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The establishment phase of a silvopastoral national network experiment in the UK

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Abstract

Silvopastoral agroforestry can satisfy some objectives required of European land-use systems: reduced agricultural production, increased timber production, increased product diversity and environmental enhancement. A national network experiment was set up on four sites, each representative of a UK grassland farming area, with three replicates of common treatments: sycamore (*Acer pseudoplatanus* L.) at two silvopastoral planting densities [100 (S100) and 400 (S400) stems ha^{-1}] protected by tree shelters and an agricultural control (ACONT) all with grazing sheep; a woodland control (WCONT, 2500 trees ha^{-1}) without grazing. Common management protocols were applied and common measurements recorded. Results are provided for the first six years. There were no significant differences between S100, S400 and ACONT in agricultural productivity, though there were significant differences between sites ($P < 0.001$). There were no significant differences in tree survival between the silvopastoral treatments and WCONT (mean 92.5% ± 0.74) but there was a difference between S100 and S400 (90.8 vs 94.7%: $P < 0.001$). There were significant differences between the sites (range 86.5–96.2%: $P < 0.001$) and between the first three years, when replacement of dead trees took place, (82.5, 95.1 and 96.9% for years 1, 2 and 3 respectively: $P < 0.001$). There were significant differences in the total height of the trees in years two to four between WCONT, S100 and S400 (113.5, 154.1 and 194.5 cm respectively in year four: $P < 0.001$). However, by year six WCONT and S100 were similar (180.7 ± 17.31 cm) while S400 were taller (219.0 ± 22.80 cm: $P < 0.05$). It is concluded that tree shelters maintained silvopastoral tree survival at the level of conventional woodland. Tree height extension was compromised on S100 where a higher animal:tree ratio resulted in greater animal activity and soil compaction around trees compared to S400. The site with poorly-drained soil proved to be unsuitable for sycamore-based silvopastoral agroforestry.

1. Introduction

There is little tradition of silvopastoral systems in the UK. Grazing of orchards in order to control weeds has been practised but has been replaced by chemical control. There is a tradition of parkland around large houses on estates where grazing took place amongst well protected trees, but this was for landscape effect and not for practical reasons of agriculture or forestry. Grazing was a feature of a poplar-based (*Populus*) system for growing timber for the manufacture of matches. Intercropping of the widely spaced poplars was carried out for the first few years after planting. When crop growth became uncommercial, the understorey was replaced with a grass-clover mixture and grazing was rented to local farmers for a few years before canopy closure. However, this system ran for only a few years and was abandoned in the 1970s (Beaton, 1992).

A resurgence of interest in agroforestry in the UK became evident in the mid 1980s as a result of a number of pressures which are listed below:

- Reduction of agricultural production following changes in the European Common Agricultural Policy (CAP);
- Increased diversity of rural production;
- Maintenance of rural employment/infrastructure;
- Reduction of timber imports (the UK imports 90% of its timber and timber products);
- Environmental enhancement (e.g. biodiversity (see, HMSO (1994), nature conservation);
- Improved animal welfare.

The potential of silvopastoral agroforestry as an alternative land use capable of satisfying the multiple objectives highlighted in the above list, and the apparent success of silvopastoral systems in the temperate environment of New Zealand (Knowles, 1991), indicated that such systems could be applied in the UK. Prior to field experimentation, models were constructed to assess the potential of silvopastoral systems in the UK (Tabbush et al., 1985; Doyle et al., 1986). They suggested that such systems could generate economic returns that were at least as good as conventional livestock farming systems. Because there is little remaining of traditional silvopastoral systems in the UK, there are no existing examples upon which research could be conducted. In consequence, a silvopastoral National Network Experiment (NNE) was established under the auspices of the UK Agroforestry Forum (Sibbald and Sinclair, 1990).

The rationale behind the setting up of the NNE was to provide knowledge, information and experience on the establishment of silvopastoral systems over a range of climatic and edaphic conditions in the UK.

In order to allow the effects of planting density and choice of tree species to be directly interpreted, individual experimental plots are confined to a single planting density of a single tree species with individual pasture and livestock management control. In order to allow direct comparison with more conventional uses of the land for agriculture and farm woodland, an agricultural control of grazed pastures without trees and a woodland control at a conventional planting density without grazing were included. The basis of the NNE is a series of common treatments, management protocols and assessment procedures. Sycamore (*Acer pseudoplatanus* L.) was chosen as the common tree species because it has potential over the range of sites to produce timber of good quality (Harris, 1987; Stern, 1982) and is at least as good as most other broadleaved trees planted in the UK with respect to its ability to support a population of invertebrates and, consequently, larger fauna, especially birds (Boyd, 1992; Stern, 1982). Sites have, additionally, included other treatments based upon tree species of local value, these treatments are not reported here. The two silvopastoral planting densities in the experiment (100 and 400 trees ha^{-1}) are at the extremes of the range which, on the basis of modelling in the UK (Tabbush et al., 1985; Doyle et al., 1986) supported by practical experience in New Zealand (Knowles, 1991), is likely to generate acceptable levels of economic output.

2. Materials and methods

The four NNE sites in this phase of the network cover a geographic range throughout the UK, see Figure 1. Two sites are classified as lowland and two as upland sites, see Table 1. Each site is representative of an important UK grassland farming area.

2.1. *Treatments*

Sycamore is planted at the two silvopastoral densities of 100 (S100) and 400 (S400) stems ha^{-1} in a regular, square pattern (10 × 10 m for S100 and 5 × 5 m for S400). There is also a woodland control with no grazing planted at 2500 stems ha^{-1} (WCONT, 2 × 2 m square pattern) and an agricultural control of grazed pasture without

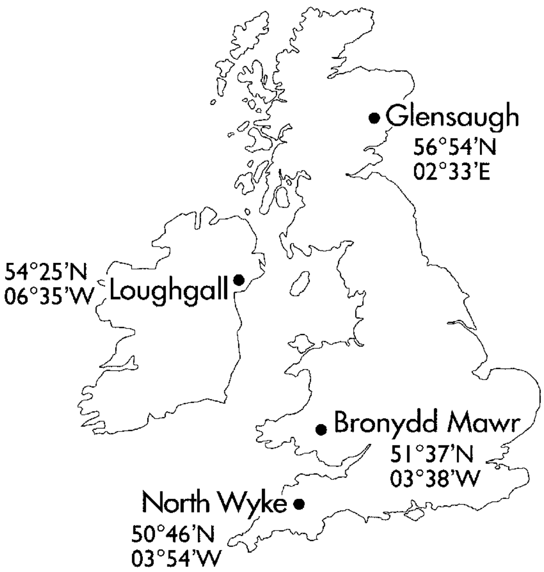


Figure 1. Map of the UK showing locations of the four study sites of the silvopastoral National Network Experiment.

trees (ACONT). There are three replicates of each treatment laid out in a randomised block design at each site.

2.2. *Experimental plots*

The area of the grazed plots (S100, S400 and ACONT) varies according to the mature live weight of the sheep used at individual sites. Plot size varies from 0.5 to 0.8 ha depending on site and sheep breed. The area was set such that a minimum of eight breeding female sheep (ewes) with their lambs could be maintained on each plot throughout the grazing season, see Table 2. A group of eight ewes was considered to be large enough to cover the normal age range and suckling type (number of lambs ewe^{-1}) found in UK flocks and to allow for subsequent reductions in stocking capacity as the experiment developed.

The minimum plot area (0.1 ha) for WCONT was such that a core group of 25 (5 × 5) measurement trees was surrounded by at least four rows of guard trees.

2.3. *Management protocols*

All sites are managed on the basis of a set of common protocols.

2.3.1. *Tree planting and maintenance*

The planting stock used was seed-grown from German (NW, BM, GS) or Czechoslovakian (LG) sources. The seedlings were one year old when planted in autumn 1987 at BM, spring 1988 at GS and spring 1989 at NW and LG. The trees in the silvopastoral treatments (S100 and S400) were notch-planted beside an 8 cm diameter, 1.5 m tall, treated larch stake. Each tree was protected by a rigid plastic shelter (Tubex Ltd®) fixed to the stake with plastic ratchet ties. The heights of the tree shelters depended on the size of the sheep breed used or on the risk from wild red deer (*Cervus elaphus*) at the individual sites (NW, LG and BM 1.5 m; GS 1.8 m), in order to prevent the sheep or deer from browsing emerging shoots. A short (45 cm) square wooden peg (2.5 × 2.5 cm) was used on the opposite side of each tube from the main stake to prevent the tubes from being turned when sheep rubbed on them. The protection was based upon the provisional results of earlier studies (McAdam, 1991; Nixon et al., 1992). Two trees were planted on opposite sides of the stake at the upland sites (BM and GS) in order to provide limited selection. The tree with the better growth form was retained when they emerged from their shelters, the poorer tree and its shelter were removed in year three, on average.

Before planting, a 1 m diameter vegetation-free zone was created around each stake by application of glyphosate. This was maintained for three years by subsequent annual applications of glyphosate (BM, NW), propyzamide (GS) or both (LG). The WCONT trees were planted at the same time as the trees in the silvopastoral plots into a similar 1m diameter vegetation-free zone but tree shelters were not used. Hand-weeding, slashing or application of propyzamide were carried out where required around each WCONT tree for three years to maintain a vegetation-free zone. Each WCONT plot was fenced against grazing and browsing animals, including deer, hares and rabbits. For the first three years, dead trees were replaced by plants of similar stock in all treatments.

2.3.2. *Fertilizer management*

All grazed treatments (S100, S400 and ACONT) receive 160 kg of nitrogen ha^{-1} annum^{-1} in four aliquots. This rate of fertilizer application reflected normal usage on permanent pastures in the UK.

Table 1. Site details of the silvopastoral National Network Experiment, UK.

Site name	Symbol	Site type	Location	Altitude (m)	3-year average monthly 100 mm soil temperatures (°C)			Precipitation (mm $annum^{-1}$)	Soil (FAO classification, FAO/UNESCO, 1974)	Drainage
					Min	Max	Mean			
North Wyke	NW	Lowland	50°46′ N 03°54′ W	180	5.5	17.3	10.9	1008	Gleysol	Poor
Loughgall	LG	Lowland	54°25′ N 06°35′ W	30	2.5	16.8	9.3	910	Eutric cambisol	Imperfect
Bronydd Mawr	BM	Upland	51°37′ N 03°38′ W	330	2.8	15.6	8.5	1471	Dystric cambisol	Free
Glensaugh	GS	Upland	56°54′ N 02°33′ E	250	2.4	17.4	9.1	1050	Dystric cambisol	Free

Table 2. Breeds and characteristics of sheep used at different sites of the silvopastoral National Network Experiment, UK.

Site	Breed of ewe	Mature ewe live weight – (kg)	'Normal' prolificacy (lambs born alive ewe^{-1})	Commencement of mating period	Start of grazing in each year	End of grazing in each year	Weaning date
NW	Masham	71	2.0	Early-November	April	October/November	July/August
LG	Greyface	76	1.9	Mid-October	April	November/December	July
BM	Brecknock Cheviot	55	1.2	Mid-November	April	November	August
GS	Greyface	75	1.7	Late-October	Early-May	Late-October	July

Applications of phosphorus and potassium were adjusted to the pasture maintenance requirements of the local sites and based upon soil analysis. Fertilizers were applied as compounds in granular form.

2.3.3. *Pasture management*

The pastures were dominated by ryegrass (*Lolium perenne*) but included other grass species (*Festuca* spp., *Agrostis* spp., and *Poa* spp.) and often white clover (*Trifolium repens*). They are termed permanent pastures in the UK having been sown at some time in the past with a view to their long-term use. The pastures were maintained on the basis of a seasonal sward surface height (sward height) profile by adjustment of animal stocking rate based on weekly measurements of sward height. The objective of this management is to maintain a dense, leafy sward with minimal formation of flowers and seed heads so that the grazing animals, irrespective of site and treatment, have access to a diet of high quality and adequate biomass. The rationale behind the use of the seasonal sward height profile and the methods for measuring sward height are given in Maxwell et al. (1993). The pastures on the lowland sites often had sward heights in excess of 5 cm at the start of the grazing season. Thereafter, they were managed to achieve a sward height of 5 cm by the end of spring through to late summer, rising to 6 cm in early autumn and grazed down thereafter to 3.5 cm. The upland sites were managed to achieve a sward height of 4 cm from spring to mid summer rising to 5 cm in late summer, 6 cm in early autumn and 7 cm by the end of the pasture growing season. They were grazed down thereafter to 3 cm which permitted grazing to continue for several weeks after pasture growth had ceased. The calculations for determining the appropriate animal stocking rate are adapted from those given in Maxwell et al. (1993). The use of a common seasonal sward height profile ensures even grazing pressure in relation to differences in the seasonal pattern of pasture productivity across the range of sites.

2.3.4. *Animal management*

Sheep were used as the grazing animals throughout the NNE but the ewes at individual sites were different breeds of local value. The breeds have different mature liveweights and potential prolificacies (see Table 2). The same terminal sire (Suffolk) was used at all sites. The cross-bred lambs which result have a carcass confirmation suitable for UK and European meat markets.

Lambing in the UK is traditionally timed to coincide with the start of pasture growth, and this pattern is adhered to at the individual sites. The date of the start of the mating period is set accordingly (see Table 2). The ewes generally gave birth to their lambs indoors after a winter period off the experimental area when they were provided with grazing or with the fodder and supplements necessary to maintain them in a condition that guaranteed peri-natal lamb survival. The ewes and their lambs were moved to the experimental plots (turn-out) a few days later. Sheep grazed the experimental plots from turn-out each spring until they were removed to their wintering areas (see Table 2). In some years at NW and at LG, sheep at low stocking rates, continued to graze throughout the winter. Lambs were removed from the experimental plots each year at the traditional weaning date for the site (see Table 2).

The core group of ewes (see 2.2 above) and, before weaning, their lambs, remained on individual plots throughout the grazing season. If sward height fell below the required seasonal profile, supplementary feed could be provided according to an agreed set of rules. During the first six years of the experiment, however, no supplementary feed was provided at any site. When pasture growth rate exceeded the capacity of the core group to maintain the sward height profile, extra ewes and lambs (the buffer group) were added (see 2.3.3 above). If sward height fell below the required seasonal profile and buffer group animals were present, an appropriate number of them were removed. Additions and removals of buffer group animals were determined on the basis of calculations based on change in sward height and estimates of sward density (dry matter per unit area per unit of sward height) and animal intake (dry matter per grazing unit (ewe plus lamb(s) in season)).

2.4. *Measurement protocols*

2.4.1. *Tree measurements*

Total tree height was recorded for a core group of 25 trees per plot at the time of planting, thereafter total height was recorded annually. Tree survival was also recorded annually on each core group of 25 trees. Survival percentages in any single year were based on the number of surviving and replacement trees at the start of that year. Replacement trees and those which survived from the original planting were uniquely identified.

2.4.2. *Pasture measurements*

Forty individual sward height measurements were recorded weekly on each plot throughout the grazing season using the HFRO sward stick (Barthram, 1986). These data were used as a basis for pasture management (see above).

2.4.3. *Animal measurements*

Ewes (and lambs before weaning) in the core group were weighed monthly during the grazing season. Buffer ewes (and lambs) were weighed when they went on and off the plots. Records of the stocking rates required to maintain the sward height profile were also kept. Stocking rates, against the background of a maintained seasonal sward height profile, reflected seasonal patterns of pasture growth, account having been taken of the provision of supplementary feed through the use of substitution rates (Milne et al., 1986). They were used, together with animal liveweights, to calculate an annual animal stock carrying capacity for which the units are tonne (live weight) days ha^{-1} $annum^{-1}$. The results take account of the varying length of growing season and fluctuations in seasonal pasture growth between the sites. Animal liveweight gains, as an indicator of individual animal performance, were also calculated.

2.5. *Statistical analysis*

Analyses of variance were carried out on all variables measured as single values for each plot using Genstat (Lawes Agricultural Trust, 1987) and treating replicates as a blocking factor.

3. Results

3.1. *Tree survival*

The mean annual rate of survival over the first six years was 92.5 (±0.74) %. There was no significant difference in the annual rate of tree survival, using data from all six years, between the silvopastoral treatments (S100 together with S400) and the woodland control (92.7% vs 92.0%). There was a small but highly significant difference ($P < 0.001$) between the trees on S100 and those on S400 (90.8 vs 94.7%). This arose from the two upland sites (BM and GS) which demonstrated significantly lower rates of survival at S100 than at S400 (92.6% vs 98.7%; $P < 0.001$). This was not the case for the lowland sites (NW & LG; 89.0% and 90.1% for S100 and S400 respectively). There were significant differences ($P < 0.001$) between sites and between years (Table 3) and a significant interaction ($P < 0.001$) between sites and years. The significant interaction resulted from a particularly poor survival rate of S100 at NW in the first year (47.3%; see Table 4) and from falling rates of survival in all treatments at NW in years five and six, see Table 4. There were no significant differences between sites in years two, three and four. By the end of the six-year period, mean annual survival for the three sites, excluding NW, was 94 ± 1.68 % with a range over the three sites and three treatments of 84% to 100%.

Different rates of survival resulted in different numbers of replacement trees on treatments and sites. The numbers of replacement trees per 100 planted during the first three years are shown in Table 5. Differences between the four sites are significant ($P < 0.05$) but there are no significant differences between the three sites when NW is excluded. The replacement rate for S400 (5.3 ± 0.76%) is less than that for S100 and WCONT (30.8 ± 7.10%) on the upland sites ($P < 0.05$).

3.2. *Tree height*

Using data from all six years, there were significant differences ($P < 0.001$) between treatments, between sites and between years in plot mean total height of trees. Tree heights were similar on all treatments in year one, see Figure 2a. Agroforestry trees (S100 and S400) were significantly taller

Table 3. Mean annual survival rates of sycamore trees for all treatments combined for the different sites [Lowland (L), Upland (U)] and years in the silvopastoral National Network Experiment, UK.

Site (type)	Year 1 (%)	Year 2 (%)	Year 3 (%)	Year 4 (%)	Year 5 (%)	Year 6 (%)	Site mean (%) (s.e.m.)
NW(L)	66.0	97.6	95.6	95.2	87.8	76.8	86.5[a] (2.03)
LG(L)	87.8	97.4	98.3	97.2	94.9	98.0	95.6[c] (0.98)
BM(U)	85.7	88.8	95.9	94.3	94.3	90.0	91.7[b] (1.39)
GS(U)	90.4	96.6	98.0	98.3	99.6	94.2	96.2[c] (0.87)
Year mean (s.e.m.)	82.5[a] (2.68)	95.1[c] (1.76)	96.9[c] (0.62)	96.3[c] (0.72)	94.1[c] (1.19)	90.0[b] (2.05)	92.5 (0.74)

Values in the column and row of means which have different superscripts are significantly different (P = 0.001).

Table 4. Mean annual survival rates of sycamore trees for individual treatments [woodland control (WCONT) and agroforestry (S100, S400)] at the NW site of the silvopastoral National Network Experiment, UK.

Treatment	Year 1 (%)	Year 2 (%)	Year 3 (%)	Year 4 (%)	Year 5 (%)	Year 6 (%)	Site mean (%) (s.e.m.)
WCONT	82.7	94.0	96.0	95.0	91.7	81.0	90.1[b] (2.14)
S100	47.3	100.0	94.7	94.7	85.0	72.0	82.3[a] (4.67)
S400	68.0	98.7	96.0	96.0	86.7	77.3	87.1[ab] (3.19)
Year mean (s.e.m.)	66.0[a] (5.84)	97.6[d] (1.16)	95.6[cd] (0.99)	95.2[cd] (1.79)	87.8[c] (2.67)	76.8[b] (4.10)	86.5 (2.03)

Values in the column and row of means which have different superscripts are significantly different (P = 0.001).

Table 5. Total number of replacement trees required per 100 planted for sites [Lowland (L), Upland (U)] and treatments [woodland control (WCONT) and agroforestry (S100, S400)] during the first three establishment years of the silvopastoral National Network Experiment, UK.

Site (type)	WCONT	S100	S400	Site mean (s.e.m.)
NW(L)	27.3	58.0	37.3	40.9 (5.81)
LG(L)	15.3	8.0	26.0	16.4 (4.63)
BM(U)	44.0	38.7	6.3	29.7 (10.25)
GS(U)	22.6	18.0	4.3	15.0 (3.22)
Treatment Mean (s.e.m.)	27.3 (6.22)	30.7 (3.04)	18.5 (5.30)	25.5 (3.60)

(P < 0.001) than WCONT trees in year two. In years three, four and five, S400 trees were significantly taller (P < 0.001) than S100 trees which were significantly taller (P < 0.001) than WCONT trees, see Figure 2a. By year six, S400 trees were significantly taller (P < 0.05) than WCONT trees with S100 trees intermediate in height and similar to the two extremes. These differences in total height resulted from differences between treatments in annual height increments, see Figure 2b.

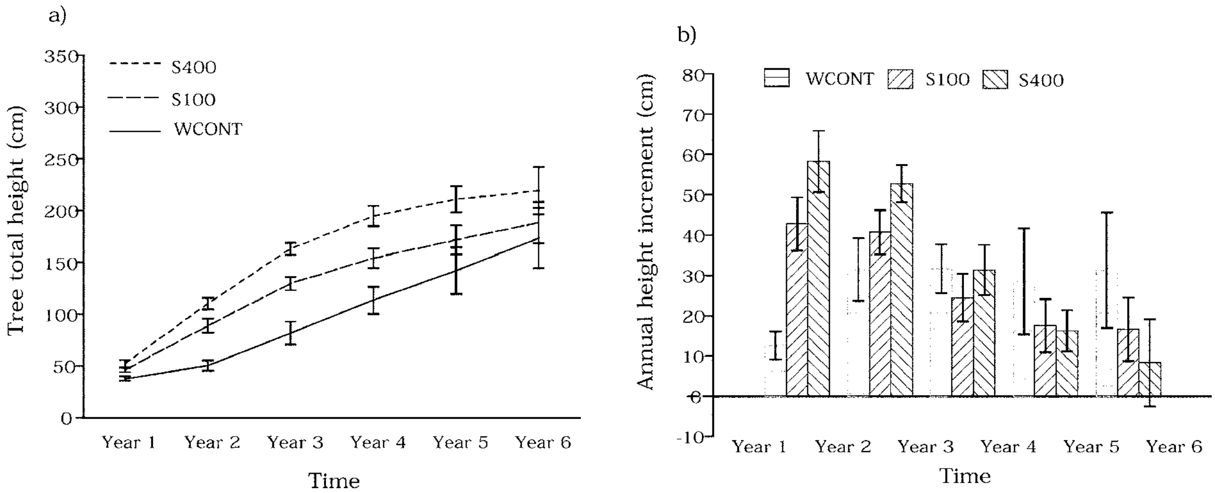


Figure 2. Heights of trees under different treatments by years for all four sites of the silvopastoral National Network Experiment, UK: a. total height; b. annual height increment.

Annual height increments were greatest in years one and two then fell gradually to their lowest level in year six ($P < 0.001$). However, there were significant treatment by year interactions ($P < 0.001$). Agroforestry trees (S100 and S400) grew significantly faster than WCONT trees in year one ($P < 0.001$), thereafter there was a trend for the WCONT trees to catch up and then to exceed the height extension rates of the agroforestry trees.

There were significant effects of site on tree top height and height extension ($P < 0.001$). Trees on all treatments on the lowland site at NW followed the general pattern of height extension until year three, thereafter height extension effectively ceased in year four and became negative in years five and six (Figures 3a and b). Because of the apparent unsuitability of the NW site for sycamore, the data for the site were excluded from further analyses.

The pattern of annual height increment, excluding the NW site, (Figures 4a and b) was similar to the four-site pattern (Figures 2a and b)

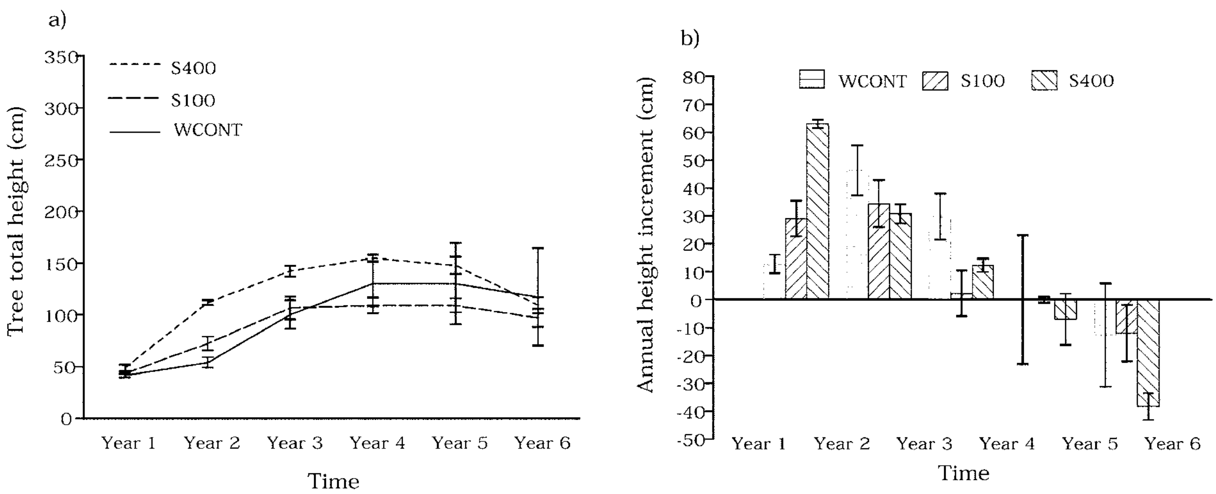
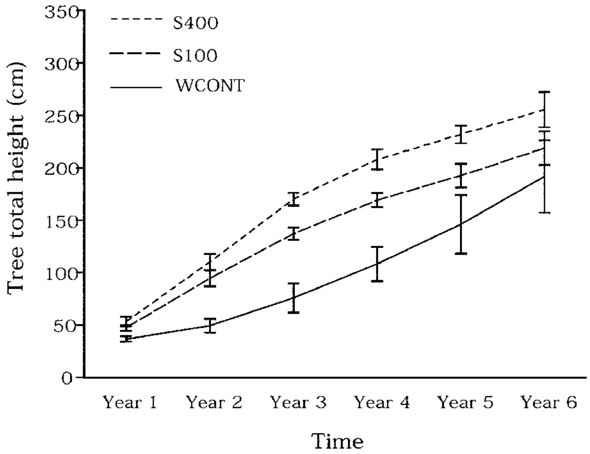


Figure 3. Heights of trees under different treatments by years for the North Wyke site of the silvopastoral National Network Experiment, UK: a. total height; b. annual height increment.

a)



b)

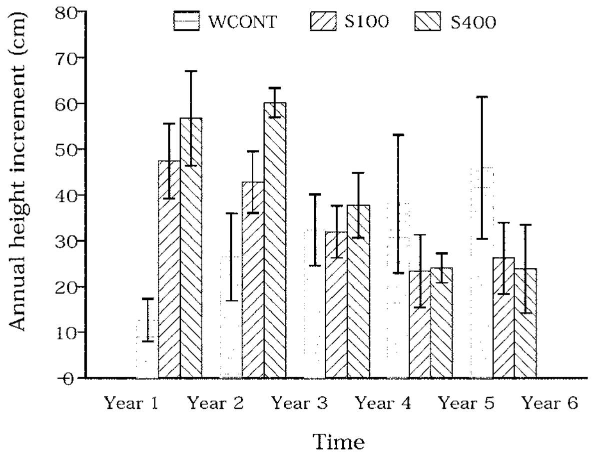
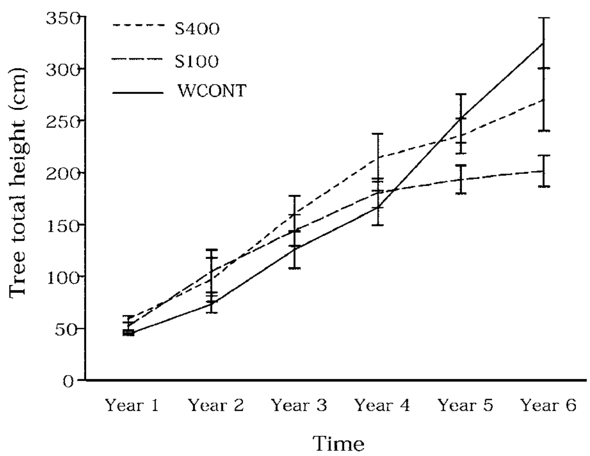


Figure 4. Heights of trees under different treatments by years for three sites (North Wyke excluded) of the silvopastoral National Network Experiment, UK: a. total height; b. annual height increment.

for the first five years but with greater rates of increment in years four, five and six (Figure 4b) resulting, overall, in taller trees (Figure 4a). The annual height increments of WCONT trees (Figure 4b) increased each year such that the increment from year five to six was significantly greater ($P < 0.05$) than that for year one to two. Over the same period, the height increment of the S400 trees reduced such that the increment from year five to six was significantly less ($P < 0.05$) than that for year one to two (Figure 4b). There was no significant difference between years in the annual height increment of the S100 trees. As a consequence of these patterns of annual height increment, there was a trend ($P < 0.10$) for the S400 trees in year six to be taller than the S100 and WCONT trees which were similar (Figure 4a).

The pattern of development of top height in the WCONT trees was largely influenced by the trees on the LG site. Annual height increments at LG were similar for all treatments for the first three years (Figure 5b). Between years four and five, the increments of the WCONT trees were greater than those on the agroforestry treatments (S100

a)



b)

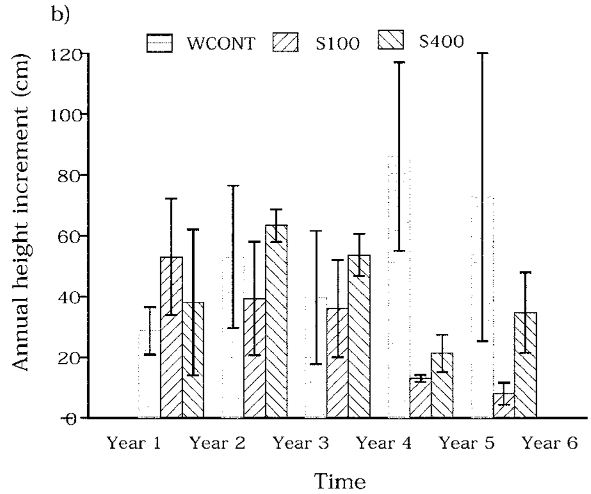


Figure 5. Heights of trees under different treatments by years for the Loughgall site of the silvopastoral National Network Experiment, UK: a. total height; b. annual height increment.

and S400). Between years five and six, the WCONT trees increased in height more than the S100 trees ($P < 0.05$), the S400 trees were similar to the WCONT trees. These relative patterns of annual height increment at the LG site produced, by year six, the tallest trees on the WCONT and S400 treatments, the S100 trees were significantly shorter ($P < 0.05$; Figure 5a).

The trees on the two upland sites had different patterns of top height development to the trees on the lowland LG site. Up to year three, the S400 trees grew faster than the S100 trees which grew faster than the WCONT trees ($P < 0.05$) (Figures 6b and 6c). This led, by year three, to significant differences in top height for the three treatments (Figure 6a). After year three, annual height increments on the WCONT treatment on the upland sites were similar to the other treatments and so, by year six, the WCONT trees were significantly shorter ($P < 0.05$) than the agroforestry (S100 and S400) trees. After year three, however, there were significant site by treatment interactions in annual height extension between the agroforestry treatments on the two upland sites

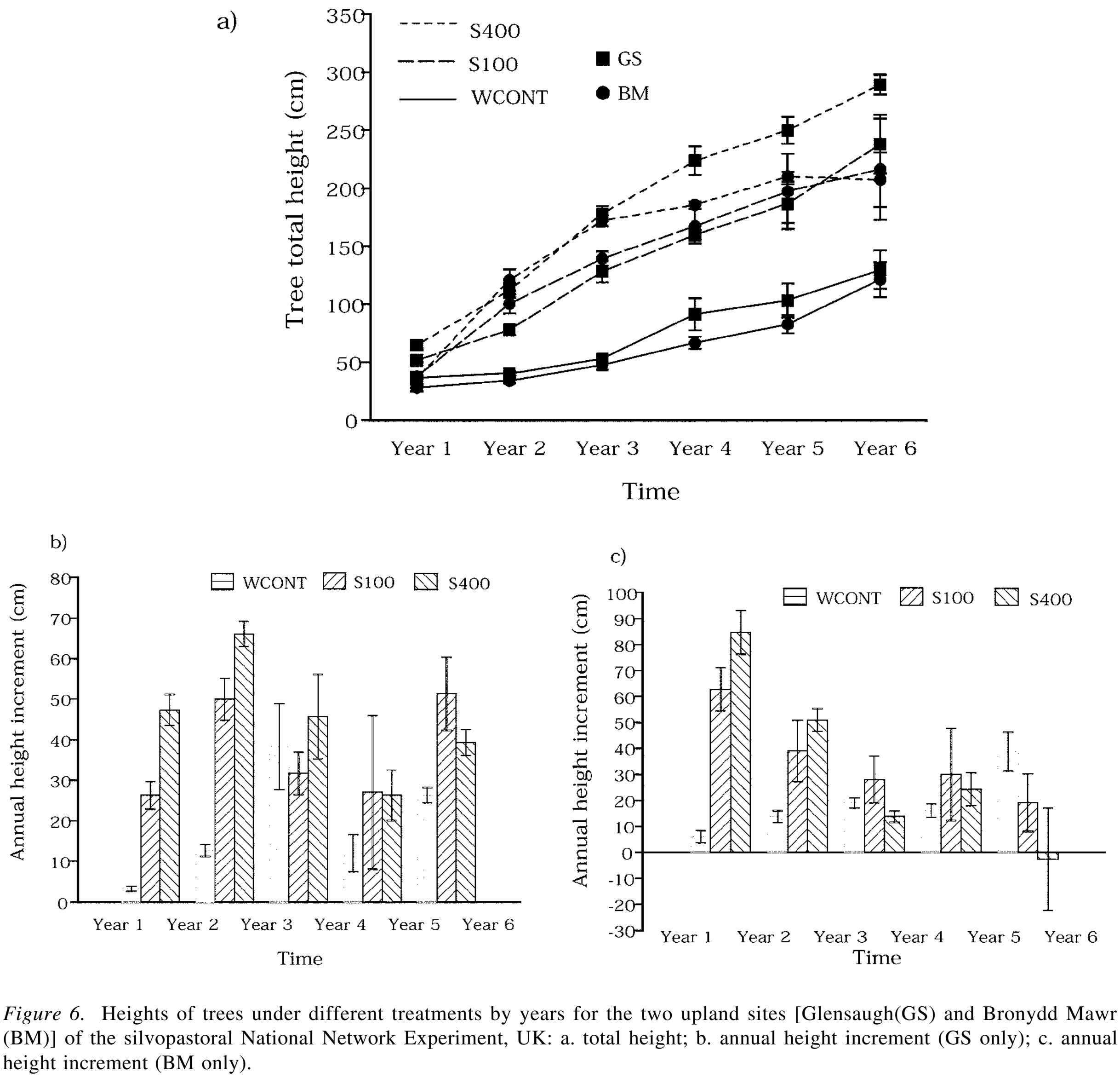


Figure 6. Heights of trees under different treatments by years for the two upland sites [Glensaugh(GS) and Bronydd Mawr (BM)] of the silvopastoral National Network Experiment, UK: a. total height; b. annual height increment (GS only); c. annual height increment (BM only).

(Figures 6a and b). By year six at the GS site the trees on the S400 treatment were taller than those on the S100 treatments ($P < 0.05$; Figure 6a). In year six on the BM site, the S400 and S100 trees were of similar height (Figure 6a) because of a slowing of the annual height increment of the S400 trees (Figure 6c).

3.3. *Animal production*

There were no statistically significant differences between treatments over the six year period, when data from the four sites were pooled, in either individual animal performance, measured as lamb liveweight gain from turnout to weaning (see Table 6) or in overall agricultural performance measured as stock carrying capacity (see Table 7). There were significant differences over time ($P < 0.001$) in both variables but these were consistent across all treatments since their treatment by year interactions were not statistically significant. There were significant differences between the upland and the lowland sites in both of these variables for the pooled four-site data ($P < 0.001$). The LG site had a significantly higher level of stock carrying capacity than NW ($P < 0.05$). Agricultural productivity on the silvopastoral treatments at the NW site could have been influenced by the poor performance of the trees at that site, however, exactly the same trends were found when the NW site was excluded from the statistical analyses.

4. Discussion

There was no significant difference in tree survival between the silvopastoral treatments (S100, S400) when they were combined and compared with woodland control (WCONT), suggesting that the use of tree shelters to protect the silvopastoral trees from the grazing sheep was successful. The significant difference in survival between silvopastoral planting densities (S100, S400) of

Table 6. Mean lamb live-weight gain over the first six years for sites [Lowland (L), Upland (U)] and treatments [agricultural control (ACONT) and agroforestry (S100, S400)] in the silvopastoral National Network Experiment, UK.

Site (type)	ACONT (g head^{-1} d^{-1})	S100 (g head^{-1} d^{-1})	S400 (g head^{-1} d^{-1})	Site mean (g head^{-1} d^{-1}) (s.e.m.)
NW(L)	249	258	256	254^{b} (5.0)
LG(L)	261	260	238	253^{b} (5.5)
BM(U)	242	237	245	241^{a} (2.9)
GS(U)	244	241	237	241^{a} (2.7)
Treatment mean (s.e.m.)	249 (4.0)	249 (3.6)	244 (3.7)	247 (2.2)

Values in the column of site means which have different superscripts are significantly different ($P = 0.001$).

Table 7. Mean stock carrying capacity over the first six years for sites [Lowland (L), Upland (U)] and treatments [agricultural control (ACONT) and agroforestry (S100, S400)] in the silvopastoral National Network Experiment, UK.

Site (type)	ACONT (tonne days ha^{-1} annum^{-1})	S100 (tonne days ha^{-1} annum^{-1})	S400 (tonne days ha^{-1} annum^{-1})	Site mean (tonne days ha^{-1} annum^{-1}) (s.e.m.)
NW(L)	293	279	296	290^{b} (4.8)
LG(L)	360	336	315	337^{c} (7.2)
BM(U)*	216	223	239	226^{a} (5.0)
GS(U)	215	223	225	221^{a} (3.2)
Treatment mean (s.e.m.)	276 (8.9)	269 (7.4)	272 (6.2)	272 (4.4)

* Data are available for only four of the six years for the BM site.
Values in the column of means which have different superscripts are significantly different ($P = 0.001$).

sycamore indicates greater stress on the trees at the lower planting density. This difference was evident only on the two upland sites where conditions for the establishment of sycamore may be less favourable than on the lowland sites. The lack of any site or treatment differences in years two, three and four indicates that the greatest risk to the survival of the trees is in the first year after planting. Site differences in tree survival indicate the range of potential for the growth of sycamore on the four sites. The increased losses of trees across all three treatments in years five and six at NW (Table 4) point to generally unsuitable conditions for sycamore development at the site; this is discussed in more detail later in this section.

The cost, per 100 trees planted, of replacing dead trees for, which is normally carried out for the first three years after planting (Table 5), would be less for sycamore planted at 400 trees ha^{-1} than for conventional woodland or sycamore 100 ha^{-1} on upland sites. This is not the case for lowland sites.

The survival and height extension results from NW indicate quite clearly that the site is not suitable for sycamore. Sycamore was probably intolerant of the frequent water logging that occurred on the site; the only one in the experiment with poor drainage (Table 1). Despite that fact, the trees at NW followed a similar pattern of height development as the other sites for the first three years. However, the other three sites form the most useful basis for general discussion of tree height developments.

Plot mean total height of trees on the other three sites was significantly affected by planting density by year two at which stage the agroforestry trees (S100 and S400, 102.2 ± 5.64 cm) were taller than the WCONT trees (49.2 ± 6.95 cm). In years three, four and five, S400 trees (three-year mean 203.2 ± 6.70 cm) were taller than those in S100 (three year mean 166.3 ± 6.42 cm) which, in turn, were taller than those in WCONT (three year mean 109.9 ± 12.58 cm). By year six, the WCONT (191.9 ± 34.55 cm) trees had caught up with the S100 trees (218.6 ± 16.09 cm) but the S400 trees were taller (255.6 ± 16.73 cm), suggesting that the early advantage in height growth of the S100 trees over those on WCONT was lost by year six.

The WCONT trees increased their height less than the agroforestry trees in the first year, see Figures 4a and b. Figure 7 shows annual relative height increment, this is the annual height increment expressed as a percentage of the height in the previous year and it represents a more sensitive assessment of tree height increment. Figure 7 shows that, after the first year, the WCONT trees maintained their relative height increment while the relative height increment of the silvopastoral trees reduced significantly over time. By year six the WCONT trees (35 ± 7.2%) showed relative growth rates which were significantly greater ($P < 0.001$) than the silvopastoral (S100 and S400) trees (11 ± 2.8%).

The significant difference in plot mean total height of trees ($P < 0.001$) between the silvopastoral treatments (S100 and S400; 212.1 ± 8.35) and WCONT (146.0 ± 27.92) after five year's growth can be explained by the use of tree shelters which have been shown to promote initial growth rates in sycamore (Tuley, 1982) and by the application of fertilizer at agricultural rates. Although different weeding methods were used on the silvopastoral plots and the woodland control plots to reduce competition between the trees and the pasture vegetation, they are unlikely to have led to differences in plot mean tree height extension since the objective of achieving a weed-free zone around each tree was achieved for three years in all cases. However, the advantage to the shelter-protected agroforestry trees reduced rapidly and

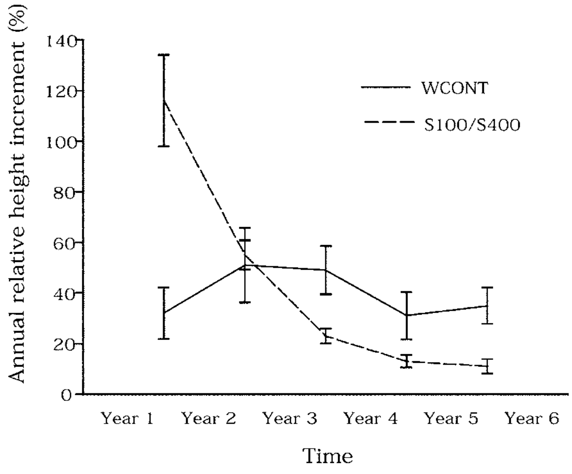


Figure 7. Annual relative height increments for woodland control (WCONT) and agroforestry (S100 and S400) trees for three sites (North Wyke excluded) in the silvopastoral National Network Experiment, UK.

the likelihood is that the WCONT trees will overtake the agroforestry trees in a few years, indeed they have already started to do so at the lowland site at LG, see Figure 5. The same pattern appears to be developing but more slowly at the upland sites, see Figure 6. This suggests that the shelters have provided a longer-term advantage to the agroforestry trees on these higher altitude and more exposed sites although the general trend for the WCONT trees to catch up appears to be present here too. These comparative patterns of height extension for shelter-protected and unprotected trees are similar to those found by Tuley (1982).

The use of a herbicide-treated zone around each tree in the silvopastoral plots resulted at one of the sites (BM) in higher concentrations of nitrate in soil water samples beneath the zone than in the undisturbed pasture areas between the trees during the summer (Cuttle and Gill, 1991). The use of herbicide therefore resulted in a greater potential availability of nitrogen to the trees than would have been the case if herbicide had not been used. However, no results were quoted for the woodland control area so the greater rates of height extension in the silvopastoral trees cannot necessarily be attributed to increased availability of nitrogen through the use of herbicide. The authors concluded that with planting densities of 100 and 400 trees ha^{-1}, the increased nitrate content of water draining from the agroforestry area would be small so that the environmental impact in terms of increased nitrate leaching from the use of herbicide would also be small.

The differences in plot mean total height of trees between S400 and S100 cannot be explained by the difference in planting density; the trees were too small to provide mutual shelter and they were individually protected by tree shelters. The explanation could lie in the sheep:tree ratio. As has been demonstrated, there are no measurable effects on agricultural production so the same number of sheep is required on each plot (allowing for site differences) to maintain the seasonal sward height profile. The sheep:tree ratio is therefore higher at S100 than at S400. It has also been shown that, in silvopastoral systems in the UK, sheep are attracted to trees (Sibbald et al., 1995) with a greater attraction to the trees at the lower planting density (Sibbald et al., 1996). These combined effects will generate more frequent trampling around the smaller number of trees in S100. One result of this could be greater compaction of soil around trees. In experiments conducted at NW (Laws et al., 1992), GS (Wairiu et al., 1993) and LG (W. Hutchinson, unpublished MSc thesis), greater soil compaction was measured close to trees than at a distance from them and greater soil compaction close to trees at 100 than at 400 stems ha^{-1}. Increases in soil compaction have been shown elsewhere to result in the reduced growth of tree seedlings in silvopastoral systems (Bezkorowajnyj, et al., 1993) and are the most likely explanation of the differences in tree height extension between the S100 and S400 treatments.

The lack of a difference in the individual performance of the lambs between treatments is to be expected because of the control of the sward through the implementation of the seasonal sward height profile which resulted in very similar quantities and structure of pasture on offer to the grazing animals across sites and treatments within years. Differences in individual lamb performance between sites reflect the different breeds used on the upland and the lowland sites and differences between newly-sown and older, permanent pastures. There were no effects of the planting density of the trees or of the development of the trees over the first six years on animal productivity measured as annual stock carrying capacity. Differences in stock carrying capacity reflect the range of agricultural potential resulting from climatic and edaphic differences between the sites and highlight the contrast between the production potential of the upland and lowland sites. Differences between years, which were reflected across all treatments, are a consequence of the year to year variability of the climate and its impact on agricultural productivity.

5. Conclusions

It has been shown that sycamore with individual protection can be planted at wide spacing into existing sheep-grazed pastures in the UK without any measurable reduction in agricultural output for at least the first six years after planting. This is in line with the predictions of a number of models of silvopastoral systems constructed for use in the UK (Tabbush et al., 1985; Doyle et al., 1986).

The range of survival of sycamore across the sites gives an indication of the range of suitability for this species. The very poor survival in the first year at NW and the subsequent poor performance of the trees in the later years indicates that the site is not suitable for sycamore. Agroforestry with sycamore cannot be recommended for sites with poorly drained soils. The statistically significantly lower survival at S100 (90.8%) compared to S400 (94.7%) is interesting in terms of the biological interactions taking place within the system. It may also be enough, in absolute terms and on its own, to justify the greater planting density in practice because of the cumulative effect over the three-year period during which dead trees were replaced, especially at the upland sites.

Rates of height extension of sycamore in silvopastoral systems, with the benefits of individual tree protection and application of agricultural rates of fertilizer, exceeded those of trees planted in a more conventional farm woodland system over the first four years of the establishment period. The significantly lower rate of height extension at 100 trees ha^{-1} compared to 400 trees ha^{-1} over this period at the upland sites may have implications for the longer-term performance of the trees at the lower planting density. The rates of height extension achieved at 400 trees ha^{-1} were also significantly higher than those achieved by the conventional farm woodland system at the upland sites indicating that a planting density of 400 trees ha^{-1} is likely to be generally appropriate for sycamore-based silvopastoral systems in the UK. The 400 trees ha^{-1} planting density also benefits marginally from a higher early survival rate.

The results reported in this paper cover only the first six years of a silvopastoral system. The longer term effects of the interactions between the animals, the trees, the pastures and the soil will need to be studied before reliable conclusions can be drawn about the best management for these complex systems.

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