Can agroforestry systems in the UK enhance ecosystem services and biodiversity? A case study from East Anglia.

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DECLARATION

I, Ben McLellan, declare that the work submitted in this dissertation is the result of my own work and investigation and all the sources I have used have been indicated by means of completed references.

Signed: *Ben McLellan*

Date: 11/05/2023

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Abstract

Ecosystem services (ES) are benefits for human wellbeing and quality of life provided by healthy ecosystems. Biodiversity is essential for the delivery of ES, and for overall ecosystem function and health. However, due to deforestation and agricultural expansion, ES and biodiversity are being lost around the world, including the UK. Agroforestry (AF), the cultivation of trees within agricultural systems, can deliver a range of ES and biodiversity whilst ensuring food security. However, the extent of AF in the UK is very limited due to farmers' uncertainty of its benefits and perceptions that AF hinders profitability. The aim of this study is to provide evidence that AF systems in the UK can provide the same ES provided by systems around the world, and to discuss how profitability could be improved in the UK. Wakelyns, an AF system in the UK, was visited to assess ES, biodiversity, and fungal activity. Regulating and supporting services at Wakelyns were assessed by calculating above ground carbon (C) storage and assessing soil health. Fungi diversity was used as a proxy for ecosystem biodiversity and to indicate fungal activity. In the sample, Wakelyns stores an average of 2,096 kg C per tree and a total of 54,496 kg C, most of which being stored in the timber system. A high overall soil health was found across the system. Using Margalef's diversity index, fungi at Wakelyns has an overall diversity of 2.8, higher than the 0.9 of monoculture systems in the region. It was concluded that AF systems in the UK can enhance biodiversity whilst delivering regulating and supporting services. Mushroom cultivation in the treelines could improve profitability and further enhance ES. This study provides evidence that AF systems in the UK can improve ES, promote biodiversity, and could enhance profitability. Further research is needed to understand the benefits of other AF systems in different regions of the UK.

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1.0 Introduction

Ecosystem services (ES) can be defined as the direct and indirect benefits from healthy ecosystems and the natural environment for human wellbeing and quality of life, and are essential for human survival (Pearce, 2023). There are four defined ecosystem services: provisioning, regulating, supporting and cultural (Hasan et al., 2020). Provisioning services are tangible goods that can be harvested from the environment such as food, water, materials, and natural medicines. Regulating services maintain ecosystem health and have a number of environmental benefits such as water filtration, erosion control, disease and natural pest control and climate regulation. Supporting services are essential for the function of the ecosystem and include soil health, nutrient cycling and habitat creation and protection. Cultural services include ways in which nature impacts people's health and wellbeing, such as physical health and mental wellbeing. These services are all interdependent and are underpinned by biodiversity, which has a key role at all levels and is essential for the delivery of ES (Mace et al., 2012; FAO, n.d.). However, globally ES and biodiversity are being lost due to deforestation and forest degradation, among other causes. (Ciccarese et al., 2012). Reforestation and afforestation are therefore important for ensuring that ES provided by forests are restored and improved (Mori et al., 2016). Much of this deforestation is because of the need for agricultural expansion to ensure food security (Chakravarty et al., 2012). One land management strategy which can ensure food security whilst promoting ES through reforestation and afforestation is agroforestry (AF) (Smith et al., 2019).

Agroforestry is an agricultural practice which involves the cultivation of trees within agricultural systems, with the aim of providing environmental benefits such as carbon (C) sequestration, biodiversity conservation and soil enrichment, without reducing agricultural productivity (Jose, 2009; Torralba et al., 2016). Two main methods of AF exist: silvopastoral; the combination of forestry and livestock agriculture, and silvoarable; the combination of forestry and arable agriculture (FAO, 2015). Globally AF, if defined by tree cover on agricultural land of greater than 10%, makes up 43% of agricultural land - over 1 billion hectares (Zomer et al., 2014). The majority (approximately 78%), of the area under AF is in the tropics, with 22% located in temperate regions (Nair et al., 2021). AF is limited in Europe and comprises roughly 15.4 Mha, just 8.8% of the total agricultural land, 15.1 Mha of which is dedicated to silvopastoral AF (Herder et al., 2017).

Currently, AF is even more limited in the UK compared to the rest of Europe, comprising just 3.3% of the total agricultural land (just over 500,000 ha) (Herder et al., 2017). The majority of this AF is silvopastoral, with the area under silvoarable being much more limited (Pagella and Whistance, 2019). More widespread AF in the UK has the potential to promote biodiversity and ES which have been lost by intensive arable agriculture (Varah et al., 2013). One area of the UK where intensive arable farming is dominant is East Anglia, where arable agricultural practices comprise 78% of the total agricultural land area (Defra, 2023). The main cause of deforestation in the UK is the transformation of forest to agricultural land, which has allowed for the creation of arable systems such as those found in East Anglia (Levy and Milne, 2004). However, although the creation of agricultural land has boosted provisioning services, the deforestation which has facilitated this has hindered a number of other ES (Levy and Milne, 2004). This means that the adoption of AF in the UK could help restore ES lost by deforestation whilst ensuring provisioning services and food security are maintained (Smith et al., 2019).

Therefore, it is important to understand the potential of AF in this region to promote biodiversity and ES. This is essential for the widespread adoption of AF in the UK as farmers' concerns with adopting AF is due to uncertainty regarding the benefits of AF for ES and the assumption that adopting AF will hinder profits (Graves et al., 2017). This study focuses on Wakelyns, a silvoarable AF farm in Suffolk, East Anglia which was established in 1992 by Martin Wolfe to understand the benefits of promoting diversity on all levels in an AF system, to encourage productivity and ecosystem health (Smith and Westaway, 2020a). The aims and objectives of this study are as follows:

Aim:
To determine the extent to which the AF system at Wakelyns provides and promotes ecosystem services, and to understand the potential of mushroom cultivation to further ecosystem services and enhance profitability.

Objectives:

To calculate above ground carbon storage across the system.

To assess soil health across the site.

To calculate biodiversity, by using fungi diversity as a proxy for ecosystem biodiversity.

To discuss the potential of mushroom cultivation for ES enhancement.

2.0 Literature Review

2.1 Agroforestry practices

AF is practiced in many ways around the world. As stated earlier, the two main systems are silvoarable and silvopastoral, but AF can be practiced in many other ways. Other AF practices include hedge rows, which are man mare rows of trees or shrubs enclosing or separating fields (Burel, 1996); homegardens, which are small-scale agroforestry systems providing sustainable food security for individual houses (Kumar and Nair, 2006); shelterbelts and windbreaks, which involve the planting of woody perennials in agricultural systems to provide shelter for crops and livestock (Caborn, 1965). Forest farming is the cultivation of shade-tolerant crops in forest ecosystems (Baker and Saha, 2018). Forest farming is frequently practised in the US for the cultivation of *Lentinula edodes* and involves the management of shade, creation and inoculation of substrates, and mitigation of fungal competition to create the optimum conditions for *L. edodes* growth (Baker and Saha, 2018; Bruhn et al, 2009). One of the most common AF practices is alley cropping: a method of silvoarable AF which involves the planting of crops between widely spaced rows of trees (Garrett et al., 2021). Nitrogen (N) fixing tree species are frequently used in both temperate and tropical alley cropping systems to enhance nutrient cycling, improve soil health and provide woody biomass as an alternative crop (Garret et al., 2021; Tsonkova et al., 2012).

2.2 Agroforestry for ecosystem services and biodiversity

AF systems from around the world have been seen to promote both ES and biodiversity. Firstly, AF provides regulating services, including C sequestration for climate regulation. AF is a recognised greenhouse gas (GHG) mitigation strategy under the Kyoto Protocol due to its C sequestration potential (Nair et al., 2009). In fact, AF systems could potentially store a minimum total of 5.3x10^9 Mg C in soil alone (Shi et al., 2018). Tropical AF systems have shown to also store C above ground, at a rate of 4.85 tC/ha/yr (Feliciano et al., 2018), showing that AF systems can store C both above and below ground. Temperate AF systems also have the potential to sequester C. Potential systems in the US could sequester C at a rate of 548.4 Tg/yr, which could offset current emission rates from burning fossil fuels by 34%, providing regulating services for the climate (Udawatta at Jose, 2011). Furthermore, AF systems in Alberta, Canada store 699.9 Mt C across 9.5 Mha of land, valuing at $102.7 billion in C stocks (An et al., 2022). This shows that AF systems in different climates sequester substantial amounts of C both above and below ground, providing climate regulation and provisioning services through C stocks. In the UK carbon sequestration payments could contribute up to 88% of the establishment costs of an AF system (Staton et al., 2022). However, there is limited research into the C sequestration potential of AF systems in the UK, although there is evidence that silvopastoral systems in Wales contain higher levels of soil organic carbon (SOC) than conventional grassland soil samples (Kilta et al., 2011). This shows that silvopastoral systems in the UK can sequester C below ground but highlights the importance to research above ground C storage and the C sequestration of silvoarable systems, as this could influence farmers' perspectives of establishment costs and profitability of AF systems (Graves et al., 2017).

In addition to climate regulation, AF systems can promote other regulating services such as the control of plant disease, pests, and weeds. For example, tropical AF systems involving the cultivation of perennial crops (such as coffee, cocoa, and plantain) are associated with a lower abundance of plant diseases, pests, and weeds (Pumarino et al., 2015). Temperate AF systems also help reduce plant disease due to high diversity and complexity, which limits pest accessibility and increases predator and parasitoid densities (Smith et al., 2012). This shows that AF systems can regulate plant diseases, pests and weeds and thus create healthier environments for crop cultivation. This reduction in plant disease has subsequent benefits for the provisioning services of the AF system by reducing yield loss. For example, AF systems in Cameroon reduce the abundance of coffee berry disease by roughly 20%, reducing yield loss, when compared to more exposed plantations (Bedimo et al., 2008). In cocoa AF systems in Bolivia and Côte d'Ivoire, yields were 46% higher than yields in monoculture systems, and in no cases did AF have smaller yields than monoculture, due to the disease and pest control benefits from the AF systems (Andres et al, 2016). AF has also shown to improve yields in many temperate European systems, although the benefits among different crop species vary as, for example, AF significantly benefits winter wheat but can limit potato yields (Pardon et al., 2018). UK AF also has yield benefits by promoting higher pollination rates than monocropping systems, which is essential for increasing yields (Varah et al., 2020). This shows that disease and pest regulation as well as enhanced pollination promotes provisioning services in AF systems around the world and in the UK. However, in the UK AF systems are predicted to have a substantial period (>7 years) of negative cash-flow before the income benefits of the integration of trees into arable systems are achieved (Staton et al., 2022). This is likely why farmers assume adopting AF systems hinders profitability (Graves et al., 2017), so widespread adoption is unlikely unless profitability can be enhanced in the early stages of AF adoption in the UK.

As well as provisioning and regulating services, AF systems in both temperate and tropical regions have also been proven to provide many supporting services for soils by improving soil nutrient availability, increasing soil fertility, and enhancing soil microbial dynamics (Dollinger and Jose, 2018). High tree diversity in tropical AF systems results in high soil fertility, due to a more complex occupation of space above and below ground which produces a wider range of litter, increasing soil biodiversity and nutrient cycling and thus soil health (Pinho et al., 2012). Furthermore, alley cropping AF systems in the Mediterranean have been seen to increase soil quality by 20% over 21 years, when compared to adjacent monocropping systems, as well as having 50% more soil organic carbon (SOC), essential for soil health (Guillot et al., 2012). Benefits for soil quality, such as improved soil biodiversity and fertility, have also been seen in many temperate AF systems, without limiting productivity and provisioning services (Torralba et al., 2016). Soil health is also improved in temperate AF systems where the presence of trees encourages nutrient cycling due to leaf fall and litter in the crop alleys which encourages soil nitrate production (Smith et al., 2012). Furthermore, the relatively high levels of SOC found by Kilta et al. (2011) indicates that silvopastoral systems in the UK significantly benefit soil health compared to regular grassland. This shows that AF systems around the world provide supporting services and promote soil health. However, the impact of silvoarable systems on soil health in the UK is not well-understood and so the provisioning services of these systems cannot be claimed.

Like supporting services, biodiversity is also essential for the delivery ES, and can be improved by AF in both tropical and temperate regions (FAO, n.d.; Jose, 2012). For example, AF systems in Madagascar have 12% more species and 38% more endemic species than fallows previously used for monocropping, meaning the AF systems here encourage and conserve biodiversity (Wurz et al., 2022). In addition, a meta-analysis of research into the biodiversity and ES provided by AF systems in the Brazilian Atlantic Forest found that AF systems have 45% higher biodiversity and provide 65% more ES than monoculture systems (Santos et al., 2019). In Atlantic and Continental Europe, integrating trees in arable systems can enhance biodiversity, whilst maintaining agricultural productivity (Torralba et al., 2016). This shows that AF promotes biodiversity without sacrificing yields and hindering profits. Enhanced biodiversity, using butterfly diversity as a proxy, has also been seen in silvoarable and silvopastoral systems in the UK when compared to monocropping systems (Varah et al, 2013). This shows that the biodiversity benefits of AF systems in the UK are also known, although using another bioindicator of biodiversity will help consolidate these findings.

Therefore, it is evident that AF systems around the world deliver and enhance ES and biodiversity. However, to promote widespread adoption of AF in the UK, more research is needed to highlight these benefits in UK systems. Focus is needed on the above ground and silvoarable C storage to fully understand the C storage potential of AF systems in the UK, which could change farmers' perceptions due to carbon sequestration payments (Staton et al., 2022; Graves et al., 2017). Further research is also needed regarding soil health and biodiversity of UK silvoarable systems to better the understanding of the environmental benefits of these systems. Additionally, research is needed to suggest novel methods to ensure profitability and boost the provisioning services of AF systems in the first seven years of operation, to address current farmer perceptions of AF benefits and profitability (Staton et al., 2022; Graves et al., 2017).

2.3 Fungi and mushroom cultivation for ecosystem services

A potential method to promote ES and profitability in the early stages of UK AF systems is to cultivate mushrooms in the treelines, following practices similar to those of forest farming systems. The natural occurrence of fungi in AF systems can already provide and enhance a number of ES and biodiversity. For example, mycorrhizal fungi in tropical AF systems protect root systems from pathogens, enhancing the mitigation of plant diseases and provisioning services of these systems (de Carvalho et al., 2010; Pumarino et al., 2015). Mycorrhizal relationships in these tropical AF systems were also found to maintain biodiversity as well as increase nutrient cycling, form and maintain soil structure, increase the input of SOC, therefore enhancing supporting services (de Carvalho et al., 2010). Furthermore, the inoculation of seedlings with arbuscular mycorrhizal fungi enhanced nutrient cycling and water uptake of seedings in an Ethiopian AF system, on land previously deemed to be unsuitable for agriculture (Hailemariam, 2018). This shows that inoculation with arbuscular mycorrhizal fungi allows for the development of AF systems to improve food security in areas of poor-quality soil, enhancing both provisioning and cultural services. This shows that the natural occurrence of fungi in AF systems can promote and enhance ES and biodiversity.

The cultivation of mushroom species in AF systems has also been seen to provide a number of ES and environmental benefits. For example, the cultivation of edible mushroom *Stropharia rugosoannulata* alongside bamboo improves soil health by enhancing soil fauna species diversity and abundance, in addition to increasing organic matter and water content (Zhao et al, 2022). The cultivation of mushrooms alongside other crops has also been seen to enhance provisioning services in mid-tropical India, where cultivation of *Pleurotus ostreatus* in alley cropped AF systems provides significant economic benefits and livelihood security for smallholders and therefore enhanced profitability of the system (Singh et al, 2016). *P. ostreatus* was also consumed by farmers, providing them with sufficient levels of vitamin C and iron whilst providing 47% of the required Vitamin A and 20% of calcium and phosphorus minerals, therefore benefiting the physical health and wellbeing of the farmers. This shows that mushroom cultivation in tropical AF systems can provide provisioning, supporting and cultural services.

The presence, incorporation and cultivation of fungi and mushroom species in AF systems are therefore presented to have benefits for all ES and promote and enhance biodiversity. However, the effects of fungi in AF systems in the UK are unknown, and the potential benefits of mushroom cultivation in temperate alley cropped AF systems for ES provision and biodiversity enhancement also have limited understanding. Therefore, the present study aims to display the ES (focussing on C sequestration and soil health) and biodiversity provided by temperate AF system Wakelyns, and discuss the potential ES and biodiversity provided by the cultivation of mushrooms here as suggested by late owner and founder Martin Wolfe (2021). This evidence is important for changing farmer's perceptions of AF in the UK and for promoting the widespread adoption of AF in the UK for both environmental and economic benefits.

3.0 Methodology

3.1 Study site

Wakelyns is located at 52.36°N, 1.36°E, in Suffolk, East Anglia (seen in Figure 1.1). It has an annual average of 606 mm rainfall, and an average daily low/high temperature of 6.0 °C / 13.8 °C. It is a 22.5 ha alley-cropped, silvoarable AF system with 56 treelines, which vary in length from 75 m to 225 m (Figure 1.2). It is a diverse production system, with a range of tree and crop species. The first trees, planted in the Far Field site (Figure 1.3) in 1994, are cultivated for timber; consisting of oak, birch, ash, sycamore, and others. Since then, other tree species have been introduced to the system including short coppice rotation (3 years) willow, walnut, apple, pear, plum trees, and others. Crops grown Wakelyns are diverse, including cereals, legumes, and vegetables which are all grown in alleys between the treelines.

Figure 1.1: Map displaying the location of Wakelyns in the UK

Figure 1.2: Map displaying the treelines at Wakelyns

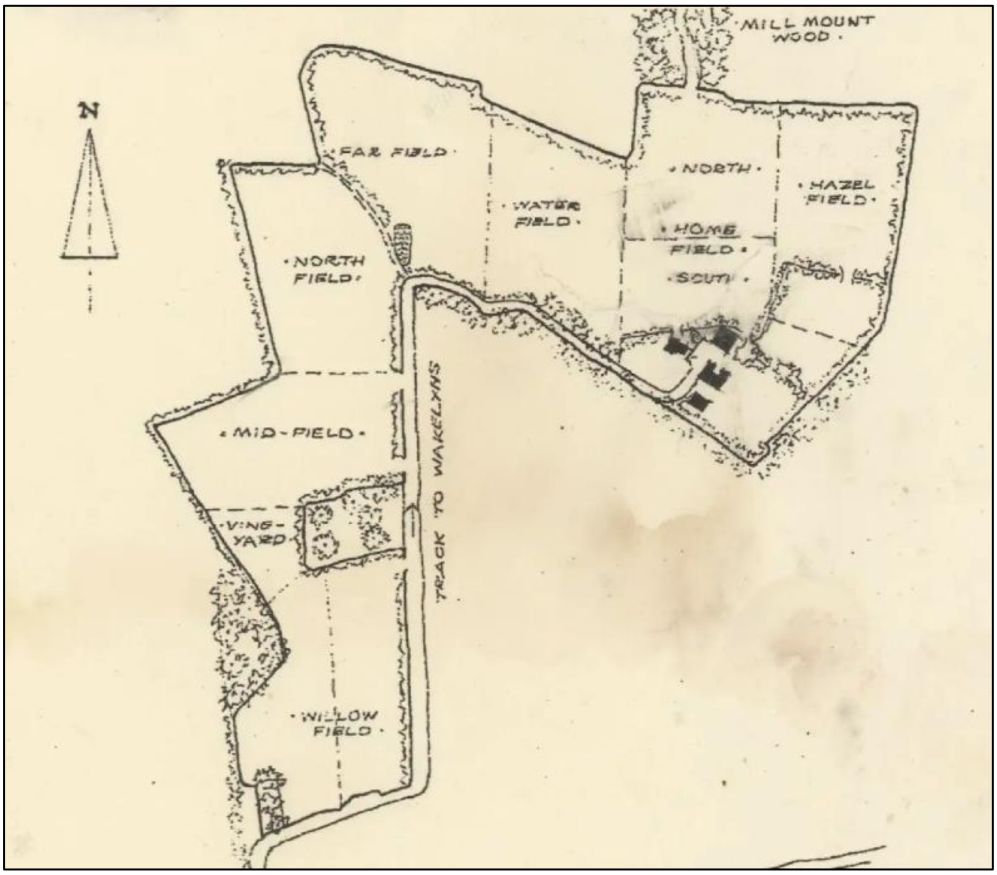

Figure 1.3: Sketch from Wakelyns (n.d.) displaying the field names

3.2 Data collection

Tree lines were selected using systematic sampling, selecting every three tree lines (i.e., 1,4,7…), leaving two treelines between each sampled one. A total of nine tree lines were sampled: three willow, two fruit/nut and four hardwoods. On the East side of each treeline a 2m quadrat was placed every 25m. This provided a total of 42 sample sites across the 9 sampled treelines. The following data was collected at each site.

Firstly, all fungi and mushroom species present were identified using mushroom identification mobile applications (Shroomify, 2022; Picture Mushroom, 2022) and the Kingfisher mushroom field guide (Pegler, 1990). If it was not possible to identify mushroom/fungi species in the field, photographs were taken and shape, gill colour/type, smell and size were recorded. The Roger Phillips mushroom identification guide (not suitable for use in the field) was then used for identification (Phillips, 2006). Fungi species richness and abundance was then recorded.

A small, temporary soil sample (roughly 6 cm deep) was then taken and observed. Following the methodology of Pennock et al. (2008) for soil sampling, the following characteristics were noted: colour, porosity, texture, moisture content, and scent. Although these are subjective observations, they provide an indication of overall soil health and content at each site (Hengl and MacMillan, 2019; Goodwin, 2019). Any presence of organic matter and biological activity in the sample was also noted.

At sites where trees were present, tree height and circumference were recorded. Tree height was measured using a clinometer and measuring tape, pointing the clinometer at the top of the tree at a 45° angle and then measuring the distance from the base of the tree to create an isosceles triangle. This measurement is added to eye level height (1.64 m) to give an accurate measurement of tree height. The circumference of the tree trunk was measured at breast height (1.3 m), using a tape measure following the Forestry Commission's "Forest Mensuration Handbook" instructions (Hamilton, 1988). However, for the SRC willow trees, most of the trunks had a very small circumference, so following the Forestry Commission's measurement instructions, trees of this size (<7 cm diameter at breast height) were not measured.

3.3 Equations and data analysis

The Margalef's diversity index was used to calculate the diversity of fungi species at Wakelyns, both overall and in each of the tree systems. The equation is as follows, where S is the number of species and N is the number of individuals:

$$DMg = \frac{(S-1)}{lnN}$$

This equation is the most appropriate for the sampling method used in the present study, and has been successfully used in measuring species diversity in AF systems in this region (Varah et al, 2013). This allowed for mushroom diversity to be used as a proxy for ecosystem biodiversity (Halme et al, 2017).

Using the tree measurements, the amount of carbon stored above ground was then calculated. This was done by, firstly, dividing the measured circumference by Pi (3.14) to provide the diameter of the tree at breast height. This was then used in the following equation from Chave et al (2014), where D is diameter at breast height, H is tree height and n is wood density:

$$ABC = \frac{n(D^2H)}{2}$$

Wood densities, seen in Table 1 were taken from the Wood Density Database (n.d.), although Quince tree density could not be found. Although Chave et al.'s (2014) equations were designed for tropical trees, they have been successfully used for calculating the amount of carbon stored in temperate trees (Paul et al., 2015).

Table 1: Wood densities taken from Wood Density Database (n.d.)

Tree Species	**Density**
Willow	0.396
Alder	0.417
Cherry	0.481
Walnut	0.563
Sycamore	0.565
Plum	0.589
Oak	0.604
Ash	0.608
Field Maple	0.615
Hornbeam	0.665
Hawthorn	0.711
Quince	Unknown

The observations of soil characteristics were then ranked on a scale of 1-5, to make them quantifiable. For example, soil porosity observations ranged from low to high, so this was applied to the scale of 1-5 where 1 is low, 2 is low-medium, 3 is medium, 4 is medium to high and 5 is high. For colour, 1-5 represents shades of brown, with 1 representing light brown and 5 representing dark brown. For texture, 1-5 represents extent of friability, with 1 representing low friability and 5 representing high friability. This scale was applied to all characteristics, quantifying the data.

Once the soil data was quantified in Excel, it was transferred into SPSS to highlight all significant differences in soil characteristics between the tree systems. To determine the most appropriate test for this, by checking if the data is normally distributed, a Shapiro-Wilk test was conducted. This revealed the data did not meet the assumption of normality, meaning a nonparametric test was required. Therefore, a Mann-Whitney U test was deemed the most appropriate test to compare soil characteristics between tree systems.

4.0 Results

Overall, general observations of the site at Wakelyns suggest a healthy and diverse environment, as a number of bird species were heard and seen and other animal activity was observed, such as burrowing holes and faeces.

Calculating the amount of carbon stored above ground revealed that the trees in the sample store an estimated total of 54,496 kg C. The majority of this is stored in the timber system, which contain an estimated 34,041.9 kg C, as seen in Table 2. On average, the trees in this sample store 2,096 kg C and the system with the highest average C per tree is, again, timber with 2,836.8 kg C, 1,668 kg C higher than the system with the lowest average (fruit) as presented by Table 2. There is a large range in the amount of stored carbon in trees as the highest amount of carbon stored in a tree was 7,603.1 kg C and the lowest was 9.8 kg C, both of which were willows. Figure 2 shows that, in total, willow trees store the most carbon out of the tree species sampled, storing 13,441.4 kg C and that oak stores the second highest amount with 11,009.6 kg C. However, it also highlights that on average willows stored a relatively low amount of carbon, with 1,680.2 kg C compared to oak which has the highest average of 3,669.9 kg C. It also shows that there is tree diversity at Wakelyns, as the trees identified in this study have a species richness of 9. Finally, it shows that field maple and hawthorn store very little carbon, both on average and in total.

Table 2: The average and total carbon content for each tree system at Wakelyns

Tree system	**Average kg C**	**Total kg C**
Fruit	1,168.8	7,012.7
Timber	2,836.8	34,041.9
Willow	1,680.2	13,441.4

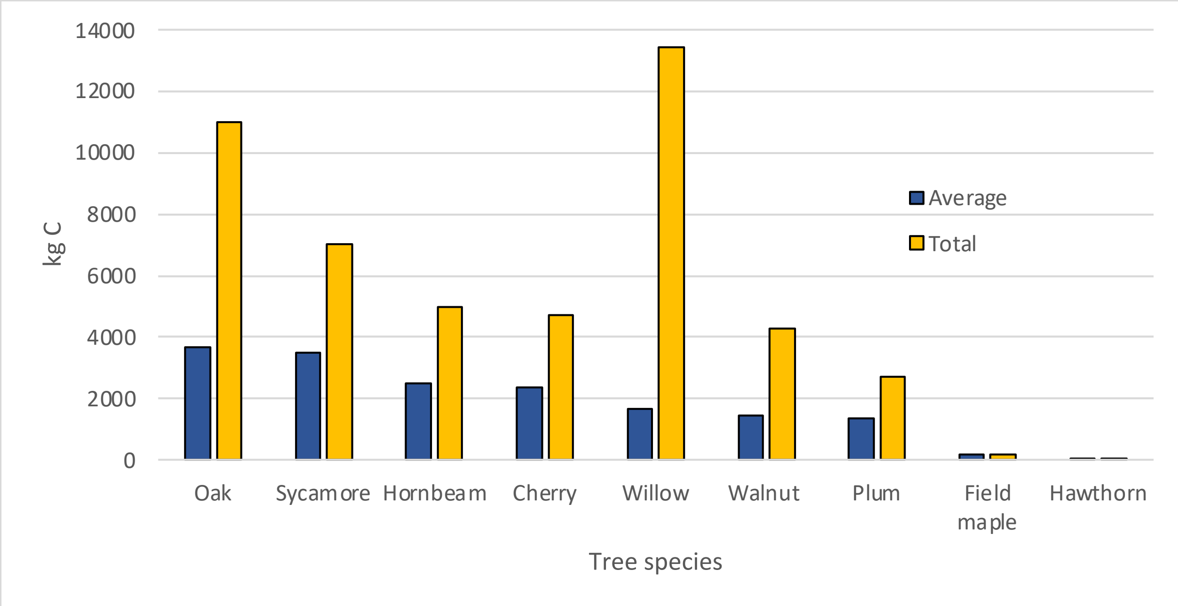

Figure 2: Graph displaying the average and total carbon storage for each tree species measured at Wakelyns

Soil observations revealed that soil at Wakelyns had a fresh and earthy scent, with an average rating of 4.4; a medium to high crumbliness, with an average rating of 3.7; a medium moisture content, with an average rating of 2.6; a medium porosity, with an average score of 3 and a medium colour, also with an average score of 3. A high organic content was found in soil samples from every system at Wakelyns. Based on these observations, it is suggested that soil at Wakelyns has a high over all health (Hengl and MacMillan, 2019; Goodwin, 2019).

Table 3 shows the different mean score for each soil characteristic in each tree system at Wakelyns, highlighting that each system has a high overall health, with soils ranking particularly in smell. It also highlights there are differences in soil characteristics between the systems.

Table 3: Mean score for each soil characteristic in each tree system at Wakelyns

System	Colour	Porosity	Moisture content	Texture	Smell
Willow	3.25	2.80	2.60	4.00	4.30
Fruit	1.89	2.11	3.67	2.22	4.00
Timber	3.31	3.85	1.92	4.15	4.69

Conducting the Mann-Whitney U test revealed that there were many significant differences in soil characteristics between the systems. Results from the Mann-Whitney U test were considered significant if $p<0.05$. Firstly, colour was found to rank significantly lower in the fruit system than both the timber system ($U= 24.5$, $p<0.05$) and the willow system ($U= 35$, $p<0.05$), as seen in Table 4.1 and 4.2. Soil was also observed to be red in some samples from the fruit system. Furthermore, Table 4.1 and 4.2 also show that texture ranks significantly lower in the fruit system than both the timber system ($U= 16.5$, $p<0.05$) and the willow system ($U= 31$, $p<0.05$), and some samples were very dense and even sticky in parts. It was also found that smell ranked significantly higher in the timber system compared to both the fruit system ($U= 27$, $p<0.05$) and the willow system ($U= 79$, $p<0.05$), as presented by Table 4.1 and 4.3.

Table 4.1: Summary of the significant Mann-Whitney U test results for the fruit and timber systems soil characteristics

Soil characteristic	Tree type	Mean rank	Mann-Whitney U	p value
Colour	Fruit	7.72	24.5	0.010
	Timber	14.12		
Porosity	Fruit	6.39	12.5	0.001
	Timber	15.04		
Moisture content	Fruit	15.61	21.5	0.009
	Timber	8.65		
Texture	Fruit	6.83	16.5	0.001
	Timber	14.73		
Smell	Fruit	8.00	27	0.019
	Timber	13.92		

Table 4.2: Summary of the significant Mann-Whitney U test results for the willow and fruit systems soil characteristics

Soil characteristic	Tree type	Mean rank	Mann-Whitney U	p value
Colour	Willow	17.70	36	0.002
	Fruit	9.00		
Texture	Willow	17.99	31	0.004
	Fruit	8.44		

Table 2.3: Summary of the significant Mann-Whitney U test results for the willow and timber systems soil characteristics

Soil characteristic	Tree type	Mean rank	Mann-Whitney U	p value
Porosity	Willow	13.73	64.5	0.009
	Timber	22.04		
Smell	Willow	14.45	79	0.029
	Timber	20.92		

Table 5: The species and species abundance of fungi at Wakelyns

Species	Species Abundance
Xylaria hypoxylon	102
Unknown2	40
Lentinus Tigrinus	30
Unknown4	28
Unknown5	24
Pluteus longistriatus	17
Marasmius epiphyllus	13
Mycena galopus	13
Stereum hirsutum	12
Crepidotus variabilis	6
Unknown6	5
Psathyrella candolleana	3
Unknown3	3
Mycena clavicularis	2
Mycena metata	2
Conocybe apala	2
Unknown1	1

A range of fungi species were found at Wakelyns, with species being found at 50% of the sites. Table 5 displays that fungi has a species richness of 17 at Wakelyns, most of which are saprophytic (decomposing). It also shows that the most common species was *Xylaria Hypoxylon*, which had a species abundance of 102. The mean species abundance for the 17 species was 17.8, lower than that of *X. Hypoxylon*, highlighting the variation in species abundance seen in Table 5. Fungi species had a diversity of 2.8 using Margalef's diversity index. Fungi was also found elsewhere across the site, such as *Volvopluteus gloicephalus,* which was found in the crop alley to the east of treeline 12, which was in a ley period.

Furthermore, as well as observing mushroom species, fungal activity was frequently seen across the site and mycelial mats and strands were seen on many logs, even where mushrooms were not observed.

Table 6: Fungi species richness, abundance and diversity in each tree system at Wakelyns

System	Species Richness	Total abundance	Diversity
Willow	12	129	2.3
Fruit	2	4	0.7
Timber	8	170	1.4

Table 6 displays that there were relative differences in fungi species richness, total abundance, and diversity between the three systems. For example, fungi diversity was highest in the willow system with 2.3 compared to 0.7 in fruit and 1.4 in timber, although timber had the highest total abundance with 170 compared to 129 in willow and just 4 in the fruit system.

5.0 Discussion

5.1 Carbon sequestration

A substantial amount of C is stored above ground in the trees at Wakelyns. The majority of this C is stored in timber trees, due to their age, size and density which allows for more C storage following Chave et al.'s (2014) equation. However, the tree species with the highest total C storage is willow. This is likely due to the sample size, which is considerably larger than any other species. However, the tree with the highest individual C storage was a willow, suggesting that although on average they have relatively low C storage, they do have potential for high C storage towards the end of the coppice rotation. Willow plantations in temperate regions such as Sweden also store considerable amounts of C, both above and below ground at rates of 3.92 Mg C/ha/yr and 2.39 Mg C/ha/yr respectively (Rytter, 2012)**.** Therefore, the results of the present study and Rytter (2012) present that willow is a viable tree species for cultivation in temperate AF systems and the UK to promote substantial C storage at high rates. Of the tree species identified at Wakelyns, oak had the highest average stored C per tree. This is likely due to the high age and density of the oak trees at Wakelyns. Although providing a high over all C storage, the slow growth rate of oaks means it takes a considerable amount of time to achieve this C storage (Twedt, 2006). However, the combination of willows and oaks at Wakelyns allows for both high-rate C sequestration and high overall C sequestration. This highlights the benefit of combing fast-growing trees with slow-growing species of higher densities, to help optimise C storage in AF systems in the UK and thus enhance climate regulating services. The low C storage of the field maple and hawthorn is due to their young age and subsequent size, highlighting the importance of reassessing above ground C storage in the future, when trees such as these are older and store more C. Therefore, the benefits of the tree species selection at Wakelyns are understood, highlighting effective species for the promotion of C storage in AF systems in the UK.

The benefits of the AF system at Wakelyns for below ground C storage are also understood and highlighted in previous research. Smith and Westaway (2020a) report the findings of a soil C analysis of samples taken from treelines in the timber section and a control sample from a no-tree field. They report that there was a higher quantity of stored C in the timber treeline. This shows that AF systems in the UK sequester more C than arable monoculture systems of the same region, and that temperate AF systems in the UK, have the capacity to store C both above and below ground as has been widely seen in tropical systems (Islam et al., 2015). It is also likely that the high fungi diversity and abundance at Wakelyns plays a role in this below ground C sequestration. Fungi, particularly mycorrhizal, enhances soil C sequestration and helps distribute SOC in the system (Jansa and Treseder, 2017; Baird and Pope, 2022). Furthermore, storing C above ground also has the potential to enhance provisioning services as stored C can be sold as Carbon Credits to the UK government or privately owned businesses (GOV UK, 2023; Woodland Carbon Code, 2019) which, as mentioned earlier, can cover up to 88% of the establishment costs of an AF farm in the UK and ensure profitability in the first 7 years of operation (Staton et al., 2022). Therefore, the results of the present study is important evidence for promoting AF to farmers in the UK, as it shows that converting to AF does not diminish profitability due to the economic benefits of C sequestration.

5.2 Soil health

Previous research has also been conducted into the soil health at Wakelyns, which supports the overall high soil health found in the present study. Smith and Westaway (2020a) report the results of a soil analysis conducted at Wakelyns. Soil samples were taken from the treelines in the timber system and adjacent crop alleys and analysed for the following indicators of soil health: CO2 respiration rate; available phosphate, potassium, and magnesium; soil organic matter and soil pH. Sufficient quantities of these nutrients are essential for plant growth and development and thus for ensuring ecosystem productivity and health (Silva and Uchida, 2000). The results of the soil sample reveal that there is high nutrient availability and organic matter content in both the treeline and crop alley. There was also a significant difference in CO2 respiration, with much higher readings found in the treeline than the crop alley. A high CO2 respiration rate indicates high microbial activity and a high rate of decomposition in the treeline, which benefits overall soil health (Parkin et al., 2015). This research therefore supports the present study, displaying that soil health at Wakelyns is very high and that AF systems in the UK can deliver supporting services through improving soil health.

The high soil health found in the timber treeline in both the present study and Smith and Westaway (2020a) could be due to the soil C sequestration mentioned earlier which increases SOC content, essential for soil health (Kumar et al., 2022). This soil C sequestration could therefore also help explain the high CO2 respiration rate recorded by Smith and Westaway (2020a). The high CO2 respiration rate could also be explained by the high fungal activity in the timber treeline, observed in the present study, which includes a high abundance of saprophytic species resulting in high rates of decomposition and SOC distribution, thus increasing CO2 respiration (Stamets, 2005; Baird and Pope, 2022). Management practices at Wakelyns also promote soil health and fungal activity. For example, Wakelyns incorporate ley periods into the system, as was seen in the present study in the crop alley adjacent to treeline 12 which also hosted *V. gloicephalus*. Ley periods provide multiple benefits including soil conservation, nutrient provision, and nutrient cycling (Martin et al., 2020). They also enhance soil structure, which simultaneously improves soil health whilst reducing soil erosion, enhancing both supporting and regulating services (Puerta et al., 2018). Ley periods also promote fungal activity and are understood to have a positive impact on saprophytic fungi, explaining the presence of *V. gloicephalus* adjacent to treeline 12 (Albizua et al., 2015). Ley periods also promote mycorrhizal fungal activity which enhances the supporting services provided by leys for soil health (Williams and Hedlund, 2014). Therefore, this suggests that the high soil health found at Wakelyns is due to ley periods and fungal activity and the interaction of these, therefore highlighting the benefits of ley periods and fungal activity for promoting ES in AF systems in the UK.

However, the Mann-Whitney U test revealed significant differences soil characteristics from samples of each assessed system. Firstly, it was revealed that soil in the fruit system was much lighter, relative to the timber and willow systems. This indicates that soil in the fruit system has a lower fertility than the other systems at Wakelyns (Rossel et al., 2006). The red colour observed in some samples from the fruit system is likely due to a higher clay mineral content, which has previously been observed at Wakelyns (Smith and Westaway, 2020b). This clay content would also explain the lower texture ranking of the fruit system soil samples, as clayey soils are dense with low friability, and are sticky when wet (Finch et al., 2014). The lower fertility could be due to the relatively low fungal, particularly saprophytic, activity in the fruit system treelines which results in limited nutrient cycling and decay of organic matter (Stamets, 2005). Therefore, although the soil health in the fruit system is of overall high health, it is relatively lower than the other two systems assessed likely because of a higher clay content and lower fungal activity. This shows that AF in the UK can benefit overall soil health, although the extent of these benefits is limited by soil type. However, this could potentially be improved by promoting fungal activity and adopting management practices such as ley periods to improve soil health.

5.3 Fungal biodiversity

The fungi diversity score of 2.8 on Margalef's diversity index shows that biodiversity is enhanced at Wakelyns and is higher than that of monoculture arable systems in the region which have scored 0.9 in previous research (Varah et al., 2013). The high biodiversity found in the present study supports previous research into biodiversity at Wakelyns. For example, research into the biodiversity of ground beetles and earthworms at Wakelyns found 11 species of ground beetles in a sample of 124 and 10 species of earthworm in a sample of 172 (Smith and Westaway, 2020a). By applying the Margalef diversity index to the species richness and sample size of this study, it was revealed that ground beetles have a diversity score of 2.1 and earthworms had a diversity score of 1.7 at Wakelyns. Furthermore, an RSPB bird survey was also conducted at Wakelyns which found 43 species of birds, including both farmland and woodland species (Smith and Westaway, 2020b). This shows that the AF system at Wakelyns enhances the supporting services as well as promoting biodiversity, by providing a multitude of habitats supporting a variety of bird species.

The overall fungi diversity is likely the result of a number of factors. Firstly, tree diversity has a strong positive correlation with fungi species diversity (Tomao et al, 2020). This would explain the overall high fungi diversity as Wakelyns has an overall high tree diversity, which increases the diversity of saprophytic fungi in particular by providing a high diversity of substrates (Tomao et al., 2020). An increase in diversity of saprophytic fungi will have subsequent benefits for biodiversity, as saprophytic fungi have a key role in the food chain and support wider ecosystem biodiversity (Stamets, 2005; Baird and Pope, 2022). This means that there is a positive feedback loop between ecosystem biodiversity and fungi diversity, increasing the overall biodiversity delivered by the system.

However, by applying Margalef's diversity index to fungi in each tree system it is revealed that the willow system, the system with the lowest tree diversity, has a higher fungi diversity than the timber system, which has the highest tree diversity. A possible explanation for this is competition between fungi species. *X. hypoxylon* has a very high abundance within the timber system, suggesting it out-competes other fungi species, by effectively colonising the diverse range of litter, and thus reduces the overall fungi diversity (Boddy and Hiscox, 2016). However, although relatively lower than the willow system, fungi diversity in the timber system is still higher than monoculture arable systems assessed by Varah et al. (2013). On the other hand, the fruit system scores lower on Margalef's diversity index than the monoculture arable systems assessed by Varah et al. (2013), and there was an overall lack of fungal activity. This is likely due to a limited quantity of litter and organic matter in the treelines, meaning there was a lack of substrate for saprophytic fungi to colonise compared to the willow and timber systems (Stamets, 2005). Furthermore, compared to the willow and timber systems, the fruit system is more exposed to sunlight, which greatly reduces fungi's ability to disperse spores and survive (Braga et al., 2015). However, since data collection for the present study, grape vines have been planted between trees in the fruit system which will increase the amount of shade and litter available, providing a more suitable environment for fungi colonisation (Wakelyns, 2022). Overall, there is high fungal activity and diversity at Wakelyns which helps to further ecosystem biodiversity and although there is limited fungal activity in the fruit system at Wakelyns, this is likely to increase in the future due to the addition of grape vines in the treelines. This shows that AF systems in the UK promote fungal activity, providing there is sufficient substrate availability.

5.4 Mushroom cultivation potential

It is clear that fungi at Wakelyns provide a number of ES and enhance biodiversity. However, the cultivation of specialty mushroom species in the treelines could enhance ES, biodiversity and profitability further. Of the 17 fungi species found at Wakelyns, there are a number of naturally occurring specialty mushrooms. For example, *X. hypoxylon* has potential medicinal uses and has been seen to treat diseases such as pneumonia due to its antimicrobial activity against the bacteria *Klebsiella pneumoniae*, which causes pneumonia in humans (Canli et al., 2016). However, more research is required into *X. hypoxlyon* before it is widely used for medicinal uses, although cultivation for medicinal uses could enhance provisioning services in the future as demand for natural products with antimicrobial activity is increasing (Saridogan et al, 2021). In addition to *X. hypoxylon,* other specialty mushrooms such as *Lentinus tigrinus* were also recorded, which is cultivated for both edibility and medicinal uses (Kalaw et al, 2021).

Firstly, *L. tigrinus* is cultivated for its medicinal properties such as high activity against fungal microorganisms such as *Candida*, including multidrug-resistant pathogen *C. krusei,* which causes candidiasis in humans (Sevindik, 2018; Pfaller et al., 2008). Moreover, *L. tigrinus* also has anticancer potential, containing compounds and proteins which can kill cancer cells, although more research is needed before this is widely accepted (Mohammadnejad et al, 2019). *L. tigrinus* is also edible, providing a number of nutritional benefits for human consumption (Dulay et al., 2014). Due to its edibility and medicinal uses, *L. tigrinus* also provides benefits for human health and wellbeing. Therefore, cultivation of *L. tigrinus* at Wakelyns could enhance provisioning services and subsequently cultural services, heightening the overall ES provided by the AF system. In addition to the enhancement of provisioning and cultural services, *L. tigrinus* also exacerbates the supporting services provided by AF at Wakelyns through enhancing soil health and quality. *L. tigrinus* is often used in mycoremediation projects due to its ability to improve soil health by removing toxic chemicals (Thakur, 2018; Purohit et al., 2018). Furthermore, as a saprophytic fungus *L. tigrinus* also helps promote nutrient cycling, by recycling carbon, hydrogen, nitrogen, phosphorus, and minerals into nutrients available for uptake by trees and crops alike (Stamets, 2005). This therefore shows that *L. tigrinus* can provide supporting services in AF systems in the UK and ensures that other ES can be upheld and further enhanced.

The natural occurrence of *L. tigrinus* at Wakelyns suggests that the right conditions are present for larger scale cultivation. In fact, *L. tigrinus* can be cultivated using both wheat straw and waterlogged offcuts of hardwood as a substrate, which are both waste products at Wakelyns (Lechner and Papinutti, 2006). *L. tigrinus* can also be cultivated all year round making it a good mushroom to enhance productivity and to ensure there is a consistent supply of produce (Kalaw et al, 2021). This means that no external inputs are required for substrate provision, and productivity can be enhanced and diversified efficiently by cultivating *L. tigrinus*, which were reasons Wolfe established the farm in 1992 (Smith and Westaway, 2020a). The high fungal activity and natural presence of *L. tigrinus* at Wakelyns suggest that conditions are suitable for the cultivation of other specialty mushrooms which require similar conditions, such as *L. tigrinus'* sister species *L. edodes* (Niazi et al., 2022). *L. edodes* is the leading specialty mushroom in North America, and is often cultivated in forest farming systems, as mentioned earlier (Chen et al., 2000; Baker and Saha, 2018; Bruhn et al, 2009). Therefore, adopting forest farming practices to cultivate high-value specialty mushrooms such as *L. tigrinus* and *L. edodes* in the treelines at Wakelyns, and other AF systems in the UK, could promote ES and biodiversity whilst enhancing profitability.

5.5 Conclusion

Overall, it is evident that the AF system at Wakelyns delivers a range of ES and enhances biodiversity. Wakelyns provides regulating services through substantial above and below ground C sequestration, which could also enhance provisioning services through C credits. The AF system also benefits supporting services by maintaining and improving soil health. Biodiversity is also enhanced, with benefits for fungi diversity. This study therefore highlights that AF systems in the UK can provide the same ES benefits, as have been seen elsewhere around the world. Following forest farming practices, the cultivation of specialty mushroom species in treelines could further these ES and biodiversity benefits whilst enhancing profitability of the system at Wakelyns and other AF systems in the UK where similar conditions are present. However, future research is needed to reassess the C sequestration potential of this system, once younger trees have developed; the fungal activity in the fruit system since grape vine cultivation began, and seasonal differences in fungal diversity. Research is also required at other AF systems in the UK with different environmental conditions to fully understand the potential of widespread AF adoption. Therefore, this study provides evidence that AF can be successful for enhancing the ES and biodiversity delivered by agroecosystems in the UK and highlights the potential benefits of mushroom cultivation in these systems for enhancing ES, biodiversity, and profitability.

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