the landscape to improve gamma diversity.

Temporal changes in the shading of the restored and created ponds has likely influenced differences in their community composition. Both created and restored ponds showed a slight increase in canopy cover over time with the restored ponds showing a greater rise (**Fig. 11**). At 8 – 12 years, the species richness of the restored ponds was still relatively high and did not resemble that of typical late-stage terrestrialised ponds characterised by low macrophyte cover (Sayer *et al.* 2012). The reason terrestrialisation didn't take place in the restored ponds was likely due to regular maintenance which included coppicing and flailing by the landowners to retain a mosaic of habitat surroundings around each pond (J. Hawkins, pers. comm., 6 March 2021). In contrast, most created ponds never developed any shading as they were largely located in meadows grazed by stock. Cattle grazing can affect the composition of wetland plants by suppressing the growth of marginal macrophytes (Declerck *et al.* 2006). This can often lead to assemblages dominated by tough grazer-resistant species such as *J. effusus*, which was present across several created ponds in this study (Gioria *et al.* 2010). Alternatively, tall emergent plants such as *Phragmites australis*, which are negatively affected by grazing were only able to grow in restored ponds located in arable fields that were free from cattle (Biggs *et al.* 1994). Grazing and trampling by livestock can also create muddy margins with complex micro-topography which in this study gave rise to species of high conservation value (Biggs *et al.* 1994). For example, a number of wetland plants unique to created ponds such as *Calamagrostis epigejos* and *Lathyrus pratensis*, are suited to the open ground conditions resulting from livestock activity (**Fig. 16**) (Dawson and Warman 1987; Smith and Rushton 1994; Hazi *et al.* 2011). This shows that differences in the land use surroundings of created and restored ponds are able to provide unique habitat conditions that could give rise to a greater diversity of aquatic species.

5.2. Colonisation patterns and temporal development

5.2.1. Early colonisation

The created and restored ponds colonised in very different ways in the first two years following management. The species richness between the created and restored ponds was significantly different ($P<0.0001$) over this period with a median species richness of 10 macrophytes in the restored ponds and a median species richness of two in the created ponds (**Fig. 13**). This could be explained by differences in the origins and colonisation history of both types of ponds. The restored ponds, which are thought to be around 400-500 years old, were likely once nestled within damp hay meadows in farmlands which were abundant with wildlife (Riley 2005). There were also more cattle in pre-industrial agricultural landscapes which could allow greater seed dispersal meaning a large diversity of aquatic plants could have colonised these old restored ponds. To survive habitat desiccation, like the infilling and neglect experienced by farmland ponds following the intensification of agriculture, many macrophytes have evolved dormant propagules which can allow for the rapid species' re-establishment following restoration (Bonis and Grillas 2002; Carta 2016). Of the ten most common species to rapidly colonise restored ponds in the first two years of this study (**Table 7**), *C. vulgaris, J. inflexus, P. natans* and *R. aquatilis* have been shown to have long-lived seedbanks that can remain viable for many decades (Beltman and Allegrini 1997; Kaplan *et al.* 2014; Alderton *et al.* 2017). Of these species, the charophytes are typical pioneer plants which are suited to uncompetitive open waters and could promote complex habitat structure but have rapidly declined in agricultural landscapes due to wetland degradation (Lambert and Davy 2011). Furthermore, floating-leaved plants which likely arose from seed banks such as *P. natans* have shown to be particularly beneficial to increasing the diversity of odonates in farmland ponds by enhancing water quality and providing foraging resources (Raebel *et al.* 2012). As typical farmland ponds in the UK support between 7 to 14 aquatic plants, pond restoration in this study has been shown to increase macrophyte diversity and the connectivity of pond habitats whilst also giving rise to high-conservation value species over a very short time period (Davies *et al.* 2008).

Table 7. Most commonly occurring species in created and restored ponds across each time period. The number in brackets shows the percentage of ponds in which this species was found within that time and management category (n = number of ponds in time category).

Time since management	Created ponds (C)	Restored ponds (R)
1-2 years	*Agrostis stolonifera* (45)	*Agrostis stolonifera* (69)
	Chara spp. (73)	*Alisma plantago-aquatica* (52)
C (n = 11)	*Juncus inflexus* (36)	*Chara vulgaris* (58)
R (n = 36)		*Epilobium hirsutum* (56)
		Juncus inflexus (50)
		Potamogeton natans (67)
		Ranunculus aquatilis (50)
		Ranunculus sceleratus (47)
		Solanum dulcamara (47)
		Typha latifolia (53)
3-7 Years	*Agrostis stolonifera* (76)	*Agrostis stolonifera* (44)
	Chara globularis (54)	*Alisma plantago-aquatica* (44)
C (n = 13)	*Chara vulgaris* (62)	*Carex otrubae* (44)
R (n = 18)	*Juncus articulatus* (54)	*Epilobium hirsutum* (56)
	Juncus inflexus (77)	*Iris pseudacorus* (39)
	Potamogeton natans (69)	*Juncus effusus* (39)
		Juncus inflexus (67)
		Lycopus europaeus (61)
		Mentha aquatica (61)
		Potamogeton natans (44)
		Ranunculus aquatilis (50)
		Typha latifolia (39)
8-12 years	*Agrostis stolonifera (93)*	*Agrostis stolonifera* (56)
	Alisma plantago-aquatica (57)	*Alisma plantago-aquatica* (61)
C (n = 14)	*Carex flacca (50)*	*Carex otrubae* (39)
R (n = 18)	*Chara vulgaris (57)*	*Epilobium hirsutum* (67)
	Eleocharis palustris (50)	*Juncus effusus* (50)
	Glyceria fluitans (43)	*Juncus inflexus* (72)
	Juncus articulatus (64)	*Lemna minor* (39)
	Juncus inflexus (79)	*Lemna trisulca* (44)
	Potamogeton natans (93)	*Lycopus europaeus* (39)

Pulicaria dysenterica (71)	*Potamogeton natans* (56)
Typha latifolia (43)	*Solanum dulcamara* (61)
	Sparganium erectum (39)

The lower species richness of the newly created ponds in the early years following management could be explained by the reliance of these ponds on other mechanisms of seed dispersal rather than seed banks. One of the most common transport mechanisms for seeds across wetland landscapes is through animal dispersal which means it could take time for plant propagules to reach the site (Figuerola and Green 2002; Williams *et al.* 2008). In the first two years following management the most frequently occurring species found in the new ponds were *A. stolonifera, Chara* spp. and *J. inflexus* (**Table 7**). Of these, *Chara* spp. and *J. inflexus*, which occurred in 73% and 36% of created ponds, respectively, have been shown to produce viable oospores in the digestive tracts of waterfowl which could spread easily between ponds (Kristiansen 1996; Espinar *et al.* 2006). In particular, *Chara* spp. can thrive in unpolluted and uncompetitive environments which could provide an explanation for its colonisation across many of the early-successional created ponds (Beltman and Allegrini 1997). Most of the newly created ponds surveyed at 1-2 years were located in BBVNR, and in the PCA were clustered together indicating they had a similar species composition (**Fig. 17**). This was likely due to their close physical proximity which has meant they were probably exposed to the same seeds arriving from animal or wind dispersal. In contrast, the only newly created pond surveyed at 1 -2 years outside BBVNR was WYK14 which had a higher species richness of 9 macrophytes and quite different species composition than other ponds in this management category (**Fig. 17**). This included aquatic plants such as *E. hirsutum*, which has seeds with a high terminal velocity and could have travelled over several kilometres to the pond by wind dispersal (Soons 2006). Therefore, the reason for the greater variation in species composition between newly created ponds that are located further from each other could be due to the differences in seed dispersal influenced by environmental factors such as proximity to other wetlands and local vegetation (Beltman and Allegrini 1997). Hence, the advantage of digging new ponds is that they can be located in various locations and surroundings which could help improve gamma diversity due to differences in the types of macrophytes available to colonise.

5.2.2. Later colonisation

In the mid – later years following management, the created and restored ponds continue to colonise at different speeds and show various changes in species compositions. The difference in species richness of the restored ponds at 3-7 and 8-12 years was not statistically significant from 1-2 years and shows a stabilisation in the median number of macrophytes per restored pond (**Fig. 13**). However, there was a change in the species composition of the restored ponds over the later periods with more dominant and competitive species such as *T. latifolia*, *Sparganium erectum* and *L. minor* becoming more common, whilst the early colonisers such as the charophytes becoming less a feature (**Table 7**). The seeds of these competitive plants are likely already dormant in the sediment of the old ponds and so can quickly come to life following restoration and reach a dominant position very quickly. Although the abundance of each macrophyte was not recorded in this study, given the typical growth trajectories of these invasive plants, species like *T. latifolia* can rapidly spread to form dense rhizome mats that contribute to anoxic conditions in the pond, reducing the opportunities for submerged and floating plants to establish (Houlahan and Findlay 2004). Therefore, the later years of colonisation of the restored ponds were typical of later stage pond succession which show an increase in the structural diversity of macrophytes as more emergent species become established (Barnes 1983). In this study, this involved the encroachment of marginal plants such as *C. otrubae*, *J. effusus*, *L. europaeus*, *M. aquatica* and *S. dulcamara* which likely arrived through animal and wind dispersal, becoming some of the most common species to occur in the restored ponds in later years (**Table 7**). This stage of pond colonisation can often benefit invertebrate species richness, given the complexity of vegetative habitat structures that can be colonised by more specialised insects (Nilsson 1984). However, if these previously restored ponds are left unmanaged, the overgrowth of these emergent plants could eventually lead to terrestrialisation and the loss of diverse macrophytes (Sayer *et al.* 2012; Sayer *et al.* 2013). Hence, the need for regular pond management, to remove the dominant plants and provide opportunity for less competitive macrophytes to periodically thrive.

In contrast to the restored ponds, the macrophyte richness of the created ponds continued to rise in the later years of management. This increase was statistically significant across all time periods and was likely due to the time it takes for seeds of different macrophytes to arrive through mainly animal and wind dispersal (**Fig. 13**). In the PCA, the created ponds surveyed at 8 – 12 years and the restored ponds at 1 – 2 years, occupy a similar space in the bottom two quadrants of the ordination (**Fig. 17**). This suggests that it takes around 8-12 years for the created ponds to reach a similar successional stage that the restored establish quite early after management. The species that were common between the early stage restored ponds and the created ponds in later years included A. *stolonifera, A. plantago-aquatica, C. vulgaris, J. inflexus, P. natans* and *T. latifolia* (**Table 7**). Furthermore, unlike the later-stage restored ponds, there hasn't been a rapid development of a diversity of marginal species at these created ponds at 8-12 years. This is likely due to the regular grazing and poaching of emergent plant growth by livestock which slows down their colonisation (Biggs *et al.* 1994). Furthermore, many of the created ponds are also quite shallow with gently sloping sides which could allow cattle to enter and bathe, allowing the regular disturbance of the sediment floor to naturally reset succession. It shows that created ponds, located in meadows, could providing quite stable habitats conditions that may allow a range of macrophytes to survive over long periods with little management.

5.3. Conservation implications

5.3.1. Rare and unique species

A key target of conservation measures in Suffolk has been the protection of rare and unique species. Across all time periods, the restored ponds gave rise to 0.5 unique species/pond compared to only 0.13 unique species/pond in the created ponds (**Fig. 16**). Furthermore, at the landscape scale restored ponds gave rise to considerably more macrophytes across all time periods (**Fig. 14**). This was likely the result of quicker colonisation from seed banks as well as absence of livestock activity which allows a greater number of unique macrophytes to colonise the restored ponds over time (Biggs *et al.* 1994; Alderton *et al.* 2017). Furthermore, the grass margins (>6m) used around the arable field ponds appeared to be effective buffers against agricultural pollution, allowing restored ponds to remain species rich over decadal timescales. Although at present there is a greater emphasis in the UK on pond creation, these results suggest that if restored ponds are managed in an optimum way, as part of the everyday farm system, they will likely provide richer environments than newly created ponds that rely on chance for plants and other species to colonise.

At 1 – 2 years following management, three of the four rare unique species that were able to colonise the restored ponds were priority conservation stonewort species that are nationally scarce (**Table 6**). This included *N. capillaris*, which was thought to be extinct in England since 1959, as well as *T. glomerata* and *T. intricata* (Hawkins 2019). What was also interesting about the re-appearance of these three rare stoneworts was their relationship to the timing of pond restoration. At least 60% of ponds at BRO supported 2 – 3 rare stoneworts the following spring after restoration that took place from August to September. Whereas ponds restored from October to January contained either one or no rare stoneworts. It is hypothesised that this is likely due to the greater competitive advantage that rare stoneworts can have over more dominant species if they are able to germinate from dormant seed banks in Autumn as they can remain in a state of hibernation until the spring (J. Hawkins, pers. comm., 6 April 2021). However, ponds which were cleaned later in the autumn or winter were more at risk from being outcompeted by more dominant species that also tend to become established from dormant oospores around this period (J. Hawkins, pers. comm., 6 April 2021). Therefore, ideally the timing of mechanical restoration works should take place in Autumn, but preferably around October/November to minimise the disturbance to *T. cristatus* which tend to hibernate until September (SWT 2020).

The created ponds in this study only gave rise to unique rare species in the later years following management (**Table 6**). Of these, *T. glomerata* was the only rare stonewort that was recorded in the created ponds. It seems unlikely that created ponds will ever establish a similar number of rare species as the restored ponds given that colonisation in newly created ponds is mainly influenced by slower mechanisms of seed dispersal that are often dependent on chance. This is especially the case for the rare pioneer plants, such as the stoneworts, that only have a small window of opportunity to arrive and establish when the created ponds are in the early stages of succession. Therefore, to improve the chances of rare stoneworts growing in the created ponds, in 2011 the Freshwater Habitats Trust funded a translocation experiment of *T. intricata* from the restored pond in which it was found

(BBV5), to five other created ponds in the same reserve (BBV13, BBV14, BBV15, BBV16, BBV19) (SWT 2017). It is hoped that by transporting the mud and material, which may contain the *T. intricata* oospores, it may be possible to secure new populations of stoneworts (Hawkins 2019). To date, *T. intricata* has not yet grown in the newly created ponds. This could be due to various reasons from differences in the physico-chemical conditions in the new ponds or even lack of seed banks in the soil that was translocated. Nevertheless, it seems important to understand why *T. intricata* oospores could not grow in the new ponds as it may help to identify the ideal conditions that promote germination. This could be useful for carefully planning future translocation projects that could increase the resilience of rare macrophytes across Suffolk through creating more stable metapopulations.

5.3.2. Surrounding land use and connectivity

Managing the surrounding land use of the different types of ponds in this study was important to influencing their biodiversity over different time periods. The created ponds, which were mostly located in meadows, were appropriately managed to support wildlife communities over the long term. Across the three time periods, regular poaching and grazing by cattle at pond margins helped slow succession meaning most of the new ponds never developed any shading. Given that newly created ponds in this study have only been monitored for a maximum of twelve years, uncertainties still remain as to how they will continue to colonise. It is possible, given the intensity of grazing around these newly created ponds, they are unlikely to develop a high diversity of marginal or shade-tolerant species that are characteristic of the mid-late successional restored ponds. Therefore, created ponds may remain relatively unshaded and less competitive habitats that allow a greater diversity of submerged and floating plants to survive for long periods with little management. However, allowing trees and shrubs to develop around ponds could also be beneficial, especially for farmland birds which have been shown to utilise trees for food resources, shelter and nesting (Lewis-Philips *et al.* 2020). As created ponds colonise more slowly, the presence of trees at these ponds could increase seed dispersal by birds, thus improving the speed of colonisation by possibly more diverse wetland plant species. Therefore, it could be interesting to fence off some of meadow ponds to see how they develop in the absence of livestock. Not only could this lead to a divergence in the typical plant communities that colonise the created ponds, but also the emergence of different species of insects and birds that are adapted to more shaded conditions.

One of the main advantages of pond management in Suffolk has been improvement to the connectivity and species dispersal across various land use settings across the pondscapes. However, it is also important to acknowledge the plethora of problems associated with higher connectivity, particularly the spread of pathogens or invasive species through livestock, humans or machinery (Jackson and Pringle 2010). In Suffolk, there is growing concern about the spread of invasive plant *C. helmsii*, which to date has been found across three ponds monitored by the SWT. Given *C. helmsii*'s high plasticity in its photosynthetic processes, reproductive mechanisms and morphology, currently most control measures are not consistently effective at eradicating this species (Van Der Loop *et al*. 2018). However, given its low occurrence in Suffolk ponds so far, the best course of action will likely be to contain the population by experimenting with elimination measures as well as fencing of *C. helmsii* ponds to prevent spread by livestock (Smith and Buckley 2020). Similarly, if all other invasive plants are controlled and monitored, they are unlikely to interfere with improvements in connectivity and biodiversity resulting from pond management.

Overall, there appears to be much benefit in having both created and restored ponds at different successional stages across the Suffolk pondscape. Restored ponds have a higher gamma diversity, whilst also giving rise to more rare and unique wetland plants over the three time periods studied (**Fig. 14**, **Table 5, 6**). Although created ponds gave rise to fewer species on the landscape scale, the PCA shows they are comprised of different macrophyte communities compared to the restored ponds, thus enhancing landscape biodiversity (**Fig. 14**, **17**). Furthermore, as there is greater control over the location of newly created ponds, they can be dug in close proximity to the restored or other created ponds to improve habitat connectivity. This is especially important as both types of ponds undergo succession and rare species that start to decline can be renewed by dispersal to nearby ponds with more suitable conditions (Briers 2002). This highlights the importance of ensuring ponds are rotationally managed to maximise the types of habitats available at one time so that more species are able to disperse and colonise. It suggests restored and created ponds, if managed effectively, can help to improve biodiversity in agricultural regions through increasing heterogeneity in the habitat conditions and enhancing metapopulation dynamics.

6. Conclusion

To conclude, both pond creation and restoration have been shown to be good for biodiversity conservation in an agricultural setting. Although the dominant approach to pond conservation in the UK has been pond creation, this study has shown that restored ponds contribute significantly more species to the landscape, as well as more rare and unique macrophytes, than created ponds. This is likely due to the disturbance of long-lived seed banks in the restored ponds which allows a wide range of species, including those which were more abundant during previous centuries, to colonise very quickly following management. Given that most pond restoration takes place in arable fields, there is concern restored ponds may have a higher risk of eutrophication and have shorter lifespans without regular management (Freshwater Habitats Trust 2021a). However, this study has shown that both created and restored ponds can produce species rich habitats over decadal timescales if their surrounding land uses, such as agricultural operations and livestock activity, are managed effectively. It suggests that in an agricultural landscape, we should not neglect pond restoration, as the ability of restored ponds to disperse through time is likely what will bring many rare species back onto the landscape. This could be used effectively alongside pond creation which can help spread these high-quality habitats across the countryside, helping to improve biodiversity across species-poor environments.

This study also highlights the importance of using collected data to evidence and inform future conservation works. The huge efforts of the Suffolk Wildlife Trust and Juliet Hawkins to regularly monitor these Suffolk ponds over the last two decades has provided a wealth of data for this study. However, as shown by the ongoing Norfolk Ponds Project, underpinning data in research and science could bring greater confidence in the potential for conserving biodiversity through farmland pond management (Sayer and Greaves 2020). In this study, the findings have helped to provide a strong evidence base for the biodiversity value of pond restoration, which could be used effectively in combination with pond creation to improve gamma diversity. Promoting this type of science-led conservation can be vital to improving freshwater biodiversity by helping to give farmland pond management, especially pond restoration, greater priority within the UK's conservation agenda.

Auto-critique

As the first study to compare pond creation with restoration, this dissertation has shown that created and restored pond can provide a unique contribution to biodiversity across an agricultural landscape. The strong biological emphasis of this study, based on comparing species richness and macrophyte communities, was a strength as it helped to understand the biodiversity value and habitat quality of both types of ponds in the years following management. I did not include any control sites, as there were few terrestrialised ponds that had been surveyed by the Suffolk Wildlife Trust. Although numerous studies have shown improvements in pond biodiversity following restoration, including control data could have helped to provide a more accurate indication of the extent to which restoration affected biodiversity. Due to the extremely time intensive nature of compiling the data, I was only able to look at macrophytes. However, it may have also been beneficial to include invertebrate and vertebrate data for this study, particularly the presence of amphibians could have helped give a clearer indication of the connectivity of the managed pondscapes. Comparing the rare and unique species of the restored and created ponds was another strength of this study as it showed that restored ponds have a considerably higher biodiversity value than the created ponds, suggesting it is important not to neglect restoration. The created ponds have only been monitored for a maximum of twelve years so it is possible over time more of the rare species could disperse from the restored ponds into the created, especially if they are within close physical proximity. Therefore, next time I think it would be interesting to include created ponds in this study which are older than 12 years and to assess the relationship between the connectivity between both created and restored ponds and their relationship to the types of rare and unique macrophytes.

Assessing the differences in the habitat characteristics of the created and restored ponds has helped clarify the extent to which pond morphology, shading and surrounding land use influenced the macrophyte assemblages and their persistence through time. It would have also been helpful to collect water chemistry data for the ponds such as temperature, pH, oxygen, nitrate and phosphate levels. This could help establish the relationship between the macrophyte communities and their environment such as helping to clarify the extent of eutrophication within the arable field ponds.

Ultimately, this study only looks at ponds across the county of Suffolk. The patterns that have been established in this region may not be applicable to other agricultural settings due to differences in the types of vegetation or the way created and restored ponds have been managed. Therefore, it could also be useful next time to look at how pond creation and restoration compare in other farmland regions to help further validate the patterns found across pondscapes in Suffolk.

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Appendices

Appendix 1 – Moodle Source Data Upload

File name: suffolkpondsdata.xls
File content: Biological and habitat data for all pond surveys used in this study.

Appendix 2 – Summary of all pond surveys used in this study.

Pond Code	Management Status	Year of management	Surveys
BRI4	Created	2009	2018
BRI5	Created	2009	2018
BRI6	Created	2009	2019
BBV3	Restored	2008	2009, 2010, 2017
BBV4	Restored	2008	2017
BBV5	Restored	2008	2017, 2020
BBV6	Restored	2008	2011, 2017
BBV8	Restored	2008	2012, 2017
BBV9	Restored	2008	2017
BBV10	Restored	2008	2012, 2017
BBV13	Created	2010	2010, 2011, 2012, 2017, 2020
BBV14	Created	2010	2012, 2013, 2017, 2020
BBV15	Created	2010	2012, 2017, 2020
BBV16	Created	2010	2017, 2020
BBV17	Created	2010	2012, 2014, 2017, 2020
BBV18	Created	2010	2012, 2017, 2020
BBV19	Created	2010	2012, 2013, 2017, 2020
BBV20	Created	2010	2012, 2013, 2017, 2020
BRO1	Restored	2018	2019
BRO2	Restored	2018	2019, 2020
BRO3	Restored	2018	2019, 2020
BRO4	Restored	2018	2019, 2020
BRO5	Restored	2018	2019, 2020
BRO6	Restored	2019	2020
BRO7	Restored	2019	2020
BRO8	Restored	2019	2020
BRO9	Restored	2019	2020
BRO10	Restored	2019	2020

BRO11	Restored	2019	2020
BRO12	Restored	2019	2020
BRO13	Restored	2019	2020
BRO15	Restored	2019	2020
BRO16	Restored	2019	2020
BRO22	Restored	2019	2020
BRO23	Restored	2019	2020
BRO24	Restored	2019	2020
EAR5	Restored	2009	2019
EAR6	Restored	2018	2019
EAR7	Restored	2018	2019
EAR8	Restored	2009	2018
EAR9	Created	2009	2018
EAR10	Restored	2018	2019, 2020
EAR14	Restored	2018	2019
EAR16	Restored	2009	2018
EAR17	Restored	2019	2020
EAR18	Created	2009	2018
EAR19	Created	2009	2018
EAR20	Restored	2009	2018
EAR21	Restored	2009	2019
ILK1	Restored	2016	2020
ILK3	Restored	2014	2020
ILK4	Restored	2008	2013, 2017, 2020
ILK6	Restored	2016	2017, 2020
ILK8	Restored	2011	2020
ILK10	Restored	2016	2020
ILK11	Restored	2014	2017, 2020
WYK1	Restored	2002	2005, 2013
WYK2	Restored	2007	2009, 2013
WYK3	Restored	2007	2005, 2013
WYK5	Restored	2007	2013, 2018

WYK6	Restored	2007	2009
WYK7	Restored	2007	2009, 2013
WYK8	Restored	2007	2013, 2018
WYK12	Restored	2004	2005, 2013
WYK14	Created	2007	2009, 2013, 2018

Appendix 3 - Example of a pond recording sheet used in this study for restored ponds. This version has been adapted by Juliet Hawkins and is based on the Suffolk Wildlife Trust recording sheet.

Suffolk Ponds Project RESTORATION RECORDING Sheet

Suffolk Wildlife Trust

Pond Owner	Name	Owner?	Holding/fm name
Address:			
Postcode:	Phone Nos:	Email:	
Secondary contact details:			
Surveyor Name		**Owner's map pond number**	
Date of Visit		Pond **Grid Reference**	
Pond name/number/reference to aid location			
Nearest Village/**Parish**	HSI Pond **Size** m2	Public **Access**? Y / N	
First surveyed by:	Date/year advised		
Pond type	Arable field edge/ Arable mid-field/ Arable buffered by grass margin/ Improved grass/ Unimproved grass / Woodland / Garden/ Farmyard/ Other describe: Good terrestrial habitat and links to other ponds?		
Date restored	Monitoring year after restoration 1 2 3 4 5 6 7 8 9		
Work done: Coppiced margins/Organic matter removed/ Buffered with margin/Some scrub left/Historic integrity maintained/Other .... What?	Grant aid? Other ponds restored nearby?		

Subjective measure of how well the pond was restored: 1 poor - 5 really well: 1 2 3 4 5
Historically appropriate: Yes / No .... describe
Really well no need to do any more
Partial might need some more coppicing work
Partial might need some more de-silting/re-grading
Essential ongoing coppicing/sallow removal to keep pond open

Who did coppicing?	Farm staff	Contractor (who)	Cost if known
Who did de-silting?	Farm staff	Contractor (who)	Cost if known
Where was spoil put?	On arable	On grass spread thinly	In heap
How many other ponds restored at the same time?			
Has the pond filled up with water	Completely full	Partially full	Empty
Did pond experience a bad flush of algae	Yes (1st year)	Yes until .... year	No not so far/No never
Other problem/comments			

HSI Water quality Good / Some problems / Polluted | Average winter depth cm: < 50 cm / > 50

Describe problems: Full of leaf litter / Turbid / Green (phytoplankton) / Blanketweed/ Oil on surface / Evidence of spray drift on banks / duck stirring/enrichment

Underwater bank profile: Almost vertical all perimeter/ Varied steep & gentle 1 in 4 gradients/ Gentle all perimeter

HSI How much of pond was **dense with vegetation pre-restoration?**	< 25%	25-50%	50-75%	>75%	
HSI How much of pond is **dense with vegetation post-restoration?**	< 25%	25-50%	50-75%	>75%	
HSI How much of pond edge was o**verhung by trees pre-restoration**?	< 25%	25-50%	50-75%	>75%	100%
HSI How much of pond edge is o**verhung by trees post-restoration**?	< 25%	25-50%	50-75%	>75%	100%
How much **algae post-restoration?** Blanketweed/ suspended	< 25%	25-50%	50-75%	>75%	
How much was d**ominated by duckweed pre-restoration**?	< 25%	25-50%	50-75%	>75%	

How much was d**ominated by duckweed post-restoration**?	< 25%	25-50%	50-75%	>75%
HSI **Waterfowl** impacts no noticeable impact / noticeable (runways-footprints-feathers) / heavy impact				
Describe impact: Eroded edges / turbid water / green water / grazed edges /ducklings	**Moorhen** present: Seen or heard/ nest			

Amphibian species present (use combi code eg AR4 – see above)		AILE? Egg search/netted/refugia	
GREAT CRESTED NEWT	Nos Eggs Laid on what plants	Est of GCN pop size (based on egg no, larvae no, pond size, no of plants, pond health, time of yr):	Status before R
SMOOTH NEWT	Nos Eggs laid on what plants		Present before R
FROG	Nos?		Present before R
TOAD	Nos?		Present before R
Grass snake		BAP inverts? Sample taken	

No fish/ Fish suspected/seen:: Stickleback / Rudd or roach / Goldfish / Koi carp / Carp or bream or tench / Other:

BAP spp	Water vole	Reed bunting	Song thrush	Turtle dove	Bats	Plants
Stoneworts	Chara					Sample taken
Submerged	Callitriche sp		Ceratophyllum demersum (hornwort)	Pot crispus (curled pondweed)	Ranunculus sp (crowfoot)	
Other submerged: *name if poss*					**Total No of Submerged Species**	
Floating-leaved	Pot. natans	Other floating-leaved:			**Total no of floating leaved**	
Free-floating	Lemna minuta(l) minor/gibba/	Lemna trisulca	Blanketweed	Green Water (phytoplankton)	**Total no free-floating sp**	
Grasses in water	Glyceria fluitans	Agrostis stolonifera			**Total grass sp**	
Emergent	Apium nodiflorum (fool's watercress)	Carex acutiformis (lesser)	Carex otrubae (false fox)	Eleocharis palustris (spike rush)	Epilobium hirsutum (hairy willowherb)	Iris pseudocorus (flag)
Juncus effusus (soft)	J inflexus (hard)	Juncus artic. (jointed)	Lycopus europaeus (gypsywort)	Plantago alisma-aquatica	Mentha aquatic (water mint)	Myosotis scorpiodes (Forget-Me-Not)
Phragmites communis	Phalaris arund (reed canary gr)	Pulicaria dysenterica (fleabane)	Ranunculus repens (creeping buttercup	Ranunculus scleratus (Cel-lvd crowfoot)	Rorippa nasturtium (watercress)	
Sparganium erectum (br burreed)	Solanum dulcamara (bittersweet	Schoenoplectus lacustris (comm. Club rush)	Ver beccabunge (brooklime)	Ver catenata (pink water speedwell)	Ver anagallis aquatic (blue w speedwell)	
Typha latifolia/angustifolia				**Total no emergent sp**		
Invasive non-native plants:						
Check for BAP & other						

INVERTS/MOLLUSCS ETC Sample taken?

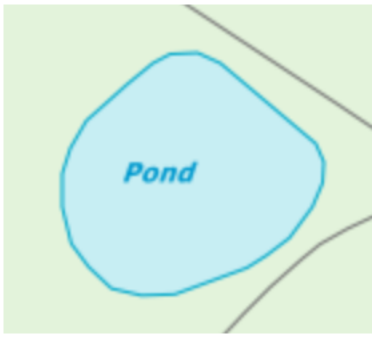
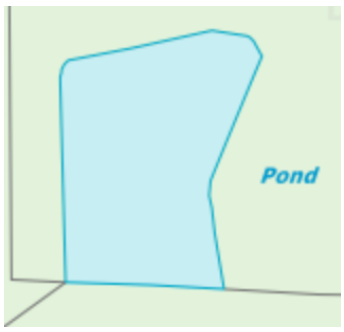
Pond skater	Saucer bug	Water beetle spp	Hoglouse	Freshwater shrimp	Water scorpion
Water boatmen	Pond snail	Ramshorn snail	Mayfly numph	Dragonfly nymph	Damselfly nymph
Other species properly identified:					

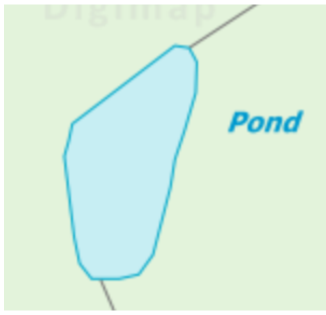
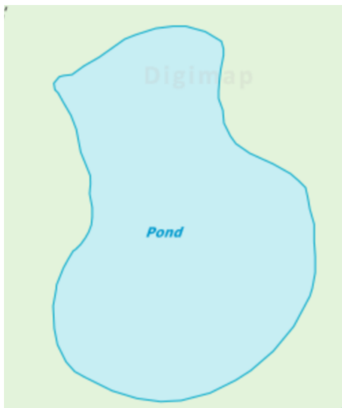
Dragonflies	Large red	Red-eyed	Azure	Common blue	Blue-tailed	Variable	Banded	Emerald	Small red-eyed	
Hairy	Broad-bo chaser	Black-tail skimmer	4-spot chaser	Scarce chaser	Norfolk hawk BAP	Emperor dragon	Brown hawker	Ruddy darter	Common darter	Southern hawker
Migrant hawker	Others	White legged damsel								

NZ pigmyweed /parrots feather/Canadian pondweed/water fern/least duckweed/other:

Threats to site	Shade/leaf litter / succession / changed drainage - drying out / agri-pollution / fish / duck / Other:		
Mgmt recommended	Let light in/monitor	Remove organic matter/de-silt	Remove fish/ don't restock/publicise no fish
Coppice shading shrubs	Pollard smaller trees	High-prune landscape feature trees - let light in	Leave/pile up dead wood
Re-profile accessible/other edges	Consult archaeological before re-profiling/changing shape		Care in spoil disposal
Remove invasive/alien plant:	See to source of pollution		Re-coppice regularly:
Do not introduce plants	Publicise no-fish policy	Create grass margin	Link pond with others (grass/hedge etc)
Dig a new pond nearby	Discourage/stop feeding duck	Other	

Appendix 4 – How marginal complexity scores for each pond was calculated in this study (adapted from Pond Action 1998)

Marginal Complexity Score	Description (Quotes from Pond Action 1998)	OS Map Image (1:25,000)
1	**<u>Circle</u>**: 'Very simple, i.e. circle'	 *(e.g. BRI4)*
2	**<u>Square</u>**: '10% greater length of margin (i.e. square not a circle)'	 *(e.g. BRO12)*
3	**<u>Elongated</u>**: In between 'square shape' and 'length c. double bank length that pond would be if a circle'	 *(e.g. BBV6)*

4	**<u>Elongated</u>**: 'length c. double bank length that pond would be if a circle'	 *(e.g. EAR14)*
5	**<u>Elongated</u>**: 'length c. 3x bank length that pond would be if a circle'	 *(e.g. EAR9)*
6	**<u>Elongated</u>**: 'length c. 4x (or more) bank length that pond would be if a circle'	 *(e.g.BBV18)*
7	**<u>Complex:</u>** two distinct sections within the pond.	 *(e.g. LKT4)*

8	**<u>Complex</u>**: Three distinct sections within the pond.	 *(e.g. BBV19)*
9	**<u>Complex:</u>** Four distinct sections within the pond.	 *(e.g. EAR4)*
10	**<u>Complex</u>**: 'pool with an impossibly convoluted margin and/or many islands' i.e. having 4+ unequal sections in the pond	*No example as I have judged that no ponds in the study fall in this category.*

Appendix 5. The percentage of created (red) and restored (black) ponds that each species occurs in each time since management category across each time period (Key: underlined species = invasive species, bold species = regionally rare species, n = number of ponds in each time category).

	1-2 years (n = 11) (n = 36)	3-7 years (n=13) (n=18)	8-12 years (n=14) (n=18)	All time periods (n=38) (n=72)
Agrostis stolonifera	45 (69)	76 (44)	93 (56)	74 (60)
Alisma plantago-aquatica	18 (52)	31 (44)	57 (61)	37 (53)
Apium nodiflorum	- (6)	- (-)	- (-)	- (3)
<u>*Azolla filiculoides*</u>	- (-)	- (6)	- (-)	- (2)
Berula erecta	- (-)	- (11)	- (-)	- (3)
Calamagrostis epigejos	- (-)	8 (-)	14 (-)	8 (-)
Callitriche spp.	- (14)	- (17)	- (-)	- (11)
Callitriche obtusangula	- (-)	- (-)	- (6)	- (2)
Callitriche stagnalis	- (3)	- (-)	- (6)	- (3)
Carex acutiformis	- (-)	- (-)	- (6)	- (2)
Carex flacca	- (3)	15 (6)	50 (6)	24 (4)
Carex hirta	- (-)	- (6)	- (-)	- (2)
Carex otrubae	9 (14)	8 (44)	36 (39)	18 (28)
Carex pendula	- (-)	- (-)	- (6)	- (2)
Carex pseudocyperus	- (-)	- (-)	- (11)	- (3)
Carex remota	- (-)	- (-)	- (6)	- (2)
Carex riparia	- (-)	- (-)	- (11)	- (3)
Carex vesicaria	- (3)	- (-)	- (6)	- (3)

Ceratophyllum demersum	- (-)	- (-)	14 (-)	5 (-)
Chara spp.	73 (11)	38 (11)	- (-)	34 (8)
Chara globularis	- (28)	54 (6)	36 (11)	32 (18)
Chara hispida	- (-)	- (-)	- (6)	- (2)
Chara virgata	- (6)	- (-)	- (-)	- (3)
Chara vulgaris	27 (58)	62 (6)	57 (6)	- (32)
Cirsium palustre	- (3)	- (-)	- (6)	- (3)
<u>*Crassula helmsii*</u>	- (-)	- (-)	7 (-)	3 (-)
Deschampsia cespitosa	- (-)	- (17)	- (-)	- (4)
Eleocharis palustris	- (3)	15 (33)	50 (33)	24 (18)
Epilobium hirsutum	9 (56)	23 (56)	36 (67)	24 (58)
Equisetum palustre	- (-)	- (-)	- (6)	- (1)
Filipendula ulmaria	- (-)	- (6)	- (6)	- (3)
Galium palustre	- (3)	- (11)	- (11)	- (7)
Glyceria fluitans	- (11)	- (17)	43 (22)	16 (15)
Iris pseudacorus	- (11)	- (39)	- (22)	- (21)
Juncus acutiflorus	- (-)	- (-)	- (6)	- (1)
Juncus articulatus	18 (36)	54 (22)	64 (28)	47 (31)
Juncus bufonius	- (8)	- (-)	- (-)	- (4)
Juncus effusus	- (33)	8 (39)	7 (50)	5 (39)
Juncus inflexus	36 (50)	77 (67)	79 (72)	66 (60)
Lathyrus pratensis	- (-)	- (-)	7 (-)	3 (-)
Lemna gibba	- (8)	- (6)	- (-)	- (6)
Lemna minor	- (8)	- (28)	14 (39)	5 (21)

Lemna minuta	- (6)	- (11)	7 (6)	3 (7)
Lemna trisulca	- (8)	8 (28)	14 (44)	8 (22)
Lotus pedunculatus	- (3)	- (-)	- (-)	- (1)
Lycopus europaeus	- (14)	15 (61)	29 (39)	16 (32)
Mentha aquatica	9 (25)	8 (61)	21 (33)	13 (36)
Myosotis scorpioides	9 (6)	- (6)	29 (17)	13 (8)
Myriophyllum spicatum	- (8)	8 (11)	- (-)	3 (7)
Nitella capillaris	- (6)	- (-)	- (-)	- (3)
Oenanthe aquatica	- (22)	- (11)	14 (-)	5 (14)
Oenanthe fistulosa	- (-)	- (6)	- (11)	- (4)
Persicaria amphibia	- (3)	- (6)	- (-)	- (3)
Phalaris arundinacea	- (3)	- (11)	- (-)	- (4)
Phragmites australis	- (11)	- (11)	- (6)	- (10)
Potamogeton crispus	9 (14)	15 (28)	- (11)	8 (17)
Potamogeton natans	- (67)	69 (44)	93 (56)	58 (58)
Potamogeton trichoides	- (-)	- (17)	- (6)	- (6)
Pulicaria dysenterica	- (6)	31 (17)	71 (11)	37 (10)
Ranunculus aquatilis	18 (50)	8 (50)	36 (17)	21 (42)
Ranunculus flammula	- (3)	15 (6)	7 (-)	8 (3)
Ranunculus peltatus	- (-)	- (6)	7 (-)	3 (1)
Ranunculus sceleratus	- (47)	- (22)	- (6)	- (31)
Ranunculus trichophyllus	- (3)	8 (17)	- (17)	3 (10)
Rorippa nasturtium-aquaticum	- (25)	- (22)	7 (28)	3 (25)

Rumex crispus	- (8)	- (-)	7 (-)	3 (4)
Schoenoplectus lacustris	- (3)	- (-)	7 (-)	3 (1)
Schoenoplectus tabernaemontani	- (-)	- (-)	14 (-)	5 (-)
Scrophularia auriculata	9 (3)	- (-)	- (6)	3 (3)
Silene flos-cuculi	- (3)	- (-)	- (-)	- (1)
Solanum dulcamara	- (47)	8 (28)	14 (61)	8 (46)
Sparganium erectum	- (36)	- (28)	7 (39)	3 (35)
Tolypella glomerata	- (6)	8 (-)	7 (-)	5 (3)
Tolypella intricata	- (6)	- (-)	- (6)	- (4)
Typha angustifolia	- (-)	- (-)	- (6)	- (1)
Typha latifolia	27 (53)	31 (39)	43 (28)	34 (43)
Veronica anagallis-aquatica	- (-)	- (6)	- (-)	- (1)
Veronica beccabunga	9 (8)	- (22)	- (-)	3 (10)
Veronica catenata	- (3)	- (17)	14 (6)	5 (7)
Zannichellia palustris	- (3)	- (17)	7 (6)	3 (7)