Wakelyns Agroforestry: 25 years of agroforestry

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Summary

An oasis of trees, alive with bird song and insects, surrounded by a sea of large-scale conventional arable production, Wakelyns Agroforestry integrates trees for timber, energy and fruit production into an organic crop rotation. Wakelyns was established by the late plant pathologist, Prof. Martin Wolfe, to put into action his theories of agro-biodiversity being the answer to achieving sustainable and resilient agriculture. For over two decades the farm has been the focus of research into organic crop production and agroforestry. In this review, we summarise some of the key theories investigated and the evidence produced by Martin and fellow researchers from the Organic Research Centre.

The report is arranged into five sections:

1) Farm description
2) Decentralised food and energy production
3) Tree:crop interactions and total productivity
4) Functional diversity
5) Sustainability

Wakelyns Agroforestry

Wakelyns Agroforestry incorporates four silvoarable systems; short rotation coppiced (SRC) willow, SRC hazel, mixed top fruit and nut trees, and mixed hardwood trees with 10-12m-wide crop alleys between tree rows. Data on soil characteristics including bulk density and soil carbon, microclimate measurements within the alleys including air temperature and relative humidity identified differences both within the agroforestry systems and in comparison with fields that have no trees. Tree measurements have been collected from the timber alley cropping system over the last 15 years, with new data collected in autumn 2019 to bring the measurements up to date.

Decentralised food and energy production

A key element of Wakelyns has been to investigate different approaches to decentralise and localise agriculture, food and energy production and to provide a model to both prove the concept and act as a demonstration for others. This section pulls together the results of the different trials into a comprehensive comparison of the different approaches to bioenergy production.

Tree:crop interactions and total productivity

Research on interactions between the trees (short rotation coppice and standard trees) and crops (including cereals and fertility-building ley) are reviewed and summarised. This includes work on the wheat composite cross population which is a genetically highly diverse cereal pioneered by Martin through evolutionary breeding approach.

Functional diversity

Diversity is a key driver in the design and management of Wakelyns, and this section focuses on research carried out into both planned (e.g. impact of tree diversity on apple disease) and associated (e.g. pollinators and decomposers) biodiversity.

Sustainability

Agroforestry systems such as Wakelyns are often promoted as sustainable alternatives to the highly industrialised agricultural model with its associated negative environmental externalities. A combined approach applying a range of tools and metrics helps to reveal costs and benefits from a range of perspectives (environmental, economic, social) and helps determine

the extent to which agroforestry systems such as Wakelyns can deliver on a range of sustainability objectives.

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Introduction

Established by the late plant pathologist Prof. Martin Wolfe, to put into action his theories of agrobiodiversity being the answer to achieving sustainable and resilient agriculture, Wakelyns Agroforestry in Suffolk integrates trees for timber, energy and fruit production into an organic crop rotation. For two decades the farm has been the focus of research into organic crop production and agroforestry. In this review, we summarise some of the key theories investigated and the evidence produced by Martin and the agroforestry team from the Organic Research Centre.

The report is arranged into five sections:

1) Farm description. An overview of the farm and its agroforestry systems, data on soil characteristics including bulk density and soil carbon; microclimate measurements within the alleys including air temperature and relative humidity; timber tree growth.
2) Decentralised food and energy production. A key element of Wakelyns has been to investigate different approaches to decentralise and localise agriculture, food and energy production and to provide a model to both prove the concept and act as a demonstration for others. This section pulls together the results of the different trials into a comprehensive comparison of the different approaches to on farm woodchip production for bioenergy and soil fertility. New data on hedge re-growth was collected in autumn 2019.
3) Tree:crop interactions and total productivity. Research on interactions between the trees (short rotation coppice and standard trees) and crops (including cereals and fertility-building ley) are reviewed and summarised. This includes work on the wheat composite cross population which is a genetically highly diverse cereal pioneered by Martin through evolutionary breeding approach.
4) Functional diversity. Diversity is a key driver in the design and management of Wakelyns, and this section focuses on research carried out into both planned (e.g. impact of tree diversity on apple disease) and associated (e.g. pollinators and decomposers) biodiversity.
5) Sustainability. Agroforestry systems such as Wakelyns are often promoted as sustainable alternatives to the highly industrialised agricultural model with its associated negative environmental externalities. A combined approach applying a range of tools and metrics helps to reveal costs and benefits from a range of perspectives (environmental, economic, social) and helps determine the extent to which agroforestry systems such as Wakelyns can deliver on a range of sustainability objectives.

Martin and Anne's drivers

Martin and Ann Wolfe bought the fields that become Wakelyns Agroforestry in 1992, with the intention of trialling new farming systems and methods that were highly productive and sustainable without the necessity of inputs from outside the farm. Their aim was to provide both scientific evidence and a practical demonstration that alternative ways of food production are not only possible but advantageous.

When bought by Martin and Ann, the farm had been under intensive chemically-aided crop production for many years. Over the next few years, they began the process of transforming the fields into the verdant haven encountered today when arriving at Wakelyns.

Diversity at all levels underpins the philosophy and approach to the development of Wakelyns Agroforestry. Martin firmly believed that the future of sustainable agriculture was rooted in Darwinian evolutionary processes, where adaptation to the agricultural abiotic and biotic environment leads to increases in overall productivity and resilience. This would be achieved by moving away from the industrialised monoculture approach towards polycultures with major increases in diversity both within and among crops, trees and livestock. Martin's early research showed how, for example, mixing just three varieties of cereal crop together in one field could restrict disease and stabilise crop yields. This simple principle has been extended to mixtures of species and ultimately to agroforestry systems involving multiple types combinations of crops, from annual cereals and vegetable to perennial herbs and trees, together with livestock.

Figure 1. Martin and Ann Wolfe

Farm description

Wakelyns Agroforestry is a diverse organic agroforestry system in eastern England (52.4°N, 1.4°E: Figure 2) which incorporates four silvoarable systems; short rotation coppiced (SRC) willow, SRC hazel, mixed top fruit and nut trees, and mixed hardwood trees with 10-12m-wide crop alleys between tree rows (Figure 3).

The reasons behind establishing such a diverse system were manifold: to reduce pest and disease pressure by increasing the distance between individuals of the same species; to increase biodiversity including beneficials such as pollinators and natural enemies; to provide resilience to a changing climate; and to diversify production and reduce the risks associated with farming single commodities (Benjamin et al, 2000).

Figure 2. Wakelyns from the air, September 2019. Photo credit: Jeremy Gugenheim

Figure 3. Agroforestry systems at Wakelyns, clockwise from top left: Mixed fruit and nut tree system; Hazel SRC system; Mixed timber system; Willow SRC system.

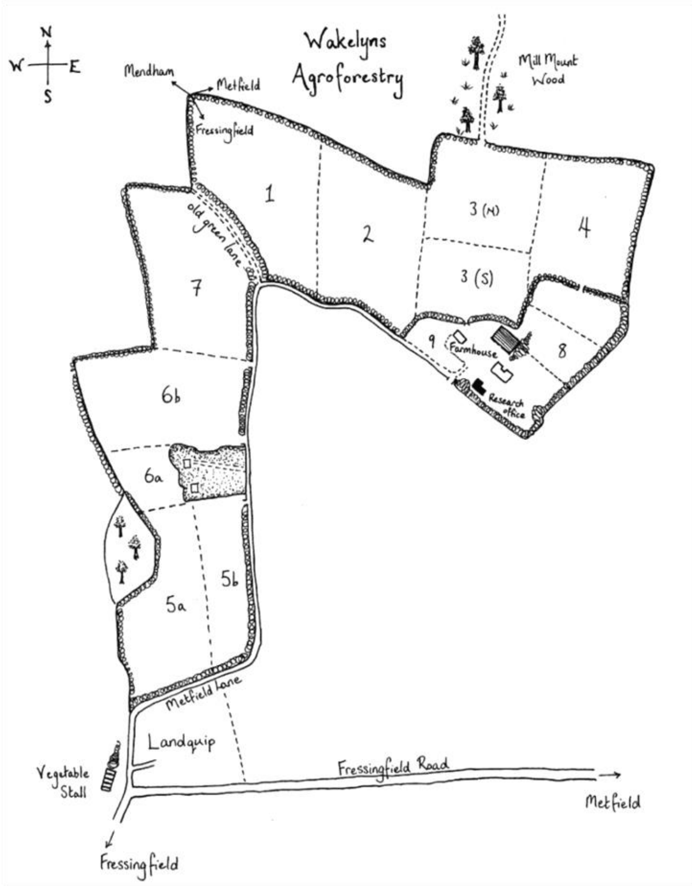


Figure 4. Wakelyns Agroforestry Map

1. **Far Field** 2+ ha • tree rows planted Feb '94 to 310 trees of 7 timber species (Ash, Wild Cherry, Italian Alder, Small-leaved Lime, Sycamore, Oak, Hornbeam)
2. **Water Field** 2+ ha • tree rows as Far Field plus 42 apple trees of 21 old varieties
3. **Home Field** 2+ ha • tree rows partially planted, starting in 2001, to fruit and nut trees (plum, cherry, apple, pear, quince, apricot, peach, hazel), each of multiple varieties
4. **Hazel Field** 2+ ha • tree rows planted Feb '95 to 1200 hazel bushes, each individual genetically distinct; each row coppiced every 7-8 years
5. **Willow Field** 4ha • tree rows planted Mar '98 to a mixture of 5 fast-growing willow varieties; each row coppiced every 2 years
6. **Vineyard** (6a) and **Mid Field** (6b) 3+ ha • No trees yet
7. **North Field** 3+ ha • tree rows planted in Feb '01 to 20 walnut trees and in Jan '02 interspersed with varieties of plum; other walnuts and plums have been added occasionally since then, and one row is not yet planted
8. **Old Paddock** (sometimes used for compost-making)
9. **Kitchen Garden**

Soil Characteristics

Bulk density

Soil bulk density was assessed by intern Murielle Ruedy from Switzerland in April 2012. Samples were taken from the willow SRC system, the mixed timber system (Waterfield) and the 'no-trees control' (Mid-Field), along three transects in each system. In the two agroforestry systems, samples were taken along the transect from under the tree rows and at 3m and 6m into the alleys, with the same spacing of samples taken in the open field control. Bulk density was assessed at each sample point by extracting a soil core of a set volume from each sample at 0-15 cm and 15-30 cm depths. Cores were oven dried to remove moisture and bulk density calculated (g/cm³). In contrast to the 'no-trees control', the agroforestry systems showed a difference in soil bulk density at a depth of 0-15 cm within the alley. The bulk density increased in both agroforestry fields from the tree rows to the middle of the alleys, but this relationship was only statistically significant in the Willow SRC system (Figure 5). Conversely, the data suggests that bulk density at the lower soil horizon (15-30 cm) was higher within the tree row than in the alley within the Mixed timber system, although this was not statistically significant.

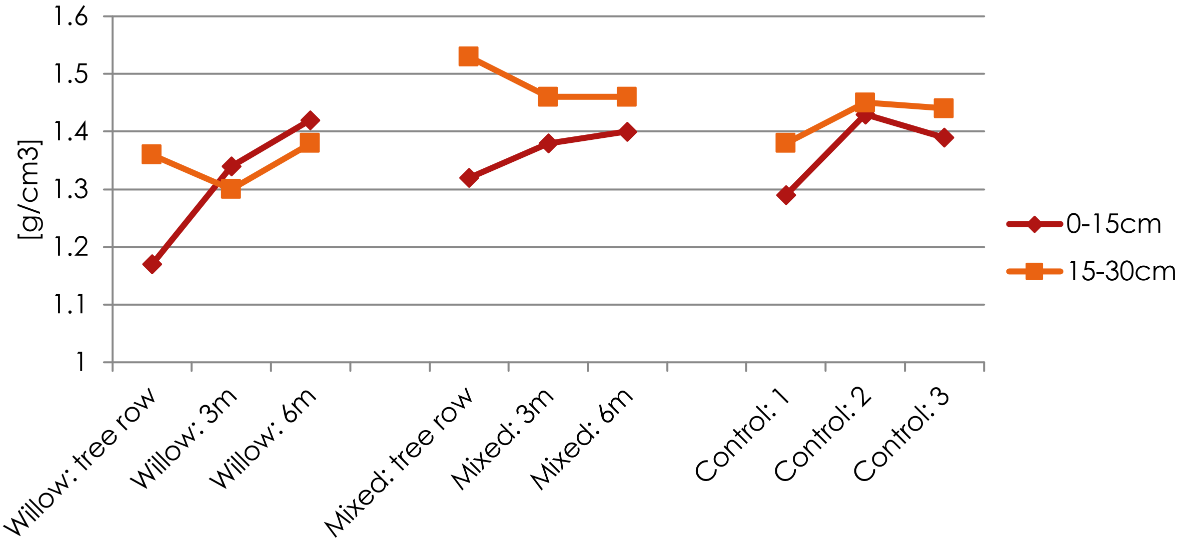


Figure 5. Soil bulk density in the willow SRC and Mixed timber agroforestry systems and 'no-trees' control field at two depths.

Soil carbon

Soil carbon analyses were carried out by Alexa Varah, a PhD student based at the University of Reading and co-funded by the Organic Research Centre (Smith et al, 2014). Soil samples were collected from the willow SRC agroforestry system and no-tree control field in early June 2013. Soil cores were taken to a depth of 40 cm and divided into three subsamples; 0-20 cm, 20-30 cm and 30-40 cm on one transect in the agroforestry alley and one in the no-tree control. Samples were collected at five points in the agroforestry system (centre of the alley west of tree row, 2 m west of the tree row, within the tree row, 2 m east of tree row and centre of the alley east of the tree row) and at six points in the no-tree control, spaced 4 m apart.

Soil samples were air-dried and sieved to 2 mm to remove coarse organic matter and stones, dried at 105 ºC for 16 hours to remove all soil moisture, and then analysed for organic carbon content using a LECO SC 144DR Carbon analyser set at 600 ºC at the University of Reading. This temperature was chosen to avoid evolving carbon contained in calcium carbonate known to be present in the soil. Bulk density of the soil was measured in 2012 at depths of 0-15 cm and 15-30 cm at each location within the willow SRC agroforestry and control system. There were no significant differences in bulk density between locations and depths (ANOVA: P>0.1) and so an average bulk density of 1.36 g/cm^3 was used to convert C concentrations to t/C/ha.

Soil organic carbon values were higher in the agroforestry system within both the 0-20 cm and 20-30 cm soil horizons (Table 1). An unusually high C content was recorded within the 30-40 cm horizon for the Centre alley west sample; this is assumed to be a sampling error and so the value is not included in the agroforestry mean. At this depth, soil organic carbon content was higher within the tree rows than in the no-tree control, while values for the other locations within the agroforestry were similar to those in the control.

Table 1. Carbon content (%) in the agroforestry and control systems

	% Carbon		
Soil Horizon	0-20 cm	20-30 cm	30-40 cm
Agroforestry location			
Centre alley west	2.13	1.19	*2.05**
2m west	1.97	1.63	0.60
Tree row	2.30	2.06	1.04
2m east	2.35	1.62	0.71
Centre alley east	2.30	1.30	0.57
Agroforestry mean (se) (n=5)	2.21 (0.07)	1.56 (0.15)	0.73 (0.11)
Control mean (se) (n=6)	1.43 (0.08)	1.12 (0.10)	0.64 (0.10)

*high value assumed to be sampling error so removed from agroforestry mean (n=4)

SOC content was higher in topsoil horizon in the agroforestry, translating to an additional 21.11 t/C/ha when compared with the no-tree control. This difference has also been found in other studies e.g. Gupta *et al* (2009) observed increases in SOC from 0.36 % in monocropped cereals to 0.66 % in poplar/cereal agroforestry soils, amounting to 2.9-4.8 t/ha more SOC in agroforestry soils. In a study of a poplar agroforestry system and a barley monocrop in Ontario, Canada, total soil carbon was 78.5 t/C/ha in the 18 year old barley-poplar system and 65 t/C/ha in the barley monocrop (Peichl et al, 2006).

Higher levels of soil carbon were recorded in lower soil horizons (30-40 cm) under the willow tree rows which is likely to be due to the lack of tillage. Upson & Burgess (2013) also found that soil organic carbon in the top 60 cm under rows of poplars in England was greater than in the no-tree control pasture (161 t/C/ha compared with 142 t/C/ha respectively). When considering soil horizons below 60 cm, however, they found lower levels of soil carbon beneath the trees, resulting in no overall differences in soil carbon between the agroforestry and control when a total soil depth of 1.5 m was considered (Upson & Burgess, 2013). The authors suggest that this effect may be due to soil drying under the trees, leading to oxidation, and the priming effect of newly accessible carbon. As the current study did not investigate soil depths below 40 cm, it is possible that the differences in carbon stocks between the agroforestry and no-tree control are over-estimated.

Soil quality

As part of the Co-Free project (Smith et al, 2016a), soil quality was assessed using the Solvita gel system to measure soil CO_2 respiration (Haney et al, 2008), to quantify the impact of management on soil microbial activity as an indicator of soil fertility. Soil samples were taken in early October 2015 within the mixed timber system, from the western tree row and centre of the crop alley in four plots (i.e. total of four samples from tree rows and four from crop alleys). At each point, three soil cores were taken at least 10 cm apart, and combined to give a composite sample. The samples were sent for analyses to the NRM laboratory using the Soil Health Analytical Package (Cawood Scientific Ltd, 2015). In addition to soil respiration rate (CO_2 burst mg/kg), this also analysed available phosphorus (mg/l), available potassium (mg/l), available magnesium (mg/l), soil organic matter (LOI %), soil pH, and soil particle size distribution (Table 2).

Soil P, K, Mg, SOM, pH and respiration rate data were analysed using a one-way ANOVA with location (WAF tree row, WAF crop alley) as a fixed factor. Where a significant effect was found, *post-hoc* pairwise comparisons of means were performed using Tukey's HSD test to identify significant differences between locations.

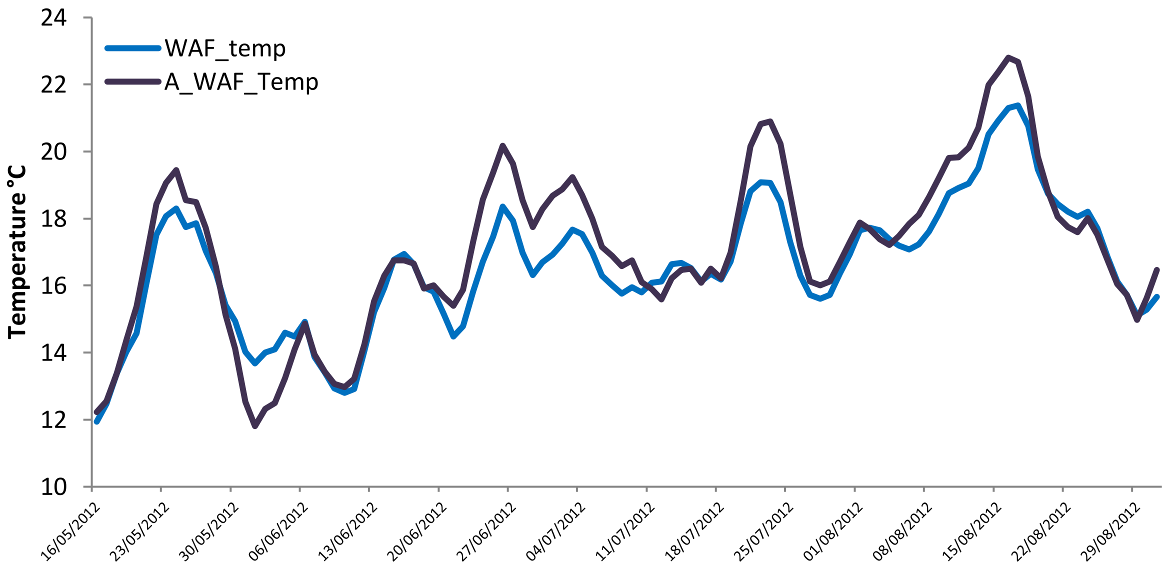
The soils at Wakelyns are classified as sandy clay to clay loams (sand 49 %, silt 23 %, clay 28 %). There were no statistically significant differences between soil P, K and Mg in the samples from the Wakelyns tree rows and crop alley. Soil organic matter was borderline significantly different between the tree row and crop alley at Wakelyns ($P=0.056$)). Soil respiration was significantly lower in the crop alley compared with the tree row at Wakelyns Agroforestry ($F=7.756$, $P<0.05$).

Table 2. Soil quality

Location	P (mg/l)	K (mg/l)	Mg (mg/l)	Organic matter (LOI %)	pH	CO_2 burst (mg/kg)
Crop alley	14.7	134.75	55.5	4.825	8.1	25.625
Tree row	20.4	165.5	67.075	6	8.175	149.3

Microclimate: Air temperature and relative humidity

Regulation of the microclimate was assessed monthly in the Mixed Timber system as part of the Co-Free project (Smith et al, 2016a). From mid-May to end of August 2012 data loggers recorded air temperature and relative humidity hourly. These data loggers were stationed at 1.5m aboveground in four tree rows and four alley centres. Figure 6a shows that air temperature was generally lower in the tree rows (WAF_temp) than within the crop alleys (A_WAF_temp), while relative humidity was generally lower in the alleys (Figure 6b), indicating the differences in microclimate between the two zones in the agroforestry, with the tree rows being cooler and more humid in the summer months, while the alleys are more exposed to the sun and wind.



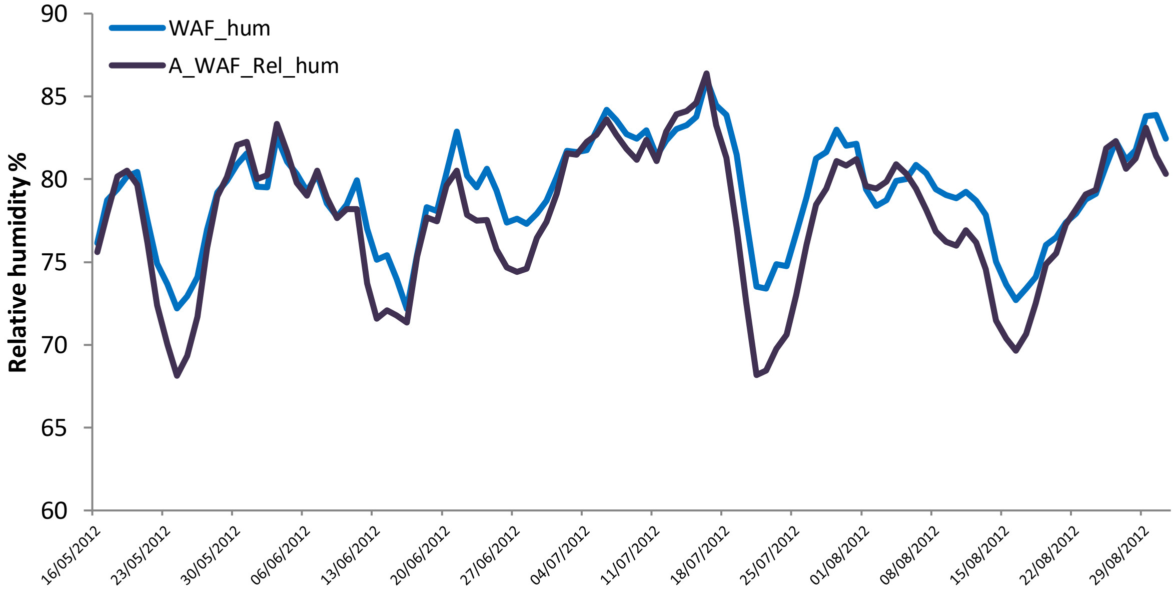


Figure 6. Top (a): air temperature. Bottom (b): relative humidity in the mixed timber agroforestry system. WAF_temp = tree row; A_WAF_temp = alley centre.

Timber tree growth

The mixed hardwood and fruit tree system in Far and Water Fields consists of eight species:

- apple *(Malus domestica)*
- small-leaved lime *(Tilia cordata)*
- hornbeam *(Carpinus betulus)*
- wild cherry *(Prunus avium)*
- Italian alder *(Alnus cordata)*
- ash *(Fraxinus excelsior)*
- oak *(Quercus petraea?)*
- sycamore *(Acer pseudoplatanus)*

Trees were planted in February 1994, with two trees of the same species planted at each station at an average of 1.6 m apart, with roughly 10 m between pairs. Trees were planted in a randomised complete block design, with a total of 44 replicate blocks, so that each block contained all eight species in a random arrangement. Since establishment, lower limbs have been pruned to maintain form and facilitate crop management, and the prunings generally left in place. A grassy sward has regenerated naturally within the tree rows and has been cut on a regular basis to prevent scrubby growth. This has been relaxed in the last few years, and now new trees are establishing naturally with thick patches of bramble and dog rose developing in some areas.

Tree trunk circumference at 1.3 m above ground of all 363 trees in Rows B to M in Far Field has been measured in August 2009, May 2016 and October 2019. Tree height of the same trees has been measured using a clinometer in September 1996, August 2009, May 2016 and October 2019. Since winter 2013/2014, pollarding and coppicing of selected trees within the system has been carried out. For those trees that have been pollarded, the height of the cut, and the height of the regrowth has been measured, as well as circumference at 1.3 m above ground. See Appendix 1 for the full data set.

Twenty-nine trees have died since planting; just one in the first two years, 16 between 1996 and 2009, nine between 2009 and 2016 and three between 2016 and 2019. Five new trees have been planted in the gaps.

For the standard trees, the Italian Alders have consistently been the largest trees, both in terms of height as well as girth, followed by Ash, with Lime being the thinnest trees (Figure 7 and Figure 8).

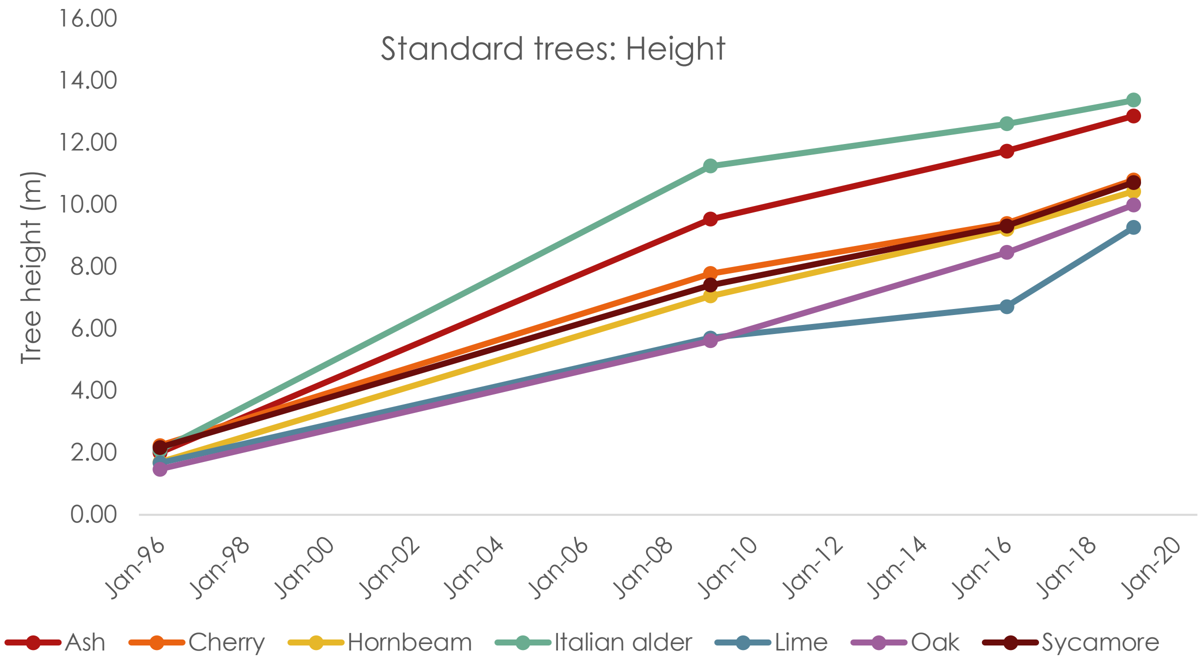


Figure 7. Tree height

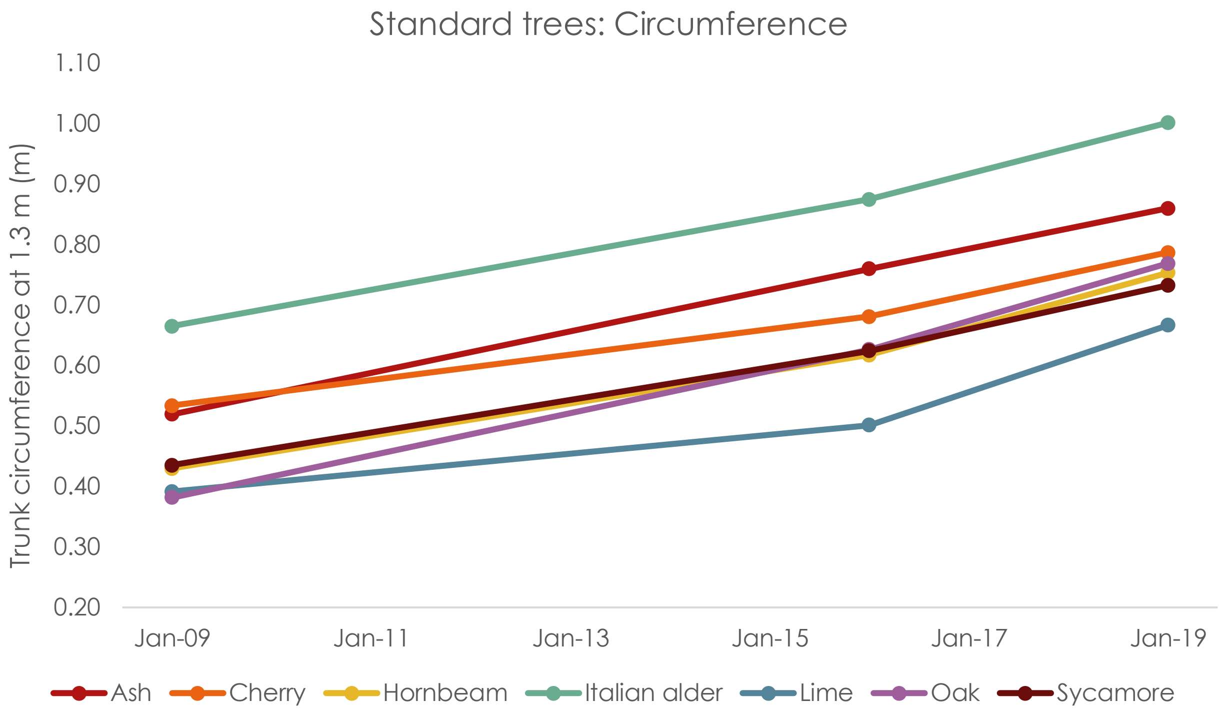


Figure 8. Tree trunk circumference at 1.3 m

Mixed timber system timeline


2012

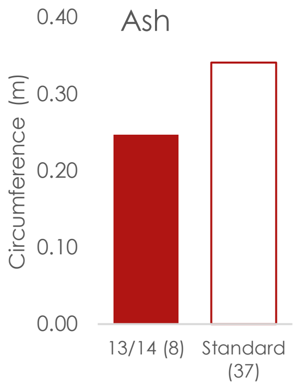

2013

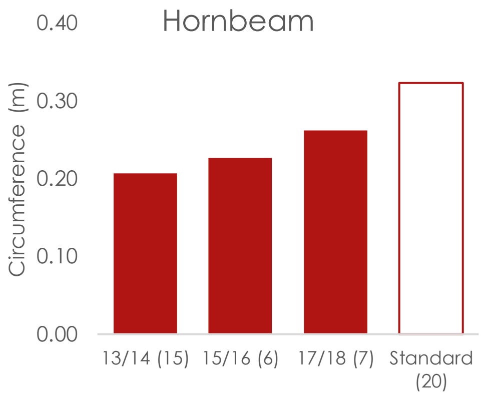

2016

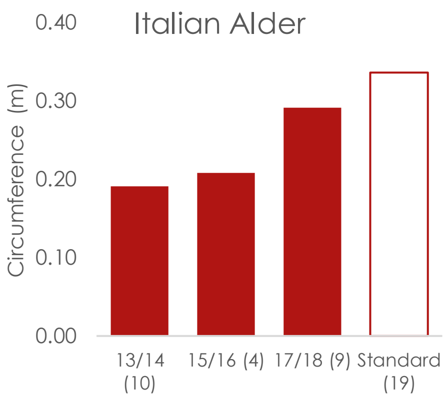

2017

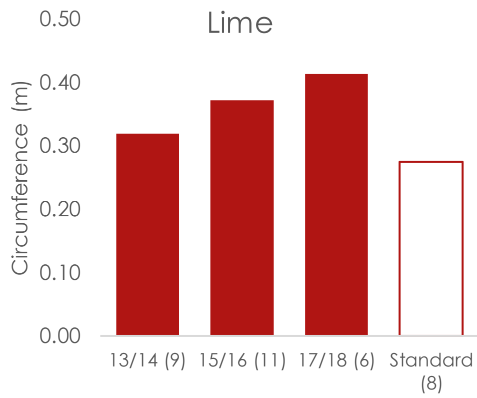

2019

Pollarded trees









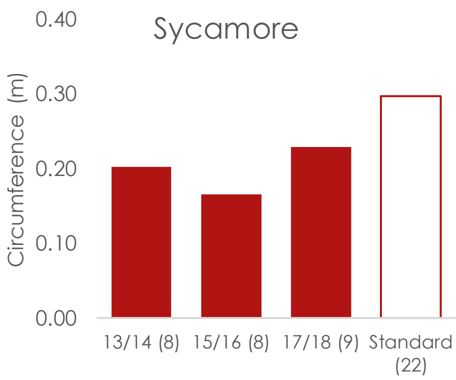


Figure 9. Increase in tree trunk circumference between 2009 and 2019 in pollarded (Year of pollard (no. of trees)) and unpollarded (Standard) trees,

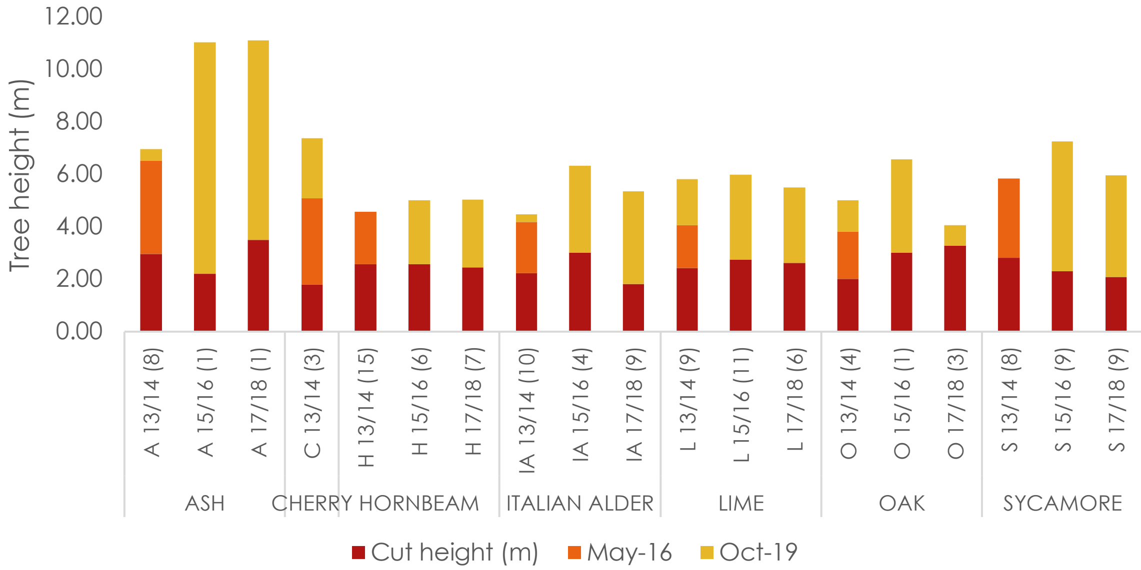


Figure 10. Tree height (m) of pollarded trees. Height of cut and subsequent regrowth (Year of pollard (no. of trees))

Martin introduced pollarding to keep the trees in their most productive phase in terms of biomass, with an associated benefit of opening up the canopy and allow more light into the alleys. General advice is to first pollard the trees when the trunk is the size of a person's fist; the trees at Wakelyns were bigger than this when first cut and there were concerns that this may have a detrimental effect on recovery and regrowth. When looking at increase in trunk circumference, it seems that pollarding has slowed the growth of all species except Lime (Figure 9). Several of the trees cut first in 2013/14 have now appeared to stop growing taller (Ash, Hornbeam, Sycamore). The benefits to the crops growing in the adjacent alleys with regards increasing available light have not been studied; as trees have been pollarded rather randomly, there is still shadow from adjacent standard trees. Ideally, all trees in a tree row would be pollarded at the same time to increase light levels (similar to the situation within the short rotation coppice systems).

Decentralised food and energy production

A key element of the research at Wakelyns has been to investigate different approaches to decentralise and localise agriculture, food and energy production and to provide a model to both prove the concept and act as a demonstration for others.

Figure 11. Wakelyns products.

Martin and Ann's core ethos of decentralising food production led them to work with the local community and local businesses to enable food produced locally to be consumed locally and challenge multinational models of food production and distribution. The diverse range of produce that has originated from Wakelyns over the years demonstrates how truly productive a small plot of land can be. Products have included bioenergy and craft materials from willow and hazel coppice, timber, fruit, vegetables, cereals and pulses, nuts, eggs, and juice and cider. Martin and Ann helped the local shop remain open as a community shop and worked closely with the champion of UK grown pulses Hodmedod's, playing host to some of Hodmedod's early naked barley trials and pioneering at Wakelyns, amongst other things, British grown lentils. Lunch was an important part of any event at the farm with visitors encouraged to enjoy eating the produce from the farm including the wild harvest of sausage rolls made from muntjac deer from the farm in partnership with a local deerstalker.

Martin and Ann aimed to achieve decentralised energy production by using the short rotation coppice (SRC) agroforestry tree rows and traditional field boundary hedgerows to produce woodchip for fuel. Woodchip from the SRC and the hedges is used to power a small 20 kw boiler which provides the year-round heat requirements for the farmhouse with additional woodchip left over for other purposes. The coppice species used for woodchip production are hazel (*Corylus avellana*), cut on a five-year rotation and willow (*Salix viminalis*) cut on a two-year rotation. Harvesting is carried out in winter using a tractor mounted circular saw and chipped the following summer using a small hand fed chipper. In this section we focus on our research into the different approaches to energy production.

Figure 12. Decentralised food production at Wakelyns

Bioenergy production from Short Rotation Coppice

Short rotation coppice agroforestry tree rows were established in two of the fields at Wakelyns to provide biomass feedstock for the boiler to heat the farmhouse and farm buildings. In February 1995 hazel (*Corylus avellana*) trees were planted at a spacing of 1.5 m between trees, 1.5 m between twin rows (i.e. 2 lines of trees in each tree row). In March 1998 willow (*Salix viminalis*) trees were planted at a spacing of 1.2 m between trees, 1.5 m between twin rows (i.e. 2 lines of trees in each tree row). The copping alley between each tree row is 10 m and the tree rows are approximately 3m wide. Trees were planted through a mypex weed control barrier, and no tree protection was used.

Biomass production of the SRC willow has been measured since 2011 and the hazel since 2014 (Smith et al. 2016c; Smith et al. 2017). Willow is harvested on a two-year rotation with every other row being harvested in a particular year (i.e. 50% of the rows are harvested each year). Hazel is harvested on a five-year rotation, with only one side of the twin row being cut in any year. Before the main harvest, sample stools were cut by hand with a chainsaw and weighed using a spring balance mounted on a tractor.

Stools were randomly selected every 12 m along the tree row. With the willow, the twin rows within each tree row are both harvested and so stools from alternate rows (east/west) were sampled. With the hazel, only one of the twin rows (east or west) is cut in any year and so all stools were from the same side (from 2-3 rows) with an average of 23 trees sampled per year. In addition to the 5-year regrowth samples, some additional samples were collected from different aged regrowth, but with fewer replications and from only single years (4-year regrowth in 2016, 6-year regrowth in 2014, 7-year regrowth in 2013 and 9-year regrowth in 2015). Sub-sampling and oven-drying of the willow and hazel in previous years have indicated a moisture content of on average 50% for willow and 32% for hazel and this is used to convert fresh weight to oven dry weight (ODW). Biomass production is first presented as ODW kg/tree and then converted to ODW per ha of agroforestry and annual ODW calculated for comparison (Table 3).

Table 3. Biomass production of hazel and willow short rotation coppice at Wakelyns Agroforestry

Species and age of regrowth	N*	Tree density per 100 m	Tree row area (m^2)	Crop area (m^2)	Trees density per hectare	Moisture content (%)	Oven dry weight		
							(kg/tree)	(t/ha)	(t/ha/yr)
Hazel 4 yr	8	133	300	1000	1023	32	24.92	25.49	6.37
Hazel 5 yr	92	133	300	1000	1023	32	23.65	24.19	4.84
Hazel 6 yr	10	133	300	1000	1023	32	25.69	26.28	4.38
Hazel 7 yr	10	133	300	1000	1023	32	32.91	33.67	4.81
Hazel 9 yr	10	133	300	1000	1023	32	37.74	38.61	4.29
Willow 2 yr	181	165	300	1000	1269	49	7.64	9.70	4.85

*Number of trees sampled.

In 2015, the calorific content of woodchip was analysed (for the project TWECOM) as a measure of the energy content of the fuel. Woodchip samples were sent to the BioComposites Centre at Bangor University and their calorific content determined. Each one litre woodchip sample was milled to a fine powder using a Glen Creston mill. The powder was dried overnight and then combusted and analysed using a Parr 6100 bomb calorimeter. The results were reported in MJ/Kg and converted to GJ/t and annual energy production (Table 4).

Table 4. Energy production of hazel and willow short rotation coppice at Wakelyns Agroforestry

	Energy content (GJ/t)	Annual energy yield (GJ/ha)
Hazel 4 yr	19.35	123.32
Hazel 5 yr	19.35	93.63
Hazel 6 yr	19.35	84.76
Hazel 7 yr	19.35	93.08
Hazel 9 yr	19.35	83.02
Willow 2 yr	19.11	92.65

The two species of SRC produce very similar yields under current rotations (hazel 5 years and willow 2 years), when converted to annual biomass production. This gives farmers two options to produce a similar outcome; a willow system where the canopy is removed every other year so reducing the amount of shade on the alley crops, but requiring more frequent harvest (and potentially more competitive with crops for water and nutrients) versus a hazel system with slower growing trees, potentially casting more shade, but with fewer harvests to achieve the same yield. A detailed study of crop yields and microclimate conditions in the two systems would allow us to calculate and compare total productivity. It would also be good to include other ecosystem services such as biodiversity impacts (e.g. willow provides early season resources for bumblebees).

Yields of the four-year regrowth hazel suggest that harvesting one year earlier than current practice may be more productive. However, these data were from only a single year and a limited number of trees, so further investigation would need to be carried out before changing the rotation. It may also be that harvesting on a four-year rotation would impact future regrowth and yields.

Bioenergy production from boundary hedges

Hedgerows are a ubiquitous feature of the English landscape and an important part of the cultural heritage of the countryside. Hedgerows have always been regarded as multi-functional. Established mainly to improve the husbandry of livestock, to prevent damage to arable crops and to mark property boundaries, they were also highly valued as a source of food, materials and firewood (Baudry et al, 2000). Nowadays they are largely valued for their wildlife and landscape values and for the wide range of ecosystem services they provide, including regulation of water quality and quantity (Wolton et al, 2014) and crop pest control (Ricci et al, 2009). This contribution to ecosystem services is recognised by policy makers, with hedgerow maintenance, conservation, creation and restoration through agri-environment schemes within the Common Agricultural Policy and protected from removal by the UK hedgerow regulations act 1997.

However, despite this support, the majority of hedges in the UK are in poor condition as a result of both agricultural impacts and inappropriate management. Opinions of hedgerows differed widely between stakeholders interviewed as part of the value chain analysis carried out by von Oppenkowski (2017) from 'an unnecessary burden' to being 'crucial to the farm'. There are currently few practical or economic reasons for farmers to manage their hedges well, especially in arable areas and most UK hedges are flailed annually or neglected altogether; both practices are eventually detrimental. Hedges need periodic rejuvenation work by either laying or coppicing, both relatively time consuming and costly management options. Identifying practical economic uses for hedges and hedge material, for example as woodfuel or as a soil improver, could offer a solution and encourage farmers to manage their hedges sustainably.

Schemes to encourage more home-grown biomass such as the UK government's Energy Crop Scheme saw low adoption, with farmers and landowners being risk averse and unwilling to plant areas with perennial woody crops (Convery et al. 2012). By managing existing landscape features such as hedgerows for bioenergy, farmers do not need to choose between producing food or energy from their land. Woodchip outputs could be sold off-site or used to fuel on-farm woodchip boilers, thus increasing sustainability further. There are concerns, however, about the feasibility of fuel-grade woodchip from farm hedgerows, related to the scale of operation (economies of scale for optimal machinery operation) and the quality and quantity of woodchip produced. Research at Wakelyns and Elm Farm aim to answer some of these questions. The aim of this research is to examine the practicalities and impacts of managing a proportion of the hedgerows on for woodfuel production. Coppicing, cutting all woody growth at ground level on a 15-20-year cycle, is the management technique assessed.

A mature mixed species and a single species hazel field boundary hedge were coppiced at Wakelyns as part of the EU funded project TWECOM (www.twecom.eu) hedgerow harvesting machinery trials in February 2015 (Chambers et al. 2015). The aim of the trials was to assess the feasibility, efficiency, costs and viability of mechanising the process of coppicing hedges and processing the resultant hedgerow material as a local and sustainable source of woodfuel. The selection criteria for the hedgerow harvesting machinery was a range of sizes of machinery, with the associated range of hire or purchase cost, and a range of cutting mechanisms to investigate the impact on stem cut and stool regrowth. Machinery was loosely classified as small, medium and large scale, and one machine of each scale was trialled at each of the two sites, Elm Farm and Wakelyns Agroforestry. At Wakelyns the trials compared the performance of manual fell, a circular saw and a felling head (Figure 14). This trial was attended by around 10 local stakeholders.

Figure 13. Machinery trial, Wakelyns, February 2016

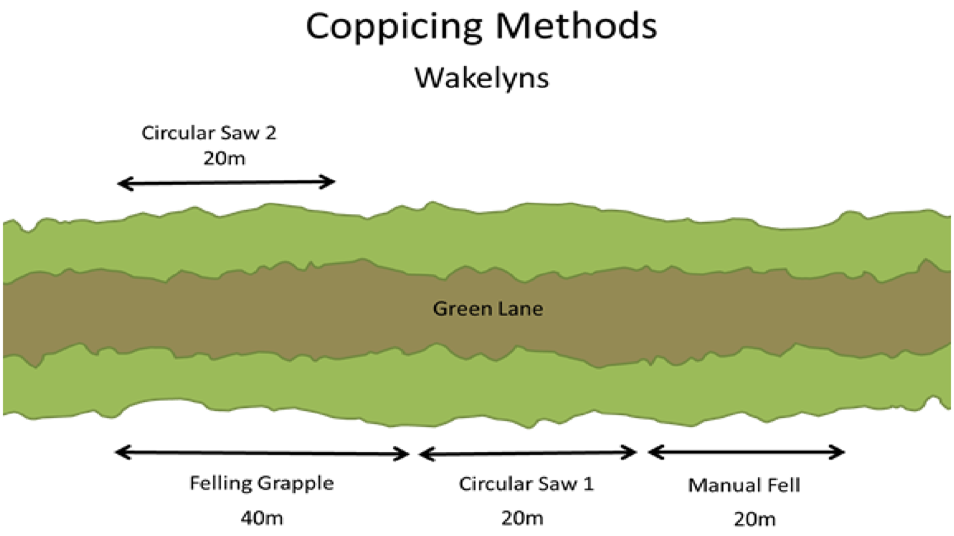


Figure 14. Trial design 2015

In January 2017, as part of the SustainFARM project, additional coppicing trials were carried out in different agroforestry types (traditional boundary hedge and short rotation coppice) at Wakelyns Agroforestry (Westaway, 2018). The main aim of the trial was to compare harvesting methods, machinery and the logistics of woodchip production from different agroforestry types.

The agroforestry types:

1. Traditional boundary hedge (Figure 15a). The hedge selected was an unmanaged mature mixed species hedge approximately 160m long. There is a central ditch with the hedge on both banks. Counts of the rings on a sample of the cut stools indicated that the average age of the stems was 21 years, suggesting that this is when the hedge was last cut.

2. Hazel short rotation coppice (SRC), grown in an alley cropping agroforestry system combined with arable cropping (cereals, vegetables, fertility building legume ley), with double rows coppiced on a 5 year rotation (Figure 15b). Originally planted in 1995 and described in more detail in the previous section.

Figure 15. Agroforestry types included in the trials at Wakelyns Agroforestry (a: left) mature unmanaged traditional boundary hedge (b: right) Hazel short rotation coppice

Harvesting methods

All material within marked sections of the boundary hedge or SRC was coppiced (i.e. cut once near the base of the stems). Approximately one hedgerow tree every 50 m was marked and left to grow on to become a mature tree in the hedge. All cut material was removed from the hedge or SRC and placed in a marked area in the grass agroforestry alley, with all the butts facing the hedge and the stems perpendicular to the hedge.

Different machinery was trialled for cutting the different agroforestry types to ascertain the effectiveness of each machine in terms of both their ability to cut the material and the relative cost and time of the options.

1. Tree shears: 360-degree tree shears with a scissor action mounted on 7.5 tonne excavator (Figure 16a). The cutting capacity is up to 35 cm.
2. Bracke C16.c Felling Head. Accumulating felling head with circular saw cutting blade mounted on a purpose-built Valmet 901.4 (Figure 16b). The cutting capacity is up to 26 cm and the saw blade theoretically leaves a cleaner cut than the shears.
3. Chainsaw: Data from previous trials and the Elm Farm trial on the economics of manual (chainsaw) coppicing of boundary hedges and SRC is included in the analysis to allow comparison of different harvesting methods.

Figure 16. (a: left) Tree shears harvesting mixed species boundary hedge (b: right) Bracke felling head in action on the SRC

One section of hedge and one section of hazel SRC were coppiced using the tree shears and a different section of each using the felling head. After an initial warm up in each section, both machines cut continuously for 30 minutes and the length of hedge or SRC coppiced in this time was recorded. The cleanness of cut was also recorded along with overall fuel use and any comments on the job from the contractor. Where necessary the hedge stems were tidied up with a chainsaw after cutting, and in some cases the SRC was tidied up with a circular saw. All coppiced material was left in the field to dry and chipped in the summer 2017.

Following passive drying in the field and chipping of all material from the hedge, woodchip samples were collected using a composite sampling method. The samples were sent off to be tested for particle size distribution, ash content and total calorific value by Knight Energy Services. The volume of chip from the hedge and SRC was calculated as it was chipped giving a measure of productivity of each of the systems. The results were then compared with data from the Organic Research Centre's Elm Farm trials, and differences in quality were assessed against the costs of woodchip production from each different method and agroforestry type for each operation.

Generally, the tree shears were much slower at spinning and laying the material down with less dexterity than the Bracke. Even though the Bracke was a bigger machine, the low pressure wide tyres meant that there was less damage to the ground from the Bracke compared with the tracked excavator that tree shears were mounted on. The shears left a better finish on the hedge with less disturbance to the tree roots, but they were not well equipped to handle the smaller multi-stemmed material of the SRC; the crushing action of the blades caused the wide coppice root ball to move and there was significant splitting in the stems. As a result, the trial of the shears on the SRC was abandoned and only a few stools cut and marked to monitor regrowth. The Bracke felling head was much better suited to the SRC and worked through the stools quickly. However, the stools needed lowering by chainsaw behind both the machines.

Harvesting methods using large excavators, such as the tree shears and assisted fell methods, need good ground conditions to operate in order to support machinery, with concern about compaction and rutting when the ground is wet. By contrast, hedges can be manually felled with a chainsaw in most ground conditions. The main limitation of manual felling is the size of timber which can be manually extracted and moved without an excavator to assist and cordwood needs to be cut into shorter lengths.

Biomass production

The volume of woodchip produced from the hedge at Wakelyns was calculated at 29.1 m^3 per 100 m of hedge or 10.2 tonnes per 100 m at c. 30% moisture content. The SRC grown in an agroforestry system produces less woodchip per 100 m on an annual basis. However, over the course of a coppice cycle, production is higher than that of the boundary hedges by almost double (Table 5). Hazel is cut on a 5-year cycle and willow biennially, but the annual biomass production from the two SRC species works out the same (see also Table 3).

Table 5. Woodchip production (* results from Smith et al 2017. ** results from Westaway and Smith, 2018)

	Tonnes/100m @30% mc	Years of regrowth at coppicing	Tonnes/100m/yr[1]
Wakelyns hedge	10.2	21 years	0.49
Elm Farm hedge**	7.34	15 years	0.49
Willow SRC*	1.64	2 years	0.82
Hazel SRC*	4.09	5 years	0.82

[1]Assumes that the trees are re-coppiced after the same number of years regrowth

Woodchip quality

While woodchip boiler systems can be designed to burn a variety of woodchip sizes, most are designed to work at high efficiencies requiring woodchip of the correct size, with a low proportion of fine material which would reduce the combustion efficiency and a low proportion of large shards which could jam the feed system. The European biomass industry has accepted woodfuel standards to ensure consistency and quality of woodfuels. The Austrian ÖNORM M7 133 standard for woodchip is widely used and has three standard sizes which are G30 (60 - 100 % of particles: 3 - 16 mm), G50 (60 – 100 % of particles: 6 - 32 mm) and G100 (60 – 100 % of particles: 11 - 63 mm). Previous research (Chambers et al, 2015) has shown that the standard of G30 can be achieved from hedgerow woodchip.

In contrast to earlier trials (Chambers et al, 2015) all samples collected for SustainFARM failed to attain the G30 wood fuel accreditation standard on the maximum length of particle in the sample submitted (Table 6). To pass G30 the maximum length must not exceed 8.5cm. Screened and dried samples were generally more even sizes with less of the sample falling into the large and small categories, but the maximum length was still too large to pass at G30 specification. The presence of long shards and slithers in the chip is one of the biggest issues with hedgerow or SRC woodchip, and even when screened the chip from these trials failed to pass the G30 standards on maximum particle length. This was the only criteria most of the samples failed on and was a parameter that was not included in the TWECOM assessments, which all passed the G30 standard (Chambers et al, 2015). Despite this the chip from Elm Farm was sold into a woodfuel hub, where they were satisfied with the quality, although where quality is low, they blend with higher quality chip for resale. The chip from Wakelyns was used in the on-farm Gilles 20kw boiler to heat the farmhouse. Differences in the calorific values and ash content between the TWECOM and SustainFARM trials suggest that the testing at different laboratories may have influenced the results. Interestingly the lowest ash content was seen in the hazel SRC, which is unexpected as this material was only 5 years old and as such has a high bark to core wood ratio, the material is dried in the field prior to chipping and it is possible that this can be explained by some of the bark falling off the hazel as it dries.

Table 6. Woodchip quality analyses (* results from Chambers et al 2015)

Site	Drying method	Hedge and chipper	MC (%)	Ash content (%)	Gross Calorific Value	G30 particle size distribution				
						>16	>2.8	>1	<1	Max length
Elm Farm	Chipped green and passively dried in shed	Hazel hedge - bigger chipper	26.6	2.2	17.2	7.2	82.7	7.2	2.9	10.9
		Hazel hedge - small chipper	28.7	2.2	17.3	15.0	75.6	6.8	2.6	14.6
		Hazel hedge - fuel grade chipper *	30.6	3.6	19.1	7.7	83.0	8.0	1.3	
	Actively dried	Hazel hedge -small chipper	10.0	2.2	17.2	9.5	85.4	4.3	0.8	11.8
	Actively dried and sieved	Hazel hedge -small chipper	10.0	1.8	17.2	6.3	88.1	4.8	0.8	12.9
Wakelyns	Dried in field chipped 6 months later	Mixed hedge - fuel grade chipper	27.5	2.6	17.2	13.9	81.2	3.8	1.1	11.0
		SRC Willow - small chipper *	24.3	1.7	19.1	1.5	77.2	18.3	3.0	
		WAF SRC Hazel - small chipper *	17.8	2.9	19.4	4.8	85.4	8.0	1.8	

Gross calorific values (Mj/kg) were similar from all of the chip samples (Table 6). They were, however, lower than the 2014 values collected by Chambers et al (2015). The ash content of woodchip that had been left to air-dry in the field for six months ranged from 1.7% for the willow SRC woodchip to 2.9% for the hazel SRC. The woodchip produced from the Elm Farm hedge in 2014 had the highest ash content at 3.6%, the hazel hedge coppiced and chipped in 2016 had lower ash content of 2.2%. Screening (sieving) the chip reduced the ash content to 1.8%. The air-dried material had an average moisture content of 23.2% and the barn dried chip had an average moisture content of 28.6%. However, the short rotation coppice hazel woodchip which was air dried in the field had the lowest moisture content by a long way and skews these averages.

Hedge regrowth following coppicing

Regrowth of the hedges that were coppiced as part of the TWECOM and SustainFARM trials was monitored in 2016, 2018 and 2019. A representative sample of stools from each hedge were selected at each monitoring visit. As per Croxton et al. (2004) the five longest shoots from each of these live stools are measured and an average per stool calculated. In blackthorn hedges there may be root suckers emerging from the ground even when no shoots are produced from the adjacent stool. Root sucker regrowth is recorded as associated with a stool if it occurs within 20cm of the stool.

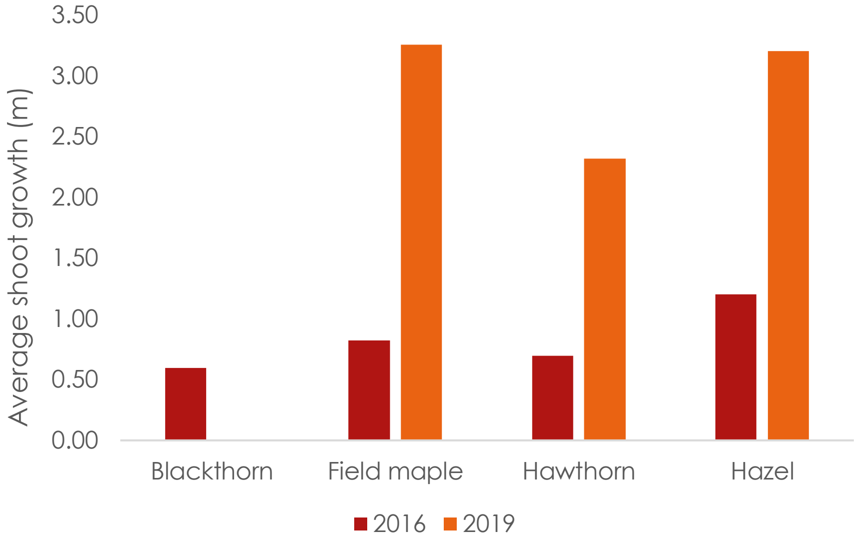


Figure 17. Average regrowth of different species in a mixed species hedge that was coppiced in February 2015

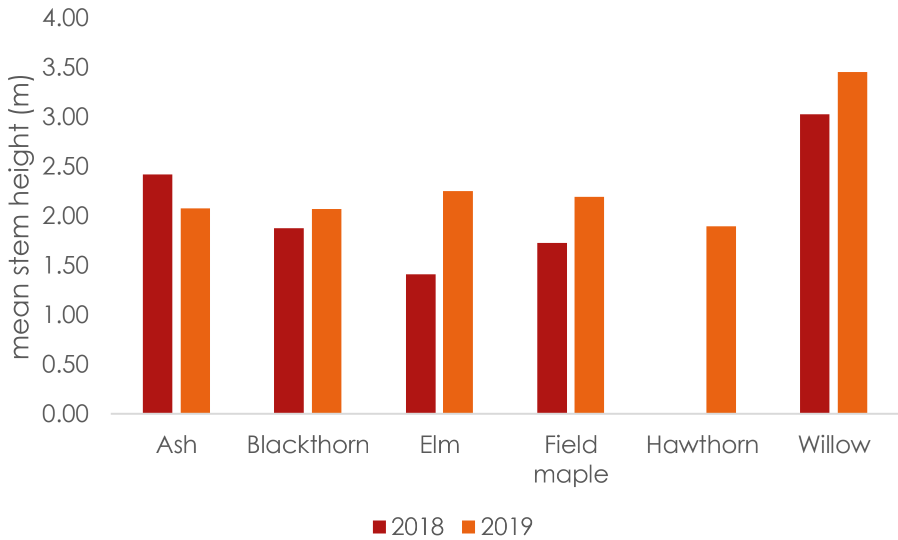


Figure 18. Average regrowth of different hedge species a mixed species hedge that was coppiced in January 2017

All species regrew strongly following coppicing, putting on an average of 0.83 m of growth in the first year following coppicing in 2016 (Figure 17). Regrowth in the 2017 hedge was in general greater than the 2015 hedge, with the average regrowth after one year 2.08m (Figure 18). This may be due to the more open situation of this hedge with greater light levels available to the coppice stools. However, the 2017 hedge was also a farm boundary hedge and the neighbouring farmer has flailed the coppice regrowth back hard on his side of the hedge which has affected the regrowth of some of the coppice stools in this hedgerow, and regrowth was not measured on stools that had been flailed.

How many trees are needed to heat a farmhouse?

A typical 20 kw farmhouse boiler such as the one at Wakelyns uses approximately 80 m^3 of woodchip/year. Therefore, based on the calculations in Table 7:

● 2800 m of SRC (double rows of willow or hazel) is needed to heat the farmhouse. Converting into field area with 3 m wide tree rows and 10 m wide alleys this equates to approximately 3.62 ha of agroforestry.

● 320 m of hedgerow is needed every year to heat the farmhouse; on a 15-year harvesting rotation, a total of 4.8 km of hedgerow would need to be in a coppice rotation to meet this demand.

● Wakelyns Agroforestry has 3.7 km of boundary hedgerow, 2.18 km (3.2 ha) of willow short rotation coppice, and 1.5 km (2.4 ha) of twin rows of hazel short rotation coppice as alley cropping agroforestry, so is easily able to meet this need (Table 7).

Table 7. Woodchip production at Wakelyns (Smith et al. 2017; Westaway and Smith, 2018)

	Length (m) at Wakelyns	Volume of woodchip per metre (m^3)	Coppice rotation length (years)	Length coppiced in one year (m)	Annual woodchip production (m^3)
Willow SRC	2175	0.0574	2	1087.5	62.42
Hazel SRC	1500	0.1432	5	300	42.96
Boundary hedge	3700	0.25	15	247	61.75

Decentralised energy production: key conclusions

- Woodchip offers potential as a viable alternative to other fuel sources, especially heating oil, and is well suited to rural areas, especially farms with the option of self-supply from hedgerows or other woody elements.
- Hedgerows and short rotation coppice are both possible woodfuel sources and management for woodfuel can fit into a whole farm management plan. Hedgerow management is a cost to farmers and using the material produced as a fuel can offer farmers an option to offset some or all of this cost. In addition, self-supply of fuel offers the farmer resilience against future rises in fuel costs.
- Willow and hazel SRC and field boundary hedges offer farmers alternative system options but with similar returns. Trees have an influence on the adjacent agricultural land, this influence varies between growth stage and species. Willow and hazel SRC, given their different management requirements, differ in their effects. Both species, however, provide similar net yields. There is therefore flexibility for farmers to choose the tree species best suited to their wider farm system without suffering any consequences in returns regarding

tree biomass. The decision of species on the basis of the wider agricultural system – as opposed to the fastest growth and shortest harvest cycle – should thus be encouraged. It is possible that this also extends to other tree species; this would offer an even greater range of choices and options to suit any system.

- The average annual production over the whole coppice cycle was almost double for the SRC agroforestry rows than boundary hedges. It must be kept in mind, however, that the SRC is grown within fields and so displaces a proportion of crop or pasture production, although the shelter and nutrient recycling from the trees can also benefit the crops/pasture and so lead to increased production overall (Smith et al, 2012). An interesting avenue for further investigation will be to coppice boundary hedges on a shorter rotation, to capture the peak growing period, similar to SRC systems. This will depend on species composition of course, but hedges of hazel, willow and alder could be potentially harvested every 5 years or so.
- The heating needs of a typical farmhouse can be met by a relatively small area of agroforestry or length of hedge. Given a farmhouse boiler of 20 kW and a system design the same as Wakelyns (3 m wide twin tree rows and 10m wide alleys), approximately 3.62 ha of agroforestry is needed to fully meet the annual heating needs of a typical farmhouse. Field boundary hedges offer a potential alternative to in-field trees for production of woodchip biomass requiring 320 m of hedgerow on a 15-year harvesting rotation, a total of 4.8 km to meet the boiler demand.
- Fuel quality can be an issue and boiler specifications will need to be matched. Depending on the farming system there may be alternative uses for the chip that would be better suited, for example as livestock bedding or as a soil improver.

Connecting trees and crops: woodchip for soil health

Another possible way to integrate trees and hedges into the farming system is to use the woody material from hedges or SRC as a soil improver. This could be in the form of composted material, or alternatively applied fresh, as ramial chipped wood (RCW).

Ramial Chipped Wood (RCW) is fresh un-composted woodchip made from smaller diameter material from hedges and trees. Young branches are nutritionally the richest parts of trees, as they are exposed to the most light, and are the most actively growing. Young branches can contain as much as 75% of the minerals, amino acids, proteins, phytohormones and enzymes found in the tree. As such, material harvested and chipped from smaller tree branches or hedges provides ideal material for the production of RCW. A review of the use of RCW in agricultural systems was carried out by researchers at Laval University, Quebec, Canada in 2000 (Caron et al. 1998). The report documents evidence for increased soil biological activity and soil organic matter (SOM) associated with application of RCW. In addition, results from a 15-year experiment on a Soil Conservation Service research farm in Marcellus, USA from 1951-1965, found that adding 10 tons/acre of fresh woodchip each year did more to maintain soil quality than grass cover crops or resting the soil with harvested alfalfa sod hay crops (Free, 1971). However, few, if any studies, have followed up on these findings. To produce RCW the above research suggests that hedge material should be cut and chipped without green leaves. Green leaves contain chemical elements easily accessible to bacteria and these bacteria can prevail over the fungi white rot (Basidiomycetes). Research by Caron et al. (1998) recommends using smaller diameter material for chip production (less than 7 cm in diameter) and for Germain (2007) up to 5 to 10 cm length. Chipping or crushing ramial wood encourages fast entry of soil microorganisms, enabling both nutrients and energy to be transferred to the humus complex (Lemieux, 1993), chipped fresh when the leaves are off, as younger branches are more nutritionally dense. The branches, which make the RCW, represent the richest part of the tree. They contain 75% of minerals, the amino acids, proteins and catalyst (Noel, 2006).

The Woodchip for Fertile Soils (WOOFS) EIP Operational Group in the UK is researching the addition of uncomposted RCW sourced from on-farm woody resources as a soil improver (Westaway, 2019). As part of the Operational Group trials have been established on three farms in Southern England in winter 2017/2018 and will run until 2020. Wakelyns hosts one of these trials.

The RCW trial at Wakelyns

The trial is situated in the control fields (Figure 4, field 6b). The block size is approximately 97 m x 45 m. The field was sown at the end of July 2017 with a mixed species ley following a trial of different wheat sowing rates. A cereal crop will be sown in spring 2020. Four woodchip treatments were applied in March 2018 at a rate of 40m^3 per hectare. Material was cut, chipped and then spread as soon as possible so that it was still fresh at application. The treatments were:

1. Willow short rotation coppice woodchip (from 2 year old growth)
2. Hazel short rotation coppice woodchip (from 5 year old growth)
3. Poplar woodchip (2-3 years since last coppice)
4. Woodchip from mixed species hedge material supplied free of charge by BTS Utility Arboriculture Management Group
5. Control with nothing added

The trial block was split into 15 plots giving three replicates of each treatment. Replicates were randomised across the field. In late March 2019 half of each plot (apart from the poplar) was given a second application with double the rate of woodchip (80 m^3 per hectare). Substrate analysis was carried out on the woodchip prior to application and soil samples collected in summer 2018 and 2019. Earthworm counts have also been carried out in autumn 2018 and 2019, with a detailed analysis of earthworm population planned for March 2020 prior to the plots being ploughed.

Initial results

Results from the first two years have shown no significant differences between the RCW treatments and the control plots for most of the soil parameters measured (P, K, Mg, SOM, pH and CO2 burst).

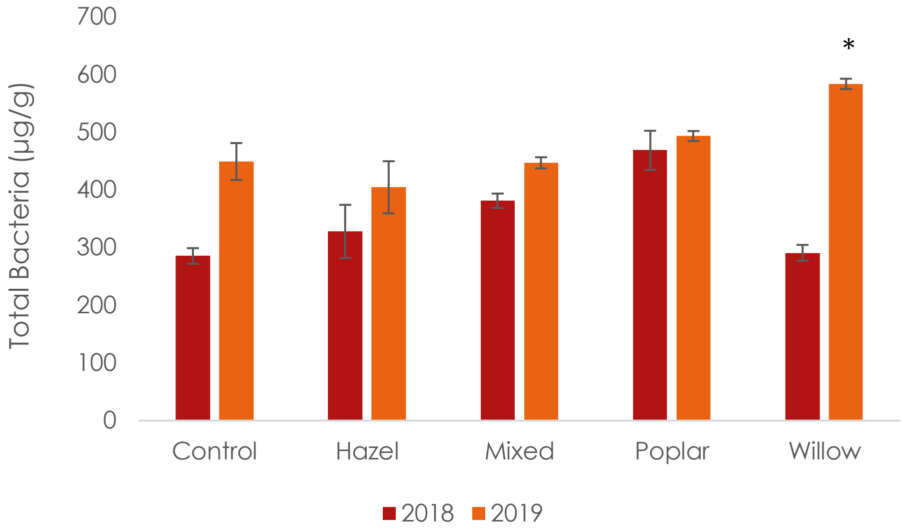


Figure 19. Total bacteria between different RCW treatments and years at Wakelyns Agroforestry (mean +/- standard error) * indicates significant results

Some small differences between treatments in soil biological activity were observed. For example, in 2019 total bacteria was significantly higher in the willow woodchip plots (Figure 19) when compared to the other treatments, a pattern not seen in 2018. The total biomass of bacteria provides an indicator of abundance of food for predators, nutrient capacity and general diversity of the bacterial population and the health of the soil, suggesting some positive effects of the woodchip over the control treatment. However, mycorrhizal root colonisation, fungi counts and fungi to bacteria ratios were also measured with no clear patterns seen between treatments at this stage.

Figure 20. Sampling worms in the RCW trial at Wakelyns Agroforestry

Worm diversity and abundance also gives a good indicator of overall soil health. An increase in total numbers of worms was observed between 2018 and 2019 (Figure 21), however this is likely to be a result of the reduced cultivation associated with the long term leys and no significant differences in the total number of worms were seen between treatments and the control.

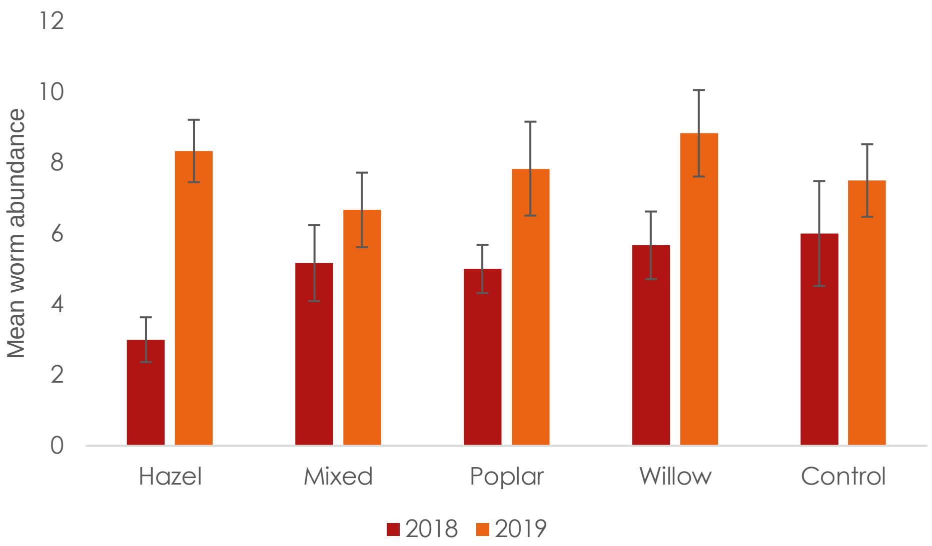


Figure 21. Total worm abundance (adults and juveniles) found in different RCW treatments in 2018 and 2019 at Wakelyns Agroforestry (mean +/- standard error)

The fact that there a have been few significant differences observed between treatments for most of the soil and other parameters measured suggests that applying woodchip green may be a viable alternative source of organic material, especially when applied to the ley phase of a rotation. However, the breakdown of woodchip, colonization by fungus and subsequent action on the soil is a long-term process (Lemieux and Germain, 2000) and to confirm these results these trials need to be studied over a long period of time and over a number of crop rotations.

Tree:crop interactions and total productivity

In agroforestry systems, interactions between the tree and crop/livestock components can be positive, negative or neutral. Positive interactions can lead to an increased capture of a limiting resource, resulting in greater total production than if the two components had been grown separately. Conversely, negative interactions occur when the two components overlap in their resource use and can result in lower productivity than if the components are grown separately. These interactions are likely to change over time, so that there may be complementarity between the components in the early stages of an agroforestry system, which then shifts into competition for resources as the tree component reaches maturity. Yield impacts can be reduced by designing a system that minimises the interface between trees and crops, and by managing both components to encourage complementary rather than competition in resource use.

The three main limiting resources are light, water and nutrients. Demand for these resources vary temporally and spatially and depend on physical and phenological characteristics of the species involved. Within northern temperate regions, the main limiting resource for plants is usually light and some studies have shown that shading has reduced yields in temperate agroforestry systems (Chirko et al. 1996; Reynolds et al. 2007). This is a key concern for farmers contemplating establishing agroforestry. In this section we report on studies carried out within the organic silvoarable alley cropping systems at Wakelyns, where we have investigated the impact of trees on crops in the adjacent alleys.

Cereals and timber trees

In 2009 tree:crop interactions were investigated in the hardwood tree system. The 15-year-old trees were between 5 and 11 metres high at this point and a spring wheat (mixture of Paragon and Tybalt varieties) crop, a winter wheat (Hereward, Solstice, Spark mixture) crop and oats (Tardis variety) were growing in the alleys in between.

The mixed hardwood and fruit tree system in Far and Water Fields consists of eight species:

- apple *(Malus domestica)*
- small-leaved lime *(Tilia cordata)*
- hornbeam *(Carpinus betulus)*
- wild cherry *(Prunus avium)*
- Italian alder *(Alnus cordata)*
- ash *(Fraxinus excelsior)*
- oak *(Quercus petraea)*
- sycamore *(Acer pseudoplatanus)*

These species are likely to vary widely in their influence on the neighbouring cereal crop. For example, Italian alder, like other alders, establishes symbioses with the nitrogen-fixing Actinobacteria *Frankiella alni*. These bacteria convert atmospheric nitrogen into soil-soluble nitrates which can be utilized by the alder, and favourably enhances the soil fertility, therefore benefitting neighbouring plants. By contrast, ash develops an extensive root system which is likely to compete strongly for water and nutrient resources, and sycamore cast heavy shade due to its big leaves.

Using the plot combine, we harvested the cereals in 5m-long strips (1.2m wide) centred on each tree trunk, parallel to the tree rows (Figure 22 & Figure 23). We also harvested the 'between trees' cereals into separate sacks, and 10m-long strips from the centre of each alley.

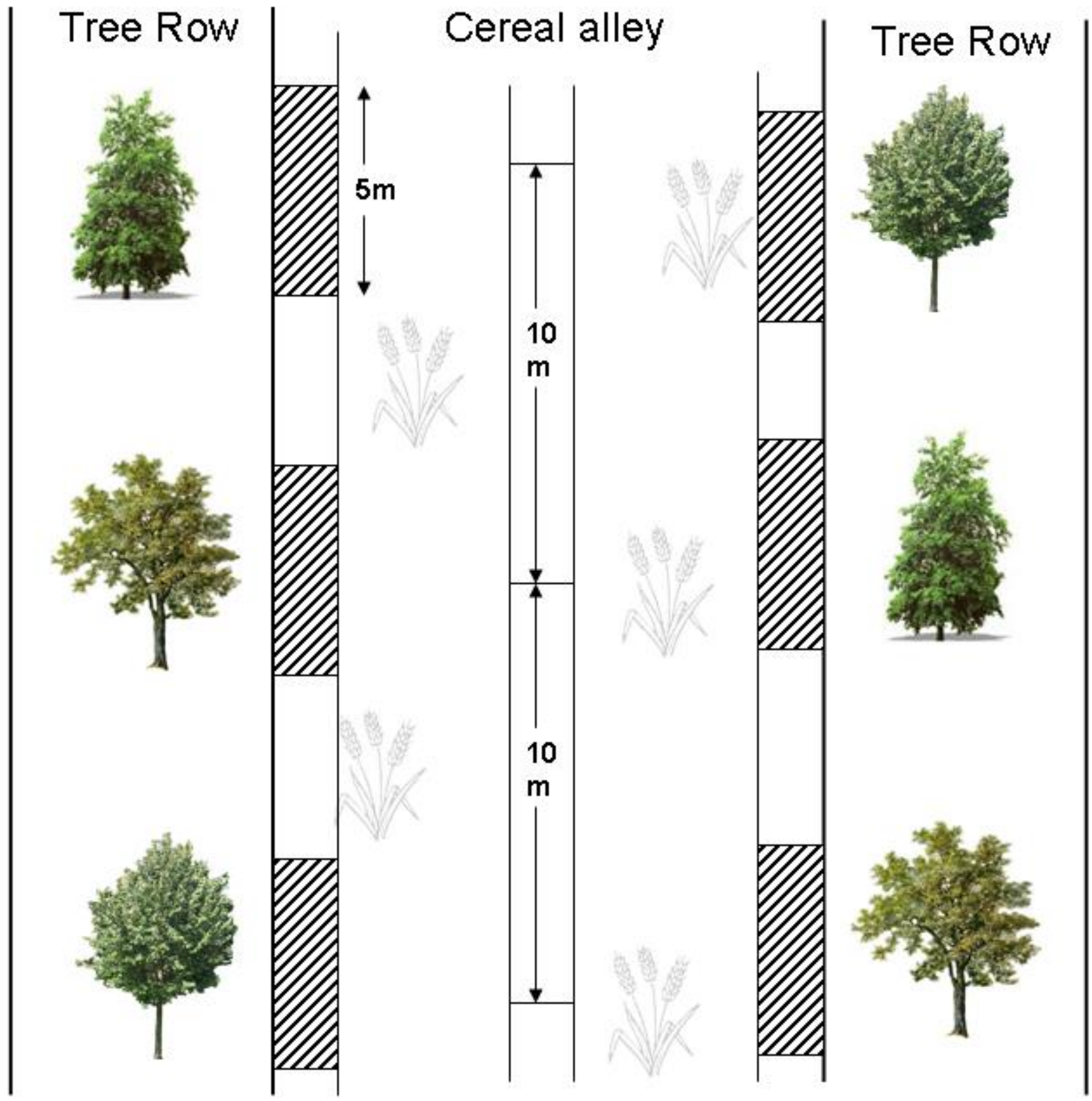


Figure 22. Strips 5 m long by 1.2m wide were harvested adjacent to the trees in the mixed species agroforestry system. 10m strips were harvested from the centre of each cereal alley.

Figure 23. Harvesting wheat in the alleys (Aug. 9-10th 2009)

Interesting to note is that while the wheat yields at the edges of the alleys were just over 50% of the yields from the centre plots, the oat crop seems more competitive with around a 25% decrease in yields at the edge compared with the centre (Figure 24). This suggests that some crops may be better suited to the more competitive environment of growing with trees.

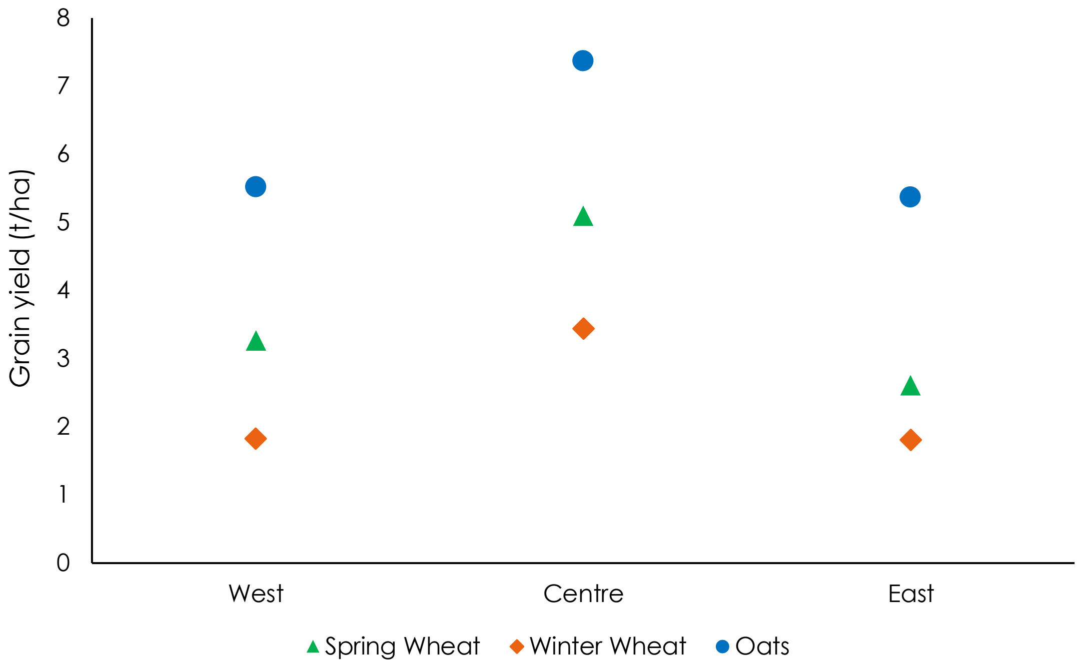


Figure 24. The mean grain yield of a spring oat, spring wheat and winter wheat in three positions across a 10m wide cropping alley between timber tree rows (@ 15% moisture content)

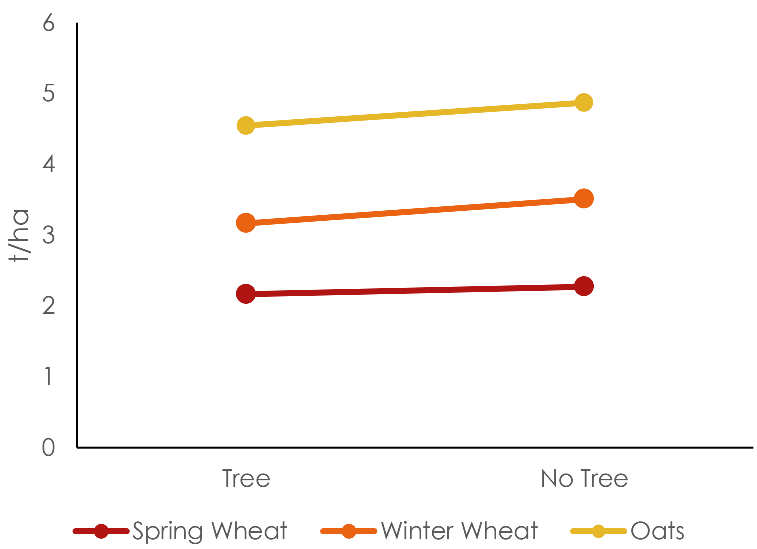


Figure 25. Grain yield from plots adjacent to trees or no trees.

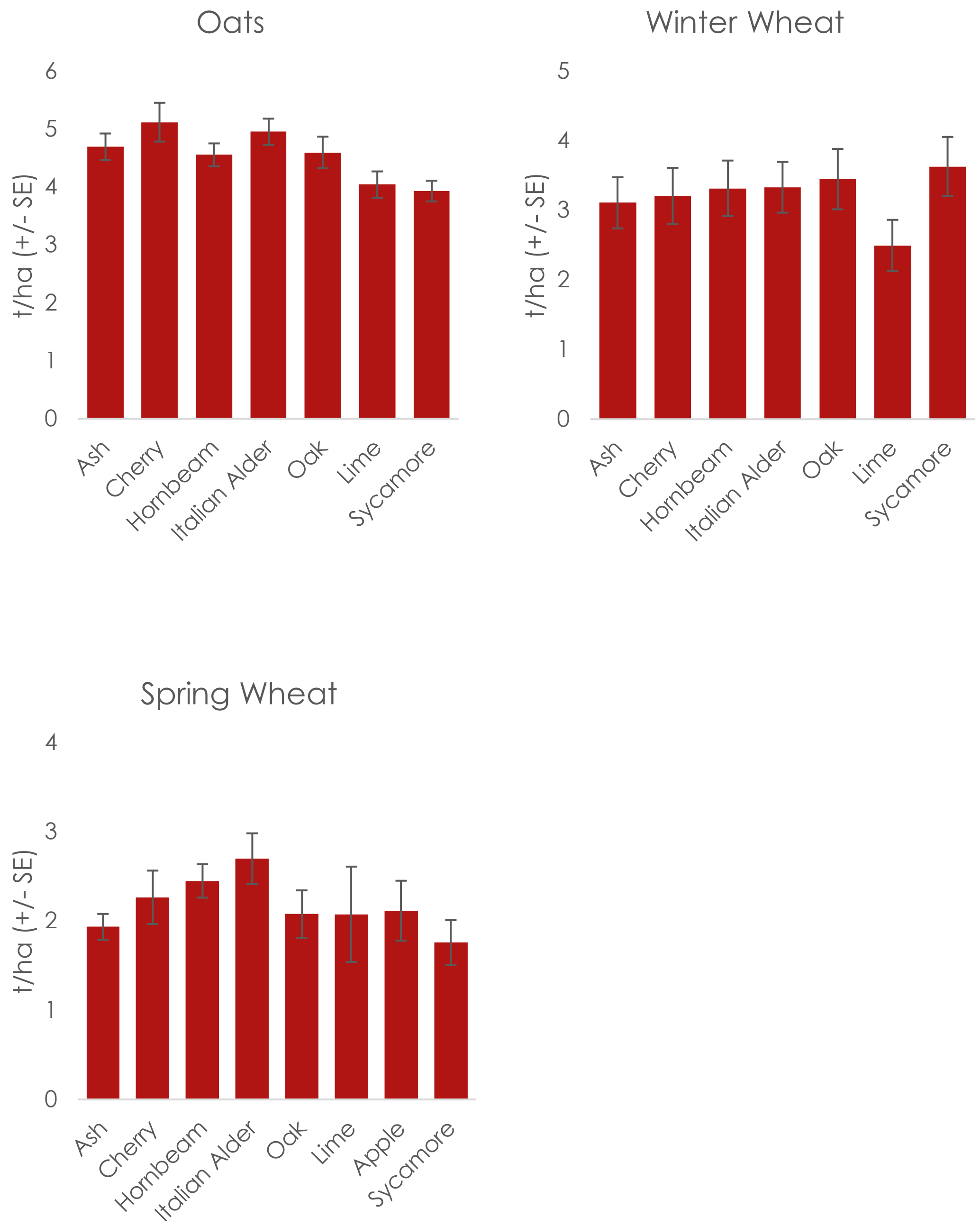


Figure 26. Cereal yields from plots adjacent to different tree species.

Yields from the 'inter-tree' plots were slightly higher by 5-10% (Figure 25). When comparing yields adjacent to different tree species (Figure 26), oat yields were highest adjacent to cherry and Italian alder and lowest adjacent to sycamore and lime; winter wheat yields adjacent to ash were highest, with lowest yields next to hornbeam and cherry; while for spring wheat yields adjacent to Italian Alder were the highest, yields by sycamore 35% lower and from ash 28% lower. This indicates that there is no obvious general response of cereal yields to individual tree species, although yields of both oats and spring wheat appear higher adjacent to Italian alder and lower adjacent to sycamore.

Fertility-building ley and short rotation coppice willow

A central hypothesis in agroforestry is that while productivity of the individual components of an agroforestry system may be lower than in farming systems without trees, overall productivity will be higher due to complementarity of resource use. Trees can access resources both below ground (i.e. deeper soil horizons) and above ground (i.e. above the 1-2m canopy of crops) as well as temporally (i.e. earlier or later growing period) that the crops do not use (Cannell et al, 1996). As well as productivity impacts, incorporating trees within a pastoral system can influence the nutritional value of the herbage in the alleys as species composition changes in response to differences in microclimate and soil properties (Benavides et al, 2009). This section reports on research carried out in 2012 and 2013 within the SOLID project to investigate the productivity, nutritional value and species composition of a fertility-building ley within a bioenergy agroforestry system in comparison with a neighbouring no-tree control at Wakelyns Agroforestry.

The following three hypotheses were tested:

> *H1: Ley productivity within the agroforestry system varies spatially with competition with trees reducing productivity adjacent to the tree rows while productivity in the centre of the agroforestry alleys remains equal to or higher than that in the no-tree control field due to differences in the microclimate.*
>
> *H2: The plant community within the agroforestry alleys has a higher percentage of grasses compared to plant communities grown in the no-tree control field due to a greater shade tolerance of grasses than forbs.*
>
> *H3: Herbage from the agroforestry alleys has a higher nutritional value than herbage grown within the no-tree control field.*

The agroforestry system consists of twin rows of a mix of five varieties of willow with 10-12m wide crop alleys between. Willows were planted March 1998 into a mypex (plastic) weed barrier. Alternate hedges are cut every two years so that within the system there are hedges with first- and second-year re-growth. Coppicing for bioenergy takes place in December or January.

Within the crop alleys, a fertility-building ley was sown in late May 2011, of the following species with an overall seed rate of 6 kg/ha:

- white clover varieties (39.5%: varieties Alice (25.5%), Klondike (7%), Grasslands Bounty (7%))
- red clover varieties (39.5%: varieties Merviot (25.5%), Corvus (7%), Aberuby (7%))
- lucerne (7%),
- yellow trefoil (7%)
- chicory (7%)

The species mixture used within the ley in both the agroforestry and no-tree control has been developed for a stockless arable system and so does not contain grasses.

These alleys contained potatoes in 2010 and ley in 2009. As a comparison, a neighbouring field was used as a control. Managed as part of the organic arable rotation, this area has no trees within the field, although there are mature hedgerows at the margins. This field was sown with the same ley mix as the willow field, at the same time (end of May 2011). Prior to this, it contained cereals in 2010 and ley in 2009. The ley within the agroforestry and no-tree control field was mown regularly to enhance weed control for subsequent cropping. A forage cut was taken once in June 2012 and the herbage taken off field and composted.

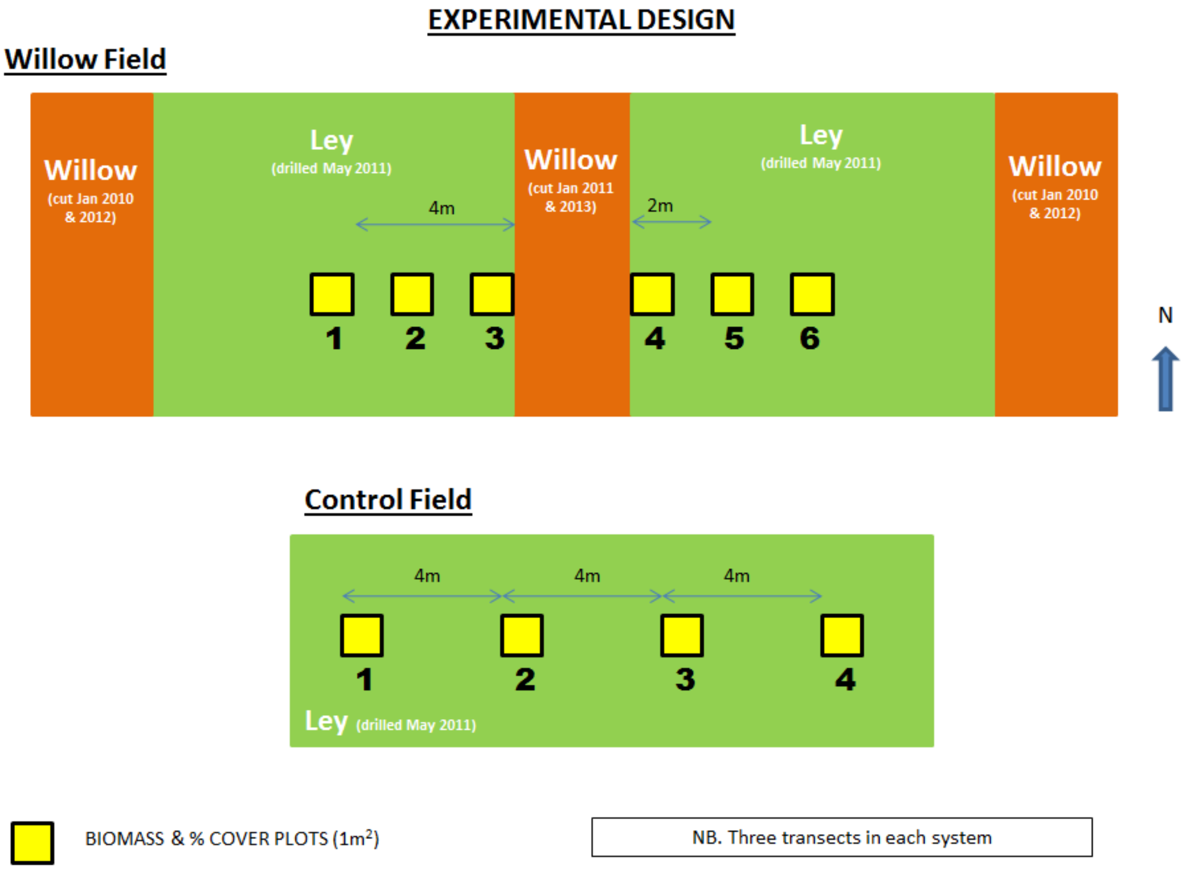


Figure 27. Experimental design of sample points

Experimental design and methodology

Three transects were established within each system (i.e. agroforestry and control), running east to west. Within the agroforestry system, transects ran from alley centre to alley centre, with the willow tree row in the centre of the transect (Figure 27). This design allows spatial and temporal variation within the alleys to be studied as the willow goes through the 2-year rotation between harvests, with each transect centred on willow rows cut on the same rotation (January 2011 and 2013). On each agroforestry transect, 1 m^2 quadrats were located at 4 m, 2 m and alley edge west and 4 m, 2 m and alley edge east of the tree row to give 6 quadrats per transect and 18 in total in the agroforestry system. Within the no-tree control, four 1 m^2 quadrats were spaced 4 m apart on each transect, to give a total of 12 quadrats.

Productivity of the ley was assessed throughout the growing period in the spring and summer of 2012 and 2013. The herbage within each 1 m^2 quadrat was cut to 5 cm above ground, prior to the alley being mown. In 2012, five cuts were carried out (12th May, 6th June, 6th and 30th July, and 20th August). In 2013, four cuts were made (21st May, 19th June, 9th July and 9th September).

Herbage was collected into a polythene bag and sealed to prevent water loss. After weighing for fresh weight, each sample was oven dried at 100 °C until a stable weight was reached (oven dried mass: ODM).

The statistical analysis was carried out using R version 2.10.0 (R Development Core Team, 2009). Total biomass production (ODM) per m^2 quadrat was analysed separately for 2012 and 2013, using a one-way ANOVA with sample location as a fixed factor. Where a significant effect was found, *post-hoc* pairwise comparisons of means were performed using Tukey's HSD test.

The agroforestry alleys and no-tree control field were sown with the same species mixture in late May 2011 (see above). To identify changes in species composition in the two years following establishment, species percentage cover within 1 m^2 quadrats (same quadrats as for ley productivity assessments) was assessed monthly from May to July 2013. Due to difficulties of identifying non-flowering grasses, a single percentage cover for all grass species was recorded. In addition to percentage cover of individual species data, species cover was aggregated into six categories: clover spp., chicory, lucerne, grasses, bare soil and 'weeds' (all non-sown forb species).

To investigate differences in species composition between the agroforestry and no-tree control plots, species % cover data from the final assessment on 9th July 2013 were analysed using canonical ordination techniques in Canoco 4.5.1 (Ter Braak & Šmilauer, 2003). A preliminary DCCA produced short gradient lengths (<2) indicating that linear ordination methods were most appropriate for these data (Lepš & Šmilauer, 2003). A redundancy analysis (RDA) was carried out on the species % cover data, with treatment (agroforestry vs. no-tree control) as the explanatory variable. A global test of the first canonical axis was performed using a Monte Carlo permutation test (full model, 499 repetitions) to determine the significance of the treatment in explaining variation in species composition.

A second RDA was performed on the species % cover data from 9th July 2013 to identify spatial variation in species composition within the agroforestry system only. Location (4m, 2m and alley edge west and 4m, 2m and edge east of the tree row) was included as the explanatory variable, with location coded as nominal variables. Forward selection of the nominal variables was performed using a Monte Carlo permutation test (full model, 499 repetitions) with transect number treated as a covariable defining the permutation tests.

A final ordination analysis was performed on the categorised data from all months to identify temporal shifts in community composition as the summer progressed. Months were treated as categorical variables and the interactions between month and treatment (agroforestry vs. control) were statistically tested using Monte Carlo permutation tests (full model, 499 repetitions) with permutations restricted within the four replicates from each plot (i.e. repeated measures).

Following the herbage productivity cut on the 9th July 2013, half of the biomass from each quadrat was oven dried at 60 °C. Samples from the four quadrats on each control transect were aggregated to produce a total of three samples from the control field. Samples were sent to NRM Ltd (www.nrm.uk.com) for analyses of macro-nutrient concentrations (P, K, Mg, Ca and S), total N and C, C:N ratio and micronutrients (Cu, Zn, Mn, Fe, and B). Nitrogen was analysed using the Dumas method and crude protein calculated as 6.25 x N concentration.

The nutrient data was analysed using a one-way ANOVA with sample location as a fixed factor using R version 2.10.0 (R Development Core Team, 2009). Where a significant effect was found, *post-hoc* pairwise comparisons of means were performed using Tukey's HSD test to identify significant differences between locations.

Results

Biomass production

There was a significant difference in total biomass production (ODM) from different locations in 2012 (F value = 7.07, p=0.00032, df 6,21). A *post-hoc* Tukey HSD test identified significant differences in productivity between plots at the edge of the agroforestry alleys (edge east and edge west) and the no-tree pasture control plots (these can be seen in Figure 28), and also between the plots at the edge of the alleys west of the tree row, and plots at 4m west, 2m east and 4m east of the tree rows. Analysis of total biomass in 2013 showed no significant differences between plots (F value = 1.37, p>0.05, df 6, 21) and Figure 29 agrees with the statistical analysis showing that productivity in the agroforestry plots is less variable than in 2012, with biomass production in the edge plots no different to those in the centre of the alley or no-tree control. However, it is worth noting that overall biomass production in 2013 was less than half that in 2012.

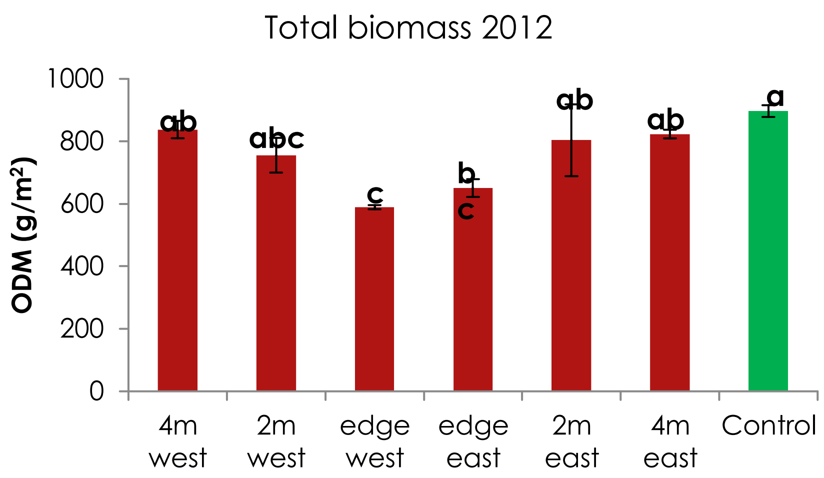


Figure 28. Total biomass production (oven dried mass; ODM) of the ley in the agroforestry and no-tree control plots 2012 (average per plot +/- se). Different letters denote significant differences.

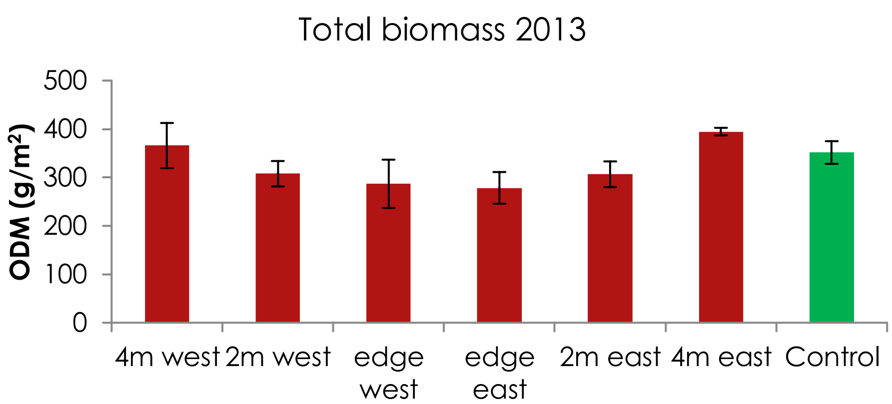


Figure 29. Total biomass production (ODM) of the ley in the agroforestry and no-tree control plots 2013 (average per plot +/- se).

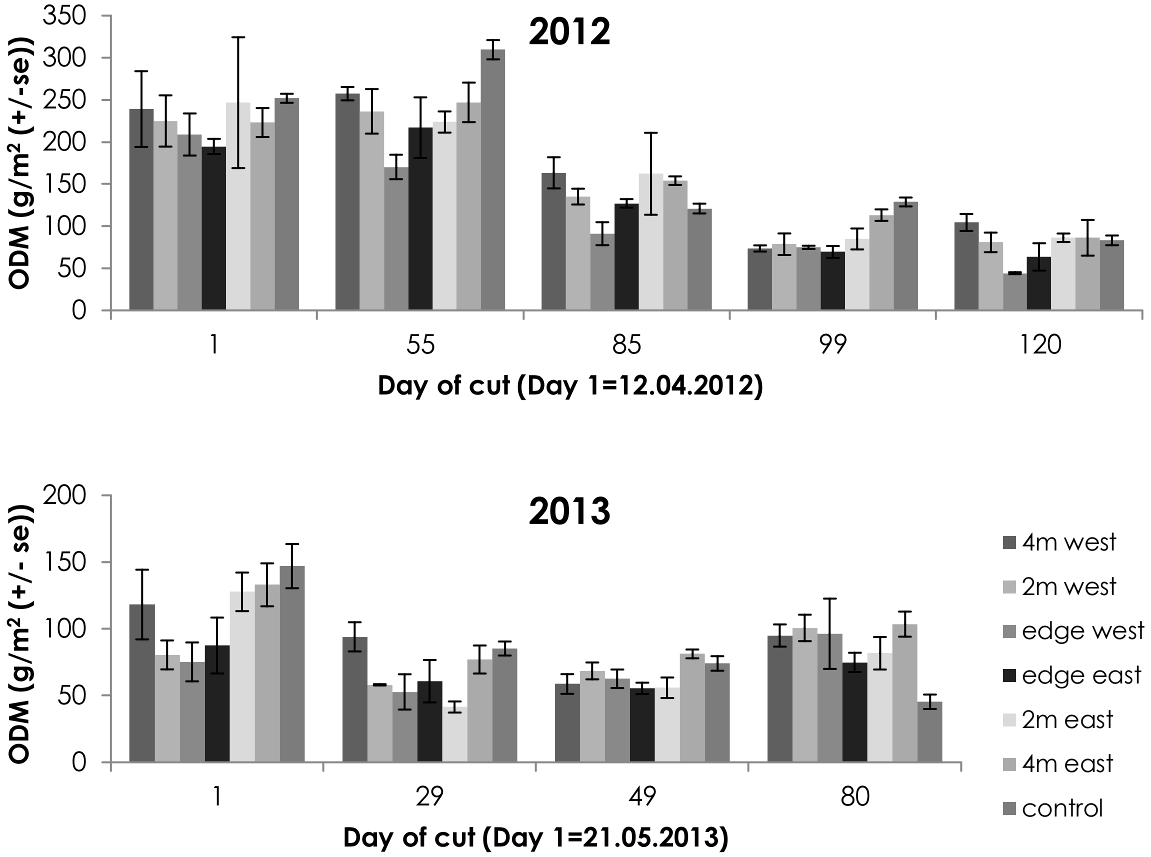


Figure 30. Ley biomass production (ODM) by cut date for 2012 and 2013.

Species composition

RDA analysis indicated that species composition was significantly different between the agroforestry and control plots, with the canonical axis (Axis I) accounting for 71 % of the variability in the species data (Eigenvalue Axis I = 0.71, F-ratio = 68.61, p-value = 0.002). The resulting ordination diagram (Figure 31) shows that this difference is primarily due to a higher cover of grasses and *Taraxacum officinalis* (dandelions) in the agroforestry plots, with higher cover of clovers (*Trifolium* spp.), lucerne (*Medicago sativa*) and most other non-sown forbs in the control plots. There was also a higher percentage of bare soil in the control plots.

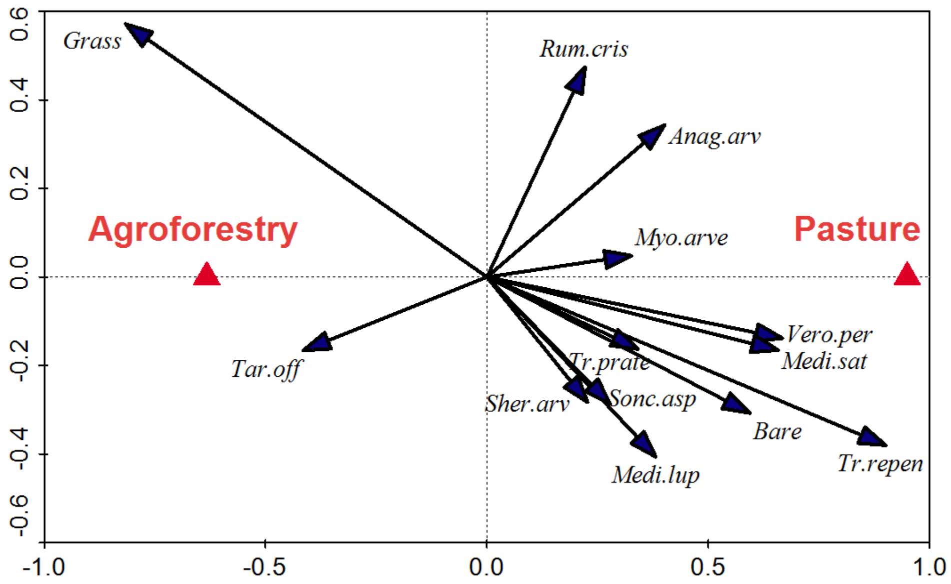


Figure 31. RDA biplot showing only species with a fit greater than 10%. The environmental variables are shown as filled triangles: Agroforestry and Pasture Control.

RDA analysis of the agroforestry-only data to identify spatial variation in species composition within the agroforestry indicated no significant differences in species composition within the alleys (sum of all canonical axes = 0.138, F-ratio = 0.556, p=0.846; bi-plot not shown).

Differences between the agroforestry and control plots with regards to changes in the species cover through the season were identified as significantly significant with Axis I (the canonical axis) accounting for 56% of the variance in the species cover data (Eigenvalue Axis I = 0.562, F-ratio = 170.847, p-value = 0.002). This can be attributed to a shift in the agroforestry plots from a more balanced diverse community towards one dominated by grass cover, while in the control plots, there was a shift from a high percentage of bare soil towards a community dominated by clovers (Figure 32).

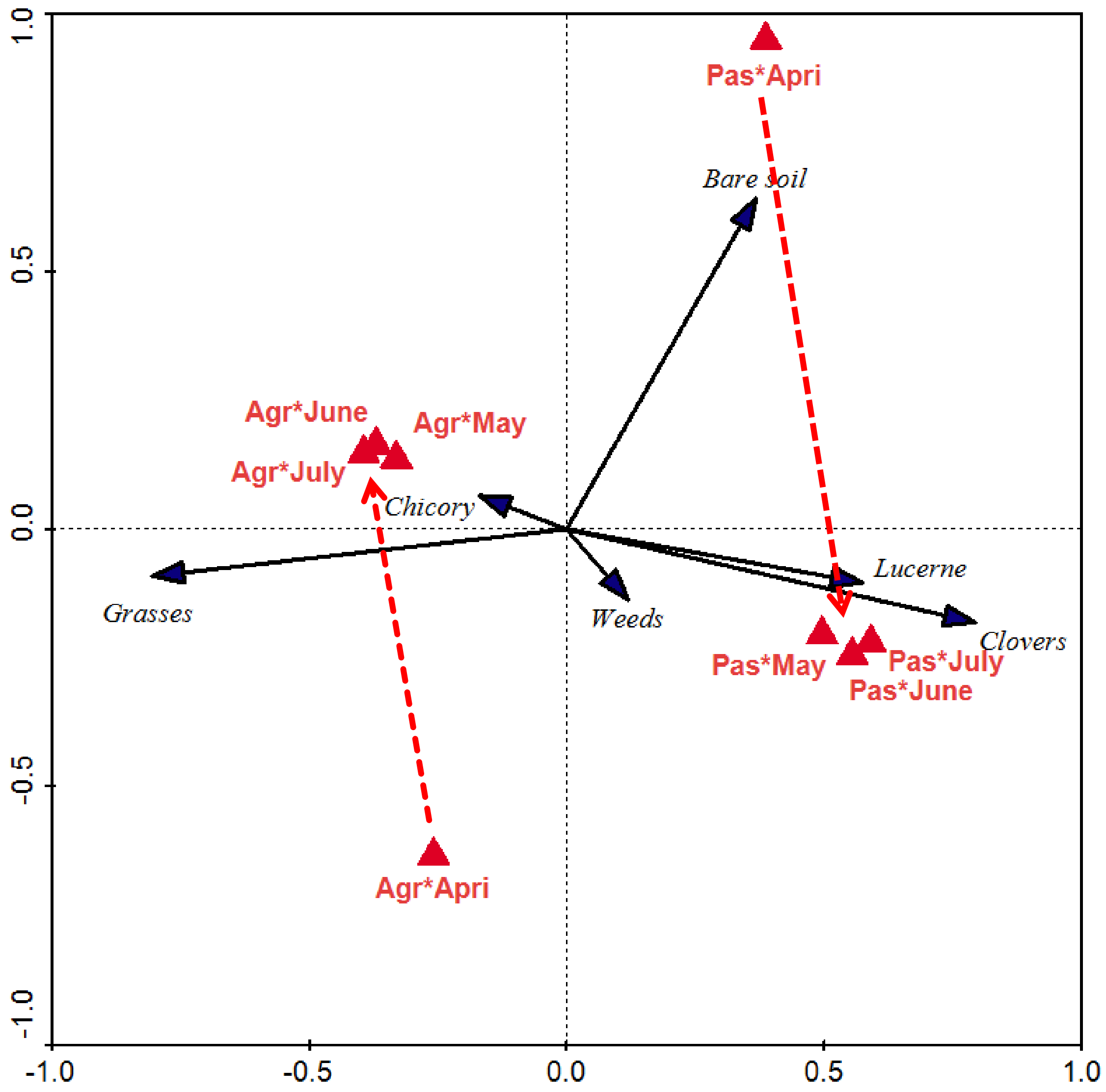


Figure 32. RDA biplot of species cover and the interaction between month and treatment. Pas = Pasture control; Agr = Agroforestry. Red dashed arrow shows the shift in community composition through the season.

Nutrient analyses

There were significant differences in percentage N (and crude protein), the C:N ratio and concentrations of the macro-minerals (P, Mg, Ca and S), and the micro-minerals (Cu and B) in the ley plots from different locations in 2013 (Table 8) but no significant differences in concentrations of K, Mn, Zn or Fe, or % C. In most cases of significant differences, the levels of nutrients were significantly higher in no-tree control plots compared with one or other or both of the agroforestry edge samples.

Table 8. Nutrient analyses of ley from the agroforestry and control plots. *P<0.05; ns = no significant difference. Different letters denote significant differences between means based on Tukeys post-hoc tests.

		Centre	2m West	Edge West	Edge East	2m East	Control	F ratio
N Dumas	Mean	2.94^{ab}	2.88^{ab}	2.55^{a}	2.40^{a}	2.82^{ab}	3.30^{b}	4.17*
% w/w	SE	0.22	0.15	0.04	0.18	0.16	0.11	
Crude protein	Mean	18.4^{ab}	18.0^{ab}	15.9^{a}	15.0^{a}	17.6^{ab}	20.6^{b}	4.17*
% w/w	SE	0.23	0.94	0.99	1.11	1.38	0.72	
Phosphorus	Mean	2.87^{ab}	2.92^{ab}	3.23^{ab}	3.35^{ab}	2.72^{a}	3.37^{b}	4.04*
g/kg DM	SE	0.11	0.77	0.12	0.05	0.25	0.12	
Potassium	Mean	17.3	17.1	15.8	16.2	15.7	16.7	0.68ns
g/kg DM	SE	0.75	0.32	1.25	0.81	0.96	0.51	
Calcium	Mean	9.84^{ab}	10.3^{ab}	9.46^{a}	8.75^{a}	10.7^{ab}	14.2^{b}	4.02*
g/kg DM	SE	1.19	1.30	0.30	0.79	0.86	0.97	
Magnesium	Mean	1.78^{ab}	1.73^{ab}	1.55^{ab}	1.48^{a}	1.78^{ab}	1.90^{b}	4.09*
g/kg DM	SE	0.09	0.01	0.14	0.07	0.08	0.01	
Sulphur	Mean	2.29^{ab}	2.12^{ab}	2.31^{ab}	2.43^{a}	2.27^{ab}	1.68^{b}	3.80*
g/kg DM	SE	0.20	0.14	0.07	0.04	0.22	0.02	
Carbon	Mean	44.4	44.9	43.6	43.3	44.2	44.4	1.20^{ns}
%	SE	0.65	0.07	0.12	0.49	0.86	0.40	
C:N Ratio	Mean	15.1^{ab}	15.7^{ab}	17.2^{ab}	18.3^{a}	15.8^{ab}	13.5^{b}	4.13*
	SE	0.95	0.84	0.15	1.32	0.73	0.43	
Manganese	Mean	22.9	22.4	30.3	33.6	23.7	25.7	1.62^{ns}
mg/kg DM	SE	2.76	0.70	1.76	3.88	6.75	2.03	
Copper	Mean	6.50^{ab}	5.83^{ab}	4.23^{ab}	3.60^{a}	6.33^{ab}	8.17^{b}	3.34*
mg/kg DM	SE	1.56	0.90	0.40	0.46	1.13	0.03	
Zinc	Mean	19.9	18.2	18.4	20.5	19.7	22.7	1.59^{ns}
mg/kg DM	SE	1.47	0.62	0.52	2.22	1.41	0.61	
Iron	Mean	623	440	744	1175	868	1238	1.62^{ns}
mg/kg DM	SE	307	165	167	202	318	263	
Boron	Mean	15.47^{ab}	15.73^{ab}	12.97^{a}	12.83^{a}	16.67^{ab}	23.63^{b}	3.28*
mg/kg DM	SE	3.14	2.12	0.42	1.73	2.06	2.62	

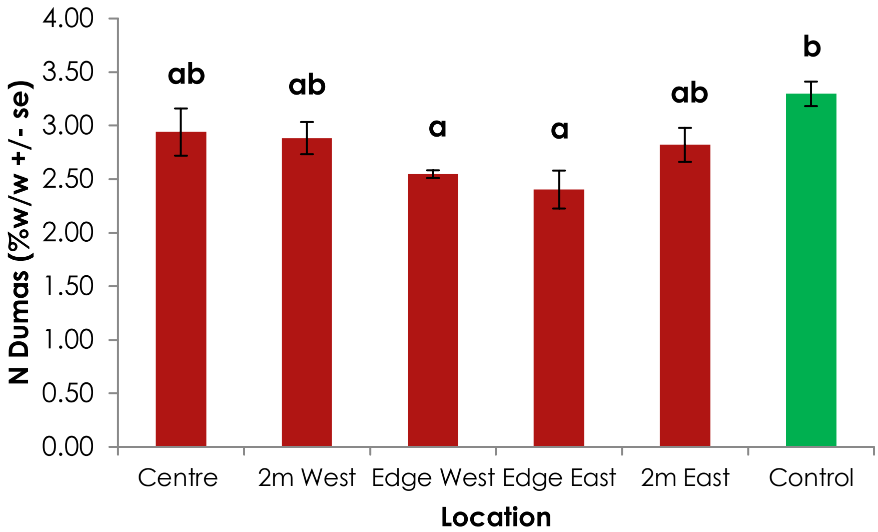


Figure 33. Nitrogen content (% w/w) of ley in the agroforestry and no-tree control. Different letters denote significant differences

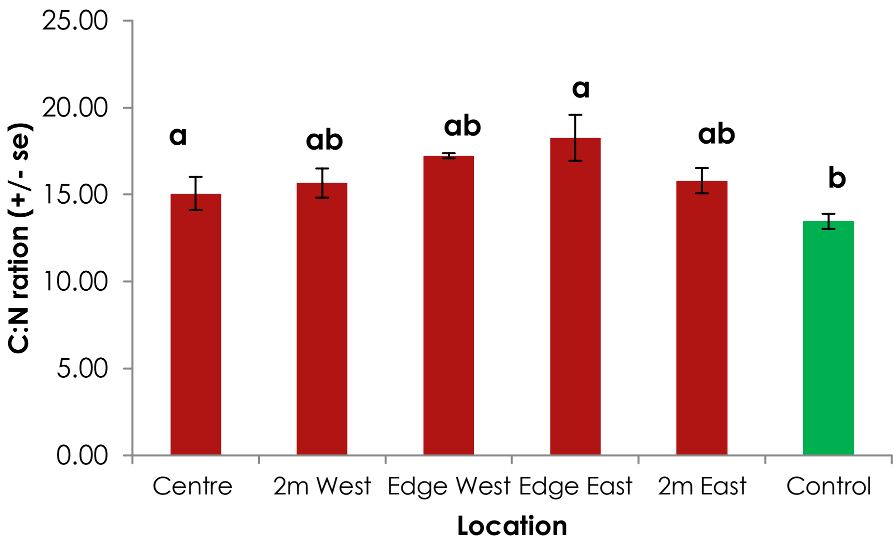


Figure 34. C:N ratio of ley in the agroforestry and no-tree control. Different letters denote significant differences.

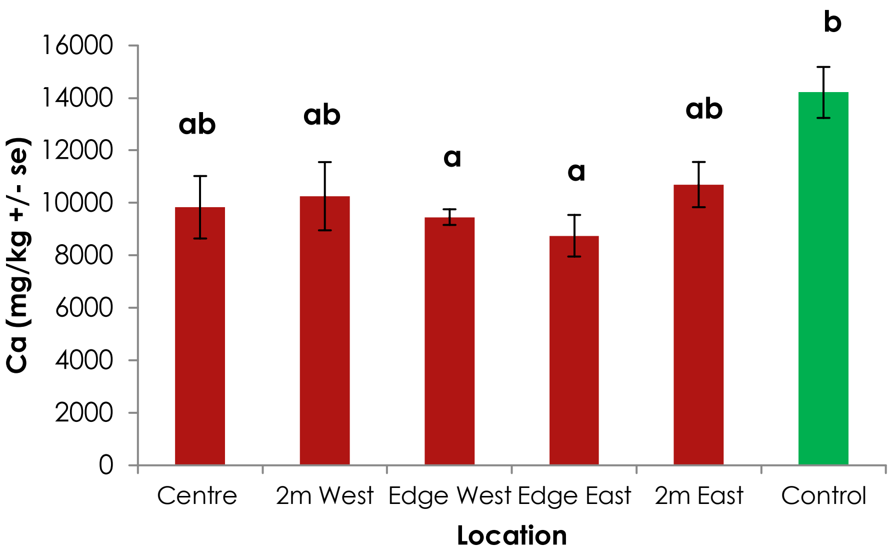


Figure 35. Calcium content (mg/kg) of ley in the agroforestry and no-tree control. Different letters denote significant differences.

Discussion

Biomass production

Regarding Hypothesis 1, biomass production within the agroforestry system varied spatially in the first year of the study (2012), with lower productivity in the plots adjacent to the willow rows, and production from the centre and 2m from the edge of the agroforestry alleys equal to (but not higher than) that in the no-tree control plots (H1). This suggests that there is competition for resources between the willow and ley at the edge of the alleys, but this competition decreased or was compensated for by positive impacts on growth as distance from the alley edge increased. Looking in more detail at the individual biomass cuts throughout the summer, the significant difference in total biomass in 2012 is likely to be due primarily to much higher production in the control in early June (Day 55) while productivity at the other time points was similar among the locations. This may be due to differences in microclimate; average air temperatures at 20 cm aboveground level in the agroforestry system were shown to lag behind those in the no-tree control by 3 days which could impact early spring growth in the alleys.

There were, however, no significant differences in biomass production in the second year of the study. While productivity in the control was slightly higher in the first cut in May, subsequent production was equal to or lower than that in the agroforestry, thus resulting in no significant difference in total biomass production. This indicates that there was a balance between positive and negative interactions between the tree and ley components. One explanation could be that the willow was harvested in January 2013, the trees being cut down to roughly 30cm, and thus removing the shading effect on the alleys, and potentially reducing other competitive interactions e.g. for water and nutrients. Another factor is that summer 2013 was warmer and drier than 2012; the trees in the agroforestry are likely to have reduced evapotranspiration rates from the ley due to reduced wind speeds and so reduce water stress.

Other studies have found that while the tree canopy and their roots can compete with pasture for water and nutrients, increases in pasture productivity may occur where trees have improved microclimatic conditions, for example, on very wet or erosion prone sites (Guevara-Escobar et al, 2000; Wall et al, 1997). Higher pasture yields have been recorded in young agroforestry systems compared to open pasture; beneath a 3 year old stand of *Pinus radiata*, pasture yields were 16% higher (Hawke 1991, in Benavides et al, 2009). Trees may also enhance pasture growth by lowering soil water contents in damp situations as well as controlling hill erosion.

Species composition

Regarding Hypothesis 2, species composition in the understory is modified by changes to the microclimate and soil properties caused by trees, as well as the impact of grazing livestock which may also be influenced by the presence of trees (Benavides et al, 2009). Despite being sown with the same species mixture, the species compositions in the agroforestry and control have diverged into different communities, with the agroforestry sward being dominated by grasses, and the no-tree control by legumes. This agrees with other studies that have shown a shift from pasture assemblages containing legumes and *Lolium perenne*, to a greater dominance of grasses due to greater shade tolerance, tillering ability, phenological development and growth in winter (Benavides et al, 2009).

Other studies have found that species compositions vary with the tree age and density, and also with climate (Benavides et al, 2009). Species composition varies also with distance from tree trunk, aspect and season due to differences in shading and leaf litter effects (Benavides et al, 2009). Within the willow agroforestry system at Wakelyns, there was no significant difference in species composition within the alley, although composition in both the agroforestry and control plots changed over the summer, with the agroforestry plots becoming increasing dominated by grasses, and the control plots shifting from a high percentage of bare soil towards a community dominated by clovers.

Nutrient analyses

Nutritional value is determined by species composition and microclimatic changes. Regarding hypothesis 3, statistically significant differences in percentage N (and crude protein), the C:N ratio and concentrations of the macro-minerals (P, Mg, Ca and S), and the micro-minerals (Cu and B) were found in the agroforestry compared with the no-tree control leys. The greatest differences observed were between the ley at the edge of the alleys and the control plots, with higher levels of nutrients found in the control ley. These differences are likely to reflect the differences in species composition between the agroforestry and control plots; control plots were dominated by clovers, which will have higher nitrogen and calcium levels, while agroforestry plots were characterised by grasses. The analysis of other major nutrients such as different type of carbohydrates (i.e. starch, cellulose, hemicellulose) will provide further knowledge of the feed value for ruminants in agroforestry systems.

Other studies have also shown an impact of trees on nutritional value of the understory with pastures under poplar having a lower content (% DM) of soluble carbohydrate and higher contents of neutral and acid detergent fibre than open pastures (Guevara-Escobar et al, 2007). By contrast, some studies have recorded higher crude protein contents in pasture under poplar and *Pinus radiata* (Benavides et al, 2009; Peri et al, 2007). This has been attributed to a reduction in light reaching the understory which causes a decrease in carbohydrates with a following increase in N concentration; or alternatively, to an increased N availability from enhanced soil OM mineralisation rates under trees (Benavides et al, 2009; Peri et al, 2007). Peri *et al.* (2007) investigated dry matter production (DM), sward morphology, crude protein (CP%), organic matter digestibility (OMD) and macro-mineral concentrations (P, K, Mg, Ca and S) in a grazed cocksfoot (*Dactylis glomerata* L.) pasture under different light intensities in a 10 year *Pinus radiata* forest in New Zealand. They found that mean total dry matter production decreased from 8.2 t DM ha^{-1} yr^{-1} in open pasture to 3.8 t DM ha^{-1} yr^{-1} under 24% photosynthetic photon flux density. Shading influenced cocksfoot morphology, with higher canopy heights and reduced tillering in shaded plots. Measures of forage quality such as crude protein and macro-mineral concentrations, increased as shading increased (Peri et al, 2007). The authors suggest that shaded pastures limit animal production due primarily to lower dry matter productivity, rather than nutritive value, with lower pre-grazing pasture mass and reduced bulk density and bite size (i.e. lower harvestable amount per single bite reducing pasture intake by each individual animal). This would not appear to be the case at Wakelyns Agroforestry, where production of biomass was similar in the agroforestry and no-tree control (except at the edge of the agroforestry alleys), but differences in species composition resulted in differences in nutritional value.

In conclusion, while it is apparent that there is some competition between trees and plants in the crop alleys, this appears to be restricted to the edge of the alleys and will vary depending on weather conditions and the stage of tree growth and harvest. By reducing the amount of 'edge' by increasing the width of crop alley, the overall impact of competition between the tree and crop component can be minimised. The presence of trees will impact on species composition within the alleys, with shade-tolerant species dominating the sward, and other species such as clovers declining in abundance. This may have implications for nitrogen fixation and also for the nutritional value of the sward for ruminant production. Careful selection of species with greater shade-tolerance (including a range of forage grasses) should be carried out to establish a productive sward for agroforestry systems.

Cereals and short rotation coppice

Evolutionary plant breeding can be used to develop varieties that are particularly well adapted to growing in close proximity to trees. The principle is to let natural selection act on these diverse crop populations to select the plants that are best suited to the prevailing conditions i.e. develop an 'alley-edge' population and an 'alley-centre' population. As part of the AGFORWARD project, this theory was put to the test over three years of cropping in the short rotation coppice systems (Smith et al. 2017). A spring wheat composite cross population (CCP) was grown in plots across the willow system agroforestry alleys in 2014. Plots of bulk CCP were harvested separately from plots on either side of the alley. In 2015, this seed was used to sow 12 m^2 plots in a replicated cross-over trial to test the effect of the population adapting under natural selection to each environment (Fradgley and Smith, 2015). This was repeated in 2016 (Smith et al. 2017).

2014 cereal trials

The trial plots were drilled on the 19th March 2014 in two cropping alleys (alleys 2 and 4) in a willow agroforestry system (Fradgley and Smith, 2015). Plots measured 1.2 m x 10.2 m, seed was sown in 20 cm row widths and seed rates were adjusted based on thousand grain weights to achieve 425 seeds m^2. Trial entries included a spring oat variety (Canyon), a spring barley variety (Westminster), a spring triticale variety (Agrano), two spring milling wheat varieties (Paragon and Tybalt), an equal mixture of Paragon and Tybalt and a spring wheat Composite Cross Population (CCP). The trial in each alley was drilled in six beds across each 10 m wide alley. Trial plots were arranged so that plots of the same entry were adjacent across all six beds and were repeated twice in each alley. Alley 4 included all wheat entries and oats whilst alley 2 included the wheat CCP, barley and triticale. Both willow tree rows in alley 2 and the tree row on the west side of alley 4 were coppiced in January 2014. The tree row on the east side of alley 4 was left standing throughout the season. Assessments of crop emergence were made at growth stage 11 and each plot was harvested with a plot combine to measure grain yield.

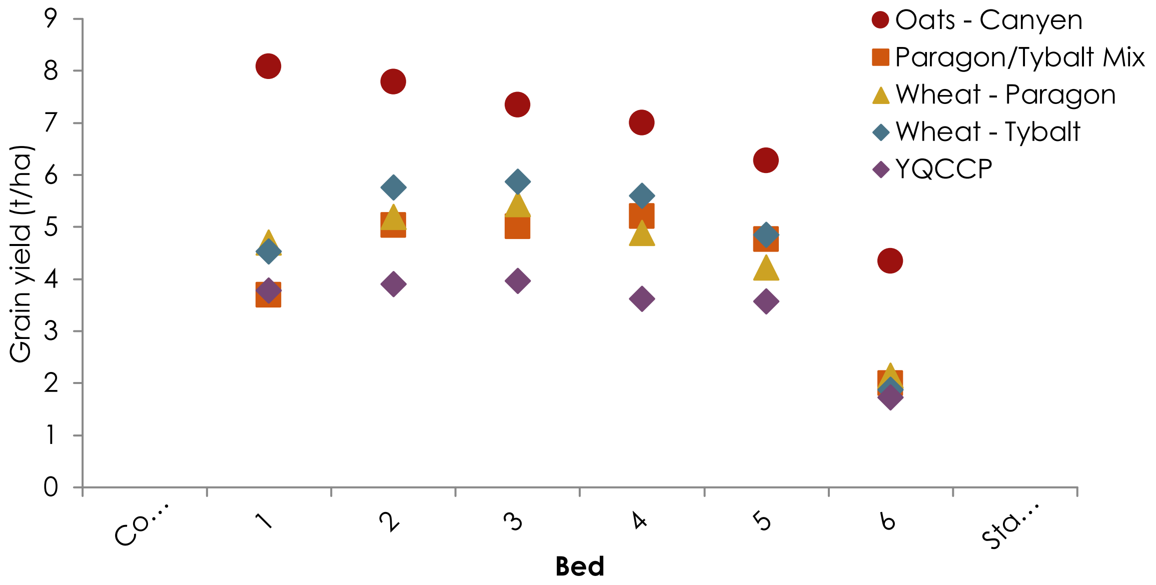


Figure 36. The mean grain yield (n = 2) of a spring oat and wheat varieties, mixture and composite cross population (YQCCP) in six positions across a 10 m wide agroforestry cropping alley (Alley 4) between a coppiced and standing willow tree row in 2014.

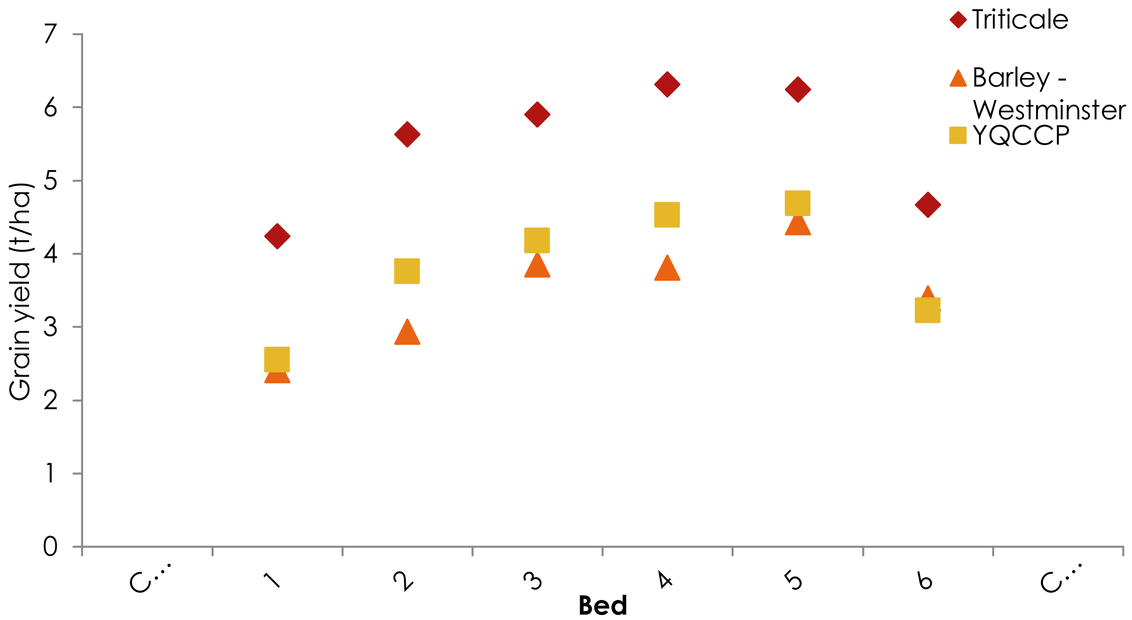


Figure 37. The mean grain yield (n = 2) of spring triticale and barley varieties and a composite cross population (YQCCP) in six positions across a 10 m wide agroforestry cropping alley (Alley 2) between coppiced willow tree rows in 2014.

Results

Analysis of variance revealed significant differences among crop yields (F_{48} = 80.65, P<0.001) although the performance of wheat varieties and the mixture did not significantly differ from each other. There was a highly significant effect of bed position in each alley (F_{48} = 53.91, P<0.001) with the alleys nearest the tree rows yielding lowest (Figure 36 and Figure 37). Wheat yields in the bed nearest the standing hedge were on average 62% lower than in the highest yielding bed near the centre the alley 4. Whereas, the wheat yields in the bed next to the coppiced hedge in alley 4 were 18% lower than the highest yielding bed. In alley 2, wheat yields in the east and west beds next to the coppiced hedges were 46 and 31% lower than the highest yielding bed respectively. This yield loss near to the tree rows was greatest for the standing tree row in alley 4 which had not been coppiced. This could suggest that the un-coppiced tree was providing greater competition than the coppiced trees with shading likely to be a key effect. Moreover, the results showed no evidence of a yield loss in oats next to the tree row that was coppiced.

No crop variety by bed interaction was found indicating that the wheat varieties, mixture and population demonstrated a comparable yield loss due to trees. Therefore, these results do not support the hypothesis that greater within crop diversity per se can help to stabilise yield in the more marginal environments close to the trees. However, this may be due to the limited number of replicates. Trials over several years and in other tree systems could reveal clearer results.

Crop emergence rates were also lower in beds next to the trees in alley 2 ($F_7 = 13.64$, $P<0.001$) and alley 4 ($F_6 = 20.61$, $P<0.001$). Linear regression indicated that this lower crop emergence resulted in lower yields in wheat ($P<0.001$) and triticale ($P<0.01$) (Figure 38) but not oats or barley. These results suggest that crop yields, particularly of wheat and triticale, are reduced as a result of poorer crop establishment when sown in plots adjacent to the tree rows. This may be a direct effect of poorer soil conditions when drilling as well as increased competition for resources with tree roots.

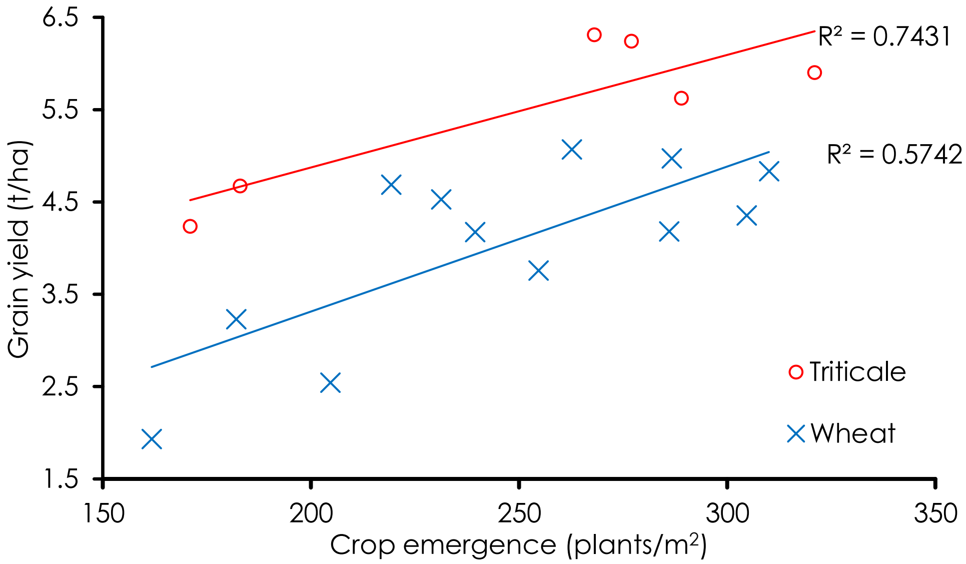


Figure 38. The relationship between grain yield and crop emergence for a spring triticale variety and wheat varieties, mixture and population.

2015 cereal trials

The results of the 2015 trial were reported in a poster presented at the 3rd European Agroforestry conference in Montpellier in May 2016 by Smith et al. (2016d). Some key parts of the poster are reproduced below.

Developing agroforestry-adapted cereals using an evolutionary plant breeding approach

In 2015, an experiment was established to test material selected in contrasting environments near to and away from the agroforestry tree rows. A replicated cross-over experiment aimed to compare performance of selected material in each environment based on the hypothesis that wheat lines will perform best in the environment from which they were selected (i.e. 'alley-edge' selected lines will perform better in the 'alley-edge' plots than 'alley-centre' lines). A spring wheat composite cross population (CCP) was grown in plots across a willow system agroforestry alley in 2014. Plots of bulk CCP were harvested separately from plots on either side of the alley, adjacent to the tree rows (East of Trees (EOT), West of Trees (WOT)) and the alley centre (Centre of Alley (COA)). In spring 2015, Plots measuring 1.2 m by 10.2 m were drilled in a replicated cross-over trial in a hazel SRC agroforestry system to test the effect of the population adapting under natural selection to each environment. Yield measurements (t/ha, hectolitre weight (g), and thousand grain weight (TGW)) were carried out in autumn 2015 when the plots were harvested.

The statistical analysis was carried out using R version 2.10.0 (R Development Core Team, 2009). To identify the effect of alley location on the wheat populations, yields, hectolitre weight and thousand grain weights were analysed with a two-way ANOVA. Alley location (EOT, COA, WOT), wheat population (EOT, COA, WOT) and the interaction between the two were included as the fixed factors, and replicate block as the random effect.

Results

Yields ranged between 0.90 and 3.99 t/ha (@15% moisture content); hectolitre weights between 367.83 g and 383.79 g (@15% m.c) and thousand grain weights between 42.90 and 50.48 g (@ 15% m.c). There was a significant effect of location on yield ($F_{2,17} = 48.89$, $p < 0.001$) and hectolitre weight ($F_{2,17} = 4.81$, $p < 0.05$), but not on TGW. Yields and hectolitre weights were significantly higher in the centre of the alley than at either edge (Figure 39). There were no significant differences between the different populations for any of the yield parameters, and no significant interactions between the populations and their locations. This suggests that at this stage, there is no adaptation of populations to their selected locations (i.e. EOT populations do not perform any better in the EOT locations than in the other locations)

Crop yields at the edges of the alleys were roughly half what they were in the centre of the alley, but there were no significant interactions between populations and their locations. This suggests that, in this first year, there is no evidence of adaptation to alley location. It is perhaps unsurprising that there has been no obvious adaptation over such a short period; in a five year project investigating the level of adaptation that may occur when CCPs are grown continuously at the same specific sites for a number of years, molecular data and comprehensive field trials found no evidence of wheat populations adapting to the cropping conditions under which they were grown (Girling et al. 2014). The authors attributed this to the influence of yearly fluctuations in weather conditions that counteracted any adaptation to the site-specific factors associated with cropping management and soil conditions. It may be necessary to carry out more detailed selection of high performing individual plants by hand, which are then bulked up, to develop specific 'alley edge' populations for agroforestry.

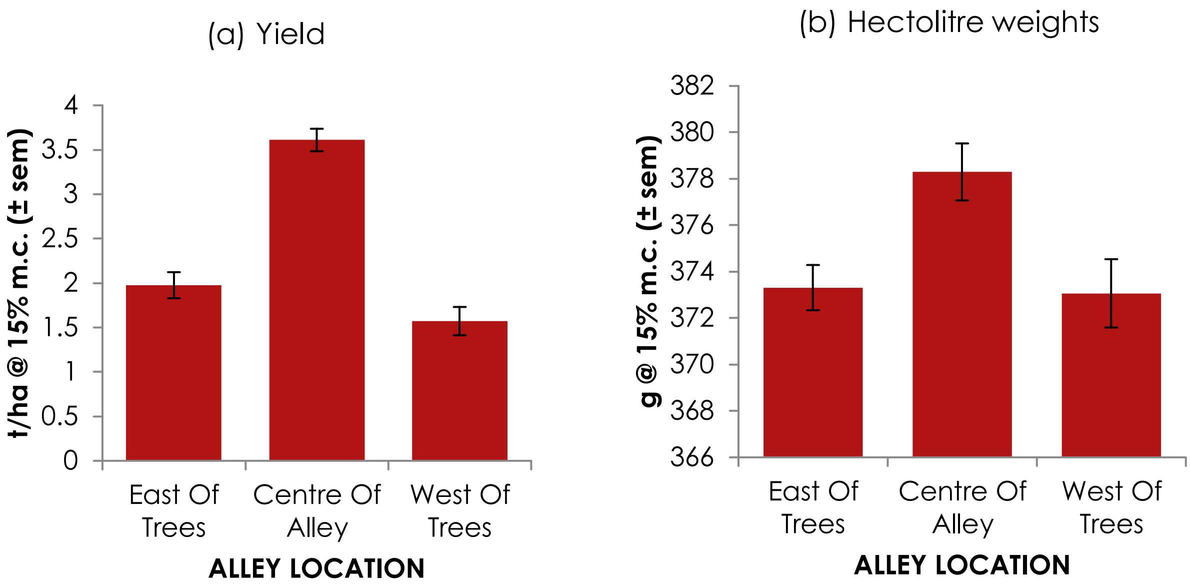


Figure 39. (a) The mean grain yield and (b) hectolitre weights of a composite cross population (YQCCP) in three positions across a 10 m wide alley.

2016 cereal trials

The experiment has been repeated in the 2016 growing season with a similar experimental design in a North-South-oriented alley between two willow rows with differential management, as the west row was coppiced. Yield results were analysed through a two-ways RCB designs. Every factor was split into sets of two orthogonal linear contrasts to partition difference between:

- Centre of alley vs. Edges, and WOT (West -) vs. EOT (East-of-trees) positions as far as the position in the alley is concerned;
- Centre of alley vs. Edges, and WOT (West -) vs. EOT (East-of-trees) CCP selections as far as the populations position in the previous year is concerned.

The effect of the position in the alley (BED) was highly significant (p = `9.88e-08 ***)` (Figure 40). The situation is completely different from the previous season. In fact, here, the western tree row has been coppiced prior to drilling. Yield was:

- 51% more than field average East of the (coppiced) tree row (EOT),
- Intermediate (20% less than field average) in the centre (COA)
- Lowest (32% less than field average) West of the (non-coppiced) tree row (WOT).

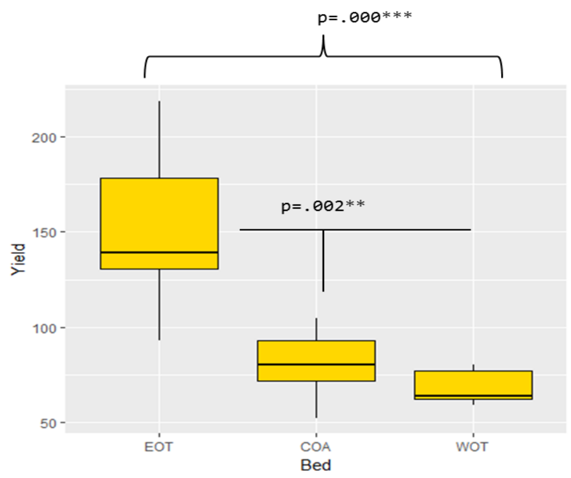


Figure 40. Wheat grain yield averaged by position in the alley in the 2016 growing season. P-values of orthogonal linear contrasts "Centre (COA) vs. edges of alley", in the middle of the chart, and "East (EOT) va. West of trees (WOT)", above the chart, are shown.

Unlike in 2015, in 2016 a significant effect of the variety, i.e. the selection of the CCP multiplied in EOT, COA or WOT position in the previous seasons, was detected (p = 0.012*). Although the COA-selected CCP did not differ from the average of the EOT and WOT-selected CCP, selection from the two field edges differed between each other, with the EOT selection yielding nearly 35% more than the WOT selection (Figure 41).

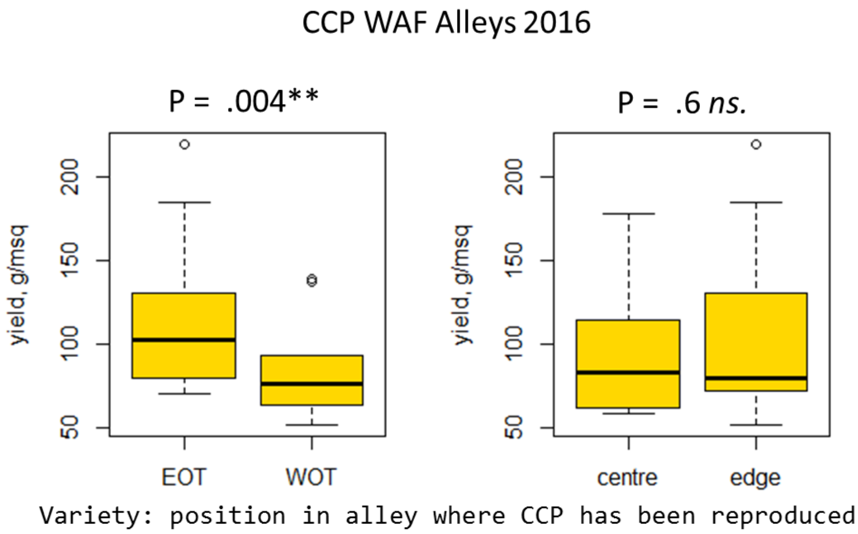


Figure 41. Wheat grain yield averaged by wheat CCP selection – reproduction position in the alley in the previous growing season. P-values of orthogonal linear contrasts 'East (EOT) vs. West of trees (WOT)' selection, and 'centre vs. edge' selection are shown.

This result seems to confirm the hypothesis that, in a North-South alley, conditions alongside a transect orthogonal to the tree rows are differentiated and able to exert a differential selection pressure over a wheat genetically diverse population. Whether the EOT selection is better adapted to a silvoarable context, or the WOT may instead accumulate seed-borne diseases due to higher persistence of humidity on the western side of the tree row, is not clear. However, this experiment brings the important conclusion that the yield potential of a wheat population can be influenced by the position in an alley between two North-south oriented tree rows where it has been multiplied.

Total productivity; the Land Equivalent Ratio

The Land Equivalent Ratio (LER), first proposed by Mead and Willey (1980), is a means of comparing productivity of intercropping and monocropping systems. It is calculated as the ratio of the area needed under sole cropping to the area of intercropping at the same management level to obtain a particular yield. A LER of 1 indicates that there is no yield advantage of the intercrop compared to the monocrop, while an LER of 1.1 indicates a 10 % yield advantage i.e. under monocultures, 10 % more land would be needed to match yields from intercropping (Dupraz & Newman, 1997). The LER reflects the ability of crops to partition resources in space and time, so that lower values of LER are recorded from mixtures of grasses in pasture, intermediate values from dissimilar vegetables, cereals and legumes, and highest values in agroforestry systems (Newman, 1987, in Dupraz & Newman, 1997).

Overall productivity (as oven dry weights) in the agroforestry system and the no-tree control was compared using the data collected in 2012 and 2013 on biomass production of the ley and fodder and bioenergy production from the willow as part of the SOLID project (Smith et al. 2016c). The following assumptions were made:

- Productivity (t/ha) of the individual components of the agroforestry system was calculated based on the proportion of land area they occupy where tree rows are 3m wide and alleys 10m wide: tree rows = 23 %; ley alleys = 77 %.
- To account for the spatial variation in ley productivity within the alleys, where production from the plots adjacent to the tree rows was significantly lower than elsewhere in the alley, the area of the alley (77 %) was further divided into 'edge' (1 m at each alley edge = 2 m = 15 %) and 'main' (rest of alley = 8 m = 62 %), and data averaged across plots accordingly.
- As yields of both the willow and ley varied considerably from 2012 to 2013, calculations were made separately for each year.
- Fodder production was assessed only once – in 2012. Production has been calculated as the average of samples from the first- and second-year growth, on the basis that within a hectare of agroforestry where alternate tree rows are harvested every other year, there will be both first and second re-growth. This assumes that the willow can be harvested for fodder each year (but only once a year), without impacting bioenergy production.
- Willow is harvested on a 2-year cycle, so annual production is calculated by dividing the harvested yields by 2.
- Calculations do not take into account inputs into the system. Main differences in inputs will be from the machinery and labour associated with harvesting the willow for fodder and bioenergy.
- LERs are calculated for 2012 and 2013 separately. As there is no 'Tree-only Control' on site, the willow yields are compared with standard figures for yields of short rotation coppice willow plantations from Nix (2013) which are given as 25 odt/ha (oven dry tonnes per hectare) every 3 years (i.e. 8.33 odt/ha/yr). Yields of the agroforestry ley are compared with actual yields from the 'No-Tree Control'. Fodder yields are not included as there are no standard figures with which to compare them. The following calculation was made:

$$LER = \frac{Tree\ agroforestry\ yield}{Tree\ monoculture\ yield} + \frac{Ley\ agroforestry\ yield}{Ley\ monoculture\ yield}$$

Results

Productivity of all components in the agroforestry system combined (weighted by the proportion of land area they covered) was 9.86 t/ha (as ODM) in 2012 and 8.75 t/ha in 2013 (Table 9). This compares favourably with the production of ley in the No-tree Control which was 8.97 t/ha in 2012 and 3.52 t/ha in 2013 (Figure 42).

Table 9. Overall productivity of the agroforestry and no-tree control in 2012 and 2013.

	2012			2013		
	Yield (odt/ha)	% land area	Weighted (odt/ha)	Yield (odt/ha)	% land area	Weighted odt/ha
Agroforestry						
Ley edge	6.20	15.00	0.93	2.83	15.00	0.42
Ley main	8.05	62.00	4.99	3.44	62.00	2.13
Total ley			5.92			2.56
Fodder yield	1.10	23.00	0.25	1.10	23.00	0.25
Wood yield	16.04	23.00	3.69	25.83	23.00	5.94
Total			9.86			8.75
Control						
Ley	8.97	100.00	8.97	3.52	100.00	3.52

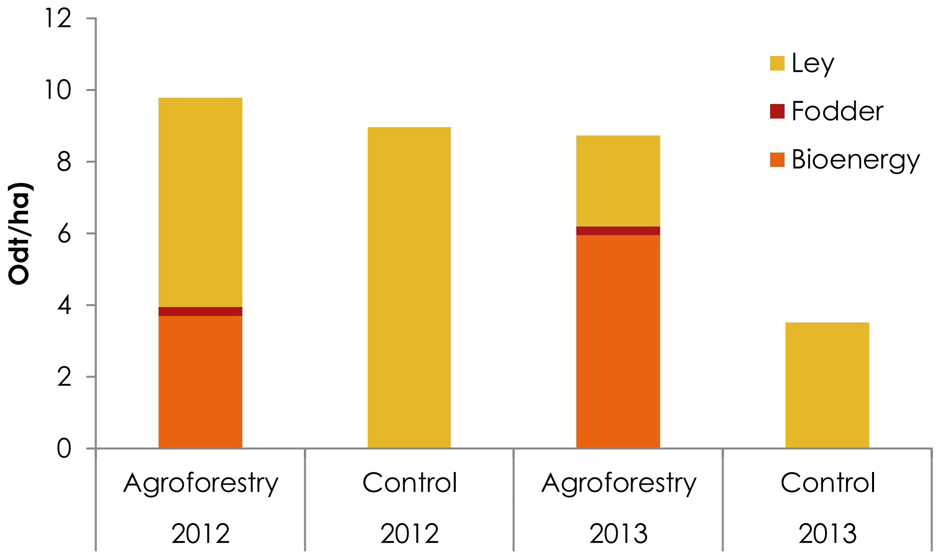


Figure 42. Overall productivity of the agroforestry system and no-tree control in 2012 and 2013 (odt/ha).

The LER for 2012 was 1.10 (LER = (3.69/8.33) + (5.92/8.97)) and in 2013 was 1.44 (LER = (5.94/8.33) + (2.55/3.52)). This equates to a 10 % yield advantage for agroforestry in 2012 and a 44 % yield advantage in 2013.

Discussion and conclusions

Integrating trees in agricultural land reduces the land area available for crops or livestock thus reducing agricultural output, and further reductions can occur where competition for resources exists, especially along the tree:crop interface. This reduction in agricultural yield can be compensated for by output from the tree component of the agroforestry system, as well as beneficial interactions such as enhanced nutrient supply or modifications of the microclimate that may result in an increase in agricultural yield. Agroforestry theory proposes that overall productivity should be higher in an agroforestry system compared with monocropped systems, due to complementarity of resources use and positive interactions between components. Calculations of overall productivity of the agroforestry system at Wakelyns in 2012 demonstrate that while there was a reduction in ley productivity, probably due to competition at the alley edge, and a reduction in land area under ley (77 % of land area), overall productivity was higher than in the 'No-tree Control' by just over 1 odt/ha, and a LER of 1.1.

In the second year of the study, when ley productivity in both the agroforestry and control plots was less than half that of the previous year, overall productivity was much higher in the agroforestry (8.75 odt/ha compared with 3.52 odt/ha, and a LER of 1.44), with increased wood biomass production compensating for the lower ley yields in the agroforestry. This suggests that an agroforestry approach can help buffer against fluctuations in yields by spreading the risk across a number of components.

Other studies of agroforestry systems have also recorded LERs greater than 1; for example, Van der Werf (2007) calculated Land Equivalent Ratios (LER) for two lowland poplar silvoarable trial systems in lowland England and found that LER's stayed above 1 for the 12 years after establishment. Newman (1986, in Dupraz & Newman, 1997) calculated LER values of 1.65 and 2.01 relating to economic and biomass yield respectively for a pear orchard/radish (*Raphanus sativus*) system. Dupraz (1994, in Dupraz & Newman, 1997) modelled LERs for a *Prunus avium*/*Festuca arundinacea* system in France and estimated annual LERs of 1.6 in the early years after establishment, declining to 1.0 later in the rotation, with an average of 1.2 over the 60 year rotation.

The LER values calculated here must be viewed with some caution as standard figures were used for comparison of willow yields – it may be that yields from willow grown in plantation-densities at Wakelyns would be higher than these standard figures and so reduce the LER. Fodder yields were excluded from the LER calculations as there is no standard data available on productivity of tree fodder against which to compare. It would be valuable to measure LERs of the system over a number of years to assess productivity over the entire rotation of the system (i.e. until the SRC willow reaches the end of its productive life, estimated at around 20 years).

In addition to higher yield potentials of agroforestry, product diversification should increase the potential for economic profits, by providing annual and periodic revenues from multiple outputs throughout the rotation and reducing the risks associated with farming single commodities (Benjamin et al, 2000). Tree products can be used on the farm (e.g. for fence posts, fodder or bioenergy) and this, combined with greater resource-use efficiency (e.g. nutrient use), should reduce inputs and increase the 'eco-efficiency' of the farming system.

Woodchip from the willow SRC at Wakelyns feeds into the biomass boiler that heats the farmhouse – this saves an estimated £1200/yr on heating oil (M. Wolfe pers. comm.).

In terms of overall productivity, the LERs of the agroforestry were higher than 1 in both years, indicating a yield advantage when compared with monocropping systems. While managing a more diverse and complex system will provide challenges for the farmer, it appears to be a more resilient and stable system that buffers against a fluctuating environment.

As with other agroforestry systems, the Land Equivalent Ratio was estimated as greater than one, indicating a yield advantage of 10% in 2012 and 44% in 2013 when compared with no-tree systems. In terms of actual biomass production, the agroforestry system performed particularly well in 2013, when lower productivity in the ley was offset by higher productivity of willow (Figure 43). This indicates the potential of agroforestry to buffer against variability in crop yields caused by fluctuations in the climate, although this potential is only likely to be realised if the woody component of the agroforestry system is managed as a productive element of the system. One way is illustrated in this example, where the willow is used for woodchip to produce bioenergy used on-farm, which makes sense economically as it replaces the input of fossil fuel to heat farm buildings. If the woodchip was marketed and sold off-site, the income generated is unlikely to be sufficient to off-set the loss of land to trees. This simple analysis, however, fails to take into account the wider benefits of integrating trees for biodiversity, animal welfare etc. (and any additional economic values associated). In an ideal scenario, the tree component should be managed as a productive element in its own right. Other potential on-farm uses for the willow woodchip, in addition to bioenergy and fodder, would be for animal bedding, and as a feedstock for an anaerobic digester (potentially of interest in dairy systems where anaerobic digestion of slurry may already be an attractive option). Willow rods are also popular for fencing and sculptures and these attract a higher price than woodchip.

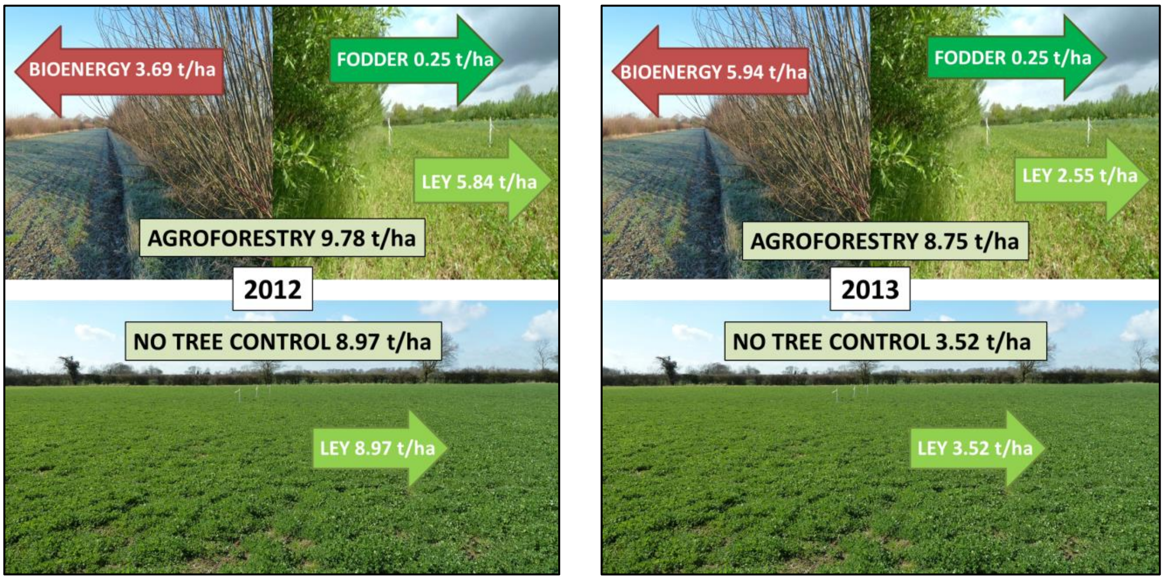


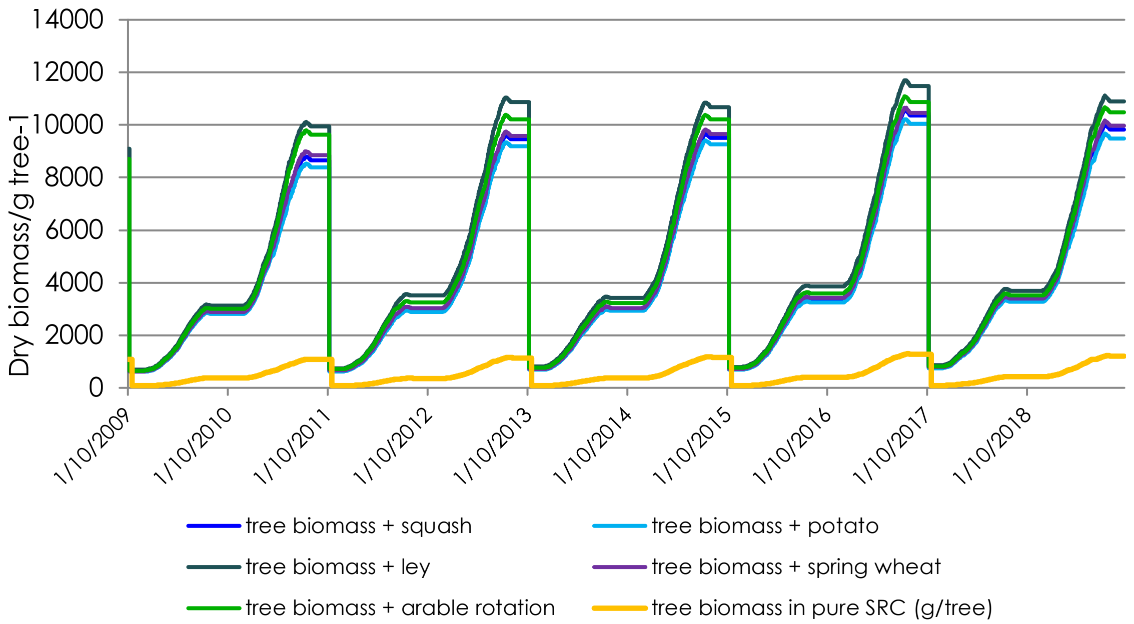
Figure 43. Biomass production in the agroforestry and no-tree control in 2012 and 2013.

Modelling productivity

The Yield-SAFE model, developed by Wageningen and Cranfield Universities in 2006 (van de Werf et al. 2007), permits the productivity of agroforestry systems over time to be modelled. It uses calibrated bio-parameters of tree and crop species to predict daily growth of the species in question given localised weather data and specified soil conditions and management practices.

Using the model as was, as part of the AGFORWARD project it was possible to model the yields that might be expected at Wakelyns Agroforestry in the case of a pure arable system, a pure willow SRC system and a willow-arable agroforestry system for the coppice rotation (Smith et al. 2017). It was assumed that trees would show consistent growth characteristics across rotation cycles, with the exception of the first cycle (initial planting to first full harvest), which was modelled separately. Arable crops added to the model for this purpose were: spring wheat, winter squash, potatoes and a two-year mixed ley. The modelled rotation was spring wheat – ley – potato – ley – winter squash – ley (repeat).

Figure 44 show the modelled biomass of SRC willow at WAF for a ten year period 30 years into the coppice system. As the model does not pick up aging of the trees due to calibration limitations (there are no aged yields in coppicing systems), the model projection assumes that the coppice cycles have reached some sort of stability. The modelled period is 2009-2018, selected because the weather data should be most accurate for recent history. Figure 44(a) shows the productivity of an individual tree within the system as compared to a pure SRC (density of 15 000 trees ha^{-1}) whilst Figure 44(b) takes account of the density of trees per hectare and therefore the absolute biomass production per unit area. The graphs clearly imply that whilst overall production of woody biomass is higher in a pure coppice system, tree performance improves dramatically at lower densities, reaching almost similar levels of stand biomass. With an 80% reduction in tree-covered area (equivalent to a 20% reduction in area for agricultural use), only 11% reduction in total tree biomass occurs (mean biomass difference at tree harvest under the described crop rotation). Crops have different impacts on tree growth, with the percentage effect on total tree biomass at tree harvest ranging from 5% with a grass ley to 19% when coupled with potatoes.



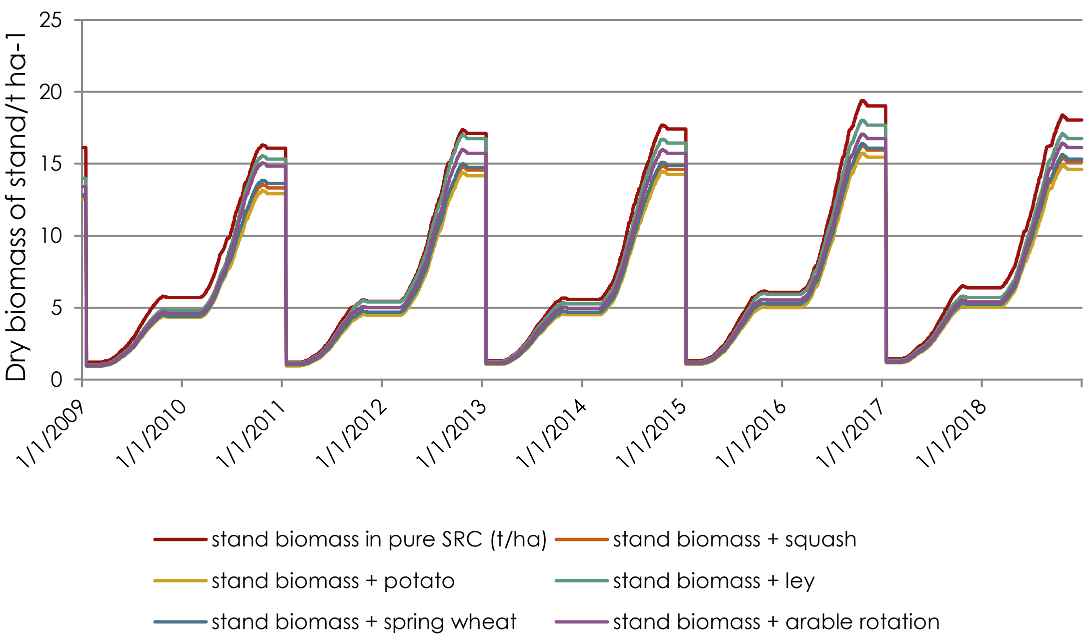


Figure 44. Modelled biomass of the SRC willow at Wakelyns Agroforestry from 01/01/2009-31/12/2018 on (a: top) a tree by tree basis and (b: bottom) for the stand as a whole. 'Rotation' refers to the modelled crops in the rotation specified above. 2009 harvest is winter squash.

Crops similarly show a modelled decline in biomass production when in an agroforestry system (Figure 45). As before, this was modelled taking into account the reduced area of crop cover and extrapolating the growth under agroforestry up as if the whole field was arable (equivalent to a plant by plant basis).

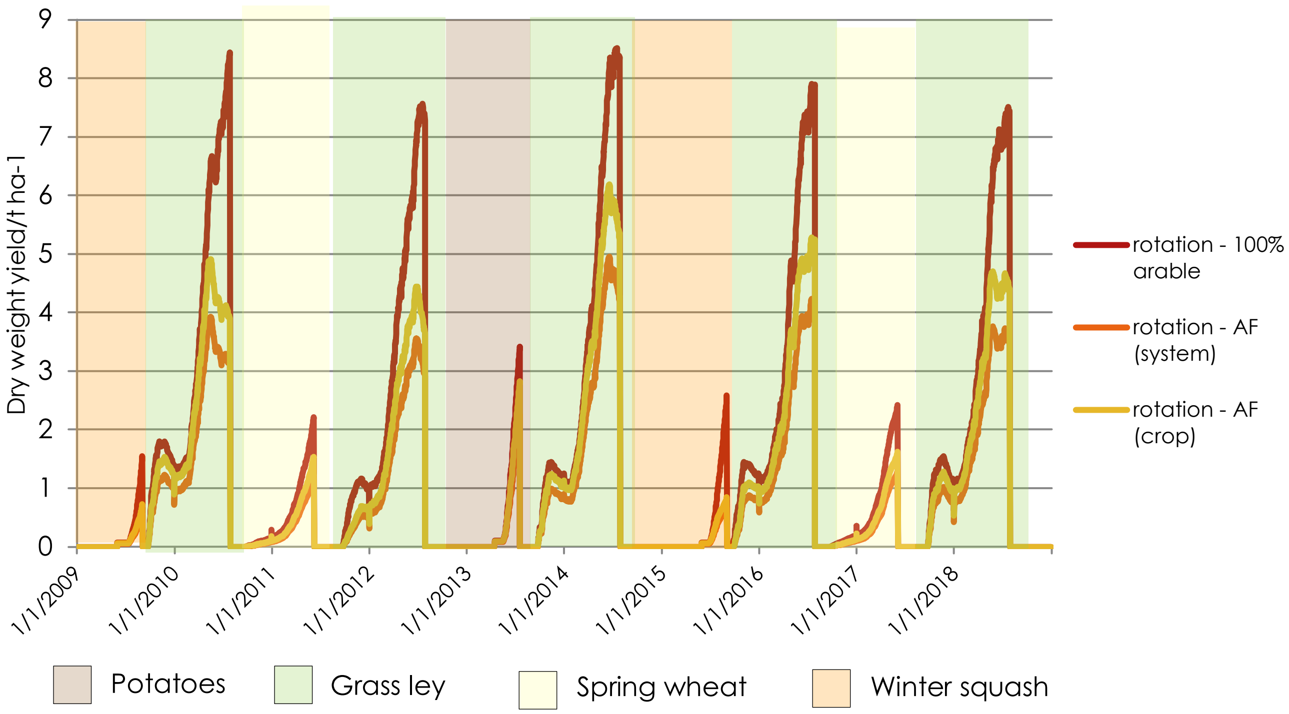


Figure 45. Modelled crop biomass at Wakelyns Agroforestry for the period 01/01/2009–31/12/2018 for a 100% arable system; the agroforestry system as is currently at Wakelyns: rotation (AF (system)); and the cropped area of the agroforestry (AF (Crop)).

The final thing that the models facilitate is comparison between a specialist arable or coppice system and an agroforestry system. Figure 46 below, for example, shows the comparison between the biomass production in the three scenarios 100% arable, 100% coppice and 20:80 willow: arable system (by area as if redistributed into two distinct blocks. This is the relative proportions found in the Wakelyns system).

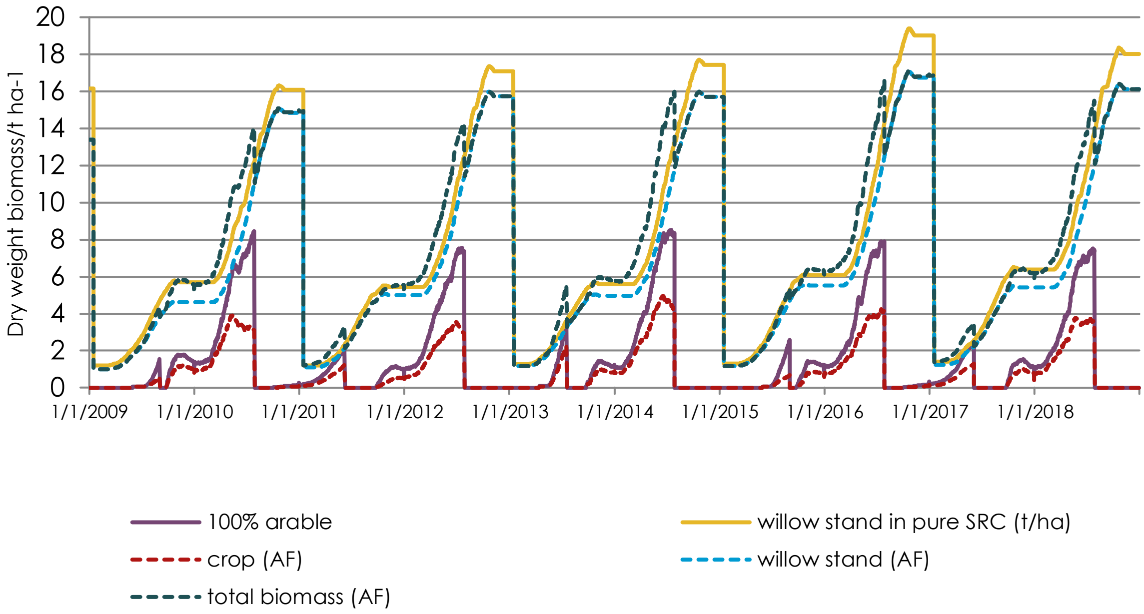


Figure 46. Modelled total biomass production at Wakelyns Agroforestry for the period 1 January 2009 to 31 December 2018 for an arable, a coppice and an agroforestry (AF) scenario. Pure SRC is modelled as 15 000 trees ha-1.

Figure 46 shows that there is more total biomass in the pure SRC than in agroforestry systems. This does not, however, mean a lower biomass harvested: total harvested biomass – tree and crop – over the course of one full crop rotation (three coppice cycles) is modelled at 57 t ha^{-1} under the described agroforestry system, compared to 47 t ha^{-1} under pure SRC (15 000 trees ha^{-1}) and 32 t ha^{-1} under pure arable.

These figures can be used to calculate a Land Equivalent Ratio (LER) – the ratio of productivity under agroforestry versus that in disparate systems. A ratio > 1 indicates that greater production is achieved under agroforestry than by an identical area of disparate production – in other words, that a greater area of land is needed to produce equivalent yields if arable and coppice are spatially seperated than when they are combined in an agroforestry system.

The LER was calculated across one full arable rotation (i.e. six years), starting from 2010 to allow the tree component of the model to settle (Table 10).

Table 10. Modelled yields used for LER calculation

	2010	2011	2012	2013	2014	2015	Totals
Squash (AF) $_{a}$	-	-	-	-	-	0.67	
Squash (arable) $_{b}$	-	-	-	-	-	2.59	
Grass ley (AF) $_{c}$	3.03	-	2.92	-	4.23	-	
Grass ley (arable) $_{d}$	8.21	-	7.28	-	8.36	-	
Spring wheat (AF) $_{e}$	-	1.23	-	-	-	-	
Spring wheat (arable) $_{f}$	-	2.21	-	-	-	-	
Potatoes (AF) $_{g}$	-		-	2.26	-	-	
Potatoes (arable) $_{h}$	-		-	3.42	-	-	
Total crops (AF) $_{a+c+e+g}$							14.34
Total crops (arable) $_{b+d+f+h}$							32.07
Willow (AF) $_{i}$	-	13.72	-	14.55	-	14.54	42.81
Willow (pure SRC) $_{j}$	-	14.87	-	15.81	-	16.11	46.79

$$LER = \frac{14.34}{32.07} + \frac{42.81}{46.79} = 0.45 + 0.91 = 1.36$$

This sort of modelling provides the basis for development to compare systems in terms of harvested yields, total profits, optimal coppice:arable ratios etc. One could even set targets (based, for example, on the amount of woodchip required to meet the farm's own energy needs) and calculate the system design required to meet them.

Tree:crop interactions and total productivity: key conclusions

- Trials investigating cereal yields in the mixed timber system showed that some crops may be better suited to the more competitive environment of growing with trees. Farmers can use this knowledge to select species or varieties that perform better within an agroforestry system.

- Within the fertility-building ley/willow SRC system, there was some competition between trees and plants in the crop alleys, but this appeared to be restricted to the edge of the alleys and varied depending on weather conditions and the stage of tree growth and harvest. By reducing the amount of 'edge' by increasing the width of crop alley, the overall impact of competition between the tree and crop component can be minimised. The presence of trees impacted on species composition within the alleys, with shade-tolerant species dominating the sward, and other species such as clovers declining in abundance. This may have implications for nitrogen fixation and also for the nutritional value of the sward. Careful selection of species with greater shade-tolerance (including a range of forage grasses) should be carried out to establish a productive sward for agroforestry systems.

- Cereal yields are negatively impacted by proximity to tree rows. Data for all studied cereal crops indicate a decline in yield with greater proximity both to hedge (coppiced or standing) and tree rows. The exception is for oats, which seems, in fact, to benefit from proximity to a coppiced hedge. Further trials are however needed to confirm this as an interaction with the hedge as opposed to a field-scale effect.

- One year is insufficient for composite cross population to show any adaptation to environmental conditions. In accordance with previous studies, seed selection from a composite cross population for different distances from tree rows does not result in any noticeable change in crop characteristics over the course of a single growing season. Some differences do seem to become apparent after two years, however. More targeted selection and breeding may be needed for the development of 'alley edge' populations.

- The Land Equivalent Ratio is a means of comparing productivity of intercropping and monocropping systems. As with other agroforestry systems, the LER of the willow/ley system was estimated as greater than one, indicating a yield advantage of 10% in 2012 and 44% in 2013 when compared with no-tree systems. In terms of actual biomass production, the agroforestry system performed particularly well in 2013, when lower productivity in the ley was offset by higher productivity of willow. This indicates the potential of agroforestry to buffer against variability in crop yields caused by fluctuations in the climate, although this potential is only likely to be realised if the woody component of the agroforestry system is managed as a productive element of the system. The LER of an entire crop rotation was calculated as 1.36, suggesting that there is a 36% yield advantage for the agroforestry system compared to when the components are grown separately as monocultures.

- Modelling can be used in partnership with field trials and to assist with management decisions and system design. Biological based models such as Yield-SAFE allow for the modelling of specific locations and systems. This offers a number of potential contributions: modelling possible effects of future climatic changes and consequent changes in management needs (introduction of irrigation, for example); designing systems to produce sufficient quantities of specific products; and calculating land equivalence ratios for agroforestry versus specialised production represent just a few of the possibilities.

Functional biodiversity

Novel land use systems such as Wakelyns that integrate woody species into the agricultural landscape have the potential to balance productivity with protection of the environment and the maintenance of ecosystem services (Jose, 2009). An emphasis on managing rather than reducing complexity promotes a functionally biodiverse system with both ecological and economic interactions between trees and crops and livestock (Lundgren, 1982). Although the potential of agroforestry-based agricultural systems has been demonstrated in principle (Quinkenstein et al., 2009), information on their usefulness in the context of European organic and low-input production systems is lacking. As part of the European FP7-funded project 'Innovative strategies for copper-free low-input and organic farming systems (CO-FREE, www.co-free.eu)', we evaluated an innovative apple/arable agroforestry system as a potentially sustainable strategy for reducing copper inputs in organic and low input systems (Smith et al. 2016a and 2016b). The aim was to provide information on the potential of agroforestry in the European context.

Apple production in diverse silvoarable systems

Integrating top fruit production into an agroforestry system, where woody species are integrated with crop production, may have a beneficial effect on the control of plant pathogens such as scab (*Venturia inaequalis*) due to a number of mechanisms:

- A greater distance between tree rows in agroforestry systems, with crops in the adjoining alleys, is likely to reduce the spread of pathogens. This has been recorded for crop pathogens in agroforestry systems (Schroth et al., 1995) but the evidence for tree pathogens is inconsistent (Schroth et al., 2000).
- Lower densities of trees compared with orchards favour increased air circulation which has been shown to reduce the severity of scab by reducing leaf wetness duration (Carisse & Dewdney, 2002).
- Regular cultivations within the crop alleys will incorporate leaf litter into the soil, thus enhancing decomposition and reducing the risk of re-inoculation from overwintered scabbed leaves the following spring.

This research aimed to evaluate an apple-arable agroforestry approach as a sustainable strategy for reducing copper inputs in organic and low input systems using Wakelyns Agroforestry as a case study. The results presented here focus on three elements that are likely to be impacted by an agroforestry systems approach to apple production: (i) yield and quality of apples; (ii) emergence of primary and secondary pests and diseases; and (iii) biodiversity of beneficial insects (predators and pollinators).

Methods

Within the 2-ha apple-arable agroforestry system, a diverse mix of 21 varieties of apple trees on MM111 rootstock are interspersed with seven timber species, in north/south rows with 12 m-wide crop alleys between adjacent rows. Cereals, potatoes, field vegetables and fertility-building leys are grown in rotation within the alleys. The apple trees cover 2.5% of the land area in the 2-ha system. A local modern 0.6 ha organic orchard acted as a benchmark for comparison (Clarkes Lane Orchard).

Research was carried out in 2012 and 2013. The experimental design at Wakelyns consisted of four plots, each plot including two tree rows and the crop alley in between, with 7-10 apple trees in each plot interspersed with timber trees. At Clarkes Lane Orchard there were also four plots, each plot consisting of two tree rows and the narrow grass alley in between.

Figure 47. Mixed apple and timber tree system at Wakelyns Agroforestry, Suffolk, UK

Yield and quality of apples

In autumn 2012 and 2013, all apples harvested from each site were graded as Class I/Class II/processing/waste and weighed per class and variety. The grading followed Commission implementing regulation (EU) No 543/2011 available at www.gov.uk.

Pests and diseases

Pests and diseases were assessed in the plots at three points – small fruits in July 2012 and 2013, large fruits in August 2012 and 2013, and the harvested apples (September to November 2012 and 2013). Scab levels and incidences of other pests and diseases in the agroforestry and orchard plots in 2012 and 2013 were compared statistically using t-tests, using R version 2.10.0 (R Development Core Team, 2009). Each sample consisted of 100 plant units chosen randomly from all trees in the plot area (i.e. 100 small developing fruits; 100 large fruits pre-harvest; 100 harvested fruits). Each plant unit was thoroughly inspected for eggs, insects or insect damage and diseases.

Pollinators and predators

This method focused on measuring pollinators and natural enemies. Each cluster of pan traps consisted of one each of UV-bright yellow, white and blue pan traps, suspended from the trees, filled with 400ml water and a drop of detergent (Westphal et al, 2008). Traps were left active for 48 hours and the collected specimens stored in 70% ethanol until identification. There were two clusters of traps per plot i.e. 8 clusters per site, located within a tree row next to apple trees (Figure 48). Traps were set mid-May, mid-July and end of August in 2012. The invertebrates collected in each pan trap were sorted to order, and their abundances recorded. The Hymenoptera were then sorted to family and the bees (Apoidea) identified to species. The wasps were divided into parasitic and predatory morphogroups based on antennal segment numbers. For the pan trap invertebrate data a general linear mixed model was used (Bouffartigue, 2013). Abundances were log (N+1) transformed. Mixed models were made to find the dependence of the abundance of the main orders, families and species on the treatment (WAF vs CLO), the months (May, July, August) and the interaction between the two. Treatment and months were included as fixed factors (Model I). Another model per taxa was then designed using temperature, relative humidity and the interaction between them as explanatory variables (Model II). Deletion of non-significant parameters was performed to achieve model simplification and only the results of the simpler model are displayed. Finally, a third model integrating the best explanatory variable of each model was designed and compared to the first two using the AIC (Akaike's Information Criterion).

Figure 48. Pan traps in apple tree at Wakelyns Agroforestry

Results

Yield and quality of apples

Apple production in England in 2012 was severely affected by heavy rain from April to June and late frosts, with some fruit farmers reporting losses of up to 90% of their crop. In the agroforestry and orchard sites, some varieties failed to set fruit (e.g. Cornish Gillyflower at Wakelyns; Spartan and Winter Gem at Clarkes Lane Orchard) or had very low fruit set. In addition, high levels of scab impacted on yields at the orchard (see below) and so the resulting total apple yields were very low (Figure 49). Yields within the agroforestry were higher; even allowing for the fact that apple trees cover only 2.5% of the area (tree plus understorey). Comparing yields with standard figures from the Organic Farm Management Handbook (Lampkin et al., 2014) by calculating the yield of 100% agroforestry apples (i.e. multiplying by 40), the yields from the agroforestry compare favourably with standard yields (Class I & II: 15.7 t/ha from the agroforestry vs. 14 t/ha from orchards at peak production). Apple yields in 2013 were substantially better than in 2012. Yields within the organic orchard were 2.24 t/ha (Class I, II and processing) compared with 0.72 t/ha from the agroforestry (Figure 49), which when scaled up to 100% apples, again compares favourably with standard figures (Class I & II: 19.25 t/ha from the agroforestry vs. 14 t/ha from orchards at peak production (Lampkin et al 2014)).

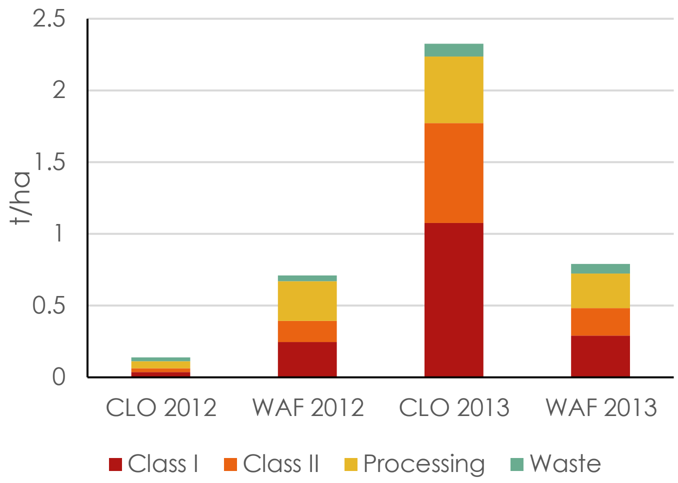


Figure 49. Apple yields (t/ha) from the agroforestry (WAF) and orchard (CLO) sites in 2012 and 2013. NB. Apple trees account for 2.5% of land area in the agroforestry system.

Pests and diseases

Neither the agroforestry apple trees or orchard trees are sprayed for scab, and there were high levels of scab in both systems in 2012 (Figure 50). However, scab levels of both small and large fruits were over twice as high in the orchard compared with the agroforestry site and analyses showed a statistically significant difference (small fruits $t = 4.25$, $p < 0.01$; large fruits $t = 3.44$, $p < 0.05$), but there were no significant differences between scab levels in the harvested agroforestry and orchard apples (Table 11). There was a higher incidence of insect damage to small developing fruits by sawflies ($t = -3.29$, $P < 0.05$, Figure 51) and to large fruits by codling moths ($t = 3.94$, $P < 0.03$) in the agroforestry system compared with the orchard (Figure 51b, Table 11). At harvest, capsid damage was significantly higher in the agroforestry apples ($t = -4.57$, $P < 0.01$; Figure 51c). In 2013 scab levels of both small, large and harvested fruits were several times higher in the orchard compared with the agroforestry site (Figure 50) although due to wide variation within sites, there was only a significant difference between sites in the small fruits ($t = 3.11$, $P < 0.05$; Table 11). In the small fruit, statistically significant differences were found only for occurrences of open flesh (likely caused by birds, $t = -4.37$, $P < 0.05$, Figure 51d). In the large fruit, there were significantly higher levels of aphid damage ($t = -3.17$, $P = 0.05$) and moth damage ($t = -2.66$, $P < 0.05$) in the agroforestry, and significantly higher levels of codling moth damage in the orchard ($t = 8.69$, $P < 0.01$, Figure 51e). There were no significant differences found in the harvested fruit (Figure 51f).

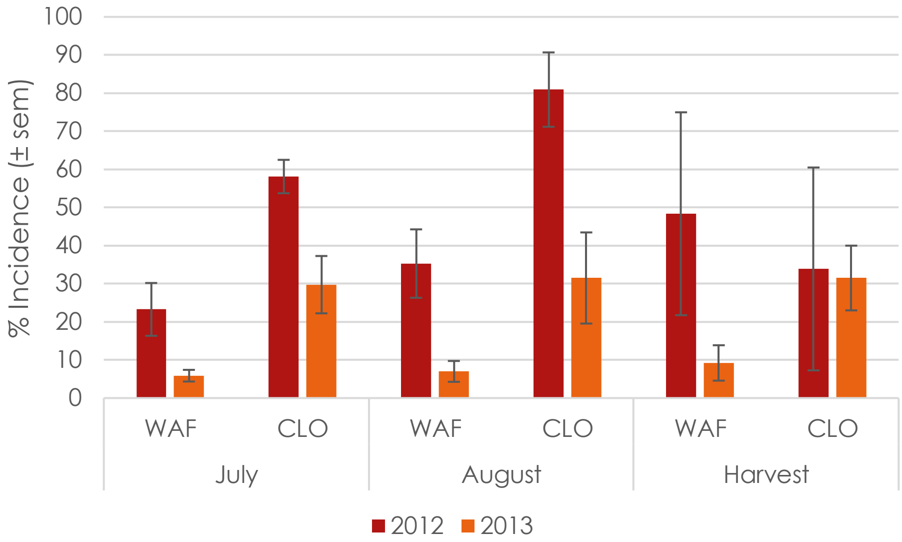


Figure 50. Mean scab incidence per plot in the agroforestry (WAF) and orchard (CLO) in 2012 and 2013.

Table 11. P-values of t-tests comparing diseases and pests in the agroforestry and orchard plots.

	Small fruit		Large fruit		Harvested fruit	
	2012	2013	2012	2013	2012	2013
Scab	**	*	*	NS	NS	NS
Sawfly damage	*	NS	NS	NS	NS	NS
Capsid damage	NS	NS	NS	NS	**	NS
Codling damage	NS	NS	*	**	NS	NS
Aphid damage	NS	NS	NS	*	NS	NS
Moth damage		NS		*		
Open flesh	NS	*	NS	NS	NS	
Brown Rot			NS	NS	NS	NS

* P ≤ 0.05; ** P < 0.01; *** P < 0.001, NS = not significant, Blank = no incidences recorded

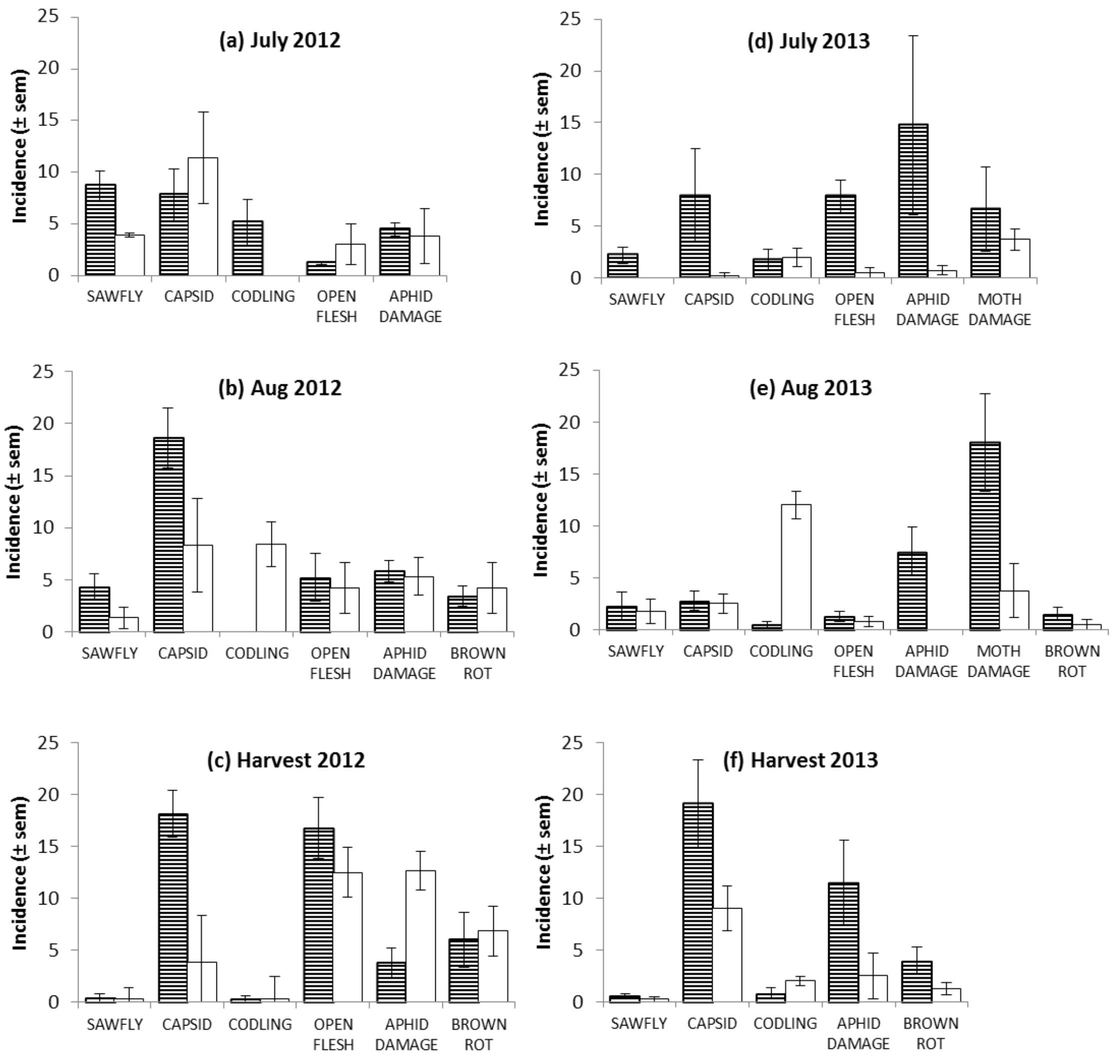


Figure 51.a-f. Pest and disease damage to fruit in the agroforestry (striped bars) and orchard (white bars) in 2012 and 2013.

Pollinators and predators

In 2012 a total of 20,089 individuals were collected, consisting of 12 orders (dominant orders detailed in Table 12) (Bouffartigue, 2013)). The most abundant order was the Coleoptera with 14,946 individuals. Within the Hymenoptera there were 171 bees comprised of 21 species, 129 parasitic wasps and 336 predatory wasps. Statistical analyses using general linear mixed models found no significant difference in total Hymenoptera abundance between the agroforestry and orchard. At the family level, there were significantly more *Lassioglossum* and *Bombus* in the orchard than in the agroforestry, and more predatory and parasitic wasps in the agroforestry (Table 13, Figure 52).

Table 12. Abundance of the main taxa sampled in pan traps in the orchard (CLO) and agroforestry (WAF).

	Coleoptera	Diptera	Heteroptera	Hymenoptera
CLO Total	**10297**	**1879**	**339**	**323**
May	65	422	2	27
July	10180	742	222	203
August	52	715	115	93
WAF Total	**4649**	**1616**	**401**	**329**
May	21	422	6	19
July	4590	685	370	180
August	38	509	25	130

Table 13. Results of repeated measures analysis of abundances of Apoidea families. NS= not significant and excluded from model, *P<0.05, **P<0.01, ***P<0.001.

Fixed effects	*Andrena*	*Bombus*	*Lasioglossum*
	Model I		
Treatment	NS	F=11.76**	F=24.51***
Month	F=11.45***	NS	F= 38.64***
Treatment*Month	NS	NS	F=15.16***
	Model II		
Temperature	F= 14.46***	F= 4.22*	F= 10.81**
Relative Humidity	NS	NS	NS
Temperature*Relative humidity	NS	NS	F= 4.38*
	AIC		
Model I	71.14	49.59	86.87
Model II	80.02	62.36	154.95
Model III	79.06	57.66	114.76

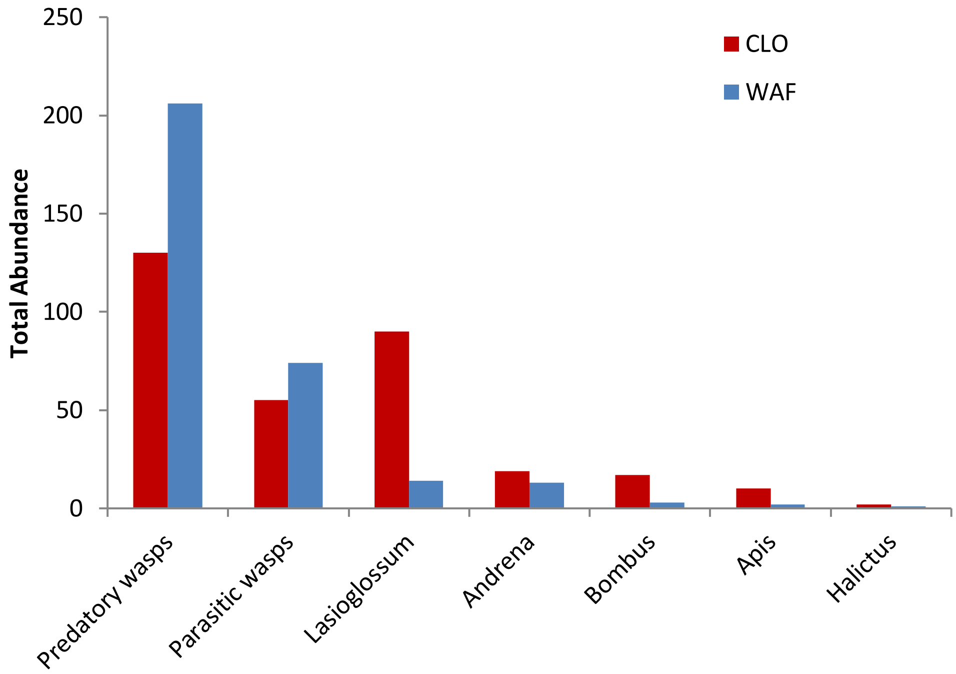


Figure 52. Total abundance of Hymenoptera in the agroforestry (WAF) and orchard (CLO) systems in 2012.

While we found no significant difference in total Hymenoptera abundance between the agroforestry and orchard, there were differences at the family level, with significantly more *Lassioglossum* and *Bombus* in the orchard than in the agroforestry, and more predatory and parasitic wasps in the agroforestry. Compared with an orchard, the agroforestry system is subject to more frequent disturbances (relating to crop production) and this may impact on pollinator diversity. In addition, floral resources may be lower in the agroforestry – even when there is a clover fertility-building ley in the crop alleys, these are cut regularly so there are gaps in the provision of flower resources. The orchard is surrounded by a floristically diverse hedgerow, and the grass understorey was not cut during the two years of this study, so this may have provided a stable habitat with consistent floral resources. The higher levels of predators and parasitic wasps in the agroforestry system may reflect a more consistent supply of prey species in the agroforestry.

Discussion

Yields at Wakelyns in 2012 and 2013 were comparable with standard figures when scaled up from 2.5% land area under apple production to 100% apples, and even at just 2.5% cover, appeared to out-perform the organic orchard used for comparison. With so few apple trees, this would probably not be acceptable for large scale apple producers who rely on economies of scale. However, this approach could work well in a diverse, potentially small-scale system such as a market garden, where apples could contribute to direct marketing channels such as vegetable box schemes or farm shops. Having such a wide range of varieties within the system means that harvesting would occur over a longer period. This requires careful planning and may be a challenge for selling to wholesalers if only small amounts are ready at any one time. New approaches to marketing could address this problem, for example, creating mixed bags of varieties, categorizing by taste, e.g. 'sweet' apple bag, or 'sharp' apple bag; or by making more of a feature of the varieties if going into vegetable box schemes e.g. 'apple of the week'.

Neither sites spray to control for scab or other diseases or pests, and scab was detected in both sites during the years of study. At Wakelyns, scab levels were several times lower than in the nearby organic orchard in both 2012 and 2013. Although no firm general conclusion can be drawn from this two-year study, it appears as if there may be indications of a potential positive impact on reducing scab levels within the agroforestry. This could be due to the very low densities and high diversity of apple tree varieties. Also, that while some varieties may fail to set fruit or have high levels of scab, the high diversity of apple varieties within the agroforestry means that other varieties will compensate and so buffer against extreme losses of yields. However, further research will be required to confirm this theory.

The impacts of secondary pests and diseases varied between the agroforestry system and the orchard. This supports previous research on agroforestry systems that while some pests are reduced in agroforestry systems, other pest groups may be observed in higher numbers, and shifts in relative importance of pest groups may present novel management problems and influence crop choice (Griffiths et al., 1998).

In conclusion, the low density, high diversity approach at Wakelyns Agroforestry seemed to have benefits in terms of reducing disease levels, and could work well in a diverse, potentially small-scale system such as a market garden, where apples could contribute to direct marketing channels such as vegetable box schemes or farm shops.

Carabid beetles

The biodiversity of ground beetles was assessed by intern Alice dos Santos from France in May 2012. Pitfall traps were set up in the mixed timber/fruit tree agroforestry alleys (Waterfield) for 32 days in April-May 2012. In four alleys, pitfall traps were installed within the tree rows and at 3m and 6m (i.e. centre) into the alleys, on three transects (total of 36 traps). Individuals of the Carabidae (ground beetles) were identified to species using Luff (2007). A total of 124 beetles were identified (Figure 53; total of 14 in the tree rows, 55 at 3m and 55 at 6m). Of the 11 species, four were represented by just one individual. The most common species was *Pterostichus cupreus* (74 individuals), followed by *Bembidion obtusum* (16 individuals) and *Pterostichus madidus* (10 individuals).

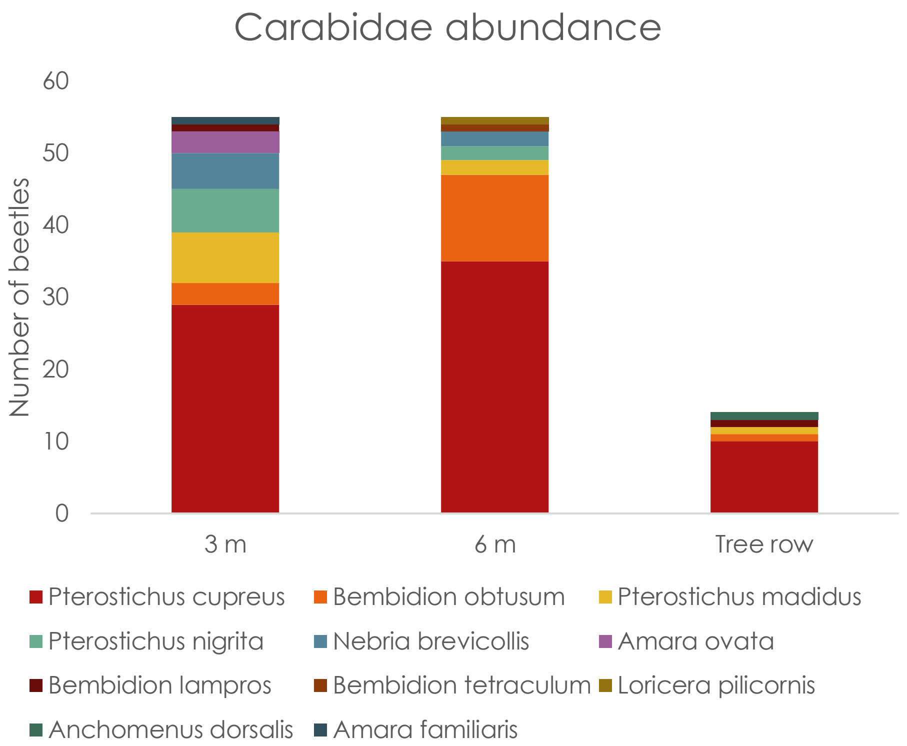


Figure 53. Total abundance of ground beetles at each location in the mixed timber system.

Earthworm biodiversity

The biodiversity of earthworms was assessed by intern Murielle Ruedy from Switzerland in April 2012. Soil samples measuring 25 x 25 cm to a depth of 10 cm were dug out, hand-sorted and earthworms extracted. Samples were taken from the willow SRC system, the mixed timber system (Waterfield) and the 'no-trees control' (Mid-Field), along three transects in each system. In the two agroforestry systems, samples were taken along the transect from under the tree rows and at 3m and 6m into the alleys, with the same spacing of samples taken in the open field control. A total of 172 earthworms were extracted (Figure 54, 51 from the willow system, 59 from the timber system and 62 from the control); of these 118 were juveniles. There were 10 species identified, the most common being *Aporroectodea caliginosa* (31 individuals) and *Apporectodea longa* (11 individuals). The other species were represented by only one or two individuals.

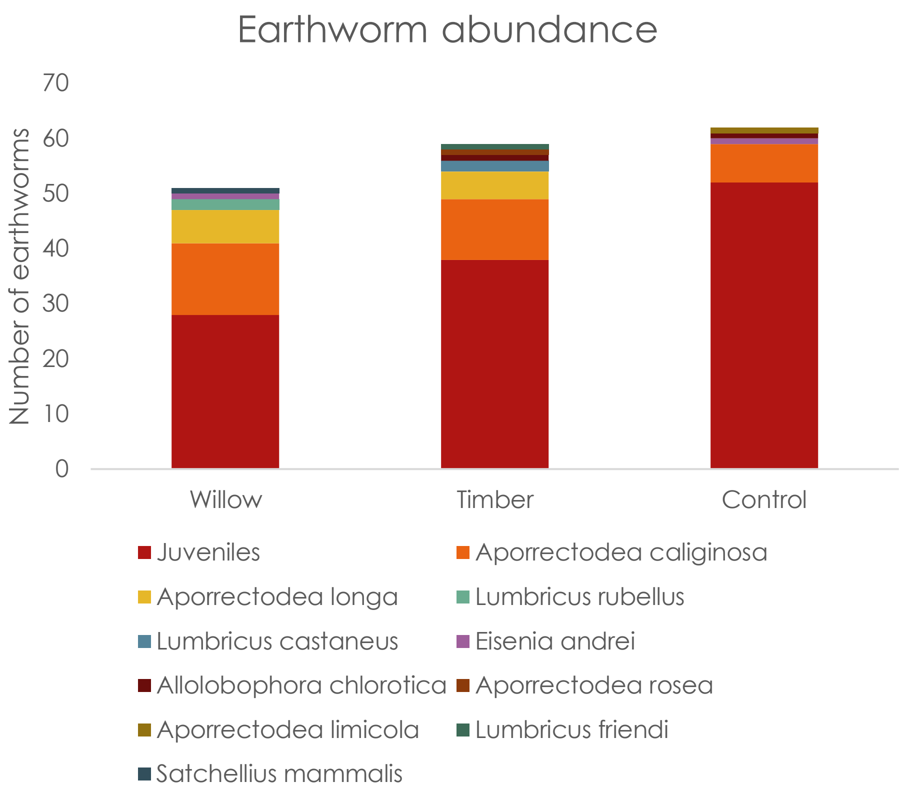


Figure 54. Total earthworm abundance in the willow system, timber system and control 'no-trees' system.

Functional Biodiversity: key conclusions

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Sustainability

Agroforestry systems such as Wakelyns are often promoted as sustainable alternatives to the highly industrialised agricultural model with its associated negative environmental externalities. However, our research often focuses on just a single factor (or limited range) of sustainability measures. A combined approach applying a range of tools and metrics can help to reveal costs and benefits from a range of perspectives (environmental, economic, social) and help determine the extent to which contrasting agroforestry systems can deliver on a range of sustainability objectives.

We used a comprehensive sustainability assessment tool, the SustainFARM Public Goods Tool, which is modified for agroforestry systems, to consider the many aspects of sustainability (ORC, 2019; Smith 2019). The SustainFARM Public Goods Tool helps farmers assess the sustainability of their farming system within a 12-month period. It can also be used as a decision support tool for farmers and land managers, to help them to identify possible impacts of changing the system on performance across the full range of sustainability indictors.

The assessment takes a broad approach, using information that a farmer would have in their farm records already. It takes between 30 minutes and an hour to complete, depending on the complexity of the farm. It assesses a farm on a number of areas (spurs) which may be impacted by agricultural management practices and are related to public goods such as water quality, air quality, etc.

These “spurs” are:

- Soil management
- Landscape and heritage
- NPK balance
- Energy and carbon
- Food security
- Agricultural systems diversity
- Social capital
- Farm business resilience
- Animal health and welfare management.
- Governance

Each spur is assessed by asking questions based on a number of key “activities”. Answers are scored on a scale between 1 (poor) and 5 (excellent) and an overall score given for each spur. Results are captured on a radar diagram to give an instant visual overview of the sustainability of the farm. Within the SustainFARM PG Tool the LER is calculated for the whole agroforestry area of the farm (i.e. if there are multiple agroforestry systems on the farm, it combines them into a single calculation). Standard yield data for the typical arable or fruit crop and tree timber or woodfuel crop for the specific country are used for the monocrop yield (converted to Metabolisable Energy), as most farms won’t have monocrop yields available for the comparison. This means that the LER produced is a simple indication of the performance of the agroforestry system compared with standard monocrop systems typical of the country, rather than a robust on-site comparison that fully reflects the complex interactions between trees and crops/livestock.

As a diverse organic farm, Wakelyns scores highly across nearly all the spurs (Figure 55) achieving a top score in soil management and agricultural systems diversity. Its lowest score is for the NPK balance; currently the fertility building legume ley fixes more nitrogen than is exported in crops, thus risking leaching of nitrogen from the farm (Figure 55). This shows how the SustainFARM PG Tool can highlight areas for improvement. The LER is 1.34 which suggests that 34% more land is needed under a monocropping scenario to achieve the same level of production (based on metabolizable energy) as the agroforestry system on the farm.

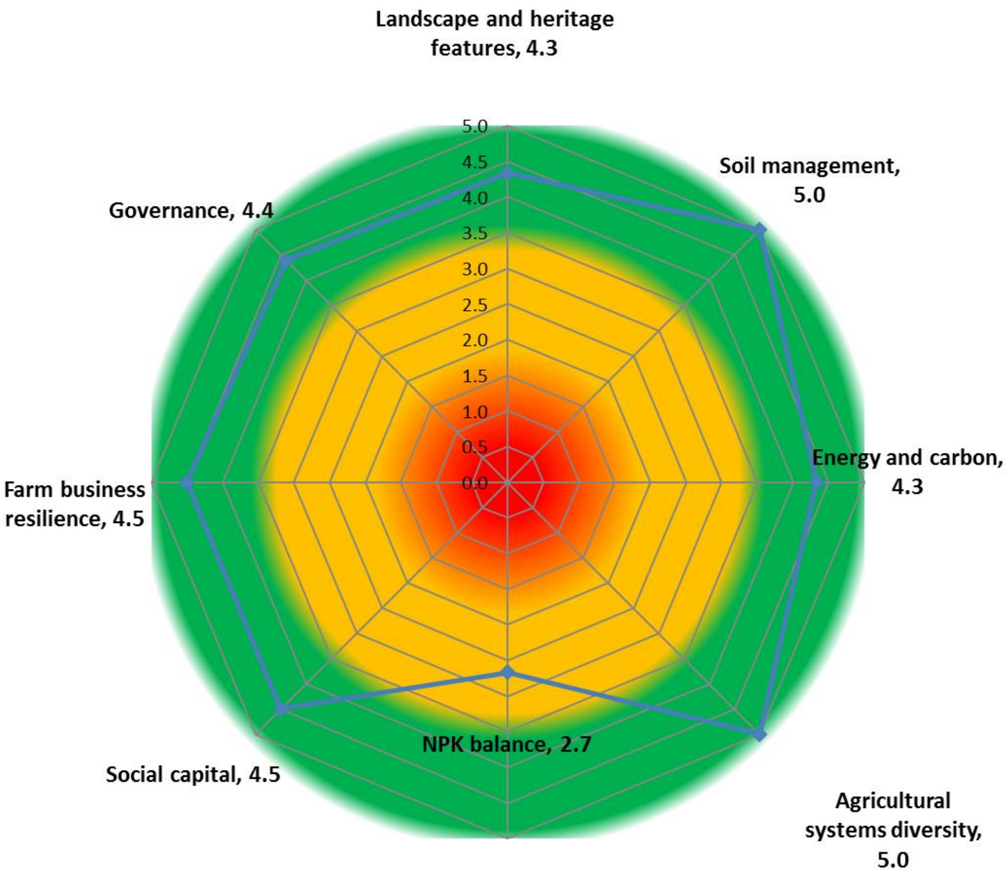

Figure 55. Radar diagram showing the results of the SustainFARM PG Tool assessment at Wakelyns.

An energy and emissions audit was carried out at Wakelyns in 2009; this assessed energy production and consumption of the farm business including the domestic property (Smith, 2009). The whole estate energy production, including woodchip from the SRC, was 1086 GJ, while the whole estate energy consumption was 189 GJ. This gives a production: consumption ratio of 5.1:1. The farm's total energy use was just 26% of the benchmark for an arable farm with similar land use. Energy benchmarking using the SustainFARM PG Tool found that although the arable enterprise uses only 61% of arable benchmark, the domestic energy use is considerably higher than an average farmhouse (367% of benchmark). The farmhouse at Wakelyns is a beautiful, but old and leaky building that is hard to insulate. However, 80% of the farm energy use is from renewable sources (photovoltaic panels and woodchip from the agroforestry system and the CO2 balance is -10.2 tonnes CO_2 equivalent per year.

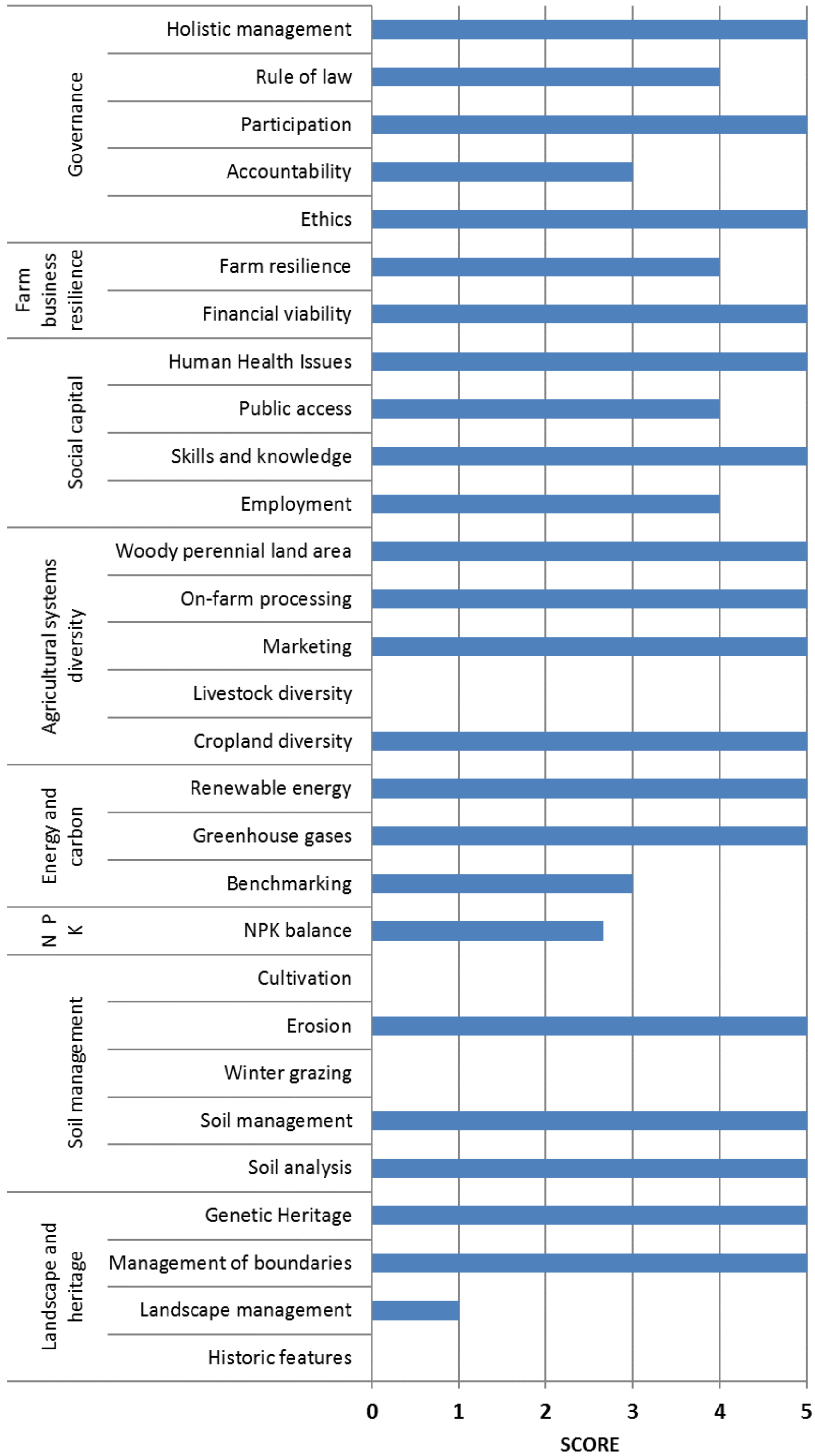

Figure 56. Bar chart showing sub-spur scores for Wakelyns Agroforestry.

Key assessment criteria		
Land Equivalent Ratio	**1.34**	
Farm gate NPK balance		
N balance per ha	91	kg
P balance per ha	-2	kg
K balance per ha	-12	kg
Energy benchmarks (energy use as % of average figures)		
Arable	61%	
Beef & sheep	No beef or sheep	
Dairy	No dairy	
Pigs	No pigs	
Poultry - layers	No layers	
Poultry - broilers	No broilers	
Domestic	367%	
Total farm renewable energy	80%	
CO_2 balance	-10.2	tonnes CO_2 equivalent yr
Labour use - ALUs	2.7	**Please note:** 1 ALU is one full-time employee working 2200 hours per year

Figure 57. Key results from the SustainFARM PG Tool assessment for Wakelyns.

As a research site, income to support the trials and maintain the farm was primarily from research funding. Going forward, Martin's sons, David and Toby, are working closely with farm managers Paul and Mark Ward to demonstrate that organic agroforestry is also financially viable, and therefore all-round sustainable.

Sustainability: key conclusions

As a diverse organic farm, Wakelyns scores highly in the sustainability achieving top scores in soil management and agricultural systems diversity. Its lowest score, the NPK balance; reflects that fact that the long term fertility building legume leys in a stockless low output system fix more nitrogen than is exported in crops. The LER suggests that 34% more land would be needed under monocropping to achieve the same level of production.

Energy benchmarking found that the arable enterprise uses only 61% of arable benchmark, but that domestic energy use is considerably higher than an average farmhouse benchmark and improvements could be made here. However, 80% of the farm energy use is from renewable sources (photovoltaic panels and woodchip from the agroforestry system and the CO2 balance is -10.2 tonnes CO2 equivalent per year.

Inspiration

Since Martin and Ann first started planting trees, Wakelyns has played host to thousands of visitors from across the world, inspiring and motivating farmers, foresters, growers, students, researchers, bakers, artists, politicians, industry, conservationists…….. Although he must have given literally hundreds of tours of the farm over the years, Martin still retained and conveyed his enthusiasm for sharing the Wakelyns message.

Kimberley Bell of the Small Food Bakery first visited Wakelyns in 2017; this visit changed not only her bread, but the whole philosophical framework around the bakery:

"As bakers, we went to Martin looking for a sustainable wheat, having read a snippet about agroforestry online and thinking that growing the alley cropping system could be the answer. We got so much more than we bargained for, the outputs from Wakelyns were certainly as diverse and productive as the agricultural system being proposed! The YQ, a heterogeneous 'Population' he created & grew amongst trees at Wakelyns defied the status quo on every level."

Stephen Briggs, pioneering organic farmer and advisor, took inspiration from Wakelyns when designing and planting 4500 apple trees as the UK's largest commercial silvoarable system on his farm in the Cambridgeshire fens:

"Martin was a pivotal sounding board with whom to discuss my ideas of developing commercial agroforestry at Whitehall Farm. Sharing ideas and experiences helped shape our direction. Martin's quiet wisdom encouraged us all to look more deeply at Nature and try and take lessons to shape our farming systems – his inspiration will live on long through many".

Shropshire organic farmer, Mark Lea, has been growing the ORC Wakelyns wheat population for the last few years, because of its increased resilience to pest, disease and climatic risks gained from having so much genetic diversity in the mix:

"I feel so privileged to have known Martin and been able to integrate his work into our farming system. With YQ he completely changed the direction of wheat growing here and our avenues

of hazel for coppicing and walnuts will be here long after we are. His influence and his wisdom changed me and this farm for the better!"

Maria Finckh, professor of organic farming at the University of Kassel, based at Witzenhausen, has been part of the Wakelyns story from the start:

"Some very special times were the planting of trees at Wakelyns in 1994 and 1995 and the beginnings of the work with the CCPs. Martin's vision was to enhance diversity among crops and within crops. This has inspired scientists across Europe and the wheat composite cross populations (CCPs) are now in the F18, growing from Hungary to the UK".

Looking forward

As the agroforestry systems at Wakelyns age, the interactions between the trees and crops are changing. In the SRC systems, the regular coppicing of the trees means that aboveground competition for light is controlled and it is likely that arable cropping can continue in the alleys for years to come, potentially until the trees need replacing. In contrast, the timber trees have grown to heights of up to 13m and viewed from above, the system is now starting to resemble a woodland (Figure 58). The shading impacts on crop yields are likely to mean that commercial arable cropping will be eventually unviable; however, over recent years, Martin introduced pollarding to manage the tree canopies and provide more light into the alleys. An alternative approach would be to selectively thin or harvest the trees to reduce tree densities and open up the canopy or to convert the alleys to pasture and introduce grazing animals to the system. Natural tree regeneration has been occurring between the planted trees and when you look across the tree rows, you can now see a wonderfully diverse, mixed-age, low-density deciduous woodland.

Figure 58. Aerial view of the mixed timber system (credit Jeremy Gugenheim)

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Appendix 1

Tree status, circumference and height. Tree number within each alley runs from north to south.

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Oak	Standard	B	1	E	0.59	0.96	1.19	1.9	7.75	10.25	13.35	
Oak	Dead	B	1	W				1.5				
Hornbeam	Pollarded 17/18	B	2	E	0.46	0.61	0.67	1.8	8.25	9.75	3.57	1.5
Hornbeam	Standard	B	2	W	0.58	0.76	0.9	2	8.75	10.75	13.14	
Cherry	Standard	B	3	E	0.55	0.64	0.70	2.5	10	11.5	12.02	
Cherry	Standard	B	3	W	0.84	0.98	1.1	2.6	10.75	12	13.82	
Sycamore	Pollarded 17/18	B	4	E	0.7	0.87	0.91	2.8	11.25	9.25	5.36	3.75
Sycamore	Standard	B	4	W	0.67	0.87	1.04	2.8	10.25	14.5	15.09	
Lime	Pollarded 13/14	B	5	E	0.53	0.68	0.80	1.7	7.5	6.5	9.91	3
Lime	Standard	B	5	W	0.5	0.71	0.875	1.7	7.5	8	12.06	
Ash	Standard	B	6	E	0.55	0.74	0.79	1.8	12.25	13	14.84	
Ash	Standard	B	6	W	0.62	0.78	0.885	2.4	12	14	12.31	
Italian Alder	Dead	B	7	E				1.4				
Italian Alder	Dead	B	7	W				1.9				
Cherry	Standard	C	1	E	0.67	0.83	0.96	2.3	8	10.5	12.52	
Cherry	Standard	C	1	W	0.72	0.82	0.89	2.2	8.25	10.5	12.22	
Hornbeam	Standard	C	2	E	0.52	0.73	0.85	2	8.5	12.5	13.50	
Hornbeam	Coppiced 13/14	C	2	W	0.05		0	1.7	2	0	0.94	
Ash	Standard	C	3	E	0.57	0.75	0.83	2.5	10.5	12.5	7.24	
Ash	Standard	C	3	W	0.58	0.76	0.842	2.6	10.5	12.5	13.23	
Italian Alder	Pollarded 13/14	C	4	E	0.86	0.94	1.00	2.4	14.5	4	2.90	2
Italian Alder	Standard	C	4	W	0.75	0.94	1.115	2.6	11.5	13	15.76	
Oak	Standard	C	5	E	0.48	0.8	1.02	1.4	7.75	10.5	12.21	
Oak	Coppiced 2016	C	5	W	0.05			1.4	2	0	0.91	
Sycamore	Pollarded 2016	C	6	E	0.47	0.74	0.75	1.9	8	3.5	9.02	3.5

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Sycamore	Standard	C	6	W	0.67	0.85	1.04	2.9	9.25	11.5	14.53	
Lime	Coppiced 2016	C	7	E	multi		0.00	1.2	0.75		3.56	
Lime	Pollarded 17/18	C	7	W	0.69	1.05	1.1	2	7.5	10.5	6.36	2.8
Ash	Standard	C	8	E	0.65	0.94	1.03	2	10.25	13.5	13.76	
Ash	Pollarded 13/14	C	8	W	0.5	0.58	0.635	1.8	10.75	6.5	9.51	3.5
Lime	Pollarded 2016	C	9	E	0.65	0.9	0.92	1.8	8	3.5	5.99	3.5
Lime	Coppiced 13/14	C	9	W	multi			0.8	1	3.5	6.25	
Italian Alder	Standard	C	10	E	0.79	1.02	1.18	2.4	15	17.5	15.68	
Italian Alder	Pollarded 13/14	C	10	W	multi	0	0.775	2.3	3	1.75	6.39	1
Cherry	Standard	C	11	E	0.58	0.7	0.73	2.4	10.75	12	13.17	
Cherry	Standard	C	11	W	0.64	0.75	0.85	2.4	9.75	11.5	13.75	
Oak	Standard	D	1	E	0.38	0.65	0.90	1.2	5.25	9.5	12.10	
Oak	Standard	D	1	W	0.47	0.73	0.923	1.5	7.25	10	12.69	
Sycamore	Pollarded 2016	D	2	E	0.42	0.57	0.60	1.8	7.25	2.75	5.21	2.75
Sycamore	Standard	D	2	W	0.5	0.71	0.785	2.3	7.25	9	11.15	
Hornbeam	Standard	D	3	E	0.44	0.61	0.77	1.7	6.5	9	10.36	
Hornbeam	Pollarded 2016	D	3	W	0.5	0.71	0.695	1.7	7.25	0	5.27	2.25
Italian Alder	Pollarded 2016	D	4	E	0.79	0.97	0.99	2.5	14.5	4	7.70	4
Italian Alder	Pollarded 17/18	D	4	W	0.86	1.06	1.17	2.4	12.75	13.5	2.05	1.75
Oak	Standard	D	5	E	0.55	0.83	1.05	1.7	5.5	10	11.02	
Oak	Pollarded 13/14	D	5	W	0.52	0.62	0.635	1.8	5.75	3	4.29	2
Cherry	Standard	D	6	E	0.65	0.73	0.78	2.1	8.25	9.5	9.95	
Cherry	Standard	D	6	W	0.56	0.66	0.742	2.2	8	10.5	9.69	
Sycamore	Pollarded 13/14	D	7	E	0.4	0.46	0.51	1.7	7	4	6.33	2.75
Sycamore	Pollarded 2016	D	7	W	0.35	0.53	0	1.7	7	0.87	4.75	0.87
Hornbeam	Standard	D	8	E	0.44	0.55	0.67	1.5	7.75	10	10.63	
Hornbeam	Pollarded 17/18	D	8	W	0.46	0.7	0.68	1.7	8	12	5.92	3.5
Ash	Standard	D	9	E	0.42	0.68	0.79	1.7	8.75	13	13.48	
Ash	Standard	D	9	W	0.64	0.88	0.922	2.2	8.75	10	13.83	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Lime	Coppiced 2016	D	10	E	multi			1.6	1.5	0	5.22	
Lime	Pollarded 2016	D	10	W	0.42	0.62	0.685	1.9	6.5	2.5	6.21	2.5
Sycamore	Dead	D	11	E	0.03			1.9	1.4			
Sycamore	Standard	D	11	W	0.2	0.28	0.33	2	4.25	4.5	7.27	
Cherry	Dead	D	12	E	0.23			2.4	3.15			
Cherry	Standard	D	12	W	0.6	0.78	0.93	2.3	7.75	9.5	10.40	
Ash	Standard	E	1	E	0.43	0.65	0.76	2	8.25	10.5	11.77	
Ash	Standard	E	1	W	0.57	0.8	0.955	2.3	9	10	14.66	
Lime	Standard	E	2	E	0.53	0.89	1.09	1.9	7	9	11.73	
Lime	Pollarded 2016	E	2	W	0.5	0.82	0.78	1.8	3.75	2	5.16	2
Hornbeam	Pollarded 13/14	E	3	E	0.46	0.59	0.64	1.6	8	2.5	5.67	1.75
Hornbeam	Standard	E	3	W	0.55	0.84	1.02	2.4	9	10.5	12.04	
Italian Alder	Pollarded 2016	E	4	E	0.76	1.04	1.05	2.1	13.75	4	5.42	4
Italian Alder	Standard	E	4	W	0.83	1.07	1.238	2.7	14.25	13.5	16.54	
Oak	Coppiced 13/14	E	5	E	0.04			1.4	1.75	5.5	1.524	
Oak	Standard	E	5	W	0.51	0.8	0.97	1.4	6.5	9.75	10.63	
Cherry	Standard	E	6	E	0.47	0.66	0.81	1.9	8.75	10	12.23	
Cherry	Dead	E	6	W			0	2.3				
No Tree	No trees	E	7	E								
No Tree	No trees	E	7	W								
Lime	Pollarded 13/14	E	8	E	0.55	0.76	0.95	1.5	6.25	4	6.94	2.4
Lime	Pollarded 2016	E	8	W	0.44	0.99	1.113	1.6	3.25	2.1	6.34	2.1
Italian Alder	Pollarded 13/14	E	9	E	0.82	0.97	1.10	2.2	11.5	5	2.75	2.2
Italian Alder	Pollarded 17/18	E	9	W	0.62	0.82	0.91	2.6	12.25	11	3.31	1.75
Oak	Standard	E	10	E	0.06		0.15	0.9	1.5		3.87	
Oak	Standard	E	10	W	0.37	0.65	0.855	1.5	6.5	8.5	10.90	
Sycamore	Pollarded 2016	E	11	E	0.51	0.74	0.76	2.4	8.5	3	8.76	3
Sycamore	Standard	E	11	W	0.49	0.67	0.79	2.7	8.75	11	12.13	
Hornbeam	Standard	E	12	E	0.54	0.75	0.86	2	7.25	9.5	12.67	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Hornbeam	Pollarded 13/14	E	12	W	0.51	0.68	0.73	1.7	9.75	4	6.68	2.5
Ash	Standard	E	13	E	0.51	0.86	1.01	1.3	11.25	11.5	14.40	
Ash	Pollarded 13/14	E	13	W	0.72	0.96	1	2	12.25	6.75	6.67	3.5
Sycamore	Standard	F	1	E	0.51	0.76	0.81	2.5	8.5	11	11.49	
Sycamore	Standard	F	1	W	0.6	0.87	0.99	2.9	10.25	11.5	12.29	
Ash	Standard	F	2	E	0.59	0.83	0.92	1.8	8.5	12	13.42	
Ash	Standard	F	2	W	0.45	0.65	0.765	1.9	9.25	12.5	12.78	
Cherry	Standard	F	3	E	0.4	0.51	0.59	2.2	6.75	8.5	9.36	
Cherry	Standard	F	3	W	0.56	0.77	0.93	2.1	7.5	9	11.07	
Hornbeam	Pollarded 13/14	F	4	E	0.47	0.6	0.66	1.8	7.75	4	3.14	2
Hornbeam	Standard	F	4	W	0.46	0.68	0.815	1.8	7.5	10.5	11.91	
Lime	Coppiced 2016	F	5	E	multiple			1.9	4.25	0	4.32	
Lime	Pollarded 13/14	F	5	W	0.52	0.77	1	1.5	6	3.5	3.83	2
Italian Alder	Standard	F	6	E	0.73	0.95	1.13	1.9	10.25	11.5	14.78	
Italian Alder	Pollarded 17/18	F	6	W	0.79	0.97	1.03	2.2	12.25	12.5	4.48	1.9
Oak	Pollarded 2016	F	7	E	0.4	0.7	0.74	1.6	6.75	3	6.56	3
Oak	Pollarded 13/14	F	7	W	0.3	0.45	0.57	1.5	5.5	3.5	2.74	2
Hornbeam	Pollarded 13/14	F	8	E	0.48	0.64	0.70	1.6	6.75	4	3.47	2
Hornbeam	Standard	F	8	W	0.41	0.66	0.82	1.6	6.75	8.5		
Oak	Standard	F	9	E	0.37	0.74	0.90	1.3	5.5	7.9	10.02	
Oak	Dead	F	9	W				1.4				
Italian Alder	Standard	F	10	E	0.58	0.8	0.96	1	11	12.5	11.33	
Italian Alder	Pollarded 13/14	F	10	W	0.72	0.85	0.865	1.8	10.75	7	6.48	3.5
Cherry	Pollarded 13/14	F	11	E	0.45	0.52	0.60	2.2	3	6.5	8.45	1.6
Cherry	Standard	F	11	W	0.58	0.82	0.905	2.2	7.75	9.5	10.11	
Lime	Pollarded 2016	F	12	E	0.64	1.01	1.11	1.8	6.75	2.5	6.45	2.5
Lime	Coppiced 2016	F	12	W	multi stemmed			1.7	0.5		4.15	
Sycamore	Pollarded 13/14	F	13	E	0.77	0.95	1.01	2.8	11.25	7.5	5.51	3.25

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Sycamore	Pollarded 17/18	F	13	W	0.43	0.7	0.755	2.4	7.75	9.5	4.03	1.5
Ash	Standard	F	14	E	0.66	0.95	1.03	1.7	10	13	12.56	
Ash	Standard	F	14	W	0.6	0.78	0.85	2.2	10.75	13	12.38	
Hornbeam	Pollarded 17/18	F	15	E	0.58	0.76	0.79	1.8	8	10	3	2.75
Hornbeam	Pollarded 13/14	F	15	W	0.41	0.53	0.61	1.3	4.25	7.5		2.5
Cherry	Standard	G	1	E	0.51	0.68	0.79	2.1	8	9	9.62	
Cherry	Standard	G	1	W	0.5	0.66	0.83	1.9	7.5	9	10.08	
Lime	Standard	G	2	E	0.49	0.74	0.90	2	6.5	8.5	10.68	
Lime	Coppiced 2016	G	2	W	multi			1.8	1.5	0	3.11	
Italian Alder	Standard	G	3	E	0.67	0.9	1.01	2.1	11.5	12.5	14.81	
Italian Alder	Standard	G	3	W	0.5	0.65	0.725	2.4	11.25	12	13.60	
Sycamore	Pollarded 2016	G	4	E	0.29	0.37	0.52	2	6	2.5	8.15	2.5
Sycamore	Standard	G	4	W	0.29	0.49	0.748	1.9	6.5	8	10.00	
Ash	Pollarded 13/14	G	5	E	0.36	0.5	0.56	1.7	6.75	7	9.72	1.75
Ash	Standard	G	5	W	0.35	0.61	0.71	2	7.75	10.5	11.93	
Oak	Replanted	G	6	E	0.08	0.25	0.38	1.7	2.25	4.5	10.56	
Oak	Standard	G	6	W	0.36	0.6	0.77	1.5	5.5	7	9.39	
Lime	Pollarded 13/14	G	7	E	0.5	0.64	0.82	1.6	5.75	4.75	3.54	2.5
Lime	Standard	G	7	W	0.3	0.52	0.66	0.8	4.5	6.5	8.91	
Hornbeam	Pollarded 2016	G	8	E	0.33	0.59	0.58	1.5	6.5	2.5	2.03	2.5
Hornbeam	Pollarded 13/14	G	8	W	0.41	0.52	0.62	1.8	6.75	4.5	3.35	2.5
Sycamore	Standard	G	9	E	0.4	0.68	0.79	1.9	7	10	11.51	
Sycamore	Pollarded 17/18	G	9	W	0.35	0.51	0.53	1.8	6.5	9.5	5.92	1.75
Oak	Standard	G	10	E	0.35	0.65	0.87	1.3	5.5	7.5	11.18	
Oak	Replanted	G	10	W	0.08		0.14	1.3	2.25		1.95	
Cherry	Standard	G	11	E	0.71	0.88	0.96	2.3	9.25	10	12.95	
Cherry	Standard	G	11	W	0.55	0.65	0.705	2.2	8.25	9.5	11.75	
Italian Alder	Pollarded 17/18	G	12	E	0.38	0.62	0.63	0.7	9.75	13.5	5.67	1.7
Italian Alder	Standard	G	12	W	0.8	0.96	1.08	1.8	12.25	14.5	15.28	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Ash	Standard	G	13	E	0.49	0.65	0.67	2.2	8.75	10.5	11.21	
Ash	Dead	G	13	W				2.2				
Italian Alder	Pollarded 13/14	G	14	E	0.66	0.8	0.86	2.2	12.25	8.5	2.53	4.5
Italian Alder	Pollarded 13/14	G	14	W	0.9	1	1.142	2.1	4	3.5	3.02	1.5
Ash	Standard	G	15	E	0.69	0.98	1.09	2.6	11.75	16	17.57	
Ash	Standard	G	15	W	0.57	0.85	0.98	2	10.25	13.5	18.21	
Lime	Pollarded 17/18	G	16	E	9.25	1.06	1.15	2.2	0.68	14.5	6.27	3
Lime	Coppiced 13/14	G	16	W				1.8		4	1.98	
Cherry	Dead	H	1	E	0.48			2.6	6.75			
Cherry	Standard	H	1	W	0.59	0.69	0.79	2.2	7.75	8.5	9.05	
Sycamore	Standard	H	2	E	0.56	0.75	0.89	2.6	8.5	10.5	11.70	
Sycamore	Standard	H	2	W	0.44	0.6	0.68	1.9	7.75	10	11.19	
Oak	Dead	H	3	E				1.4				
Oak	Standard	H	3	W	0.32	0.59	0.81	1.2	4.75	7.5	8.79	
Hornbeam	Pollarded 17/18	H	4	E	0.53	0.8	0.87	1.8	7.25	10.5	6.15	2.7
Italian Alder	Standard	H	4	W	0.1	0.32	0.45	1.6	4	7	9.54	
Italian Alder	Pollarded 13/14	H	5	E	0.78	1.05	1.03	2.2	10.75	2	2.90	2
Italian Alder	Coppiced 13/14	H	5	W	regen			2.4	4	5	1.78	
Ash	Dead	H	6	E	0.4	0.6		2	7.75	9.5		
Ash	Pollarded 13/14	H	6	W	0.37	0.49	0.75	1.6	7.75	5	3.00	3
Lime	Standard	H	7	E	0.33	0.49	0.64	1.9	4.25	6.5	8.65	
Lime	Coppiced 2016	H	7	W	regen			1.6	1.5	0	3.89	
Cherry	Standard	H	8	E	0.29	0.47	0.56	2.3	4.5	6.5	7.40	
Oak	Standard	H	8	W	0.06	0.15	0	2.3	2.5	6	5.69	
Hornbeam	Pollarded 2016	H	9	E	0.42	0.61	0.67	1.7	6.25	3	6.67	3
Hornbeam	Pollarded 17/18	H	9	W	0.4	0.64	0.69	1.6	6.75	10	6.59	2.7
Oak	Standard	H	10	E	0.44	0.7	0.90	1.8	6	9	11.22	
Oak	Standard	H	10	W	0.04	0.15	0.24	1.5	1.5	3.5	5.82	
Sycamore	Pollarded 2016	H	11	E	0.37	0.57	0.59	1.9	5.75	2.5	8.71	2.5

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Sycamore	Standard	H	11	W	0.52	0.75	0.85	2	8.5	11	12.25	
Oak	Standard	H	12	E	0.4	0.7	0.85	1.3	6.25	9	11.08	
Oak	Standard	H	12	W	0.53	0.78	0.93	1.7	6.75	10	12.17	
Cherry	Standard	H	13	E	0.48	0.7	0.78	1.6	7.25	9.5	11.02	
Cherry	Standard	H	13	W	0.5	0.7	0.75	2	7.25	9.5	10.64	
Hornbeam	Standard	H	14	E	0.44	0.64	0.72	1.4	7	9.5	11.02	
Hornbeam	Pollarded 13/14	H	14	W	0.66	0.85	0.83	1.6	8.25	5	3.94	3.5
Lime	Pollarded 2016	H	15	E	0.68	0.82	1.04	1.9	8.25	3	7.37	3
Lime	Pollarded 13/14	H	15	W	0.56	0.75	0.84	1.6	6.5	4	7.09	3
Italian Alder	Standard	I	1	E	0.59	0.74	0.82	2.3	10.25	11.5	12.69	
Italian Alder	Standard	I	1	W	0.58	0.72	0.795	2.1	10.75	12.5	12.65	
Sycamore	Standard	I	2	E	0.49	0.65	0.75	1.5	8.25	9.5	11.20	
Sycamore	Standard	I	2	W	0.43	0.59	0.655	2.3	7.75	9.5	9.48	
Ash	Standard	I	3	E	0.42	0.7	0.85	1.8	6.75	9.5	10.46	
Ash	Dead	I	3	W								
Sycamore	Standard	I	4	E	0.4	0.58	0.64	2	6.25	7.5	8.39	
Sycamore	Dead	I	4	W	0.31		0	2	5.5			
Lime	Coppiced 2016	I	5	E	multi			1.7	1		3.83	
Lime	Pollarded 13/14	I	5	W	0.38	0.55	0.64	1.6	5.25	3.25	6.23	2
Oak	Standard	I	6	E		0.3	0.38	na		4.75	6.33	
Oak	Pollarded 17/18	I	6	W	0.33	0.64	0.71	1	4.75	6.5	4.49	3.5
Cherry	Standard	I	7	E	0.24	0.45	0.45	2.1	4.5	6	8.21	
Cherry	Standard	I	7	W	0.24	0.45	0.41	2.2	4.75	6	8.23	
Hornbeam	Standard	I	8	E	0.32	0.56	0.70	1.4	7.5	9.5	10.77	
Hornbeam	Pollarded 13/14	I	8	W	0.23	0.35	0.41	1.5	5.5	4.5	6.16	2.3
Italian Alder	Pollarded 17/18	I	9	E	0.74	0.96	1.03	2.2	13.25	13.5	5.07	1.8
Italian Alder	Pollarded 13/14	I	9	W	0.7	0.82	0.925	2.3	12.25	4.5	3.80	2
Ash	Standard	I	10	E	0.58	0.77	0.88	1.9	10	10.5	13.66	
Ash	Standard	I	10	W	0.59	0.86	0.97	2.4	10.75	12	13.91	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Hornbeam	Standard	I	11	E	0.51	0.72	0.84	1.9	7.75	10.5	11.23	
Hornbeam	Pollarded 2016	I	11	W	0.2	0.37	0.37	1	4.25	2.2	4.19	2.2
Ash	Standard	I	12	E	0.47	0.73	0.86	1.9	10	10.5	11.37	
Ash	Coppiced 17/18	I	12	W	0.43	0.58		2	8	10.5	3.58	
Sycamore	Pollarded 13/14	I	13	E	0.48	0.6	0.67	2.2	7.75	5.5	3.28	3
Sycamore	Pollarded 17/18	I	13	W	0.54	0.77	0.84	2.1	8.5	11.5	5.50	2
Oak	Standard	I	14	E	0.45	0.74	0.94	1.7	7.25	9.5	11.95	
Oak	Coppiced 17/18	I	14	W	0.05	0.15		na	1.5	4	5.75	
Italian Alder	Dead	I	15	E				2.5				
Italian Alder	Pollarded 17/18	I	15	W	0.76	0.98	1.025	1.2	12.25	12	4.54	1.75
Cherry	Standard	I	16	E	0.58	0.77	0.87	2.5	8.25	10.5	12.16	
Cherry	Standard	I	16	W	0.62	0.77	0.895	2.5	8.5	11	11.63	
Lime	Coppiced 13/14	I	17	E	multi			1.6	0.75	4.5	1.52	
Lime	Pollarded 17/18	I	17	W	0.56	0.85	0.95	1.9	7.5	10	5.87	3
Sycamore	Pollarded 17/18	I	18	E	0.62	0.89	0.89	2.3	10.25	12	10.34	1.8
Sycamore	Pollarded 13/14	I	18	W	0.58	0.68	0.77	2.7	9.75	7.5	5.36	3
Cherry	Standard	I	19	E	0.51	0.7	0.79	2.5	8.75	9.5	14.83	
Cherry	Standard	I	19	W	0.5	0.68	0.785	2.2	8.5	9.5	13.39	
Oak	Standard	J	1	E	0.33	0.59	0.77	1.7	5	8	9.91	
Oak	Standard	J	1	W	0.36	0.55	0.665	1.4	5.25	8	8.63	
Hornbeam	Standard	J	2	E	0.24	0.4	0.51	1.3	5.75	8.5	9.09	
Hornbeam	Pollarded 13/14	J	2	W	0.37	0.5	0.59	1.9	5.75	4.5	7.25	2.2
Lime	Pollarded 2016	J	3	E	0.26	0.35	0.50	1.4	3.25	1.6	4.44	1.6
Lime	Pollarded 2016	J	3	W	0.41	0.7	0.78	1.9	6	3	5.58	3
Ash	Standard	J	4	E	0.42	0.71	0.92	1.8	7.75	11	11.23	
Ash	Dead	J	4	W	0.34	0.47		1.5	6.75	6		2.5
Italian Alder	Pollarded 17/18	J	5	E	0.72	0.94	1.01	1.9	11	11.5	5.95	1.6
Italian Alder	Standard	J	5	W	0.68	0.94	1.1	1	9.75	11	10.78	
Cherry	Dead	J	6	E	0.22			2.2	3.255			

ORGANIC RESEARCH CENTRE ELM FARM

SPECIES	STATUS	TREE ROW	TREE NO.	ORIENTATION IN ROW	TREE CIRCUMFERENCE AT 1.3m (m) Aug-09	May-16	Oct-19	TREE HEIGHT (m) Sep-96	Aug-09	May-16	Oct-19	POLLARD HEIGHT (m)
Cherry	Standard	J	6	W	0.4	0.62	0.72	2.2	6.25	8.5	8.93	
Lime	Coppiced 2016	J	7	E	multi			2.1	1.5	0	4.05	
Lime	Pollarded 2016	J	7	W	0.54	0.85	0.91	1.8	6.25	4	6.05	4
Ash	Standard	J	8	E	0.48	0.74	0.83	1.7	9.25	12	13.22	
Ash	Pollarded 13/14	J	8	W	0.45	0.58	0.53	2	7.5	4	5.10	3
Sycamore	Pollarded 2016	J	9	E	0.42	0.59	0.63	2	7.25	1.7	7.08	1.7
Sycamore	Standard	J	9	W	0.4	0.55	0.655	2.2	7.25	9	9.58	
Italian Alder	Pollarded 13/14	J	10	E	0.64	0.8	0.84	2.2	11	4.5	9.16	2.5
Italian Alder	Standard	J	10	W	0.71	0.9	1.03	2.5	11.25	13.5	13.93	
Hornbeam	Pollarded 13/14	J	11	E	0.36	0.52	0.62	1.6	6	5.5	3.46	3
Hornbeam	Standard	J	11	W	0.38	0.58	0.73	1.6	6.25	8.5	8.95	
Oak	Coppiced 17/18	J	12	E	0.09	0.32		1.5	2	4.5	2.49	
Oak	Standard	J	12	W	0.51	0.79	0.96	1.8	7	10.5	13.01	
Oak	Pollarded 17/18	J	13	E	0.24	0.54	0.64	1.5	4.5	8	3.19	2.8
Oak	Standard	J	13	W	0.33	0.56	0.74	1.6	5.25	8	9.48	
Sycamore	Pollarded 13/14	J	14	E	0.47	0.61	0.73	2.1	7.5	5.75	4.85	2.5
Sycamore	Pollarded 17/18	J	14	W	0.46	0.64	0.74	2.4	8.25	9	4.47	1.8
Lime	Coppiced 2016	J	15	E	multi			1.8	1.25	0	1.78	
Lime	Pollarded 13/14	J	15	W	0.6	0.82	0.87	2	7.25	4	3.63	3
Cherry	Standard	J	16	E	0.67	0.9	1.06	2.4	8.25	10.25	11.85	
Cherry	Standard	J	16	W	0.61	0.23	0.83	2.3	8.5	9	11.93	
Italian Alder	Dead	J	17	E	multi			2	2.5			1
Italian Alder	Pollarded 17/18	J	17	W	0.8	1.06	1.12	2.4	12	14.5	12.44	1.75
Hornbeam	Pollarded 13/14	J	18	E	0.48	0.61	0.65	1.5	6.75	4.5	3.32	3
Hornbeam	Standard	J	18	W	0.5	0.77	0.89	1.6	6.75	10	9.90	
Ash	Standard	K	1	E	0.27	0.47	0.55	1.7	7	9.5	11.36	
Ash	Standard	K	1	W	0.5	0.77	0.885	1.6	7.75	10.5	12.26	
Ash	Standard	K	2	E	0.48	0.78	0.94	1.6	9	7	11.51	
Ash	Standard	K	2	W	0.34	0.49	0.552	1.6	7.25	9.5	9.62	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Hornbeam	Coppiced 2016	K	3	E	multi	0.12		1.5	3	3.5	3.65	
Hornbeam	Pollarded 2016	K	3	W	0.4	0.58	0.597	1.6	6.25	3	5.67	3
No Tree	No tree	K	4	E								
No Tree	No tree	K	4	W								
Oak	Standard	K	5	E	0.35	0.65	0.85	1.5	5.75	7.5	9.11	
Oak	Standard	K	5	W	0.25	0.54	0.68	1.2	4	7.5	9.36	
Lime	Coppiced 13/14	K	6	E	multi			1.6	0.5	3.5	5.63	
Lime	Pollarded 2016	K	6	W	0.47	0.7	0.77	1.7	5.75	3	5.94	3
Hornbeam	Standard	K	7	E		0.17	0.29	2		5	6.07	
Cherry	Standard	K	7	W	0.45	0.6	0.72	2.3	6.25	7	8.80	
Sycamore	Standard	K	8	E	0.42	0.61	0.67	2	7.5	9	9.81	
Sycamore	Pollarded 2016	K	8	W	0.35	0.53	0.63	2.3	7	2.2	6.64	2.2
Italian Alder	Standard	K	9	E	0.75	0.97	1.08	2.5	13.25	13.5	11.51	
Italian Alder	Dead	K	9	W		0.17	0	2.4		3.5		
Sycamore	Standard	K	10	E	0.3	0.49	0.59	1.8	6.5	8	8.14	
Sycamore	Pollarded 13/14	K	10	W	0.35	0.49	0.53	2.1	7	5.5	4.14	3
Lime	Standard	K	11	E		0.15		1.6		4	5.27	
Lime	Pollarded 2016	K	11	W	0.54	0.9	1.04	1.5	5.75	3	6.29	3
Hornbeam	Pollarded 13/14	K	12	E	0.29	0.44	0.49	1.6	5.75	4.5	3.20	3
Hornbeam	Standard	K	12	W	0.43	0.66	0.815	1.5	6.25	8	9.07	
Ash	Standard	K	13	E	0.52	0.78	0.87	1.9	9.75	11	13.05	
Ash	Standard	K	13	W	0.59	0.84	0.91	2.7	10	13	11.87	
Oak	Pollarded 13/14	K	14	E	0.35	0.47	0.52	1.4	4.5	4.75	7.21	2.2
Oak	Standard	K	14	W	multi	0.35	0.545	0.9	2.5	6.5	7.40	
Cherry	Standard	K	15	E	0.59	0.75	0.85	2.5	10.25	11.5	12.29	
Cherry	Standard	K	15	W	0.65	0.8	0.86	2.4	9.25	10.5	10.36	
Italian Alder	Standard	K	16	E	0.82	1.04		2.5	15.25	15.5		
Italian Alder	Pollarded 2016	K	16	W	0.76	0.95	0.99	2.2	15	2	7.00	2
Oak	Standard	K	17	E	0.57	1.03	1.09	1.6	9	13.5	13.62	

SPECIES	STATUS	TREE ROW	TREE NO.	ORIENTATION IN ROW	TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				POLLARD HEIGHT (m)
					Aug-09	May-16	Oct-19	Sep-96	Aug-09	May-16	Oct-19	
Oak	Standard	K	17	W	0.7	0.93	1.21	1.7	9.75	13.5	14.27	
Ash	Pollarded 13/14	K	18	E	0.62	0.79	0.90	2.8	11.25	7	3.33	3
Ash	Standard	K	18	W	0.5	0.78	0.89	2	11	13.5	13.70	
Sycamore	Standard	L	1	E	0.42	0.59	0.72	1.9	7	8.5	11.67	
Sycamore	Standard	L	1	W	0.47	0.72	0.875	1.9	7	8.5	11.88	
Hornbeam	Standard	L	2	E	0.4	0.62	0.77	1.6	6	8.5	9.13	
Hornbeam	Pollarded 17/18	L	2	W	0.28	0.45	0.52	1.7	5.5	3.25	5.95	2.2
Cherry	Pollarded 13/14	L	3	E	0.33	0.43	0.61	1.8	4.75	4.25	7.02	1.7
Cherry	Pollarded 13/14	L	3	W	multi	0.27	0.41	2.1	2	4.5	6.63	2.1
Italian Alder	Pollarded 13/14	L	4	E	0.73			1.7	6.75	1	4.73	1
Italian Alder	Pollarded 17/18	L	4	W	0.57	0.75	0.94	1.3	7	2.25	4.73	2.25
Lime	Coppiced 2016	L	5	E				1.7		3.5	5.94	
Lime	Pollarded 13/14	L	5	W	0.37	0.64	0.7	1.3	6.5	2	6.26	2
Ash	Standard	L	6	E	0.44	0.67	0.68	1.9	7.75	10.5	11.92	
Ash	Pollarded 2016	L	6	W	0.38	0.62	0.69	1.8	6.75	9.5	11.02	2.2
Lime	Standard	L	7	E	0.2	0.36	0.50	1.4	4.5	6.75	7.56	
Lime	Pollarded 17/18	L	7	W	0.29	0.47	0.53	1.9	5.5	7.25	4.37	2.4
Hornbeam	Replanted	L	8	E		0.14	0.22	0.8		4	3.59	1.9
Oak	Standard	L	8	W	0.19	0.41	0.59	0.9	3	5.5	7.05	
Hornbeam	Pollarded 13/14	L	9	E	0.43	0.56	0.62	1.6	6.75	3.5	3.30	3
Hornbeam	Standard	L	9	W	0.33	0.52	0.69	1	6.25	8	8.66	
Sycamore	Standard	L	10	E	0.24	0.39	0.47	2.2	5.75	7	8.65	
Sycamore	Pollarded 17/18	L	10	W	0.34	0.51	0.56	2.1	6	8.5	6.79	2.2
Italian Alder	Pollarded 2016	L	11	E	0.66	0.79	0.78	1.8	9.5	2	5.18	2
Italian Alder	Standard	L	11	W	0.61	0.85	1.02	2.3	9.75	12.5	12.47	
Cherry	Dead	L	12	E				2.1				
Cherry	Standard	L	12	W	0.47	0.63	0.78	2	5.5	7.5	8.95	
Lime	Coppiced 2016	L	13	E		0	0.00	2		0	3.63	
Lime	Pollarded 17/18	L	13	W	0.55	0.76	0.78	2	6.5	9	4.44	2

SPECIES	STATUS	TREE ROW	TREE NO.	ORIENTATION IN ROW	TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
					Aug-09	May-16	Oct-19	Sep-96	Aug-09	May-16	Oct-19	POLLARD HEIGHT (m)
Lime	Standard	L	14	E		0.15	0.00	2.1		4.5		
Cherry	Standard	L	14	W	0.54	0.72	0.835	2.2	7	8	8.30	
Italian Alder	Standard	L	15	E	0.82	1.1	1.22	2.4	10.75	12.5	12.88	
Italian Alder	Dead	L	15	W				2				
Hornbeam	Pollarded 2016	L	16	E	0.4	0.62	0.70	1.4	6	2.5	6.17	2.5
Hornbeam	Pollarded 13/14	L	16	W	0.46	0.65	0.754	1.4	6.25	4.5	6.30	3
Sycamore	Pollarded 2016	L	17	E	0.5	0.68	0.71	2.2	10.25	1.7	6.91	1.7
Sycamore	Pollarded 13/14	L	17	W	0.63	0.74	0.83	2.6	10	6.5	3.97	2.5
Ash	Standard	L	18	E	0.57	0.78	0.85	2.2	9.75	11.5	11.87	
Ash	Standard	L	18	W	0.62	0.84	0.95	2.2	11.5	13.5	13.29	
Oak	Standard	L	19	E	0.45	0.57	0.65	1.4	6.5	8	9.09	
Oak	Dead	L	19	W				1.4		x		
Oak	Standard	M	1	E	0.46	0.7	0.85	1.6	6.25	9	10.60	
Oak	Standard	M	1	W	0.34	0.41	0.53	1.5	5.25	8	9.26	
Hornbeam	Standard	M	2	E	0.27	0.49	0.66	1.8	5.25	7.5	8.65	
Hornbeam	Standard	M	2	W	0.41	0.64	0.76	1.9	7.25	9.5	11.41	
Lime	Coppiced 17/18	M	3	E	0.22	0.41	0.00	1.4	4	0	4.47	2
Lime	Pollarded 13/14	M	3	W	0.34	0.47	0.61	1.4	4.5	4.5	4.93	2
Cherry	Dead	M	4	E	0.22			1.4	4.5			
Cherry	Standard	M	4	W	0.55	0.72	0.81	2.3	6.25	9.5	9.97	
Apple	Standard	M	5	E	0.12	0.55	0.45	1.8	3.75	3.5	5.50	
Apple	Standard	M	5	W	0.25	0.36	0.622	1.8	4.25	5	5.40	
Ash	Pollarded 13/14	M	6	E	0.35	0.48	0.80	2.2	6.5	8.5	9.20	3
Ash	Pollarded 17/18	M	6	W	0.33	0.64	0.525	2.2	6.25	6	11.10	3.5
Sycamore	Pollarded 17/18	M	7	E	0.25	0.45	0.50	2	5.25	8	6.23	2.5
Sycamore	Pollarded 13/14	M	7	W	0.25	0.37	0.51	1.8	5	4.5	4.35	2.5
Lime	Replanted	M	8	E		0.14	0.24	1.7		3	4.30	
Italian Alder	Standard	M	8	W	0.65	0.83	1	1.7	10.5	11.5	13.55	
Sycamore	Standard	M	9	E	0.16	0.28	0.36	1.7	3	6	6.42	

					TREE CIRCUMFERENCE AT 1.3m (m)			TREE HEIGHT (m)				
SPECIES	**STATUS**	**TREE ROW**	**TREE NO.**	**ORIENTATION IN ROW**	**Aug-09**	**May-16**	**Oct-19**	**Sep-96**	**Aug-09**	**May-16**	**Oct-19**	**POLLARD HEIGHT (m)**
Sycamore	Pollarded 17/18	M	9	W	0.32	0.5	0.346	2	5.75	7.5	5.00	1.5
Apple	Standard	M	10	E	0.15	0.41	0.00	1.5	2.5	5.5	6.26	
Apple	Standard	M	10	W	0.34	0.78	0.817	1.7	4.75	5.5	6.26	
Cherry	Standard	M	11	E	0.34	0.5	0.59	2.2	6	8.5	8.54	
Cherry	Standard	M	11	W	0.38	0.51	0.59	2.3	7	8.5	9.30	
Hornbeam	Pollarded 17/18	M	12	E	0.18	0.38	0.51	1.5	4.75	6.5	4.12	1.8
Hornbeam	Pollarded 13/14	M	12	W	0.3	0.43	0.505	1.5	5.25	5.5	2.91	2.5
Oak	Pollarded 13/14	M	13	E	0.31	0.37	0.41	1.3	4.25	4	5.78	1.8
Oak	Dead	M	13	W	0.27	0.59		0.8	3.75	6.5		
Italian Alder	Dead	M	14	E				2				
Italian Alder	Standard	M	14	W	0.68	0.92	1.07	1.9	11.25	11.5	12.83	
Ash	Standard	M	15	E	0.5	0.79	0.92	2	9.5	12.5	14.80	
Ash	Standard	M	15	W	0.46	0.67	0.786	2	9.75	12.5	13.28	
Lime	Replanted	M	16	E		0	0.00	1.8		4.5	3.58	
Lime	Pollarded 17/18	M	16	W	0.43	0.68	0.74	2.2	6.25	7.5	5.68	2.5
Oak	Standard	M	17	E	0.26	0.45	0.61	1.3	5.5	7	8.57	
Oak	Pollarded 17/18	M	17	W	0.36	0.45	0.46	1.6	5.75	7	4.47	3.5
Ash	Standard	M	18	E	0.52	0.8	0.91	2.2	9.75	12.5	13.97	
Ash	Pollarded 13/14	M	18	W	0.47	0.61	0.64	2.4	3.75	7.5	9.14	3