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Poplar (*Populus* spp) growth and crop yields in a silvoarable experiment at three lowland sites in England

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Abstract

In early 1992, a silvoarable experiment, comprising four poplar (*Populus* spp.) hybrids (at a spacing of 10 m x 6.4 m) and four arable treatments, was established at three contrasting lowland sites in England. By the end of 1998, seven years after planting, the height of the poplar hybrid Beaupré (11.9 m) was greater than those of the hybrids Gibecq, Robusta and Trichobel (8.9-9.8 m). The trees at the most exposed site had the shortest height (9.2 m) and the greatest diameter at breast height (173 mm). Tree growth was also affected by the arable treatments. The height (9.5 m) and diameter (143 mm) of the trees bordered on both sides by a continuous rotation of arable crops were 89% and 79%, respectively, of those bordered on both sides by a regularly cultivated fallow. This result could be explained by competition for water. Across the three sites, in the presence of the trees the yield per unit cropped area, relative to that in the control areas, was an average of 4% less in the first three years and an average of 10% less between years four and six. However the specific responses were dependent on the arable crop. The experiment also included an alternately-cropped arable treatment, where the crop was alternated with a one-year bare fallow. The benefits of a preceding fallow, rather than a cereal crop, for yield were greatest for wheat (*Triticum aestivum* L.) and barley (*Hordeum vulgare* L.) and least for field beans (*Vicia faba* L.), peas (*Pisum sativum* L.) and mustard (*Brassica alba* L.).

Introduction

Two objectives of European and British agricultural policy are the reduction of agricultural surpluses and increased tree planting on farms. However tree planting on farms in lowland Britain has often seemed unattractive because of the time required to produce marketable timber. To some extent, this constraint has been reduced by the introduction of fast-growing hybrid clones of poplar (*Populus* spp) from Belgium that are able to produce a harvestable timber crop in 25 years (Potter et al., 1990; Tabbush, 1995).

A second constraint to the planting of trees is the negative cash flow between planting and harvest. However, because poplars are sometimes planted at low density (156 trees ha^{-1}) and left unthinned throughout the rotation (Beaton, 1987; Tabbush, 1995), one method of maintaining a positive cash flow in the initial years, in the absence of government subsidies, is to grow an arable crop between the trees - a practice known in Europe as silvoarable agroforestry. Such a practice was successfully implemented by Bryant and May (Forestry) Ltd on their estates in East Anglia and Herefordshire, UK during the 1960s and 1970s (Jobling, 1990). Financial analyses have also predicted that agroforestry with the new hybrids of poplar could again be viable on good arable land in the UK (Willis et al., 1993).

However the predicted profitability of a silvoarable practice depends on the actual interaction between tree growth and crop yield. In 1992, a silvoarable experiment with poplar was established at a national network of three lowland sites in England to investigate the effect of the interaction on profitability. This paper describes the experiment and reports some of the measurements of tree growth and crop yield during the first seven years.

Materials and methods

Sites and climate

The sites are in three of the major arable areas in lowland England (Table 1). The wettest and most westerly site is on the Royal Agricultural College Farm at Fosse Hill near Cirencester in Gloucestershire (lat. 51°44’N, long. 2°0’W). The coolest and most northerly site is on the Leeds University Farms near Tadcaster in West Yorkshire (lat. 53°53’N, long. 1°15’W); the warmest and driest site is at Silsoe in Bedfordshire (lat. 52°0’N, long. 0°26’W) in eastern England. The soil textures at the Cirencester, Leeds and Silsoe sites are clay loam over limestone, sandy clay loam over limestone, and clay over clay respectively.

Poplar hybrids

Four poplar hybrids were chosen to represent the major groups of poplars being grown in Britain. Trichobel is an intraspecific hybrid of black cottonwood (*Populus trichocarpa* Torrey & A. Gray ex Hook.), a species originally from western North America. Gibecq is a ‘*euramericana*’ hybrid produced by crossing eastern cottonwood from eastern North America (*Populus deltoides* Bartram ex Marshall) with European native black poplar (*Populus nigra* L.). Beaupré is an ‘*interamericana*’ hybrid, produced by crossing the two cottonwood species from North America. Trichobel, Gibecq and Beaupré were bred at the Poplar Research Centre at Geraardsbergen, Belgium in the 1960s, and imported into the

UK in 1985 (Jobling, 1990). Robusta is a natural '*euramericana*' hybrid originally selected in the 1890s in the north-east of France (Jobling, 1990).

Table 1. The characteristics of the three lowland sites in England.

	Site		
Characteristic[1]	Cirencester	Leeds	Silsoe
Altitude (m)	130	50	60
Annual rainfall (mm)	800	634	629
Mean air temperature (°C)	9.7	9.3	10.0
Daily wind run (km)	n/a	238	150
Slope	'Gentle'	'Gentle'	Flat
Aspect	South-east	West-north-west	None
Topsoil depth (m)	> 0.5	0.5	> 0.5
Soil description	Clay loam over limestone	Sandy clay loam over limestone	Clay over clay

[1] Rainfall, temperature and daily wind run are the means of the annual values from 1992 to 1998.

Experimental design

At each site, the main experiment covers 2.5 ha and comprises three replicate blocks that include each combination of the four poplar hybrids and three of four arable treatments (Fig. 1). The poplar hybrids were planted between March and April 1992 as 1.5-2.0 m unrooted sets to a depth of 0.6 m, at intervals of 6.4 m in a North-South direction in rows 10 m apart, along parallel lengths of 1.5-m-wide black polythene-film mulch. The edges of the plastic were buried under the soil mechanically to leave an exposed strip of plastic 1-m-wide. Along each row, the four hybrids were planted as contiguous groups of five trees, with a guard tree (buffer) at each end of each row.

Each autumn, an 8-m-wide strip was ploughed, in the middle of each 10-m-wide alley, leaving the tree row as an uncultivated 2-m-wide strip, including the polythene mulch. This deep cultivation broke any poplar roots in the top 20 cm of the arable area. Within each block, six alleys were allocated in adjacent pairs to three arable treatments designated as 'continuously-fallow', 'continuously-cropped' and 'alternately-cropped'. Hence every second row of poplars, termed a 'measurement' row (M, Fig. 1), was subjected to one of three arable treatments. The two adjacent alleys comprising the continuously-fallow treatment were regularly cultivated so that the measurement row of poplars between them would have minimal competition from crops or weeds. The continuously-cropped treatment comprised a rotation of two to four years of cereals in two adjacent alleys followed by a break (non-cereal) crop. In the alternately-cropped treatment, the alley on one side of the measurement row of trees was cropped whilst the alley on the opposite side was kept fallow; the cropped and the fallow areas were reversed each year.

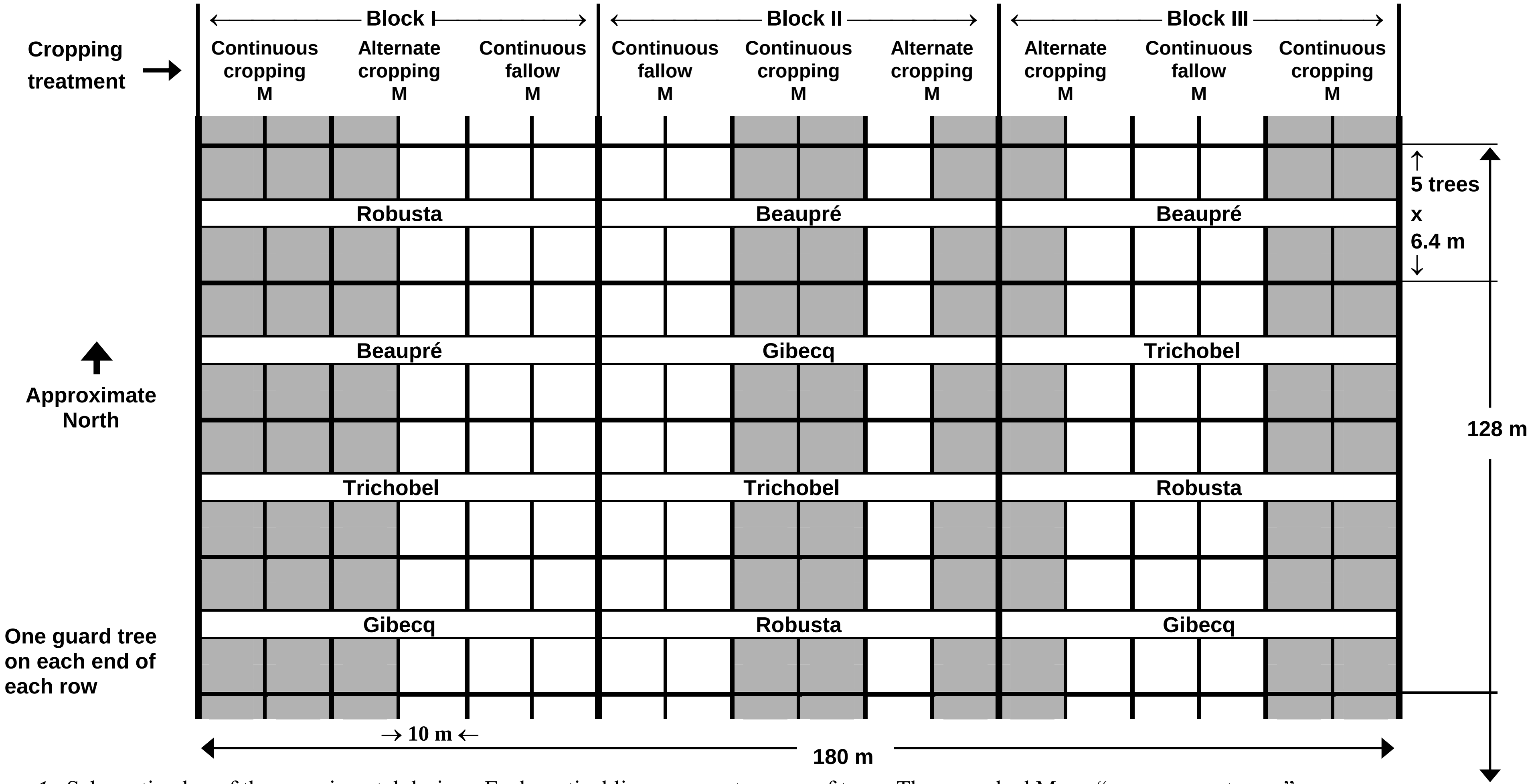

Figure 1. Schematic plan of the experimental design. Each vertical line represents a row of trees. Those marked M are "measurement rows". Unshaded alleys are either permanent fallow or fallow alternating with crop; shaded alleys are either permanently cropped or crop alternating with fallow. The hybrid name of each of the four sets of trees randomised in each block is designated by a banner across the set.

In the experiment, the crops are termed either 'winter' (if planted between September and November so that they are in the ground during the winter) or 'spring' (if planted in March or April). In each case, the crops were harvested between the following July and September and hence only one crop was harvested each year. Starting in 1992, the rotation at Cirencester comprised three crops of barley (*Hordeum vulgare* L.), field beans (*Vicia faba* L.), wheat (*Triticum aestivum* L.), barley, and field beans. Also starting in 1992, the rotation at Leeds comprised barley, peas (*Pisum sativum* L.), two crops of wheat, barley, mustard (*Brassica alba* L.), and wheat. At Silsoe, following poor crop yields in the initial three years, a wheat crop was harvested in 1995, followed by two wheat crops and field beans.

The cropped areas were managed in the same way as commercial crops, receiving standard applications of fertiliser, herbicides, fungicides and insecticides as appropriate. At Leeds and Cirencester the mid-point of the tractor tramlines was offset 6 m from the edge of the measurement tree row; at Silsoe it was centred in the alley 4 m from the edge of the tree row. Lastly the fourth arable treatment, a 'control area' adjacent to the main experiment, but at least 15 m from the base of the nearest poplar, was managed in the same way as the continuously-cropped treatment.

Measurements and analysis of data

From 1992, the height of each tree in the measurement row of each arable treatment was measured each winter between November and March. From 1994 at Cirencester and Leeds, and from 1995 at Silsoe, the diameters of the same trees were measured at breast height (1.3 m above the ground) each winter.

Each year, the grain, bean or pea yield, within each poplar-hybrid x arable-treatment plot was determined by harvesting with a plot combine at three distances from the trees in the measurement row. The approximate distances were: 1.0-2.5 m, 2.5-4.0 m and 4.0-5.5 m giving three sub-plots in each alternately-cropped treatment and six sub-plots in each continuously-cropped treatment. Corresponding measurements were also taken within the control area; within a specific year the number of replicates ranged from 1 to 24 at Cirencester and from 12 to 27 at Silsoe. A consistent 24 measurements of control yield were taken each year at Leeds. The dry matter yield of the spring mustard 'cover' crop, at Leeds in 1997, was determined by measuring the total yield of fresh mass of the above-ground part of each sub-plot of the crop and taking sub-samples for dry matter determination.

The crop yield data were analysed by ANOVA (SAS) in a split/split plot design. Because there were only three replicate cropped alleys in the alternately-cropped treatment, the design was not balanced in terms of the number of replicates with a westerly or an easterly aspect relative to the measurement row of trees. Therefore each year the yields from the continuously-cropped treatment were analysed first to determine the effect of the west-east aspect. If there was no effect of aspect then the whole experiment (continuously- and alternately-cropped treatments) was analysed as one set to determine the effect of the arable treatment. If there was an effect of aspect (as at Cirencester in 1993, at Leeds in 1995, 1996, 1997 and 1998, and at Silsoe in 1998) then in the comparison of continuously-cropped and alternately-cropped treatments only those continuous plots which had the same aspect as the alternate plots were included in the analysis. The control crop data were analysed by a two-way ANOVA and compared with the other treatments by t-test at $P = 0.05$.

In order to assess shading by the trees, total short-wave solar radiation was measured beneath three Trichobel trees at the Silsoe site at monthly intervals between 24 April and 24 July 1997. At this time, the mean height of the three trees was 7.6 m, the mean canopy depth was 5.0 m, and the mean maximum canopy diameter was 3.9 m. Below each tree, five tube solarimeters which had been calibrated against a standard Kipp solarimeter, were placed along a 10-m transect centred on the tree and perpendicular to the tree-row. A sixth solarimeter was placed outside the experiment where there was no significant shading.

Silvoarable management

The successful management of a silvoarable practice requires two additional activities not usually associated with traditional forestry or agriculture. First, in order to produce the maximum volume of high quality knot-free timber, the branches of the poplar were pruned before they reached a diameter of 5 cm (Jobling, 1990). The lowest branches were removed during the first year after planting, and subsequently whorls were removed during the second, fourth, sixth and seventh year. The trees at Cirencester and Silsoe were pruned between harvest and autumn cultivation. After 1995, the trees at Leeds were pruned during the winter. Second, it was necessary to manage the understorey vegetation in the tree row between the edge of the black plastic mulch and the crop i.e. in two strips 50-cm wide. At Leeds and Cirencester, this vegetation was controlled as required by herbicide (glyphosate) applied from a knapsack sprayer. At Silsoe, the vegetation was controlled with a hand-held petrol-driven strim-mower.

RESULTS

Establishment of trees

During the first year, the proportion of sets in the measurement rows, which did not establish, ranged from 9-10% at Silsoe and Cirencester to 34% at Leeds (Table 2). Across the three sites, the losses ranged from 4% for Beaupré to 37% for Robusta. The loss over all hybrids in the year of establishment was 18%. The particularly poor establishment of two hybrids at Leeds may have been linked to the greater exposure of the site to wind and the relatively shallow topsoil (Table 1). Although the dead trees were replaced with healthy transplants at the end of the first season, the differences in the proportions replaced would have affected subsequent height and diameter measurements.

Table 2. Proportion (%) of the 45 trees of each hybrid lost from the measurement rows at each of three lowland sites in England during the year of establishment.

	Site			
Hybrid	Cirencester	Leeds	Silsoe	Mean
Beaupré	7	4	2	4
Trichobel	7	7	22	12
Robusta	20	73	18	37
Gibecq	2	53	0	19
Mean	9	34	10	

Height and diameter of trees

At the end of 1998, seven years after planting, there were significant effects of site, hybrid, and arable treatment on height ($P<0.01$) and diameter ($P<0.01$). Although there was no significant ($P<0.05$) interaction between hybrid and arable treatment, there were interactions between hybrid and site on height ($P<0.05$) and diameter ($P<0.05$).

The main effect of site was that the height of the trees at Cirencester and Silsoe (10.4 m) was greater ($P<0.01$) than that at Leeds (9.2 m) (Table 3). In contrast the diameters of the trees at Cirencester and Silsoe (156 and 155 mm) were less ($P<0.01$) than that at Leeds (173 mm).

The main effect of hybrid across the sites was that the height of Beaupré (11.9 m) was 21-34% greater than those for the other three hybrids (8.9-9.8 m). Likewise, the diameter of Beaupré (189 mm) was 18-28% greater than the diameters of the other three hybrids (148-160 mm). At each of the three sites, the heights of Trichobel and Robusta were similar. A significant site x hybrid (tree) interaction was that the diameter of Gibecq was less ($P<0.05$) than that of Trichobel at Cirencester, the opposite of that at Silsoe. The relatively poor growth of Trichobel at Silsoe is probably, in part, a result of the poor establishment of this hybrid at Silsoe in the year of planting (Table 2).

Table 3. Height and diameter at breast height (dbh) of each of four poplar hybrids at each of three lowland sites in England at the end of the seventh growing season after planting.

		Site			
Property	Hybrid	Cirencester	Leeds	Silsoe	Mean
Height (m)	Beaupré	12.5 a	11.2 a	12.1 a	11.9 a
	Trichobel	10.4 b	9.3 b	9.6 b	9.8 b
	Robusta	9.8 bc	8.8 b	9.7 b	9.4 bc
	Gibecq	9.1 c	7.7 c	10.0 b	8.9 c
	Mean	10.4	9.2	10.4	
Dbh (mm)	Beaupré	184 a	199 a	184 a	189 a
	Trichobel	163 b	175 b	141 c	160 b
	Robusta	141 c	162 b	142 c	148 c
	Gibecq	139 c	157 b	154 b	150 c
	Mean	156	173	155	

Values followed by the same letter are not significantly different for that site at $P = 0.05$ ($n = 41$-45, except for Robusta at Leeds ($n = 30$); where trees are less than 45 in a set, some trees have died or are evidently of a different cultivar).

Effects of arable treatment on tree growth

In December 1998, seven years after planting, the heights of the trees in the continuously-cropped treatment at each site (8.8-9.9 m) were only 89-91% of those in the continuously-fallow treatment (9.7-11.1 m) (Table 4). An even greater difference was apparent in the measurements of diameter. The diameters of the poplars in the continuously-cropped treatment (133-156 mm) were only 75-83% of those in the continuously-fallow treatment (174-188 mm). The heights and diameters in the alternately-cropped treatment were intermediate in value.

Table 4. Effect of arable treatment on height and diameter at breast height (dbh) of poplar hybrids at each of three lowland sites in England at the end of the seventh growing season after planting.

		Site			
Property	Arable treatment	Cirencester	Leeds	Silsoe	Mean
Height (m)	Continuously-fallow	11.0 a	9.7 a	11.1 a	10.6 a
	Alternately-cropped	10.6 ab	9.2 a	10.1 b	10.0 b
	Continuously-cropped	9.8 b	8.8 a	9.9 b	9.5 c
Dbh (mm)	Continuously-fallow	178 a	188 a	174 a	180 a
	Alternately-cropped	158 b	176 a	151 b	162 b
	Continuously-cropped	133 c	156 b	140 c	143 c

Values followed by the same letter are not significantly different for that site at P = 0.05 (n = 50-60 for Cirencester and Leeds sites, and n = 60 for the Silsoe site). Where n ≠ 60 in a set, some trees have died or are evidently of a different cultivar).

The heights and diameters described in Table 4 are the cumulative effect of seven years of growth. However the effect of the arable treatment on the annual increase in height varied with year, and in 1994 and 1997 there were significant ($P < 0.05$) site x arable treatment interactions. In the second season after planting (1993), which was particularly wet between April and August, at each site the increases in tree height were similar in the three arable treatments (Table 5). During the third season (1994) at Cirencester and the third and fourth seasons (1994 and 1995) at Leeds, the increase in tree height in the continuously-fallow treatment was greater ($P<0.05$) than that in the continuously-cropped treatment. After this, the effect of arable treatment on the increase in tree height was not significant. By contrast at Silsoe, which was often the driest site, the arable treatments had a significant effect on the annual increase in tree height during the third, fourth, fifth, sixth and seventh seasons (1994-1998) after planting. For each of the last four seasons, the increase in tree height in the continuously-fallow treatment was greater ($P<0.05$) than that in the continuously-cropped treatment (Table 5).

Table 5. Effect of arable treatment on the increase in height (m) at each of three lowland sites in England for each of six growing seasons, together with the corresponding April to August rainfall (mm).

		Growing season (year)					
Site	Treatment and rainfall	1993	1994	1995	1996	1997	1998
Cirencester	Continuously-fallow	1.25 a	1.17 a	1.96 a	1.47 a	1.93 a	1.50 a
	Alternately-cropped	1.35 a	1.12 ab	1.50 a	1.44 a	1.91 a	1.33 a
	Continuously-cropped	1.27 a	0.99 a	1.30 a	1.45 a	1.81 a	1.45 a
	Rainfall	361	245	106	220	331	291
Leeds	Continuously-fallow	1.17 a	1.15 a	1.64 a	1.36 a	1.88 a	1.35 a
	Alternately-cropped	1.14 a	1.12 a	1.23 b	1.32 a	1.81 a	1.38 a
	Continuously-cropped	1.05 a	0.95 b	0.99 c	1.35 a	1.69 a	1.28 a
	Rainfall	286	206	102	207	394	331
Silsoe	Continuously-fallow	1.22 a	0.99 b	1.82 a	1.67 a	2.05 a	1.71 a
	Alternately-cropped	1.26 a	0.99 b	1.65 b	1.33 b	1.75 b	1.59 ab
	Continuously-cropped	1.37 a	1.19 a	1.25 c	1.41 b	1.41 c	1.47 b
	Rainfall	334	194	92	157	224	294

Values followed by the same letter are not significantly different for that year at P = 0.05 (n = 12 to 60). 1998 was the seventh growing season after planting.

In contrast to the height increment, the effect of the arable treatments on the diameter increment was more consistent from year to year and across sites (Table 6). In four out of five years at Cirencester and Leeds, and in four out of four years at Silsoe, the diameter increment of the trees in the continuously-fallow treatment was greater ($P<0.05$) than that in the continuously-cropped treatment. At Leeds, the only year where there was no significant effect of the arable treatment on diameter increment was 1997, which was also the year with the greatest April to August rainfall.

Table 6. Effect of arable treatment on the increase in the diameter at breast height (mm) at each of three lowland sites in England for each of five growing seasons, together with the corresponding April to August rainfall (mm).

		Growing season (year)				
Site	Treatment and rainfall	1994	1995	1996	1997	1998
Cirencester	Continuously-fallow	21 a	35 a	36 a	34 a	19 a
	Alternately-cropped	21 a	27 b	27 b	31 b	17 b
	Continuously-cropped	17 a	22 c	25 c	27 c	16 b
	Rainfall	245	106	220	331	291
Leeds	Continuously-fallow	27 a	38 a	33 a	34 a	39 a
	Alternately-cropped	25 a	30 b	29 b	35 a	39 a
	Continuously-cropped	20 b	21 c	25 c	33 a	36 b
	Rainfall	206	102	207	394	331
Silsoe	Continuously-fallow	n/a	33 a	34 a	36 a	29 a
	Alternately-cropped	n/a	30 b	25 b	29 b	27 b
	Continuously-cropped	n/a	24 c	24 c	23 c	24 c
	Rainfall	194	92	157	224	294

Values followed by the same letter are not significantly different for that year and site at $P = 0.05$ ($n = 12$ to 60).

Yields in the control area and continuously-cropped treatment

Within the control areas at Cirencester and Leeds, the yields for winter wheat (8.2-10.1 t ha^{-1}), winter barley (7.6-8.2 t ha^{-1}), spring barley (5.2-7.7 t ha^{-1}) and peas (5.5 t ha^{-1}) were similar to those achieved on other well-managed highly-productive farms (Nix, 1997) (Table 7). By contrast, due to management problems, the yields obtained at the Silsoe site between 1992 and 1994 were very low and therefore they are not presented. The control yields obtained from the winter wheat at Silsoe between 1995 and 1997 were acceptable (5.4-7.8 t ha^{-1}) but still relatively low.

In 1992, the year that the poplars were planted, the crop yields in the alleys at Cirencester and Leeds were greater than those in the control areas (Table 7). In contrast, between 1995 and 1998, when the trees were larger, the yields in the continuously-cropped treatment at Cirencester and Leeds were less than those in the control areas. At Silsoe, where the overall yields were lower, the first significant difference between the yields in the continuously-cropped treatment and the control area occurred in 1998. Overall during the first three years after planting, the yield in the continuously-cropped treatment at Cirencester and Leeds was 4% less than that in the corresponding control area. Between the fourth and the sixth years after planting, the yield reduction across the three sites was 10%, and in the seventh year, the reduction at Leeds and Silsoe was 14%.

Table 7. Yields of the arable crops in the control area, the continuously- and alternately-cropped treatments in the silvoarable experiment at each of three lowland sites in England from 1992 to 1998, expressed in terms of the cropped area.

Site	Year	Crop	Arable treatment				
			Control	Continuously-cropped		Alternately-cropped	
			Yield ($t\ ha^{-1}$)	Yield ($t\ ha^{-1}$)	Relative yield (%)	Yield ($t\ ha^{-1}$)	Relative yield (%)
Cirencester	92	Spring barley	5.2 b[1]	5.5 a	106	5.5 ab	106
	93	Spring barley	7.7 [2]	6.8 b	88	7.3 a	94
	94	Winter barley	8.2 a	6.9 b	83	8.4 a	102
	95	Winter beans	2.8 a	2.0 b	71	2.0 b	71
	96	Winter wheat	10.1 a	7.9 c	77	8.6 b	85
	97	Winter barley	7.6 a	6.5 b	85	7.4 a	97
	98	Winter beans	Crop failure in all treatments				
Leeds	92	Spring barley	6.3 b	6.6 a	104	6.6 a	105
	93	Spring peas	5.5 a	4.8 b	88	4.6 b	84
	94	Winter wheat	8.7 b	9.2 a	106	8.4 b	97
	95	Winter wheat	8.2 b	7.8 c	96	8.8 a	108
	96	Winter barley	7.7 a	6.9 b	90	7.0 b	91
	97	Spring mustard	4.2 a	3.6 b	85	3.3 c	80
	98	Winter wheat	10.6 a	9.6 b	91	8.2 c	77
Silsoe	94	Spring wheat	Low yields				
	95	Winter wheat	7.8 b	8.1 b	104	8.6 a	110
	96	Winter wheat	7.5 b	7.3 b	98	9.1 a	121
	97	Winter wheat	5.5 a	5.6 a	104	5.8 a	108
	98	Winter beans	4.4 a	3.6 b	82	3.3 c	76

[1]Values followed by the same letter for each year and site (i.e. each row of the table) are not significantly different at P = 0.05. [2] In 1993 at Cirencester, only a single measurement of the control yield was made. Relative yields are expressed as a proportion of the control.

Yields in the alternately-cropped treatment

There were eight occasions (three years at Cirencester, two years at Leeds and three years at Silsoe) when a cereal crop was preceded by another cereal in the continuously-cropped treatment (Table 7). On two of these occasions there was no significant difference in the yields between the continuously- and alternately-cropped treatments (in 1996 at Leeds and in 1997 at Silsoe). However on six of the eight occasions (in 1993, 1994 and 1997 at Cirencester; in 1995 at Leeds, and in 1995 and 1996 at Silsoe), the yield in the alternately-cropped treatment was significantly ($P<0.05$) greater than that in the continuously-cropped treatment. The increase in yield across the eight occasions was 11%.

Between 1993 and 1998, there were also four occasions when a successful break crop (beans, peas, or mustard) was grown in the continuously-cropped treatment (Table 7). On three of these occasions (in 1994 and 1997 at Leeds and in 1998 at Silsoe) the yield in the alternately-cropped treatment was significantly less ($P<0.05$) than that in the continuously-cropped treatment. Across the four occasions, the yield in the alternately-cropped treatment was 5% less than that in the continuously-cropped treatment.

On the three occasions when a cereal crop was grown after a break crop in the continuously-cropped treatment, the corresponding yield in the alternately-cropped treatment was once significantly higher (in 1996 at Cirencester) and twice significantly lower (in 1994 and 1998 at Leeds).

DISCUSSION

Choice of poplar hybrid

The superior performance of Beaupré, an *interamericana* hybrid, relative to *P. trichocarpa* and *euramericana* hybrids, across each of the three sites in this trial, is similar to the response of Beaupré compared to *P. trichocarpa* and *euramericana* hybrids across nine sites in England, Scotland, and Wales reported by Tabbush and Beaton (1998). The fact that Beaupré has shown the greatest height and diameter across a range of sites suggests that it is generally well-adapted to most lowland environments in the UK. Milne et al. (1992) and Souch and Stephens (1998) have related the high growth rate of Beaupré, in comparison to Robusta and Trichobel, to the development of a larger leaf area and hence a capacity to intercept a higher proportion of radiation. Although this might be expected to cause a greater reduction in crop yields, during the seven years Beaupré did not show a greater effect on crop yields than the other three hybrids. This is probably a result of the pruning regime which maintained the canopy depth of each tree equal to approximately half of the tree height.

Because of the high growth rate, some farmers in the UK have recently planted monocultures of Beaupré. Although this may appear sensible based on timber production measurements alone, large blocks of a single hybrid can be particularly vulnerable to new strains of disease. At the end of 1997 and in 1998, the Beaupré trees at the Cirencester site were particularly affected by a new race of the leaf rust *Melampsora larici-populina* (Lonsdale and Tabbush, 1998) previously only reported in Continental Europe. This may explain, in part, the reduction in the annual diameter increment of the poplar in the continuously-fallow treatment at Cirencester from 34-36 mm between 1995 and 1997 to only 19 mm in 1998 (Table 6). Although in 1998, the cumulative growth of Beaupré was still superior to the other three hybrids, in order to minimise disease susceptibility Lonsdale and Tabbush (1998) recommend planting a mixture of cultivars of differing genetic origins.

Timber formation

The individual measurements of tree height for each hybrid in the fallow treatment at the end of 1998 (seven-years after planting) can be used to determine a value for the 'top height', which in turn can be used to predict the maximum mean annual increment of timber volume (yield class) for that stand. The 'top height' is the mean height of those hundred trees per hectare with the largest diameter at breast height (Hamilton, 1975), and therefore it ignores the heights of the smallest third of the trees at a density of 156 trees per hectare. Using the tables presented by Christie (1994) for a density equivalent to 156 trees per hectare, the predicted maximum mean annual increment for Beaupré within the continuously-fallow plots ranged from 14 m^3 ha^{-1} a^{-1} at Leeds to 20 m^3 ha^{-1} a^{-1} at Cirencester (Table 8).

However the above analysis ignores the fact that the trees at Leeds have a substantially larger diameter for a given height, than the trees at Cirencester and Silsoe (Table 8). An alternative method for comparing the relative productivity of the three sites is to calculate the cumulative timber production (V; m^3 ha^{-1}) from the number of trees (N; trees ha^{-1}), the mean height (h; m), the mean diameter at breast height (dbh; m) and a form factor (f) (Philip, 1994) (Equation 1).

$$V = N\, h\pi \left(\frac{dbh}{2}\right)^2 f \qquad \text{Equation 1}$$

Assuming 156 trees ha^{-1} and a form factor for seven-year-old poplar of 37% (Hamilton, 1975), and using the values for the mean height and diameter for Beaupré in the continuously-fallow treatment (Table 8), the estimated timber volume of the trees at Leeds is similar to those at Silsoe. These results show that it can be misleading to predict a yield class for widely-spaced poplar based on measurements of top height alone. The greater diameter growth per increment of height growth for poplar at Leeds, relative to Silsoe, is probably a result of the greater exposure of the site to wind (Table 1).

The predicted maximum mean annual increments of 14 to 20 m^3 ha^{-1} for Beaupré indicates the superior performance of this cultivar to the other three cultivars in the trial. Jobling (1990) reported maximum mean annual increments for traditional poplar cultivars, such as Robusta, as being in the range of 4 to 14 m^3 ha^{-1}. Beaupré, growing on a sheltered valley site at Old Wolverton near Milton Keynes in Buckinghamshire, UK has been reported by Newman et al. (1995) as having an even greater maximum mean annual increment of 26 m^3 ha^{-1}. Such differences in volume production indicates that careful site selection is critical if new poplar hybrids are to achieve the maximum mean annual increments of 22 to 28 m^3 ha^{-1} used in some financial analyses of silvoarable agroforestry (Willis et al., 1993).

Table 8. The predicted maximum mean annual increment in timber volume for Beaupré in the continuously-cropped treatment, based on the top height seven years after planting and an interpolation of Christie's (1994) provisional tables for poplar, at each of three lowland sites in England.

	Site		
Characteristic	Cirencester	Leeds	Silsoe
Top height (m)	13.7	11.8	13.1
Predicted maximum mean annual increment (m^3 ha^{-1} a^{-1})	20	14	18
Height (m)	13.0	11.6	12.7
Diameter at breast height (mm)	212	218	203
Estimated timber volume at seven years[1] (m^3 ha^{-1})	26	24	24

[1] The estimated timber volume after seven years, is based on top height, diameter and a form factor of 37%.

Effect of the arable treatments on tree growth

After seven years, the mean height and the diameter of the trees in the continuously-cropped treatment were respectively 10% and 21% less than those in the continuously-fallow treatment (Table 3). Assuming a form factor of 37%, the estimated marketable timber from the seven-year-old trees in the continuously-cropped treatment would be only 56% of that in the continuously-fallow treatment. This is similar to reductions in tree growth rates of 20-60% caused by competition with grass in a silvopastoral system (Campbell et al., 1994).

The principal cause of the lower tree growth rates in the continuously-cropped, compared to the continuously-fallow treatment, is likely to be competition for water and/or nutrients. In an investigation of the effects of a competing grass crop on the growth of apple trees, Hipps et al. (1990) reported that the availability of water was probably a more important limiting factor than nitrogen. Certainly an important role for water is supported by the observation that the effect of the arable treatment on height increment was particularly strong during the dry summer of 1995 (Table 5).

The possibility of significant competition between the trees and the crop for water was also indicated in a detailed study of the soil water content within an alternately-cropped treatment at Silsoe during 1995 (Burgess et al., 1996). Between 27 April and 3 August 1995, the decline in the soil water content within the cropped area of winter wheat and the uncultivated 2-m wide area at the base of a Beaupré hybrid (141-192 mm) was substantially more than the decline within the fallow area (5-127 mm). Souch (1996), comparing the responses of two-year-old poplar hybrids, reported that Beaupré showed a reduction in transpiration once the soil water potential reached –43 kPa, and that each subsequent litre reduction in water use resulted in approximately 4.4 kg less total dry matter production. At the site at Silsoe, a soil water potential of –43 kPa is equivalent to a deficit of about 50 mm within the top metre of soil (Burgess et al., 1996). These results indicate that during a dry summer, the availability of water in the soil beneath an autumn-sown crop is likely to be less than that within a fallow. The implication is therefore that this reduction is sufficient to cause a difference in the growth of recently-established trees.

The above results suggest that, during a dry summer, the water use of an arable crop could be sufficient to reduce the growth of recently-planted poplar, compared to the situation where the poplar was surrounded by a bare-earth fallow. This is despite the arable crop being cultivated at a distance of at least 1 m from the base of the trees and weed growth at the base of the trees being suppressed by a black plastic mulch.

The effect of the experimental silvoarable system on crop yields

The first effect of the experimental silvoarable system on crop yields is a direct reduction in the cropped area. The practical experience across the network sites was that the tree rows should have a minimum width of 2 m to minimise the risk of damage to the trees from agricultural machinery, and vice versa. Hence as the tree row spacing on the trial sites was 10 m, it was only possible to crop 80% of the original area. Obviously, the proportion of the uncultivated land will decrease if the spacing between the trees is greater. In fact as most agricultural machinery in the UK is designed to work at widths of 12, 18 or 24 m, after allowing 2 m for the tree row, a spacing of 14, 20 or 26 m, between tree rows is likely to be more appropriate than 10 m on commercial farms.

Across the three sites, in the presence of trees, the yield per unit cropped area, relative to the crop yield in the control areas, was an average of 4% less in the first three years and an average of 10% less between years four and six. These reductions are substantially less than decreases of 31, 36 and 82% reported by Newman et al. (1995) for spring wheat and barley under three, five and six-year-old poplar respectively when planted at a particularly close spacing of 14 m x 1 m and with a predicted yield class of 26 (i.e. the predicted maximum mean annual increment, if the spacing had been 8 m x 8 m, would be 26 m^3 ha^{-1} a^{-1}). However they are comparable to a yield reduction of 9% reported for spring wheat below six-year-old poplar, also with a yield class of 26, at a spacing of 14 m x 6 m in Buckinghamshire, UK (Newman et al., 1995). The possible reasons for the effect of the trees on the yields in the continuously-cropped treatment include shading, competition for water (Foulkes et al., 1993), the ingress of weeds (Milsom et al., 1994), and slug damage (Griffiths et al., 1994).

The potential effect of shading by the trees on the yield of an understorey crop (*Y*; g m^{-2}), such as wheat, can be directly related to the incident short-wave solar radiation (*S*; MJ m^{-2}), assuming that the proportion of radiation intercepted by the crop canopy (f_S; %), the ratio of total dry matter production to intercepted radiation (ε_S ;g MJ^{-1}), and the harvest index (*HI*) remain constant (Monteith, 1977) (Equation 2).

$$Y = S \cdot f_s \cdot \varepsilon_s \cdot HI \qquad \text{(Equation 2)}$$

Using a more detailed model of the growth and development responses of winter wheat to radiation, Kocabas et al. (1993) indicated that a 20% reduction in radiation throughout the growing season would result in a 15% lower yield.

The tube-solarimeter measurements taken at Silsoe between April and July 1997, six-years after planting, indicated that the amount of short-wave radiation beneath the five-year-old trees was only 82% and 88% of that in the control treatment, at distances of 2.5 m and 4.5 m perpendicular to the tree row respectively. Such a reduction in radiation would appear sufficient to explain why the yields in the continuously-cropped treatment at Cirencester and Leeds were only 85% of those in the control treatment. In contrast the lack of an effect of trees on crop yield and the relatively low winter cereal yields at Silsoe (5.4 t ha^{-1}) suggests that a factor or factors other than solar radiation were constraining yields at that site.

The influence of shade rather than competition for nutrients in constraining the yield of the arable crops, is also supported by the observation that the poplar had a greater effect on the yield of break crops than that of winter cereals. For example, between 1995 and 1998, the yield of the spring mustard and winter beans in the continuously-cropped treatment was only 79% of that in the control treatment. In contrast over the same time period, the yield of the winter cereals in the continuously-cropped treatment was 93% of that in the control (Table 7). Such an effect would be expected, as the spring mustard and the winter bean crops were planted and harvested later than the winter cereals. Hence the peak light requirement of such crops is likely to coincide with the period from July to October when the poplars intercept the most light.

The alternately-cropped treatment

On the eight occasions, when a cereal crop was preceded by another cereal crop in the continuously-cropped treatment, the mean crop yield in the alternately-cropped treatment was 11% greater than that in the continuously-cropped treatment. A similar increase of 12% across five sites was also reported by Froment and Grylls (1992), when the yield from wheat, immediately following a bare fallow was compared to the yield of continuous wheat in the maritime temperate climate of Britain. Froment and Grylls (1992) related the high yields after the bare fallow to an increase in the soil mineral nitrogen content.

In contrast on three of the four occasions when a break crop was grown, the yield in the continuously-cropped treatment was greater than that in the alternately-cropped treatment. Overall, across the four occasions, the yield in the alternately-cropped treatment was 5% lower than that in the continuously-cropped treatment. These results suggest that break crops gain minimal yield benefit from being preceded by a fallow rather than a cereal crop. A possible reason for the lower yield in the alternately-cropped treatment is that the trees had both taller and broader canopies than those in the continuously-cropped treatment (Table 4).

Although the exact response depends on the crop combination, as discussed above, the individual yields per cropped area within the alternately-cropped treatment were between 80% and 120% of that from the continuously-cropped treatment (Table 7). However when the yields are expressed in terms of the total area, there is obviously a large reduction in yield because only 8 m out of every 20 m were sown to an arable crop; this is half the area within the continuously-cropped treatment. Therefore if the alternately-cropped treatment is to be used commercially, the economic costs of only planting a small proportion of the area, must be outweighed by increased returns from the trees or savings in management costs.

An important potential advantage for management of the alternately-cropped treatment is that the fallow alleys allow year-round access to the poplar trees for pruning. In contrast if all of the alleys are allocated to continuous autumn-sown crops, then in order to minimise damage to crops, pruning activities may be limited to August and September between the harvest of one crop and the cultivation for the next. These are amongst the busiest months on arable farms and the availability of labour for pruning is likely to be minimal unless specialist pruners are employed. Secondly in the 1960s and 1970s, Bryant and May used alternate-cropping because, as the poplar trees sometimes delayed the harvesting of one crop, it would still allow the sowing of the next season's crop. Although this effect may be apparent in the future as the trees grow, there has been no noticeable delay in the harvesting of the crops within the alleys during the first seven years.

Conclusion

The analysis of the first seven years of tree growth and crop yields reported in this paper provides an initial basis for comparing the productivity and profitability of this experimental silvoarable system with conventional arable cropping and poplar production practices (Burgess et al., 2000). Future work will investigate the tree-crop interactions beyond the first seven years and assess the most profitable combination of poplar and arable crop for a given site.

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