The Impact of Silvoarable Agroforestry with Poplar on Farm Profitability and Biological Diversity

Final Report to DEFRA
Project code: AF0105

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1. Introduction and objectives

1.1 Silvoarable systems (the intercropping of trees and arable crops) with poplar provide an opportunity for achieving the national policy goals of diversifying farm incomes, increasing tree planting and improving farm biodiversity. The use of new poplar hybrids should enable a grower to produce a timber crop within 30 years and the intercropping of arable crops allows an annual income to be derived (in the absence of government grants) after tree establishment. Compared to arable systems, silvoarable agroforestry has also been reported to increase the number and diversity of airborne arthropod species (Peng *et al.*, 1993) and small mammals (Wright, 1994).

1.2 In 1992 a silvoarable experiment, comprising three replicate blocks of four poplar (*Populus* spp.) hybrids (at a spacing of 10 m x 6.4 m) and three arable treatments, was established at Cirencester in Gloucestershire, Leeds in West Yorkshire and Silsoe in Bedfordshire. Incoll *et al.* (1996) and Burgess *et al.* (1998) reported the results for the first three years and the fifth year to MAFF respectively. This report covers a four-year period from April 1999 to April 2003. The objectives of the project were:

1. To determine the effects of arable cropping and fallow on the growth of four poplar hybrids (7 to 10 years after planting).
2. To determine the effects of poplar trees 7 to 10 years after planting on arable crop yields.
3. To evaluate the economics of the system relative to agriculture and closely-spaced poplar.
4. To determine the costs and botanical impact of two vegetation management strategies relative to arable farming.
5. To determine the effect of silvoarable management practices relative to arable farming, on the number and diversity of ground invertebrates.

2. Methodology

2.1 Details of the methodology are given in the main report.

3. Effects of hybrid, site, arable cropping and fallow on the annual growth of four poplar hybrids

3.1 Ten years after planting, the greatest height and diameter at Leeds and Silsoe was achieved by the hybrid Beaupré. Seven years after planting, Beaupré also had the greatest height and diameter at Cirencester. However during 1999, 2000 and 2001, eight to ten years after planting, infection by a new race of poplar rust meant that Beaupré at Cirencester showed smaller height and diameter increments than the hybrid Trichobel. To minimise susceptibility to such damage, growers should select a range of hybrids when planting a poplar plantation.

3.2 A bare fallow area on both sides of the tree rows, rather than an annual crop, led to greater increments in height and diameter for the period 4 to 6 years and 3 to 8 years after planting respectively. This effect was not significant in the ninth or tenth year after planting. These results show that in the initial years of a silvoarable system, competition from an arable crop for water and nutrients, relative to a bare fallow, can reduce tree growth rates.

3.3 The greatest yield class achieved in the cropped treatment is predicted to be 14 by Beaupré at Silsoe, 12 by Beaupré at Leeds and 10 by Trichobel at Cirencester. Across all three sites the predicted maximum mean annual increment of the four hybrids is calculated to be 9 m^3 ha^{-1} a^{-1}. These values are substantially less than that (22 m^3 ha^{-1} a^{-1}) reported by Newman *et al.* (1995) for poplar on an alluvial flood plain sheltered from wind. This shows the importance of site selection to maximise poplar yield.

4. Effects of trees on arable crop yields

4.1 During the first seven years of the experiment, the yield in the continuously-cropped silvoarable alleys ranged from 86% to 105% of that in the control area. In years eight (1999) and nine (2000) after tree planting, the relative crop yields remained between 87% and 93%; this is higher than previously predicted. The relative yields declined to 74% in year ten (2001) and 69% (58% if the result from Cirencester is included) in year eleven (2002). The decline in year eleven was partly associated with the cessation of pruning.

4.2 A model, based on shading by the canopy, was developed to calculate the potential effect of the trees on crop yield. The model, assuming a light extinction coefficient of 0.5, a leaf area index of 4, a yield class of 14, and a stated pruning regime to year nine, could explain 55% of the inter-annual variation in the mean yield across the three sites. A yield class of 14, rather than of 9 (indicated by the mean size of the trees in the cropped treatment across the three sites), resulted in a better explanation of the annual change in relative yield. This suggests that the yield reductions were not only due to shading, but partly caused by other factors such as competition from trees and weeds for water and nutrients.

5. Economics of the system relative to agriculture and closely-spaced poplar

5.1 The economics of silvoarable agroforestry with poplar at four different spacings (10, 14, 20 and 40 m) were compared with an arable rotation and two forestry systems (poplar planted at spacings of 8 m x 8 m or 4 m x 2 m).

5.2 Four scenarios for the management of the understorey in the silvoarable system were considered for the first 13 years. Predicted total costs of this for the 10-m system range from £380 to £900 ha^{-1}; equivalent to about £30-70 ha^{-1} a^{-1}.

5.3 The duration of profitable crop production within a silvoarable system depends on the assumed 'control' crop yield, crop prices, crop costs and the alley width. In the absence of grants and based on assumptions described in the report (for example a wheat price of £63 t^{-1}), the net margin of the crop component of the agroforestry system with a 10-m alley width remains profitable until year 5. At alley widths of 14, 20 and 40 m, the crop component is predicted to remain profitable until years 5, 9 and 13 respectively. If grain prices increase by 20%, the predicted duration of profitable cropping for the same four spacings is 10, 13, 13, and 21 years respectively.

5.4 The cost of establishing and managing the 8 m x 8 m poplar forestry system over 30 years (about £2,390 ha^{-1}) is predicted to be £1,400 ha^{-1} less than that for the 4 m x 2 m system (£3,780 ha^{-1}). In contrast, the predicted timber incomes from the two systems are similar (£7,890-£7,970 ha^{-1}). Hence in the absence of grants, planting poplar at the wide spacing gives a greater net margin than the closely-spaced forestry system at all discount rates. Including receipts from the current Woodland Grant Scheme and the Farm Woodland Premium Scheme, the net margin from the 4 m x 2 m system becomes similar to that of the 8 m x 8 m poplar system. Hence the current grant system undermines the planting of widely-spaced poplar, and thereby the opportunity for agroforestry.

5.5 In the absence of grants, planting poplars at a 10 m x 6.4 m (156 trees ha^{-1}) spacing in a silvoarable system led to small but increased net margins, compared to a sole-stand of poplar at a 8 m x 8 m spacing at all discount rates. However the predicted benefit (about £180 ha^{-1} over a 30-year period at a discount rate of 5%) is small. It is questionable that, without additional incentives, a grower would consider this financial benefit worth the additional management time.

5.6 In the absence of all grants (including arable area payments) and the assumptions given in the main report, the silvoarable system with poplars at spacings of 10 or 14 m was predicted to be more profitable than the arable system at discount rates of less than 2.5%. However if a grower assumes a discount rate of 3% or more then, in the absence of grants, the arable system was more profitable than the silvoarable systems, which were more profitable than the forestry systems. Hence, if the nation wishes to gain the proposed biodiversity and carbon sequestration benefits of integrating trees on farms, it appears that the government will need to support such initiatives. Supporting agroforestry appears a cost-effective way of doing this; and examples of initiatives being used in France are cited in Section 5.8.

6. Effects of silvoarable management practices on vegetation

6.1 It was possible to establish a grass-clover sward in the 2-m wide understorey of the poplar, seven years after planting the trees. The establishment of *Dactylis glomerata* and *Festuca rubra* was successful at each site. Whilst *Trifolium repens* and *Phleum pratense* established well at Leeds, they showed poor establishment at Silsoe. The grass sward appeared to successfully reduce the number of weed species within the understorey, although *Agropyron repens* and *Alopecurus myosuroides* remained problems on the clay soil at Silsoe.

6.2 At Cirencester and Leeds, there were generally more plant species and a greater cover of non-crop species in the alleys of the silvoarable system than in the arable control area. This indicates that the arable component within a silvoarable system faced increased competition for light, water and nutrients from invasive weeds.

6.3 At Leeds there were more plant species and 30-130% greater cover of non-crop species in the alleys subtending vegetated understoreys than in the alleys subtending bare understoreys. Although there were no consistent significant differences, a similar trend was often observed at Cirencester and Silsoe. The results seem to suggest that a bare-understorey is likely to reduce competition within the crop from weeds, whilst the vegetated understorey could be appropriate where a grower wishes to decrease herbicide applications whilst minimising invasive weeds.

7. Effects of silvoarable management practices on ground-active invertebrates

7.1 The effect of four silvoarable habitats (vegetated understorey, bare understorey; a cropped alley next to a vegetated understorey, and a cropped alley next to a bare understorey) and an arable control on the number and diversity of ground invertebrates was assessed by monthly pitfall trapping at all three sites from January 2000 to December 2002. Carabid beetles, spiders and slugs were the principal taxa caught; there were smaller numbers of staphylinid beetles and carabid beetle larvae. For each of the sites and taxa, with the exception of the beetle larvae, maximum numbers were generally found in July and August.

7.2 The effect of ground storey treatment on the overall numbers of carabid beetles, spiders and slugs was examined for each site and the results are presented for the Leeds site where there were three consecutive cereal crops. The proposed benefit of a vegetated understorey was that it would provide a good habitat for overwintering carabid beetles, which could recolonise the adjacent arable crops in the spring and summer. However, on many occasions the number of captured carabid beetles was statistically equally or solely the lowest in the vegetated understorey. One result, which could show that carabid beetles were moving from the vegetated understorey into the adjacent crop, is that in 2001, numbers in the vegetated understorey peaked in June, a month before the peak in the arable treatments.

7.3 Numbers of slugs were generally least in the bare understoreys and greatest in the vegetated understoreys but there appeared to be no positive correlation of numbers in the understoreys with their associated alley habitats.

7.4 In contrast to the carabid beetles, greater numbers of spiders were captured in the vegetated understorey than the other four treatments. The use of a vegetated understorey appears to be an option to encourage this class of invertebrate.

7.5 During the three years across the three sites, 38,705 carabid beetles were captured and identified to species level. The numbers of species found at Cirencester, Leeds and Silsoe were 29, 29 and 27 respectively. The most common species accounted for 29-61% of the total catch at a particular site in a given year.

7.6 The number of carabid beetle species captured within the four silvoarable habitats (See 7.1 above) within a given year (range: 16 to 25 species) was broadly similar to that (range: 13 to 23 species) recorded for the arable control. Hence no individual component of the agroforestry system appears to encourage a greater diversity of carabid beetle species than that in the arable control.

7.7 At each site and for each year, the effect of ground storey treatment on each individual carabid beetle species was examined when more than one carabid beetle was caught per trap per year. When there were significant differences, greater numbers were generally captured in the arable control area than in the alleys and the two types of understorey. One possible explanation for this result could be that the agroforestry system provides a more stable habitat with a greater diversity of both plants and animals, which could result in there being less chance of carabid beetle species reaching very high population densities.

1. Introduction

Two objectives of European and British agricultural policy are the reduction of agricultural surpluses and increased tree planting on farms. However tree planting in lowland Britain has often seemed unattractive because it can take at least 40 years to recover the money spent on establishing the trees. During the 1980s, new fast-growing hybrids of poplar, which are able to produce a harvestable timber crop in 25 years, were introduced to England from Belgium (Potter *et al.*, 1990). The area of land on which poplars should be the first choice for tree planting has been estimated by the Forestry Commission to be about 690,000 ha in England and Wales, of which 340,000 ha is in East Anglia.

In Britain, poplars have sometimes been planted at a wide spacing (i.e. 8 x 8 m) and left unthinned throughout the rotation (Beaton, 1987). In such circumstances, and without relying on government grants, one method of obtaining an annual income is to grow an arable crop between the trees, a system known as silvoarable agroforestry.

The British Government also has a goal to conserve and enhance biological diversity in the UK. The diversity of plants along the trees rows of a silvoarable system is likely to attract a more diverse and abundant fauna than a monoculture of arable crops (Stamps and Linit, 1997). Research at Leeds (Peng *et al.*, 1993) has shown that both the number of individuals and the number of airborne arthropod species within an agroforestry system (both along the tree row and within the alleys) were greater than in an arable control. Similarly a silvoarable system at Leeds with a grass understorey increased the number of bank voles (*Clethrionomys glareolus*), wood mice (*Apodemus sylvaticus*), field voles (*Microtus agrestis*) and common shrews (*Sorex araneus*) compared to an arable control area (Wright, 1994). Other reports have shown that the creation of a non-cultivated area of flowers and grass can also provide a beneficial habitat for farm birds (Clarke *et al.*, 1997; Sotherton and Rands, 1986).

In 1992, MAFF sponsored a research project (CSA 2817) to study the first three years of a silvoarable experiment at three lowland sites in England. This research was reported by Incoll *et al.* (1996). In 1997, MAFF agreed to support further investigations for a further year during the period January to December 1997 (Burgess *et al.*, 1998). This report covers a four-year period from April 1999 to April 2003. The objectives of the project during this period were:

Objectives

Section 1: to determine the effect of silvoarable agroforestry with poplar on farm profitability. The specific objectives of this section were:

1.1. To determine the effects of arable cropping and fallow on the annual growth of four poplar hybrids (7 to 10 years after planting).
1.2. To determine the effects of poplar trees 7 to 10 years after planting on arable crop yields.
1.3. To evaluate the economics of the system relative to agriculture and closely-spaced poplar.

Section 2. To determine the effect of silvoarable management practices relative to arable farming, on ground flora and ground invertebrates.

2.1 To determine the costs and botanical impact of two vegetation management strategies relative to arable farming.
2.2 To determine the effect of silvoarable management practices relative to arable farming, on the number and diversity of ground invertebrates.

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2. Methodology

The location, climate, layout, treatments and design of the experimental sites for the period 1992 to 1997 are fully described by Incoll *et al.* (1996) and Burgess *et al.* (1998). However for clarity they are summarised below, including some additional information relating to the period from 1998 to 2002.

2.1 Location and climate

The three experimental sites are located on the Royal Agricultural College Farm (51°44′N; 2°0′W) near to Cirencester in Gloucestershire, on Leeds University Farms (53°44′N, 1°15′W) in West Yorkshire and on the Cranfield University Farm (52°0′N, 0°26′W), Silsoe in Bedfordshire. The sites range in altitude from 50 m at Leeds to 130 m at Cirencester (Table 2.1). The Cirencester and Leeds sites are on gently sloping ground but with opposite aspects; the site at Silsoe is relatively flat. The soils at Cirencester and Leeds are both clay loams over limestone, but the average soil depth at Leeds is only 50 cm. The clay soil at Silsoe contains a high proportion of montmorillinite, which can lead to substantial shrinkage cracks during dry summers and waterlogging during wet winters.

Table 2.1 *Summary of the altitude, topography and soil type at the three sites.*

Property	Cirencester	Leeds	Silsoe
Altitude (m)	130	50	60
Slope	‘gentle’	‘gentle’	flat
Aspect	South-east	West-north-west	-
Topsoil depth (cm)	> 50	50	> 50
Soil description	Clay loam over limestone	Sandy clay loam (Aberford series) over Magnesian limestone	Clay (Holdenby series) over clay

Between 1992 and 1998, the first seven years of the experiment, the mean annual rainfall at Leeds and Silsoe (634 and 629 mm respectively) was only 79% of that at Cirencester (800 mm) (Table 2.2). For the same period, the mean air temperature at Leeds (9.3°C) was less than that at the other two sites (9.8 and 10.0°C). During the period 1999 to 2002, the mean rainfall was 13-14% higher than the preceding seven years, at Silsoe and Leeds (721-722 mm) and 21% higher at Cirencester (965 mm). The particularly high rainfall at Silsoe between September 2000 and May 2001, combined with the clay soil, meant that the site was waterlogged for much of that period. Between 1999 and 2002, the mean temperature at each site was between 0.3ºC (at Leeds and Cirencester) and 0.6ºC higher (at Silsoe) than that in the preceding seven years.

Table 2.2 *Summary of annual rainfall and the mean air temperature at each site for each year from 1992 to 2002.*

Year	Cirencester		Leeds		Silsoe	
	Total rainfall (mm)	Mean temp. (°C)	Total rainfall (mm)	Mean temp. (°C)	Total rainfall (mm)	Mean temp. (°C)
1992	827	9.5	606	9.3	854	9.7
1993	924	8.8	694	8.8	733	9.5
1994	834	10.2	678	9.6	573	10.3
1995	775	10.4	563	9.9	593	10.2
1996	592	9.0	507	8.6	403	9.2
1997	756	10.2	667	9.8	486	10.6
1998	891	10.0	722	9.5	758	10.7
1999	982	10.3	655	10.0	567	11.0
2000	1,103	10.0	880	9.8	870	10.2
2001	812	9.8	590	9.0	787	10.1
2002	964	10.4	765	9.8	659	10.9
Mean 1992-98	800	9.8	634	9.3	629	10.0
Mean 1999-02	965	10.1	722	9.6	721	10.6
Mean 1992-02	860	9.9	666	9.5	662	10.2

2.2 Experimental treatment and design

The principal commercial poplars grown in Europe can be grouped into three main species: the black and eastern cottonwoods from Western and Eastern North America respectively, and the black poplar which is native to Europe. The black cottonwood (*Populus trichocarpa*) is generally thought to grow best in high rainfall areas and in areas with a low soil pH (down to 5.0) (Tabbush, 1995). Trichobel is a hybrid of this species. The eastern cottonwood (*Populus deltoides*) has been crossed with the native black poplar (*Populus nigra*), to produce '*euramericana*' hybrids such as Robusta and Gibecq. Lastly the two American species have been crossed to produce '*interamericana*' hybrids such as Beaupré. The four hybrids selected for the experiment were:

- Trichobel (*Populus trichocarpa x Populus trichocarpa*),
- Robusta (*Populus deltoides x nigra* syn. *Populus euramericana*),
- Gibecq (*Populus deltoides x nigra* syn. *Populus euramericana*), and
- Beaupré (*Populus deltoides x trichocarpa* syn. *Populus interamericana*).

From 1992 to 1998, three cropping treatments were included:

- Continuous cropping in the alleys each side of a treatment row (Crop, Figure 2.1),
- Cropping and fallow alternating in the alleys each side of a treatment row, the positions changed annually to give a two-course rotation (CropN, Figure 2.1), and
- Continuous fallow in alleys each side of a treatment row (Fallow, Figure 2.1).

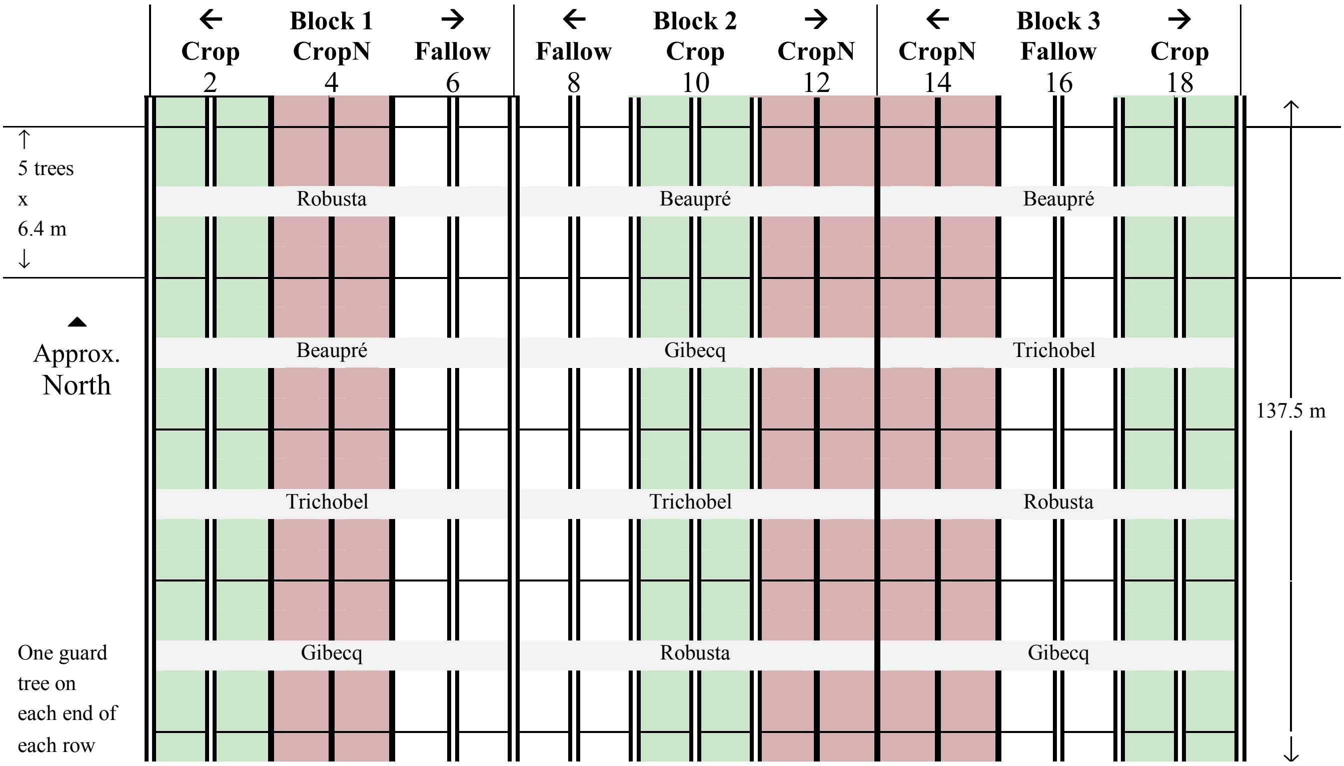

Figure 2.1 *Schematic plan of the experimental design at the Leeds and Silsoe sites. The layout of the cropping treatments was different at the Cirencester site. All thick vertical lines represent rows maintained clear of vegetation. Treatment rows are numbered.*

During the autumn of 1999, the alternately cropped treatment was changed so that a crop was grown on both sides of the tree-row in each subsequent year. In addition between July and October 1999, the continuous black plastic mulch in the middle of each tree row was removed. Between September 1999 and March 2000, along the six treatment-rows of the 'continuous-cropping' and the 'continuous-fallow' treatments, a grass-clover understorey was established using a seed mixture comprising cocksfoot (*Dactylis glomerata* L.), timothy (*Phleum pratense* L.), red fescue (*Festuca rubra* L.) and white clover (*Trifolium repens* L.). In the understorey of the three treatment rows of the 'alternate' treatment, the surface vegetation was minimised by one or two annual applications of glyphosate or paraquat from a knapsack sprayer. The three cropping treatments from the autumn of 1999 were therefore:

- Continuous cropping in the alleys each side of a treatment row, and a grass-clover sward established in the tree-row,
- Continuous cropping in the alleys each side of a treatment row, and vegetation in the tree-row minimised by application of herbicide, and
- Continuous fallow in alleys each side of a treatment row, and a grass-clover sward established in the tree-row.

Each combination of the four poplar hybrids and three cropping treatments was included within three replicated blocks at each site (Figure 2.1). Twenty two poplars were spaced at intervals of 6.4 m along each row of trees. The rows were 10-m apart (156 plants ha^{-1}). The four hybrids were planted in groups of five consecutive trees, with a single guard tree at the start and end of each row. Rows between treatments, which are not used for measurements of tree growth, are called non-treatment rows. At each site there were 180 treatment trees and 238 non-treatment trees. In addition a ‘control’ arable crop area was planted each year at each site, at a distance of at least 20 m from the trees. In 2000, a second arable control area was introduced at the Leeds and Cirencester sites for measurements of botanical and faunal biodiversity.

2.3 Establishment and management of trees

Between March and April 1992, each of the poplar hybrids were planted at each site as unrooted 1.5-2.0 m sets along the central line of a 1.2-m-wide black plastic mulch. The outer 10-15 cm of the edges of the mulch were buried to prevent lifting (Incoll *et al.*, 1996). The initial layout comprised a one-metre width of plastic, eight metres for arable cropping, and an approximately 50-cm-wide crop / plastic interface on either side of the plastic, which remained uncropped. At Cirencester and Silsoe spiral tree guards were fitted around the base of all trees for protection against rabbits. At Leeds, the sets were protected by 0.6-m-high tubular plastic tree-shelters.

During the first year, the average establishment losses within the treatment rows, ranged from 9% and 10% at Silsoe and Cirencester respectively, to 34% at Leeds (Table 2.3). Across the three sites, the mean losses ranged from 4% for Beaupré to 37% for Robusta. The poor establishment at Leeds was probably linked to the high level of exposure to wind and the relatively shallow soil. Although each of the dead trees was replaced with healthy transplants at the end of the first season, the differences between hybrids in establishment will affect the subsequent measurements of mean height and diameter.

Table 2.3 *Proportion (%) of trees of each hybrid in the measurement rows lost during the year of establishment (1992) at each site.*

Hybrid	Site			
	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	18

Pruning policy

The branches of the poplar were pruned before they reached a diameter of 5 cm (Jobling, 1990) to produce high value timber whilst minimising pruning costs. To prevent damage to the arable crop, the trees at Cirencester and Silsoe were pruned between harvest and autumn cultivation. However after year three (1995), the trees at Leeds were pruned during the winter between December and February. The pruning of the trees was a relatively time-consuming operation, but it was quicker on hybrids such as Beaupré, which have a dominant leading shoot, than on hybrids like Trichobel which have more branches. Full details of the pruning policy are given in Section 4.3. Because of its poor form, the decision was taken to leave Gibecq unpruned after 2000.

Wind damage to trees

In November 2000, high wind speed speeds led to the upper 3-5 m of the leading shoot being broken from four trees of the hybrid Trichobel at Silsoe (Table 2.4). At this time the Trichobel was still in leaf and was therefore more susceptible to wind damage than the other three hybrids. Subsequently similar damage has been reported to Beaupré, the tallest hybrid at each of the three sites.

Table 2.4 *Proportion (%) of trees of each hybrid in the measurement rows losing their leading shoots between January 2001 and March 2003.*

Hybrid	Site			
	Cirencester	Leeds	Silsoe	Mean
Beaupré	7	9	2	6
Trichobel	0	2	9	4
Robusta	0	0	0	0
Gibecq	0	0	0	0
Mean	2	3	3	2

2.4 Management of crops

From 1992 to 1998, a crop was planted each year in the cropping treatments and the control area at each site. In the autumn of 1999, a winter wheat crop was established at each site (Table 2.5). In October 2000, winter wheat was planted at Leeds. Because of the prolonged wet weather after September 2000, a winter crop was not established at Cirencester until December 2000. In fact the establishment was so poor that a replacement spring wheat crop was planted on 1 May 2001. Similarly, excess rainfall meant that many of the alleys at Silsoe were waterlogged from October 2000 to May 2001 and it was not possible to establish an autumn-sown or a spring-sown crop. The cropped areas were therefore maintained as a bare fallow. The crops at Leeds and Cirencester were harvested in August and September 2000 respectively. In October 2001, a winter barley crop was established at Leeds and Cirencester. In the autumn of 2001, the field at Silsoe was again wet and it was only possible to plant winter barley in the alleys and in a limited control area in November 2001. The winter barley crops were harvested in August 2002 (Figures 2.2-2.4).

2.5 Measurements of height and diameter of trees and crop yield

The height and diameter at breast height (1.3 m) of each treatment in the treatment rows was measured at each site during the winter of each year. Trees, which were damaged by the wind, were removed from the analysis. At each site, the crops were harvested in three parallel 1.5-m wide strips next to the measurement tree row and each side of it and in sections matching each set of five trees of one hybrid i.e. 32 m long. In the arable control area, the number of replicates varied between sites according to the layout of the control area in relation to the agroforestry plot e.g. at Leeds there were four replicate blocks each containing three parallel strips 32 m long each side of the tramlines, giving 24 replicate samples.

2.6 Botanical surveys

At each site, the botanical diversity and cover (%) was determined twice a year in 1-m^2 quadrats, divided into 100 sub-squares. In 2000, a second arable control area was introduced at the Leeds and Cirencester sites for measurements of botanical and faunal biodiversity. In 2000, the vegetation was assessed at each site between March and May, and again in June. In 2001, the vegetation was surveyed in March (Leeds), May (Silsoe) and June to July (at all three sites). No survey was made at Cirencester in March 2001 due to Foot and Mouth restrictions on access to the site. In 2002, the vegetation was surveyed in March to April (Leeds and Cirencester), and April to May (Silsoe), and between June and July 2002 at all three sites.

Within the tree rows, sampling was carried out at points equidistant between the five trees of each of the four poplar hybrids (i.e. four quadrats per hybrid) and for each of the two understorey treatments. Within the arable alleys there were two quadrats opposite vegetated and herbicide-treated understoreys (one to the east of the tree rows, one to the west) for each of the four poplar hybrids, and in the arable control areas there were sets of eight quadrats in three different areas. Cover was assessed by noting the number of intersections in the quadrats under which individual species (or bare ground) occurred.

Table 2.5 *Description of tree and crop management at each site from January 2000 to December 2002.*

a) Cirencester

	2000												2001												2002											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Poplar in leaf					🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Crop	Wheat	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨			Wheat	🟨	🟨	🟨	🟨	SWheat	🟨	🟨	🟨		Barley	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨				
Stubble									🟨	🟨	🟨										🟨												🟨	🟨	🟨	🟨
Fallow area																																				
Herbicide																																				
Cultivation							🟫									🟫			🟫			🟫							🟫							
Understorey																																				
Herbicide					🟥													🟥									🟥									

b) Leeds

	2000												2001												2002											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Poplar in leaf					🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Crop	Wheat	🟨	🟨	🟨	🟨	🟨	🟨	🟨		Wheat	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨		Barley	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	OSR	🟨	🟨	🟨
Stubble									🟨												🟨															
Fallow area																																				
Herbicide																																				
Cultivation										🟫							🟫	🟫	🟫			🟫											🟫			
Understorey																																				
Herbicide																	🟥															🟥				

c) Silsoe

	2000												2001												2002											
	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M	J	J	A	S	O	N	D
Poplar in leaf					🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩						🟩	🟩	🟩	🟩	🟩	🟩	🟩	
Crop	Wheat	🟨	🟨	🟨	🟨	🟨	🟨	🟨																Barley	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨				
Waterlogging											↓	↓	↓	↓	↓	↓	↓																			
Stubble									🟨	🟨	🟨	🟨																					🟨			
Bare-soil													🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨	🟨												🟨	🟨	🟨
Fallow area																																				
Herbicide				🟥																																
Cultivation							🟫											🟫	🟫	🟫			🟫					🟫	🟫	🟫	🟫					
Understorey																																				
Herbicide			🟥												🟥			🟥					🟥							🟥						

Note: OSR: oilseed rape. SWheat: Spring wheat. All the crops are winter crops except the wheat crop at Cirencester sown in May 2001.

2.7 Faunal surveys

The faunal diversity and abundance was determined by placing 48 pitfall traps within the silvoarable plot of hybrid poplar and 12 in the arable control area. The pitfall traps were positioned in such a way to enable the effect of five ground storey treatments (the arable control, the alleys subtending the vegetated understorey, the vegetated understorey, the alley subtending the bare understorey and the bare understorey) on the invertebrate fauna to be determined. At each site these traps were opened for one week every month during 2000, 2001 and 2002. The catch from each trap for each sampling occasion underwent preliminary sorting and counting to separate specific taxa (carabid beetles, carabid larvae, staphylinid beetles, spiders, and slugs) from others. The carabid beetle catch was then identified and counted to species level.

Figure 2.2 *Part of an agroforestry area containing winter barley at the Cirencester site in June 2002.*

Figure 2.3 *Part of an agroforestry area containing oilseed rape at the Leeds site in May 2003.*

Figure 2.4 *Part of an agroforestry area containing winter barley at the Silsoe site in July 2002.*

3. Effect of arable cropping and fallow on the growth of four poplar hybrids

The first objective of the research project (Objective 1.1) was to determine the effects of arable cropping and fallow on the annual growth of four poplar hybrids (7 to 10 years after planting). For the period 1997 to 2002, the measurements of poplar height and diameter continued to show significant ($P<0.05$) main effects of site, hybrid, cropping treatment, and significant ($P<0.05$) site x crop and site x hybrid interactions. Because, across the three sites, there were no significant ($P<0.05$) interactions between hybrid and cropping treatment, the effects of hybrid are presented separately from those of cropping treatment.

3.1 Main site effect

The main effect of site on height was different from that on diameter. During the winter 2000/2001, ten years after planting, the mean tree height at Silsoe (15.0 m) was 9-13% greater than that at Leeds and Cirencester (13.3-13.7 m) (Table 3.1). By contrast the mean diameter of the trees at Leeds (21.9 cm) was similar to those at Silsoe (21.8 cm) and 7% greater than those (20.5 cm) at Cirencester. This is probably because the Leeds site is particularly exposed to wind, as trees mechanically perturbed by wind tend to be shorter and to have thicker stems (Holbrook and Putz, 1989).

3.2 Main hybrid effect

During the winter period 2001/2002, ten years after planting, the mean height of Beaupré (16.1 m) across the three sites was 14% greater than Trichobel (14.1 m), 19% greater than Robusta (13.5 m) and 29% greater that than that of Gibecq (12.5 m) (Table 3.1a). Similarly the mean diameter of Beaupré (23.7 cm) was 6% greater than Trichobel (22.3 cm), and 19-20% greater than Robusta and Gibecq (19.7-20.0 cm) (Table 3.1b). This ranking of hybrids in terms of height and diameters is the same as that recorded during the winter period 1998-1999.

Table 3.1 a) *Mean height (m) and b) mean diameter (cm) during the winters of 98/99 and 01/02. The range of the number of measured trees per hybrid at each site (n) is also shown.*

a) Height

Hybrid	Cirencester		Leeds		Silsoe		Mean	
	98/99	01/02	98/99	01/02	98/99	01/02	98/99	01/02
Beaupré	12.5^{a}	15.3^{a}	11.0^{a}	15.4^{a}	12.1^{a}	17.7^{a}	11.9^{a}	16.1^{a}
Trichobel	10.4^{b}	14.4^{ab}	9.1^{b}	13.4^{b}	9.6^{b}	14.5^{b}	9.7^{b}	14.1^{b}
Robusta	9.8^{bc}	13.4^{b}	8.7^{bc}	12.6^{bc}	9.7^{b}	14.3^{b}	9.5^{bc}	13.5^{c}
Gibecq	9.1^{c}	11.9^{c}	8.0^{c}	11.7^{c}	10.0^{b}	13.6^{b}	9.0^{c}	12.5^{d}
Mean	10.4	13.7	9.2	13.3	10.4	15.0	10.0	14.0
n	41-43	39-45	30-45	30-45	45	41-45	116-133	116-134

b) Diameter

Hybrid	98/99	01/02	98/99	01/02	98/99	01/02	98/99	01/02
Beaupré	18.3^{a}	21.8^{a}	19.9^{a}	24.2^{a}	18.4^{a}	25.2^{a}	18.9^{a}	23.7^{a}
Trichobel	16.3^{b}	22.7^{a}	17.5^{b}	23.2^{a}	14.1^{c}	20.8^{b}	16.0^{b}	22.3^{b}
Robusta	14.1^{c}	19.1^{b}	15.9^{bc}	20.4^{b}	14.2^{bc}	20.8^{b}	14.8^{c}	20.0^{c}
Gibecq	13.8^{c}	18.3^{b}	15.7^{c}	19.8^{b}	15.4^{b}	20.5^{b}	15.0^{c}	19.7^{c}
Mean	15.7	20.5	17.3	21.9	15.5	21.8	16.2	21.4
n	41-44	41-45	30-45	30-45	45	41-45	116-133	116-135

Note: Within each column, numbers followed by the same superscript letter are not significantly different at $P = 0.05$.

3.3 Hybrid x site interaction

In 1998, Beaupré had a greater mean height and diameter than each of the other three hybrids at each of the three sites. At the end of 2001, this was still the case at Leeds and Silsoe. However during 1999, 2000 and 2001 at Cirencester, the annual height and diameter increment of Beaupré declined relative to the other three hybrids (Figure 3.1). The probable reason for the reduction in the growth rate of Beaupré is its susceptibility to the new race of poplar rust (race E4) which first appeared in the UK in 1994 (Lonsdale and Tabbush, 1998). The effect on leaf area duration of poplar rust infection is known to be greater in the west of England than the east.

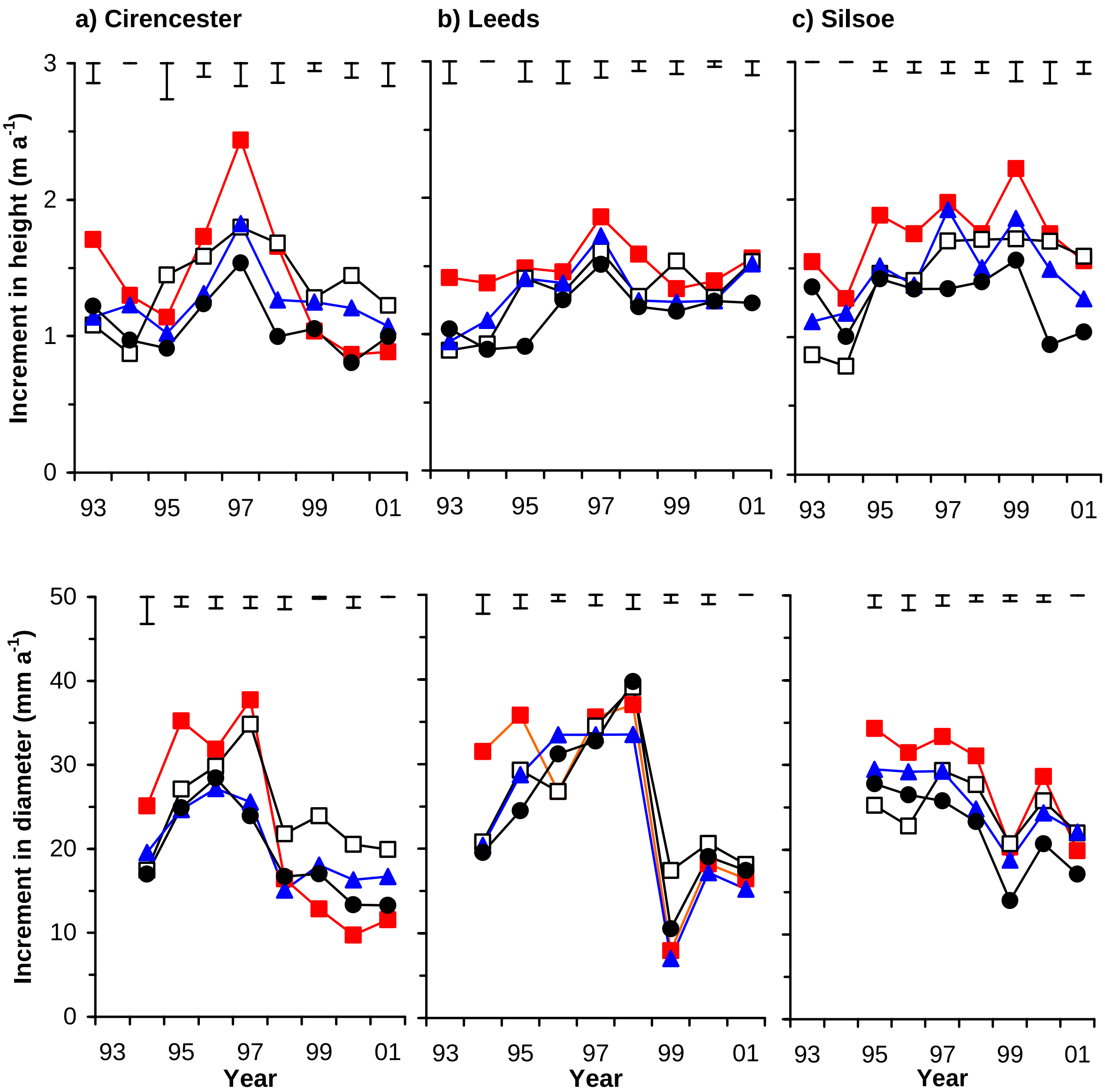

Figure 3.1 *The effect of hybrid on the mean annual increment in a) height and b) diameter from 1994 to 2001 (Beaupré,* ■; *Trichobel,* □; *Robusta,* ▲; *Gibecq,* ●. *The error bars show the standard error of difference (d.f.=6).*

3.4 Main cropping treatment effect

From 1992 to 1999, each pair of adjacent alleys had one of three treatments: 1) continuously-cropped, 2) alternately cropped and fallow, or 3) continuously-fallow. Since the autumn of 1999, both the alternately-cropped and the continuously-cropped alleys have been continuously cropped with a bare and a vegetated understorey respectively. At the end of 1998, the mean height of the trees, across the three sites, in the continuously-fallow treatment (10.6 m) was 6% greater than that in the alternately-cropped (10.0 m) treatment and 11% greater than that (9.5 m) in the continuously-cropped treatment (Table 3.2a). At the same time, the mean diameter of the trees, across the three sites, in the continuously fallow treatment (18.0 cm) was 11% greater than that in the alternately-cropped (16.2 cm) treatment and 26% greater than that (14.3 cm) in the continuously-cropped treatment (Table 3.2b). The relative effect of the cropping treatment was therefore greater on diameter than height.

Table 3.2 a) *Mean height (m) and b) mean diameter (cm) during the winters of 98/99 and 01/02 of the four poplar hybrids across each of the three cropping treatments at each site. The range of the number of measured trees per cropping treatment at each site (n) is also shown.*

a) Height

Treatment	Cirencester		Leeds		Silsoe		Mean	
	98/99	01/02	98/99	01/02	98/99	01/02	98/99	01/02
Fallow	11.1^{a}	14.6^{a}	9.7^{a}	13.7^{a}	11.1^{a}	15.6^{a}	10.6^{a}	14.6^{a}
Alternate[1]	10.6^{b}	13.8^{ab}	9.4^{a}	13.5^{a}	10.1^{b}	15.1^{b}	10.0^{b}	14.1^{b}
Cropped	9.7^{c}	12.9^{b}	8.8^{b}	12.8^{b}	9.9^{b}	14.4^{c}	9.5^{c}	13.4^{c}
Mean	10.4	13.7	9.2	13.4	10.4	15.0	10.0	14.0
n	50-59	51-60	52-59	51-59	60	56-60	162-176	158-176

b) Diameter

Treatment	98/99	01/02	98/99	01/02	98/99	01/02	98/99	01/02
Fallow	17.9^{a}	23.1^{a}	19.0^{a}	23.9^{a}	17.4^{a}	23.9^{a}	18.0^{a}	23.5^{a}
Alternate[1]	15.8^{b}	20.5^{b}	17.8^{b}	22.2^{b}	15.1^{b}	21.6^{b}	16.2^{b}	21.4^{b}
Cropped	13.3^{c}	17.9^{c}	15.6^{c}	20.4^{c}	14.0^{c}	20.1^{c}	14.3^{c}	19.5^{c}
Mean	15.7	20.5	17.3	22.2	15.5	21.9	16.2	21.4
n	53-60	54-60	52-59	52-59	60	56-60	165-176	162-176

Note: Within each column, numbers followed by the same superscript letter are not significantly different (at P = 0.05).

[1]: Since autumn 1999, the alternately-cropped treatment has been continuously cropped with a bare understorey.

Although the trees in the fallow treatment were still taller and wider than those in the continuously-cropped treatments in 2001, this effect is a result of treatment effects in the first seven years of planting, rather than significant effects (at P = 0.05) during the period 1999 to 2001. Prior to 1999, the effect of cropping treatment on increments in height was significant at Cirencester in 1994 and 1997, at Leeds in 1995, and at Silsoe from 1994 to 1997 (Figure 3.2). Since 1999, there has been no significant effect of cropping treatment on the increments in height at Cirencester or Silsoe. The only significant response occurred at Leeds in 2000, when the increment in height was greater in the two cropping treatments than in the fallow treatment. The effect of the cropping treatments on increment in diameter is more consistent, and it was significant from 1995 to 1997 at Cirencester, from 1994 to 1998 at Leeds and from 1995 to 1999 at Silsoe. Since 1999, the only significant effect ($P<0.05$) has been at Cirencester in 2000, where the increment in the fallow treatment was greater than in the cropped treatments.

The cropping treatments have had a greater relative effect on increment in diameter than in height (Figure 3.3). Across the three sites the effect of cropping treatment on height increment was only significant between 1995 and 1997 (4-6 years after planting) when the mean reduction was 19%. The effect on increment in diameter was significant between 1994 and 1999 (3-8 years after planting) when the mean reduction was also 19%.

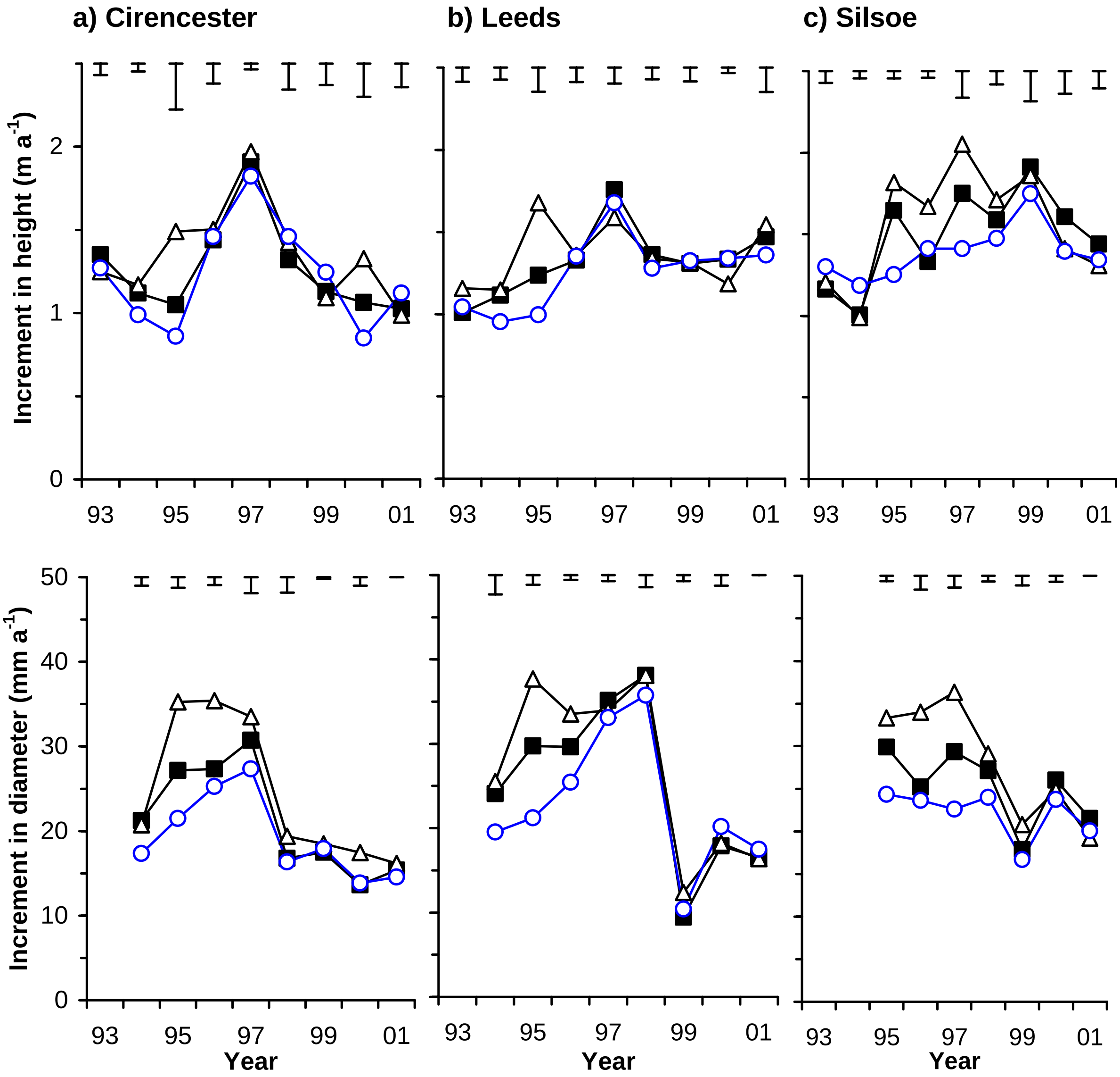

Figure 3.2 *The effect of cropping treatment on the annual increment in diameter from 1994 to 2001 (fallow,* △*; alternately-cropped,* ■*; and continuously-cropped,* ○ *. The error bars show the standard error of difference (d.f.=6).*

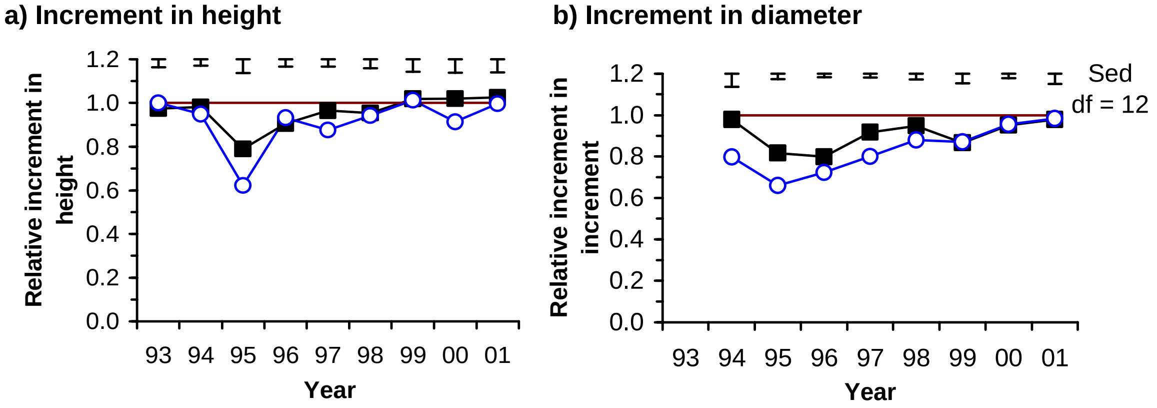

Figure 3.3 *Effect of cropping treatment on the a) relative increment in height and b) the relative increment in diameter in the: alternately-cropped (*■*) and continuously-cropped (*○*), treatment compared to that in the continuous fallow treatment.*

3.5 Prediction of future timber yield

In order to determine the economics of the agroforestry system, it is necessary to predict the timber volume from the system. Using the height (h) and the diameter (dbh) measurements for each tree within the continuously-cropped treatment from 1992 to 2002, the cylindrical volume of each tree ($h\,\pi(dbh/2)^2$) was calculated for each year. The volume of timber was then determined by multiplying the cylindrical volume by a form factor (f) to account for the taper of the tree. Using the data presented by Christie (1994) for poplars at a spacing of 8 m x 8 m, a curvilinear relationship was found between the form factor of widely-spaced poplar and the cylindrical volume (Figure 3.4).

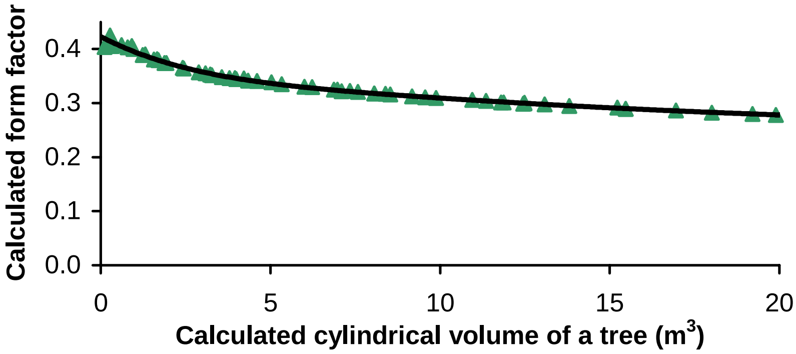

Figure 3.4 *Relationship between form factor (f) calculated from Christie (1994) and the cylindrical volume of a tree (V) (with relationship fitted to data points,* ▲ *of* $f = 0.4231 - 0.032647V + 0.0046804\,V^2 - 0.000411516\,V^3 + 0.000020254\,V^4 - 0.00000051615\,V^5 + 0.0000000052953\,V^6$; $R^2=0.995$; $n = 68$*).*

Using this relationship, the volume of each hybrid at each of the sites was calculated from the mean height (h) and the mean diameter at breast height (dbh) for each year from April 1993 to April 2002. In April 2002, Beaupré showed the greatest volume at both Silsoe and Leeds. In contrast at Cirencester the greatest volume was achieved by Trichobel. The predicted cumulative increase in the timber volume of Beaupré within the continuously-cropped treatment at Silsoe and Leeds, and that for Trichobel at Cirencester were plotted against time after planting, and compared with the provisional curves for poplars planted at an equivalent plant density (156 trees ha^{-1}) presented by Christie (1994) (Figure 3.5).

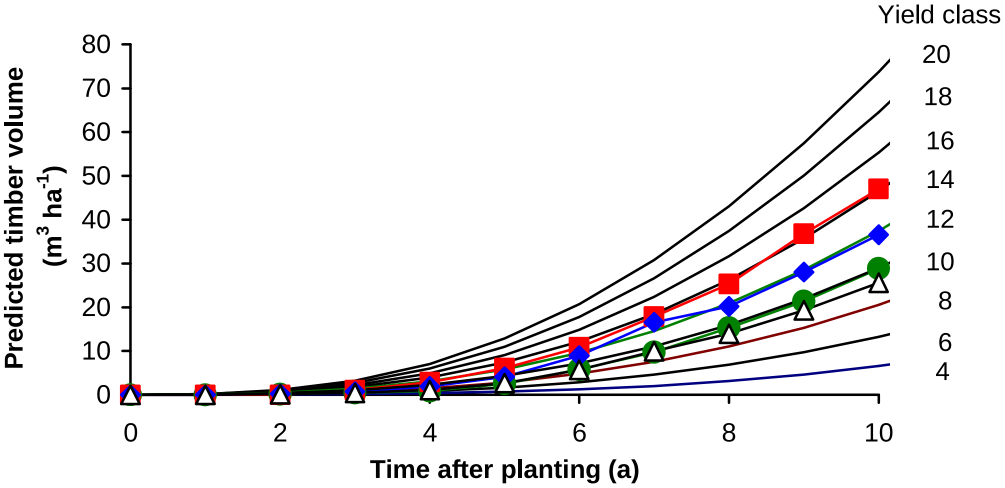

Figure 3.5 *Comparison of the calculated development of timber volume for poplar hybrids, surrounded on both sides by a continuously-cropped alley, from one year to 10 years after planting with the volume production functions of poplars at a spacing of 8 m x 8 m described by Christie (1994) for yield classes 4 to 20. Beaupré at Silsoe,* ■*; Beaupré at Leeds,* ◆*; and Trichobel at Cirencester,* ●*, and the mean value for all hybrids in the continuously-cropped treatment,* △*.*

The cumulative timber volume of Beaupré at Silsoe most closely matched that of yield class 14; i.e. the predicted maximum mean annual volume increment of the stand is predicted to be 14 m^3 ha^{-1} a^{-1}. The volume production curve of Beaupré at Leeds and Trichobel at Cirencester most closely matched yield classes 12 and 10 respectively. The mean timber volume of all the hybrids in the cropped treatments across the three sites appeared to match a yield class of 9. In the absence of other information, the yield class curves provide a possible method for predicting future timber yield (Figure 3.6).

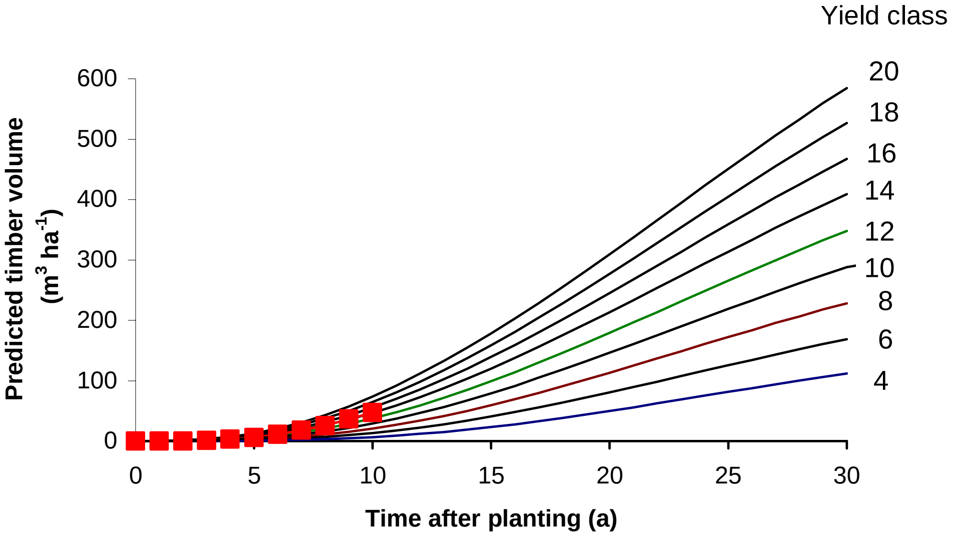

Figure 3.6 *Comparison of the calculated development of timber volume for poplar hybrids, surrounded on both sides with a continuously-cropped alley, from one year to 30 years after planting with the volume production functions of poplars at a spacing of 8 m x 8 m described by Christie (1994) for yield classes 4 to 20. Beaupré at Silsoe:* 🟥.

3.6 Conclusions

Ten years after planting, the greatest height and diameter at Leeds and Silsoe was achieved by the hybrid Beaupré. Seven years after planting, Beaupré also had the greatest height and diameter at Cirencester. However during 1999, 2000 and 2001, eight to ten years after planting, infection by the new race of poplar rust has meant that Beaupré at Cirencester showed smaller height and diameter increments than Trichobel. To minimise susceptibility to such damage, growers should select a range of hybrids when planting a poplar plantation, and the most appropriate hybrids are likely to be site-specific.

The creation of a bare-fallow area to both sides of the trees led to greater increments in height and diameter for the period 4 to 6 years, and 3 to 8 years after planting respectively. This effect was not significant in the ninth or tenth year after planting. These results show that controlling competition for water and nutrients can increase initial poplar growth. However for the purpose of predicting future returns, timber production was based on the continuously-cropped treatment.

The greatest yield class achieved in the cropped treatment is predicted to be 14 by Beaupré at Silsoe, 12 by Beaupré at Leeds and 10 by Trichobel at Cirencester. Across all three sites, the predicted maximum mean annual increment of the four hybrids is calculated to be 9 m^3 ha^{-1} a^{-1}. These values are substantially less than values of 22 m^3 ha^{-1} a^{-1} discussed by Newman *et al.* (1995). In March 2003, the mean height of the 15-year-old poplar trees at Wolverton in Buckinghamshire was 25.6 m and the mean dbh was 36.5 cm. As the trees were planted in February 1988, this appears to indicate a yield class between 18 (height=25.1 m) and 20 (height = 26.2 m). These values show the importance of selecting an appropriate site for poplar. The Wolverton site is an alluvial flood plain sheltered from wind - an ideal site for poplar. In contrast the site at Leeds is a free draining shallow soil over Magnesian limestone - not a natural choice for growing poplar.

4. Effect of trees on arable crop yields

The second objective of the project (Objective 1.2) was to determine the effect of poplars 7 to 10 years after planting on arable crop yields.

4.1 Control and relative yields

The four cropping seasons from 1999 to 2002 were successful at Leeds, where four consecutive cereal crops gave yields of between 5.6 t ha^{-1} and 7.9 t ha^{-1} (Table 4.1). By contrast, the yields obtained on the control area of the six cereal crops grown at Cirencester and Silsoe were low (3.4 t ha^{-1} to 5.4 t ha^{-1}). At Silsoe, part of the reason for the low yields was late sowing of the crop and subsequent waterlogging on the heavy clay soil. In fact waterlogging of the Silsoe site prevented the establishment of a crop during the winter and spring of 2000/2001. Problems with the layout of the winter bean crop at Cirencester in 1999 mean that these results are not included.

Table 4.1 *Mean yields (t ha^{-1}) of the crops in the control, the continuously-cropped and what was the alternately-cropped treatments in the silvoarable system at each site for 1999, 2000, 2001 and 2002, expressed in terms of the cropped area. The values in brackets express the yield as a proportion (%) of the control.*

Site	Year	Crop	Treatment						
			Control		Continuously-cropped			Alternately-cropped[1]		
Cirencester	1999	Winter beans	-		-			-		
	2000	Winter wheat	4.10	a	3.60	b	(88)	3.69	b	(90)
	2001	Spring wheat	4.19	a	3.10	b	(74)	3.12	b	(74)
	2002	Winter barley	5.38	a	2.02	c	(38)	2.72	b	(51)
Leeds	1999	Winter barley	5.63	a	5.50	b	(98)	6.40	a	(114)
	2000	Winter wheat	6.55	b	6.04	c	(92)	7.04	a	(107)
	2000	Winter wheat	*8.97*[2]	*a*	*6.04*	*c*	*(67)*	*7.04*	*b*	*(78)*
	2001	Winter wheat	6.38	a	4.70	b	(74)	4.00	c	(63)
	2002	Winter barley	7.86	a	5.39	b	(69)	5.28	b	(67)
Silsoe	1999	Spring wheat	3.42	a	2.64	b	(77)	2.19	c	(64)
	2000	Winter wheat	4.53	a	4.49	a	(99)	4.29	b	(95)
	2001	Bare fallow	0.00		0.00			0.00		
	2002	Winter barley	4.21	a	2.96	b	(70)	2.58	c	(61)

Note: Yields followed by the same letter are not significantly different for that year and site.

[1]: In 2000, 2001 and 2002, the alternately-cropped treatment has been continuously-cropped with a bare understorey.

[2]: This control yield is taken from a separate faunal control area.

Across the three sites, the mean relative yield in the continuously-cropped treatment was 87% (range: 77-98%) in 1999 and 93% in 2000 (range: 88-99%) (Table 4.1). Similar values across the three sites were also recorded in the alternately-cropped treatment (89-97%). These values of relative yield are similar to those relative yields recorded during the period 1992 to 1998 (range: 86% to 105%) (Burgess *et al.*, 2003) (Figure 4.1). The high relative yields in 2000 are surprising as the poplar were unpruned during the period September 1999 to March 2000 and hence shading would be expected to increase. However the values are sensitive to the choice of the control yield; for example in 2000 the yield from the arable control area at Leeds (6.55 t ha^{-1}) was reduced due to an infestation of couch, sterile brome, and cleavers. In contrast the yield in the faunal and botanical control area was 8.97 t ha^{-1}, and if this yield is used as the 'control' yield, then the relative yield in the continuously-cropped treatment at Leeds would have been 67% in 2000 (Table 4.1).

The relative yields in the continuously-cropped treatments in 2001 (74%) and 2002 (range: 38% to 70%) were substantially lower than in previous years. A similar decline in yields was also recorded in the alternately-cropped treatment (Table 4.1). The decline in the mean relative yield from 2000 to 2002 can be explained in part by an increase in shading, as Gibecq (due to its poor form) and Beaupré (due to already achieving its maximum bole height) were not pruned between September 2001 and March 2002. The relative yield within the continuously cropping treatment at Cirencester in 2002 appears particularly low (38%). Field observations suggest that the crop within the continuously-cropped alleys was affected by rabbit damage, waterlogging and soil compaction, and therefore this result may not be representative of the general effect of the trees.

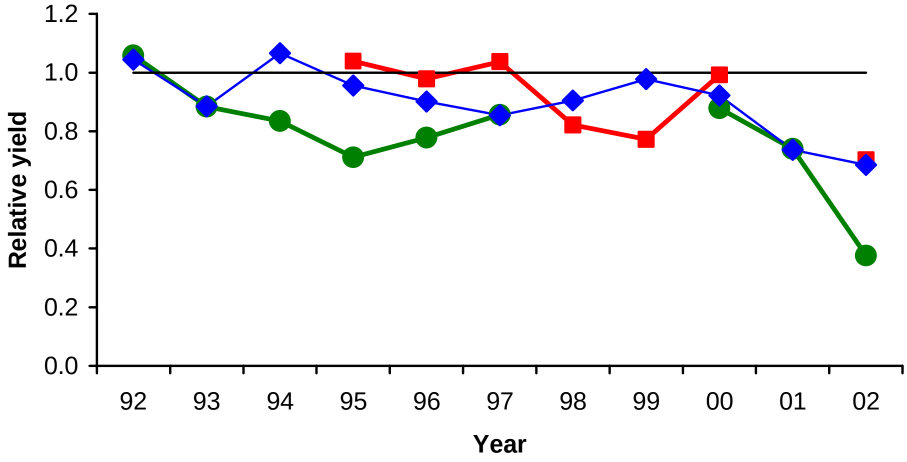

Figure 4.1 *Effect of age of trees on the crop yield in the continuously-cropped alleys relative to control yields at Cirencester:* ●, *Leeds:* ◆, *and Silsoe:* ■.

4.2 Prediction of future crop yield

The relative yield within the continuously-cropped treatments declined from an average of 105% in 1992 (in the year of tree planting) to 69% in 2002 (ten years after planting). The possible causes for this include competition for light, water, and nutrients, the effect of the trees and associated understorey on weeds, pests and diseases, the effects of leaf litter, and soil compaction. To predict the economic impact of the agroforestry system, it is necessary to predict relative crop yields until the end of the tree rotation, assumed to be 30 years. Therefore a model relating relative yield to the size of the tree canopy was developed.

It can be advantageous to consider the incident light available to the understorey crop (I) as having two components (Jackson and Palmer, 1989). The first component is the available light that misses the trees altogether (I_f); the second component is the light that passes through the canopy of the trees (I_c). Jackson and Palmer (1989) reported that the amount of light passing through the canopy that actually reaches the understorey crop is also dependent on the leaf area index of the tree canopy (LAI) and the light extinction coefficient within the tree canopy (k) (Equation 4.1).

$$I = I_f - I_c e^{-k\,LAI} \qquad \text{Equation 4.1}$$

The amount of light that passes through the tree canopy (I_c) is dependent on the size, shape and nature of the tree canopy and the incident light, which will vary with latitude, the time of year and the time of day.

4.3 Dimensions of the tree canopy

A key variable in many canopy models of light interception is the width of the canopy (C_w; unit m). Because the branches of a free-growing tree are assumed to spread equally in each direction, the canopy width can also be referred to as the canopy diameter. In one version of an economic agroforestry model for poplar (T. Thomas, personal communication), the value of C_w was determined from the depth of the crown (C_{depth}; unit m) and the diameter of the trunk at breast height (Dbh; unit m) (Equation 4.2).

$$C_w = 2.74 + 0.00238Dbh - 0.194C_{depth} \qquad \text{Equation 4.2}$$

However Equation 4.2 predicts that the canopy width declines as the canopy depth increases. This is not intuitive as canopy width is expected to decrease, for example, with pruning operations, which reduce canopy depth. To develop a new relationship, tree height, diameter at breast height, canopy depth, and canopy width of Beaupré were measured at Silsoe in June 1998 (n = 5), June 1999 (n = 15) and February 2003 (n = 5). In addition measurements were taken on one-to-two-year-old poplars planted at Warren Wood farm in Bedfordshire (n = 15) and on 15-year-old Beaupré and Boelare hybrids in March 2003 at Wolverton in Buckinghamshire (n = 22). These sites have been described Burgess *et al.* (2000a) and Newman *et al.* (1995) respectively. These data show a linear relationship between maximum canopy width and canopy depth for Beaupré (Figure 4.2a). Data for the Robusta and Trichobel hybrids also gave a similar linear relationship. Measurements on the Gibecq hybrid also showed a linear relationship, but the canopy width for a given canopy depth was greater than for the other hybrids. The new relationship predicts smaller canopy widths when the canopy depth is small and larger canopy widths for deep canopies than Thomas does (Figure 4.2b).

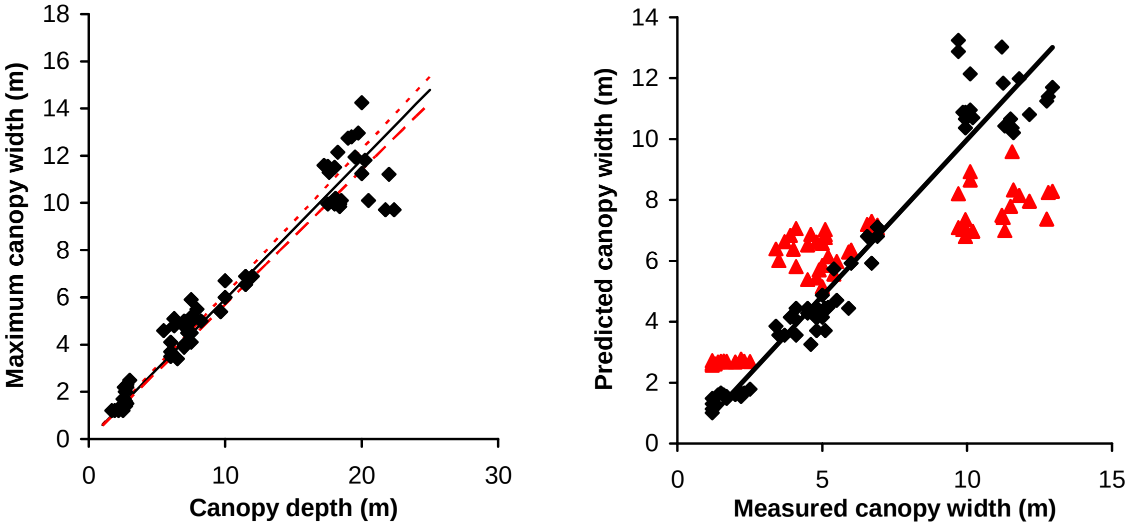

Figure 4.2 *(a) Relationship between the canopy depth of Beaupré and the maximum canopy width (the fitted line is $C_w = 0.5919(\pm 0.0103)\ C_{depth}$ (d.f.=64; R^2=93%), and (b) a comparison of the measured and predicted canopy width from the new relationship ◆ and that predicted by Thomas ▲; the fitted line is a 1:1 relationship.*

Whilst measurements of tree height and diameter at breast height were recorded each year, the depth of canopy was first routinely recorded during the winter of 2001/02. The principal management practice affecting canopy depth is pruning. Hence, to predict the canopy depth from planting to the present, it was necessary to describe the pruning at each site (Table 4.2). The principal aim of the pruning regime was to achieve an optimum bole about 8 m high, whilst maintaining a canopy depth equal to about half of the tree height (Figure 4.3). The management of pruning at Cirencester, Leeds and Silsoe followed the same protocol.

Table 4.2 *The pruning policy practised which was essentially the same at each of the three sites.*

Winter period and year	Potential number of whorls	Number of whorl removed	Comments
Sept 92-Mar 93	1		Trimmed to half height
Sept 93-Mar 94	2	1	Pruned to leave 1 whorl
Sept 94-Mar 95	3		No pruning
Sept 95-Mar 96	4	2	Pruned to leave 2 whorls
Sept 96-Mar 97	5		No pruning
Sept 97-Mar 98	6	3	Pruned to leave 3 whorls
Sept 98-Mar 99	7	4	Pruned to leave 3 whorls
Sept 99-Mar 00	8		Selective pruning to half total height
Sept 00-Mar 01	9	5	Pruned to leave 4 whorls
Sept 01-Mar 02	10	6*	Selective pruning
Sept 02-Mar 03	11		No pruning

Note: * Beaupré typically unpruned as already pruned to height of 7-8 m; Gibecq unpruned because of poor form; Robusta and Trichobel pruned to leave 4 whorls

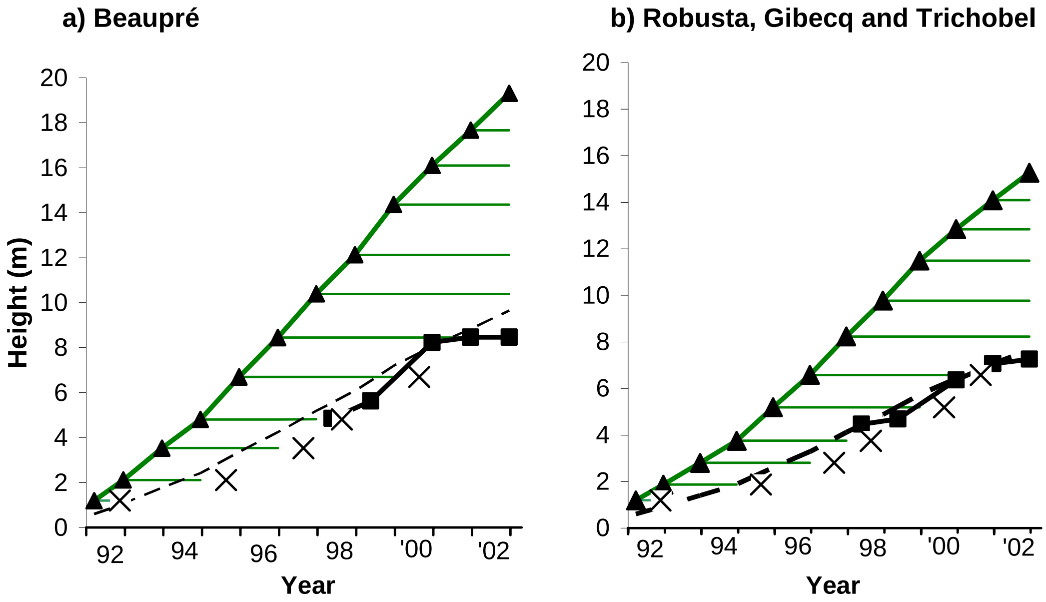

Figure 4.3 *Comparison of the pruning regime at Silsoe on a) Beaupré and b) Robusta, Gibecq and Trichobel. The top full line shows the tree height and the position of each whorl:* ▲*; the dotted line shows 50% of tree height. The measured height of lowest whorl or branch;* ■ *, and the dates of pruning (×) are also shown.*

4.4 Calculation of light interception by the tree canopy

For a tree of minimal height near the ground, the shaded area can be assumed to be equal to the projected area of the canopy. The projected area of shading (A_{shade}) can be derived from the width of the canopy (C_w), the intra-row spacing (the distance between trees in the row, R_w) and the alley width (A_w) (Figure 4.4). If the tree can grow freely in each direction, then the vertically projected shape of the canopy (A_{shade}) is circular.

An early model of shading (Burgess *et al.*, 2000a) assumed that any overlapping of tree canopies resulted in compensatory growth of the tree canopy into the alley. Observations of closely-spaced fifteen-year-old poplar at Wolverton in March 2003, suggested that, whilst it is correct to assume minimal mixing of poplar canopies, there is little evidence of compensatory growth. Between the point of no canopy overlap (Equation 4.3) and the maximum possible canopy area (equivalent to A_w

multiplied by R_w), a set of rules (Equations 4.4 and 4.5) was developed to describe the growth of the tree canopies:

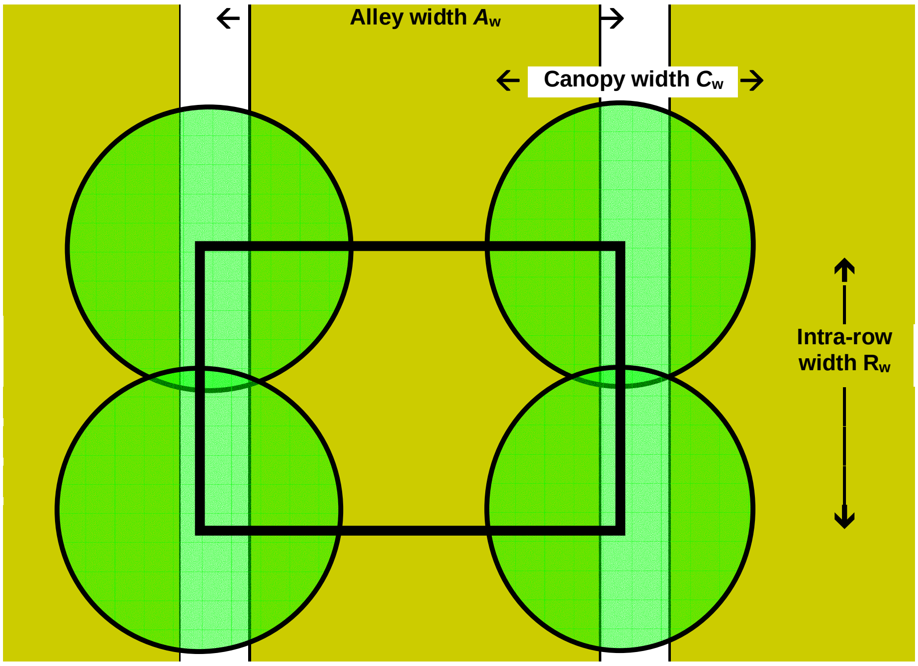

Figure 4.4 *Calculation of the projected area of the canopy. Yellow = alley; white = tree row understorey; green = tree.*

If $C_w < R_w$, then

$$A_{shade} = \pi(0.5C_w)^2 \tag{Equation 4.3}$$

If $C_w > R_w$, but $< A_w$ then

$$A_{shade} = \pi(0.5C_w)^2 - 2\left[\operatorname{acos}(R_w / C_w)(0.5C_w)^2 - (0.5C_w)\sin\operatorname{acos}(R_w / C_w)(0.5R_w)\right] \tag{Equation 4.4}$$

If $C_w > R_w$ and $> A_w$ then

$$A_{shade} = A_{shade} - 2\left[\operatorname{acos}(A_w / C_w)(0.5C_w)^2 - (0.5C_w)\sin\operatorname{acos}(A_w / C_w)(0.5A_w)\right] \tag{Equation 4.5}$$

If $C_w > R_w / \sin\operatorname{atan}(R_w / A_w)$, then

$$A_{shade} = R_w A_w \tag{Equation 4.6}$$

Jackson and Palmer (1972) developed a computer model that showed that a two-dimensional model of shading, such as that above, which ignored the effect of tree height would underestimate the amount of shading from a continuous hedgerow. For example, they calculated that, between 7 May and 28 October at a latitude of 51°N, triangular-shaped hedgerows, spaced 10 m apart with a north-south orientation and presenting a solid block of vegetation which was 10-m-high and 5-m-wide at the base, would intercept 81% of the solar radiation, rather than 50% estimated from canopy width alone. However, whereas Jackson and Palmer's model assumes a continuous hedgerow, within the experiment there were significant gaps between the trees in the row. Making assumptions about the effective height of the trees, a version of the Jackson and Palmer model was used to determine the possible effect of canopy height on shading within the experiment. An initial analysis for one specific day (22 June) indicated that including an effect of tree height, at a 10-m alley width, resulted in the shading being only between 0% and 7% greater than that predicted from the two-dimensional model. Hence, because of the relatively small effect, the effect of tree height on shading was ignored. Also the relevant calculations are complex and ideally would need to be undertaken for each hour for each day of the whole season.

In some canopy models (Norman and Wells, 1983; Reid and Ferguson, 1992; Chen *et al.*, 1994), it is possible to estimate the shading at each point in the alley. This can be useful for estimating changes in potential yield across transects. However Jackson and Palmer (1989) reported that when the height of a hedge, aligned north-to-south, was equal to the alley width, then the shading across the alley surface became relatively uniform. In the case of our experiment, the depth of the canopy was close to the alley width by seven years after planting. Hence, to simplify the model, it was assumed that the shading by the canopy occurs uniformly across the alley.

4.5 Establishing parameters for the model

Having developed a shading model to establish an annual value of I_c, the model also requires values for the light extinction coefficient, the leaf area index (LAI), and the relationship between solar radiation and the yield of the alley crop. A value of 0.5 was initially chosen for the light extinction coefficient. This is same as the value used for aspen by Stadt *et al.* (2001). Cannell *et al.* (1988) also reported that the light extinction coefficient for poplar varied between 0.4 and 0.6 during the growing season.

The leaf area index of a deciduous canopy, such as poplar, varies during the season. Hall *et al.* (1996) recorded that the leaves of short-rotation poplar coppice (cv Beaupré) in southern England emerged in mid-April, that the leaf area index reached 2 by mid-May, peaked at 4 from mid-June to mid-September, with leaf fall complete by the end of November. Cannell *et al.* (1998) reported poplar in Scotland having a LAI less than 1 at the end of June, reaching a maximum of about 4.5 between August and September before declining to zero by the end of November. Stadt *et al.* (2001) predicted that young stands of aspen in Canada had a maximum leaf area index of about 6, whilst Isebrands and Nelson (1982) reported indices of 7.6 to 8.8 for five to seven-year old stands of short-rotation coppice poplar in Canada. Ceulemans *et al.* (1993) reported maximum values of LAI for Beaupré of 5.6-6.7 and for Robusta of 3.9-4.3. For the purposes of the model a leaf area index of 4 was chosen.

The relationship between the relative yield of the crop ($Y_{actual} / Y_{potential}$) was assumed to be linearly related to the amount of solar radiation available (I) divided by the potential solar radiation (S) (Scott *et al.* 1992) (Equation 4.7).

$$Y_{actual} / Y_{potential} = I / S \qquad \text{Equation 4.7}$$

4.6 Sensitivity to the light extinction coefficient and the leaf area index

The effect of tree shading on crop yields within the experiment was initially calculated from the light interception model by using the mean tree height and diameter for all four hybrids within the cropped treatments across the three sites (i.e. yield class 9). During the first ten years, the yields predicted by the model are relatively insensitive to the assumed light extinction and the leaf area index (Figure 4.5).

Between April and July 1997, the relative levels of short-wave radiation perpendicular and directly below the canopies of three Trichobel and three Beaupré trees were recorded at Silsoe (Bechtel, 1997) (Figure 4.6). The prediction of the light interception model, assuming a leaf area index of 4, closely matched the measured light interception between late May and late June.

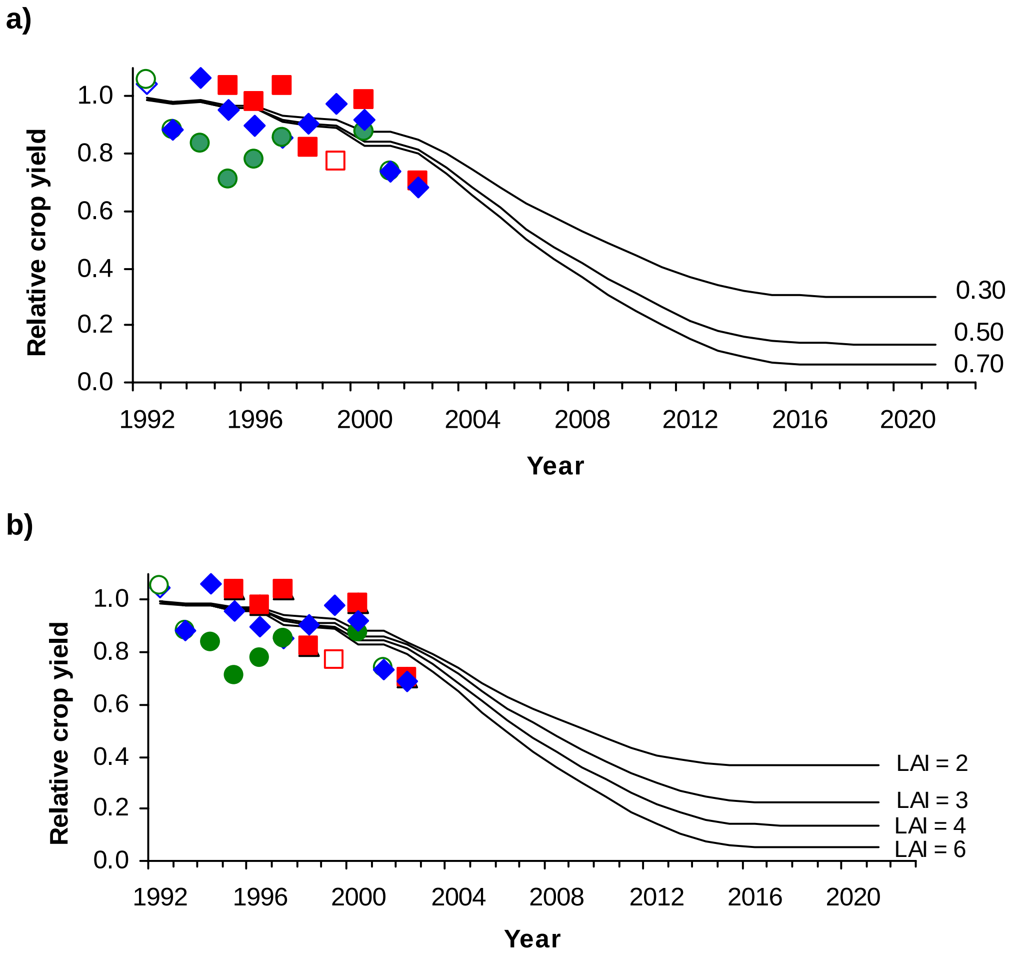

Figure 4.5 *The sensitivity of crop yield relative that of a sole crop to a) light extinction coefficient 0.3-0.7 assuming an leaf area index of 4, and b)leaf area index from 2 to 6 assuming a light extinction coefficient of 0.5, as predicted by the model (lines). Measured relative crop yields: winter crop at Cirencester* ● *; spring crop at Cirencester:* ○*; ; winter crop at Leeds* ◆*; spring crop at Leeds:* ◇*; winter crop at Silsoe:* ■*; spring crop at Silsoe:* □

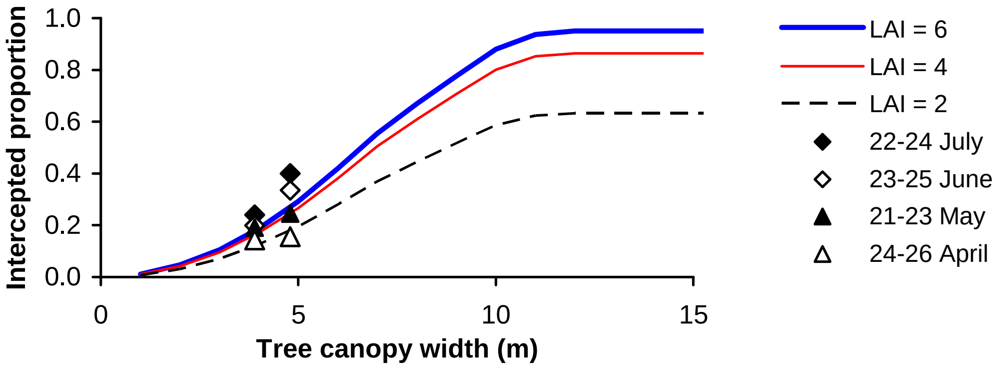

Figure 4.6 *Comparison between the predicted proportion of radiation intercepted by the tree canopy at three leaf area indices (LAI) (lines) and measured interception (symbols) over a 4-month period at the Silsoe site in 1997 (Bechtel, 1997).*

The appropriate value of the 'mean' leaf area index for predicting the effect of poplar on crop yield is also dependent on the temporal complementarity between the seasonal shading pattern of the poplar and the light requirements of the crop. For example an autumn-planted cereal crop can intercept substantial radiation in the spring before the poplar comes into leaf, and hence the poplar may only compete for about 50% of the light that could be intercepted by the crop. By contrast poplar may compete for about 75% of the light that could be intercepted by a spring-planted crop. Hence there is an argument for assuming a higher leaf area index when determining the effect of the trees on a spring-planted crop.

4.7 Sensitivity of crop yield to yield class and pruning regime

The model was used to predict the differences in relative yield that could result from differences in tree canopy growth and pruning regime. During the first eight years, the predicted relative yields were relatively insensitive to whether the trees had a yield class of 9 (relative yields = 91-99%) or 14 (relative yields = 86-99%) (Figure 4.7). This is because the pruning regime ensures that the canopy sizes of the slow and fast growing trees are maintained relatively similar. However after the eighth year, once the maximum bole height of about 8 m is reached for the fastest growing trees and pruning is stopped, shading and hence the reduction in crop yield, is predicted to increase rapidly. There is some evidence for this effect at Leeds, where the yield below unpruned Gibecq was reported to be less than that below the other hybrids for the first time in several sub-plots in 2001.

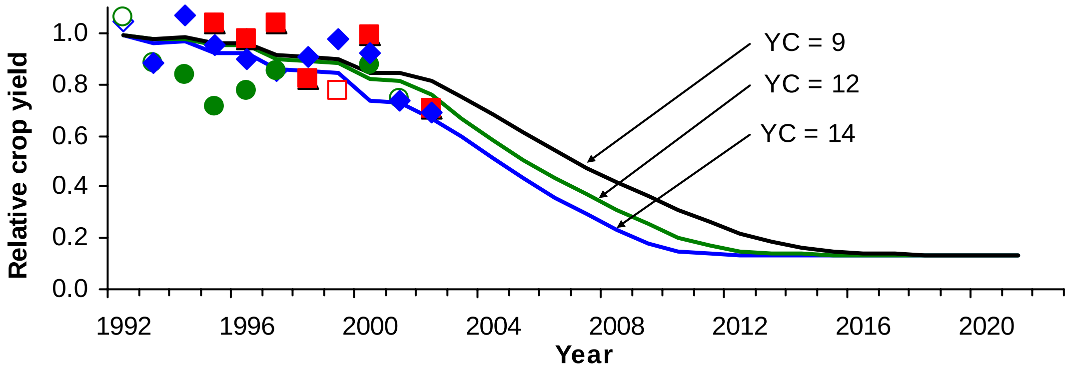

Figure 4.7 *The predicted crop yields relative to a sole crop for each of three yield classes (14, 12 and 9), assuming a leaf area index of 4 and a light extinction coefficient of 0.5). Actual relative yields at each of the three sites in each year: winter crop at Cirencester ●; spring crop at Cirencester: ○; winter crop at Leeds ◆; spring crop at Leeds: ◇; winter crop at Silsoe: ■; spring crop at Silsoe: □.*

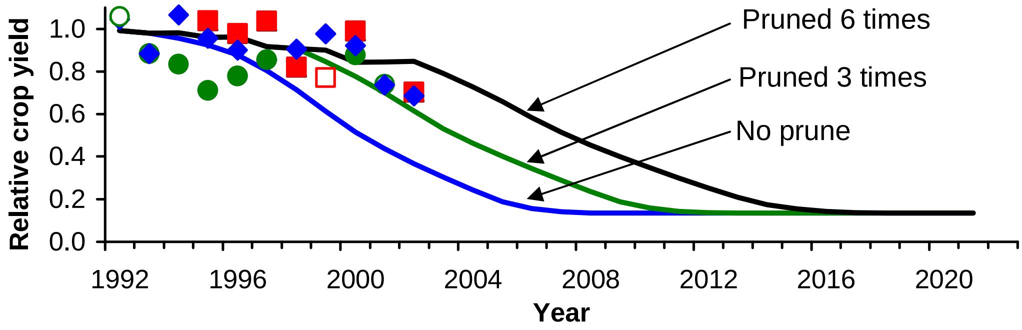

Figure 4.8 *The predicted effect of pruning on crop yields relative to that of a sole crop with a yield class of 9 (assuming a leaf area index of 4 and a light extinction coefficient of 0.5). Actual relative yields at each of the three sites in each year: winter crop at Cirencester ●; spring crop at Cirencester: ○; winter crop at Leeds ◆; spring crop at Leeds: ◇; winter crop at Silsoe: ■; spring crop at Silsoe: □.*

The effect of pruning regime on relative yield was investigated by three pruning programmes: no pruning, pruning to a height of about 4 m (pruned in years 2, 4 and 6), and pruning to a height of about 8 m (pruned in years 2, 4, 6, 7, 9 and 10) (Figure 4.8). The analysis suggests that the relative crop yield is very sensitive to the pruning regime. For example, the predicted relative yield in the tenth year after planting (2002) was 44% with no pruning, 70% when pruned three times and 84% when pruned six times.

The analysis of the sensitivity of the model shows the importance of the pruning regime and the choice of the yield class beyond year 8. A regression analysis of the predicted relative yields against the actual yields recorded in the experiment indicates that, although the mean yield class of the trees in the cropped areas was 9, a better fit was obtained by assuming a yield class of 14. In fact such a relationship could explain 55% of the inter-annual variation in the mean relative yield across the three sites (Figure 4.9). The possible reason why a higher yield class gave a better fit than the actual yield class is that, in addition to the effect of shading, crop yields within the alleys could also be reduced by competition from trees and weeds for water and nutrients and the negative effects of leaf litter.

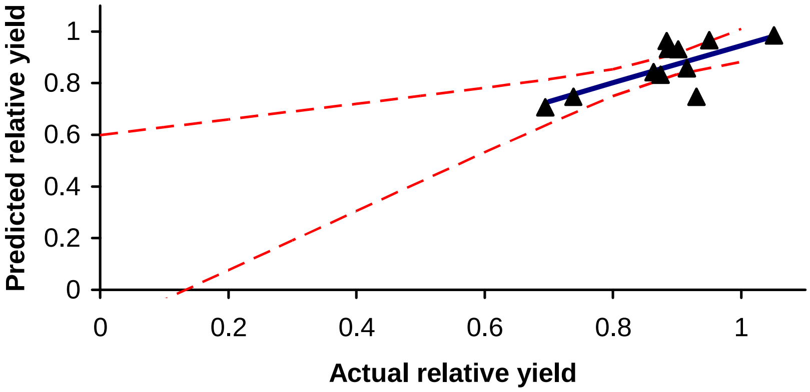

Figure 4.9 *Relationship between the predicted mean annual yield and the annual yield (▲) calculated assuming a yield class of 14, pruning in years 2, 4, 6, 7, and 9, a leaf area index of 4, a light extinction coefficient of 0.5; data for Cirencester in 2002 is excluded (fitted regression line: y = 0.723 (± 0.200) + 0.223 (± 0.177); R^2 = 0.547).*

4.8 Conclusions

During the first seven years of the experiment, the yield in the continuously-cropped treatments ranged from 86% to 105% of that in the control area. The mean relative yield then remained between 87% and 93% in 1999 and 2000, eight to nine years after planting, before declining to 74% in 2001 (year ten), and 69% in 2002 (58% if the result from Cirencester is included). The decline in year eleven was partly associated with the cessation of pruning.

A model was developed to calculate the potential effect of shading by the tree canopy on crop yield. The model, assuming a light extinction coefficient of 0.5, a leaf area index of 4, a yield class of 14, and a stated pruning regime to year 9, could explain 55% of the inter-annual variation in the mean yield across the three sites. Hence, in the absence of other information, such a model could be used to predict future crop yields. A yield class for the poplar of 14, rather than a value of 9 (as indicated by the mean size of the trees in the cropped treatment across the three sites) resulted in a better explanation of the annual change in relative crop yield. One reason for this is that the reductions in yield beneath the trees are not only due to the effect of shading, but to other factors such as competition with trees and weeds for water and nutrients, and leaf fall.

5. Economics of the system relative to agriculture and closely-spaced poplar

The third objective of the project (Objective 1.3) was to evaluate the economics of the silvoarable system relative to agriculture and closely-spaced poplar. To achieve this, the financial costs and benefits of agricultural, poplar forestry and silvoarable systems were analysed using a spreadsheet model developed from POPMOD (Thomas, 1991; Willis *et al.*, 1993; Burgess *et al.*, 2000a). The two key components of the model were a) the physical and financial data of the arable component of the systems, and b) the physical and financial data of the poplar component.

5.1 Physical data for the crop components

The physical data for the arable system and the crop component of the silvoarable system were based on the yields and rotation used at Leeds. Actual yields were recorded from the control plots at Leeds for first winter wheat (8.67-10.55 t ha^{-1}), second winter wheat (6.38-8.17 t ha^{-1}), winter barley (7.68-7.86 t ha^{-1}), peas (5.46 t ha^{-1}), spring mustard (4.17 t ha^{-1}) and spring barley (6.34 t ha^{-1}). The typical rotation comprises wheat, wheat, barley and a break crop. However in the experiment, this rotation was interrupted in 2000, when a wheat crop was grown after barley in order to synchronise the cropping rotation of the three Network sites.

For the economic analysis, it was assumed that a continuous rotation of wheat, wheat, barley and oilseed rape would be practised. It was assumed that the yield of the first wheat would be the average of the crops at Leeds in 1994 and 1998 (9.61 t ha^{-1}), that the yield of the second winter wheat would be the same as the crop in 1995 (8.17 t ha^{-1}), and the yield of barley would the average of the yield in 1996 and 2002 (7.77 t ha^{-1}). It was assumed that the break crop would be oilseed rape with an 'average' yield of 3.20 t ha^{-1} (Nix, 2002).

The relative yield within the cropped alleys of the silvoarable system was determined by the model described in Section 4. It was assumed that the height and diameter of the poplar would be the same as that recorded for the Beaupré hybrid in the continuously-cropped treatments at Silsoe for years 1 to 11, and thereafter follow the growth characteristic of poplar with a yield class of 14. It was assumed that pruning would occur in years 2, 4, 6, 7 and 9 (as in the experiment), the mean leaf area index was 4 and the light extinction coefficient was 0.5. Silvoarable systems can be planted at a range of alley widths to accommodate conventional sizes of agricultural machinery, which typically operate over widths of 12 to 24 m (Incoll and Newman, 2000). Using the shading model, yield curves were predicted for systems with 10-, 14-, 20-, and 40-m alleys, in each case assuming a 2-m-wide tree row. As expected, narrow alley widths led to earlier reductions in crop yields (Figure 5.1).

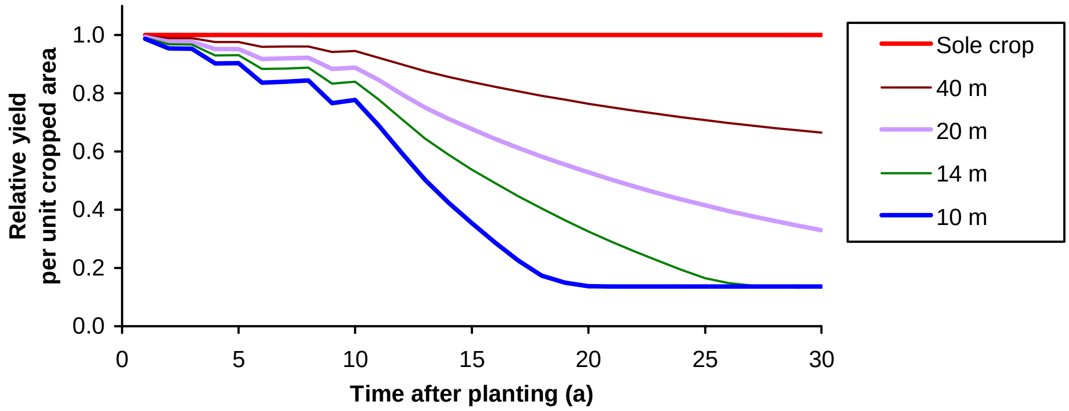

Figure 5.1 *Predicted effect of alley width on the relative yield of the arable crop with trees of yield class 14.*

5.2 Financial data for the crop components

The financial data for the arable systems (variable costs, operating costs and fixed costs) were largely based on values provided by Nix (2001, 2002) (Table 5.1).

Table 5.1 *Values of crop revenue, grants and costs used in the model.*

Crop	Grain price[1]	Area[2] payment	Seed[3]		Fertiliser (N)[4]		Sprays[5]		Total variable costs[8]	Labour [6]	Mach-inery[7]
			Rate	Cost	Rate	Cost[6]	No.	Cost			
	£ t^{-1}	£ ha^{-1}	kg ha^{-1}	£ kg^{-1}	kg ha^{-1}	£ kg^{-1}		£	£ ha^{-1}	hr ha^{-1}	£ ha^{-1}
Wheat 1	63	227	230	0.17	180	0.40	5	21	216	10	162
Wheat 2	63	227	230	0.17	220	0.40	5	21	232	10	162
Barley	60	227	210	0.19	180	0.38	3	26	186	10	162
Oilseed	135	261	6	5.00	210	0.42	4	22	206	12	122
Set-aside	0	227	0	0.00	0	0	0	0	0	1	11
Pasture		0	0	0					0		

1. Crop prices are based on values in Nix (2002). Cereal prices are based on values for feed wheat or barley.
2. Area payment for cereals, oilseeds and set-aside (£227 ha^{-1}) are based on estimated 2002 values for England (Nix, 2002). It is assumed that fallow areas would not be eligible for set-aside payment under current rules because of the regular cultivation and the need for green cover by mid-January.
3. Seed rates for each crop are based on the Farm Management Handbook (The Scottish Agricultural College, 1999). Seed costs are based on seed price (Nix, 2002) divided by the seed rate.
4. Fertiliser rates are based on those recommended for medium and deep clay soils, and shallow soils over rock (not chalk) with a soil nitrogen supply (SNS) index of 1 (MAFF, 2000): Second winter wheat: 220 kg N ha^{-1}; first winter wheat and barley: 180 kg N ha^{-1}; winter oilseed rape: 210 kg N ha^{-1}. Fertiliser costs are based the fertiliser price (Nix, 2002) divided by the fertiliser rate.
5. Spray rates relate to the typical number of applications. Spray cost is assumed from the spray price given by Nix (2002) divided by number of applications. The calculated variable costs match those provided by Nix (2002).
6. Labour costs are based on values provided by Nix (2002). A half-day charge is assumed for the set-aside, including a £20 ha^{-1} charge for grass-topping (Nix, 2001). Set-aside land must not be grazed after mid-January. A day charge is also assumed for the maintenance of the fallow area comprising ploughing and two cultivations.
7. The machinery costs are based on the average of contractor and farmer prices for the agricultural operations of each enterprise (page 148-151, Nix, 2001) minus the assumed cost of the labour.
8. Nix (2002) quotes that the average price for grass keep can fall below £100 ha^{-1} in some eastern counties. However for this analysis it is assumed that any receipt covers maintenance costs and therefore there is no net cost or benefit.

5.3 Physical data for the tree components

The closely-spaced poplar system was based on an initial spacing of 2 m x 4 m, which gives a density at planting of 1250 plants ha^{-1}. A set of current annual increment curves was derived for poplar at three spacings: 3 m x 3 m, 4 m x 4 m and 8 m x 8 m (Christie, 1994) at a yield class of 14. The total length of the rotation was assumed to be 30 years.

Thinning (the removal of selected trees) is an important aspect of forestry management. The thinning of diseased and stunted trees allows future growth to be concentrated on the most saleable trees. Although frequent thinning helps to maximise the current annual increment, infrequent thinning can be more cost-effective because of the expense of setting up the felling equipment. The thinning regime was assumed to be the same as that used by the Poplar Tree Company (Poplar Tree Company, 1999). Thinning was assumed to start in year 6 (25%) and continued in year 8 (25%), year 10 (50%) and year 12 (55%) (Table 5.2). The effect of thinning on timber production was based on estimates of current annual increments for unthinned poplar at three spacings (Christie, 1994) and interpolations following a procedure described by Burgess *et al.* (2000a). It should be noted that the estimate of the timber volume produced by the closely-spaced system is 46% greater than those estimated by Christie (1994) for a 3 m x 3 m system thinned in years 7 and 11 to a final density of 133 trees ha^{-1}. Approximately half of the difference between the two approaches can be explained by the difference in the thinning regime and the lower final stand density.

Table 5.2 *Estimated timber yields from the silvoarable system with the poplars at a spacing of 10 m x 6.4 m,and a widely-spaced (8 m x 8 m) and a closely-spaced (2 m x 4 m) poplar system, assuming a yield class of 14.*

Time after planting (years)	Factor	Silvoarable 10 m x 6.4 m		Poplar 8 m x 8 m		Poplar 4 m x 2 m	
		Density of poplar trees (ha^{-1})	Yield of timber (m^3 ha^{-1})	Density of poplar trees (ha^{-1})	Yield of timber (m^3 ha^{-1})	Density of poplar trees (ha^{-1})	Yield of timber (m^3 ha^{-1})
1	At planting	156		156		1,250	
6	After 1st thinning					938	22
8	After 2nd thinning					703	28
10	After 3rd thinning					352	64
12	After 4th thinning					158	52
30	At clear fell	156	417	156	417	158	381

5.4 Financial data for the tree components

The financial data for the tree components comprise the timber revenue, the costs of woodland establishment and management, and grants.

Timber revenue

Whiteman *et al.* (1991), as quoted by Hart (1994), estimated a long-term relationship between the standing value of hardwood trees and average tree volume (Figure 5.2). This curve assumed no upward or downward long-term trend in timber prices. The predicted value of hardwood ranged, for example, from £24 m^{-3} for a tree with a volume of one cubic metre, to £40 m^{-3} for a tree with a volume of 3.2 m^3. Davenport (1995) reported actual values of the standing value of some 28- to 32-year-old poplar harvested in 1995. He calculated that the standing value of the trees, which had an average volume of 3.2 m^3, was about £24 m^{-3} (Table 5.3). This is 40% lower than the value predicted by Whiteman *et al.* (1991).

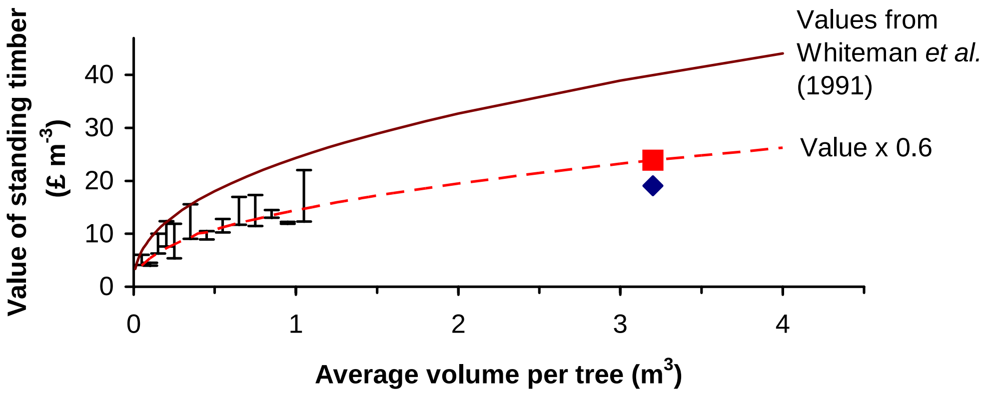

Figure 5.2 *Predicted long-term price curve for the standing value of hardwood (Hart 1994, quoting Whiteman et al. (1991) and estimates for poplar based on calculation from Davenport (1995)* ■ *and current prices:* ◆. *The bars show the highest and lowest mean prices received for standing softwood sales in 2000 and 2001 (Forestry Commission, 2003).*

From April 1994 to April 2002 the nominal value of standing timber sales in the UK declined by 53% from about £16 m^{-3} to £7.50 m^{-3}. The value of sawlogs also declined by 35% from about £40 m^{-3} to £26 m^{-3} (FCAP Supply and Demand Sub-committee, 2002). Using recent quotes for poplar timber (C. Irwin, personal communication 2001; G. Snell, personal communication 2003), the current standing value of poplar trees with a volume of 3.2 m^3 is estimated to be about £19 m^{-3} (Table 5.3). This is only 48% of the value estimated by Whiteman *et al.* (1991) (Figure 5.2). It might be expected that UK timber prices would increase following recent decreases in the value of the pound sterling against the Euro. Hence, for the purposes of this analysis, it is assumed that the long-term value of poplar is 60% of the value suggested by Whiteman *et al.* (1991). This curve would match the price received by Davenport (1995) and, for low timber sizes, it matches prices received for standing timber in England in 2001 and 2002 (Forestry Commission, 2003).

Table 5.3 *Estimates of the standing value of a mature poplar plantation.*

Product	Proportion of each product (%)[1]	Volume per tree[1] (m^3)	1995 estimated standing value[1] (£ m^{-3})	2003 estimated price at sawmill[2] (£ m^{-3})	Cost of transport, felling and extraction[3] (£ m^{-3})	2003 Estimated standing value (£ m^{-3})
Veneer[4]	60	1.93	28.08	36.00	11.70	24.30
Pallets	15	0.47	18.52	23.00	11.70	11.30
Pulp	16	0.51	12.28	18.00	11.70	6.30
Sawlogs	9	0.29	26.54	31.00	11.70	19.30
Total			23.92			19.02

1. Derived from information provided by Davenport (1995).
2. C. Irwin, Aston Timber Products (personal communication, 2001) quoted a price for peeler logs (30.5 cm to 68 cm diameter) at the factory of £36 m^{-3}, and for sawlogs of £31 m^{-3}. G. Snell, Poplar Tree Company Ltd (personal communication, 2003) quoted current values of £33 m^{-3} for veneer, £23 m^{-3} for pallets and £18 m^{-3} for pulp.
3. Davenport (1995) estimated a cost of felling and extracting poplar to the roadside of £4.70 m^{-3} and C. Irwin (personal communication, 2001) estimated a transport charge from Bedfordshire to Suffolk of £7 m^{-3}.
4. Peeler logs for veneer must be high-pruned with dimensions between 30 cm (12 inches) and 68 cm (27 inches) over bark (C. Irwin, personal communication, 2001).

Costs for the tree component

The costs associated with the forestry system and the tree component of the silvoarable systems were based on numerous sources. These are reported in Table 5.5, and compared with previous analyses.

Woodland grants and premiums

Woodland grants and premiums consist of revenue from the Woodland Grant Scheme (WGS) and the Farm Woodland Premium Scheme (FWPS) (MAFF, 1998). The forestry and silvoarable systems can both benefit from the WGS Planting Grant (70% in year 1 and 30% in year 5), and the WGS Better Land Supplement (year 1). For the 4 m x 2 m and the 8 m x 8 m poplar systems, the supplement is paid at the full-rate. It is assumed that the silvoarable system would receive the Better Land Supplement on a pro-rata basis. The FWPS receipts were assumed to occur over a period of 10 years, to provide the farmer with the option of harvesting the poplar before year 30 (Table 5.4).

Table 5.4 *Woodland-related grants received for two forestry systems and a 10 m x 6.4 m silvoarable system.*

Year	Grant	Poplar (4 m x 2 m) (£ ha^{-1})	Poplar (8 m x 8 m) (£ ha^{-1})	Silvoarable (10 m x 6.4 m) (£ ha^{-1})
1	WGS planting grant (70%)	945	134	134
1	WGS BLS	600	600	85
5	WGS planting grant (30%)	405	57	57
1 to 10	FWPS (@ £300 ha^{-1} yr^{-1})	3,000	3,000	0
	Total	4,950	3,791	276

Table 5.5 *Estimates of forestry costs used in the model.*

Operation	Unit	Thomas and Willis (2000)	Burgess *et al.* (2000b)	Silvoarable system	Poplar	Poplar forestry
Spacing between tree-rows	(m)	20	10	10	8	4
Intra-row spacing	(m)	6.4	6.4	6.4	8	2
Tree density	(tree ha^{-1})	78	156	156	156	1250
Establishment						
Cost of plant[1]	(£ tree^{-1})	1.00	1.00	0.80	0.80	0.80
Cost of individual tree protection[2]	(£ tree^{-1})	0	0.16	0.16	0.16	0.16
Cost of continuous tree mulch[3]	(£ m^{-2})	0.10	0.10	0.10		n/a
Cost of individual tree mulch[4]	(£ tree^{-1})			0.40	0.40	n/a
Ground preparation[5]	(£ ha^{-1})	0	0	0	150	150
Labour for planting trees[6]	(min tree^{-1})	1.5	3.0	3.0	3.0	2.0
Labour for tree protection[7]	(min tree^{-1})	0	0.4	0.4	0.4	0.4
Labour for continuous mulching[8]	(min m^{-2})	1.7	1.7	1.7		n/a
Labour for mulch mats[9]	(min tree^{-1})			1.7	1.7	n/a
Maintenance						
Single herbicide of tree row[10]	(min m^{-2})	0.50	0.20	0.08	n/a	n/a
Annual cost of herbicide[10]	(£ m^{-2})	0.001	0.005	0.0015	n/a	n/a
Removal of continuous mulch[11]	(min m^{-2} mulch)			1.5	n/a	n/a
Cost of grass seed for inter-row[11]	(£ m^{-2})			0.035	n/a	n/a
Labour to establish grass sward[11]	(min m^{-2})			0.5	n/a	n/a
Labour for grass cut intra-tree[12]	(min m^{-2})			0.3	n/a	n/a
Grass cut between tree rows[13]	(£ ha^{-1})				20	20
Tree maintenance[14]	(min tree^{-1})	2.3	1.15	1.15	1.15	0.57
Pruning						
Height at first prune	(m)	2	2	1	1	1
Labour per tree at first prune[15]	(min tree^{-1})	4	4	0.5	0.5	0.5
Labour to remove first prunings[17]	(min tree^{-1})	0	0	0.5	0.5	0.14
Height at last prune	(m)	8	8	8	8	8
Labour per tree at last prune[16]	(min tree^{-1})	12	12	15	15	4
Labour to remove last prunings[17]	(min tree^{-1})	0	0	4	4	0.14
Administration						
Insurance management[18]	(£ ha^{-1})	0	0	9	9	9
Thinning						
Marking up & labour[19]	(min m^{-3})	0	0	n/a	n/a	3

Notes:

1. Davenport (1995) reported poplar sets costing 95 pence each. Thomas and Willis (2000) reported a value of £1 per plant. Woodland Improvement and Conservation (2002) report a cost of rooted plants of Beaupré at 80 pence; whilst G. Snell (personal communication, 2003) reports that the Poplar Tree Company can supply 1.2 m sets of high yielding poplar hybrids at a cost of 60 pence. Each of these costs is higher than a typical cost of 25 pence for general broadleaf species. To account for transport costs and to account for the purchase of 1.8-m sets rather than 1.2-m, a value of 80 pence is chosen for the analysis.
2. Nix (2001) and Woodland Improvement and Conservation (2002) report a cost for a 75-cm plastic spiral guard to protect against rabbits of 22 pence. Tubex (1999) quote a price of 18 pence for 75-cm spirals. A value of 24 pence per guard was reported for a silvoarable site at Arlesey in Bedfordshire (Burgess *et al.*, 2000a). A value of 16 pence, as used by Burgess *et al.* (2000b) is assumed for this analysis.
3. Thomas and Willis (2000) and Burgess *et al.* (2000b) assumed that the tree would be planted into continuous 1-m-wide plastic sheeting. The material cost was assumed to be 10 pence m^{-2}. This cost is lower than the 40 pence m^{-2} reported for 1–m wide polythene roll from Woodland Improvement and Conservation (1997).
4. In the current analysis it is assumed that mulch mats would be used. Burgess *et al.* (2002a) assumed a mulch mat cost of 47 pence each. Woodland Improvement and Conservation (2002) report a cost of 40 pence for a 0.85 m x 0.85 m polythene mulch mat. The cost of 40 pence per tree is assumed in this analysis.
5. The cost reported for ploughing, cultivation and spraying in preparation of a poplar forestry site at Ampthill in Bedfordshire of £125 ha^{-1} (Burgess *et al.*, 2000a). The Poplar Tree Company (1999) reports a cost of £150 ha^{-1}. No cost of preparation is included for the silvoarable system as the site is being prepared for an arable crop.
6. Thomas and Willis (2000) assumed a labour requirement for planting poplar of 1.5 minutes per tree. It is assumed that the value for planting automatically includes the cost of marking out the stand. For a dense broadleaf-farm-woodland establishment at Church Farm and Clapham in Bedfordshire, an average labour cost of 20-25 pence per plant was

recorded (Burgess *et al.*, 2000a). Assuming £7 h^{-1}, this is equivalent to 1.7-2.1 minutes $tree^{-1}$. Nix (2002) reports a cost of £650 for planting and protecting 2500 trees; assuming a labour cost of £7 h^{-1}, this is equivalent to 2.2 minutes $tree^{-1}$. The marking-out costs per tree for a silvoarable system are likely to be higher than for a conventional forestry system because of the need for regularly-spaced rows. For the analysis the value of 3.0 minutes $tree^{-1}$ (used by Burgess *et al.*, 2000b) is chosen for the silvoarable system and 2.0 minutes $tree^{-1}$ for the forestry system.

7. An average labour cost of 9 pence for a solid guard with rod was recorded at a farm-woodland system established at Church Farm in Bedfordshire (Burgess *et al.*, 2000a). Assuming a labour cost of £7 h^{-1} this is equivalent to 0.7 minutes $tree^{-1}$. Assuming that it is quicker to transport and install spiral guards, a value of 0.4 minutes $tree^{-1}$ used by Burgess *et al.* (2000b) is used.
8. Thomas and Willis (2000) reported a cost of laying a continuous plastic mulch of £100 for 78 trees; assuming a labour cost of £7 $hour^{-1}$, this is equivalent to 11.0 minutes per tree or 1.7 minutes m^{-2}. Burgess *et al.* (2000b) assumed a similar rate.
9. For a silvoarable system at Arlesey in Bedfordshire, Burgess *et al.* (2000a) assumed an average labour cost of 24 pence per mulch mat. Assuming a labour cost of £7 h^{-1}, the labour requirement for installing mulch mats would be 2.0 minutes $tree^{-1}$. However for the analysis, the same labour rate as that used for the continuous mulch, is used of 1.7 minutes m^{-2}.
10. Thomas and Willis (2000) reported an annual cost of the herbicide applied to the tree row of £1 for 78 trees at a 6.4 spacing and an assumed 2-m row width (0.1 pence m^{-2}), with a labour requirement of 0.5 minute m^{-2}. Assuming a 2-m row width, Burgess *et al.* (2000b) reported a herbicide cost of 0.5 pence m^{-2} and a labour requirement of 0.2 minutes m^{-2}. By contrast across the three sites in 1999, the mean time for a single spray was 0.085 minutes m^{-2}. When frequent spraying led to a low number of weeds, the time for each spraying reduced to 0.06 minutes m^{-2} at Leeds and Cirencester in 2001. Hence a mean value of 0.08 minutes m^{-2} seems appropriate for a single spray. The cost of glyphosate was about 0.15 pence m^{-2}.
11. In the autumn of 1999, eight years after tree planting, the plastic mulch was removed from each of the rows at the Network sites. Across the three sites, the average cost of removing 2675 m^2 of plastic sheet was estimated to be £480 (£0.18 m^{-2}). Assuming an hourly-wage cost of £7 h^{-1}, this is equivalent to 1.5 minutes m^{-2}. This is similar to the time requirement for installation (1.7 minutes m^{-2}). At the Leeds and Silsoe sites, the mean cost of grass and clover seed for establishing a 1690 m x 2 m (3380 m^2) was £120 (£0.035 m^{-2}). The average labour and machinery cost across the three sites for establishing the sward was £192 (£0.057 m^{-2}). Assuming a labour charge of £7 h^{-1}, this is equivalent to about 0.5 minute m^{-2}.
12. At Silsoe in 2000, the estimated cost of cutting the grass sward within the tree-row of 1690 m x 2 m (2289 m^2) once with a brush cutter took 11 hours. This is equivalent to 0.3 minutes m^{-2}. In 2001, at Cirencester and Leeds, it took between 16 and 22 hours to cut 1690 m x 2 m (0.4-0.6 minutes m^{-1}). A lowest estimate of 0.3 minutes m^{-2} is assumed.
13. The Poplar Tree Company estimates an annual mowing cost within the tree rows of £10 ha^{-1}. Nix (2001) suggests a contractor charge for grass topping of £20 ha^{-1}.
14. An annual charge of £21 ha^{-1} was assumed by Burgess *et al.* (2000b) to allow the annual removal of epicormic shoots from 156 trees ha^{-1}. Thomas and Willis (2000) assumed a cost of £21 to remove the epicormic shoots of 78 trees ha^{-1}. Assuming a labour charge of £7 h^{-1}, this would be equivalent to about 1.15 minute $tree^{-1}$ and 2.3 minute $tree^{-1}$ respectively. A. Beaton (personal communication, 2003) assumed that it would typically take about 7.5 hours to remove the epicormic shoots from 418 trees (1.1 minute $tree^{-1}$). A value of 1.15 minute per tree is assumed. The Poplar Tree Company assume a cumulative cost of £75 to remove the epicormic shoots from a stand of 156 trees ha^{-1} between year 16 and 24 (about 4 minutes $tree^{-1}$). The value for the silvoarable system is also assumed for the forestry system after the date of the last thinning.
15. Thomas and Willis (2000) assumed that the first prune of poplar (at age 3) requires 4 minutes per tree. I. Seymour (personal communication, 2003) reported that his experience was that it would have taken about 1.5 minutes per tree for early pruning operations. A lower value of 1 minute per tree is chosen for closely-spaced poplar.
16. In both 2000 and 2001, at Cirencester a contractor, using a ladder and chainsaw was contracted to remove one whorl from 418 trees at a height of about 7 m at a cost £700-£750. Assuming a labour charge of £7 h^{-1}, this would be equivalent to 15 minutes $tree^{-1}$. This is similar to an estimate of 12 minutes $tree^{-1}$ for a nine-year poplar reported by Thomas and Willis (2000). The Poplar Tree Company assumes that the last prune of the trees, in year 15, costs £75 for a stand of 156 trees ha^{-1}, which would be equivalent to 4 minutes $tree^{-1}$.
17. D. Corry (personal communication, 2003) estimated that pruning in year 2 took about 0.5 minute per $tree^{-1}$. I. Seymour (personal communication, 2003) reported that in the 'year 4' pruning at the Silsoe site took about seven hours to remove the prunings from 418 trees (about 1 minute $tree^{-1}$). By contrast he estimated that the larger branches in the final pruning would have required about 28 hours to remove the pruning from the 418 trees (about 4 minutes $tree^{-1}$). The cost for removing the prunings from the poplar forestry system is based on a chopping cost of £20 ha^{-1} (Poplar Tree Company, 1999). Assuming a labour charge of £7 h^{-1}, this would be equivalent to 0.14 minutes $tree^{-1}$.
18. Cost of insurance of £9 ha^{-1} a^{-1} based on records from Arlesey in Bedfordshire to insure the trees from vandalism and fire (Burgess *et al.*, 2000b).
19. Nix (2001) reports a cost of marking up the trees for thinning of 35 pence m^{-3}. Assuming a labour charge of £7 h^{-1}, this is equivalent to 3 minutes m^{-3}.

5.5 Analysis of tree and tree understorey costs

In analysing the tree costs, it was assumed that each stand of trees had a yield class of 14, and that the trees were pruned in years 2, 4, 6, 7, and 9 to create a bole about 8 m high. In the silvoarable systems, the tree costs were assumed to include the costs of managing the two-metre-wide understorey. For the 10-m wide system, the establishment cost was predicted to be £212 ha^{-1} in year 1 and £9 ha^{-1} for beating up in year 2 (assuming a 5% failure rate). Assuming a labour cost of £7 h^{-1}, the total cost of pruning was estimated to be £910 ha^{-1}, increasing from £42 ha^{-1} in year 2 to £322 ha^{-1} in year 9 (Figure 5.3). The cost of annual tree maintenance (£21 ha^{-1}) and insurance (£9 ha^{-1}) totalled £628 ha^{-1} and £270 ha^{-1} respectively over a 30 year period. The total cost of managing the trees within a 10 m x 6.4 m silvoarable system (£2,394 ha^{-1}) was estimated to be similar to that for an 8 m x 8 m widely-spaced system (£2,377 ha^{-1}), and approximately £1500 ha^{-1} cheaper that that for a 4 m x 2 m forestry system (£3,778 ha^{-1}) (Table 5.6).

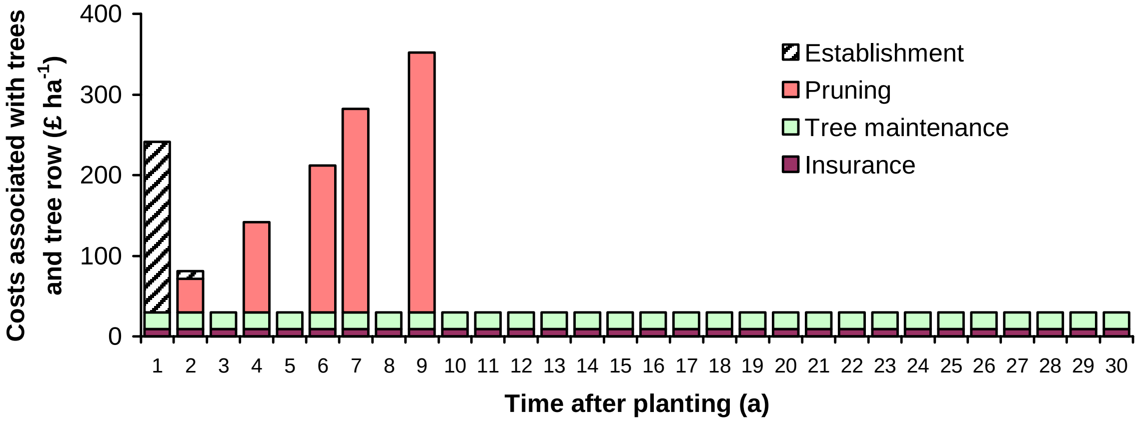

Figure 5.3 *The calculated costs directly associated with tree management. The costs of understorey management are not included.*

Table 5.6 *Comparison of the costs of establishing two forest systems and a silvoarable system.*

Operation	Forestry (4 m x 2 m)	Forestry (8 m x 8 m)	Silvoarable[1] (10 m x 6.4 m)
Tree planting	1777	469	221
Tree-row vegetation maintenance[1]			311
Weeding	100	100	54
Pruning	1220	910	910
Maintenance of trees	378	628	628
Insurance	270	270	270
Thinning	33		
Total	3778	2377	2394

[1]. Based on five years cropping.

Within the experiment, the central metre of the tree-row was initially covered with continuous plastic mulch. This was assumed to restrict weed growth during the first eight years, whilst weed growth in the 0.5-m-wide sections between the mulch and the crop were kept clear by an annual application of herbicide. In year 8, in order to establish different vegetation treatments in the experiment, the plastic was removed followed by either the planting of a grass-clover mix or annual applications of a non-selective herbicide. The grass-clover sward was cut in the year of planting but beyond that the management costs were assumed to be negligible. Based on the experience with the experiment, four scenarios for managing the tree-row have been described (Table 5.7). Scenario 1 is the system used to create the vegetated understoreys within the experiment. Scenario 2 is the system used to create bare understoreys, but in this scenario it is assumed that the plastic mulch is left in place as it offers some environmental benefits and it minimises future herbicide requirements. Scenario 3 is based on the establishment of a grass-clover sward at planting, which may be suitable for a grower seeking to maximise floral diversity in the tree-row whilst minimising arable weeds. Scenario 4 is based on a total herbicide policy. The total cost of the four systems was calculated to range from £383 ha^{-1} to about £900 ha^{-1} (Table 5.8). For the purposes of the economic analysis scenario 2 was investigated.

Table 5.7 *Four possible scenarios for the management of a 2-m-wide understorey.*

Year	**Scenario 1** Continuous mulch followed by grass mix	**Scenario 2** Continuous mulch with herbicide	**Scenario 3** Grass mix + weed control immediately around tree	**Scenario 4** Mulch mat with herbicide
1-8	1-m wide continuous plastic mulch plus annual herbicide to 0.5-m sides between mulch and crop	1-m wide continuous plastic mulch plus annual herbicide to 0.5-m section between mulch and crop	Establish grass-mix + 1-m^2 mulch mat, plus selective use of herbicide (4 m^2 per tree)	1-m^2 mulch mat, plus full herbicide over all tree-row.
8-13	Remove mulch in year 8; sow grass seeds in year 8, cut in year 8 and 9 to increase sward density	Maintain mulch and apply annual herbicide to 2 m section of tree-row	Assumed grass sward invades around tree	Continue to apply herbicide
Comment		Plastic mulch may become untidy; herbicide resistance	Reduced tree growth	Continuous use of herbicide will create resistant weeds

Table 5.8 *Assumed costs of tree-row management for a 2-m wide tree row at a spacing of 10 m x 6.4 m, assuming cropping until year 13. Emboldened values are sub-totals and totals.*

Year	Scenario	1		2		3		4	
		Continuous mulch + grass		Continuous mulch + herbicide		Mulch mat + herbicide + grass mix		Mulch mat + herbicide	
1	Continuous mulch (materials)	99		99					
	Continuous mulch (labour)	199		199					
1	Mulch mat (materials)					62		62	
	Mulch mat (labour)					31		31	
2	Maintenance (5%)	13	**311**	13	**311**	4	**97**	4	**97**
1-8	Annual herbicide	11	**88**	11	**88**	7	**56**	22	**176**
1	Establishment of sward					187			
1-2	Cut grass sward					70			
8	Removal of continuous mulch	175							
8	Establishment of sward	187							
8-9	Cut grass sward	70	**502**		**0**		**327**		
9-13	Annual herbicide		**0**	22	**110**		**0**	22	**110**
1-13	Total		**901**		**509**		**480**		**383**
	Annual cost		69		39		37		29

5.6 Economic analysis assuming no grants

In the absence of government grants and assuming current prices, the net margin of the arable system is predicted to range from £20 ha^{-1} (oilseed rape) to £157 ha^{-1} (first winter wheat) (Figure 5.4). At a discount rate of 0%, the predicted return over a 30-year period is predicted to be £2138 ha^{-1} (Table 5.10).

Within the silvoarable system, the profitability of the crop component is predicted to decline over time as the tree competes increasingly for light, water and nutrients. The duration of profitable crop production depends on the alley width (Figure 5.4). Assuming the yields stated in section 5.1 and the costs stated in Table 5.1, the net margin of the crop component of the agroforestry system with a 10-m alley width remained profitable until year 5. At alley widths of 14, 20 and 40 m, the crop component was predicted to remain profitable until years 5, 9 and 13 respectively (Table 5.9). If grain prices increased by 20% above that assumed in the analysis, then in the absence of grants, it is predicted that cropping would remain profitable at spacings of 10, 14, 20 and 40 m, until years 10, 13, 13, and 21 respectively (Table 5.9).

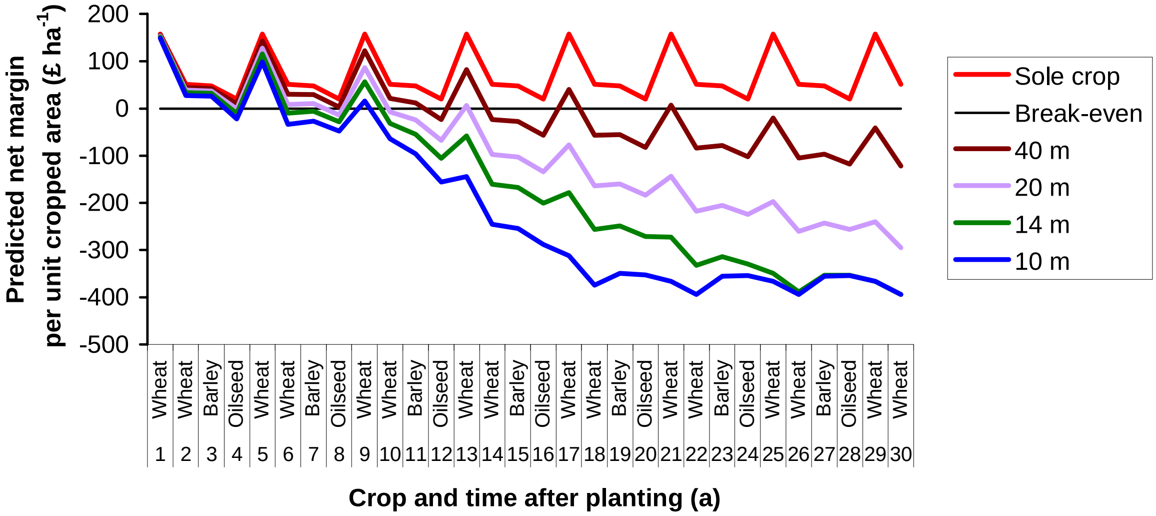

Figure 5.4 *Predicted effect of alley width on the annual net margin of the arable crop assuming no grants and a yield class of 14.*

Table 5.9 *Predicted effect of grain price and tree-row spacing on the duration of the cropping period (in years) assuming no grants.*

Tree-row spacing	Price of feed wheat (£ t^{-1})							
	-20% £50	-10% £57	Base £63	+10% £69	+20% £76	+30% £82	+40% £88	+50% £95
10-m	1	1	5	9	10	11	11	13
14-m	1	1	5	10	13	13	13	13
20-m	1	1	9	13	13	14	17	17
40-m	1	1	13	17	21	26	30	30

Note: Rotation is based on a rotation of wheat (9.61 t ha^{-1} at £63 t^{-1}), wheat (8.17 t ha^{-1} at £63 t^{-1}), barley (7.77 t ha^{-1} at £60 t^{-1}) and oilseed rape (3.2 t ha^{-1} at £135 t^{-1}).

The next stage of the analysis is to include the tree-component of the systems (Table 5.10). Assuming a discount rate of 0%, the greatest predicted net margin over a 30 year period was for the 10 m x 6.4 m silvoarable system (about £5,800 ha^{-1}) (Table 5.10). This was £200 ha^{-1} greater than for the 8 m x 8 m poplar system (£5,595 ha^{-1}). The net margin from the closely-spaced poplar (£4,110 ha^{-1}) was £1,691 ha^{-1} less than that from the most closely-spaced silvoarable system. The net margin from the other silvoarable systems declined from £4,205 ha^{-1} at a spacing of 14 m to £2,023 ha^{-1} at a spacing of 40 m, as the contribution from the tree component declined. The return from the arable system alone was £2,138 ha^{-1}.

At high discount rates, the present value of the final harvest of the trees decreases relative to more immediate revenue such as that from an annual crop. Assuming a discount rate of 5%, the net margin from the arable system (£1,170 ha^{-1}) was approximately 90% greater than that achieved by the other systems. The 40-m silvoarable system with the greatest proportion of cropping was predicted to provide a greater net margin (£435 ha^{-1}) than the closely-spaced silvoarable systems (£350-396 ha^{-1}). At a discount rate of 5%, the net revenue from the closely-spaced poplar system was negative (-£1,046 ha^{-1}). The above analyses indicate that, in the absence of grants, a farmer who assumes a discount rate of 3% or more is unlikely to grow poplars for economic reasons alone. In addition, the cash flow from the poplar systems is also less regular than that for the agricultural system (Figure 5.5).

Table 5.10 *Comparison of the predicted net revenue (£ ha^{-1}) from agriculture, four silvoarable systems and two forestry systems assuming no grants. The yield class of the poplar was assumed to be 14.*

	Arable	Silvoarable				Poplar	Poplar
	crop	40 m x 6.4 m	20 m x 6.4 m	14 m x 6.4 m	10 m x 6.4 m	8 m x 8 m	4 m x 2 m
Crop period		13 year	9 year	5 year	5 year		
Crop income	15,249	6,028	3,943	2,155	1,976	0	0
Crop costs	13,111	5,392	3,540	1,878	1,753	0	0
Timber income	0	1,993	3,986	5,723	7,972	7,972	7,891
Cost (woodland)	0	833	1,352	1,795	2,394	2,377	3,781
Net margin at discount rate of:							
0.0%	2,138	1,795	3,036	4,205	5,801	5,595	4110
2.5%	1,540	870	1,203	1,540	2,098	1,905	593
5.0%	1,170	435	359	350	396	213	(1,046)
7.5%	932	227	(26)	(200)	(376)	(552)	(1,809)
10.0%	771	126	(197)	(440)	(714)	(884)	(2,157)

Note: Silvoarable calculations are based on cropping until specified year and then renting as grazing at no net charge; negative values are shown in brackets.

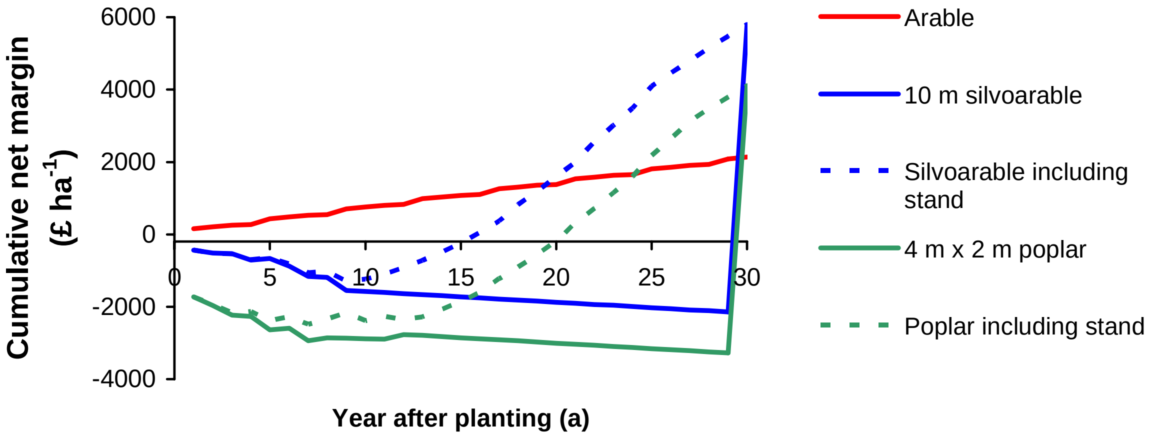

Figure 5.5 *Predicted cumulative cash flow for agriculture, a poplar forestry and a poplar silvoarable system assuming no grants.*

5.7 Economic analysis assuming current grants

If grant arrangements in 2002 are assumed to continue for the next 30 years, the annual net margin from the arable system is predicted to range from £247 ha^{-1} (oilseed rape) to £384 ha^{-1} (first winter wheat). Over a 30-year period, assuming a discount rate of 0%, the cumulative net margin would be about £8,950 ha^{-1}, of which £6,810 ha^{-1} would comprise direct grant payments (Table 5.11).

As in the 'no-grant' scenario, the duration that the crop component of the silvoarable system remains profitable depends on the alley width (Figure 5.6). For example the net margin from the crop component at a spacing of 10 m is predicted to remain profitable until year 13. At spacings of 14, 20 and 40 m, the crop component is predicted to remain profitable until years 17, 25 and 30 respectively (Table 5.11).

Under current grants and ignoring the possibility of placing the land into set-aside, a greater net margin was predicted, at a discount rate of 0%, for the two forestry systems than the four silvoarable systems. In addition the net margin from the 2 m x 4 m (£9,059 ha^{-1}) is now similar to that for the 8 m x 8 m forestry system (£9,386 ha^{-1}). Hence, the current grant schemes for poplar, compared to the no grant scenario, undermine the economic advantage of planting the poplar at a wide rather than a narrow spacing. The arable system (£8,947 ha^{-1}) was also predicted to be more profitable than each of the silvoarable systems (£6,299-£7,854 ha^{-1}). At a discount rate of 5%, the most profitable system is the arable system (£4,834 ha^{-1}); the least profitable system is the closely-spaced silvoarable system (£2,089 ha^{-1}).

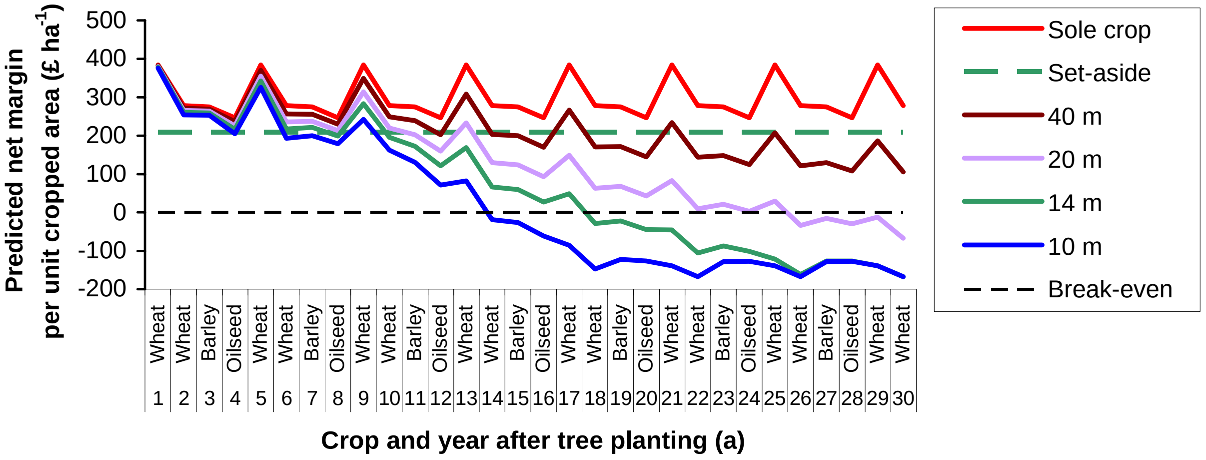

Figure 5.6 *Predicted effect of alley-width on the annual net margin of the arable crop under grant arrangements and prices in 2002.*

Table 5.11 *Comparison of the predicted net revenue (£ ha^{-1}) from agriculture, four silvoarable systems and two forestry systems assuming current grants, but set-aside is not an option. The yield class of the poplar was assumed to be 14.*

	Arable control	Silvoarable				Poplar	Poplar
		40 m x 6.4 m	20 m x 6.4 m	14 m x 6.4 m	10 m x 6.4 m	8 m x 8 m	4 m x 2 m
Crop period		30 years	25 years	17 years	13 years		
Crop income	15,249	12,118	8,416	5,826	4,321	0	0
Grant income (crop)	6,810	6,470	5,108	3,308	2,361	0	0
Crop costs	13,111	12,455	9,814	6,359	2,141	0	0
Timber income	0	1,993	3,986	5,723	7,972	7,972	7,891
Tree grants	0	67	134	198	276	3,791	4,950
Cost (woodland)	0	926	1,531	1,958	2,635	2,377	3,781
Net margin at discount rate of							
0.0%	8,947	7,267	6,299	6,738	7,854	9,386	9,059
2.5%	6,410	4,954	3,941	3,788	3,954	5,382	5,197
5.0%	4,834	3,623	2,703	2,329	2,089	3,426	3,264
7.5%	3,814	2,814	2,016	1,579	1,180	2,438	2,253
10.0%	3,125	2,293	1,611	1,176	728	1,917	1,693

Note: Silvoarable calculations are based on cropping until stated year and then arable area placed to pasture until year 30.

At present, arable areas, which are greater than 20 m in width, can be placed into set-aside (DEFRA, 2002). It is unclear if the arable alleys within the 10, 14 and 20 m alleys could be placed into set-aside, but the analysis in Table 5.12 assumes that this is possible. In this case, a farmer will take an alley out of crop production, not when it is no longer profitable, but when the net margin is less than that received from set-aside. It is assumed that the net margin from placing the cropped area into set-aside is £209 ha^{-1}. On this basis a farmer with a silvoarable system with an alley width of 10 m would carry on cropping for only 5 years (similar to the 'no grant' scenario). Likewise a farmer with a silvoarable system with alley widths of 14, 20 and 40 m would carry on cropping for 9, 10 and 13 years respectively (Table 5.12)

With this scenario, at a discount rate of 0%, the most profitable system is the silvoarable system with an alley width of 10 m (£11,165 ha^{-1}). The net margin of silvoarable systems decreases as the importance of the tree component decreases. The net margin from the forestry and the arable systems are similar (£8,947 ha^{-1} - £9,386 ha^{-1}) and the margin from the silvoarable system at a spacing of 40 m is less than that from arable cropping at all discount rates. Assuming a discount rate of 5%, the net margin from the arable cropping system (£4,834 ha^{-1}) is 25% to 48% greater than the net margin from the other systems which are broadly similar (£3,264 ha^{-1} - £3,873 ha^{-1}).

Table 5.12 *Comparison of the predicted net revenue (£ ha^{-1}) from agriculture, four silvoarable systems and two forestry systems assuming current grants,with set-aside as an option. The yield class of the poplar was assumed to be 14.*

	Arable control	Silvoarable				Poplar	Poplar
		40 m x 6.4 m	20 m x 6.4 m	14 m x 6.4 m	10 m x 6.4 m	8 m x 8 m	4 m x 2 m
Crop period		13 years	10 years	9 years	5 years[1]		
Crop income	15,249	6,028	4,354	3,659	1,976	0	0
Grant income (crop)	6,810	6,470	6,129	5,837	5,448	0	0
Crop costs	13,111	5,683	4,282	3,695	2,112	0	0
Timber income	0	1,993	3,986	5,723	7,972	7,972	7,891
Tree grants	0	67	134	198	276	3,791	4,950
Cost (woodland)	0	834	1,368	1,834	2,394	2,377	3,781
Net margin at discount rate of:							
0.0%	8,947	8,041	8,953	9,888	11,165	9,386	9,059
2.5%	6,410	5,388	5,498	5,702	6,025	5,382	5,197
5.0%	4,834	3,873	3,642	3,526	3,427	3,426	3,264
7.5%	3,814	2,961	2,597	2,348	2,071	2,438	2,253
10.0%	3,125	2,382	1,979	1,682	1,338	1,917	1,693

Note: Silvoarable calculations are based on cropping until stated year and then arable area placed to pasture until year 30.

5.8 Conclusions

Detailed tables have been developed to compare the economics of arable, silvoarable and forestry systems. The long-term price for timber was assumed to be 60% of that predicted by Whiteman *et al.* (1991). The analysis was undertaken assuming a yield class of 14 for the poplar; this was the highest value predicted from measurements of the tree in the cropped treatments of the experiment.

The duration of profitable crop production within a silvoarable system depends on the assumed 'control' crop yield, crop prices, crop costs and the alley width. In the absence of grants and based on assumptions described in the report, the net margin of the crop component of the agroforestry system with a 10-m alley width remained profitable until year 5. At alley widths of 14, 20 and 40 m, the crop component was predicted to remain profitable until years 5, 9 and year 13 respectively. If grain prices increased by 20% above that assumed in the analysis, then in the absence of grants, it is predicted that cropping would remain profitable at spacings of 10, 14, 20 and 40 m, until years 10, 13, 13, and 21 respectively.

The cost of establishing and managing the tree component of a widely-spaced poplar forestry system (about £2,380 ha^{-1}) is £1,400 ha^{-1} less than that for a closely-spaced system (about £3,780 ha^{-1}). Hence, in the absence of grants, planting poplar at a spacing of 8 m x 8 m results in a greater net margin than the closely-spaced system at all discount rates. By contrast under current grants, at a discount rate of 0%, the net margin from the densely-planted forestry systems becomes similar to the widely-spaced poplar system. Compared to the 'no grant' scenario, the current grant arrangements therefore undercut the commercial planting of poplars at traditional densities of 156 trees per hectare. Under the Government's Woodland Grant Scheme (WGS), farmers can receive a planting grant of up £1,950, when establishing poplar at 1,100 trees per hectare. However because of the fast growth of poplar, some farmers will reduce the tree density to that found in agroforestry systems by year 10. The market for the harvested thinnings is generally poor, and it can be argued that some growers are primarily planting at a high initial density because of the conditions of the planting grant. Were it not for the reduction of the WGS grant for reduced tree numbers, farmers would seriously consider widely-spaced poplar, and hence possibly agroforestry, as an option for growing poplars.

In the absence of grants, planting poplars at a 10 m x 6.4 m (156 trees ha^{-1}) in a silvoarable arrangement led to small but increased net margins compared to a sole-stand of poplar at all discount rates. However the benefit (£183 ha^{-1} at a discount rate of 5%) is small and it is questionable whether the additional management time involved in the agroforestry system would warrant the change.

In the absence of all grants (including arable area payments) and based on the assumptions stated, the silvoarable system at a spacing of 10 or 14 m was predicted to be more profitable than the arable system at discount rates less than 2.5%. The net margin from the widely-spaced (20 and 40 m) silvoarable system was predicted to be less profitable than the arable system at all discount rates. These results show that, in the absence of grants, a farmer who assumes a discount rate of 3% or greater is unlikely to grow poplars on the basis of economics alone.

Although there are few commercial silvoarable systems in England and Wales, the UK Silvoarable Agroforestry Network believes that this is principally the result of a subsidy system that actively discourages agroforestry. One example is that in silvoarable systems where the alley width is less than 20 m, it is unclear if the cropped area would be eligible for set-aside as the minimum width for set-aside area is specified as 20 m (DEFRA, 2002). A change in the arable area payment system so that farmers receive a payment that is independent of the type of crop being grown would remove such issues of eligibility for set-aside payments and also the administrative problems of monitoring the cropped area each year.

Future governmental support for rural land use will also increasingly focus on the achievement of public benefits. Agroforestry systems are an effective way of introducing trees on arable land and of creating new opportunities for employment. There are potential benefits in terms of carbon sequestration both in terms of increased soil organic matter and the accumulation of above ground biomass (Pretty and Ball, 2001 quoted by the Woodland Creation Steering Group, 2002). There are also biodiversity benefits in terms of small mammals (Wright, 1994), airborne arthropods (Peng *et al.*, 1993), and spiders (See Section 7). At present there seems to be resistance from DEFRA and the Forestry Commission to the promotion of agroforestry within the Farm Woodland Premium Scheme (DEFRA, 2003) or other agri-environment schemes. By contrast in France, the circular "Circulaire DERF/SDF/C2001-3020, DEPSE/C2001-7034 du 8 Août 2001 – PCR" allows farmers who plant trees in an agroforestry system to get compensatory payments for the uncropped area below the trees. In addition in 2001, the French government introduced an agri-environmental measure "Mesure No 2201 et 2202 Creation (2201) et Gestion (2202) d'Habitats Agroforestiers, AEM National Francaise Agroforesterie Validée" that provides an incentive for farmers who manage agroforestry systems. The payments compensate farmers for the additional costs due to the trees. It was officially approved by the STAR Committee of the EU on Wednesday 21 November 2001 and is valid for both silvoarable and silvopastoral systems. Our understanding is that there is an additional five-year payment to cover the costs of forming an agroforestry habitat of at least 50 trees ha^{-1}, and that the payment is equivalent to €240 ha^{-1} yr^{-1} for trees with crops, €240 ha^{-1} yr^{-1} for trees with sheep, and €362 ha^{-1} yr^{-1} for trees with cattle.

6. Effects of silvoarable management practices on vegetation

The fourth objective of the project (Objective 2.1) was to determine the costs and botanical impact of two vegetation management strategies in a silvoarable system relative to arable farming. Initial experience with silvoarable agroforestry has indicated that an uncropped 2-m-wide understorey at the base of the trees can cause additional weed infestation in the crop. Within the experiment, two types of understorey were examined: a grass-based sward of relatively non-invasive species and a bare understorey maintained by regular application of a non-selective herbicide. The establishment of the treatments and the botanical surveying methods are described in Section 2, and the relative costs of the treatments are described in Section 5.

Firstly, this section describes the results from the botanical surveys in describing the changes with time of the flora of the two types of understorey. Second, the surveys are used to determine if the vegetation in the arable control area was different from that in the cropped alleys next to either the vegetated or the bare understoreys.

6.1 Flora of the bare and vegetated understoreys

In June 2000, the proportion of live vegetation in the bare understorey ranged from 0.1% at Cirencester to 3.6-3.7% at Leeds and Silsoe (Table 6.1). Applications of herbicide then maintained the proportion of live vegetation at each site below 14% on the subsequent four sampling occasions. The first survey of the vegetated understoreys was undertaken in April-May 2000, soon after the removal of the black plastic mulch and the sowing of the grass and clover mixture. At that time the cover of live vegetation ranged from 12% at Silsoe to 55% at Cirencester. In June 2000, the coverage in the vegetated understorey across the three sites had risen to 66-84% and in 2001 and 2002 the coverage increased further to between 73% and 100%. The value of 60% in March 2002 at Cirencester can be explained by 32% of the area being described as having ‘dead vegetation’.

By July 2002, across the three sites, the vegetated understorey contained large proportions (greater than 20%) of *Dactylis glomerata* and *Festuca rubra*. *Trifolium repens* and *Phleum pratense* formed a large proportion of the sward at Leeds, and to a lesser extent at Cirencester. By contrast these two species did not establish well at Silsoe, where then were significant invasions of couch (*Agropyron repens*) and blackgrass (*Alopecurus myosuroides*) (Table 6.1). Thomas *et al.* (2002) report that the number of plant species within a sown beetle bank is often less than that in a field margin for the first decade.

6.2 Botanical diversity in the control area and the alleys

At Cirencester and Leeds there were generally more plant species in the alleys within the silvoarable area, irrespective of the vegetation management strategy, than in the arable control area (Table 6.2). At Silsoe there were no consistent differences between the alleys and the control area, or between the alleys subtending the two different sorts of understorey, although in two seasons there were more species in the control area than in the alleys early in the season.

At Leeds on three occasions there were more species in the alleys subtending vegetated understoreys than in the alleys subtending bare understoreys (June 2000, March-May 2001, and June-July 2001). No consistent significant differences were observed at Cirencester and Silsoe.

Table 6.1 *The proportion (%) of the ground covered with live vegetation within the bare understorey and the vegetated understorey on two sampling occasions in 2000, 2001 and 2002 at three sites. Values are means (n = 48).*

	2000		2001		2002	
	Apr-May	June	Mar-May	Jun-Jul	Mar-May	Jun-Jul
a) Cirencester						
Bare understorey	38.5	0.1		0.0	9.1	8.5
Vegetated understorey	55.2	84.3		98.0	60.2	88.9
comprising:						
Dactylis glomerata	*10.2*	*13.0*		*10.5*	*35.0*	*47.4*
Festuca rubra	*11.6*	*23.8*		*22.0*	*9.0*	*20.2*
Phleum pratense	*6.3*	*13.1*		*14.6*	*6.9*	*8.0*
Trifolium repens	*1.1*	*11.7*		*40.7*	*3.0*	*8.4*
Agropyron repens	0.0	0.0		0.2	0.2	0.0
Alopecurus myosuroides	1.0	0.3		0.0	0.4	0.0
Other di- and monocots	33.1	22.4		10.0	5.7	4.8
b) Leeds						
Bare understorey	2.9	3.7	3.9	10.4	9.9	13.4
Vegetated understorey	26.3	66.2	73.4	92.0	89.8	97.1
comprising:						
Dactylis glomerata		*11.2*	*18.9*	*18.0*	*20.6*	*31.3*
Festuca rubra		*12.5*	*27.7*	*25.2*	*37.5*	*23.4*
Phleum pratense		*14.2*	*12.2*	*15.3*	*16.0*	*18.1*
Trifolium repens		*2.6*	*10.9*	*28.7*	*14.8*	*20.8*
Agropyron repens		1.5	1.4	0.8	0.0	0.0
Bromus sterilis		10.0	1.0	0.6	0.0	0.0
Other di- and monocots		14.2	1.3	3.4	0.8	3.5
c) Silsoe						
Bare understorey	8.8	3.6	3.6	0.6	8.1	1.1
Vegetated understorey	12.1	79.3	75.1	78.5	91.7	99.5
comprising:						
Dactylis glomerata	*0.0*	*15.8*	*35.8*	*30.8*	*38.5*	*40.5*
Festuca rubra	*0.1*	*22.7*	*27.1*	*32.0*	*37.8*	*43.1*
Phleum pratense	*0.0*	*0.0*	*0.1*	*0.0*	*0.1*	*0.2*
Trifolium repens	*0.0*	*1.3*	*4.1*	*5.2*	*5.0*	*4.0*
Agropyron repens	0.0	6.0	2.6	3.4	4.8	5.1
Alopecurus myosuroides	2.0	11.3	0.2	1.3	2.2	3.5
Other di- and monocots	9.9	22.1	5.0	5.7	3.4	3.0

Table 6.2 *Number of plant species (including crop) per square metre in alleys subtending vegetated tree rows, alleys subtending bare tree rows and the arable control area on two sampling occasions in 2000, 2001 and 2002 at Cirencester, Leeds and Silsoe. Values are means (n = 24).*

Treatment	2000		2001		2002	
	Apr-May	June	Mar-May	Jun-Jul	Mar-May	Jun-Jul
Cirencester						
Arable control	7.3 a	5.3 a		3.2 a	5.7 b	7.2 a
Alley by vegetated understorey	11.5 b	10.3 b		4.9 b	4.8 a	6.3 a
Alley by bare understorey	11.6 b	9.0 b		4.6 b	6.4 b	7.1 a
Leeds						
Arable control	3.3 a	4.0 a	2.6 a	1.5 a	1.1 a	2.0 a
Alley by vegetated understorey	3.8 ab	6.6 b	3.8 b	3.3 b	3.3 c	5.6 b
Alley by bare understorey	4.2 b	4.0 a	2.5 a	2.5 b	2.2 b	5.2 b
Silsoe						
Arable control	3.4 b	3.4 a	3.5 b		2.9 a	3.6 a
Alley by vegetated understorey	2.8 a	3.2 a	1.6 a		2.8 a	3.9 a
Alley by bare understorey	2.6 a	3.5 a	2.1 a		2.7 a	3.7 a

Note: Number of species followed by the same letter are not significantly different (P=0.05) for that site and sampling occasion.

6.3 Cover of non-crop species within the control area and alleys

At all three sites, the cover of each non-crop species was determined using a 1-m^2 quadrat with 100 intersection points. By summing the cover of the individual species, a total cover of non-crop species was calculated. Because more than one species could be identified at each point (this was particularly the practice at Cirencester and Silsoe), this total could theoretically exceed 100%.

The total cover of non-crop species generally increased from March to July in each year (Table 6.3). In June-July 2001 at Leeds and throughout 2002 at Cirencester and Leeds, the total cover of the non-sown species within the silvoarable alleys was greater than that in the arable control. In addition at Leeds, on four occasions, the total cover of the non-crop species was greater in the alleys subtending vegetated understoreys than in those adjacent to bare understoreys (Table 6.3). At Cirencester, the total cover of non-sown species was also greater in the alleys bordering a vegetated understorey than in those adjacent to bare understoreys in June 2000. By contrast, at Silsoe the total cover of the non-crop species tended to be greater in the control area than in the silvoarable alleys.

Table 6.3 *The total cover (%) of non-crop species in the arable control area, alleys subtending vegetated tree rows, and alleys subtending bare tree rows on two sampling occasions in 2000, 2001 and 2002 at Cirencester, Leeds and Silsoe. Values are sums of means (n = 24).*

Treatment	2000		2001		2002	
	Apr-May	June	Mar-May	Jun-Jul	Mar-May	Jun-Jul
Cirencester						
Arable control	6.3 a	20.2 a		1.0 a	2.3 a	30.0 a
Alley by vegetated understorey	20.8 b	52.8 c		1.6 a	10.9 b	58.5 b
Alley by bare understorey	16.2 b	35.7 b		1.8 a	11.5 b	54.3 b
Leeds						
Arable control	2.2 a	16.9 ab	4.0 a	1.0 a	0.1 a	5.1 a
Alley by vegetated understorey	2.5 a	21.5 b	4.3 a	10.5 c	3.2 c	21.2 c
Alley by bare understorey	4.0 b	15.2 a	3.2 a	4.6 b	1.1 b	10.0 b
Silsoe						
Arable control	2.8 b	28.8 a	11.9 b	0.0	8.3 b	41.8 b
Alley by vegetated understorey	1.3 a	32.4 a	1.3 a	0.0	6.9 ab	23.1 a
Alley by bare understorey	0.6 a	25.8 a	1.6 a	0.0	3.1 a	16.8 a

Note: Values followed by the same letter are not significantly different (P=0.05) for that site and sampling occasion.

6.4 Cover of individual species within the control area and alleys

Between June and July of each year, the cover of the wheat or the barley crop in the control areas at each site ranged from 64% to 90%. The exception was at the Silsoe site in 2001, when poor weather meant that no crop was sown. The cover of wheat or barley within the alleys was generally lower than within the control area, most specifically at Cirencester in 2002 (Table 6.4) because of the effect of waterlogging during establishment of the crop in the alleys.

In June 2000, at Cirencester the major non-crop species in the control area was *Poa annua* (12% cover), whilst in the alleys there were substantial proportions of *Poa annua* (18-24%), *Bromus sterilis*, *Avena fatua* and *Agropyron repens* (1-9%) (Table 6.4). In 2001, the individual proportions of non-crop species in both the control and the alleys were small (0-1%). By 2002, the principal non-crop species in the control area were *Poa annua*, *Agrostis stolonifera* and *Alopecurus myosuroides*, but the cover of each of these species was again small (2-3%). By contrast, within the alleys there was a large cover of *Poa annua (16-18%), Avena fatua* and *Agrostis stolonifera* (3-7%).

In June 2000, at Leeds the principal non-crop species in both the control area and the alleys were *Poa annua* and *Veronica* species. In June 2001, the cover of non-crop species in the control area was minimal, but there were small areas of *Agropyron repens* and *Bromus sterilis* in the alleys. In June and July 2002, the principal non-crop species in both the alleys and the control area was *Agropyron* *repens*. In both 2001 and 2002, the proportion of *Agropyron repens* appeared to be greater in the alleys adjacent to the vegetated understorey than that in the alleys adjacent to the bare understorey.

In June 2000, at Silsoe, the most common non-crop species in both the alleys and the control area were *Alopecurus myosuroides* and *Agropyron repens*. In 2001, both the control and the alleys were maintained bare with cultivation in June, July and August, and this appears to have reduced the problem with *Agropyron repens* in 2002. However in July 2002, there were large proportions of *Alopecurus myosuroides* particularly in the control area (33%), but also within the alleys (6-12%).

Table 6.4 *The cover (%) of crop and selected non-crop species in the arable control area, alleys subtending vegetated tree rows, and alleys subtending bare tree rows between June and July in 2000, 2001 and 2002 at Cirencester, Leeds and Silsoe. Values are means (n = 24).*

	2000			2001			2002		
	Arable	Alley next to		Arable	Alley next to		Arable	Alley next to	
	control	veg. tree-row	bare tree-row	control	veg. tree-row	bare tree-row	control	veg. tree-row	bare tree-row
a) Cirencester									
Wheat	**75**	74	73	**64**	56	56			
Barley							**73**	39	48
Bare-ground	**15**	11	14	**36**	44	44	**14**	22	21
Agropyron repens	**0**	5	2	**0**	1	0	**0**	1	0
Agrostis stolonifera	**0**	0	0	**0**	0	1	**2**	7	5
Alopecurus myosuroides	**0**	2	1	**0**	0	0	**2**	0	4
Avena fatua	**0**	5	1	**0**	0	0	**0**	6	3
Bromus sterilis	**0**	5	9	**1**	0	0	**0**	0	1
Poa annua	**12**	24	18	**0**	0	0	**3**	18	16
b) Leeds									
Wheat	**70**	55	62	**62**	60	61			
Barley							**75**	54	60
Bare ground	**9**	18	19	**26**	22	27	**14**	25	26
Agropyron repens	**0**	2	0	**0**	5	1	**2**	8	2
Bromus sterilis	**0**	2	0	**0**	3	1	**0**	1	1
Poa annua	**10**	9	9	**0**	0	0	**0**	0	0
Veronica sp.	**4**	3	1	**0**	0	0	**0**	0	0
c) Silsoe									
Wheat	**78**	87	90						
Barley							**90**	84	87
Bare-ground	**19**	10	8	**100**	100	100	**5**	8	11
Agropyron repens	**19**	9	13				**0**	0	0
Alopecurus myosuroides	**7**	18	9				**33**	12	6
Galium aparine	**2**	0	0				**7**	1	0

Note: Abbreviation – veg. = vegetated.

6.5 Conclusions

The results show that it was possible to establish a grass-clover sward in the 2-m wide understorey of the poplar, seven years after planting the trees. The establishment of *Dactylis glomerata* and *Festuca rubra* was successful at each site, and whilst *Trifolium repens* and *Phleum pratense* established well at Leeds, they showed poor establishment at Silsoe. The establishment of the grass sward appears to have been successful in reducing the number of other species within the understorey, although *Agropyron repens* and *Alopecurus myosuroides* remained problems on the clay soil at Silsoe.

At Cirencester and Leeds, there were generally more plant species and a greater cover of non-sown plant species in the alleys than in the arable control area. This indicates that the arable component within a silvoarable system faced increased competition for light, water and nutrients from invasive weeds. This effect was not apparent at Silsoe, perhaps because of a substantial infestation of *Alopecurus myosuroides* within the control area.

At Leeds there were more plant species and a greater cover of non-crop species in the alleys subtending vegetated understoreys than in the alleys subtending bare understoreys. No significant differences were observed at Cirencester and Silsoe, although often a similar trend to that found at Leeds was apparent. The results from Leeds suggest that the establishment of a vegetated understorey could lead to greater weed problems within the adjacent alleys, than is the case with a bare-understorey. One reason for this is that, during the establishment phase, the understorey was strimmed in the late summer when ripe seed heads were present and this could have spread seed into adjacent alleys. In addition species such as *Agropyron repens* can propagate from rhizomes.

7. Effect of silvoarable management practices on ground-active invertebrates

The fifth objective of the project (Objective 2.2) was to determine the effect of the silvoarable management practices on the numbers and diversity of ground invertebrates relative to arable farming**.** Growing arable crops in conjunction with shrubs or trees is widely practised in global agriculture, however very little information is available on the effect of this cropping system on the ground fauna that inhabits agricultural land (Stamps and Linit, 1997). The methodology has been described in Section 2.

7.1 Effect on total numbers of invertebrates

An initial comparison of the number of individuals within sorted categories between the silvoarable and the control treatments for January 2000 to December 2002 is presented for each of the three sites in Figures 7.1 to 7.3. In general the most abundant classes of ground-active invertebrates were the predatory carabid beetles and spiders and the pests; slugs. For each of the sites, overall invertebrate numbers were at their greatest between May and August every year and, with the exception of the carabid beetle larvae, maximum numbers were generally found in the late summer months of July and August. Carabid beetle larvae, which were not captured in large numbers, were usually most abundant in the period January to April.

At the three sites, peaks in numbers of carabid beetles were always greater in the arable control crop area than in the agroforestry alleys and tree row understoreys. At the Leeds and the Silsoe sites, for reasons that are unclear, the number of carabid beetles caught in 2000 was less than in the subsequent two years. In contrast, at Cirencester exceptionally high numbers of carabid beetles were trapped in the control crop area in June 2000 (Figure 7.1). This may reflect the history of the arable control area for faunal measurements at this site, which had been newly created from an area adjacent to the agroforestry plot that had been in permanent pasture for some years. This pasture may have had a large population of *Pterostichus madidus*, by far the most dominant species in these arable control traps.

Peak numbers for spiders were more spread out with time than other taxa with populations increasing in late winter and early spring and maximum numbers usually recorded in the summer months. For slugs, apart from the summer peak in numbers, they were seldom very abundant in the early autumn, a period when slugs can damage autumn-planted crop plant seedlings (Griffiths *et al.*, 1998). The large number of slugs in May 2000 at Silsoe (Figure 7.3) correlates with higher than average rainfall at that time.

7.2 Effect of ground storey treatment on ground-active invertebrates

For the purposes of this report, the discussion of the effects of ground storey treatment is restricted to the results from Leeds where the rotation was successfully achieved each year. At Silsoe and Cirencester there were problems with cropping in 2001 because of very wet weather, which prevented the planned rotation. The discussion of ground-active invertebrates is also limited to three taxa: carabid beetles, slugs and spiders, which were numerically the most common of the five separated taxa. These taxa also had the longest sequences where there was more than one animal caught per trap per sampling occasion.

At Leeds, carabid beetles were most abundant in the three cropped treatments particularly after the understoreys had become established by the end of the first year of the new understorey treatments in 2000 (Figure 7.4a). This is evident particularly during the summer peak of 2001. For many of the months after June 2001, but even in April, August and November 2000, the numbers were statistically significantly greatest in the arable control area. Numbers of carabid beetles in the bare understorey were often intermediate in magnitude and only rarely were they statistically the lowest e.g. in June 2000, 2001 and 2002.

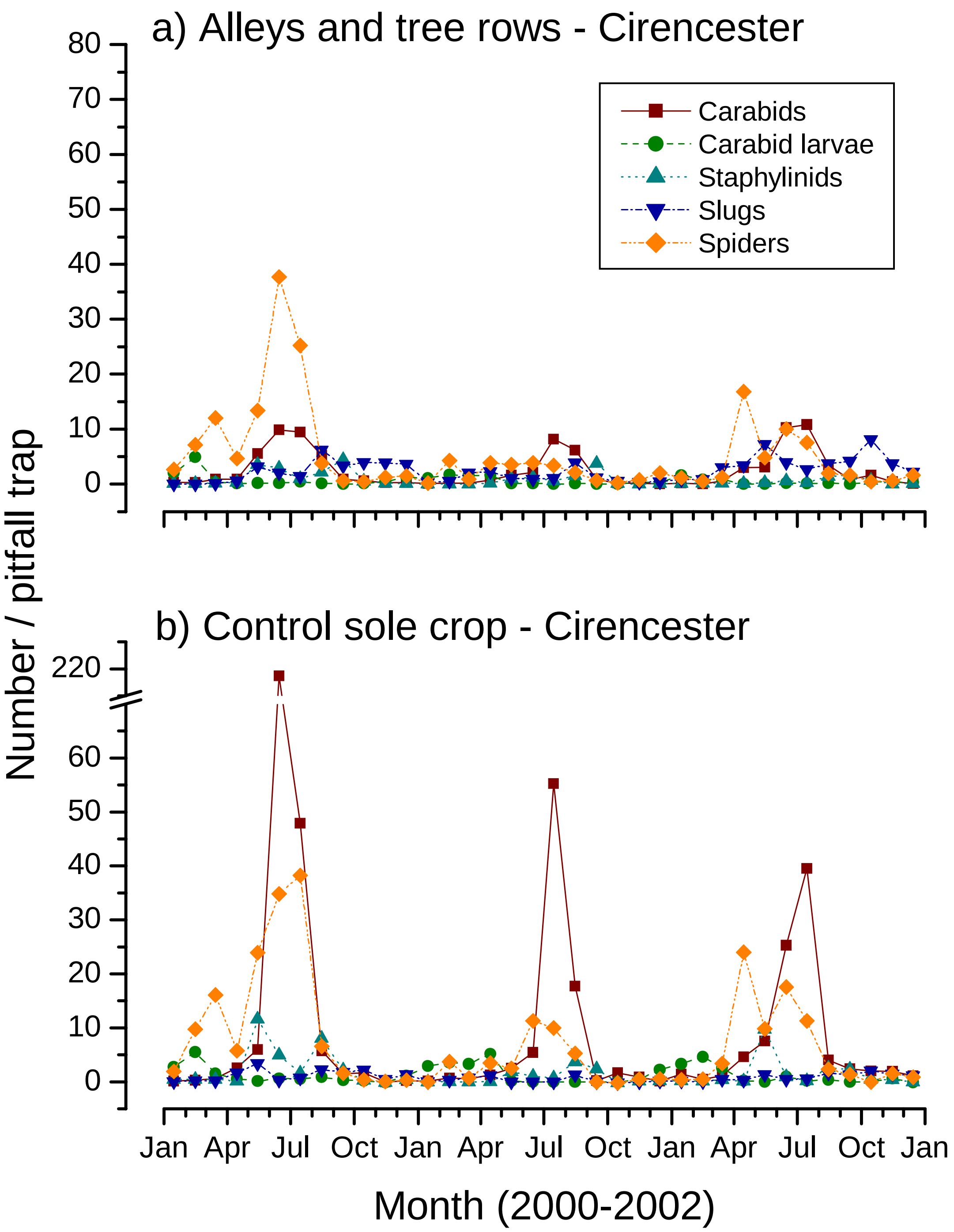

Figure 7.1 *Numbers of invertebrates within selected categories collected from pitfall traps at Cirencester in (a) the agroforestry treatment (cropped alleys and tree understoreys combined) and (b) the control crop from January 2000 to December 2002. Values are means (n = 60 and 12 respectively).*

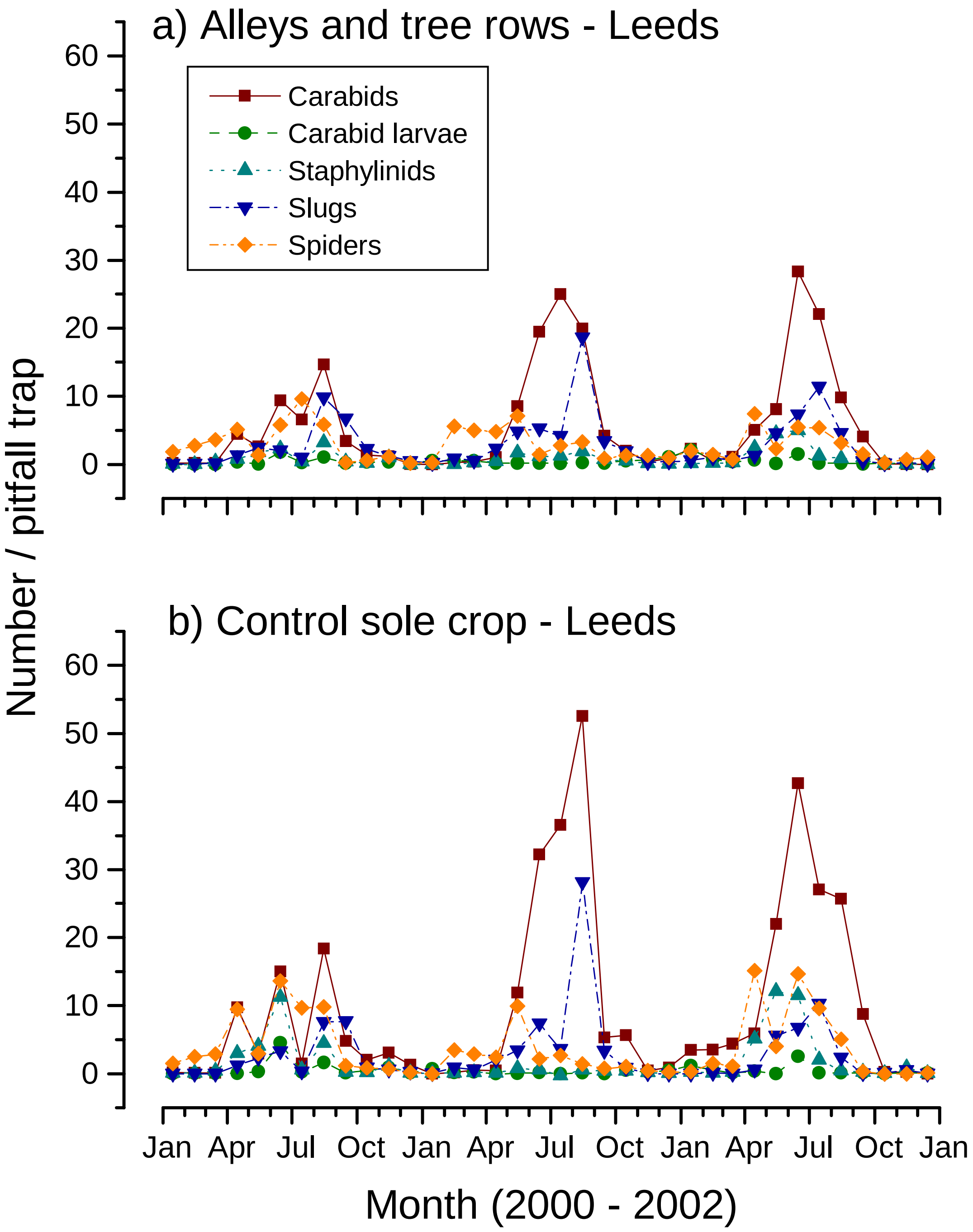

Figure 7.2 *Numbers of invertebrates within selected categories collected from pitfall traps at Leeds in (a) the agroforestry treatment (cropped alleys and tree understoreys combined) and (b) the control crop from January 2000 to December 2002. Values are means (n = 60 and 12 respectively).*

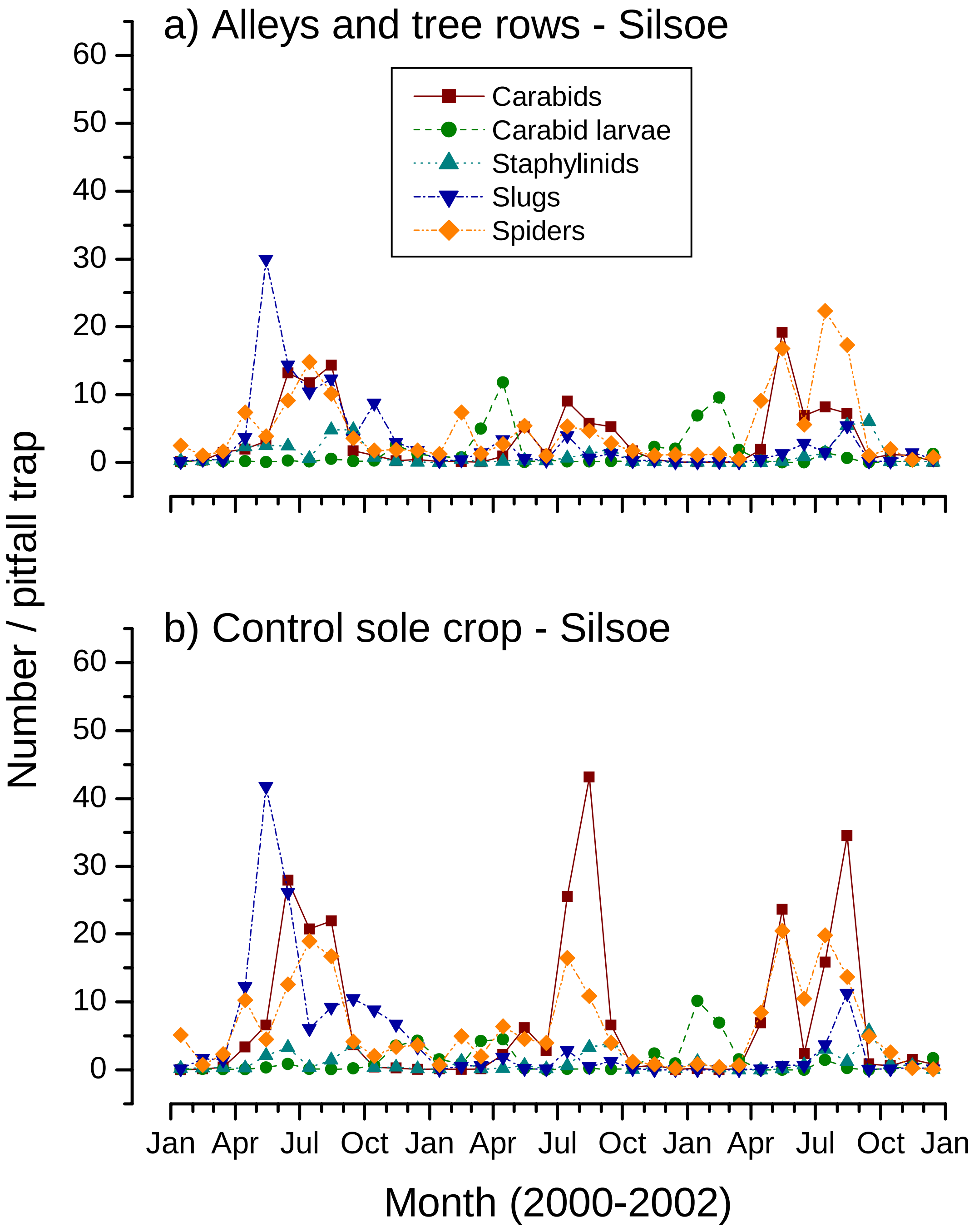

Figure 7.3 *Numbers of invertebrates within selected categories collected from pitfall traps at Silsoe in (a) the agroforestry treatment (cropped alleys and tree understoreys combined) and (b) the control crop from January 2000 to August 2002. Values are means (n = 60 and 12 respectively). The alleys and the control area were kept as a bare-earth fallow from October 2000 to August 2001.*

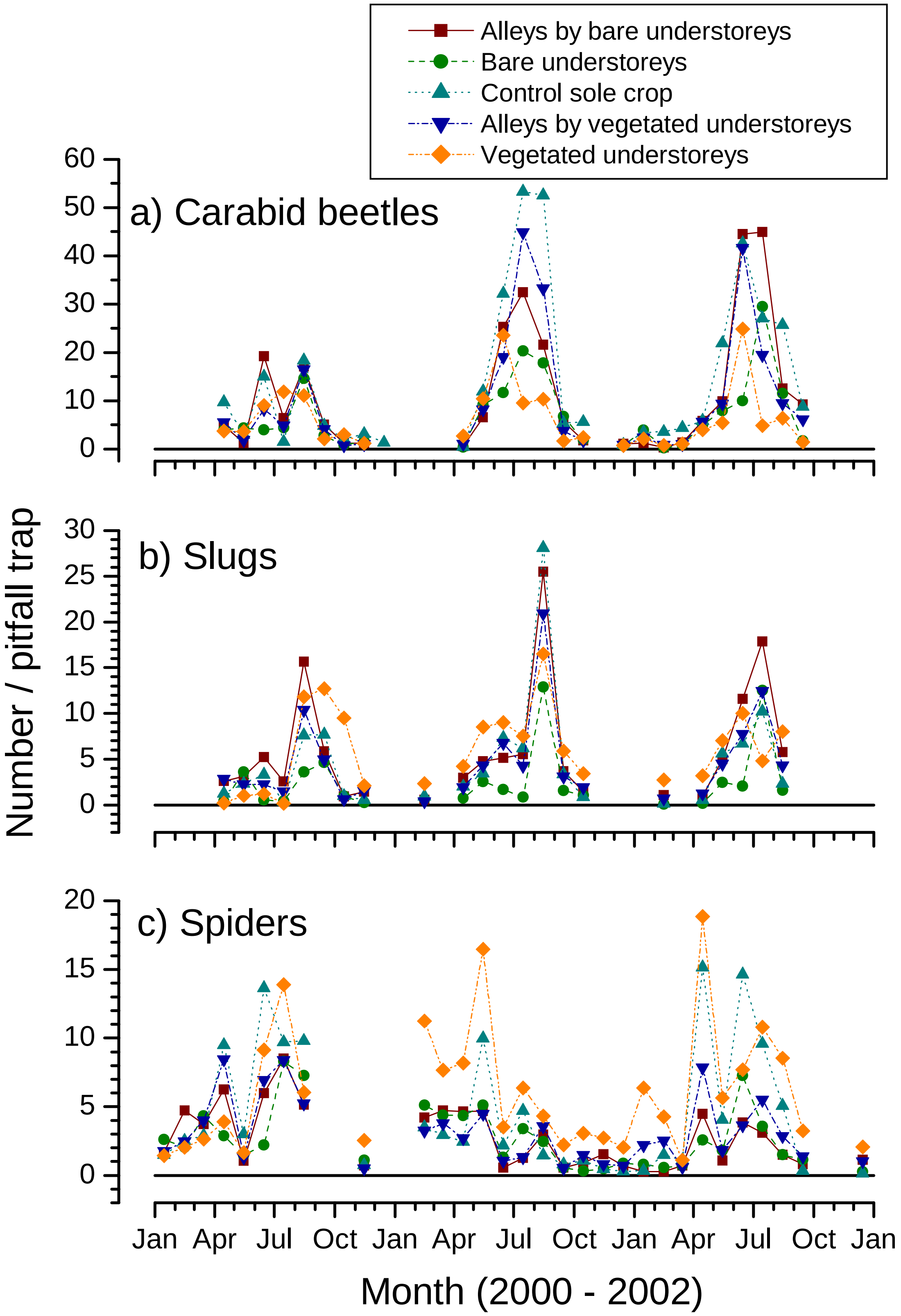

Figure 7.4 *The effect of five ground storey treatments on numbers of a) carabid beetles, b) slugs and c) spiders trapped in pitfall traps at Leeds from January 2000 to December 2002. Values are means (n = 12).*

In the vegetated understoreys after their establishment, carabid beetle numbers peaked each year in June, a month before the peaks in the arable treatments. In three months (July and October 2000, and April 2001), two of which were months of low abundances overall, numbers were statistically greatest in the vegetated understoreys. However, for most months the abundances in the vegetated understoreys were statistically equally or solely the lowest (April, August and November 2000, July to October 2001, February, March, May, July, August, and September 2002). Only rarely were the numbers in the two understorey types significantly different from each other in 2001 and 2002 (April and September 2001, and July 2002).

Bare understoreys seem to be an unfavourable environment for slugs; from June 2000 to July 2002, numbers in this habitat were statistically equally or solely lowest (at P = 0.05) on many occasions (Figure 7.4b). In contrast, from September 2000 to August 2002, numbers in the vegetated understoreys were the highest or equal highest with only two exceptions (September 2001 and July 2002). Again there appears to be no positive correlation of numbers in understoreys with their associated alley habitats. For example alleys next to the bare understorey were a favourable habitat for slugs from April to August 2000 when they statistically had the highest counts. Otherwise the values for the three cropped habitats were generally similar in magnitude in each month.

The suitability of the vegetated understoreys as a habitat for predatory spiders from November 2000 onwards, is visually very evident (Figure 7.4c). With the single exception of June 2002, this habitat contained, statistically, the highest number of spiders and on only two occasions is that position shared with another treatment viz. the arable control in April and July 2002. There is no clear evidence that the presence of large numbers of spiders in the vegetated understorey is associated with greater numbers in the subtending arable alleys compared with the other arable treatments. It is noteworthy that the spiders are present in significant numbers in all the habitats. The sequence of usable data is also longest for this taxon with one continuous sequence of 21 months.

7.3 Effect of site and year on individual carabid beetle species

Carabid beetles are often the taxon of choice in studies aimed at understanding the ways in which modern agriculture affects fauna. The reason for this preference is that carabid beetles are relatively easy to collect and identify to species level. They are also often termed ‘beneficial species’ as certain species have been shown to feed on invertebrate crop pests including slugs.

In total, over the three years with all the sites combined, 38,705 carabid beetles were captured and identified to species between February 2002 and Jan 2003 (Table 7.1). A total of 11,545, 16,217, and 10,943 carabid beetles were captured at Cirencester, Leeds, and Silsoe respectively (Table 7.1). Twenty-nine species of carabid beetle were identified from the Cirencester site and Leeds site, whereas 27 species were found at the Silsoe site. The number of species captured during the three years was declining slightly at Leeds with 27, 26 and 25 species caught in 2000, 2001 and 2002 respectively. The number of species caught at the Silsoe site was constant with 25 seen in all three years. More perturbation was seen at the Cirencester site with 25, 20 and 26 species caught in 2000, 2001 and 2002 respectively.

Table 7.1 *Summary of carabid beetle captures over three years at the three sites.*

	2000	2001	2002	Total
a) Cirencester				
Number of individuals	5,562	2,520	3,463	11,545
Number of species	25	20	26	29
b) Leeds				
Number of individuals	3,303	5,822	7,092	16,217
Number of species	27	26	25	29
c) Silsoe				
Number of individuals	3,957	3,209	3,777	10,943
Number of species	25	25	25	27

At the Cirencester site, the most numerous species captured in all three years was *Pterostichus madidus* (Table 7.2). In 2000, *Harpalus rufipes* was the second most abundant species, but in 2001 and 2002 *Pterostichus melanarius* was the second most abundant. The most numerous carabid beetle at the Leeds site in all three years was *P. melanarius* (Table 7.3) with *Trechus quadristriatus* second most numerous in 2000 and *P. madidus* holding this position in 2001 and 2002. In 2000 at the Silsoe site *H. rufipes* was the most abundant species (Table 7.4), but in the following two years the most abundant species was *P. melanarius*. *Pterostichus cupreus* was the second most abundant species at this site in 2001 and 2002. During 2000 *P. melanarius* was the second most abundant species. The most common species recorded accounted for at least 29% of the total catch at a particular site in a particular year.

Table 7.2 *Number of each species of carabid beetle (N) as a proportion of the total (Prop.) caught at Cirencester for each of three years.*

2000			2001			2002		
Species	*N*	Prop. (%)	Species	*N*	Prop. (%)	Species	*N*	Prop. (%)
Pterostichus madidus	3,414	61.38	*Pterostichus madidus*	1,291	51.23	*Pterostichus madidus*	1,286	37.14
Harpalus rufipes	453	8.14	*Pterostichus melanarius*	501	19.88	*Pterostichus melanarius*	694	20.04
Nebria.brevicollis	398	7.16	*Nebria brevicollis*	196	7.78	*Nebria brevicollis*	504	14.55
Pterostichus melanarius	308	5.54	*Pterostichus cupreus*	143	5.67	*Pterostichus cupreus*	440	12.71
Pterostichus cupreus	263	4.73	*Harpalus rufipes*	118	4.68	*Harpalus affinis*	169	4.88
Harpalus affinis	204	3.67	*Harpalus affinis*	64	2.54	*Harpalus rufipes*	66	1.91
Calathus fuscipes	196	3.52	*Notiophilus biguttatus*	49	1.94	*Amara plebja*	55	1.59
Agonum dorsale	72	1.29	*Calathus fuscipes*	32	1.27	*Calathus fuscipes*	52	1.50
Loricera pilicornis	68	1.22	*Amara plebja*	31	1.23	*Trechus quadristriatus*	39	1.13
Amara plebja	57	1.02	*Bembidion lampros*	26	1.03	*Agonum dorsale*	25	0.72
Notiophilus biguttatus	40	0.72	*Trechus quadristriatus*	13	0.52	*Bembidion lampros*	25	0.72
Bembidion obtusum	25	0.45	*Abax parrellelepipedus*	12	0.48	*Notiophilus biguttatus*	24	0.69
Trechus quadristriatus	23	0.41	*Agonum dorsale*	11	0.44	*Pterostichus strenuus*	17	0.49
Bembidion lampros	20	0.36	*Bembidion obtusum*	10	0.40	*Abax parrellelepipedus*	14	0.40
Abax parrellelepipedus	4	0.07	*Pterostichu nigers*	7	0.28	*Loricera pilicornis*	13	0.38
Bembidion aeneum	3	0.05	*Loricera pilicornis*	6	0.24	*Carabus violaceus*	8	0.23
Clivinia fossor	3	0.05	*Bembidion aeneum*	5	0.20	*Bembidion aeneum*	7	0.20
Asaphidion flavipes	2	0.04	*Synuchus nivalis*	3	0.12	*Leistus spinibarbis*	6	0.17
Carabus monilis	2	0.04	*Amara ovata*	1	0.04	*Bembidion obtusum*	5	0.14
Leistus spinibarbis	2	0.04	*Clivinia fossor*	1	0.04	*Pterostichu nigers*	4	0.12
Agonum obscurum	1	0.02				*Amara apricara*	3	0.09
Amara ovata	1	0.02				*Amara similata*	2	0.06
Agonum sexpunctatum	1	0.02				*Carabus monilis*	2	0.06
Amara apricara	1	0.02				*Amara ovata*	1	0.03
Pterostichus strenuus	1	0.02				*Agonum sexpunctatum*	1	0.03
						Clivinia fossor	1	0.03

Table 7.3 *Number of each species of carabid beetle (N) as a proportion of the total (Prop.) caught at Leeds for each of the three years.*

2000			2001			2002		
Species	*N*	Prop. (%)	Species	*N*	Prop. (%)	Species	*N*	Prop. (%)
Pterostichus melanarius	1,312	39.72	*Pterostichus melanarius*	3,458	59.40	*Pterostichus melanarius*	2,781	39.21
Trechus quadristriatus	380	11.50	*Pterostichus madidus*	958	16.45	*Pterostichus madidus*	2,343	33.04
Pterostichus madidus	344	10.41	*Nebria brevicollis*	303	5.20	*Nebria brevicollis*	411	5.80
Bembidion lampros	246	7.45	*Bembidion lampros*	201	3.45	*Bembidion obtusum*	364	5.13
Nebria brevicollis	199	6.02	*Agonum dorsale*	194	3.33	*Agonum dorsale*	354	4.99
Agonum dorsale	187	5.66	*Trechus quadristriatus*	184	3.16	*Trechus quadristriatus*	215	3.03
Harpalus affinis	134	4.06	*Calathus fuscipes*	94	1.61	*Harpalus affinis*	122	1.72
Bembidion obtusum	121	3.66	*Calathus elanocephalus*	68	1.17	*Loricera pilicornis*	100	1.41
Loricera pilicornis	100	3.03	*Harpalus affinis*	59	1.01	*Pterostichus niger*	100	1.41
Calathus fuscipes	58	1.76	*Agonum obscurum*	46	0.79	*Bembidion lampros*	59	0.83
Amara plebja	47	1.42	*Loricera pilicornis*	40	0.69	*Calathus fuscipes*	45	0.63
Asaphidion flavipes	44	1.33	*Pterostichus niger*	34	0.58	*Harpalus rufipes*	33	0.47
Notiophilus biguttatus	33	1.00	*Asaphidion flavipes*	29	0.50	*Abax parrellepipedus*	24	0.34
Harpalus rufipes	23	0.70	*Harpalus rufipes*	29	0.50	*Agonum obscurum*	23	0.32
Bembidion quadrimaculatum	20	0.61	*Bembidion obtusum*	28	0.48	*Asaphidion flavipes*	22	0.31
Agonum obscurum	11	0.33	*Abax parrellepipedus*	27	0.46	*Amara plebja*	19	0.27
Agonum sexpunctatum	9	0.27	*Notiophilus biguttatus*	27	0.46	*Agonum sexpunctatum*	16	0.23
Demetrias atricaphilus	9	0.27	*Agonum sexpunctatum*	17	0.29	*Calathus elanocephalus*	15	0.21
Abax parrellepipedus	6	0.18	*Amara plebja*	7	0.12	*Notiophilus biguttatus*	14	0.20
Calathus melanocephalus	6	0.18	*Synuchus nivalis*	6	0.10	*Demetrias atricaphilus*	8	0.11
Amara similata	3	0.09	*Stomis pumicatus*	5	0.09	*Amara similata*	7	0.10
Amara apricara	3	0.09	*Amara similata*	2	0.03	*Leistus ferrungineus*	7	0.10
Pterostichus cupreus	2	0.06	*Bembidion quadrimaculatum*	2	0.03	*Pterostichus cupreus*	5	0.07
Pristonychus terricola	2	0.06	*Amara Apricara*	2	0.03	*Pterostichus strenuus*	4	0.06
Stomis pumicatus	2	0.06	*Demetrias atricaphilus*	1	0.02	*Amara apricara*	1	0.01
Leistus ferrungineus	1	0.03	*Pristonychus terricola*	1	0.02			
Pterostichus strenuous	1	0.03						

Table 7.4 *Number of each species of carabid beetle (N) as a proportion of the total (Prop.) caught at Silsoe for each of the three years.*

2000			2001			2002		
Species	*N*	Prop. (%)	Species	*N*	Prop. (%)	Species	*N*	Prop. (%)
Harpalus rufipes	1,922	48.57	*Pterostichus melanarius*	1,121	34.93	*Pterostichus melanarius*	1,117	29.57
Pterostichusmelanarius	818	20.67	*Pterostichus cupreus*	828	25.80	*Pterostichus cupreus*	945	25.02
Pterostichus cupreus	358	9.05	*Nebria brevicollis*	431	13.43	*Nebria brevicollis*	709	18.77
Nebria brevicollis	181	4.57	*Harpalus rufipes*	390	12.15	*Harpalus rufipes*	388	10.27
Harpalus affinis	177	4.47	*Pterostichus strenuus*	62	1.93	*Harpalus affinis*	181	4.79
Notiophilus biguttatus	85	2.15	*Bembidion lampros*	50	1.56	*Carabus violaceus*	118	3.12
Carabus violaceus	58	1.47	*Notiophilus biguttatus*	43	1.34	*Pterostichus niger*	62	1.64
Pterostichus strenuous	57	1.44	*Harpalus affinis*	42	1.31	*Loricera pilicornis*	35	0.93
Leistus spinibarbis	46	1.16	*Bembidion aeneum*	38	1.18	*Amara plebja*	30	0.79
Pterostichus niger	40	1.01	*Amara plebja*	37	1.15	*Bembidion lampros*	29	0.77
Trechus quadristriatus	39	0.99	*Clivinia fossor*	34	1.06	*Notiophilus biguttatus*	28	0.74
Bembidion lampros	30	0.76	*Carabus violaceus*	32	1.00	*Clivinia fossor*	27	0.71
Agonum dorsale	25	0.63	*Pterostichus niger*	24	0.75	*Bembidion aeneum*	25	0.66
Bembidion obtusum	23	0.58	*Bembidion obtusum*	21	0.65	*Pterostichus strenuus*	24	0.64
Loricera pilicornis	22	0.56	*Loricera pilicornis*	13	0.41	*Leistus spinibarbis*	18	0.48
Pterostichus macer	17	0.43	*Stomis pumicatus*	11	0.34	*Bembidion obtusum*	10	0.26
Clivinia fossor	14	0.35	*Pterostichus macer*	7	0.22	*Trechus quadristriatus*	7	0.19
Amara plebja	12	0.30	*Amara simimlata*	6	0.19	*Amara simimlata*	6	0.16
Bembidion aeneum	10	0.25	*Leistus spinibarbis*	6	0.19	*Pterostichus macer*	6	0.16
Stomis pumicatus	6	0.15	*Bembidion quadrimaculatum*	4	0.12	*Bembidion quadrimaculatum*	4	0.11
Calathus fuscipes	5	0.13	*Trechus quadristriatus*	4	0.12	*Stomis pumicatus*	4	0.11
Pterostichus madidus	5	0.13	*Pterostichus madidus*	2	0.06	*Amara apricara*	1	0.03
Amara simimlata	4	0.10	*Agonum dorsale*	1	0.03	*Agonum dorsale*	1	0.03
Amara apricara	2	0.05	*Calathus fuscipes*	1	0.03	*Badister sp.*	1	0.03
Leistus ferrungineus	1	0.03	*Leistus ferrungineus*	1	0.03	*Calathus fuscipes*	1	0.03

7.4 Effect of ground storey treatment on abundance of individual carabid beetle species

At each site and for each year, ANOVA tests and *a posteriori* LSD tests were carried out on the pooled data species where more than one carabid beetle was caught per trap per year. At the Cirencester site in 2000, *Pterostichus melanarius*, *Pterostichus madidus* and *Calathus fuscipes* were more abundant in the arable control than in the other treatments (Table 7.5). By contrast *Harpalus affinis* and *Nebria brevicollis* were more abundant in the bare understoreys than in the other treatments. *Agonum dorsale* was more abundant in both arable alley treatments than in the other three treatments.

Table 7.5 *The effect of sole arable cropping and four agroforestry ground-storey treatments on the number of selected carabid beetle species collected per pitfall trap in 2000, 2001 and 2002 at a) Cirencester, b) Leeds, and c) Silsoe. Values per trap are means (n=12). Codes for treatments: CC, arable crop area (sole crop); AV, alleys subtending vegetated understoreys; UV, vegetated understoreys; AB, alleys subtending bare understoreys; UB, bare understoreys.*

Species	2000					2001					2002				
	Treatment					Treatment					Treatment				
	CC	AV	UV	AB	UB	CC	AV	UV	AB	UB	CC	AV	UV	AB	UB
a) Cirencester															
Agonum dorsale	**1**	1	0	3	0	**0**	0	0	0	0	**1**	0	1	0	0
Calathus fuscipes	**12**	1	1	1	3	**2**	0	0	0	0	**2**	0	0	0	1
Harpalus affinis	**2**	3	4	3	7	**1**	0	1	0	3	**3**	3	1	4	4
H. rufipes	**5**	15	6	13	6	**1**	2	2	2	3	**1**	2	0	2	0
Nebria brevicollis	**8**	4	3	4	14	**7**	1	1	2	5	**15**	8	2	10	7
Pterostichus cupreus	**3**	8	6	6	4	**0**	4	4	3	2	**3**	8	14	9	4
P. madidus	**249**	13	8	12	4	**74**	16	4	11	6	**67**	13	6	10	11
P. melanarius	**10**	7	2	5	4	**12**	13	2	10	6	**7**	19	7	17	9
Total number of species per treatment	**18**	18	16	17	17	**13**	17	14	16	18	**18**	23	22	19	16
b) Leeds															
Agonum dorsale	**2**	6	2	5	2	**6**	3	4	2	1	**12**	6	5	5	2
Bembidion obtusum	**6**	1	1	1	1	**1**	0	0	0	1	**13**	5	3	3	6
Calathus fuscipes	**0**	0	2	0	2	**6**	1	0	1	1	**1**	1	0	1	1
C. melanocephalus	**0**	0	0	0	0	**5**	0	0	0	0	**1**	0	0	0	0
Harpalus affinis	**3**	1	3	2	3	**1**	1	1	1	2	**2**	1	2	2	3
Loricera pilicornis	**4**	2	1	2	1	**0**	1	1	1	0	**3**	2	0	2	1
Nebria brevicollis	**4**	2	2	3	3	**4**	7	6	6	3	**8**	10	1	12	4
Pterostichus madidus	**1**	4	13	6	5	**7**	32	12	23	6	**13**	47	33	48	53
P. melanarius	**29**	28	17	31	13	**105**	61	27	52	40	**87**	36	17	70	22
Trechus quadristriatus	**7**	8	5	6	5	**4**	4	2	4	1	**6**	3	5	2	2
Total number of species per treatment	**23**	21	16	21	22	**21**	24	22	24	21	**22**	23	21	20	20
c) Silsoe															
Carabus violaceus	**1**	2	5	3	6	**1**	0	2	0	0	**1**	1	2	4	2
Harpalus affinis	**1**	5	6	5	6	**0**	0	2	0	1	**3**	3	1	2	7
H. rufipes	**36**	21	49	16	37	**16**	3	9	2	1	**21**	4	3	3	2
Nebria brevicollis	**4**	2	4	1	2	**7**	7	4	8	12	**8**	14	6	12	19
Pterostichus cupreus	**21**	6	21	6	16	**33**	7	18	5	5	**28**	11	14	15	11
P. melanarius	**22**	8	13	9	16	**32**	16	24	7	10	**31**	13	11	21	17
P. niger	**2**	1	1	1	1	**1**	0	1	0	0	**1**	1	2	1	0
Total number of species per treatment	**21**	20	23	23	25	**20**	21	20	16	16	**21**	21	19	19	20

During 2001 at Cirencester, *P. madidus* was again found in greater abundance in the arable control than in the other treatments. In contrast *Pterostichus cupreus* was less abundant in the arable control area than in the other treatments. As in the previous year, *H. affinis* was more abundant in the bare understoreys than in the other treatments. However in 2001, *N. brevicollis* was more abundant in the arable control, as well as the bare understoreys, than in the other treatments. In 2002 at Cirencester, *P. madidus* was again more abundant in the arable control than in the other treatments.

At the Leeds site in 2000, both *Bembidion obtusum* and *Loricera pilicornis* were more numerous in the arable control than in the four agroforestry treatments. The abundance of *Pterostichus melanarius* was also greater in the arable control and the alley subtending the bare understorey, than in the other three treatments. In contrast, the abundance of *Pterostichus madidus* was least in the arable control. In 2001, *P. melanarius, Calathus melanocephalus* and *C. fuscipes* were more abundant in the arable control than in the other treatments. In 2002, as in 2000, *P. melanarius* was again more numerous in the arable control and the alley subtending the bare understorey than the other treatments. *Agonum dorsale* and *B. obtusum* were more abundant in the arable control than in the other treatments. *L. pilicornis* was less abundant in the two understorey treatments than in the other treatments.

In 2000, at the Silsoe site*, Pterostichus cupreus* was more abundant in the arable control than in the other treatments (Table 7.5). The abundance of *Pterostichus melanarius* and *Harpalus rufipes* within the control area was also greater than that in both types of alley. *Harpalus affinis* was more abundant in the two understorey treatments than in the arable control and the two cropped alley treatments. In 2001 and 2002, *P. cupreus* and *H. rufipes* were more abundant in the arable control than in the other treatments. In both 2001 and 2002, the abundance of *P. melanarius* was greater in the arable control area than in the bare understorey and its subtending alleys. In 2002, *H. affinis* was more numerous in the bare understoreys than in the other treatments.

7.5 Conclusions

During the three years across the three sites, 38,705 carabid beetles were captured and identified to species level. The total number of species found at Cirencester, Leeds and Silsoe were 29, 29 and 27 respectively. *Pterostichus madidus* was the most numerous species in each year at Cirencester. *Pterostichus melanarius* was the most numerous species each year at Leeds, and in 2001 and 2002 at Silsoe. *Harpalus rufipes* was the most abundant species at Silsoe in 2000. The most common species accounted for 29-61% of the total catch at a particular site in a given year.

The number of carabid beetle species captured within each agroforestry treatment (vegetated understorey, bare understorey; a cropped alley next to a vegetated understorey, or a cropped alley next to a bare understorey) within a given year (range: 16 to 25 species) appeared to be broadly similar to that (range: 13 to 23 species) recorded for the arable control. Hence no separate component of the agroforestry system appears to lead to a greater diversity of carabid beetle species than that in the arable control.

In all three years at the Cirencester site, a greater number of *Pterostichus madidus* was found in the arable control than in the other treatments. By contrast at Leeds, although the difference was not always statistically significant, the numbers of *P. madidus* in the arable control were lower than in the other treatments. One possible explanation for this is that the area for faunal measurements at Cirencester was in an arable crop in an area that had been permanent pasture until 1999. *Pterostichus madidus* is known to prefer a dense sward habitat (Rainio and Nimela, 2003), and this could explain the very large numbers found in the arable control of the Cirencester site during 2000, and the decline in its numbers in subsequent years.

Harpalus rufipes and *H. affinis* are both very dependent on seeds for their food (Thiele, 1977). However *Harpalus affinis* was most abundant in the bare understorey treatment, and *Harpalus rufipes* was commonly more numerous in the arable control. *Harpalus affinis* is known as a species of open ground (Kromp, 1989) and its distribution suggests that it could be taking advantage of the seeds of invasive species in the bare understoreys. Alternatively, *Harpalus rufipes* may be less dependent on presence of open ground and able to exploit the weedy species that were equally abundant in the cropped areas (see Section 6). *Nebria brevicollis* was also commonly more abundant in the bare understoreys. This species is one of the few that has surface-active larvae (Thiele, 1977), and it is possible that the uncultivated surface of the bare understoreys could provide ideal habitat for the larvae of this species.

In terms of the abundance of individual species, where there was a significant difference between treatments, greater numbers were generally captured in the arable control area than in the alleys and the two types of understorey. The results for monthly totals of carabid beetles as a class (Section 7.2) support this conclusion. One possible explanation for this result could be that the agroforestry system provides a more stable habitat with a greater diversity of both plants and all invertebrates. This could have a stabilising effect of carabid beetle population dynamics making it less likely that certain species would occur in very high numbers. It has been shown that production hedges (tree rows) can play an important part in attracting and maintaining populations of airborne natural enemies (Peng *et al.* 1993). Stamps *et al.* (2002) also suggest that alley cropped forage crops (with black walnut) support a more stable (and diverse) arthropod fauna than adjacent monocropped forage crops.

An interesting result at Leeds is the observation that vegetated understoreys commonly had the lowest activity of carabid beetles of the five habitats. The proposed benefits of beetle banks, which also contain cocksfoot (*Dactylis glomerata*), are that they provide a good habitat for overwintering carabid beetles, which can recolonise the adjacent arable crops in the spring and summer (Thomas *et al.*, 1991; Maudsley *et al.* 2002). In the vegetated understoreys after their establishment, carabid beetle numbers peaked in June 2001, a month before peaks in the arable treatments. This result provides some evidence that carabid beetles might have moved from the vegetated understorey into the adjacent crop. However the arable control with no beetle banks had the highest numbers of carabid beetles at Leeds in the summer of 2001 when the understorey sward in the agroforestry system was well-developed. These results plus the unsuitability of the bare understoreys as a habitat for slugs would argue in favour of bare understoreys as the preferred tree row understorey, particularly if maximum tree and crop productivity was the objective. In contrast, vegetated understoreys are clearly the best habitat for spiders, which often prefer a heterogeneous sward structure. The importance of spiders for pest control in agroecosystems has been reported and reviewed by Mansour and Heimbach (1993), Marc *et al.* (1999), and Nyffeler and Sunderland (2003). However the extent to which spiders might significantly reduce numbers of crop pests would need to be investigated further before statements could be made about the biological value of vegetated understoreys in tree rows of silvoarable agroforestry systems.

8. References

Beaton, A. (1987). Poplars and Agroforestry. *Quarterly Journal of Forestry* 81: 225-233.

Bechtel, K. (1997). Light interception by two poplar clones within an agroforestry system using tube solarimeters. Unpublished MSc thesis. Cranfield University, Silsoe, Bedfordshire 46 pp.

Burgess, P.J., Graves, A.R., Goodall, G.R. & Brierley, E.D.R. (2000a). Bedfordshire Farm Woodland Demonstration Project. Final Report to the European Commission ARINCO No 95.UK.06.002. Unpublished report. Cranfield University, Bedfordshire, UK.

Burgess, P.J., Incoll, L.D., Beaton, A., Corry, D.T., Seymour, I., Taylor, J. & Evans, R.J. (1998). Final Project Report for MAFF-funded project (OC9522): Silvoarable trials with Poplar, June 1998. Cranfield University, Silsoe, Bedfordshire.

Burgess, P.J., Incoll, L.D., Corry, D.T., Beaton, A. & Hart, B.J. (2003). Poplar growth and crop yields within a silvoarable agroforestry system at three lowland sites in England. *Agroforestry Systems* (In press)

Burgess, P.J., Incoll, L.D., Hart, B.J., Beaton, A., Seymour, I., Reynolds, F.H., Wright, C., Pilbeam, D.J., Corry, D.T. & Taylor, J. (2001). Appendices to interim project report – financial year 2000/01. MAFF Project Code: AF105. Cranfield University, Bedfordshire.

Burgess, P.J., Seymour, I., Incoll, L.D., Corry, D.T., Hart, B. & Beaton, A. (2000b). The application of silvoarable agroforestry in the UK. *Aspects of Applied Biology* 62: 269-276.

Cannell, M.G.R., Sheppard, L.J. & Milne, R. (1988). Light use efficiency and woody biomass production of poplar and willow. *Forestry* 61: 125-136.

Ceulemans, R., Pontailler, J.Y., Mau, F., and Guittet, J. (1993). Leaf allometry in young poplar stands: reliability of leaf area index estimation, site and clone effects. *Biomass and Bioenergy* 4: 315-321.

Chen, S.G., Ceulemans, R. & Impens, I. (1994). A fractal-based Populus canopy structure model for the calculation of light interception. *Forest Ecology and Management* 69: 97-110.

Christie, J.M. (1994). *Provisional Yield Tables for Poplar in Britain.* Forestry Commission Technical Paper 6. Edinburgh: Forestry Commission. 35 pp.

Clarke, J.H., Jones, N.E., Hill, D.A. & Tucker, G.M. (1997). The management of set-aside within a farm and its impact on birds. In: *The 1997 Brighton Crop Protection Conference*, Vol 3, 1179-1184. Farnham, Surrey: British Crop Protection Council.

Davenport, D.J.C. (1995). Prices received for mature poplar at Foxley Estate, Spring 1995. Poplar Forum Study Day 21 June 1995.

DEFRA (2002). Arable Area Payments Scheme 2002 Edition. Explanatory Guide Part II. Accessed 4 August 2003. http://www.defra.gov.uk/farm/schemes/aaps_pt2.pdf

DEFRA (2003). Policy review of woodland creation in England under the Woodland Grant Scheme and the Farm Woodland Premium Scheme. Response of the Forestry Commission and the Department for Environment, Food and Rural Affairs to the Report of the Review Steering Group. April 2003. DEFRA.

FCAP Supply and Demand Sub-Committee (2002). Quarterly Market Reports: Forest Enterprise. Accessed 19 May 2003. http://www.forestry.gov.uk/website/pdf.nsf/pdf/feqmr.pdf/$file/feqmr.pdf

Forestry Commission (2003). Standing timber prices for England 2000-2002. Accessed 19 May 2003. http://www.forestry.gov.uk/forestry/ahen-5gbls4

Griffiths, J., Phillips, D.S., Compton, S.G., Wright, C. and Incoll, L.D. (1998) Slug number and slug damage in a silvoarable agroforestry landscape. *Journal of Applied Ecology* 35: 252-260.

Hall, R.L., Allen, S.J., Rosser, P.T.W., Smith, D.W., Hodnett, M.G., Roberts, J.M., Hopkins, R., and Davies, H.N. (1996). Hydrological effects of short rotation energy coppice. Institute of Hydrology, Wallingford.

Hart, C. (1994). *Practical Forestry for the Agent and Surveyor*. Third Edition. Stroud, Gloucestershire: Alan Sutton Publishing Ltd. pp 428-430.

Hobrook, N.M. & Putz, F.E. (1989). Influence of neighbours on tree form: effects of lateral shade and prevention of sway on the allometry of *Liquidambar styraciflua* (Sweet gum). *American Journal of Botany* 76: 1740-1749.

Incoll, L.D. & Newman, S. (2000). Arable crops in agroforestry systems. In: *Agroforestry in the UK.* pp 71-80. Eds. M. Hislop and J. Claridge. Forestry Commission Bulletin 122. Farnham: Forest Research.

Incoll, L.D., Burgess, P.J., Beaton, A., Corry, D.T. & Evans, R.J. (1996). Silvoarable trials with Poplar. Unpublished Final Report for MAFF-Funded Project: Contract Ref. CSA 2817 April 1996. Tilhill Economic Forestry, University of Leeds, Royal Agricultural College and Cranfield University. 29 pp.

Isebrands, J.G. & Nelson, N.D. (1982). Crown architecture of short-rotation, intensively cultured Populus II. Branch morphology and distribution of leaves within the crown of Populus 'Tristus' as related to biomass production. *Canadian Journal of Forest Research* 12: 853-864.

Jackson, J.E. & Palmer, J.W. (1972). Interception of light by model hedgerow orchards in relation to latitude, time of year and hedgerow configuration and orientation. *Journal of Applied Ecology* 9: 341-358.

Jackson, J.E. & Palmer, J.W. (1989). Light availability at the tree/crop interface. In: *Meteorology and Agroforestry*. pp 391-400. Eds. W.S. Reifsnyder & T.O. Darnhofer. Proceedings of an international workshop on 'The application of meteorology to agroforestry systems planning and management'. Nairobi, Kenya: ICRAF

Jobling, J. (1990). *Poplars for Wood Production and Amenity.* Forestry Commission Bulletin 92. London: HMSO.

Kromp, B. (1989). Carabid beetle communities (*Carabidae, Coleoptera*) in biologically and conventionally farmed agroecosystems. *Agriculture, Ecosystems and Environment* 40: 71-93.

Lonsdale, D. & Tabbush, P. (1998). Poplar rust and its recent impact in Great Britain. *Forestry Commission Information Note*. Farnham, Surrey: Forest Research. 4 pp.

MAFF (1998). *The Farm Woodland Premium Scheme Rules and Procedures.* Ministry of Agriculture, Fisheries and Food. 26 pp.

MAFF (2000). *Fertiliser Recommendations for Agricultural and Horticultural Crops (RB209).* London: The Stationary Office.

Mansour, F. & Heimbach, U. (1993). Evaluation of *Lycosid, Micryphantid* and *Linyphiid* spiders as predators of *Rhopalosiphum-Padi* (*Hom., Aphididae*) and their functional-response to prey density - Laboratory Experiments. *Entomophaga* 38: 79-87.

Marc, P., Canard, A. & Ysnel, F. (1999). Spiders (*Araneae*) useful for pest limitation and bioindication *Agriculture Ecosystems & Environment* 74: 229-273.

Maudsley, M., Seeley, B. & Lewis, O. (2002) Spatial distribution patterns of predatory arthropods within an English hedgerow in early winter in relation to habitat variables. *Agriculture Ecosystems & Environment* 89: 77-89.

Newman, S.M., Wainwright, J., Hutton, H., Wu, Y., Marshall, C., Amatya, S.M., Ranasinghe, D.M.S.H.K. & Morris, R.M. (1995). Spacing and variety effects on poplar silvoarable systems in the UK. *Agroforestry Forum* 6(2): 37-43.

Nix, J. (1997). *Farm Management Pocketbook.* Wye College, University of London. 220 pp.

Nix, J. (2001). *Farm Management Pocketbook.* Imperial College at Wye. 32nd Edition (2002). Melton Mowbray, Leicestershire: The Andersons Centre.

Nix, J. (2002). *Farm Management Pocketbook.* Thirty-third Edition (2003). Imperial College at Wye. Melton Mowbray, Leicestershire: The Andersons Centre.

Norman, J.M. & Welles, J.M. (1983). Radiative transfer in an array of canopies. *Agronomy Journal* 75: 481-488.

Nyffeler, M. & Sunderland, K.D. (2003). Composition, abundance and pest control potential of spider communities in agroecosystems: a comparison of European and US studies. *Agriculture, Ecosystems and Environment*. 95: 579-612.

Peng, R.K., Incoll, L.D., Sutton, S.L., Wright, C. & Chadwick, A. (1993) Diversity of airborne arthropods in a silvoarable agroforestry system. *Journal of Applied Ecology.* 30: 551-562.

Pretty, J. & Ball, A. (2001). *Agricultural Influences on Carbon Emissions and Sequestration: A Review of Evidence and the Emerging Trading Options.* UK Centre for Environment and Society Occasional Paper 2001-03 University of Essex.

Poplar Tree Company (1999). The Poplar Tree Company Joint Venture Option. Madley, Hereford: The Poplar Tree Company.

Potter, C.J., Nixon, C.J. and Gibbs, J.N. (1990). *The Introduction of Improved Poplar Clones from Belgium.* Research Note 181, Forestry Commission Research Division. 4 pp.

Rainio, J. & Niemela, J. (2003). Ground beetles (*Coleoptera: Carabidae*) as bioindicators. *Biodiversity and Conservation* 12: 487-506.

Reid, R. & Ferguson, I.S. (1992). Development and validation of a simple approach to modelling tree shading in agroforestry systems. *Agroforestry Systems* 20: 243-252.

Scott, R.K., Jaggard, K.W., & Sylvester-Bradley R. (1992). Resource capture by arable crops. In: *Resource Capture by Crops* pp 279-302. (Ed J.L. Monteith, R.K. Scott & M.H. Unsworth). Nottingham University Press.

Scottish Agricultural College (1999). *The Farm Management Handbook 1999/2000.* Editor L. Chadwick. Edinburgh: SAC. 518 pp.

Sotherton, N.W. & Rands, M.R.W. (1986). The environmental interest of field margins to game and other wildlife. In: *Field Margins.* pp 67-75. Eds: J.M. Way and P.W. Greig-Smith. Thornton Heath: British Crop Protection Council.

Stadt, K.J., Lieffers, V.J. & Pinno, B.D. (2001). Modelling light dynamics in boreal mixedwood forests. SFM Network Project: Spatially-explicit calibration of a light model for eastern and western boreal forests. Accessed 7 May 2003. http://sfm-1.biology.ualberta.ca/english/pubs/PDF/PR_2001-12.pdf

Stamps W.T., Woods, T.W., Linit, M.J. and Garrett, H.E. (2002). Arthropod diversity in alley cropped black walnut (*Juglans nigra* L.) stands in eastern Missouri, USA. *Agroforestry Systems* 56: 167-175.

Stamps, W.T., & Linit, M.J. (1997) Plant diversity and arthropod communities: Implications for temperate agroforestry. *Agroforestry Systems.* 39: 73-89

Tabbush, P. (1995). Approved Poplar Clones. *Forestry Authority Research Division Information Note* 265. Forestry Authority Research Division. 4 pp.

Thiele, H.U. (1977). *Carabid Beetles in their Environments*. Berlin, Germany: Springer-Verlag.

Thomas, M.B., Wratten, S.D. & Sotherton, N.W. (1991). Creation of 'island' habitats in farmland to manipulate populations of beneficial arthropods: Predator densities and emigration. *Journal of Applied Ecology* 28: 906-917.

Thomas, S.R., Noordhuis, R., Holland, J.M. & D Goulson, D. (2002). Botanical diversity of beetle banks; effects of age and comparison with conventional arable field margins in southern UK. *Agriculture, Ecosystems and Environment* 93: 403-412.

Thomas, T.H. (1991). A spreadsheet approach to the economic modelling of agroforestry systems. *Forest Ecology and Management* 45: 207-235.

Thomas, T.H. & Willis, R. (2000). The economics of agroforestry in the UK. In: *Agroforestry in the UK.* Ed. Max Hislop and J. Claridge. pp 107-125

Thomas, T.H., Winterbourne, J.M. & Willis, R.W. (1994). Poplars for farmers - an economist's view. In: *Poplar - The Golden Opportunity*. pp 17-32. Proceedings from the National Agricultural Conference 24 October 1994. Stoneleigh, Warwick: Royal Agricultural Society of England.

Tubex (1999). Tubex Plant Care Products. 1989/1999 Season Prices. Aberdare: Tubex Ltd.

Whiteman, A., Insley, H. & Watt, G. (1991). Price size curves for broadleaves. *Forestry Commission Occasional Paper* 32. Edinburgh: Forestry Commission.

Willis, R.W., Thomas, T.H. & Van Slycken, J. (1993). Poplar agroforestry: a re-evaluation of its economic potential on arable land in the United Kingdom. *Forest Ecology and Management* 57: 85-97.

Woodland Creation Steering Group (2002). Policy Review of Woodland Creation in England under the Woodland Grant Scheme and the Farm Woodland Premium Scheme. Report of Review Steering Group. November 2002. Report commissioned by the DEFRA and the Forestry Commission.

Woodland Improvement and Conservation (1997). *Manual Trees and Prices 1997.* Royal Forest of Dean, Gloucestershire: Woodland Improvement and Conservation Ltd. 98 pp.

Woodland Improvement and Conservation (2002). *Price List 2002/03.* Royal Forest of Dean, Gloucestershire: Woodland Improvement and Conservation Ltd. 26 pp.

Wright, C. (1994). The distribution and abundance of small mammals in a silvoarable agroforestry system. *Agroforestry Forum* 5(2): 26-28.