THE SILVICULTURE, NUTRITION & ECONOMICS OF SHORT ROTATION WILLOW COPPICE IN THE UPLANDS OF MID-WALES

ETSU B/M4/00532/13/REP

Contractor
Cardiff University

Prepared by
R J Heaton
P F Randerson
F M Slater

First published 2000

This report summarises the findings of a PhD thesis (Heaton, 2000) and the reader is referred to that for fuller details of methods, results and discussion.

Summary

The potential of short rotation coppice as a biomass crop on land over 250m (the uplands) of mid-Wales was studied.

At an altitude of 255m on a clay loam, with fertiliser application in establishment year only, the highest yielding variety, *Salix* Delamere, produced 6 oven dry tones (odt) ha^{-1} yr^{-1} after five years. The optimum planting date on this site was determined as being from January to mid-March.

After three years, at an altitude of 365m on a peaty gley, yield was found to be doubled by the addition of cattle slurry ($100m^3$ ha^{-1}) in years one and two. With fertiliser application, production of the best yielding varieties, *Salix viminalis* Bowles Hybrid, Gigantea and Q683 ranged from 1.37-2.25 odt ha^{-1} yr^{-1}. Cut back after one year was found not to influence biomass production in year three, but did lower survival. Survival rates were generally high, from 91-98% in establishment year.

In addition to increasing foliar nutrient concentrations, glasshouse studies demonstrated that yield increases were due to the slurry acting as a mulch. Further glasshouse trials showed that poultry and pig manure also increased growth, although for poultry manure this was dependant on the addition of a mulch. Root growth was influenced by fertiliser application, with increased surface rooting under liquid fertiliser additions.

Non-destructive estimates of standing biomass were produced, and although weight was successfully predicted from diameter, inaccuracies were recorded when scaling up to field level.

An economic model was written (assuming a market in the form of a local electricity plant) and in terms of Net Present Value over 25 years, returns were found to be similar to those from sheep production at a production level of 8 odt ha^{-1} yr^{-1}.

The results found in this study indicate that growing short rotation coppice willow in the uplands is a viable proposition with regard to establishment success and yields. In the event of a secure wood chip market in Wales, returns to the grower would be comparable to those from sheep production.

Acknowledgements

I would like to thank my supervisors Dr P.F. Randerson and Dr F.M.Slater for enabling me to carry out the study, and for all the support and advice they have given me over the last four years. I also acknowledge the financial assistance of MAFF, ETSU for the DTI, LRZ and ADAS for funding the study.

Contents

1 Introduction

SRC is the growing of willow and poplar at high densities (in excess of 10,000 ha^{-1}) for rotations of two to five years (Britt *et al*, 1995). The silviculture of SRC involves planting unrooted cuttings of 20-25 cm length, 0.8-1.5 mm diameter at close spacing. After one year the shoots are cut back to produce the stool. Then the stools are harvested on a three year rotation (Britt *et al*, 1995).

Ideally willow should be grown as close as possible to where it will be utilized, in order to minimize transport costs. In Wales this could result in upland land being planted (land above 250m altitude) as 62% of Wales falls into this category. One third of all farm holdings are solely in this area, and many more farmers have a proportion of land in the uplands (Welsh Office, 1997).

Currently the primary land-use in these areas is sheep production, which is heavily subsidized. With the uncertainty surrounding agricultural support for livestock farming in these areas, farmers are keen to diversify. Farmhouses and buildings are a suitable size for small-scale wood-fired heating units using short rotation coppice as a fuel. Additionally there are potential markets in the form of several proposed wood-fuelled electricity plants in mid-Wales.

In general upland soils are acidic and nutrient poor. Studies of growing willow on organic soils such as those found in the uplands have all shown a need for fertilisation (Elowson & Rytter, 1988; Firm & Hytonen, 1988; Hodson, 1995; Kanetsu, 1983) and if economic yields are to be obtained then fertilisation is likely to be essential. Organic fertilizers such as sewage sludge and slurry have benefits over inorganics in that they are readily available, cheap, enhance soil structure and also have mulching properties (Granhall, 1994).

This study determines the silviculture of SRC in upland sites in Wales, the influence of animal manures on growth and the economic potential of SRC as an alternative land use.

2 The effect of cattle slurry on the establishment and biomass production of short rotation coppice grown n the uplands of mid-Wales

A 1 ha. field trial; on a seasonally waterlogged peaty gley soil was set up at ADAS, Pwllpeiran in mid-Wales. The site had an altitude of 365m and is believed to be the highest site under SRC in the UK. Average rainfall was 1760mm $year^{-1}$.

Experimental design and treatments

The site was cut with a flail mower in June 1995 and sprayed with paraquat in July. It was cut again and resprayed with glyphosate (5 l ha^{-1}) in August 1995. The field was not ploughed, as previous experience has shown that when soils in this area are ploughed the buried mat of vegetation remains undecomposed and causes increased surface water logging and exposes *Juncus* seeds for subsequent germination (Rudeforth *et al.*1984).

In July 1996 weed growth, mainly *Epilobium palustre* and *Cardamine flexuosa,* had become a problem, overtopping the willow in some cases. The field was strimmed and the broad swathes left were then treated with glufosinate ammonium at a rate of 3 l ha^{-1}. In both December 1996 and 1997 propyzimide was applied (Kerb Flowable, 3.75l ha^{-1}), a pre-emergent herbicide to suppress grass growth.

Six willow varieties were planted by hand in Spring, 1996, on the Swedish double row system:

- S. *x dasyclados* – a (*caprea* x *cinerea*) x *viminalis* variety, found to grow well in previous upland trials (Hodson, 1995).
- S. *viminalis* Mullatin, Q683, Gigantea and Bowles Hybrid – all found to produce good yields and remain fairly insect and rust resistant.
- S. *viminalis* Jorunn – a newly released Swedish clone found in Forestry Commission trials to perfom well over a whole range of sites (although all below 200m).

A density of 20,000 ha^{-1} was chosen as this had proved successful on previous upland plantings (Hodson *et al*, 1994).

The experiment was planted as a replicated block design to allow for statistical analysis to be carried out. Two experimental treatments were applied: fertilisation with cattle slurry and cut back.

Slurry from a herd of beef cattle was applied in Spring, 1996 and 1997 at a rate of $100m^3$ ha^{-1} based on the maximum recommended quantities of slurry in the Code of Good Agricultural practice (MAFF, 1991).

Standard practice is to cut back the shoots after the first year (Britt, *et al*, 1995), although there is no evidence to support the benefits of this. It was decided to cut back half of each plot in December, 1996, and examine the influence of this on subsequent growth.

Assessments

Survival was analyzed each year, and various non-destructive measurements also taken (refer to section 7 for full details). Stem moisture content was determined each year, and leaf and stem samples were taken for nutrient analysis.

Final harvesting took place in October 1998, and trees were weighed. Soil analysis and meteorological data, and vegetation surveys were also carried out, the readers referred to Heaton, 2000 for full details.

Results and Discussion

Survival

Initial survival (1996) was excellent with mean survival for treatments ranging from 90.9-97.8%. In 1997 survival percentages were generally lower, especially for the non-slurried, cut back plots. Hare damage was also found on selected stems.

By 1998 the smaller trees such as the unslurried, cut back stools did not survive as well as bigger trees. If the stools perform poorly, as the non-slurry ones did, it may be better not to cut them back as this could influence second year survival.

The higher altitude of this site and hence colder climate was not detrimental to survival as the establishment percentages are comparable, and in some cases higher than those found in lowland experimental plantings (Mitchell *et. al.*, 1995; Riddell-Black, 1995). There was no incidence of rust or defoliation by insects, a common problem in lowland plantings. The climate could well be adverse to both rust and insects, although populations tend to build up as the stools mature (Armstrong *pers. comm.*) so longer term monitoring is necessary. Problems with frost damage reported in the lowlands were also not present, supporting the hypothesis that the damage occurs due to insect attack altering the internal chemicals and thus reducing the hardening off abilities of the plant (Armstrong, *pers. comm.*).

The hare damage did not influence survival, but biomass was lost due to the damage, and the trees became branched at approximately 50cm from the base, which could create future problems if the trees were mechanically harvested. Although not reported before in Britain, hare damage is a recognised problem within willow stands and yet there is little that can be done to prevent it (Christersson et al., 1993; Hytonen et. al., 1995). Hares can penetrate or jump fences; chemical repellents, though effective, are expensive (Pepper et al., 1996) and shooting is not really acceptable with hare populations decreasing.

In areas where there are hare populations, cutting back the trees may not be advisable as it gives the hares two opportunities to attack, when the stems are small in the first year and then again in the second season.

Biomass

Oven dry tonnes per hectare per year produced were disappointing, ranging from just 0.04 odt ha^{-1} yr^{-1} (Mullatin: slurry, uncut) to 2.25 odt ha^{-1} yr^{-1} (683: slurry, uncut).

The best variety in terms of biomass was 683, closely followed by Bowles Hybrid and Gigantea. Gigantea is renowned for its initial growth, but has been found to die off and produce lower yields as the stools mature (Armstrong, *pers. comm.*). Dasyclados performed disappointingly compared to its success in other upland trials in early years (Hodson, 1995), indicating that variety performance is site specific, and that general recommendations across sites may not be possible.

Production was low compared to yields produced in other trials, both in the UK and in Sweden, of up to 14 odt ha^{-1} yr^{-1} (Britt et. al., 1995, Christersson, 1987; Elowson and Rytter, 1988). Both rainfall and temperature sum were greater and the growing season longer than that in Swedish studies (Alrikkson, 1997). This implies that Wales has a more favorable climate for tree growing being warmer and wetter. The reason for the lack of growth could be due to the wind and exposure effects on the trees.

There were no general patterns for the influence of cut-back on stool architecture. The hypothesis of greater number of shoots being produced by cut back stools was true for 1997, but by 1998, for Bowles Hybrid and Gigantea there was a slurry interaction, with only slurry plots producing greater number of shoots if cut back, indicating that the plants did not have enough nutrients in the poor soil to produce more shoots. If there is a market for the cuttings in year one then cutting back may be appropriate, otherwise there seems little benefit to it.

Nutrient relations

Foliar phosphorus levels in 1997 increased due to slurry application, indicating that the reserves in the soil were insufficient. This is supported by the soil analysis, which indicates that there was not enough phosphorus applied in the slurry as soil reserves are also being depleted. Phosphorus is not easily leached and should accumulate in the soil and so its depletion must be due to the tree uptake (Johnson, 1989). The quantities of phosphorus applied by the slurry were adequate according to current prescriptions of 15-40kg ha^{-1} in establishment year only (Ledin and Alrikkson, 1993; Hytonen, 1996). Thus in the uplands it may be necessary to revise these recommendations.

The high levels of potassium in the slurry were reflected in the foliar concentrations and the soil, there were no indications of nutrient imbalances such as chlorotic foliage.

A reason for the greater production in the slurry plots could be due to the mulching effect produced by the slurry. In addition to the benefits of reduced moisture loss and enhanced surface rooting found under mulches (Parfitt and Stott, 1984) there was also decreased vegetation cover, reducing competition from weeds.

There were no significant differences in foliar N in 1996 and 1997, indicating that the soil was supplying enough nitrogen, and that the slurry nitrogen was unnecessary. This supports other authors' findings that N is not necessary in the first year (Hunt, 1993).

There was an increase in NH_4-N levels, indicating that mineralisation was occurring at a greater rate than the trees were taking up nutrients. However the values of NO_3 were lower than those found in other studies (Alrikkson, 1997; Ledin, 1998). Combined with the decrease in pH this indicates that denitrification was occurring. Without denitrification, leaching of nitrate would be a much bigger problem and other authors consider that the potential pollution of groundwater is influenced as much by denitrification rates as by nitrate loading

Conclusions

Even with fertilisation the yields of the most high yielding varieties were lower than those reported in the lowlands. However the trees were harvested after only a two and three year rotation and the maximum mean annual increment has been shown to be achieved on a four - five year rotation (Hytonen, 1995). There is also an increase in annual increment in the second and third rotations (Britt *et al.*, 1995) and so these stools may produce yields comparable to lowland sites in time. The economic climate in the uplands is very different to that of the lowlands, and so lower production and thus returns may be acceptable (discussed in section 8).

The key to successful growth at this altitude was fertilisation, without which growth was very poor. Additional phosphorus should possibly be applied in the future and the pH increased by liming. Cutting back should only be carried out if the stools are growing well and there is a market for the cuttings. If the stools are small then survival in the second year could be affected. Although this study indicates that nitrate leaching at application rates of $100m^3 ha^{-1}$ cattle slurry should not be a problem, more work is needed to quantify this.

3 The effect of animal manures and mulches on the establishment and biomass production of *Salix* x. *dasyclados* grown in pots under glasshouse conditions.

Introduction.
Two pot experiments were set up to assess the variation in growth and nutrients of willow in response to different types of animal manure. In 1996 a one year trial was set up with poultry, pig and cattle manure applied to willow at three rates. Two types of plant material were used, new unrooted cuttings and established stools. It has been suggested that fertiliser should not be applied to new cuttings as they do not have a root system to exploit the soil (Britt *et. al.,* 1995). The aim of this experiment was to investigate the influence of fertilisation on both newly rooted cuttings and established stools that were internally cycling nutrients, and thus may not benefit from additions.

In 1997 an experiment was set up to examine the influence of mulching as well as cattle slurry, cattle manure and poultry manure on tree growth. Studies on mulching of willow and poplar using polyphone or straw have been encouraging, indicating that with reduced moisture loss the plant showed enhanced surface rooting, and thus better use of nutrients (Parfitt and Stott, 1984). It has been suggested that manure could be a potential mulching material for coppice (Britt *et. al*., 1995), but no work to date has examined this. The experiment was designed to investigate if the enhanced growth from manure additions was due to the mulching properties or to the nutrient content of the manure.

Methods and materials common to 1996 and 1997 experiments.
The pots used throughout the 2 experiments had a capacity of 10 litres and five replicates were used per treatment. The soil was a circum-neutral free draining brown earth, low in nitrogen, potassium and magnesium but high in calcium and phosphorus. Only one variety was used for the experiments, *Salix* x. *dasyclados*, the best performing variety in previous upland trials carried out by the University (Hodson, 1995).

3.1 Influence of rate and type of animal manure on the biomass of new and established willow stools.

Methods and Materials.
The established stools were originally planted in 1994 and cut back at the end of 1994 and 1995. The new cuttings, from one year old shoots, were planted on 8/4/96.

Manure was applied immediately after planting to established and new stools. Three application rates in relation to nitrogen were chosen,

- Control (no manure)
- Pig manure 250kg N ha^{-1}, 150kg N ha^{-1}, 75kg N ha^{-1}
- Cattle manure 250kg N ha^{-1}, 150kg N ha^{-1}, 75kg N ha^{-1}
- Poultry manure (broiler litter) 250kg N ha^{-1}, 150kg N ha^{-1}, 75kg N ha^{-1}

Assessments.
The trees were harvested in January 1997 after leaf fall, and oven dried to constant weight.

Results.
The established stools produced higher biomass than the new stools in all cases, as would be expected with the established root system exploiting nutrients. The cattle manure produced

willow biomass significantly greater than the control at all application rates, pig manure only at high and medium rates and poultry manure only produced significantly greater yields at the highest application rate. Regarding the rates of manure applied, there were significant differences between yield produced at different rates for pig manure alone, with cattle and poultry manure resulting in non-significant trends.

For the new stools there was less benefit of fertilisation, but significantly greater yields than the control were produced by the pig and cattle manure at medium and high rates, indicating it would be beneficial. There were clear trends between different application rates, though none were significantly different from each other for poultry, but for cattle and pig the lowest rate produced significantly smaller yields than from the highest rate.

Discussion.
The biomass results indicate that for established stools a low rate of fertilisation is all that is necessary on fertile soils, as higher rates were not producing greater yields and could increase the risk of leaching. The stools presumably had nutrients stored in the root system and were internally cycling nutrients, thus demanding less external inputs. Contrary to Britt *et. al.,* (1995) the new stools do benefit from fertilisation, although in a field situation the benefit may be off set by enhanced weed growth and consequent smothering of young plants.

Although the cattle manure was lowest in phosphorus, the trees with this addition grew best, indicating that the soil supply was sufficient. The poultry manure, which had the best nutrient composition in terms of willow demand did not produce the best results. This indicates that factors other than nutrient supply were influencing growth. The poultry manure had a very high dry matter content, and was quickly incorporated in to the soil. The cattle and pig manures formed a hard mat on top of the soil, which may have resulted in a beneficial mulching effect such as soil warming and less evaporation of water from the soil surface.

3.2 The influence of mulching, cattle slurry, cattle manure and poultry manure on tree growth.

Methods.
In this experiment new cuttings only were used, and planted on 4/4/97. Again the manures were applied immediately after planting. An application rate of 250kg N ha^{-1} was chosen, the maximum annual amount of organic fertiliser that should be applied (MAFF, 1991). The treatments were as follows:

1. Control (no manure)
2. Mulch mat only
3. Cattle slurry
4. Cattle slurry and mulch mat
5. Cattle manure
6. Cattle manure and mulch mat
7. Poultry manure
8 Poultry manure and mulch mat

Mulch mats simulated the physical property of the manures, with no nutrient additions, to investigate if mulching only increased growth. They were made of capillary matting, approximately 5mm thick.

Assessments.
The trees were harvested on 29/9/97, leaves and stems were oven dried and weighed. The root balls were also excavated and dried and weighed.

Results.

The nutrients available to the plants from the manures were determined. All the fertilisers supplied excess quantities of potassium, but the poultry manure was the most balanced of the fertilisers and thus would be expected to give the best results in terms of above ground biomass.

Biomass production and allocation.

All treatments with mulch mats produced significantly greater stem biomass than the control, and all manure treatments with mulch mats gave significantly greater stem yield than the manures alone. As had been predicted the poultry manure and mat gave significantly greater biomass than all the other treatments. The effect of mulch mat on stem production was least for the cattle slurry.

Tissue Nutrient Concentrations.

Leaves.

The leaves of plants fertilised with poultry manure had significantly greater quantities of N and P than those fertilised with poultry manure and the addition of a mulch mat. A similar result was found for the cattle manure N. The nutrient levels in the controls were generally higher than those in the other treatments. The pattern for K was different, with lower nutrient levels in the control than in the cattle and poultry manure treatments.

Stems.

For plants fertilised with manure, there were no significant differences in N, P, and K concentrations in the stems of plants due to mulch mats. There was significantly higher P in the bare soil control than all other treatments.

Roots.

There was a significantly greater N concentration in the roots of the plants treated with cattle manure alone, than cattle manure plus mulch mat treatment. The roots of the plants in the bare soil control had highest N concentration of all treatments. There were no significant differences in P concentrations. For K, as in the leaves, there were lower concentrations in the control than in the other treatments.

Plant Nitrogen Efficiency.

Plant nitrogen efficiency (dry matter production per unit of nitrogen taken up) was determined. For all treatments except cattle slurry, efficiencies were higher with mulch mats than without.

Discussion.

Biomass and allocation.

The biomass results indicate that mulching is as important in increasing yield as nutrient additions. This has been found by other authors (Parfitt and Stott, 1984) who attribute the increased biomass to enhanced root growth, due to a combination of higher soil moisture and temperature.

The mulch mat had the least influence on the cattle slurry, indicating that slurry alone is the best natural mulch of all the manures tested, and thus is recommended for use in the field. Although the poultry manure plus mat produced greatest biomass, in the field in the uplands the use of additional mulch such as polythene is not really an option due to the high expense, and practical problems when laying onto stony and water logged soils (Clay, 1993).

Plant nutrient concentrations and uptake.

The influence of mulch mat on nutrient concentration was greatest in combination with poultry manure due to the manure's lack of natural mulching properties. The lack of significant differences in nutrient concentrations due to presence of mulch mat with cattle slurry indicate that the natural mulching properties of the slurry render an additional mulch mat unnecessary.

Nutrient proportions.

The relative proportions of P and K with N are high compared to those found by Ericsson (1984). It is known that different *Salix* varieties have different nutrient demands, (Alker, *et. al.*, 1997) and it could that *S.* x. *dasyclados* takes up nutrients differently from *S.viminalis*. This does not explain the large range of values for potassium which seem to reflect the manure composition. The exceptionally high quantities of potassium indicate uptake in excess of that which is necessary, however there were no signs of this being detrimental to growth.

Nitrogen use efficiency.

High nutrient use efficiencies, such as those found with the mulch mat treatments are useful in situations where maximum utilisation of nutrients is needed on poor sites. However if waste remediation and thus high nutrient off-take is one of the objectives of the crop then lower efficiencies are preferable. *S.* x. *dasyclados* is known to have a high N efficiency (Alker, *et. al.*, 1997), and this may account for its success in previous upland trials (Hodson, 1995). Farmers in the uplands may well have a dual objective, of slurry disposal and biomass production. The use of mulches could increase nutrient efficiency, but also the plants would grow faster and thus take up more nutrients.

Overview of both experiments.

The results of both experiments show that fertilizing in the first year significantly increases biomass production, even on a fertile soil such as that used in this experiment. On poor upland soils even better results may be gained, although weed growth may also be increased. The maximum application of organic fertiliser recommended per year (MAFF, 1991) of 250kg N ha^{-1} is suitable, with lower quantities producing less yield. For older crops lower applications may be sufficient. The high quantities of potassium in the manures in relation to willow demand do not seem to be a problem with no signs of toxicity or depressed yield at a rate of 250kg N ha^{-1}.

Mulching was shown greatly to increase the growth of willow. Poultry manure was shown to need additional mulching to produce good growth, and due to the expense of laying mulches this may not be a practical option in the field. Cattle slurry was the best mulch of the manures tested and is recommended for use in the field.

4 Root production in biomass tree crops grown under an effluent disposal system.

A visit was made to Massey University, Palmerston North, New Zealand, to utilise equipment and expertise in root studies.

Information on root growth is essential to determine the nutrient balance of the system and root growth and turnover throughout the season. Very little is known about roots and root growth, especially in short rotation forest crops (Hendrick and Pregitzer, 1993).

Studies were carried out on the root growth of Salix and Eucalyptus in response to dairy shed farm washings.

4.1 Using mini-rhizotrons to monitor root growth of Salix and Eucalyptus grown in lysimeters with dairy effluent irrigation.

A lysimeter study had been set up to ascertain the nutrient and water balance of the trees by monitoring all inputs and outputs (Riddell-Black, *et al*., 1996). One mini-rhizotron, based on the design of Upchurch and Ritchie (1984). had been installed in each lysimeter. A mini-rhizotron system consists of a camera which runs up and down a clear tube inserted into the soil. Three varieties were studied, *Salix kinuyanagi*, *Eucalyptus nitens* and *E.saligna.*

Assessments were made at approximately two week intervals, and the data (root branches and intersections with the edge of the frame) were analysed by the author.

Results.

For all species, only fine roots were seen. For one variety, *E. saligna*, roots were only detected for the first few weeks of assessment. As the tree was growing healthily, indicating a functioning root system, it is likely that there were by chance no roots near the tube.

Spatial Root Distribution

All species had few roots in the top 60mm. *S. kinuyanagi* roots were mainly at the bottom of the profile, around 360-600mm depth, *E. nitens* had two bands of roots at 0-240mm and 360-500mm and *E. saligna* had fewer roots, mainly around 150-300mm.

Temporal Root distribution

Fine roots of *Salix* first appeared in January (late spring) and remained fairly constant until a sudden flush in late winter of the second season. *E. nitens* had fairly constant root growth, with small peaks around November to February (spring to summer) in the top of the profile, which then died back until a peak in August (late winter). Lower down the profile roots first appeared in December (spring) and died back a little in February and increased again until August (winter). *E. saligna* had roots until April, when these died back no more appeared.

Discussion

Root detection.

Problems with mini-rhizotrons failing to record data have been found when the soil surrounding the tube has dried out (Upchurch, 1987), however this should not be the case with lysimeters which were continually irrigated, thus maintaining good soil - tube contact. The reason for the lack of results is more likely that there were, by chance, no roots near the tube, as only a very small volume of soil was sampled, 0.7% of the lysimeter's total volume. Roots have been found to behave differently within a very small area, called a micro-site, and differences between growth at different micro-sites have been attributed to nutrient availability with channels of effluent causing high and low root biomass (Rytter, 1997).

Biomass and spatial arrangement of root growth.
All species had few roots in the top 0-100mm. This was unexpected as previous work on effluent treated trees in a field situation has found 90% of the biomass to be in the top 100mm (Rytter, 1989), or for there to be dense mat of roots from 0-400mm (Sims *et. al.*, 1994). However both these results were obtained using soil excavation techniques, rather than mini-rhizotrons, which are known to under-estimate the root growth in the top 200mm, although the reason for this is not known (Upchurch and Ritchie, 1984)

The root pattern in *Salix* was especially surprising as rapid growth at depth is indicative of a response to drought (Grieu and Aussenac, 1988), and as the trees were irrigated, it is unlikely that this is the case. This could indicate that the observed roots do not represent a valid sample, and that as for *E. saligna*, it is isolated micro-sites that are being observed. Another explanation is the "pot effect". Willow grown in pots has been noticed to grow lateral roots near the surface until hitting the edge of the pot, when the roots grow downwards and coil around the bottom of the pot. As the lysimeters were scaled-up pots, this could be what is happening.

The results indicate that *Salix* exploits the soil differently to *Eucalyptus*. Although there are a greater quantity of roots at depth in *Salix* , *E. nitens* has a more even distribution. This has implications for effluent application as fine roots are the mechanism by which nutrients are taken up by the plant, thus possibly greater quantities of effluent could be applied to *Salix* than *Eucalyptus*. However the distribution pattern of the roots of *E.nitens* may hold the soil together better, which could be useful in areas where soil erosion is a problem.

Temporal distribution.
The flush of growth produced by *S. kinuyanagi* in spring indicates that the roots are using stored carbohydrates and starting growing early on in the season before bud burst. *E. nitens* producing fairly constant root densities over the season, as would be expected from a tree that grows for the whole year, with no seasonal cycle of growth. The small peaks and troughs in density are likely to be due to cycles of growth followed by decay. Growth and decay of fine roots has been found to occur simultaneously over the season, (Rytter, 1997), and fine root longevity has been estimated to be approximately one to two months, the time span between the peaks and troughs (Mackie-Dawson, 1991; Rytter, 1997).

The die-back of roots in September of both *S. kinuyanagi* and *E. nitens* coincided with the addition of effluent. It could be that the effluent produces anaerobic conditions and roots die-back, or as is more likely the August roots are entering a decay phase.

The patterns of root growth found using the mini-rhizotrons are difficult to interpret but both *E. nitens* and *Salix* showed flushes of growth in August. In this trial, effluent is being applied from September onwards. The results presented here indicate that root growth is vigorous before this time and so earlier applications may be appropriate.

4.2 The root growth of *Salix* and *E. nitens* in response to dairy farm pond effluent irrigation.

In 1994 a field trial was set up by researchers at Massey University to investigate the response of *Eucalyptus nitens* and nine *Salix* varieties, to dairy farm effluent irrigation.

In June 1994 field trials were planted. In May 1996 the trees were cut-back, and in September 1996 an investigation of the root growth of *E. nitens* and *Salix viminalis* PN386 and NZ1295 was carried out.

Methods

Soil coring was chosen to assess root growth. Six cores were taken in each plot, using a soil corer of diameter 2.7cm. Samples in units of 10cm length were taken down to 100cm. The six samples per plot were grouped together at each depth, giving 10 bulked samples per plot. In some plots the soil was too stony at depth and sampling could go down only to 70cm.

The soil cores were washed using a hydropneumatic elutriation system, separating the soil from the roots and discarding the soil. The root lengths were then measured using a Comair root length scanner (Commonwealth Aircraft Corporation Limited, Melbourne, Australia).

The roots were oven dried at 80°C for 24 hours and their dry weight recorded. The root length density (cm root cm^{-3} soil), root weight density (mg root cm^{-3} soil) and the ratio of the coarse to fine root weights were calculated.

Results

Fine root weight and length

There was a general trend of a dense mat of roots in the top 10cm, decreasing with depth for both effluent rates The two willow species produced significantly ($p<0.001$) greater fine root weight in the top 10cm compared to the next two depths, regardless of effluent rate. For fine root length, the depth distributions were similar regardless of species or effluent rate.

Coarse root weight and length

Fertilisation had a significant influence on depth distribution, with all species producing greater biomass in the 20-40cm depth compared to 10cm and 50-70cm. The length of coarse roots increased in 20-40cm depth with the higher rate of effluent, but this was not as obvious as for weight, with the exception of *E. nitens,* where the effluent addition produced significantly more biomass in 20-40cm than other depths. For the two willow species there are less length compared to weight so it can be assumed that the trees are producing thicker roots (greater diameter) due to effluent addition

Coarse:fine root weight ratio.

All three species perform similarly, with, at low effluent rate a gradual increase in ratio with depth, indicating that there are more fine roots at the top of the profile and more coarse roots at the bottom. With the higher effluent rate the ratio is higher at the 20-40cm depth, substantiating the finding that there are more coarse roots in that area, but also that there is not a corresponding increase in fine roots.

Discussion

The coarse roots of all the species in this study were fairly deep compared to other authors' findings (Katterer *et al*., 1995; Rytter, 1989; Rytter and Hansson, 1996). The higher effluent rate resulted in a band of roots at 20-40cm, and a much smaller quantity of roots at lower depths. This indicates that the soil below 40cm was possibly too compacted for both effluent and root penetration.

Fine roots are the plant's means of accessing soil resources, and fine root length especially is an indicator of nutrient absorbing capacity (Rytter, 1997). Generally they are known to be prolific in areas of high resource availability such as in the top horizons, under effluent irrigation (Sims, *et* *al*.,1994; Elowson and Rytter, 1993; Heilman *et al.*, 1994). Some authors have expressed concerns that drip irrigation of effluent could have a negative impact on fine roots, due to ponding, causing anaerobic conditions and thus a slower breakdown of organic matter. This was not a problem with this study, indicating that the rate of irrigation was acceptable.

A problem with the dense mat of finer roots near surface is that they could be damaged by the heavy machinery used in harvesting, either direct physical damage, or indirectly by soil compaction. Effluent additions alter the coarse:fine root ratio, with fewer coarse roots in the top horizons, and so the benefits of fertilisation may be off-set by root damage. Heilman *et. al*., (1994), working on fertilised poplar also expressed concern that roots near the surface would be more susceptible to herbicide and cultivation.

This work has implications for the fertilising of SRC in Britain. Both harvesting machinery and the application of slurry by tractor and trailer could cause soil compaction. Currently, the extent of damage to surface roots by machinery is not known, and until further research is carried out only tentative conclusions can be drawn as to the deleterious effect of machinery used in harvesting and fertiliser application. However this study has shown that fertilisation of the trees alters root distribution and may leave roots even more prone to damage.

5 The influence of fertilisation at establishment on longer term yields in the uplands.

Introduction
Cardiff University began short rotation willow coppice field trials in the uplands of mid-Wales in 1992, the initial results of these are documented in Hodson (1995). The main trial site, called Carnau, at an altitude of 255m on a stony silty clay loam of the Cegin association is believed to be the only upland SRC site in Britain other than those set up at ADAS Pwllpeiran as part of this study.

Methods
After being ploughed and harrowed the site was planted with the following varieties in January 1992:
- *Salix* x. *dasyclados*
- *Salix viminalis* Bowles Hybrid
- *Salix cinerea* McElroy
- *Salix* Delamere

Two fertiliser treatments and a control of no treatment were applied:
- Potassium (100 kg ha^{-1}) + Phosphorus (60 kg ha^{-1}).
- Potassium (100 kg ha^{-1}) + Phosphorus (60 kg ha^{-1}) + Magnesian Limestone (10 t ha^{-1}).
- Control - no treatment**.**

Assessments.
The survival was recorded and the trees were cut-back and weighed in January 1993.
In January 1997 all plots except Bowles Hybrid were harvested and weighed. In summer 1997 it was noticed that the Dasyclados plots were not growing well in comparison to the other two varieties. It was thought that the fast-growing Dasyclados may have exhausted the soil nutrient supply and soil samples were taken of each plot of Dasyclados and *S. cinerea.* In January 1998 the plots were harvested and weighed again.

Results
Establishment success
All varieties had high establishment rates, ranging from 95 to 99.4%, and there were no significant differences in terms of treatment or variety (Hodson, 1995). Bowles Hybrid performed very poorly in some of the plots and so was left out of subsequent analysis.

Biomass Data
In 1993 Dasyclados performed best overall, with a yield of 1.29 odt ha^{-1} yr^{-1} with the fertiliser and lime treatment, significantly greater than the 0.33 and 0.2 odt ha^{-1} yr^{-1} produced by Delamere and *S. cinerea* respectively. The influence of liming and fertiliser was most apparent for Dasyclados, which produced significantly greater yields with this treatment than the K + P and control treatments. There were no significant differences due to fertiliser treatment for Delamere and *S. cinerea*.

This changed in 1997 when the comparatively greater growth shown by Dasyclados in the first year was no longer apparent.

By 1998 Dasyclados performed very badly, with yields significantly lower for similar treatments of the other two varieties. *S. cinerea* performed consistently best regardless of treatment, but Delamere performed best overall with liming and fertiliser**.**

Soil data
For both varieties, the plots which had received the K + P + MgL treatment had higher magnesium levels, and the *S. cinerea* plot also had a higher pH, although the Dasyclados plot did not.

Discussion
Tree health
There were no serious outbreaks of rust or insect damage throughout the five years. In 1994 some stem infecting *Melampsora* (rust) was noticed, but only in selected plots and on infrequent stems. Previous researchers have found that rust attacks become more severe as the stools mature, with rust often appearing by year three onwards (Armstrong, *pers. comm*.). Thus the lack of any rust even on these mature stems is encouraging and indicates that rust may not be a problem on upland sites.

Fertilisation and Variety choice.
The annual increment for both Delamere and *S. cinerea* increased with stool age, as would be expected from longer term studies on these and other willow varieties (McElroy and Dawson, 1986; Stott, *pers.comm*.). The decline in annual increment shown by Dasyclados in comparison with the other two varieties suggest caution is required when basing recommendations on first year data, and indicate the importance of longer term studies. The marked decline in growth could be due to a lack of nutrients, indicating that Dasyclados needs nutrient rich soils to perform well.

The influence of lime on soil pH and magnesium levels was still evident after 5 years. The pH of the Dasyclados plots that had lime was not significantly different from the control, which could be the reason for poor growth, as in the establishment year liming produced significantly greater yields for Dasyclados.

Little information is available regarding the optimum pH and nutritional requirements of the varieties used. As the soil nutrients were similar for both Dasyclados and *S. cinerea*, yet the growth so different, the higher yields produced by Delamere and *S. cinerea* indicate that they can survive in lower nutrient environments, having a better nutrient use efficiency. This would be useful to the farmer wishing to minimise fertiliser inputs and would give a better yield. However if willow is to be used as a disposal route for slurry or sewage then a more nutrient demanding variety may be preferable.

Yield Production
The best yield was that produced by Delamere with the P + K + MgL treatment, of approximately 6 odt ha^{-1} yr^{-1}. There could have been competition for nutrients on the poor upland soil, and the yield may have been increased if nitrogen had been applied in the second and subsequent years, as found in other studies on peaty soils (Lumme and Tormala, 1987; Hytonen, 1987).

As the stools at the site mature, greater yields would be expected for at least the first nine years after establishment (McElroy and Dawson 1986). Here the annual increment of Delamere and *S. cinerea* both increased during the experiment. Had Dasyclados been fertilised in subsequent years, the growth obtained in the first year may have been maintained and improved exponentially in line with the other varieties to produce even better yields. Thus the 6 odt ha^{-1} yr^{-1} is a conservative estimate of the potential yield of willow in the uplands.

Conclusions

These results show the vast differences in performance between varieties, and highlight the need for trials of more varieties. Liming has been shown to be essential on this upland site. As the pH will vary according to the underlying geology and previous land use (soils which have been continuously ‘improved’ by the addition of fertiliser and lime over many years may not be so acidic), it is essential that soils are tested prior to planting.

There is still more to be learnt regarding nutrient cycling and variety choice with regard to nutrient uptake, but these results indicate that liming and fertilisation at establishment may be all that is necessary to achieve a crop, provided the correct variety is planted.

The biomass production from this first longer term study in the uplands is very encouraging, and indicates that yields comparable to the lowlands may be achieved with careful management. As the economic climate is very different to that in the lowlands with upland marginal land providing smaller profits, better yields may not be necessary to ensure the crop is economic. This is investigated further in section eight.

6 The influence of planting date on the establishment and growth of stored and freshly cut willow cuttings.

There is some variation in the recommended time for planting willow coppice. Mitchell *et al.*, (1993) recommend that the time of planting willow coppice in lowland Britain is late winter/early spring, and the planting dates of all the major coppice trials in UK fall in the range of mid February to late April (Britt *et. al*., 1995). However, overseas recommendations vary from mid February to March (Italy) to mid April (Canada) (Ledin and Alrikkson, 1992). All these recommendations are based on anecdotal information, with no experimental evidence to support them, and none are specifically aimed at the uplands of Britain. In addition, there are no guidelines regarding the detrimental effects on survival of planting outside the recommended times. This may sometimes be necessary due to labour availability, machinery availability, and site factors such as waterlogging or frozen ground in the early part of the year

Practicalities aside, plant growth and climate may affect choice of planting date. Early planting gives a longer growing season and the cooler, wetter soils prevent desiccation in the early stages of root growth. However the cuttings could rot in the cold wet soils prior to the beginning of the growing season, and root initiation and growth is dependent on warm soils found later in the season (Hansen, 1986). In the uplands the soil is generally wetter, so later planting dates may be acceptable with lower risk of desiccation.

If planting has been delayed it may be that no stored cuttings are available, and that fresh cuttings have to be used. Taking cuttings when the leaves are on the shoots is not recommended as the high abscisic acid levels in the stem inhibit root growth (Stanley and Toogood, 1981). This experiment examines the potential for establishment of summer cuttings of willow, and compares the success with the standard stored shoots.

Methods

An upland site, 255m, on a stony silty clay loam of the Cegin association was used for this experiment.

Willow was planted every 28 days throughout 1996, using one year old cuttings of Dasyclados which had been cut in December 1995 , loosely wrapped in polythene and stored at –4°C. At the same time fresh cuttings were taken from existing plantings at the site and planted. All cuttings were soaked in water for 24 hours prior to planting.

Soil and meteorological data were recorded, and the trees harvested and weighed in December 1997.

Results and discussion.

Survival

From January to June the establishment success was high (89 - 100%) and within acceptable limits for a commercial plantation although there were some significant differences (p=0.05) in establishment due to planting date. Generally the stored cuttings performed slightly less well for these months, with the fresh cuttings having high survival rates despite most authors cautioning against the use of non-dormant cuttings such as the April to June plantings (Sennerby-Forsse *et al*., 1993, Stanley and Toogood, 1981).

The July results show lower survival rates (27 – 55%) than the previous plantings and the stored cuttings performing significantly better than the fresh ones. This would be expected as the fresh cuttings were taken from vigorously growing stools with leaves on, so abscisic acid levels would be high , inhibiting rooting (Stanley and Toogood, 1981).

From August onwards, all plantings had low establishment success (1 – 59%), regardless of source. It would have been expected that the December fresh cuttings would have a similar establishment success as the January fresh. Possibly the conditions after planting are to blame – 1997 was generally warmer and drier than 1996 so desiccation could have occurred. The actual conditions at planting were not dissimilar although December was wetter. However excess rainfall was not shown to affect the growth of February cuttings. The stored cuttings did not survive as well as the fresh for October, November and December. In other studies, stored cuttings have been found to have lower survival rates than fresh cuttings, thought to be due the stored cuttings drying out (Sennerby-Forsse *et. al.*, 1993).

Biomass

The maximum biomass was produced by the fresh stems planted in February, although this was not significantly different from the January and March ($p=0.05$). The stored cuttings from February produced significantly lower biomass than the fresh. There is no clear explanation as to why this is as January and March cuttings showed no significant difference in yield due to cutting type. February was very wet, so possibly water logging was a problem for the stored cuttings but not the fresh, although it is unclear why this should be.

In April the biomass obtained from the fresh cuttings dropped considerably, being significantly lower than the stored. This indicates that in April the shoots were starting to lose dormancy and abscisic acid levels were increasing, inhibiting rooting. In May there was a considerable drop in biomass of the stored cuttings, and no significant difference in biomass due to cutting type. There was little rain around the time of the May planting. The clay soil at the site dries out very quickly, and the strong winds at altitude result in additional desiccation. Willow cuttings need good soil contact and a supply of moisture to grow well, and the dry soil at planting could have prevented this. The stored cuttings performed better than the fresh for the July planting, as the fresh ones were taken from trees that were in the fastest period of growth, and thus had high abscisic acid levels.

Biomass produced from August onwards was very low, as the trees only had the 1997 growing season, in comparison to the January- April trees which grew for two seasons.

Conclusions

The current UK recommendations for lowland sites of mid February to late April should be revised for the uplands with earlier planting dates of mid January to mid-March.

Planting outside these dates is not recommended. ‘Back end’ planting, that is November to December did not maximise survival or biomass. This can result in problems later on, as it is essential that willow cuttings grow as well as possible in the first year as this influences the viability throughout the entire life of the stools (Parfitt and Stott, 1988). A greater biomass in first year could result in thicker diameter stems being too big for subsequent attack by hares the following winter. Planting later in the season, such as July to August, can result in problems of weed control, with new cuttings being especially susceptible to spray drift.

The results show no need for storage facilities if willow are planted within the recommended dates, and if cuttings are stored then they should be used within 6 months.

7 Non-destructive determination of standing biomass.

Non-destructive estimation of the standing biomass of a willow crop is essential for both experimental studies and in the commercial environment. For research purposes, harvesting the entire crop to determine the intermediate yield is time-consuming, expensive and experimentally destructive. In the commercial environment an estimation of standing biomass is also necessary. In conventional forestry, trees are commonly sold standing and it is likely that this will also be the case for SRC, a farmer selling a standing crop to a company who would take responsibility for harvesting the trees. Thus it is essential for resource planning and sales negotiations that an accurate, quick and cheap method of assessing standing biomass is available.

Verification of any model is important and few studies compare predicted yields with harvest yield. This lack of validation has been recognised by several authors as being an area which needs more attention (Agren, 1981; Snowdon, 1985).

Methods

An initial exploratory approach has been taken to yield prediction. Much of the statistical analysis described below was decided during discussions with Forestry Commission growth modellers (Matthews, *pers. comm.).*

Sampling

1996

The Pwllpeiran field trial was used for this study (refer to section 2 for details). In December 1996 six shoots were selected from each plot which were judged by eye to cover the whole range of diameter classes present. The diameter at 10cm and 50cm from the base, and length were measured. The shoots were then weighed to 0.1g and dried at 85°C until constant weight.

Thirty stools were measured non-destructively from each plot, chosen systematically by walking along rows and measuring every sixth tree, the diameter and length of every shoot were measured. The length of each shoot was determined as the distance between the ground and the top of the shoot. At the end of January 1997 an assessment of the percent survival per plot was made, and the shoots harvested and weighed.

1998

Due to the very time consuming nature of processing multi-stemmed stools, in September 1998 only three shoots were selected from each plot that were judged by eye to cover the whole range of diameter classes present. The stools were processed in the same manner as for 1996. The diameter at fifty cm was excluded as in 1996 it was found to be very awkward to measure, and preliminary analysis had shown that the other measurements were sufficient to determine the relationship between weight and stem parameters.

In October 1998 measurements were made non-destructively as for 1996, the trees harvested and weighed.

Statistical Methods

The 1996 and 1998 data were analysed separately and within each year, the varieties were treated separately. Exploratory weighted regression analysis was carried out using the following models:

$$\mathbf{d^2; d^{2.5}; d^3; d^2\mathit{l}; d^2\mathit{l}^{0.5}; 1.2^{d-1}}$$

and

$$\mathbf{d^p} \text{ where } 2 \geq p \leq 4$$

where **d**= d10 (diameter at 10cm from the ground) and d50 (fifty cm from the ground).

Models failing to meet the regression assumptions were ignored, and of the remaining , the models were chosen based on a high adjusted R^2 value.

The model was validated by comparing predicted plot yield to the harvest yield. As the harvest yields were in fresh weight terms they were converted to dry weight using the moisture content for each variety determined from the destructive sub-sample

Results and Discussion

The diameter at 50cm was not found to increase adj-R^2 in comparison to diameter at 10cm. Including length in the equations did not increase the adj-R^2 by more than 1% and so models based on diameter alone were chosen.

The best models were of the form

$$odw = a + b\,d10^{\,p}$$

Where *a* and *b* are regression parameters and *p* ranges from 2 to 3.5. For 1996 the adj-R^2 values ranged from 80.9 –92.8%, and for 1998 the values were higher ranging from 93.5 - 99.2%.

The adjusted R^2 values were all acceptable, being over 80%. Thus the technique for measuring the trees proved satisfactory. The removal of shoot length will save a lot of time in future trials, and the use of diameter alone in predicting weight has also been shown by other authors to be sufficient (Matthews, *pers.comm*). Measuring the diameter at 10cm was found to be easier and faster than at 50cm, although whether it will remain so when the trees become larger remains to be seen. Measuring at a height from ground level rather than using a tape to curve around the swept bases of the stems is also considerably easier, and the high adjusted R^2 values in this trial are in agreement with other studies using this technique (Verwijst 1991).

For both years there was a general trend for the estimates to overpredict the harvest weight of the whole plot, although generally the errors are greater for the 1998 data than the 1996. The fact that the adjusted R^2 values were not so good in 1996, and yet the predicted values better, indicate that the problems lie not with the predictive equations but in the scaling up to the whole plot. An important factor is that the data used extended outside the diameter range of that used to form the predictive relationship. This could produce errors as relationships between stem parameters could change with larger sized stems. Thus the method of judging by eye when selecting samples across the diameter range for destructive sampling was not adequate.

There are no clear patterns relating to either variety or treatment for 1996. The 1998 data present clear differences in the pattern of predicted against harvest yields for different varieties. The closest predictions to harvest weight were achieved for Jorunn. Mullatin and 683 were adequate in their estimations. Bowles hybrid, Gigantea, and *S*.x.*dasyclados* were not as successful.

The moisture content of the stems against diameter at 10cm was plotted and there was no clear pattern with size, the range of moisture contents is very wide, (34.8% to 61.4%). Perhaps the most significant parameter to introduce error is the determination of moisture content, and subsequent conversion of fresh harvest weights to oven dry figures. Concerns that moisture content might vary for stems of different sizes were unfounded. A relatively small sample of wood was used for this estimation, and assuming that this is representative of the whole plot when there is such a wide range indicates that more samples may be needed.

Conclusions

The determination of relationship between stem diameter and oven dry weight was generally successful. The inconsistencies in accuracy of prediction highlight the need for model validation and also for improvements that can be made on the scaling up of the measurements to plot values.

8 The Economics of growing short rotation coppice in the uplands of mid-Wales and an economic comparison with sheep production.

An economic spreadsheet was written in Microsoft Excel (Heaton, *et al.*, 1999), comprising cashflows for the two enterprises (SRC and sheep). The model represents standard cashflows for different silvicultural regimes and allows other factors to be varied such as chip price and government subsidy level. Output from the model is in the form of Net Present Value (NPV) at four different discount rates (r); 4,6,8 and 10%.

In order to provide the farmer with annual incomes, the model assumes planting will be on a sustained yield system, that is to have as many areas of coppice as there are years in the rotation, so that annual harvests can be made. A four year rotation was assumed for this upland scenario. The model assumes the market of a woodfuelled power station, sited 10 miles away, and accepting wood chips at delivered prices ranging from £30 to £40 odt^{-1}. All costs of planting, management and harvesting were included, and discounted over 25 years, the assumed productive life of SRC stools. Cashflow data for sheep production were provided by Phillips (*pers. comm.*).

Results and Discussion

Establishment costs came to £1188.37 ha^{-1}, spread over four years of establishment. The greatest cost, £550 is plant material, the farmer providing his own cuttings in years two onwards.

There was a wide range in profitability of the enterprise with NPV varying from £848 ha^{-1} for the worst scenario (£30 odt^{-1} chip price, production of 6 odt ha^{-1} year^{-1}). Even the best scenario of £3507 ha^{-1} (£40 odt^{-1} chip price, production of 12 odt ha^{-1} year^{-1}) is lower than the income currently obtainable from sheep production of £5155 ha^{-1}.

However the profitability of sheep is due solely to subsidy. When both enterprises are placed on an even footing (all subsidies removed), SRC is more profitable than sheep farming with yields of at least 8 odt ha^{-1} year^{-1} and medium chip price (table 1).

Table 1 The profitability (NPV ha^{-1}) of SRC and sheep production in the uplands with all subsidies removed (6% discount rate, no lime).

Yield, odt ha^{-1} yr^{-1}	**Chip Price**		
	£30	**£35**	**£40**
6	297	638	979
8	729	1184	1639
10	1160	1729	2297
12	1592	2274	2956
Sheep, no subsidy = £965			

It has been proposed that, as an incentive for farmers to introduce energy crops, establishment grants for SRC should be paid at a rate equivalent to the current livestock payments. Table 2 shows that the subsidy for SRC need not be as much as this. The subsidy needed if a farmer is to obtain the same income from SRC as he currently does from sheep production (1999 prices) varies from £2199 to £4858 ha^{-1} depending on yield and assumed chip price. The current subsidy (1999 prices) for sheep production, of £304 ha^{-1} yr^{-1}, when discounted over 25 years gives a total subsidy payment of £4190 ha^{-1}. As can be seen from table 2, this is greater than that needed for SRC at all chip prices, provided 10 odt ha^{-1} yr^{-1} are produced. This should be achievable on upland sites with regular fertilization and fast growing varieties.

Table 2 Proposed discounted SRC subsidy ha^{-1} (discount rate 6%, no lime)

Yield, odt ha^{-1} yr^{-1}	**Chip Price**		
	£30	**£35**	**£40**
6	4858	4517	4176
8	4426	3971	3516
10	3994	3426	2858
12	3563	2881	2199
Current government sheep subsidy = £4190			

Conclusions

It is hard to make predictions for the future of SRC as there are rapid developments in potential markets for woodfuel, cultivar breeding, etc.

Currently SRC is not as profitable as sheep, but this is due to the subsidies being paid for sheep production. On a level basis (all subsidies removed) similar profits can be made as from sheep production. Yield of SRC is a significant factor in how great these profits will be, 8 odt ha^{-1} yr^{-1} produces greater profits than those from sheep production at £35 odt^{-1} chip price. Yields in excess of this should be achievable on most upland sites.

If proposals for SRC payments equivalent to existing sheep subsidies were to be adopted then farmers would benefit from increased profits, even at low yield production and chip price.

The future of SRC in the uplands rests on subsidies and a woodchip market. With a revised subsidy the income from SRC may be attractive to farmers but it is doubtful that financial considerations only will be enough to persuade farmers to turn over from sheep production.

9 Conclusions

Silviculture of willow in the uplands.
In Wales it is primarily upland land that is likely to be available for planting SRC in the foreseeable future, due to farmers' reluctance to plant the better lowland. The uplands offer several advantages for growing willow in comparison with the lowlands. The cold damp climate has been seen to prevent excessive insect and rust attacks. The high rainfall means that water stress is not a problem, and the low nutrient status of the soil can be seen as an advantage, enabling the application of slurry which can otherwise present problems of disposal.

Disadvantages are the shorter growing season, exposure and strong winds, all of which are detrimental to growth. The shallow soils could also be a problem in the future, facilitating wind throw of older trees. The wet ground leaves the soil intractable for much of the year, and generally the climate is not cold enough for the ground to be frozen in the winter to facilitate harvesting access. Another problem for harvesting is the hillside gradients which are unsuitable for tractor access. Weeds are less competitive than in the lowlands but rush (*Juncus effusus*) can be problem and is difficult to eradicate. Hares can cause grazing damage, although in the lowlands the problems of rabbits can be much worse.

The main field experiments in this study were carried out at altitudes of 255m or greater, and thus are believed to be the highest altitude SRC trials yet documented. Soils of the Cegin and Wilcocks series are both subject to seasonal waterlogging and together total 11.5% of total land in Wales. Temperature sum ranged from 2517 to 2876 at 255m and 2337 to 2606 at 365m. Rainfall during the growing season varied considerably between the sites, with a range of 423-761mm at 255m and 850-1982 at 365m. Duration of the growing season was similar for both sites, ranging from 209-245 days. The following guidelines are based on these climatical conditions.

Variety choice
Different varieties perform differently at different sites so general prescriptions for variety choice are hard to make. It is advisable to plant several varieties, and determine which grows best. First year results are not always reliable in predicting long term yields and so stools should be left for several years before a decision is made to grub up and replant with a different variety. In the longer term with little nutrient inputs *S*. Delamere and *S. cinerea* (McElroy) have produced moderate yields, and in the shorter term with fertiliser addition *S. viminalis* Gigantea, 683 and Bowles Hybrid have all done well.

Planting Date
In the uplands the planting season should be earlier than in the lowlands, with best results obtained from planting from January to mid-March. There is no need for costly cold storage facilities if trees are cut just prior to planting.

Cut-back
Generally if the shoots are small and performing badly then the stools should not be cut back as doing so will lower second year survival and exposes the shoots to further hare grazing damage. This decision may be revised if there is a lucrative market for the cuttings, but otherwise the cost of cutting back is not returned by higher yields later in the rotation.

Yield production
Production in these upland trials was much lower than found on lowland sites, being approximately 6 odt ha^{-1} yr^{-1}. There is potential for far greater yields with regular fertilisation and also yields will increase as the stools mature. Although prediction of yield (standing biomass) is

not yet adequate for the commercial environment, the preliminary results were encouraging and indicate further research areas. In combination with scientists at the Forestry Commission the study presented here should help predict yield production across a range of different site types.

Nutrition of willow in the uplands.

Contrary to accepted practice, fertilising in establishment year produces significant increases in yield. Cattle slurry, cattle manure, poultry manure and pig manure all increased growth in establishment year when applied at a rate equal to 250 kg N ha^{-1}. Poultry manure has the best balance of nutrients, but was found only to work well in conjunction with an additional mulch mat. Of the manures tested, cattle slurry had the best natural mulching properties, and was also seen to suppress weeds in a field situation.

The soil pH was found to decrease in all fast growing plots on both upland field trials, indicating the need for liming before establishment, and possibly between harvests. There is also a need to fertilise older stools between harvests, as additions of manure at rates equivalent to 250 kg N ha^{-1} produced increased yield of three year old stools. Yields of Dasyclados decreased annually in the field, and regular fertilisation may have overcome this.

It may be necessary to apply phosphorus in addition to the manures as generally phosphorus levels in the foliage were low. Rates of inorganic phosphorus alone of 60 kg ha^{-1} have been found to increase production (Hodson, 1995), so for cattle slurry a supplement of 40kg ha^{-1} would be advisable in addition to the approximately 20 kg supplied by cattle slurry when applied at a rate of $100m^3$ ha^{-1}.

All the manures tested were high in potassium, and the foliar concentrations of this nutrient reflected this, being higher than recommended (Ericsson, 1994). However no problems such as abnormal growth or chlorotic foliage were recorded.

Nitrate leaching should not be a problem, as it is likely that denitrification is occurring in the wet cold soil of the uplands. However more work should be carried out to quantify this.

Fertilisation was found to influence root spatial arrangement, with more roots near the soil surface. This has implications for machine harvesting, which could damage these surface roots by soil compaction or physical damage.

Economics and the future of SRC in the uplands.

With all subsidies removed the returns from SRC, although low are greater than for sheep production (assuming £35 odt chip price, yield 8 odt ha^{-1} yr^{-1}), a realistic target for the uplands. The economic climate is changing rapidly, and since the model was written the subsidies for sheep have risen and the price of lambs dropped, resulting, on a level basis, in SRC appearing even more favorable. The results presented from this study are being used by the National Assembly of Wales, Agriculture Department (NAWAD) to determine the viability of SRC in relation to other novel alternatives of farmers. This may lead to a new system of support to replace the current Woodland Grant Scheme and offer greater financial incentives to plant SRC in Wales.

The future for biomass crops is encouraging, with NAWAD perceiving biomass as a key alternative crop for farmers, and short rotation willow coppice as the crop with most potential in the uplands. Developments in energy markets for biofuels will be crucial, for example, it is fully expected that approval will be granted for wood powered electricity plants in Wales in the near future.

The results found in this study indicate that growing short rotation coppice willow in the uplands is a viable proposition with regard to establishment success and yields. In the event of a secure wood chip market in Wales, returns to the grower would be comparable to those from sheep production.

References

Agren, G. I. (1981). Problems involved in modeling tree growth. *Studia Forestalia Suecica* 160: 7-18.

Alker, G. R., Riddell-Black, D. & Smith, S. R. (1997) Investigations of nutrient uptake by willow in a soil-less system. *Aspects of Applied Biology* 49:173-180.

Alrikkson, B. (1997) Thesis: *Influence of site factors on Salix growth with emphasis on nitrogen response under different soil conditions.* Swedish University of Agricultural Sciences. Silvestria 46.

Britt, C., Heath, M. & Buckland M. (1995) *Arable Energy Coppice*. ADAS

Christersson, L. (1987) Biomass production by irrigated and fertilised *Salix* clones. *Biomass*, 12, 83-95.

Clay, D.V. (1993) *Weed control and soil management systems for short rotation coppice*. ETSU BW5/00211/REP.

Elowson, S. & Rytter, L. (1993) Spatial distribution of roots and root nodules and total biomass production in a grey alder plantation on sandy soil. *Biomass and Bioenergy*, 5 (2) 127-135.

Elowson, S. & Rytter, L. (1988). Dynamics of leaf minerals, leaf area, and biomass from hardwoods intensively grown on a peat bog. *Trees*. 2: 84-91.

Ferm, A. & Hytonen, J. (1988) Effect of soil amelioration and fertilisation on the growth of birch and willow on cut-over peat. *Proceedings of the VIII International Peat congress. Leningrad.* Section III.pp. 268-279.

Granhall. U. (1994) Biological Fertilisation. *Biomass and Bioenergy* 6 (1/2) 81-91.

Grieu P. & Aussenac G. (1988) Growth and development of the root system of seedlings of three conifer species: *Pseudotsuga menziesii, Pseudotsuga macrocarpa* and *Cedrus atlantica. Annales des Sciences Forestiere,* 45:2 117-24.

Hansen, E. A. (1986) Planting date Affects Survival and Height Growth of Hybrid Poplar. The Forestry Chronicle, June 1986 164-169.

Heaton, R. J. (2000) *The silviculture, nutrition and economics of short rotation coppice in the uplands of mid-Wales* Ph.D. thesis. University of Wales.

Heaton, R. J., Randerson, P. F. & Slater, F. M. (1999) The economics of growing short rotation coppice in the uplands of mid-Wales and an economic comparison with sheep production. *Biomass and Bioenergy* 17:59-71.

Heilman, P.E., Ekuan, G. & Fogle, D. (1994) Above and below-ground biomass and fine roots of 4-year-old hybrids of *Populus trichocarpa* x *Populous deltoides* and parental species in short rotation culture. *Canadian Journal of Forest Research*, 24 1186-1192

Hendrick, R.L. & Pregitzer, K.S. (1992) The demography of fine roots in a northern hardwood forest. *Ecology*, 73 1094-1104.

Hodson, R. W. (1995) *The Establishment of Short Rotation Coppice in mid - Wales.* Ph.D. thesis. University of Wales.

Hunt, G. (1993) *Energy Forestry in the Forest of Mercia*. ETSU Report B/W5/00241/REP. ETSU, Oxon.

Hytonen, J. (1987) Effect of fertilisation on the nutrient status and dry mass production of *Salix viminalis* on two peat cut-away areas. *Metsantutkimuslaitoksen tiedonantoja* 245: 1-31.

Hytonen, J. (1995) Effect of fertiliser treatment on the biomass production and nutrient uptake of short-rotation willow on cut-away peatlands. *Silva Fennica* 29(1) 21-40.

Hytonen, J. (1996) Thesis: Biomass production and nutrition of short rotation plantations. The Finnish Forest Research Institute, Research Paper 586.

Hytonen, J., Saarsalmi, A. & Rossi, P. (1995) Biomass production and nutrient uptake of short rotation plantations. *Silva Fennica* 29 (2) 117-139.

Johnson, D.W. (1989) Fertilisation of short rotation woody crops plantations. In: *Nutrient Relations in SRF*. A compilation of papers presented at workshops: Uppsala 1987 and Seattle 1988. IEA Report. Aberdeen University. Forest Research Paper 1989:1
Katterer, T., Fabiao, A., Madeira, M., Ribeiro, C. & Steen, E. (1995) Fine-root dynamics, soil moisture and carbon content in a *Eucalyptus globulus* plantation under different irrigation and fertilisation regimes. *Forest Ecology and Management*, 74 (1-3) 1-12.
Kaunisto, S. (1983) Nutrient and water balance *of Salix viminalis* in greenhouse conditions. In: *Workshop on the Nordic Problems in Energy Forestry*. The Finnish Forest Research Institute, Helsinki.
Ledin, S. (1998) Environmental consequences when growing short rotation forests in Sweden. *Biomass and Bioenergy* 15 (1):49-55.
Ledin, S. & Alrikkson, A. (Eds) (1992) *Handbook on how grow short rotation forests.* International Energy Agency/Swedish University of Agricultural Sciences, Uppsala, Sweden.
Lumme, I. & Tormala, T. (1987) Improvement of biomass in fast growing *Salix* species on mined peatlands in northern Finland. In: *Biomass for Energy and Industry*, 4th EC conference, (eds. G. Grassi *et al* .), France. May, 1987. Elsevier Applied Science.
Mackie-Dawson, L. A. & Atkinson, D. (1991) Methodology for the study of roots in field experiments and the interpretation of results. In *Plant Root Growth: An Ecological Perspective.* (ed. D. Atkinson) pp 25-45. Blackwells. London.
MAFF (1991) *Code of Good Agricultural Practice for the Protection of Water.* MAFF Publications, London.
McElroy, G.H. & Dawson, W.M. (1986). Biomass from short rotation coppice willow on marginal land. *Biomass* 10 225-240.
Mitchell, C.P., Watters, M.P., Stevens, E.A. & Ford-Robertson, J.B. (1995) *Establishment and monitoring of large scale trials of short rotation coppice for energy: Phase III*. ETSU B/W2/00126/REP.
Parfitt, R. I., & Stott, K. G. (1984) Effect of mulch covers and herbicides on the establishment, growth and nutrition of poplar and willow cuttings. *Aspects of Applied Biology*, 5: 305-313.
Parfitt, R. I., & Stott, K. G. (1988) Weed control for short rotation coppice for biomass. *Aspects of Applied Biology*, 16: 124-137.
Pepper, H., Neil, D. & Hemmings, J. (1996) *Application of the chemical repellent aaprotect to prevent winter browsing.* Forestry commission Research Information Note 289.
Riddell-Black, D. (1995) *Fertilisation of short rotation energy coppice using sewage sludge.* ETSU B/W5/00215/REP.
Riddell-Black, D. M., Sims, R. E. H., Roygard, J., Clothier, B., Green, S. & Edwards, R. (1996) *Water and nutrient use by fuelwood species: preliminary results from an intensively monitored lysimeter study.* Internal Report, Massey University, New Zealand.
Rytter, L. (1989) Distribution of roots and root nodules and biomass allocation in young intensively managed grey alder stands on a peat bog. *Plant and Soil*, 119 71-79.
Rytter, R-M. (1997) Fine root Production and carbon and nitrogen allocation in basket willows. Doctoral Thesis. Swedish University of Agricultural Sciences, Uppsala.
Rytter, R-M. & Hansson, A-C. (1996) Seasonal amount, growth and depth distribution of fine roots in an irrigated and fertilised *Salix viminalis* plantation. *Biomass and Bioener*gy, 11 (2/3) 129-137.
Snowdon, P. (1985) Alternative sampling strategies and regression models for estimating forest biomass. *Aust For. Res*. 15:353-66.
Stanley, J. & Toogood, A. (1981) *The Modern Nurseryman.* Faber and Faber, London. 412pp.
Sennerby-Forsse, L., Telenius, B. & Fricks, H.A. von (1993) Relation between moisture content and early growth in stem cuttings of selected fast growing willow clones. *Biomass and Bioenergy* 4(4): 249-253.

Sims R.E.H., Hodson R.W. & Watters M.P. (1994) Root production of short rotation Coppice *Eucalyptus* grown under an effluent disposal system. Proc. 8th European Biomass Conference, Vol. 1. 515-520, Vienna. Pergamon
Upchurch, D. R. (1987) Conversion of Minirhizotron-Root Intersections to Root Length Density. In *Minirhizotron Observation Tubes: Methods and Applications for Measuring Rhizosphere Dynamics.* (ed. H.M.Taylor) pp 51-66 American Society of Agronomy, Wisconsin, USA.
Upchurch, D.R and Ritchie, J.T. (1984) Battery operated colour video camera for root observations in mini-rhizotrons. *Agronomy Journal*, 76 10015-17.
Verwijst, T. (1991) Logarithmic transformations in biomass estimation procedures: violation of the linearity assumption in regression analysis. *Biomass and Bioenergy* 1(3):175-181.
Welsh Office (1997) *Welsh Agricultural Statistics 1996.* Crown Copyright, 1997.