HYDROLOGICAL EFFECTS OF SHORT ROTATION ENERGY COPPICE

Final Report to ETSU

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EXECUTIVE SUMMARY

This report describes the work carried out between March 1993 and March 1996 under ETSU Contract number B/W5/00275/00/00 by the NERC Institute of Hydrology and British Geological Survey.

OBJECTIVES

The main objective of the project was to determine the impact on water resources of Short Rotation Coppice (SRC) in the UK by gaining a fuller understanding of the mechanisms controlling its water use and by quantifying the effect of SRC on the quality of groundwater. This was achieved by the collection of environmental and biometrical data from existing SRC plantations and by the development of new mathematical models.

INTRODUCTION

The possibilty of large scale plantation of SRC in the UK in the next few years requires that careful consideration be given to the potential environmental impacts of SRC plantations. Some of the benefits are already known including: low inputs of fertilisers and pesticides, the provision of habitats for a wide range of fauna and flora and the possibility of using SRC for the utilization of sewage sludge and farm slurry. However when this project was started the hydrological consequences of increased coppice plantation were unclear. Work carried out in other countries suggested that SRC could be detrimental to water resources through increased evaporative losses but there were no direct measurements for UK conditions which could substantiate this.

If SRC is to make a significant contribution to the national energy supply then large areas would need to be planted around purpose-built power stations. This could result in reduced aquifer recharge and river flows. This would be most problematic in south eastern England where there is a relatively small difference between precipitation and evaporation and where groundwater recharge is already low. Reduced aquifer recharge would be particularly serious in those areas where groundwater is the major source of water supply.

Evaporative losses due to plants occurs by two processes: (i) by *interception* in which precipitation intercepted by the vegetation is evaporated directly from live or dead plant surfaces (including the litter layer); (ii) by *transpiration* which transfers water from the soil through live plants (roots, stem(s) and leaves) to the atmosphere.

The interception loss is dependent upon the climate, primarily the rainfall regime and evaporative demand during rainfall, and the extent and structure of the plant canopy. The transpiration loss is controlled primarily by plant physiological responses to environmental factors, e.g. solar radiation, atmospheric humidity deficit, temperature and soil water status, and is also governed by tree age, species and canopy structure.

In general, trees use more water than grassland and agricultural crops but the amount varies greatly according to species, soil type and climate. Studies by the Institute of Hydrology have shown that whereas for ash and beech in southern England the water use is similar to that of grassland, in the uplands of the UK, coniferous plantations evaporate about twice as much water as adjacent grassland. This is the result of greater interception losses from conifers. The net result is a reduction in stream flow in forested areas. Although the water use of trees is smaller in the drier, lowland areas of the UK, the effective rainfall is also small and so the effect of extensive plantation on water resources is more critical.

The large scale growth of SRC could also have a significant impact on the quality of surface and groundwater through its effect on the uptake of nutrients, especially nitrogen. In a low input system in which fertilisers are only used to replace those nutrients that are lost through cropping and which are not adequately supplied from atmospheric inputs and in which pesticides are only used during establishment, it can reasonably be expected that nitrate and pesticide leaching will be low. SRC could therefore be an attractive crop in Nitrate Sensitive Areas (NSAs) or in buffer strips close to rivers. However, it is not clear how 'low' such nitrate leaching is likely to be.

There is also interest in the application of sewage sludge to SRC and here the possible impact on water quality is less clear. The extent of nitrate leaching is again likely to be the key water quality issue and so it is important to establish its probable magnitude.

In the light of these observations, it was important that the hydrological impacts of SRC, both in terms of quantity and quality, were investigated. This study was undertaken to quantify these impacts for the SRC clones most likely to be grown in the UK.

WORK PROGRAMME

Water quantity

Water quantity measurements were made at two locations in England: during 1993-1994 at the ETSU yield-trial plot, operated by Aberdeen University at Swanbourne, Buckinghamshire on land which was previously permanent pasture; and during 1995 at Knowle Farm, Hunstrete, Avon (one of five farms involved in the Farm Wood Fuel and Energy project) on what was previously arable land. At Swanbourne, the soil is a clay-loam of the Hanslope Association and overlies Oxford Clay. There is a perched water table for much of the year and a mean annual rainfall of 659 mm. The site at Hunstrete is on a north-facing slope and the water table is more than 3 m below the surface. The soil is more freely draining than at Swanbourne. The mean annual rainfall is 855 mm. Whereas the measurements from the Swanbourne site with its perched water table may prove typical of sites favoured by farmers for coppice plantation, the Hunstrete site provided essential information on the water use of SRC under drought-stressed conditions. A range of measurements were made at each site to provide direct estimates of the transpiration and interception loss (Table 1) and also to provide weather and biometrical data required to understand the processes, and for use in the modelling.

The majority of measurements were made on the poplar clone Beaupré (*Populus trichocarpa* × *deltoides*) which was grown at both sites. At Swanbourne, measurements were made on

Table 1. Variables measured at Swanbourne and Hunstrete and the methods used

Variables measured	Site S - Swanbourne H - Hunstrete	Method	Purpose
soil water storage and potential	S, H	neutron probe and pressure-transducer tensiometers	can provide an estimate of total water use
weather including rainfall	S, H	automatic weather station	required for modelling
sap flow	S, H H H	stem heat balance heat pulse velocity deuterium tracing	used with leaf area estimate to provide an estimate of transpiration
root distribution	S	soil cores, minirhizotron and $\delta^{18}O$	location of water extraction
plant physiology: stem diameters leaf areas stomatal conductances	S, H	sampling and porometry	information on the plant responses to environmental factors
net rainfall	H	plastic-sheet net-rainfall gauge	used with the gross rain to provide an estimate of interception loss

three-year old shoots on seven-year old stools in 1993 and on two-year old shoots on eight-year old stools in 1994 of Beaupré and Dorschkamp (*P. deltoides* × *nigra*). At Hunstrete, measurements were made on three-year old shoots on four-year old stools of Beaupré and, for a more restricted set of measurements, of Trichobel (*P.* x *trichocarpa*) and the willow clone Germany (*Salix burjatica*).

Water quality

The water quality investigations focussed on the impact of SRC on nitrate leaching as this was thought to be the most likely impact of importance. Literature on the nitrogen fluxes in woodland and SRC plantations was reviewed to see to what extent nitrogen requirements might be met by atmospheric inputs.

Six existing SRC trial plantations, including both poplar and willow, were sampled. The sites were at Swanbourne (Bucks), Long Ashton (Bristol), Medmenham (Bucks), Markington (N Yorks), Downham Market (Norfolk) and another site in North Norfolk. Sewage sludge had been applied at Medmenham, Markington and the North Norfolk site. Fertilizer had been applied at Swanbourne. Estimates of the nitrate concentration in the drainage water were obtained by extracting mineral nitrogen from the soils using a neutral salt (2M KCl). Where possible, soil profiles were sampled down to about 2 m depth. Effective evaporation was estimated from meteorological data after allowing for the likely extra evaporation under SRC.

RESULTS

Water use

Annual transpiration from SRC with three-year old shoots, both measured and estimated by modelling, is higher than all other vegetation covers. Daily rates measured at both Swanbourne and Hunstrete were higher than the Penman potential rate, E_T, the rate that would be expected from short vegetation well supplied with water. We found that significant soil water deficits developed before a reduction in transpiration rates was seen. This reflects the efficient rooting of the SRC. The high transpiration rates measured were the consequence of high stomatal conductances that were unaffected by high atmospheric humidity deficits, rather than because of a high leaf area. Rates from two-year old shoots are lower but still high and rates from one-year old shoots are likely to be about 50% of those from three-year old shoots.

The consistency of the sap flow rates measured using three different methods gave confidence in the accuracy of the data and provided a sound basis for a process-based model of evaporation (WUCOP). This gave estimates of daily transpiration that were in good agreement with the rates measured at Hunstrete during the dry summer of 1995. Using a stomatal conductance which was a function of the soil water deficit enabled the model to simulate accurately the reduction in transpiration rate that occurred as the drought developed.

The interception loss measured at Hunstrete during the foliated period was 21% of the rainfall and within the range of interception losses reported from mature foliated broadleaf forest in the UK which ranges from 8% for ash to 36% for hornbeam.

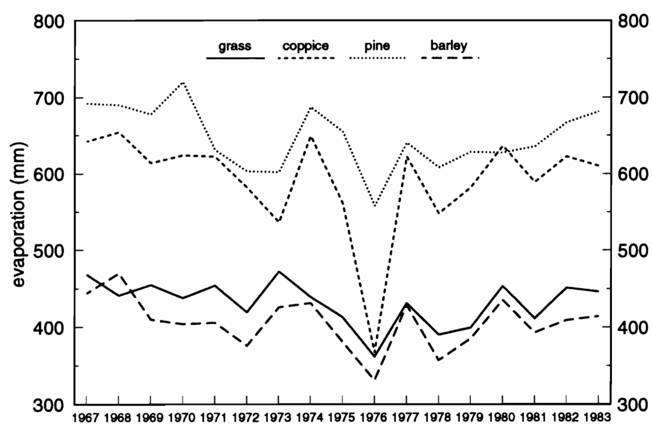

Fig. 1. Long term trends in annual evaporation predicted by SIMWUCOP for SRC (three-year old shoots), pine, grass and barley

A simplified model (SIMWUCOP) was developed to allow the water use of SRC to be compared with other crops over a long time period based upon daily rainfall and estimates of E_T together with appropriate crop factors. The model was operated for two soil types using climatological data from Grendon Underwood, Bucks., for the period 1967-1983. These calculations showed that the water use (transpiration plus interception losses) of the SRC would only be exceeded by that of coniferous forest (Fig. 1). During the drought year of 1976 the water use of SRC was the same as from grass due to large soil water deficits at the start of the summer.

Water quality

Atmospheric inputs of nitrogen to lowland forests in Southern Britain are considerable (45-65 kg N ha^{-1} a^{-1}) and while inputs to SRC are likely to be less than this, they could supply a large fraction of the nitrogen required for sustainable growth.

Of the six sites studied, the sites at Swanbourne, Long Ashton and Markington had the longest established SRC plantations (4-7 years) and had plots with no or minimal fertiliser inputs. The average nitrate concentration in the drainage water from these plots was less than 1 mg l^{-1} NO_3-N at Long Ashton and Markington, and 2-6 mg l^{-1} NO_3-N at Swanbourne. The relatively high figure for Swanbourne may have reflected the high water table and a downslope contribution from an adjacent pasture.

The results suggest that nitrate leaching under established SRC will be low and comparable to unfertilised grassland. It is likely that the overall nitrate leaching flux will be less than 15 kg N ha^{-1} a^{-1} and quite possibly less than 5 kg N ha^{-1} a^{-1}.

Average nitrate concentrations at the Medmenham, Downham Market and North Norfolk sites were higher (10-16 mg l^{-1} NO_3-N below 1 m) probably reflecting a legacy from the past arable cropping, the short time of establishment of the SRC and the low effective rainfall. The Medmenham site was complicated by a relatively high water table.

At the three sites where sewage sludge had been applied, average nitrate concentrations were significantly higher in the topsoils (13-90 mg l^{-1} NO_3-N) and some of this increase was apparent below 1 m indicating that some increase in nitrate leaching to surface and groundwaters was likely.

CONCLUSIONS

Water use

- The water use of poplar SRC (Beaupré, *Populus trichocarpa* x *deltoides*; Dorschkamp, *P. deltoides* x *nigra*) is higher than all the major agricultural crops and broadleaved trees and second only to pine forest. Our measurements on the willow clone Germany (*Salix burjatica*) gave no indication of significantly lower water use. Scandinavian work also suggests similarly high water use for willow.

- The high water use of poplar SRC results from its high transpiration rate, typically 500 mm a year, compared with 350 and 390 mm a year for conventional ash and beech forest, respectively.

- The high transpiration from poplar (Beaupré and Dorschkamp) SRC is due to high stomatal conductances with an absence of response to atmospheric humidity deficits and a delayed (but large) response to soil water deficits.

- The interception loss from poplar SRC over the growing season is about 21% of the rainfall. The annual interception loss, including the unleafed period, is about 14% of the annual rainfall (modelled). These values are typical of conventional broadleaved woodland.

- The poplar root system is efficient and appears adaptable. For example, in the well-drained Hunstrete soil, the poplar was able to extract water from depths of up to 3 m. In contrast, at the poorly-drained Swanbourne site, it was able to extract water from the surface soil when there was adequate moisture and from the water table during dry periods.

Hydrological implications

- Extensive SRC plantations will result in reduced stream flows and reduced peak flows except in the unlikely event of the conversion of coniferous forest. The reduction will be dependent upon the rainfall and the land use that the SRC replaces. For most agricultural crops the reduction will be greater than for pasture.

- Large scale plantation of SRC in the driest parts of the country will result in the annual net recharge to aquifers and drainage to rivers and streams being reduced by up to 80 mm where a grassland catchment is wholly converted to SRC.

- During the summer, SRC may cause springs and ephemeral streams to dry up sooner and for longer.

- In dry summers when there is a significant soil water deficit at the start, such as occurred in 1976, the water use of poplar SRC will be much less than that of coniferous forest and will be similar to grassland.

Water quality

The amount of nitrate leaching beneath SRC is likely to be the most important water quality issue. Although the quantity of nitrate leaching reflects a large number of site-specific factors and the amount of data available is relatively small, the following tentative conclusions can be made:

- Although atmospheric nitrogen fluxes to SRC are likely to be smaller than to a mature deciduous woodland, nitrogen inputs are likely to be substantial and so use of nitrogen fertilisers for SRC may not be required.

- In the wetter parts of Britain, the average concentration of nitrate draining from beneath established SRC plantations with minimal or no fertiliser inputs is likely to be less than 3 mg l^{-1} NO_3-N and quite possibly less than 1 mg l^{-1} NO_3-N.

- In the drier, south eastern part of Britain, the nitrate concentration in the drainage water is critically dependent on the effective rainfall. The effective rainfall is likely to be less than 150 mm a^{-1} and so even low rates of nitrate leaching could give rise to nitrate concentrations close to or exceeding the 11.3 mg l^{-1} NO_3-N limit for drinking water.

- Where there is a legacy of nitrate or mineralizable nitrogen from the previous land use, a newly established SRC plantation does not appear to be able to reduce the nitrate leaching to low levels in the first few years.

- Sewage sludge applications at rates within the current Codes of Practice give rise to a measurable increase in nitrate leaching but the effect from single applications appears to be short-lived and the amount of nitrate leaching could well be less than from land under intensive agriculture. The maximum annual amount of water applied during the application of sludge is likely to be of the order of 10-20 mm.

RECOMMENDATIONS

- Unless it is part of a sewage recycling scheme, extensive plantation of SRC should be in the wetter parts of the country where the high water consumption of the SRC will not have potentially serious consequences for the water resources. In these areas, and where the radiation is not limiting, the plentiful rain should produce high yields. In the drier parts of the country, only a small proportion of a catchment should be planted.

- Recharge and runoff is increased by using a shorter rotation period. The practice of staggering the harvest times would therefore be hydrologically beneficial.

- If large areas are to be planted then the evaporation will be reduced if plantations are in a few large blocks rather than many small blocks.

- Measurements on the growth and water use of SRC in the driest parts of the country should be made to allow the SIMWUCOP model to be calibrated for less vigorous coppice. Water use models could be incorporated into a GIS to produce maps of reduction in drainage. It would also be possible using information on the WUE to produce maps giving the potential biomass yield.

- Growers of SRC should be encouraged not to use nitrogen fertilisers unless the indications are that they definitely increase yield, and even then, only modest rates of fertiliser should be applied.

- If sewage sludge applications to SRC are to be widely used, a 'dose-response' relationship between the rate of sewage sludge application and the amount of nitrate leaching needs to be established at a few key sites. This will require continuous monitoring for at least two years after the last sludge application.

- Where there is less than 100 mm a^{-1} of effective precipitation, the concentration of nitrate in the drainage (recharge) water becomes very sensitive to the actual amount of drainage and even quite small rates of nitrate leaching (in terms of kg N ha^{-1} a^{-1}) can lead to high concentrations of nitrate in the drainage water. Therefore the concentrations of nitrate in the drainage water from well established (5 years or more old) SRC sites in the drier parts of eastern England need to be monitored closely. The long term rate of recharge should be estimated independently from physical measurements or by using the chloride mass balance approach.

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PROJECT OBJECTIVES

This report describes the work carried out between March 1993 and March 1996 under ETSU Contract number B/W5/00275/00/00 by the NERC Institute of Hydrology and British Geological Survey.

The original general objective of the project was to determine the impact on water resources of short rotation coppice (SRC) by understanding the mechanisms controlling its water use and by quantifying the effect of such coppice on the quality of groundwater. To achieve this required the following specific objectives viz:

- the determination of the total water use (trees and understorey) through monitoring changes in the soil water content;

- the determination of the transpiration rate of different clones as a function of the prevailing weather, soil water status and age into a rotation, for two periods of rotation;

- the determination of the parameters that control the magnitude of interception loss;

- an assessment of the extent of lateral rooting;

- a determination of the effects on soil water quality.

To extend the relevance of the measurements to other plantations in the UK the results of this study were to be incorporated into models which when supplied with a few readily available or measurable inputs, e.g. daily rainfall, (and possibly some other weather data) state of rotation and species and/or clone, will make it possible to extrapolate the findings of the study to other plantations.

Following Amendment 1 to the contract the following additional objectives were included:

- determine the transpiration rates from SRC in water-stressed conditions;

- make a qualitative assessment of the origin of water used by coppice, whether shallow soil or deep soil/groundwater.

1. INTRODUCTION

The production of energy by burning biomass, either directly or through gasification, is one of the most promising of the alternative sustainable energy sources, and is now being implemented on a commercial basis in some European countries including Britain. In northern Europe the tree species under consideration for this purpose include willow (*Salix sp.*) and poplar (*Populus sp.*) grown as Short Rotation Coppice (SRC). Considerable work has been done with *Salix* in Scandinavia, notably Sweden, on species and clonal selection, silviculture, harvesting, environmental impacts etc where there are now approximately 9000 ha planted. In Britain three biomass gasification projects were awarded contracts in NFFO3 (third round of the Non-Fossil Fuel Obligation). This could lead to approximately 6000 ha of SRC being planted over the next three years. At present both poplar and willow are likely to be planted for SRC. If economic and marketing difficulties can be overcome then over the next decade there is likely to be an increase in the amount of SRC as a result of the coincidence of several factors: the need to reduce the surplus of food-producing land within the EU; the ever increasing demand for energy, together with the environmental benefits of renewable energy sources; the availability of grants for planting set aside land for forestry.

Because the burning of biomass does not result in a net increase in atmospheric greenhouse gases SRC has the potential to be an environmentally benign source of renewable energy. There are other environmental benefits including: low chemical management, the provision of habitats for a wide range of fauna and flora and the possibility of using it for the disposal of sewage sludge and farm slurry. Although from these perspectives SRC provides an environmentally beneficial source of renewable energy the hydrological consequences of increased coppice plantation are as yet unclear. It is possible that SRC may be detrimental to water resources through increased evaporative demand. If biomass conversion is to make a significant contribution to the national energy supply then large areas will need to be planted around purpose-built power stations. And if the water consumption of willow and poplar coppice proves to be as great as expected then there could be reduced aquifer recharge and river flows.

The high population density and small difference between the precipitation and the evaporation, i.e. low effective precipitation, make southern England particularly sensitive to any reduction in groundwater recharge or river flow. Figure 1.1 shows a map of effective precipitation across Great Britain based on estimates of the evaporation from grass on a soil of medium water availability (see Section 1.1). Groundwater currently provides about one third of the public water supply for England and in some regions of southern England is the sole source of supply. Recent dry winters have led to below-average groundwater recharge, the drying up of spring-fed streams, widespread summer hose pipe bans, drought orders and other restrictions which have highlighted the seriousness of any reduction in groundwater supplies.

However, SRC may benefit groundwater quality by reducing nitrate leaching. Pollution of surface and groundwaters from fertilizers, pesticides, and various forms of domestic and industrial waste has required the designation of Nitrate Sensitive Areas (NSAs) around existing public supply boreholes in sensitive catchments such as the chalk. It is intended that by following low-N input strategies within NSAs the amount of nitrate leaching will be reduced. It is probable that plantation of SRC would be an acceptable option for these sensitive areas.

Clearly it is important that the hydrological impacts of SRC, both in terms of quantity and quality, are investigated for the wise planning of future plantation.

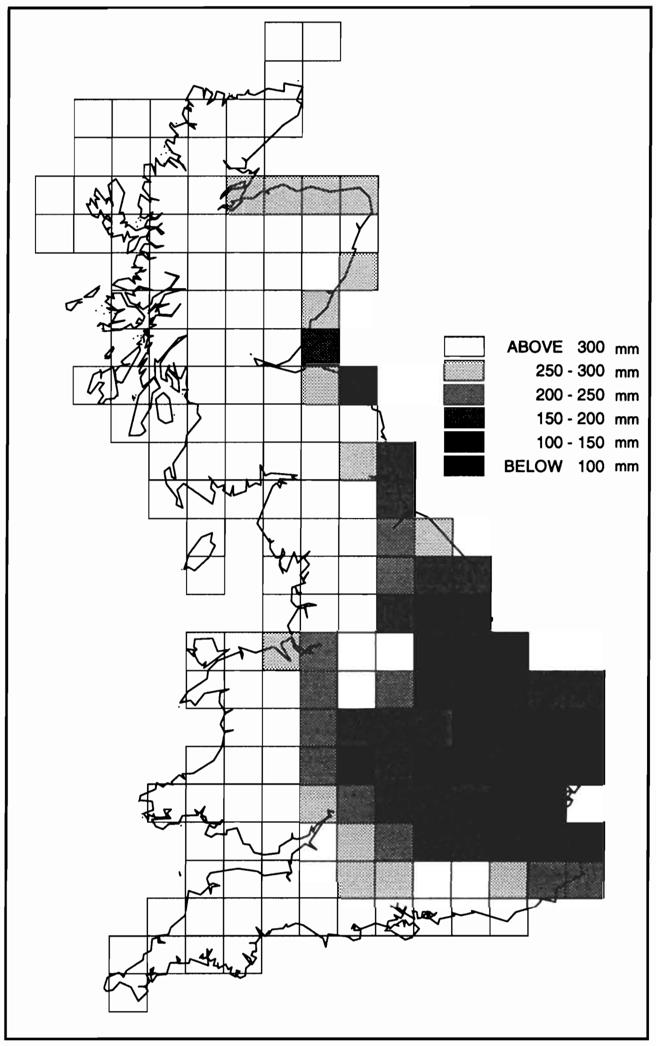


Fig. 1.1 The effective precipitation for Great Britain. Effective precipitation is defined here as the difference between the rainfall and the calculated actual evaporation from grass growing on a soil of medium water availability. This map is based upon data from MORECS. Information about MORECS may be obtained from the Met. Office, RG12 2SY.

The main objectives of this project were realised. However, this project, as with most, devoloped with time and some of the original objectives became unattainable, or partly attainable, or were seen to be of less relevance. The limitations on the original objectives arose from the shortcomings of the Swanbourne site. Firstly, the planting scheme of monoclonal rows resulted in clonal differences in water use being confounded by the effects of interclonal competition. Secondly the presence of a perched water table at the site reduced the usefulness of soil water measurements because it prevented them from being used to estimate reliably the water use of the plantation. However, other methods were used at Swanbourne that provided some useful information on the water use of coppice, and an alternative site at Hunstrete, Avon provided the opportunity to make measurements at a site where significant soil water deficits could develop. Finally because the coppice was harvested at Swanbourne sooner than originally proposed there was no opportunity to make measurements on shoots older than three years.

1.1 WATER USE

Trees have a large effect on the hydrological cycle. In a review of 92 catchment experiments worldwide Bosch and Hewlett (1982) showed an average reduction of water yield of approximately 40 mm a^{-1} for every 10% of a catchment under mature conifer forest: the equivalent figure for deciduous broadleaves is 25 mm a^{-1}.

In the uplands of the UK studies by the Institute of Hydrology (Calder and Newson, 1979) have shown that coniferous plantations evaporate about twice as much water as adjacent grassland areas resulting in reduced stream flow. Although the magnitude of the water use of trees is smaller in the drier lowland areas of the UK, the water resources (groundwater recharge and river flow) in these regions are very sensitive to small changes in water use because of the water evaporated by the vegetation annually almost equals the annual rainfall. Figure 1.1 shows that for large areas of southern England the rainfall excess is less than 100 mm.

The water use of any vegetation consists of two components: the *interception* loss, that precipitation intercepted by the vegetation and evaporated directly from live or dead plant surfaces (including the litter layer); and the *transpiration* loss, that water which is transferred from the soil through the live plant (roots, stem(s) and leaves) to the atmosphere. *Evaporative* loss is used here to refer to the total transfer of water vapour through these two routes. It represents that water which is returned to the atmosphere through the presence of plants and is therefore unavailable for runoff to lakes and rivers or drainage to groundwater.

Interception loss is dependent upon the climate, primarily the rainfall regime and evaporative demand during rainfall, and the extent and structure of the plant canopy, which determines its water holding capacity and its aerodynamic roughness. This roughness determines the efficiency of the exchange of water vapour from the wet plant surfaces to the atmosphere. In principle interception loss is easily measured as the difference between the rain falling on a canopy and the net rainfall reaching the soil. In practice uncertainties can arise due to spatial and temporal variability in both the gross and net rainfall. These difficulties are discussed further in Section 3.2.2.6.

Transpiration loss is controlled primarily by plant physiological responses to environmental factors e.g. solar radiation, atmospheric humidity deficit, temperature, soil moisture status etc. and is also governed by tree age, species and canopy structure. Pores, or *stomata*, in the leaves open and close, thereby controlling the flow of water vapour through them and thus regulating the transpiration rate. The stomata are not very sensitive to the changes in radiation and temperature typical of a British summer's day. However in many tree species the stomata are sensitive to changes in atmospheric humidity and to changes in the soil water content. The stomata close as the atmosphere or the soil become drier: the atmospheric humidity deficit and soil water deficit increase. This behaviour has been observed in a wide range of deciduous and coniferous forests in both temperate and tropical regions (Losch and Tenhunen, 1981) and it provides a mechanism by which the tree can limit its transpiration when the atmospheric demand is high thereby minimising excessive and potentially damaging desiccation. The effect of such feedback mechanisms is to reduce the variability of the annual transpiration totals of conventional forests across the whole of northern Europe (Roberts, 1983).

For broadleaved trees growing in much of the UK, where the rainfall is less than say 1500 mm, transpiration is the major component of the water use and its accurate estimation is important. The transpiration from a stand of trees (or any vegetation) can be determined in a number of ways but usually involves (one of more) of the following methodologies:

(i) measuring any reduction in the water content of the soil;

(ii) measuring any increase in the water vapour content of the atmosphere which both surrounds and is above the vegetation;

(iii) direct measurement of the movement of water through a representative sample of tree trunks;

(iv) the measurement of the loss of water vapour from both a sufficient number and sufficiently well distributed range of leaf samples within the canopy.

To provide a measure of cross checking all of these methods except for (ii) were used in this study to determine the transpiration rate from SRC. They are described in Section 3.

The rate at which water evaporates from vegetation can be estimated by a range of different formulae which contain terms that are functions of the energy available for evaporation, atmospheric humidity and windspeed. One of the most widely used of these is the Penman (1948) estimate of potential evaporation, designated E_T, and referred to throughout this report. It gives a good estimate of evaporation from short vegetation adequately supplied with water but can also be used as an general index of the evaporative demand. Daily values are often calculated using means and totals of either 24 hour or daylight hours weather data. Another index sometimes referred to is the Penman open-water evaporation, E_o which is about $1.33E_T$. The Penman formula is a special case of the more general physically-based Penman-Monteith (1965) equation that can be used to estimate the evaporation rate from any vegetation provided certain vegetation surface parameters are known. This is discussed further in Section 3.3.1.

1.2 WATER QUALITY AND SRC

SRC could have a significant long-term impact on water quality both directly and indirectly. The quality (chemistry) of surface and groundwaters depends on many factors including:

- the chemistry of the rainfall and other atmospheric inputs
- the weathering of minerals in soils and rocks
- inputs derived from diffuse agricultural sources (fertilisers or enhanced mineralization)
- man-made inputs from point sources such as individual factories or more generally from urban areas
- the amount of rainfall and evaporation

Surface waters are in general more susceptible to change than groundwaters. This applies to their potential for pollution as well as for clean-up. Whether a SRC plantation primarily affects surface waters or groundwater will depend on the underlying soils and geology. In areas overlying unconfined aquifers, the groundwater will be mostly affected whereas in areas underlain by relatively impermeable strata, the surface waters will be most affected. Below we discuss the nature of groundwater recharge and the possible impact of SRC on groundwaters. Broadly similar arguments apply to surface waters.

Groundwater recharge only occurs in the wetter winter months when the soil is close to field capacity, and so a critical factor is the concentration of solutes remaining in the soil and soil solution at this time. This is why autumn and winter applications of nitrogenous fertilisers and organic manures are not recommended in nitrate sensitive areas.

The amount of groundwater recharge is important since it determines the extent of dilution of any pollution as it makes its way to the water table. In the UK, the excess rainfall, i.e. the amount of rainfall minus the amount of evaporation, varies from less than 100 mm a^{-1} in the south east of England to more than 700 mm a^{-1} in the colder, wetter parts. This excess rainfall either drains into local surface water courses and then out to the sea, or in areas with permeable soils which are underlain by an aquifer, it passes through the unsaturated zone to the aquifer. Ultimately this groundwater will reappear at a discharge point such as a spring or river, or may be extracted by a pumping borehole.

The depth of the water table below the ground surface can vary from a few metres in low lying areas to 50 m or more on the top of hills. The area between the base of the soil and the water table is called the unsaturated zone. The rate of downward water movement through the unsaturated zone varies from about 0.5 m a^{-1} or less in the drier parts of the country to 2 m a^{-1} or more in the wetter parts. It can therefore take a decade or more before water infiltrating through the soil finally reaches the water table. This delay means that it will be many years before the effects of any changes in inputs at the surface are reflected by changes in the quality of groundwater pumped from nearby groundwater boreholes.

The three main aquifers in the UK are (in order of decreasing importance): the Chalk, the Sherwood (Permo-Triassic) Sandstone, and the Carboniferous Limestone. There are also a number of other minor aquifers, mostly on limestone or sandstone strata, or in alluvium. In the remaining areas, which are often underlain by clays and other low permeability strata, the excess rainfall tends to infiltrate the soil and then move through the subsoil (or drain) downhill to a stream. The chemistry of surface waters is therefore likely to respond to changes in land use more rapidly than that of deeper groundwaters.

2. REVIEW OF PREVIOUS WORK

2.1 WATER USE

An extensive literature exists on the water use of conifers and detailed work has been done on the processes controlling the water use. In the UK the water use of coniferous plantations ranges from about 600 mm a year in the east, where transpiration loss is the major component to about 1200 mm a year in the upland areas of western Britain where interception loss dominates.

There has been much less work on the water use of broadleaf trees. Hall and Roberts (1990) reviewing European studies concluded that annual totals of transpiration loss from broadleaf woodland were not available for the UK although there had been several studies in other parts of Europe. Data from these studies are characterised by annual transpiration totals substantially less than the potential transpiration for the site locations. However transpiration totals for mature stands of several common European species including poplar and willow were unavailable. Since that review a major study (Harding et al., 1992) examined the hydrological impacts of ash and beech in Hampshire, on chalk soils and Northamptonshire on clay. Average annual transpiration loss was estimated from plant physiological measurements and verified using soil moisture measurements for both beech and ash. On chalk the transpiration of ash exceeded that from beech (372 mm and 355 mm respectively) while the average annual transpiration of ash on clay for the same years was 327 mm (Harding et al., 1992; Roberts and Rosier, 1994). These annual values are in agreement with the values for deciduous trees listed in Hall and Roberts (1990). The total water use for beech and ash plantation on chalk and clay formations in southern England was found to be less than for grass.

There have been no studies of water use by SRC in the United Kingdom and so any guidance on the possible water use must come from foreign experience. Two very recent publications by Persson (1995), and Persson and Lindroth (1994) reporting the water use of SRC in Sweden are of most relevance to this study. Persson (1995) investigated seven plantations over a period of five years and carried out a modelling study. The plantations were on different soils and included irrigated and unirrigated coppice of differing age, species and productivity. The species were mainly of willow but also included grey alder (*Alnus incana*) and white birch (*Betula pubescens*). At one site half a raised peat bog was drained and planted to willow which was then sprinkler irrigated. Not surprisingly, comparison of the water table levels revealed that they were deeper in the planted area and that between June and September increased evaporaton was 70 mm. Persson used a detailed soil water model, described more fully by Persson and Jansson (1989), to estimate the evaporation for irrigated willow SRC on a heavy clay soil as between 370 and 420 mm for June to September inclusive. A simulation for unirrigated willow indicated a reduction in transpiration of about 100 mm.

Detailed micrometeorological measurements have also been made. Lindroth (1993) measured the aerodynamic and canopy resistances of willow as a function of leaf area making possible the estimation of evaporation rates from willow using physically-based equations and thereby providing the basis for models of willow coppice water use.

In a later study using the same site Persson and Lindroth (1994) found good agreement between simulated and measured evaporation rates. They give the highest simulated four-year mean monthly evaporation rates averaging 4.4 mm day^{-1} in July and lowest of 0.8 mm day^{-1} in October. Maximum simulated rates were 8-9 mm day^{-1} and the total evaporation ranged from 416 mm to 584 mm over the period May to October inclusive. According to Persson and Lindroth (1994) these figures are higher than values reported for coniferous forest in Sweden Cienciala et al. (1992). Persson and Lindroth (1994) concluded that the water use of willow SRC amply supplied with water exceeds that from traditional agricultural crops and coniferous forests in Sweden. However the SRC plantation was in an area where it was necessary to irrigate to ensure that there was no water limitation to transpiration and growth. In an area where the rainfall was high enough to ensure ample water supply it is likely that the high interception loss from coniferous forest would result in it having a higher water use than the SRC. When Persson (1995) used the same model on six years of variable climatic data to compare the water use of unirrigated SRC, coniferous forest, barley and grass ley she found that for the period April to October inclusive, coniferous forest used 516 mm, followed by willow (497 mm), grass ley (419) and barley (347 mm). The difference between the crops was most pronounced in those years when the precipitation was greatest, indicative of the effects of increased interception loss and the reduction in transpiration, due to soil water deficits, in the drier years. The results from all of the sites studied by Persson indicated that the evaporation from willow exceeds the Penman (1948) potential evaporation when the seasonal (May to October) rainfall exceeds 470 mm. Finnish results support these findings and indicate that when there is no limitation of water supply the rates can be extremely high. Ettala (1988) used plant physiological methods to measure the annual evaporation from unirrigated willow in Finland as 480 mm and 920 mm for irrigated willow.

Various techniques have been used to measure water use from SRC and Lindroth et al. (1995) described measurements made on willow coppice using a tissue heat balance technique (Section 3.1.2.3) that gave evaporation estimates in good agreement with measurements using micrometeorological methods. They showed that the sap flow lagged behind the evaporation rate during the mornings due to a reservoir of water available for transpiration within the trees. The maximimum flow rate was 2 kg day^{-1} for a 30 mm diameter stem. They did not scale this to a transpiration rate on a ground area basis; they judged their data too limited.

Transpiration at night from willow coppice was also measured at the same site by Iritz and Lindroth (1994). Although generally very small, on particular dry and windy nights during September and October, it amounted to 30-35% of the daytime evaporation.

Grip et al. (1984) modelled the evaporation from a mixed stand on wetland (*Salix,* 50%; *Betula,* 25%; *Alnus*, 25%) using estimated canopy parameters. They obtained values of 135 mm, 176 mm and 26 mm for the modelled transpiration, bare soil evaporation and interception loss respectively during the growing season. They commented that the interception loss appeared low when compared to the simulated interception loss for July and August and to a 21% interception loss in July and August reported by Grip (1981). Eckersten (1986) developed a model of growth and water use using synoptic weather data which compared favourably with a model using higher time resolution data. Grip et al. (1989) in a paper analysing Grip's (1981) lysimeter measurements of intensively cultivated willow (*Salix* *viminalis* and *Salix viminalis* × *caprea*) growing in a sandy loam stated that:

> "The few reports available seem to support the idea that evaporation is higher from willow than from most other vegetation covers. One reason for this is that willow is a highly hydrophillic plant that requires much transpiration for its biomass production. The large leaf area of a high producing energy forest also favours both transpiration and interception evaporation."

They also referred to other Swedish studies reporting evaporation rates exceeding the Penman (1948) E_T rate by 10% to 25%. Their own analysis supports these other studies in that the water use over the growing season from both measurements and model simulations was 526 mm compared to a Penman open water evaporation of 430 mm. They found that the largest excess over the potential rate occurred just after the maximum canopy cover and was 1.5 mm day^{-1}. Interception loss was ~14% of the precipitation plus irrigation over the growing season.

There is a little information available for the interception loss from willow. But what there is appears to some extent contradictory. Grip et al. (1989) quote Andersson (1986) as reporting interception loss from willow as increasing from 14% to 38% of the rainfall during the growing season whereas Halldin (1989) refers to the Grip (1981) as presenting interception loss as decreasing from 36% to 11% during the growing season. Ettala (1988) measured the interception loss from willow that was sprinkler-irrigated with leachate as 31% of the sum of precipitation and irrigation. Larsson (1981) showed that the specific canopy storage for *S. viminalis* is 0.2 mm m^{-2} leaf area; slightly less than the 0.27 mm m^{-2} found for beech and ash by Harding et al. (1992). Most recently Persson and Lindroth (1994) measured the interception loss from 44 rain events during the period 22 June to 22 October 1985 using troughs to collect the through fall and funnels to collect the stem flow. They also simulated the interception loss but were unable to make direct comparisons between the two. However the simulated values, which ranged from 5% to 23% on a monthly basis were generally higher than the measured values.

As with willows there were no reports on the water use of relevant poplar clones growing in the field until very recently. But this has changed with the detailed study by Hinckley et al. (1994) on a four-year-old stand of *P. trichocarpa* x *deltoides* that yielded a maximum stand transpiration rate of 4.8 mm day^{-1}. Although this study provides useful detailed information on the fluxes of water through whole trees, branches and leaves, measurements were carried out over a short time period and no modelling performed: consequently no seasonal or annual water use figure was given. However their figure for maximum stand transpiration rate is in agreement with the value for the water use found by Hansen (1988) of 4.4 to 4.8 mm day^{-1} during the second to fifth growing seasons from irrigated poplar coppice, in what appears to be the only previously published study on the water use of poplar coppice. His study site was in northern Wisconsin, USA, in a temperate climate with 770 mm annual rainfall, similar to the climate of southern England.

There have been many North American and Belgian physiological studies using potted plants in controlled glasshouse environments including *P. trichocarpa* and *P. deltoides* and their hybrids. Several papers describe very useful and relevant studies of the water relations and plant physiological responses of *Populus* clones to variations in soil water content.

Schulte et al. (1987) measured the maximum stomatal conductances for one leaf surface for *P. deltoides* and *P. trichocarpa* as ranging between from 200 to 300 mmol m^{-2} s^{-1}. However stomata can occur on both leaf surfaces for poplar and the maximum conductance could be ≈ 60% greater implying high transpiration rates. However Morrison (1987) pointed out that species having initially high stomatal conductance often have greater response to environmental factors which may offset the initially higher values. This however does not appear to apply to *trichocarpa.*

As early as 1978 Ceulemans et al (1978) reported a variation in the stomatal regulation of transpiration by four different clones in response to water stress with *trichocarpa* the least effective. Since that time there have been several studies examining this aspect of the plant physiology of *Populus* clones. Schulte et al (1987), referred to above, working on excised leaves of *P. trichocarpa*, *P. deltoides* and hybrids stated that

"...unlike the other species *P. trichocarpa* not acclimated to water stress showed an inability to control water loss at low leaf water potential".

They suggested that stomata of *P. trichocarpa* grown under well-watered conditions would remain open even when the leaves became wilted. However they qualify this by stating that periods of water stress in the field result in a increase of the stomatal response of *P. trichocarpa* to these conditions. Their work was supported by that of Braatne et al (1992) who investigated the effects of soil drying on leaf growth, transpiration and the whole-plant water balance in *P. trichocarpa*, *P. deltoides* and their F1 hybrids. Stomatal closure did not commence until the soil water content had declined by more than 40% from a well-watered condition and occurred first in the hybrids and last in *P. trichocarpa.* Once the reduction in transpiration rate had begun the reduction was greatest with increasing soil water deficit in the parent species. They suggest that the F1 hybrids are more drought tolerant then either *P. trichocarpa* or *P. deltoides.* The variation of stomatal density, size, conductance and response of different poplar clones and hybrids have been the subject of several papers by Ceulemans and colleagues (Ceulemans et al., 1984; Ceulemans and Impens, 1981; Ceulemans et al., 1988; Ceulemans et al., 1989) and Reich (1984).

The influence of the rate of declining water tables on transpiration and growth of *P. balsamifera* × *deltoides* was investigated by Mahoney and Rood (1992) who concluded that water table decline promoted root elongation but that rapid water table decline caused drought stress in poplar and was more severe in plants growing in coarse substrates.

Aspects of productivity and water use efficiency (WUE) have been the subjects of several studies. The WUE in a range of 17 clones, according to Blake et al (1984), varies between poplar genotypes with a higher abaxial stomatal resistance being associated with reduced transpiration rates in water efficient clones whereas clones of low WUE exhibit less stomatal control of transpiration. The effects of both droughting and flooding on transpiration, growth and water relations of two hybrid clones *P.* × *euramericana* Tristis, "Eugenie" and *P. tristis* × *P. balsamifera*, "Tristis" were the subjects of studies by Dickmann et al (1992) and Liu and Dickmann (1993). Although in drought conditions WUE was very low and photosynthesis was reduced more in Eugenie it produced two to three times as much biomass than Tristis.

Auclair and Bouvarel (1992) examined the influence of rotation and spacing on the growth of *P. trichocarpa* and *P. deltoides* coppice and noted that productivity was greatest per unit plot area for the highest planting densities (2.10^4 ha^{-1}) and that height growth was greatly influenced by climatic variability, principally rainfall.

Van Slycken and Vereecken (1990) used a water balance model to relate yield to water availability in an attempt to understand the variability in growth at a 2 ha poplar (species unspecified) plantation in Belgium. The model was used to predict water supply through capillary rise from the groundwater table They compared model predictions of soil moisture profiles with measurements at three sites with partial success but obtained good correlations between yield levels and the water supply through capillary rise. They concluded that there was a need for more research into clone-specific water use.

There has been considerable work on the water use of willows in Sweden but much of this was on irrigated sites. Many of the cited studies of poplar have used potted plants grown in controlled glasshouse environments. The consequences of clonal responses to multiple environmental factors operating in the field have hardly been examined and the results of the studies can only be extrapolated with a large degree of uncertainty to mature stools with established root systems growing in the different soils and climate of the UK. And to be able to make useful predictions on the hydrological effects of coppice plantation seasonal estimates of coppice water use are needed. There are none in the literature for poplar and no reports of poplar interception loss. The measurement programme we undertook provides this information.

2.2 WATER QUALITY

The potential impacts of SRC on groundwater quality can be divided into those due to the growth of the SRC itself and those which reflect the particular type of management of the SRC. Any increase in evaporation brought about by the SRC crop will have a concentrative effect on all solutes in the soil water but the consequences of this are likely to be insignificant compared with consequences of the increased loss of water.

The key factors controlling the extent of leaching are the overall balance between nutrient inputs and outputs, and the timing of these inputs and outputs in relation to the movement of water.

2.2.1 Nutrient balances, fertilisers and leaching

In general the nutrient requirement of SRC is much lower (perhaps five times lower) than for arable crops.

The annual cycle of growth and decay in deciduous trees in temperate climates leads to the uptake of nutrients from the soil and atmosphere during the growing season, and their incorporation into leaves, woody tissue and roots. Good nutrition requires the availability of a sufficient quantity of the critical nutrients, namely N, P, K, Mg and Ca and some trace elements during the growing period. Mineral nutrition also affects the efficiency with which a plant can convert sunlight into growth. A high level of dry matter production will generally require a high level of nutrients. Good mineral nutrition can also enable the plant to be less susceptible to frost damage and so enable the plant to grow over a longer season, and hence give a greater yield. Although fertilisers have given a positive response in SRC trials in Sweden and the USA, the results of fertiliser trials in the UK are still inconclusive (Mitchell et al., 1995).

Any nutrients remaining in the soil water after it has passed the root zone have the possibility of eventually reaching surface waters or groundwater. The amount that does depends on many factors depending on the amount of attenuation within the subsoil or aquifer. Denitrification below the root zone could be important, for example.

The nutrient of most concern in terms of groundwater quality is nitrogen principally in the form of the nitrate (McLauglin et al., 1985). The other nutrients are either not of concern or are normally sufficiently strongly bound to the soil or aquifer not to present a problem. Phosphate leaching is sometimes of concern in surface waters but is rarely a problem in groundwaters.

Nitrate concentrations in soil water vary greatly both in time and space but are also strongly dependent on land use, management (including fertiliser history) and climatic factors. In wet climates, nitrate concentrations in drainage waters tend to be lower than in drier climates but the total flux of N leached could be similar. Nitrogen cycling in relatively undisturbed ecosystems such as moorland and permanent grassland tends to be efficient and so such ecosystems tend to lose only small amounts of nitrate. The ability of forests to scavenge aerosols and gases from the air is such that atmospheric nitrogen inputs into many European forests may currently exceed their annual requirements for growth (see Nitrogen saturation in forests, Section 2.1.2.2). There have been no studies of the extent of atmospheric N inputs to SRC.

While modern arable farming tends to lead to a slow reduction in soil organic matter content and a breakdown in nutrient cycling, afforestation tends to lead to the slow accumulation of soil organic matter. Therefore it is reasonable to expect that nutrient leaching under most forms of modern agriculture will be considerably greater than under afforestation including SRC.

SRC can be seen as being half way between arable agriculture and traditional forestry since although harvesting normally takes place after leaf fall, and so should ensure the cycling of nutrients from the leaves, there is a regular offtake of nutrients in the cut wood. Annual leaf fall in a closely-spaced crop is about 4-6 tonne DM ha^{-1} a^{-1} (Ericsson et al., 1992) and willow leaves (Bowles Hybrid) have a N content of between 2.0%-3.5% N at senescence (Tabbush, 1993; Mitchell et al., 1995). Therefore fluxes of N in leaf fall are of the order of 80-200 kg N ha^{-1} a^{-1}. At Swanbourne, Buckinghamshire, willow had a slightly higher N content than poplar (Beaupré) (Mitchell et al., 1995).

The N content of leaves tends to decline during the growing season and increases with height up the stem. The offtake of N in the stems is in the range 30-105 kg N ha^{-1} a^{-1} depending on crop yield and the N content of the stems (Table 2.1). The offtakes of P and K are considerably less. Foliar analyses from eight SRC trial sites across the UK have shown that the macronutrient (N, P, K, Ca, Mg) content was above the critical level required for growth,

Table 2.1. Average annual offtake of nutrients in SRC plantation material

Crop	Cutting cycle/age	Biomass production	N	P	K	Reference
		t DM ha^{-1} a^{-1}	kg N ha^{-1} a^{-1}			
Poplar, harvested material, UK	2 years	11	70	10	35	Tabbush (1993)
Poplar, above ground boles and branches	4 years	9	54	8	22	after Heilman (1992)
Poplar, above ground boles and branches	4 years	11-28	60-105	10-26	-	after Heilman (1992)
Poplar, stems	5-7 years	(10)[†]	33	-	-	after Ericsson et al. (1992)
Willow, stems	1 year 2 years	(10) (10)	40 30	-	-	after Ericsson et al. (1992)

[†] Rates of Biomass Production in parentheses are nominal figures

and often above the optimum level (Mitchell et al., 1995). Phosphorus was the nutrient that was closest to the critical minimum level.

The leaves of poplar and willow contain about 3.0-3.5% N, i.e. about ten times as much in the stems on a unit weight basis. In an established crop of poplar or willow, about 60% of the total above ground N is in the leaves at the time of their senescence (Ericsson et al., 1992). This is then recycled through the soil. The leaves of poplar and willow decompose quite readily releasing as much as 30% of their N in the first year. Therefore the picture is of relatively large fluxes of N passing through the trees on an annual basis. However, this needs to be put in perspective - arable soils contain approximately 3000-6000 kg N ha^{-1}; forest soils contain twice these quantities.

2.2.2 Atmospheric inputs

2.2.2.1 *Acidification*

Soil acidification is a natural process in wet climates and it is well known that trees can increase the deposition of acidic and acid-generating chemicals from the atmosphere through their ability to scavenge particles and gases. This is a cause for concern in areas susceptible to acidification since the increased deposition of acidic or acid-generating substances can eventually lead to enhanced soil acidification and ultimately to surface and groundwater acidification. This acidification is slow and cumulative, usually taking more than a decade to be noticeable.

Most attention has been paid to acidification in coniferous areas in the uplands where surface waters may be affected but extremely acidic conditions are also found in some forested areas in Southern Britain. In general, surface waters are considerably more susceptible than groundwaters because the contact time of surface waters with the soil or rock is relatively short and because the most reactive base-rich minerals have often been removed from the surface layers of soil.

Many of the most acid-susceptible areas are already forested or protected upland or heath and so new SRC plantings are likely to be on farmland which has previously been limed to a pH of 5.5 or above. Many once acid soils are no longer acid, and although the use of fertilisers can have a strong acidifying effect, modern farming practice counters this by the regular application of lime. Therefore while SRC could in principle accelerate the natural acidification processes (compared with unfertilised grassland), lime could be applied periodically after harvest to correct for any such influence. Since trees are more tolerant of acidity than agricultural crops, it is likely that any adverse effects of acidification will be first seen in the poor nutritional status of the crop, especially of Mg and Ca, rather than in the drainage water quality. Therefore good plantation management should ensure near-neutral drainage water quality.

2.2.2.2 *Nitrogen inputs and nitrogen saturation in forests*

The high concentrations of N-containing compounds in the atmosphere, principally ammonia and ammonium salts derived from animal manures and NO_x's derived from motor vehicles, are also efficiently scavenged by forests and can lead to significant inputs of N. For forests in the south east of England, these inputs are typically 30-50 kg N ha^{-1} a^{-1} dry deposition of NH_3, another 5 kg N ha^{-1} a^{-1} of gaseous NO_2, and 10 kg N ha^{-1} a^{-1} of wet deposition comprising NO_3-N and NH_4^+ (INDITE, 1994). Therefore a total deposition of 45-65 kg N ha^{-1} a^{-1} to forests in lowland Britain is probably a reasonable estimate. Although this may be a net benefit to farmland, the amounts received by forests can exceed the demands of tree growth in mature and slowly growing forests. This has led to concern that some forests in Europe are becoming N-saturated (INDITE, 1994). Nitrogen deposited in excess of vegetation needs tends to be lost by leaching (Johnson, 1992).

Once a forest becomes N-saturated, it cannot retain the deposited N and so nitrate leaching increases sharply. Clearings within mature forests are particularly 'leaky' patches (Kinniburgh and Trafford, 1996).

The above estimates for atmospheric N inputs to forests compare with estimates of 30-45 kg N ha^{-1} a^{-1} for the total atmospheric N deposition to fallow soil and arable land at Rothamsted. It is probably reasonable to assume that atmospheric inputs of nitrogen to SRC crops lies somewhere between that for arable land and that for a long-standing forest, i.e. somewhere in the range 30-65 kg N ha^{-1} a^{-1}. In the absence of any other information, 50 kg N ha^{-1} a^{-1} is probably a reasonable estimate. Typical fertiliser inputs to arable crops are of the order of 100-250 kg N ha^{-1} a^{-1}.

2.2.3 Influence of the management of SRC

The particular way that a SRC plantation is managed can also have a significant impact on the quality of the water draining from it (Table 2.2). The most important of these management practices are discussed below.

2.2.3.1 *Fertiliser use*

One approach to nutrient management is to not fertilise until a noticeable reduction of growth is seen (Heilman, 1992). This conservative approach minimizes fertiliser use and nutrient leaching, and maximizes fertiliser use efficiency. It does not necessarily guarantee maximum yield or even maximum economic yield. This is the approach often adopted in traditional forestry.

An alternative strategy is to maintain fertility at a high level to ensure the optimum nutritional status of the crop (Ingestad and Ågren, 1988). This is likely to require high inputs of fertiliser with consequent loss of fertiliser use efficiency and increased nutrient leaching. This approach is often adopted in traditional agriculture where high value agricultural crops are grown. However, it is less likely to be widely adopted for SRC because the economic returns are relatively low and because SRC is seen as an 'environmentally friendly' crop.

In practice, the best strategy is likely to fall between these two approaches. Moderate inputs of N fertilisers do not necessarily lead to significant nitrate leaching. Bergström and Johansson (1992) found that nitrate-N and ammonium-N concentrations in groundwater beneath SRC willow in southern Sweden were less than 1 mg l^{-1} and concluded that under their conditions there was little risk to groundwater from SRC receiving up to 150 kg N ha^{-1} a^{-1} of inorganic fertiliser.

At present, it appears that applications of fertiliser have only a marginal return in the UK and so intensive applications are unlikely. It is also quite likely that the optimal nitrogen requirement of SRC may be met from a combination of residual N in the soil and from atmospheric inputs which are of the same order of magnitude as the offtake of N in stems. The residual soil N pool will be topped up by the annual return of N in leaf fall. Therefore it appears that fertiliser usage on SRC will be less than under most arable cropping systems. Maintenance applications of P, K, Ca and Mg would have no adverse effect on water quality.

Experience from overseas with high yielding poplars, principally in the USA (Heilman, 1992; Heilman and Fu-Guang, 1994), suggests that there can be a positive dry matter yield response to N fertilisation but that the response can vary from clone to clone and from year to year. Nitrogen use efficiencies varied significantly between clones: the three most productive clones produced more without added nitrogen than the three least productive did with added nitrogen (a total of 500 kg N ha^{-1} fertiliser over 3 years).

Generally poplars have shown little response in the first year or two, possibly because of

Table 2.2. Factors in the life cycle of a SRC plantation that might affect water quality

Growth phase	Potential impact on water quality
Establishment	Disturbance can lead to enhanced, short-term nitrate losses and greater runoff. Use of fertilizers and herbicides may lead to some contamination of surface and groundwaters through leaching and direct runoff. Impact likely to be reduced once a mature root structure has been established and canopy closure has occurred
Production	Impact depends on the balance between inputs and outputs in terms of atmospheric, soil and fertilizer inputs and outputs in terms of the crop offtake, immobilization, denitrification (for N) and leaching. Leaching likely to be greatest during 'fallow' period immediately after cutting
Clearance	Similar to establishment phase but there could be increased nitrate and base cation losses due to build-up of relatively high organic matter content and its subsequent mineralization. Depends on subsequent land use

limited root growth, and so fertilisers are usually not applied until at least the second or third years after establishment. Over-fertilisation when establishment is poor, eg. just after planting or just after harvesting, may lead to excessive weed growth and so is discouraged purely on production grounds.

Weed control. Reducing the competition from weeds is critical during the establishment phase of SRC. Mechanical cultivation is uneconomic and so herbicides may need to be used at the time of planting. Once well established, the canopy cover limits weed growth and so further herbicide applications are usually not required. Post-harvest applications may be necessary where weed growth has occurred.

The necessity of maintaining a weed-free area around each tree in the initial establishment phase will tend to encourage nitrate leaching. The early establishment of ground cover in farm forestry schemes was found to be an important factor in reducing nitrate leaching (Rushton, 1993).

Pesticides. In general, willow is more susceptible to pests and diseases than poplar. The leaf rust, *Melampsora spp.*, has been of particular concern for willow, including the 'Bowles hybrid' clone, and can lead to a significant reduction in productivity, and indirectly to greater weed growth. There are no reliable means of controlling these infections and the most likely approach is through the selective breeding of rust-tolerant clones rather than by using pesticides. Insecticides may be required for pest control in established plantations, e.g. for the brassy beetle *Phyllodecta spp.*, but the difficulties of spraying and economic factors will ensure that such inputs are likely to be low. Therefore over the long term pesticide inputs to SRC are likely to be much lower than under arable production.

2.2.4 The role of SRC in water quality management

2.2.4.1 *The groundwater nitrate problem*

At present the nutrient of most concern in terms of groundwater quality is nitrogen principally in the form of the nitrate. Relatively high nitrite concentrations are also quite common in some drinking water sources. The other plant nutrients are either not of environmental concern or are normally sufficiently strongly bound by the soil or aquifer not to be likely to be leached to the groundwater in significant quantities. The drinking water limit for nitrate in the UK is currently 50 mg NO_3 l^{-1} (equivalent to 11.3 mg NO_3-N l^{-1}). The nitrate concentrations in groundwater have been rising steadily in many parts of the UK for the last 20-30 years and in many cases are continuing to rise (despite recent cutbacks in N inputs).

By 1990, water from 192 public supply sources had exceeded the drinking water limit at some time. When the concentration in the source exceeds this limit, the water must either be blended with water with a lower nitrate concentration, treated or taken out of production. These options all have important economic implications. Clearly the greater the source of low nitrate groundwater that is available, the greater the options are for blending. The timescale between nitrate being input at the surface and its output at a pumping station varies with the type of aquifer and the depth of unsaturated zone but is of the order of 5-50 years. Hence a long term perspective is required. The average nitrate concentrations draining from various land uses varies considerably with land use (Table 2.3).

Concerns about nitrate leaching have led to the introduction of a number of EU and UK regulations and Codes of Practice controlling the application and timing of nitrogenous fertilisers and organic manures as well as considerable research into the nitrogen cycle (Addiscott et al., 1991; Powlson, 1993; Smith, 1996). These codes of practice aim to limit nitrate leaching to surface and groundwaters and so they focus on minimizing the application of nitrogenous fertilisers and organic manures in the most sensitive areas and at the most sensitive times. It is likely that these measures will have reduced, and will continue to reduce, nitrate leaching from farmland. Nevertheless, in the driest parts of the UK even modest nitrate losses can lead to groundwater 'exceeding' the 50 mg l^{-1} nitrate limit (Addiscott and Gold, 1994).

Regulations also exist specifically for the application of sewage sludge to farmland, namely the 'Sludge (Use in Agriculture) Regulations 1989' and the Collection and Disposal of Waste, 1988 (Smith, 1996). There is also a 'Code of Good Agricultural Practice for the Protection of Water' (MAFF, 1991) which is aimed primarily at ensuring the prevention of water pollution by normal agricultural operations but it also recommends that the maximum amount of N applied in sludge should not exceed 250 kg N ha^{-1} a^{-1}. These regulations and codes of practice are adhered to by the various water utilities responsible for the application of sewage sludge to land.

In areas designated as Nitrate Sensitive Areas (NSA's), farmers are encouraged to implement voluntary changes in agricultural practice in return for agreed payments. Nitrate Vulnerable Zones (NVZ's) are areas where the surface or groundwater already exceeds the 50 mg l^{-1} nitrate limit, or are likely to do so in the near future. The UK Government is obliged by EU legislation to develop action plans to reduce nitrate concentrations in these areas. It is proposed initially that a maximum of 210 kg N ha^{-1} a^{-1} should be applied as organic manures in NVZ's, and then only at non-sensitive times. Nitrogenous fertiliser use peaked between 1984-1990 (INDITE, 1994) and has since declined by about 10%.

2.2.4.2 *Low nitrate sources*

SRC would seem to offer a good choice of crop for nitrate sensitive areas since it is unlikely to receive large amounts of fertiliser, and it has an extensive root system which should provide an efficient means of exploiting the available N. It also guarantees a fairly benign land use over a long period. If nitrate leaching is particularly low under these conditions, then such

Table 2.3. Typical range of nitrate-N concentrations in the drainage water from various land uses in the UK

Land use	Typical range of nitrate-N concns in drainage water (mg NO_3-N l^{-1})	Comment
Unfertilized, ungrazed grassland	0.5-3	Concentration sensitive to relative timing and sizes of peaks of mineralization, plant uptake and rainfall
Moderately fertilized, grazed grassland	10-25	Normally receives less than 200 kg N ha^{-1} a^{-1}. Winter rainfall and denitrification can be important variables
Intensively managed grassland	25-60	Frequently receives more than 200 kg N ha^{-1} a^{-1} of fertilizer. 'Hot spots' around urine patches lead to uneven leaching
Lowland deciduous forest	3-10	Large atmospheric inputs of NH_3-NH_4 are important in much of Britain. Highest N leaching in clearings where trees have died or close to pig farms etc
Upland moorland	0.01-0.2	Stable system that is slowly accumulating organic N. High acidity retards mineralization. NH_4 also important. High rainfall helps to maintain very low concentration
Upland coniferous forest	0.1-0.6	Increased scavenging of atmospheric N compounds. Higher evaporation (interception) also tends to increase concentration compared with moorland. Low temperature and high acidity retard mineralization
Cereals	5-50	Depends on many factors including amount of fertilizer used, crop uptake, extent of denitrification and winter rainfall

areas of 'low' nitrate leaching could be used to offset areas of higher nitrate leaching either elsewhere in the catchment or by blending at the pumping station. In this sense, the lower the nitrate concentration the better. Clearly for such a strategy to be viable there has to be a significant proportion of a catchment under SRC.

There is also interest in the use of willows and poplars to form a 'buffer' strip for intercepting high nitrate runoff from agricultural land before it enters a river or stream (Haycock and Pinay, 1993; Paterson and Schnoor, 1993). Poplar is favoured for its deep roots and its perennial interception. The rotation on such plots is likely to be longer than for a normal SRC rotation, i.e. it maybe a 8-10 year cycle rather than a 3-5 year cycle.

2.2.4.3 *Sewage sludge applications*

There is current interest in the application of sewage sludge to forests (Wolstenholme et al., 1991; Ferrier et al., 1996) including SRC plantations. This has become of increasing interest because of the proposed ban on the dumping of sewage sludge to the sea which is due to come into effect in December 1998 and so is being actively pursued by some UK water utilities. Digested sewage sludge contains high concentrations of nitrogen, mainly as ammonia and ammonium compounds, and useful amounts of phosphorus. It also can contain high concentrations of various potentially toxic metals such as Zn, Cu, Cd and Ni which could have a deleterious effect on plant and microbial growth although such effects have not been detected when applied to forest plantations.

Applying sewage sludge to SRC offers the opportunity of recycling these nutrients in a beneficial way while at the same time avoiding potential problems of pathogens, heavy metals and public acceptability which might arise from their direct application to food crops. The environmental consequences of sewage sludge applications will depend on the quality and quantity of sludge applied, its timing and the extent to which SRC is able to take up and utilise the nutrients made available. This will depend in part on the extent to which the SRC is able to take up more nitrogen than is required for crop growth, so-called luxury uptake. There is some evidence that luxury uptake of N can take place in SRC.

In the UK, the maximum rate of application of sewage sludge is controlled by national regulations and guidelines (Smith, 1996) which aim to limit the build-up of heavy metals in soils, and in sensitive areas, to reduce excessive leaching of N.

Various trials have investigated the effect of sewage sludge applications on the growth of conifers and these occasionally have included monitoring the response in groundwater quality (Hart and Nguyen, 1994). Grant and Olesen (1984) found that anaerobic digested sludge applied to a 75-year old spruce plantation at the rate of 800 m^3 ha^{-1} led to an increase of 40% in tree growth in 4½ years after application. Immediately after application, there was a rapid rise in the concentration of nitrate in the soil water (up to 30 mg l^{-1} of both NO_3-N and NH_4-N against a background of less than 1 mg l^{-1} for both). There was a smaller and more sustained rise in the nitrate concentration in shallow groundwater beneath the plot - the nitrate concentration increased to about 10 mg NO_3-N l^{-1} and remained there for about 3 years after application. There was no detectable increase in the heavy metal content of the groundwater except for Zn. These trials were on an acid sandy soil (podzol) in which metal leaching would be expected to be relatively high. It is quite likely that more sensitive modern analytical methods would have detected more increases.

Ferrier *et al.* (1996) have recently compared the effects of N and P fertilizer with that of liquid undigested sewage sludge on the foliage nutrient status and soil nutrient fluxes of pole stage Scots pine and Sitka spruce in North East Scotland. Foliage nutrient status was increased in all treatments but there was little evidence for appreciable N or P leaching from the subsoils in the first year following sludge application.

3. THE WATER USE OF SHORT ROTATION COPPICE

Measurements have been made at two locations in England: Dodley Hill Farm, (Nat. Grid Ref. SP795281) Swanbourne, Buckinghamshire and Knowle Farm[1], (Nat. Grid Ref. ST650619) Hunstrete, Avon. At the start of the investigation the only coppice plantation available for measurements was at Swanbourne and consequently measurements during 1993 and 1994 were concentrated there. A range of measurements were made at each site to provide direct estimates of the transpiration and interception loss and also to determine the variable and parameter values required to estimate the water use by means of the Penman-Monteith equation (see Section 1.1 and 3.3). A summary of the various measurements made at each of the sites is given in Table 3.1.

From soil water measurements it became apparent that at the Swanbourne site there was a perched water table. It is likely that wet sites such as this one may prove typical of sites favoured by farmers for coppice plantation. Data collected there will be very useful for understanding the water use of poplar at such sites. However, because any soil water deficits that develop are reduced and plant responses to drought complicated by the upward flux of groundwater, the Swanbourne results, on their own, are inadequate for developing general coppice water-use models for application to sites where significant soil water stress develops. To supplement the Swanbourne data an additional measurement programme was carried out, in accordance with Amendment No. 1 of the project, to provide information on the water use

Table 3.1 Variables measured at Swanbourne and Hunstrete and the methods used

Variables measured	Site S - Swanbourne H - Hunstrete	Method	Purpose
soil water storage and potential	S, H	neutron probe and pressure-transducer tensiometers	can provide an estimate of total water use
weather including rainfall	S, H	automatic weather station	required for modelling
sap flow	S, H H H	stem heat balance heat pulse velocity deuterium tracing	used with leaf area estimate to provide an estimate of transpiration
root distribution	S	soil cores, minirhizotron and $\delta^{18}O$	location of water extraction
plant physiology: stem diameters leaf areas stomatal conductances	S, H	sampling and porometry	information on the plant responses to environmental factors
net rainfall	H	plastic-sheet net-rainfall gauge	used with the gross rain to provide an estimate of interception loss

[1]Brian Maggs Agric. Ltd: one of the five experimental farms of the Farm Wood Fuel and Energy Project

Fig. 3.1 Swanbourne (June 1994) five-year coppice (two-year old shoots on eight-year old stools) in foreground; resprouting shoots on eight-year old stools of three-year coppice in background

Fig. 3.2 The monoclonal rows and access ladders at Swanbourne

of coppice on soils where significant soil water deficits may develop. To this end, a soil water measurement plot was set up in a coppice plantation on a deep freely-draining sandy loam soil[2] at Knowle Farm Hunstrete and soil water content and potential were measured at the site from 21 July 1994 onwards. The equipment was augmented over the winter months of 1994/95 and measurements were concentrated there during the 1995 growing season.

3.1 MEASUREMENTS AT SWANBOURNE

3.1.1 Swanbourne site and trial description

The water use studies were carried out at the ETSU yield-trial plot, operated by Aberdeen

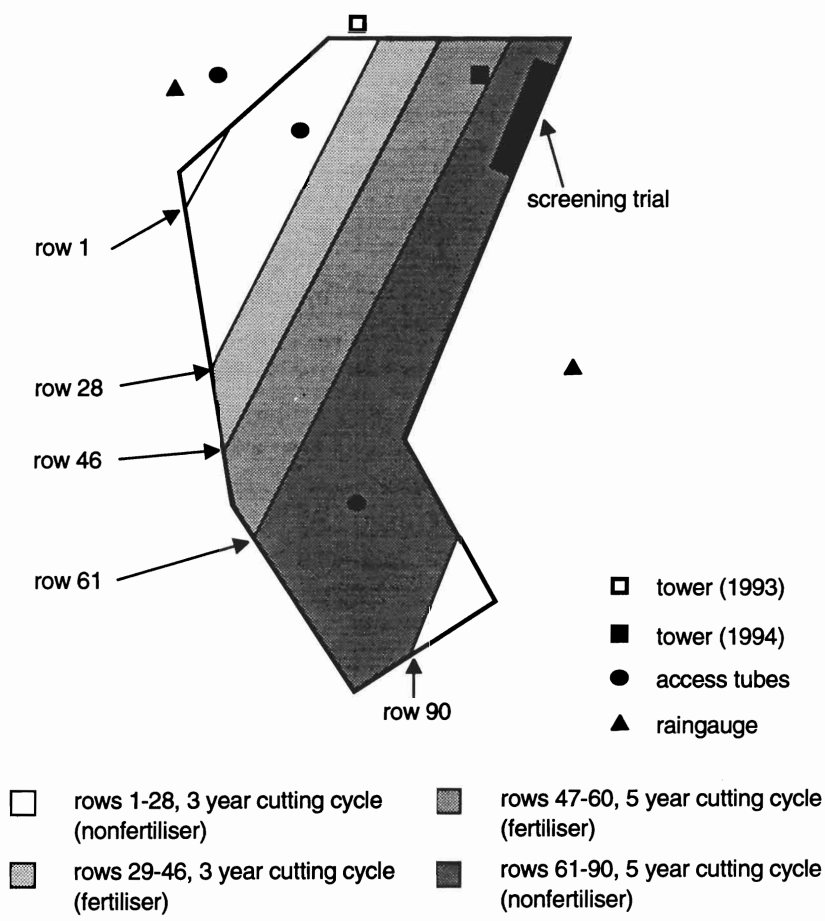


Fig. 3.3 The disposition of the equipment at Swanbourne

[2]During the course of installing soil water equipment at Hunstrete it became apparent that the soil changed dramatically within a short distance and that there was a significant clay component at the site of a second set of equipment.

University (Mitchell et al. 1995) at Swanbourne on land which was previously permanent pasture. A general view of the site is shown in Fig. 3.1. The soil is a clay-loam of the Hanslope association and overlies Oxford clay. Six clonal types of *Populus*, which are given in Table 3.2 were planted in 1987 at one-metre spacing in monoclonal rows arranged semi

Table 3.2 ***Populus* clones at Swanbourne**

Hybrid name	Common name or alias
Populus trichocarpa × *deltoides*	Rap
P. trichocarpa	Fritzi Pauley
P. deltoides × *nigra*	Dorschkamp
P. trichocarpa × *deltoides*	Beaupré
P. trichocarpa × *deltoides*	Boelare
P. (*trichocarpa* × *deltoides*) × *deltoides*	75028/3

randomly and separated by 1.5 m. The visual differences between the clones are clearly visible in Fig. 3.2. Rows 1 to 46 contain stools on a three-year cutting cycle and Rows 47 to 90 on a five-year cutting cycle. (In the rest of this report, unless the ages of the shoots and stools are given explicitly, the blocks of stools harvested on three-year and five-year cutting cycles are referred to as three and five-year coppice respectively.) Additionally the stools in Rows 29 to 46 and 61 to 90 were fertilised whereas the stools in the remaining rows were not fertilised. In addition to these four main plots there is also a small screening trial of 12 clones including the six in the main plantation. Figure 3.3 and Table 3.3 show the layout of the plantation and the clonal identity of each row in it.

3.1.2 Measurements

Of the six clones on the trial we decided not to include the clone 75028/3 in our studies as it had clearly failed to become established at the Swanbourne site. We also decided not to include Rap as it has not received authorization for commercial plantation from the Forestry Authority because of disease problems. Of the four remaining clones, we concentrated measurements on Beaupré and Dorschkamp as there was a marked difference in the size and number of leaves between these clones that may have been reflected in different transpiration rates. At the time of starting this work it was expected that commercial plantations will not be fertilised, measurements were confined to the unfertilised rows.

In 1993 measurements were made on the three-year-old shoots on seven-year-old stools in Rows 20 (Beaupré) and 21 (Dorschkamp). These and the other rows of the three-year coppice were harvested in the winter of 1993/94. In 1994 measurements were made on two-year-old shoots on eight-year-old stools in Rows 61 and 76 (Beaupré) and 62 and 77 (Dorschkamp) in the five-year coppice. In the winter of 1994/95 these rows were also harvested after only two years of regrowth as it had been decided to bring the five-year coppice onto the same three-

Table 3.3 Clonal identification of the rows at Swanbourne

Three-year cutting cycle				Five-year cutting cycle			
Unfertilised		Fertilised		Fertilised		Unfertilised	
Row	Clone	Row	Clone	Row	Clone	Row	Clone
1	Beaupré	29	75028/3	47	Beaupré	61	Beaupré
2	75028/3	30	Beaupré	48	75028/3	62	Dorschkamp
3	Boelare	31	Rap	49	Boelare	63	Boelare
4	Fritzi Pauley	32	Dorschkamp	50	Rap	64	75028/3
5	Beaupré	33	Fritzi Pauley	51	Fritzi Pauley	65	Rap
6	Dorschkamp	34	Boelare	52	Dorschkamp	66	75028/3
7	75028/3	35	Beaupré	53	75028/3	67	Dorschkamp
8	Boelare	36	Fritzi Pauley	54	Fritzi Pauley	68	Beaupré
9	Beaupré	37	Boelare	55	Beaupré	69	Boelare
10	Rap	38	Dorschkamp	56	Rap	70	Fritzi Pauley
11	Dorschkamp	39	75028/3	57	Boelare	71	Rap
12	Beaupré	40	Rap	58	Dorschkamp	72	Fritzi Pauley
13	75028/3	41	Boelare	59	Fritzi Pauley	73	Dorschkamp
14	Boelare	42	Dorschkamp	60	Rap	74	Rap
15	Rap	43	75028/3			75	75028/3
16	Fritzi Pauley	44	Fritzi Pauley			76	Beaupré
17	Rap	45	Beaupré			77	Dorschkamp
18	75028/3	46	Rap			78	Boelare
19	Boelare					79	Beaupré
20	Beaupré					80	Fritzi Pauley
21	Dorschkamp					81	75028/3
22	Fritzi Pauley					82	Beaupré
23	Boelare					83	Dorschkamp
24	75028/3					84	Rap
25	Fritzi Pauley					85	Beaupré
26	Dorschkamp					86	Boelare
27	Rap					87	Fritzi Pauley
28	Beaupré					88	Beaupré
						89	75028/3
						90	Dorschkamp

year cutting cycle as the rest of the plantation to facilitate harvesting of the coppice.

The location of the different instruments within and around the plantation are marked on Fig. 3.3. To measure the depletion of the soil water store neutron probe access tubes were installed in both the three and five-year coppice and in an adjacent pasture field. Soil water content and potential were routinely measured at least once every two weeks to determine the water use from the coppice and understorey and to compare with the pasture. A tower-mounted Automatic Weather Station (AWS) was set up over the coppice plantation. In addition to these, long-term measurements, which are necessary for understanding the hydrological interactions associated with SRC, there were three intensive data-gathering periods in each of the summers of 1993 and 1994 to measure transpiration and plant physiological variables.

With the onset of each autumn the measurement programme was scaled down. Soil water measurements were made less frequently and the AWS decommissioned. While the coppice was dormant the opportunity was taken to service and recalibrate some of the meteorological sensors. More details of the various measurements are given below.

3.1.2.1 *Weather*

Meteorological variables were measured using the AWS mounted on three and a half sections of tower at a height of 6.75 m above the ground. The AWS was logged (Model CR10, Campbell Scientific Ltd, Loughborough) at ten-minute intervals and data collection continued throughout each summer and autumn until the tower had to be dismantled prior to harvesting of the coppice. The weather was recorded during the periods from 19 June to 12 December 1993 and from 19 April to 12 December 1994. During 1993 the tower bearing the AWS was positioned at the edge of the three-year coppice (Fig. 3.4). Ideally the AWS should have been located in the middle of the plantation but because of the high planting density this would have been impossible without damaging some stools. The tower and AWS were moved on 14 December, to a position (Fig. 3.3) within the five-year coppice (but close to the edge) where several stools had failed to grow.

Sensors on the AWS measured incoming solar radiation, net-radiation, temperature (wet and dry bulb), windspeed and direction, and rainfall. The positioning of the AWS at the plantation

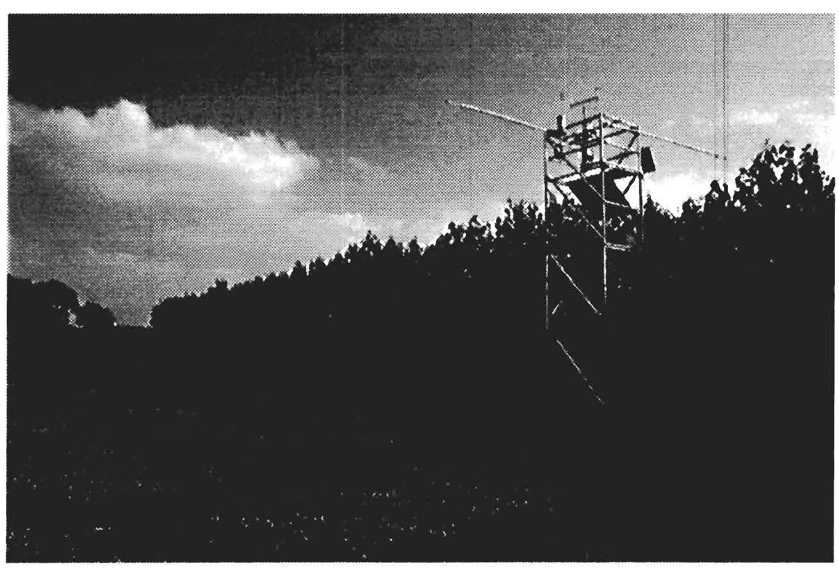


Fig. 3.4 Automatic weather station on tower at the edge of the coppice (three-year old shoots on seven-year old stools) at Swanbourne in 1993

edge, during 1993, made it possible to compare the net radiation over the coppice and over the pasture using two net radiometers on the ends of booms extending over the two crops. Over the foliated period the net radiation over the coppice exceeded that over the grass by about 5%. Two wet-bulb thermometers were used in an attempt to maximise data recovery and the accuracy of the measurement of the atmospheric humidity deficit, the most critical of the meteorological variables governing evaporation rates.

Table 3.4 Summary of the weather at Swanbourne between 9 June and 2 September

variable		min.	max.	mean	$\sigma^{\dagger}$	total
solar rad. (MJ m^{-2})	1993					1438
	1994					1557
air temp. (°C)	1993	3.9	24.7	14.3	3.8	
	1994	4.9	30.5	16.6	4.3	
humidity deficit (g kg^{-1})	1993	0	12.2	2.4	2.2	
	1994	0	17.2	3.6	2.9	
windspeed (ms^{-1})	1993	0	9.5	2.3	1.4	
	1994	0	8.8	2.8	1.6	
rainfall (mm)	1993					138
	1994					87.4
Penman E_T (mm day^{-1})	1993	0.7	5.5	3.0	1.0	
	1994	0.8	7.1	4.0	1.5	

† one standard deviation

A 0.2 mm tipping-bucket raingauge connected to the AWS measured the rainfall. Because tower-mounted raingauges tend to undercatch the rain, and to provide a better spatial average of the rainfall, this gauge was augmented by two automatically-logged (Rainlog, model DDL 04, Didcot Instrument Co. Ltd, Abingdon) groundlevel tipping-bucket raingauges installed in the pasture fields immediately to the west and east of the trial. The AWS raingauge and one of the two ground level raingauges were operated through the winter of 1993/93. Because of problems (flooding of the raingauge pit during the winter months, mechanical and electrical faults) the record from the 0.2 mm west gauge is incomplete. However the more accurate (0.1 mm per tip) east raingauge worked well giving an almost complete record of rainfall from July 1993 to November 1995.

During 1994 there was a larger difference between the rainfall recorded by the tower-mounted AWS raingauge and the east ground-level raingauge. Over the period 29 April to 18 November the rainfall recorded by the ground-level and tower-mounted raingauges was 376.1 mm and 225.2 mm respectively, a difference of ~67% compared with a 45% difference in 1993. Such differences are expected because of the enhanced wind-driven turbulence around the tower and over the tall coppice canopy. The larger difference in 1994 is consistent with rainfall over the summer period falling in frequent small storms, so that although the total rainfall was low, the longest period without any rainfall was only 12 days (10-21 June). In 1993, although there was more rain it fell in larger storms and the longest dry period was 20 days (19 June - 9 July).

The best estimate of the rainfall was taken as the average of the groundlevel gauges when both were operational. Infilling of data missing from one of the gauges was achieved using linear regressions established between the gauges. Over the period of the three intensive measurement campaigns in 1994, 9 June to 2 September, the best estimate of the total rainfall was 87.4 mm compared with 138 mm for the same period in 1993. However, both of these are lower than the long term (1961-1990) mean rainfall (from Meteorological Office records) for June to August inclusive of 170 mm. The 1993 and 1994 figures are given in Table 3.4 together with other summary values for the other measured weather variables and the mean daily Penman potential evaporation estimate based on 24 hour data.

3.1.2.2 *Stem and leaf surveys*

The approach taken in measuring the transpiration rates of the coppice has been to make measurements on a sample of individual stems using gauges that measure directly the rate of sap flowing through those stems. The use of micrometeorological techniques, which are frequently used to measure evaporation fluxes from vegetation when the site is suitable, require a uniform area of at least ~150 m in the direction of the prevailing wind and were therefore precluded by the small size of the coppice plantations.

Table 3.5 Mean stem diameters (mm) measured at Swanbourne during 1993 and 1994

survey	Beaupré	Dorschkamp
July 1993	34.21	33.71
1-4 July 1994	21.93	10.43
12-14 July 1994	24.78	12.46
1 August 1994	24.77	12.14
15-17 August 1994	26.45	13.4

With the stem-based approach it is necessary to scale up the measurements to obtain the transpiration in (say) mm depth of water over the whole plantation. Similarly, scaling factors are needed to obtain the canopy conductance from stomatal conductance measurements made on individual leaves. The canopy conductance is necessary to make quantitative estimates of the transpiration rates. These scaling factors are based upon the distribution within the canopy of leaf area L, or leaf area index, L^*, the leaf area per unit ground area. To determine the appropriate scaling factors surveys of the stem diameters and leaf areas were made during both the 1993 and 1994 growth seasons.

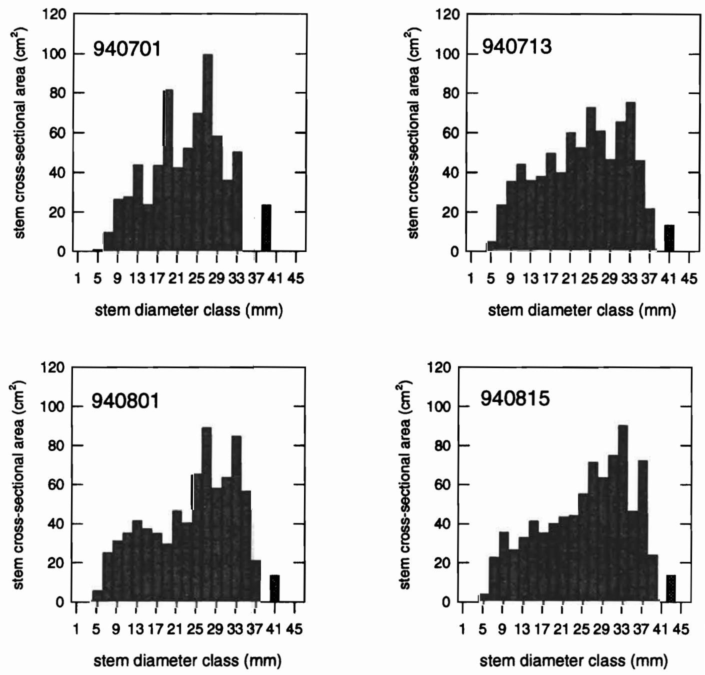


Fig. 3.5 The distribution of stem cross-sectional area by diameter class for Beaupré measured on four occasions in 1994

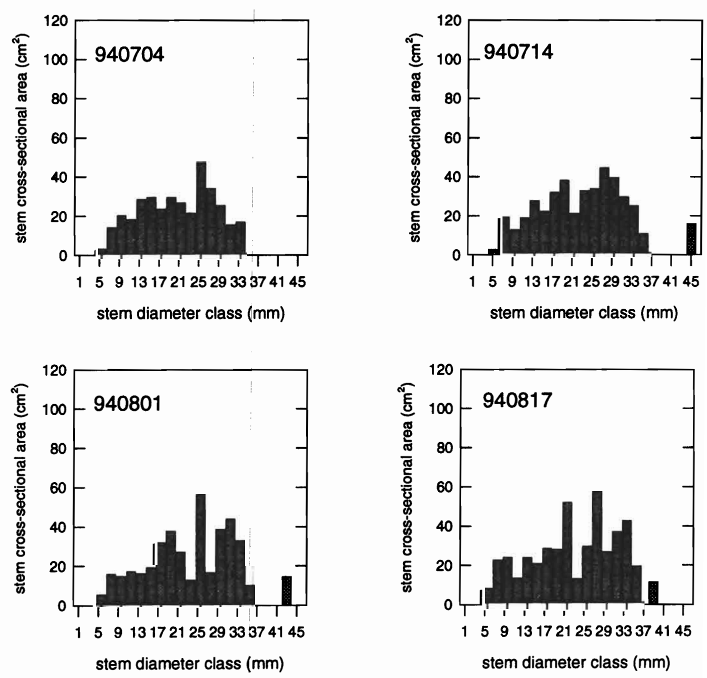


Fig. 3.6 The distribution of stem cross-sectional area by stem diameter class for Dorschkamp measured on four occasions during 1994

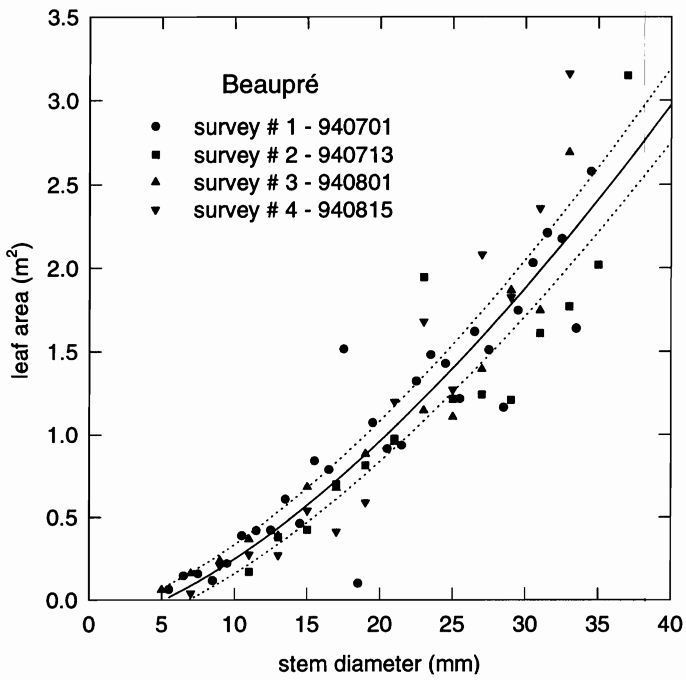


Fig. 3.7 Relationship between stem diameter and leaf area for Beaupré established from four surveys at Swanbourne during 1994 (dotted curves show 95% confidence limits).

At the beginning of July 1993 the diameters at one metre of all the stems in one complete row of the Beaupré and Dorschkamp clones were measured[3]. During the summer of 1993 different approaches were used to estimate L^* without using destructive sampling which would have interfered with measurements of the total yield. Single stems (from different stools) were chosen to represent the diameter classes which contributed significantly to the total stem cross-sectional area of the rows. The selected stems were not harvested, but each was stripped of all leaves. The total area of leaves from each stem was measured with a leaf area machine (Model 3100, LI-COR Inc., Lincoln, NE, USA) and this area plotted against stem diameter.

In 1994 four surveys were made of stem diameters and leaf areas for Beaupré and Dorschkamp during June, July and August. At each survey the diameter of each stem at one metre height was measured for 100 stools in Rows 61 (Beaupré) and 62 (Dorschkamp); the results of the surveys in 1993 and 1994 are summarised in Table 3.5. The 1994 stem survey data are also presented in Fig. 3.5 (Beaupré) and 3.6 (Dorschkamp) where the stem cross sectional area is plotted for the different stem classes.

As in 1993, to minimise the effect of destructive sampling on the plantation, a stratified sampling scheme was used for collecting leaves based on the results of the stem diameter surveys. To this end the leaf area for each stem was measured, using the leaf area machine,

[3] The results of the stem survey of a complete row of each clone were interesting in themselves. Although the distribution of stems for the two different clones is very different with many more small stems on the Dorschkamp than on the Beaupré the total cross-sectional area for the two sampled rows was almost identical.

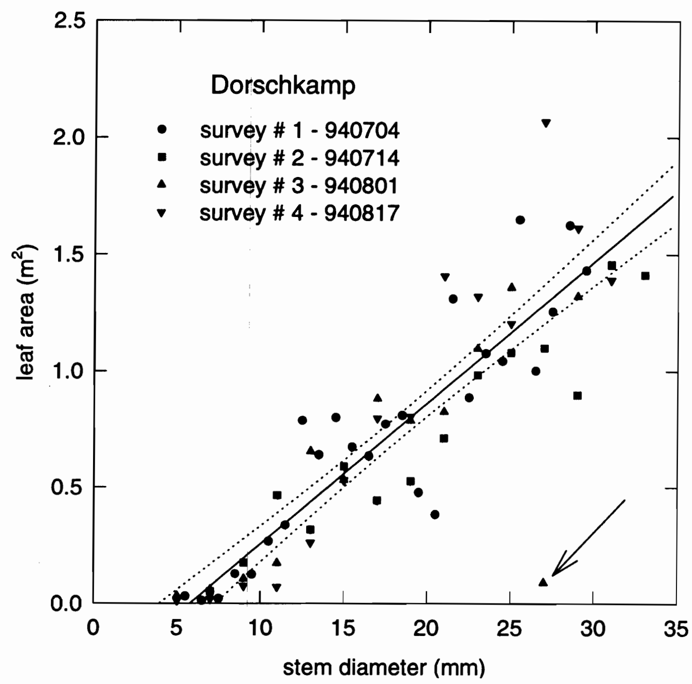


Fig. 3.8 Leaf area versus stem diameter for Dorschkamp from four surveys at Swanbourne in 1994 (dotted curves show 95% confidence limits and the arrow an outlier that was ignored).

and then plotted against the stem diameter (Fig. 3.7 and 3.8). The relationship between the leaf area and stem diameter showed little variation through the summer, so the data were considered as a single population when determining the best fitting function. This was done using a commercial software package (TableCurve™ 2D, Jandel Scientific GmbH, Erkrath, Germany).

The equations fitted to the data for the two clones are:

$$L = -0.1422 + 0.0123\, d^{3/2} \tag{3.1}$$

for Beaupré and

$$L = -0.352 + 0.06072\, d \tag{3.2}$$

for Dorschkamp where L is the leaf area (m^2) and d is the stem diameter (mm). These and the data for the two clones are shown in Fig. 3.7 and 3.8. Establishment of Equations (3.1) and (3.2) made it possible to estimate the leaf area index (see Fig. 3.9) and subsequently transpiration loss per unit ground area for the two clones: via Equation (3.6) in Section 3.1.2.3.

Equations (3.3) and (3.4) were derived retrospectively for Beaupré and Dorschkamp respectively from the 1993 data in the same way as Equations (3.1) and (3.2), but based on stem diameters and leaf areas measured, using the stratified sampling technique, on 10 September 1993 and on stem surveys of the complete rows made in early July 1993.

$$L = -1.0 + 0.0116\, d^{3/2} \tag{3.3}$$

$$L = -1.792 + 0.108\,d \tag{3.4}$$

3.1.2.3 *Transpiration*

Transpiration was estimated by measuring the mass flow rate of sap in a sample of tree stems (g s^{-1} $stem^{-1}$) and scaling up to an average value on a land area basis (mm of water per day) using information from the leaf and stem surveys (Section 3.1.2.1). The rates of sap flow in individual stems were measured with Dynagage™ (Dynamax Inc., Houston, TX, USA) sap flow gauges, which operate on a heat balance principle, developed by Sakuratani (1981) and Baker and van Bavel (1987).

The Dynagage™ is an electronic instrument which can be installed on a stem in a few minutes

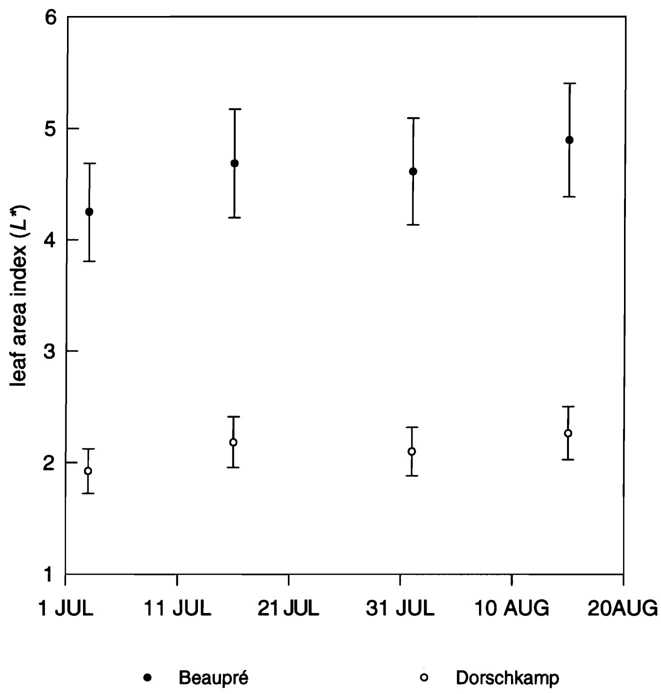


Fig. 3.9 Leaf area indices of the two clones from four surveys made at Swanbourne in 1994 (bars show standard errors)

and left in-situ for several weeks, providing automated measurements of sap flow (see Fig. 3.10). It consists of a flexible tube, split down one side, that can be wrapped around the stem, and secured tightly in position with velcro straps. The walls of the tube are made of thermally-insulating foam rubber. Around the inner surface, is an electrical heater, through which a constant amount of heat is applied to the surface of the stem. Mounted within the wall of the gauge are several temperature sensors, which measure the rate of heat loss from the gauge to the environment. From the heat balance, the difference between the applied heat and the measured losses is the amount of heat, Q_f (W) being dissipated by heating of the sap as it flows through the heated region. The gauge also measures the temperature increase of the sap, ΔT (K), so the rate of sap flow s (g s^{-1}) can be simply calculated as

Fig. 3.10 A Dynagage™ sap flow gage in situ with polythene shelter

$$s = \frac{Q_f}{c_s \Delta T} \tag{3.5}$$

where c_s (J g^{-1} K^{-1}) is the specific heat capacity of the sap (assumed equal to the value for water).

Measurements with sap flow gauges were made on the Beaupré and Dorschkamp for three periods each summer: 18 to 28 June, 21 July to 6 August and 6 to 21 September in 1993 and 10 to 28 June, 12 to 27 July and 17 August to 2 September in 1994. At the start of each measurement period, gauges were installed on a sample of eight stems of each clone. To ensure that the sample represented the variation in stem size, gauges of several different diameters were used. During 1993, the stems under study were in their third year of growth, so 19 mm, 25 mm and 35 mm diameter gauges were used to sample the population. In 1994, the stems were smaller, as they were in their second year of growth, so 16 mm, 19 mm and 25 mm diameter gauges were used. The stem diameter distributions for the two clones during 1994 are shown in Fig. 3.5 and 3.6.

During the first measurement period of 1993, a few gauges malfunctioned because the weather shields provided by the manufacturer did not provide fully effective water proofing during rainstorms. To prevent further data loss and to protect the sensitive electronics of the gauges, conical shelters were designed, to stop rainwater from running down the stems into the gauges (see Fig.3.10). The shelters were formed from circles of heavy duty polythene wrapped around the stems, above each gauge. Electrical insulation tape was used to attach them to the stems and this joint was coated with waterproof grafting wax.

The signals from the gauges were recorded every 15 s and stored as ten-minute averages with an automatic data logger (model CR21X, Campbell Scientific, Shepshed, Leics.). The quality of all the data was checked graphically, before calculating the sap flow rates. Days with complete records of ten-minute values in further analysis were integrated to produce daily total sap flows (kg day^{-1} stem^{-1})

An estimate of the transpiration on a ground area basis, T_i (mm day^{-1}), was calculated from the sap flow rate measured by each of the eight gauges on each clone using a scaling equation

$$T_i = \frac{s_i L^*}{L_i} \tag{3.6}$$

where s_i is the estimate of sap flow (kg day^{-1}) measured for the ith stem, L_i is the leaf area of the ith stem, calculated using the appropriate equation relating L_i to stem diameter and the corresponding stem diameter distribution (see Section 3.1.2.1), L^* (m^2 m^{-2}) is the leaf area index for the portion of the monoclonal row sampled. L^* was calculated as LA_g^{-1}, where L is the total leaf area (m^2), obtained by summing the L_i of all stems in a known length of monoclonal row (calculated using the appropriate equations), and A_g is the ground area occupied by the length of row (m^2). The mean transpiration for each clone was calculated as the mean of all T_i for that clone.

The mean daily transpiration rates calculated for the two clones during 1993 are shown in Fig. 3.11a. During the first measuring period, the weather was a hot and dry, with plentiful soil water, and the transpiration rates were uniformly high; the second period included several days when there was significant rainfall (24, 27 and 29 July, see Fig. 3.11c) and the transpiration totals for those days are lower, as a result of the cloudy and humid conditions; the final period in September shows lower transpiration rates over most of the period, which also included several wet days. The general downward trend through the summer was mainly caused by the increasing soil water deficit, which reached a maximum of ~150 mm in early September.

To aid assessment of the magnitude of the calculated transpiration rates, they were divided by the Penman potential (E_T) evaporation, the rate that would be expected from well-watered short grass, and this, the *transpiration ratio* plotted against time (Fig. 3.11b). Normalising the transpiration rates in this way removes variance in the data arising from the variation in the meteorological evaporative demand, and makes clearer the difference between the clones. During the first period, transpiration by the Beaupré was greater than by the Dorschkamp. For the other two periods the situation was reversed, so that over the whole summer, Dorschkamp transpiration remained fairly level, while Beaupré showed a clear declining trend. This suggests that Beaupré is more sensitive to soil water deficit.

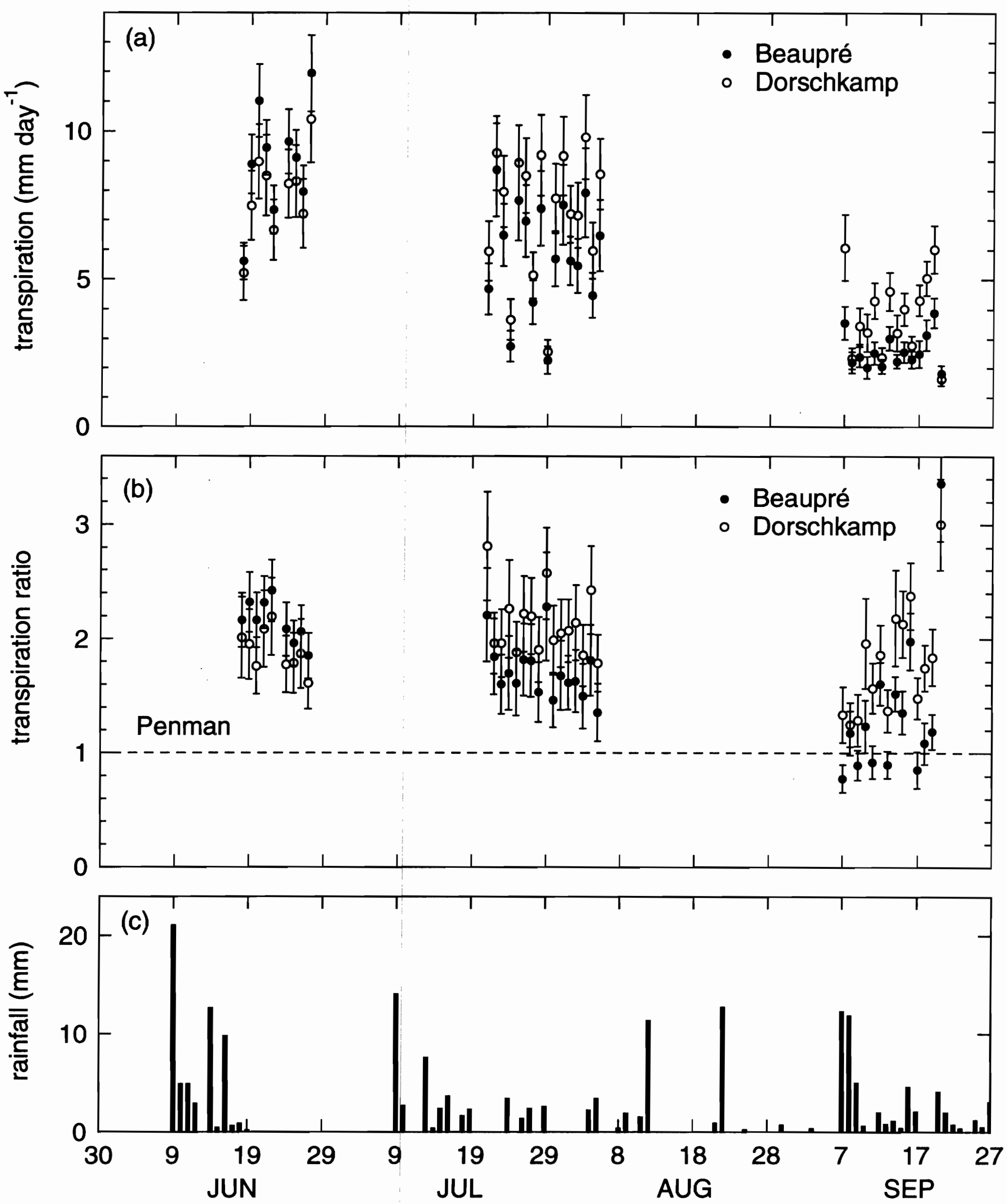


Fig. 3.11 The daily transpiration and transpiration ratio (transpiration divided by Penman E_T) for the two clones at Swanbourne in 1993

For both clones, the transpiration ratio almost always exceeded one, and during the first two measurement periods averaged about two, so both clones appeared to be transpiring about twice as much as well-watered pasture. These rates are certainly very high, but are feasible considering the observed stomatal conductances, which are much higher than would be expected for grass. Furthermore, a higher aerodynamic conductance would be expected, as a result of enhanced mixing with the atmosphere caused by greater turbulence over the taller trees, compared to short, relatively smooth pasture. This was confirmed by measurements of aerodynamic conductance made at Hunstrete in 1995 (see Section 3.3.1.1 and Appendix A).

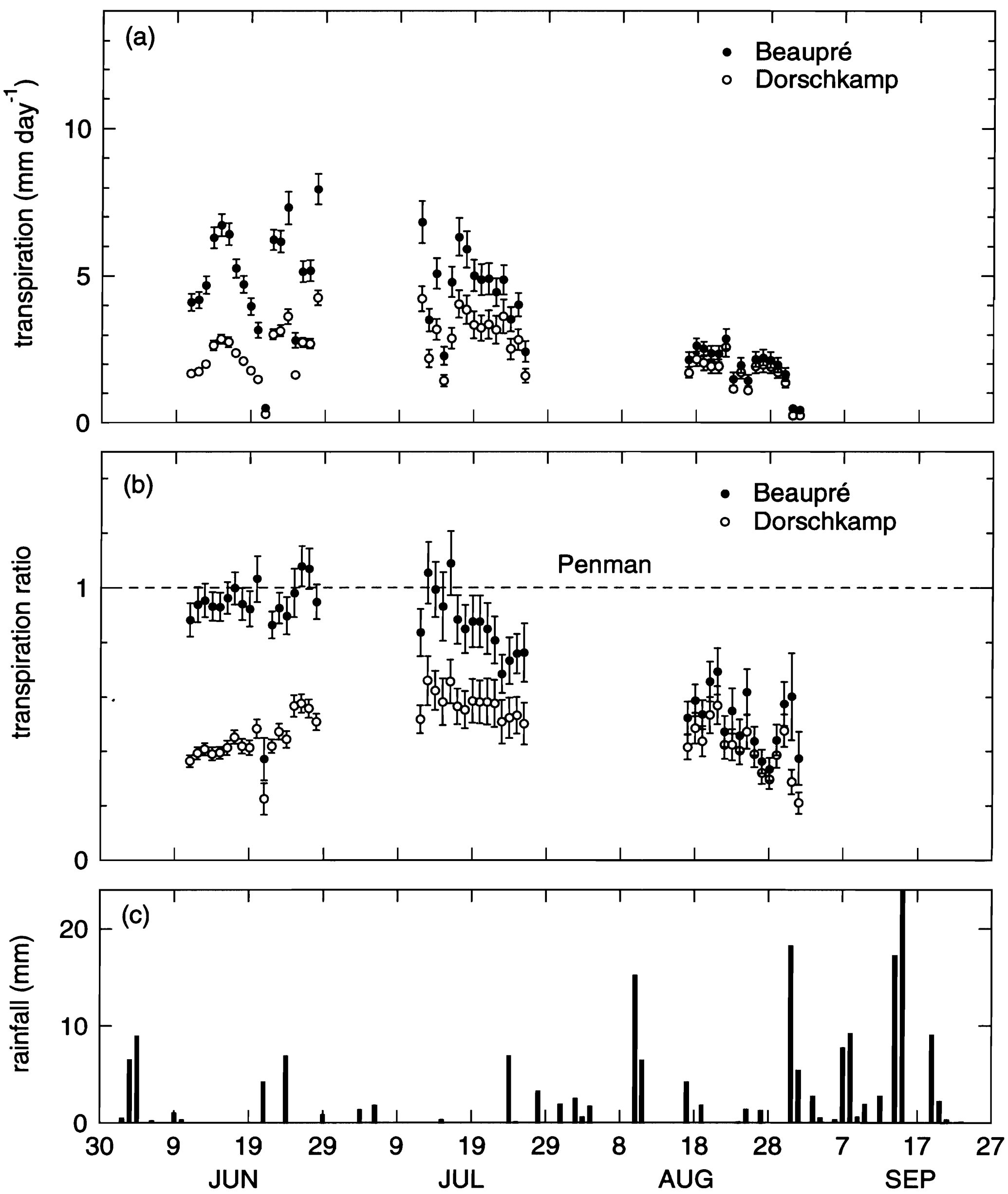


Fig. 3.12 The daily transpiration and transpiration ratio (transpiration divided by Penman E_T) for the two clones at Swanbourne in 1994

The mean daily transpiration rates for the Beaupré and Dorschkamp clones over the summer of 1994 are shown in Fig. 3.12a. The transpiration from the Beaupré exceeded that from the Dorschkamp, but the difference reduced as the summer progressed. The mean daily transpiration rate of (5.3 ± 1.4) mm day^{-1} measured during June from the Beaupré was twice that of the Dorschkamp (2.6 ± 0.8) mm day^{-1} and exceeded Penman potential, E_T, (i.e. transpiration ratio > 1, see Fig. 3.12b). The difference in the transpiration rates of the two clones measured in June, when the trees were relatively unstressed, reflects their dissimilar leaf area indices (Fig. 3.9, in Section 3.1.2.1), Beaupré having twice the leaf area of Dorschkamp. During the July and August measurement periods, the difference in transpiration

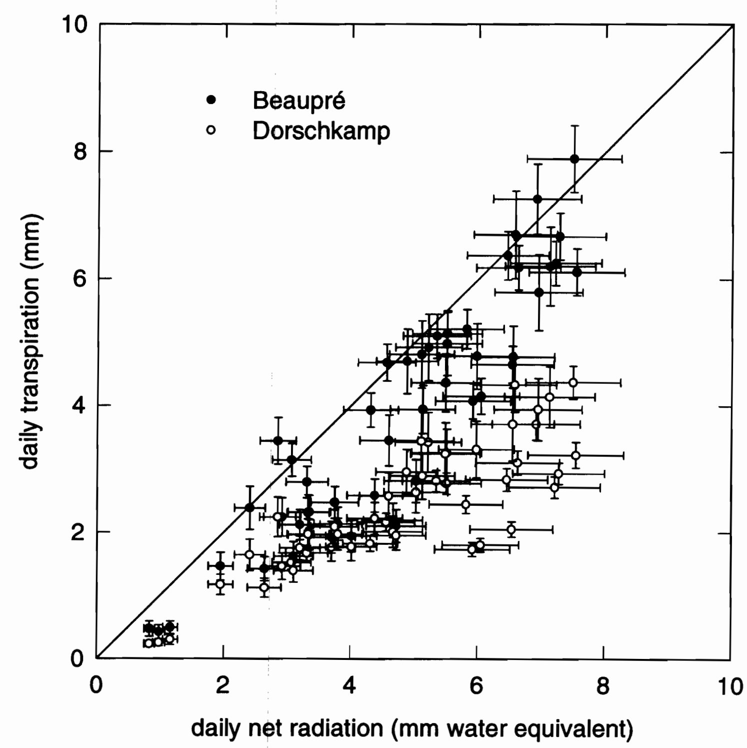


Fig. 3.13 Scatter diagram of mean daily transpiration against net radiation for the two clones at Swanbourne over the 1994 growing season (bars show standard errors).

between Dorschkamp and Beaupré narrowed, even though the difference in leaf area increased slightly. This results from the higher stomatal conductances maintained by Dorschkamp at the end of the summer (see Section 3.1.2.6, Fig. 3.16c and 3.17c). The observed transpiration rates, although high for the Beaupré, are not much larger than others recently published in the literature. Taking hourly latent heat fluxes from a graph in Lindroth and Iritz (1993) and summing over the day gives a typical daily transpiration rate of about 3.7 mm day^{-1} for a 2.6 ha plot of willow (*Salix viminalis*) coppice. More recently Hinckley et al. (1994) measured a maximum rate (of 4.8 mm day^{-1}) from a four-year old stand of uncoppiced poplar (*P. trichocarpa* x *deltoides*).

The low values on 21 June are the result of low intensity rain during much of the day (Fig. 3.12c); the higher rainfall recorded on 24 June fell during the evening and night and so did not affect the transpiration. As the summer progressed and the soil water deficit developed (see Fig. 3.21), the transpiration from the Beaupré decreased, so that by the end of August transpiration from the two clones was the same. These results suggest that the stomatal response of Beaupré to soil water stress is greater than Dorschkamp, as found in 1993. This was confirmed by the stomatal conductance measurements (see Section ?) which show a reduction in the stomatal conductance of Beaupré over the summer.

Figure 3.13 shows that on occasions during 1994 the transpiration rates from the coppice exceed the measured net radiation (the energy available for transpiration and warming the air above the canopy). Warm air blowing from the surrounding farmland could have provided the additional energy needed to drive such high transpiration rates. It is probable that the transpiration rates would be lower for coppice planted over larger areas, as the extra energy supplied by warm air would be exhausted after passing a few hundred metres from the upwind edge of the plantation.

3.1.2.4 *Stomatal conductance*

Stomatal conductance is a measure of the capacity of the leaves to transpire water vapour in response to the humidity gradient between the interior of the leaves and the atmosphere. It is through physiological control of the opening of the leaf stomatal pores, that plants are able to regulate the rate of water loss to the environment, and maintain favourable tissue water status. To achieve the objective of modelling water loss from poplar coppice, it is necessary to quantify the stomatal conductance under a full range of conditions, so that the stomatal responses to environmental variables can be described by mathematical equations.

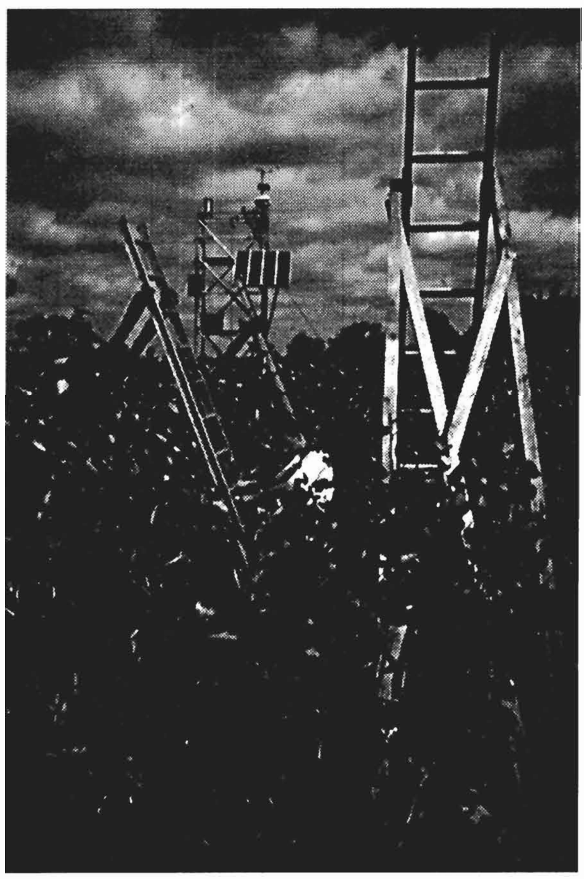
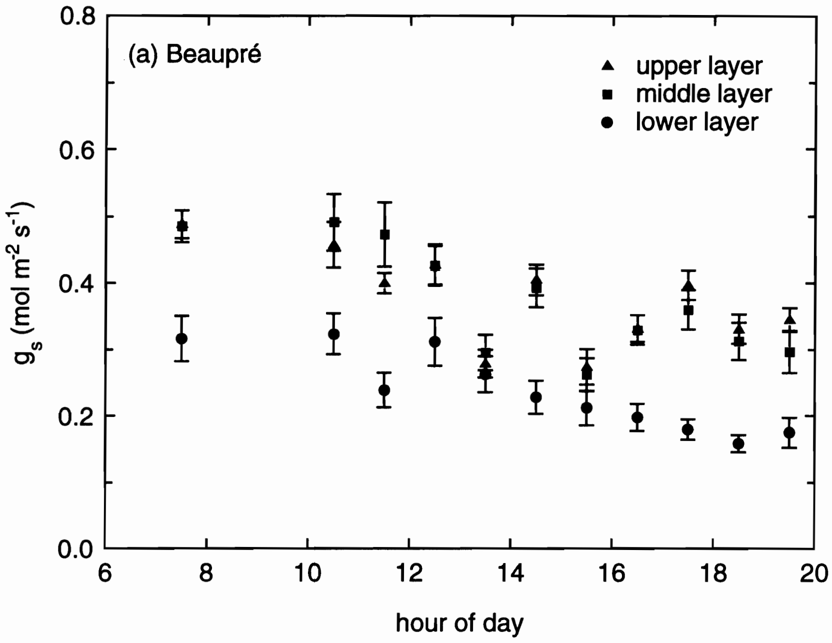


Fig. 3.14 Operator measuring the leaf stomatal conductance using a porometer. The AWS and solar panels are seen in the background.

Measurements of leaf stomatal conductances were made on both Beaupré and Dorschkamp on several days during the periods when the sap flow gauges were in place (1993: 4 days; 1994:



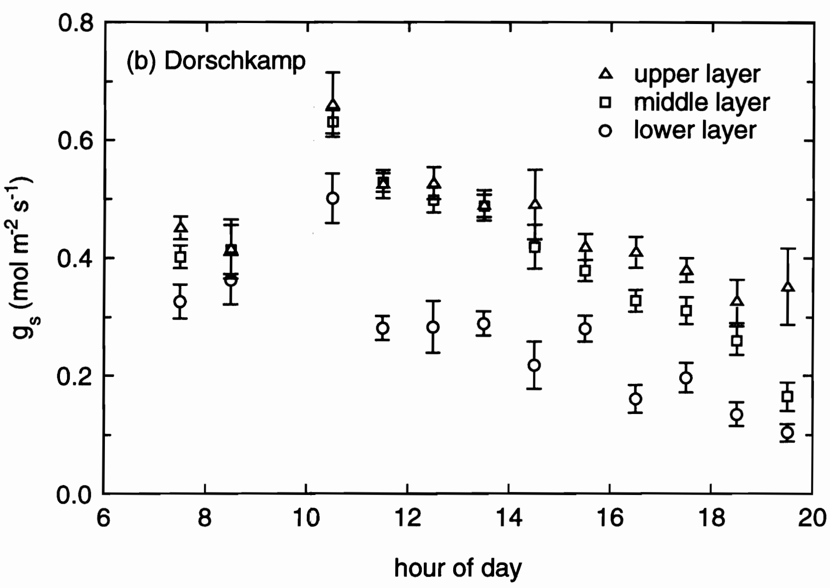


Fig. 3.15 Diurnal variation in mean leaf stomatal conductance for each canopy layer (bars show standard errors) observed at Swanbourne over the 1994 growing season.

12 days). A steady state diffusion porometer (model AP4, Delta-T Devices Ltd., Burwell, Cambs.) was used.

Leaf stomatal conductance is known to vary in response to several attributes: e.g. leaf age, orientation, position in the canopy and intensity of illumination. To allow the calculation of mean conductances representative of the whole canopy of leaves, the following sampling strategy was adopted. Two representative trees of each clone were selected for study. Access

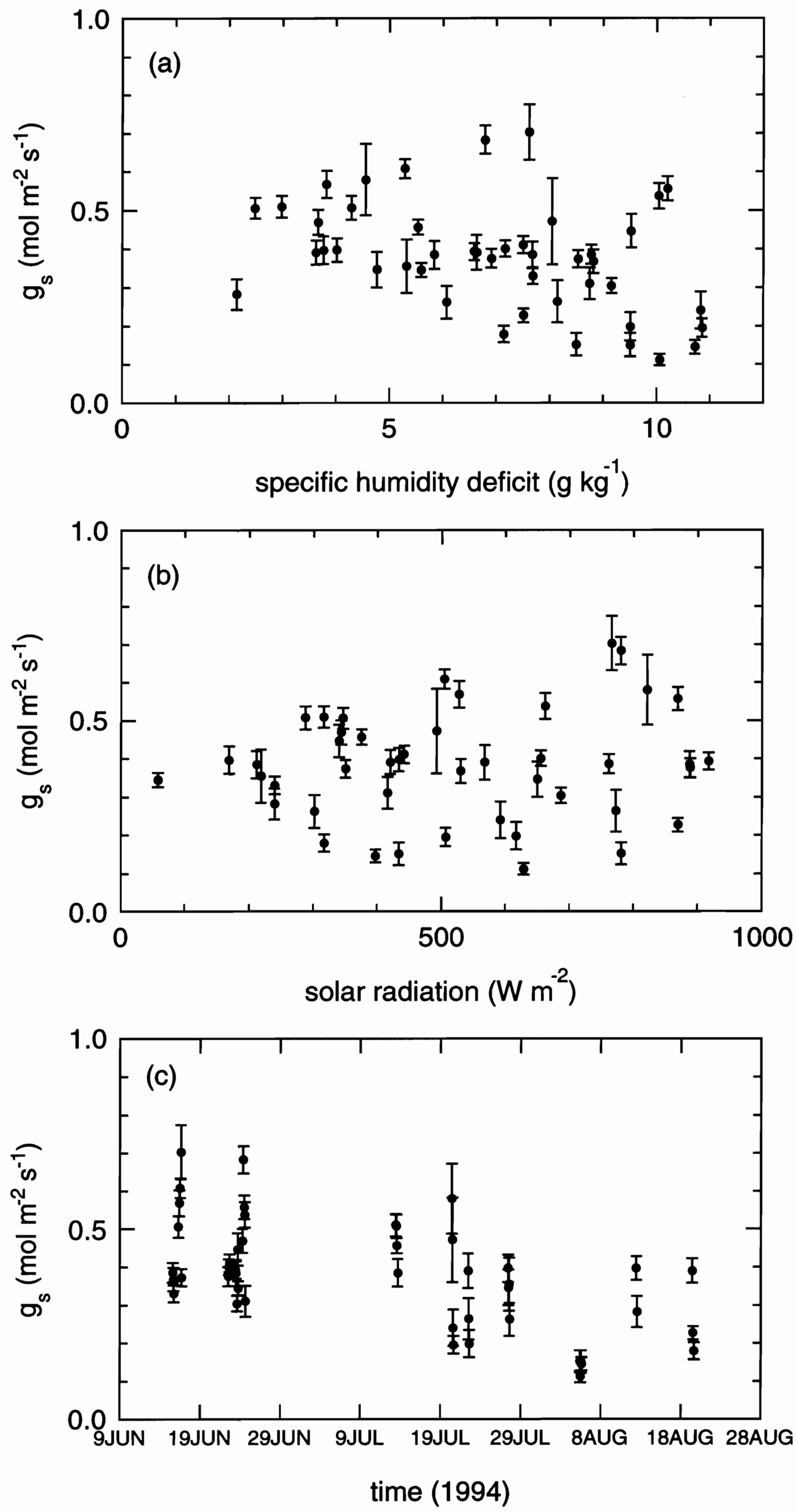


Fig. 3.16 Variation in leaf stomatal conductance of Beaupré against (a) humidity deficit, (b) solar radiation and (c) day of 1994, at Swanbourne (means and standard errors).

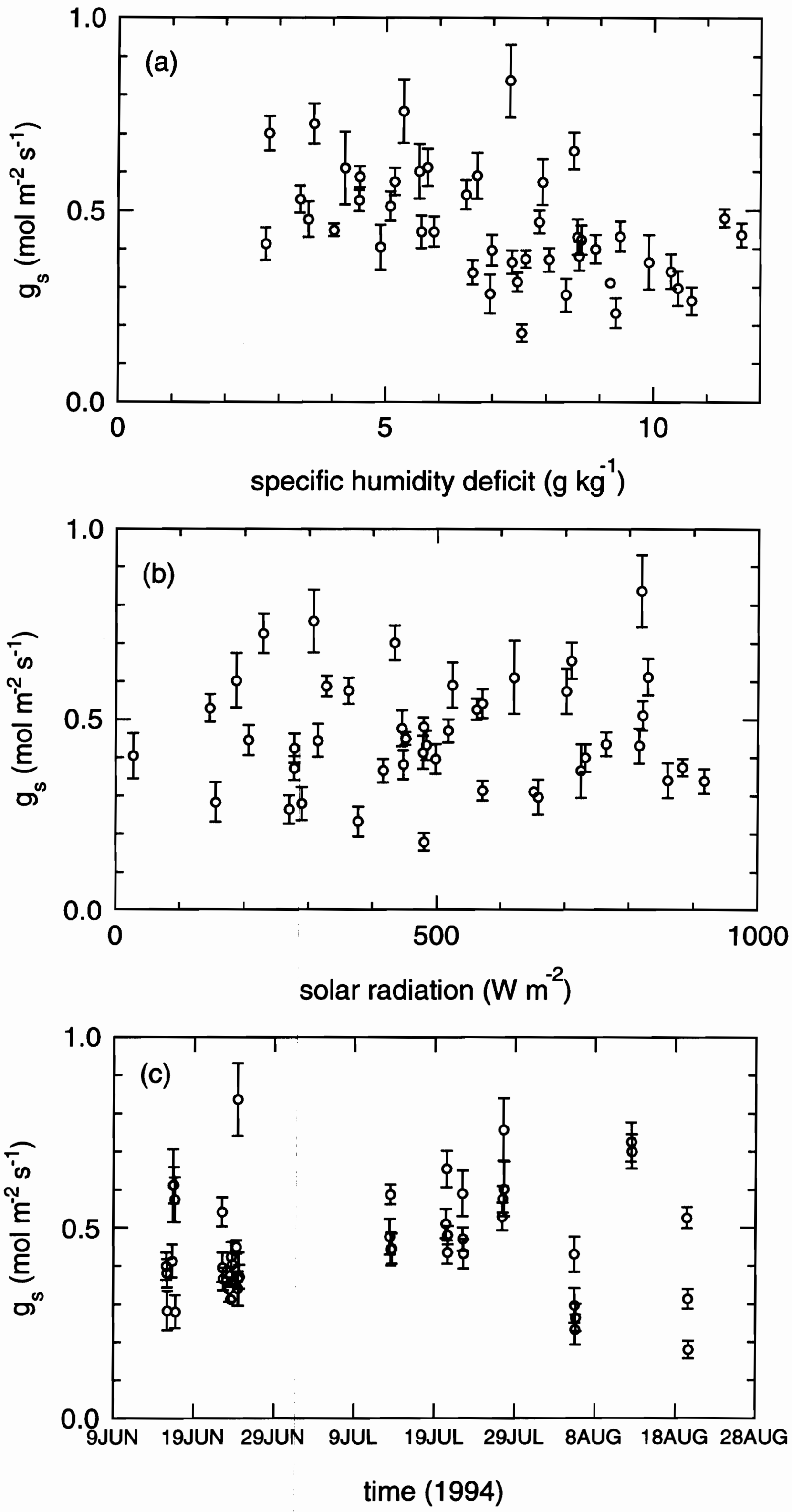


Fig. 3.17 Variation in leaf stomatal conductance of Dorschkamp against (a) humidity deficit, (b) solar radiation and (c) day of 1994, at Swanbourne (means and standard errors).

ladders, supported by wooden frames, were installed at the start of the growing season, allowing the porometer operator to reach leaves at any height (Fig. 3.14 and Fig. 3.2). The canopy was subdivided into three layers (upper, middle and lower) of equal depth. At each sampling time, measurements were made on both surfaces of four leaves in each of the three canopy layers giving a total of 96 observations at each sampling time. On each measurement day, this sampling pattern was repeated (2 to 5 times), to allow investigation of diurnal variation in conductance. For each leaf sampled, the upper and lower surface conductances were summed to obtain the total leaf conductance. These leaf conductances have been averaged in different ways to illustrate the behaviour of the two clones.

The weather during the summer of 1994 was considerably warmer and drier than 1993 (see Table 3.4) and this provided an opportunity to make measurements over a wider range of environmental conditions. Despite the presence of a perched water table at the site a soil water deficit of ~200 mm developed beneath the five-year coppice in 1994, compared with a deficit of ~150 mm in 1993. The increased water stress to which the plants were subjected resulted in the different water conservation strategies of the two clones (Beaupré, *P. trichocarpa* x *deltoides* and Dorschkamp, *P. deltoides* x *nigra*) becoming apparent. Measurements were made on 12 days, three times as many as in 1993, resulting in the collection of a large data set of more than 4000 individual measurements. As the 1994 data set is larger, and covers a wider range of conditions, than that obtained in 1993, only the data from 1994 are presented below.

Figure 3.15 shows diurnal variation in the mean stomatal conductance of each canopy layer for each clone. To produce this figure all the 1994 data were used: each point represents the mean of all observations for a particular clone/layer combination falling within a particular hour of day (bars show standard errors). The magnitudes of the conductances observed for both clones are high, compared to other temperate tree species, in agreement with other published studies (see review by Hall and Roberts, 1990). Our values are significantly higher than those published by Hinckley et al. (1994) who quote a maximum stomatal conductance of 0.48 mol m^{-2} s^{-1} for four-year old poplar trees (*P. trichocarpa* x *deltoides*) which corresponds to about the median value we measured for Dorschkamp. High stomatal conductances are to be expected for the poplars, being hybrids of species that naturally occur in wet areas, where water stress is infrequently experienced. The conductances found for Dorschkamp were generally higher than those for Beaupré. Both clones showed similar patterns of diurnal variation: during the hour from 10:00 to 11:00 GMT maximum values were observed, after which conductances fell steadily through the day, reaching minimum values after 18:00 GMT. The cause of this pattern is not yet firmly established. It was most likely caused by a response to localised soil water deficits which developed near the roots as the days progressed. For both clones, the conductances for the upper and middle layers were almost always greater than those found for the lower layer. This has often been observed in forest canopies, and results from the opening response of the leaf stomata to the greater light levels at the top of the canopy, compared to the bottom, where many leaves are shaded.
The response of the stomatal conductance to environmental variables is shown in Fig. 3.16 for Beaupré and Fig. 3.17 for Dorschkamp. Each point in these figures represents the mean of the leaf conductances measured for the upper layer of the two sample trees at a single sampling time (mean of 8 leaf conductances, with standard errors). Neither clone (Fig. 3.16 and 3.17) shows the response to humidity (decreasing conductance with increasing deficit) often observed in trees and other plants. This response serves to restrict potentially damaging water loss in dry conditions. The 1994 results agree with those from 1993 (not presented), which

also suggested that the poplar clones lack a humidity response, at least over the range of humidities that were observed. There was also no apparent response to the intensity of solar radiation (Fig. 3.16 and 3.16). Stomatal conductances are normally close to zero in the dark, but rise rapidly as light levels increase. The observations presented do not include any at light levels low enough to have restricted stomatal opening. The amount of transpiration occurring at such low intensities of solar radiation is very small, so the lack of measurements under these conditions will not affect modelling of water loss from the coppice.

The trends in stomatal conductances through the growing season for both clones are shown in Fig. 3.16c and 3.17c. Here a clear difference between the clones can be seen: the conductance of the Beaupré gradually declined through the growing season, while the Dorschkamp maintained similar conductances over the whole period. The Beaupré was probably responding to the gradual decrease in soil water over the summer, shown in Fig. 3.21. Dorschkamp conductance did not respond, but as the leaf area index of this clone was less, it perhaps suffered less stress.

3.1.2.5 *Soil water content and soil water potential*

Equipment. Eight neutron-probe access tubes were installed in the three-year coppice at positions (Fig. 3.18) selected to give a representative sampling of the soil water contents through the soil profiles down to a depth of about 2.0 m. It was thought unlikely that the roots extend below this depth. Moreover, installation of the tubes below one metre proved to be much more difficult than expected and it was necessary to compromise the desirability of having more tubes for good sampling, against expenditure, by installing fewer tubes (five) in the five-year coppice. A further four tubes were also installed in the adjacent pasture field. Because of the more uniform nature of the grass sward we considered four tubes adequate for sampling the soil water content. Readings were taken using a neutron probe meter at 10 cm depth intervals down to 1 m and at 20 cm depth intervals below that.

To determine the direction of water movement within the soil and to establish the position of the zero-flux plane eight tensiometers were installed in the three-year coppice (Fig. 3.18) and the pasture at depths of 20, 40, 60, 80, 100, 120, 180 and 240 cm. The access tubes and tensiometers were first read in June 1993 and then at about fortnightly intervals throughout the 1993, 1994 and 1995 growing seasons in the five-year coppice and pasture and in the 1993 and 1995 growing seasons in the three-year coppice. Soil water measurements were not made in the three-year coppice in 1994 for the reasons described below and because it was considered best to use the resources in collecting measurements from the Hunstrete site.

Site hydrology. The pasture site is on the floor of a valley and the tensiometer data have shown that there is a water table at, or close to the surface during the winter months. The depth to the water table increases during the summer. In 1994 the maximum depth reached was 1.4 m below ground level (bgl). There were no tensiometer data after 28 June 1995, when the water table was 1.0 m bgl, but it is probable that it fell below 1.4 m by late summer.

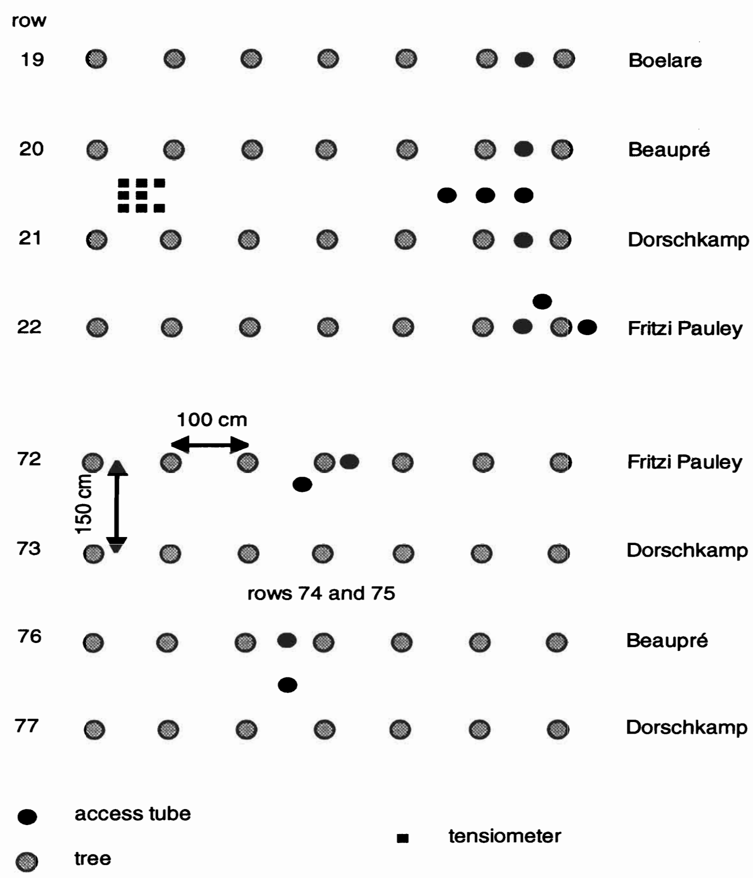


Fig. 3.18 The soil water plot layout for the three-year (top) and five-year (bottom) coppice at Swanbourne

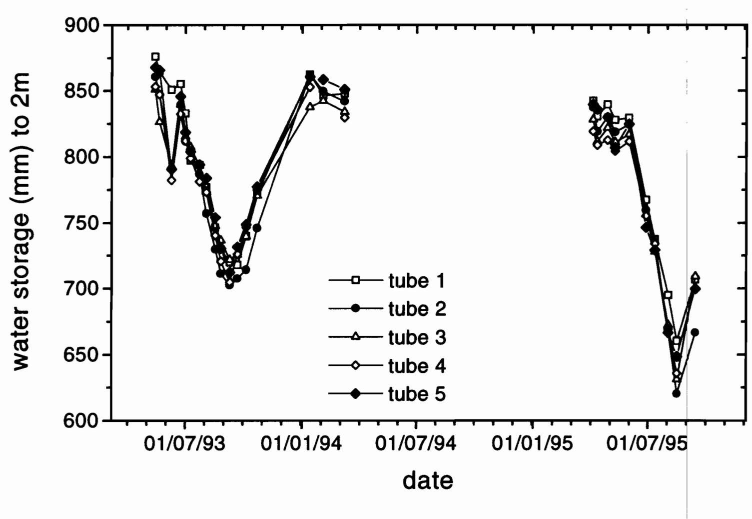


Fig. 3.19 The soil water storage for Tubes 1 to 5 beneath the three-year coppice at Swanbourne

The water table level in the valley is the result of the balance between losses: discharge to ditches and streams and water uptake by plants, and gains: through rainfall and the downslope, sub-surface movement of water to the valley floor as shallow, or perched, groundwater. The water table is maintained near the surface for longer periods than on the slopes as a result of these lateral inputs. Soil water storage changes are suppressed at these times, particularly in winter, spring and early summer, and evaporation estimated from the water balance of the soil profile will be underestimated. In the summer, the downslope contribution to the valley floor generally ceases.

This difference in the hydrology of the slope and the valley floor complicates comparisons between soil water uptake by coppice and by pasture at this site, because soil water availability (which affects yield) differs with position in the landscape, even over relatively short distances. Ideally trials should be carried out on the same part of the landscape. These considerations also complicate the comparisons of soil water uptake estimated from soil water measurements.

The use of the soil water balance to estimate transpiration loss from soil-water content data requires that losses of water due to surface runoff and deep drainage, and gains due to water rising from a water table are all insignificant. However, the tensiometer data from all three sites show that, during the summer, there was a potential gradient causing upward movement of water into the profile from the water table. Because the magnitude of this upward water flux is not readily quantifiable, the transpiration rate estimated from the water balance is subject to uncertainty. However, the data can be used to indicate a lower bound to the transpiration rate.

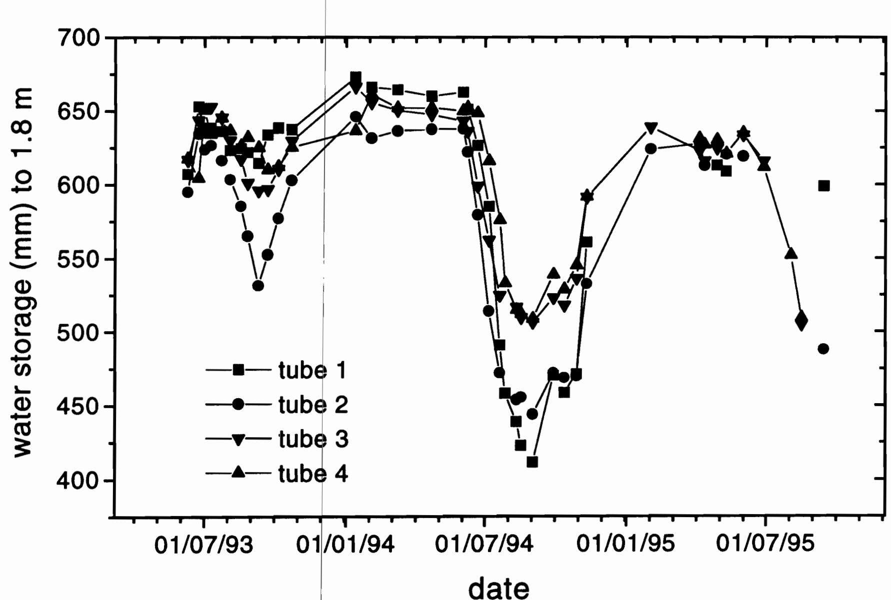


Fig. 3.20 The soil water storage for Tubes 1 to 4 beneath the five-year coppice at Swanbourne

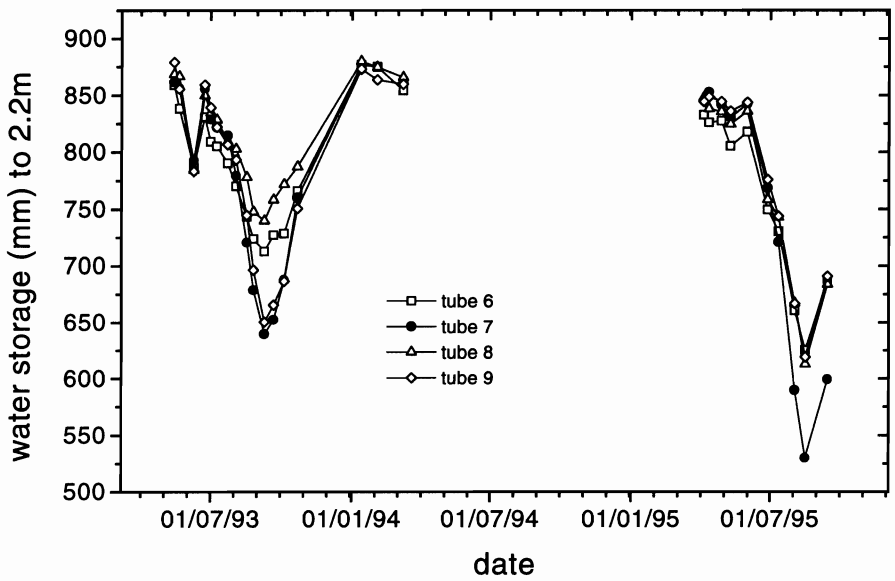


Fig. 3.21 The soil water storage for Tubes 6 to 8 beneath the three year coppice at Swanbourne

Coppice. Figures 3.19, 3.20 and 3.21 show the complete time series graphs of soil water storage for all the tubes beneath the three-year and five-year coppice. It is apparent that all the tubes at an individual site are responding in a similar consistent manner although there is more variation between the tubes in the five-year coppice.

There is little variation between the total water contents of the different tubes in the three-year coppice, except for Tubes 7 and 9 at the end of the summer in 1993, and Tube 7 in 1995, implying that the roots are generally evenly distributed. The variation in the five-year coppice in 1993 may be due to differences in root distribution caused by variable regrowth of the stools which were harvested in February 1993.

In 1993 there was more depletion beneath the three-year old shoots on seven-year old stools in the three-year coppice, than beneath the one year-old shoots on the seven-year old stools in the five-year coppice. The five-year coppice depletion was similar to that observed beneath the pasture. The contrast between the three and one-year old shoots shows the effects of leaf area, and its development, on uptake rate.

The mean soil water storage in the profile to 2 m depth is shown for the three-year coppice in Fig.3.22. The storage in four consecutive layers is shown in Fig.3.23. There were no observations made during the summer of 1994, but the data from 1993 and 1995 may be compared. Depletion in 1995 was only 80 mm more than in 1993, even though the summer of 1995 was much hotter and drier. However, the leaf area of the coppice, which was in its third year of growth in 1993 would have been larger than in 1995, when it was in its second year, having been harvested at the end of 1993.

Figure 3.23 shows that there was uptake from all layers in both 1993 and 1995. There was more uptake from each layer in 1995 but most of the increased uptake was from the upper

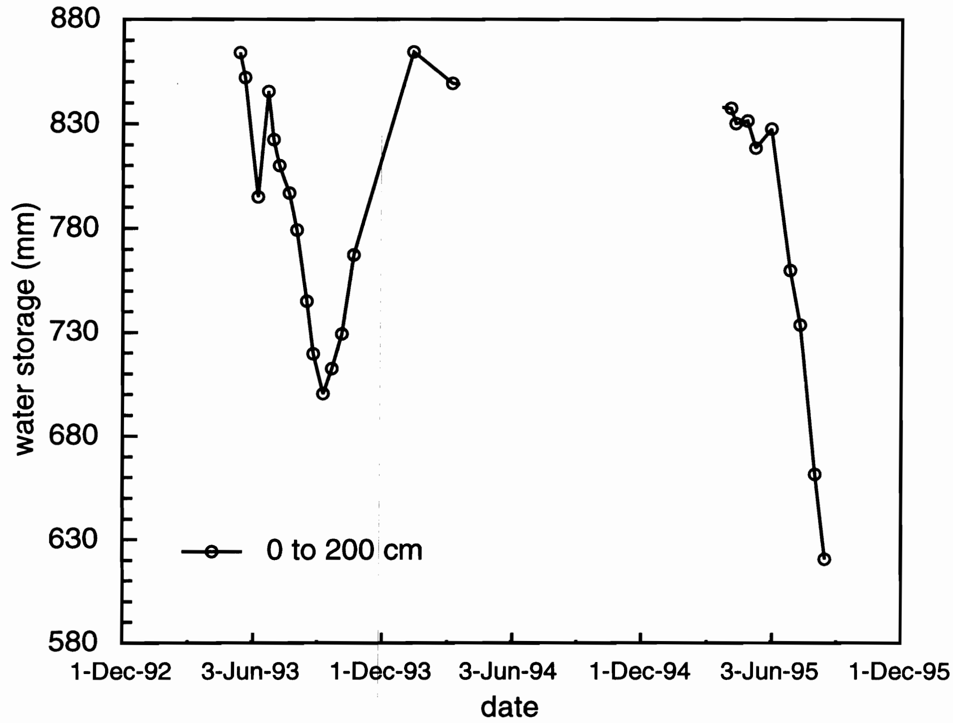


Fig. 3.22 Mean soil water storage to 2 m depth beneath the three-year coppice

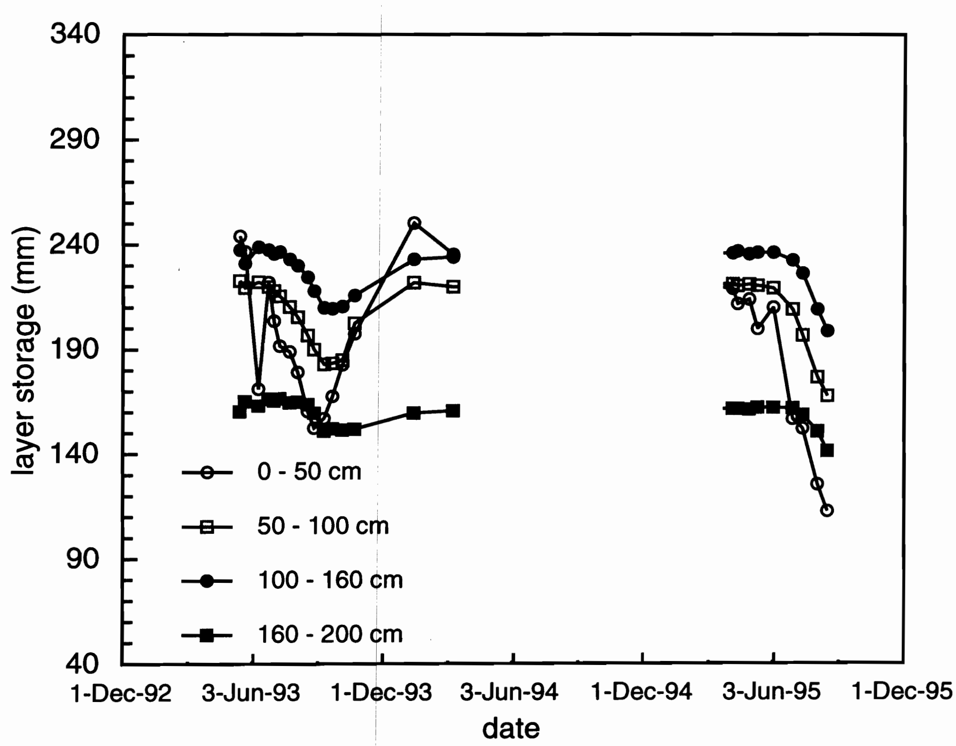


Fig. 3.23 Water storage in four soil layers beneath the three-year coppice

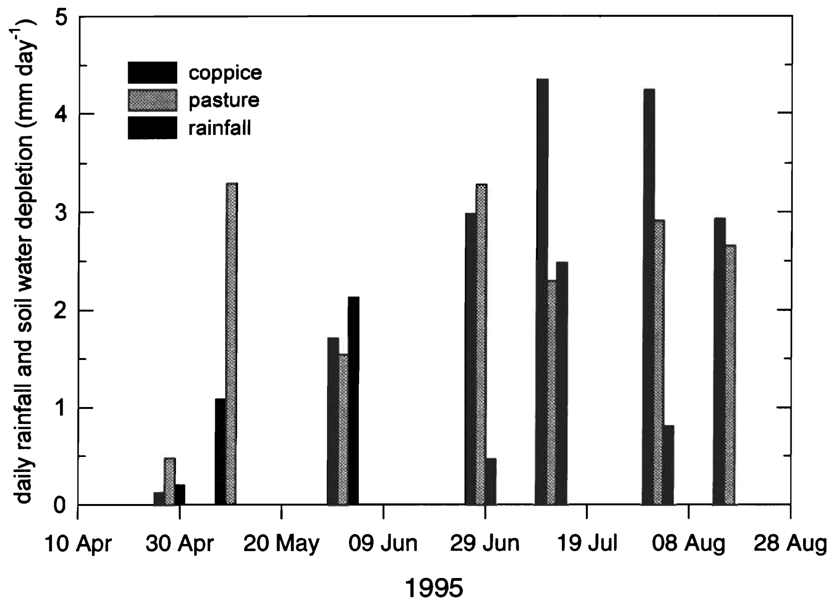


Fig. 3.24 Soil water balance components for pasture and three-year coppice (two-year old shoots on nine-year old stools in 1995)

metre of the profile. In August, there was considerable uptake occurring from all layers in this clay soil. This contrasts with the loamy soil at the Hunstrete site, where uptake from the profile had virtually ceased by late summer.(Section 3.2.2.5)

A comparison of soil water storage data in the 2 m profile for the pasture and three-year coppice show a much stronger contrast in 1993 than in 1995. The hydrological differences discussed earlier make direct comparisons difficult of storage alone. However, as the summer of 1995 was exceptionally hot and dry the loss rates (evaporation plus drainage, calculated as rainfall minus the change in soil water storage) have been determined from the water balance. It was expected that drainage losses would be negligible by July and the loss rates should be a fairly good indication of actual evaporation rates. The loss rates for pasture and three-year-old shoots on nine-year-old stools are shown in Fig. 3.24 together with the rainfall,expressed as a rate, to show its contribution to the water balance. It should be noted that the rainfall data for July and August are from a Meteorological Office gauge about 3 km away. These data were used because of a malfunction of the on-site groundlevel raingauge. In view of the convective nature of the summer rainfall and its variability, it is not known how well these data represent the rainfall at the study site.

From 12-28 April, the loss rates were small, with the pasture rate being the highest. Up to 10 May the pasture rate far exceeded the rate from the three-year-old shoots and indeed the potential evaporation rate, but this is believed to be mainly made up of drainage losses. In the previous period, it is probable that the pasture losses were low because the downslope contribution to the valley floor almost balanced the drainage and evaporation losses. To 1 June, the loss rate was similar under pasture and coppice, and there was an increase in storage in the soil. Through June, the loss rates were very similar and it was only through July that the pasture rate fell significantly below the coppice rate which exceeded 4 mm d^{-1}. In the first half of August, which was completely dry, the rates were lower but again similar. At this

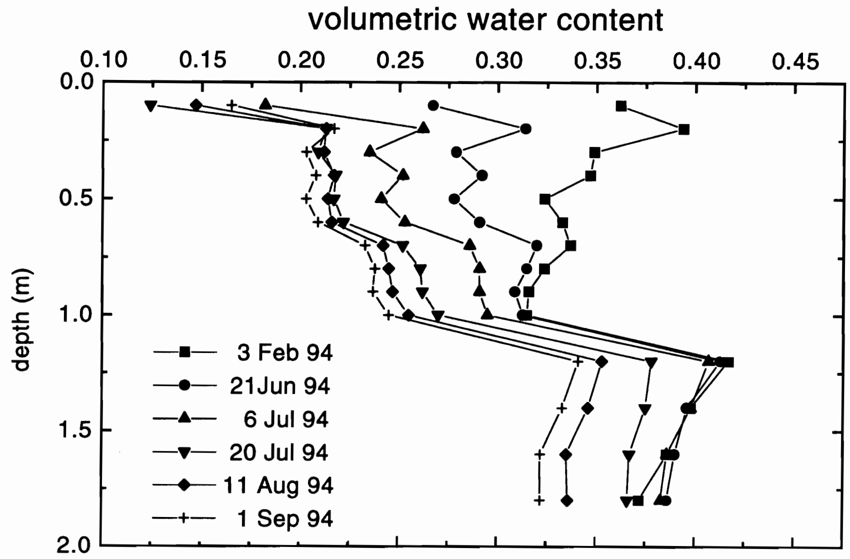


Fig. 3.25 Soil water content profile beneath the five-year coppice (two-year old shoots on eight-year old stools in 1994)

time, the coppice was taking water from the maximum depth of measurement and below, so these rates underestimate the coppice loss rate. There was no apparent uptake by the pasture from below the maximum depth of measurement, and therefore, the loss rates are probably not underestimated.

In 1994 the soil water depletion between 2 June and 11 August was 217 mm for the five-year coppice and 201 mm for the pasture. The rainfall over this period was 71 mm. These figures lead to an estimate of the mean coppice evaporation rate for the period (*taking no account of the water flux from the water table*) of 4.1 mm d^{-1}. This was consistent with the sap flow estimates of transpiration.

Figure 3.25 shows the soil water content profiles beneath the five-year coppice from the winter to the late summer in 1994. Up to 6 July, uptake was limited to the upper metre of the profile, but after this, there was a large amount of uptake from below 1m and uptake continued in the upper metre. There were significant changes of water content at the maximum depth measured.

The sequence of profiles suggest that the coppice was abstracting water from the perched water table during the first part of the summer from the top 1 m of soil: this is seen in the difference between the wetted profile 2 June 1994 and the profile for 6 July 1994. Abstraction from the top 1 m of soil continued until mid-August but with some abstraction also from the deeper clay layer (profile for 11 August 1994). By late August abstraction from the top 1 m of soil was becoming more difficult and most of the water used by the coppice came from the deeper clay layer. Despite some missing data due to malfunctioning tensiometers, support for this interpretation comes from the soil water potential data which show that at the start of the summer the water table was at about 0.6 m and subsequently dropped. This was followed by drying of the soil as evidenced by the large negative potentials.

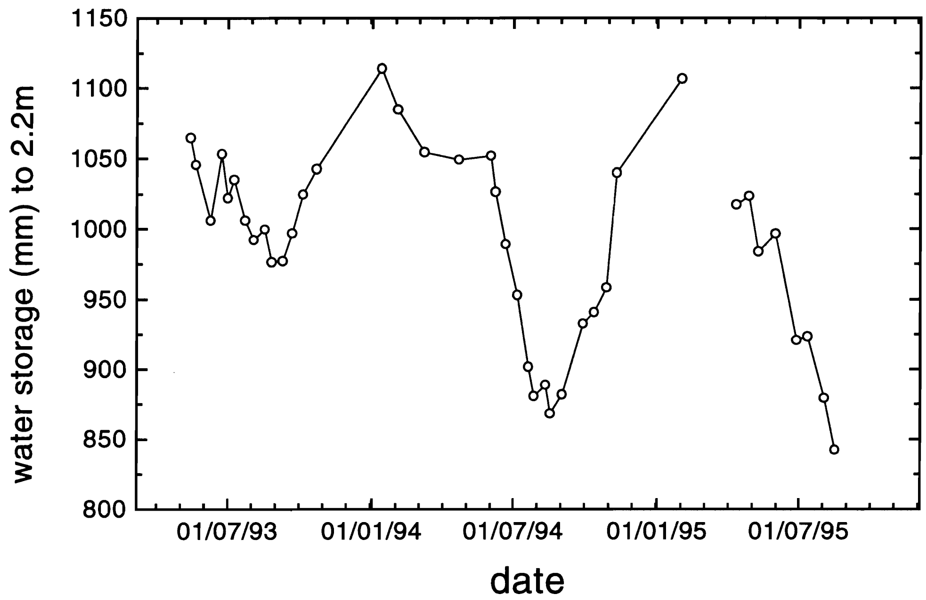


Fig. 3.26 The mean water storage beneath the pasture at Swanbourne

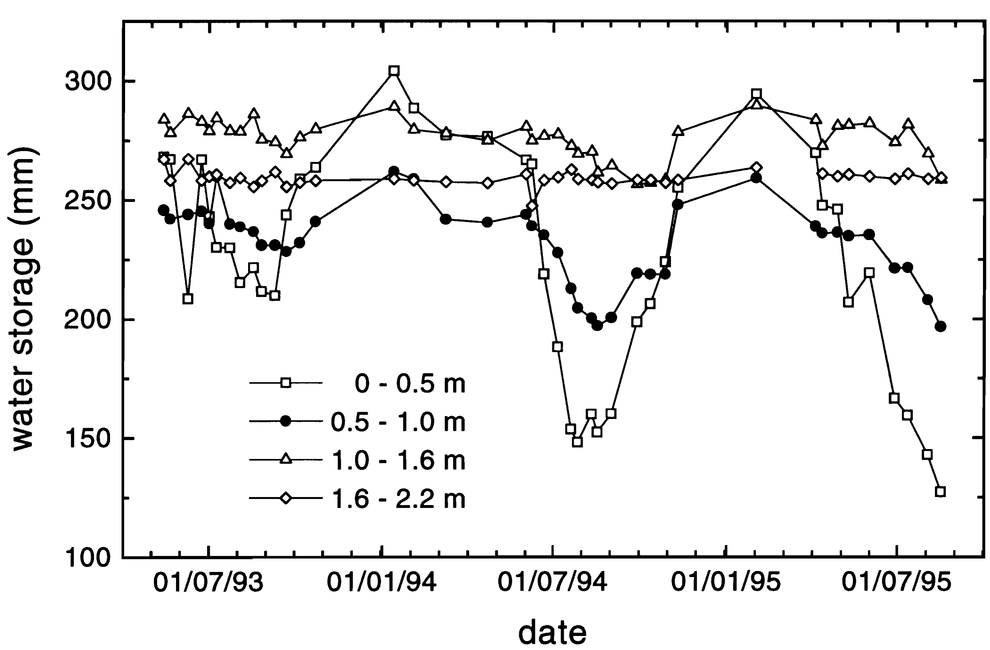


Fig. 3.27 Time series of water storage in four soil layers beneath pasture at Swanbourne

Pasture. Figure 3.26 shows the variation of mean profile water storage to a depth of 2.2 m at the Swanbourne pasture site for the period from May 1993 until August 1995. These time series data of profile water storage reflect the seasonal variation in the transpiration, with the soil water contents decreasing through the summer, despite rainfall (transpiration exceeded rainfall in all of the summers studied) and then increasing in the autumn and winter when rainfall is greater and transpiration is less.

The mean maximum storage for the two winters studied was 1110 mm. There was a large contrast in the soil water depletion between the years, with maximum measured depletions (relative to the 1110 mm maximum storage) of 134 mm, 242 mm and 268 mm in 1993, 1994 and 1995 respectively. In 1995 the maximum depletion was almost certainly greater than 268 mm because there were a further 14 virtually rainless days after the final data shown (16 August). The high rate of depletion at the end of the very dry summer of 1995 indicated that the grass was able to continue taking up water at a significant rate despite the very large soil water deficit.

Figure 3.27 shows the water storage in 4 consecutive layers (0-0.5 m, 0.5-1.0 m, 1.0-1.6 m and 1.6-2.2 m) and shows the distribution of the seasonal water storage change with time and depth. It can be seen that there was no significant change in the 1.6-2.2 m layer which was saturated almost throughout the period shown. There was a maximum change of about 20 mm in the 1.0-1.6 m layer in both 1994 and 1995, and a very small change in 1993. In the 0.5-1.0

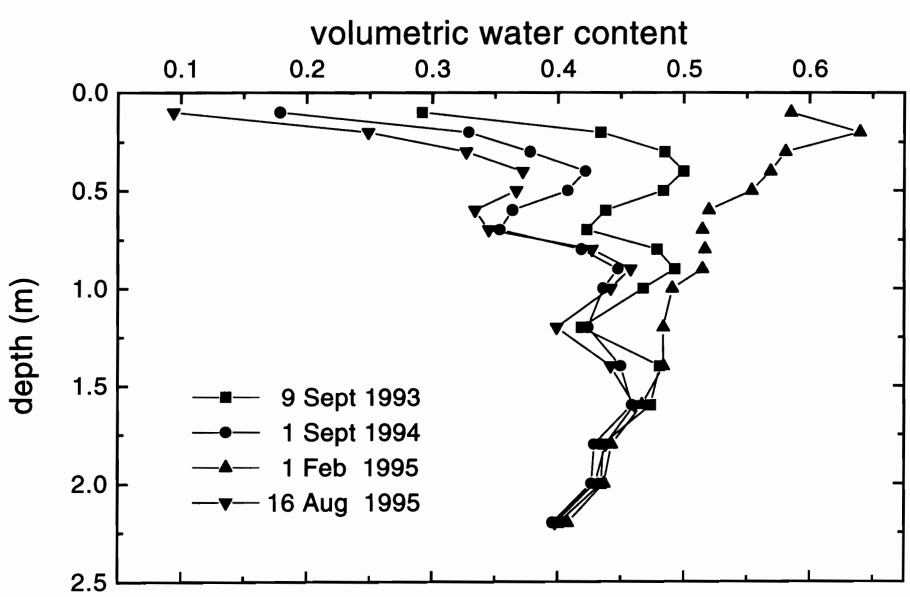


Fig. 3.28 Profiles of water contents beneath the pasture at Swanbourne

m layer, the storage changes were 31 mm larger in 1994 and 1995 than in 1993. Most of the additional uptake in 1994 and 1995, compared to 1993, was concentrated in the upper 0.5 m of the profile, where uptake in 1994 and 1995 was 58 mm and 83 mm respectively more than in 1993.

The driest conditions in the 3 summers studied are shown as profiles of water content in Fig. 3.28, with one of the wettest profiles for comparison. There appears to be a sandy lens in the profile at a depth of about 1 m which results in a sudden change of water content at that depth, probably when it drains as the water table falls. The maximum depth of uptake was

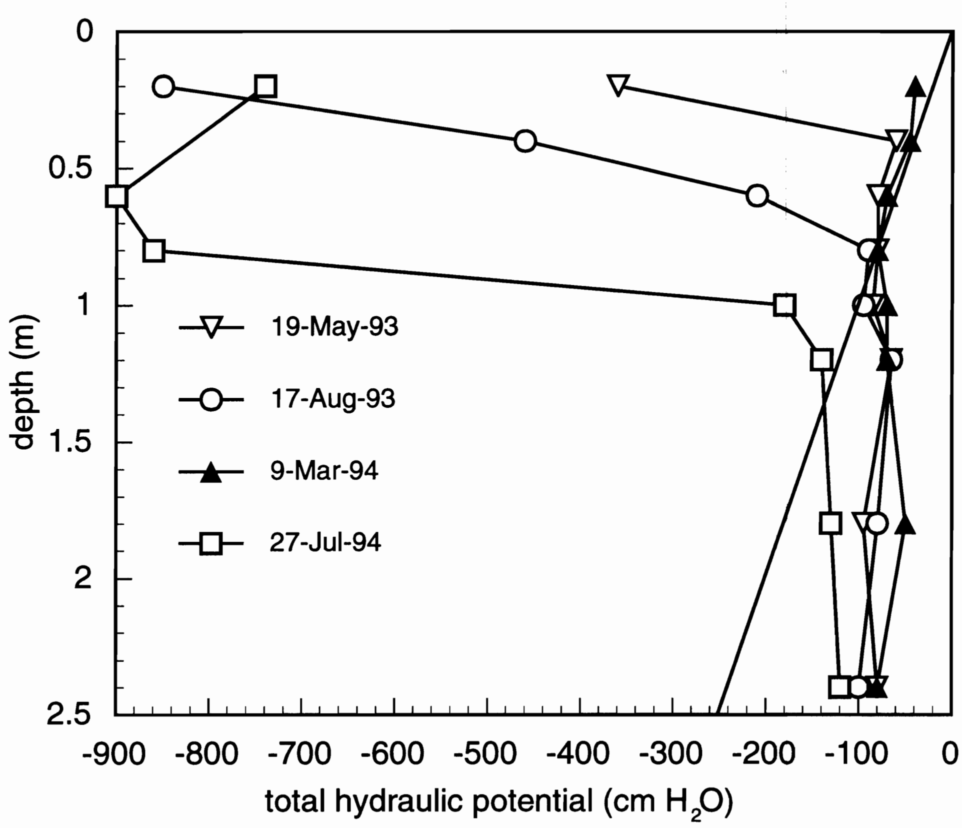


Fig. 3.29 Profiles of soil water potential beneath the pasture in 1993 and 1994

about 1.6 m in 1994 and 1995, with the main difference in uptake between those years occurring in the top 0.7 m of the profile.

Figure 3.29 shows profiles of soil water potential for various dates in 1993 and 1994. Points to the right of the diagonal "zero-tension line" indicate saturated conditions. It can be seen that the water table was at a depth of 0.8 m in mid-August 1993, but fell deeper (1.25 m) earlier in the summer in 1994 (July). In both cases there was an upward potential gradient from the water table, indicating some direct uptake of water. At this site, water content measurements are taken to below the depth of the water table (to 2.3 m) and water balance estimates will therefore take into account uptake from the water table. However, if there are significant gains and losses due to lateral water movement in the saturated zone (eg to streams or ditches, or very slow deep drainage), this will not be the case. In dry summers, when the water table is deep, the loss to ditches is probably negligible.

3.1.2.6 *Sources of water and the root length profile of poplar coppice at Swanbourne*

Observations have shown (Section 3.1.2.5) that a perched water table is present for much of the year at Swanbourne. Heavy clay with very low permeability in the lower soil horizons is thought to cause overlying soil to become saturated during periods of high rainfall, so that the depth of the water table fluctuates between a level close to the soil surface in winter and a depth of approximately 1.2 m in summer. In studies of the water balance at the site, however, it has not been possible to determine with certainty whether the coppiced trees are able to utilise water from the water table directly or whether they are only able to take up water from the unsaturated zone above the water table. Consequently, a study was undertaken in 1995 to determine the rooting characteristics of the poplar hybrids at the site and to identify the source of water used by the trees during the growing season.

The rooting characteristics of the trees will indicate from where in the soil profile the trees are capable of extracting water. Previous studies have shown that roots of poplar growing in short rotation plantations typically proliferate in the top 20 cm of the soil profile, where horizontal roots are found that grow radially away from tree stems for several metres (Dickmann and Pregitzer, 1992). Puri et al. (1994) showed that 65-80 % of the fine root biomass of nine-year-old *Populus deltoides* trees was present in the top 15 cm of the soil, suggesting that the majority of the root system of poplar is confined to the top layer of the soil. However, vertical sinker roots have been observed to branch from horizontal poplar roots near the surface and to penetrate more than 3 m (Dickmann and Pregitzer, 1992), so that uptake of water from deeper layers is possible.

The source of water taken up by woody plants can be identified by comparing the isotopic ratios of water in the xylem vessels of plant stems with water from sources below ground which are accessible to roots of the plants. Ratios of the stable isotopes of oxygen and hydrogen in water vary naturally as a result of meteorological and hydrological processes, so that differences in the isotopic ratios of groundwater and soil water near the soil surface are often found (Flanagan and Ehleringer, 1991; Brunel et al., 1995). Isotopic ratios do not change during the movement of water into plant roots (Dawson and Ehleringer, 1991; Thorburn et al., 1993) and thus, if the isotopic ratio for xylem water is also known, it is possible to identify whether woody plants are transpiring groundwater from below the water table or whether they must rely on water from recent rainfall stored in the top layers of the soil (Brunel et al., 1995). At Swanbourne, differences in the isotopic ratios of the perched water table and soil water near the surface may arise if the saturated zone is mostly constituted of winter rainfall while overlying soil contains water from summer rainfall (Heathcote and Lloyd, 1986). If such a gradient in isotopic ratios of water is found at the site, it may be possible to identify whether the root systems of the poplars use water from the saturated zone.

Assessment of root length profiles and sources of water taken up by poplar hybrids was confined to Rows 1 to 28 at Swanbourne, the non-fertilised rows of the three-year coppice. Measurements of soil water content were made to a depth of 2.0 m using a neutron probe at access tubes located between Rows 19 and 22 (see Fig. 3.18) and soil water potentials were measured using the array of tensiometers installed between Rows 20 and 21 at a range of depths between 0.2 and 2.4 m. The depth of the perched water table was monitored by measuring the depth to the water surface in a dipwell installed near row 21. Rainfall was measured using a tipping bucket raingauge installed in a field adjacent to the site, although a malfunction of this gauge meant that data for part of the summer was taken from a raingauge monitored by the Meteorological Office that was located 3 km southwest of the site.

Sampling for the isotope study. Samples of soil and tree twigs were collected on three occasions during the 1995 growing season and analysed for ratios of $^{18}O/^{16}O$; these were 10 May, 28 June and 14 September. In each case, twig samples were taken from the Beaupré and Dorschkamp hybrids only. On 10 May and 28 June, soil samples were taken from the surface and then depths of 0.1, 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 m using a hand auger. Samples of soil were collected at four locations, each in an inter-row space between rows from which twigs of Beaupré and Dorschkamp were taken, which were: (1) Rows 5 and 6; (2) Rows 9 and 11; (3) Rows 20 and 21; and (4) Rows 28 and 26, respectively. Twig samples were cut from the trees using secateurs, ensuring that only twigs with mature bark were taken. After cutting, the short (≈8 cm) twig samples were immediately sealed inside glass Exetainer vials (Europa Scientific Ltd., Crewe), as were the small amounts of soil retained from each depth in the soil. On 14 September, the same sampling strategy was used, except that a power auger was used to extract soil samples from depths of up to 2.0 m and samples were only taken at the first three of the four locations used previously. Samples of water from below the water table were taken by lowering an open Exetainer into the dipwell when water was present.

Analysis of samples for $\delta^{18}O$. Isotopic ratios of oxygen ($^{18}O/^{16}O$) in the water contained in the samples collected were measured with an isotope ratio mass spectrometer at the Scottish Crops Research Institute, Dundee, using the direct equilibration method described by Scrimgeour (1996). Ratios of stable isotopes are normally expressed relative to a standard using delta (δ) notation, with $\delta^{18}O$ given by

$$\delta^{18}O \;=\; \left(\frac{R_s}{R_{SMOW}} - 1\right)1000,$$

where R_s and R_{SMOW} are the $^{18}O/^{16}O$ ratios for the sample and Standard Mean Ocean Water, respectively (Ehleringer and Dawson, 1992). Values of $\delta^{18}O$ are expressed as fractions of a thousand, giving units of per mil (‰).

Collection and processing of root samples. Root profiles of the coppiced trees were determined from soil samples collected on 14 September, which were extracted using the power auger system from weed-free areas midway between Rows 5 and 6, 9 and 10 and 20 and 21. Samples were taken in increments of 0.2 m between the surface and a depth of 2.0 m using a gouge auger with an internal diameter of 4.8 cm. All samples were placed in plastic bags after collection and then stored in a freezer until processed.

Roots were washed from each soil sample using a sieve with a 64 μm mesh size and then stored in a vinegar solution until root lengths were determined. First, however, each sample was inspected visually and roots of other species, dead roots and other organic debris were removed. Root lengths were measured by spreading each sample out on a glass-bottomed tray and using a computer scanner to obtain a digitised image of the roots before the length of roots in each sample was determined using image analysis software (Delta-T Scan, Delta-T Devices Ltd., Burwell).

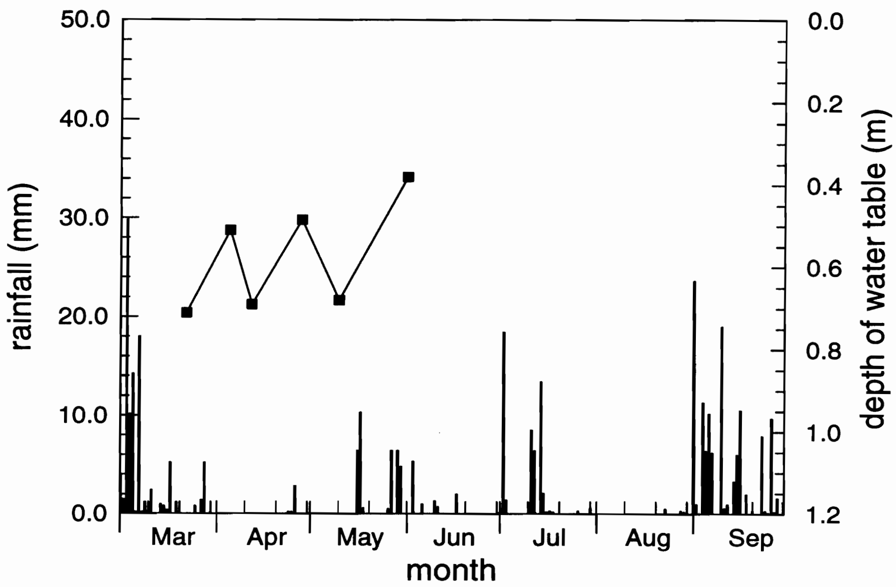


Fig. 3.30 Daily rainfall at Swanbourne during 1995 (bars) and the depth to the water table beneath two-year old shoots on nine-year old stools (line). No water table was observed from June 28 onwards.

Level of the water table. The summer of 1995, following a dry spring, was very dry, with little rain during June and from mid-July to early September (Fig. 3.30). As a result, no perched water table was found beneath the three-year coppice at Swanbourne from 28 June onwards (Fig. 3.30) because of lack of rain, drainage through the underlying heavy clay and, possibly, uptake of water by the trees from the saturated zone.

Root length profile. Extraction of water by the trees from the water table was only possible if their roots had penetrated into the saturated zone. Figure 3.31 shows that, in contrast to the root profile for poplar described by Puri et al. (1994), which showed that almost 80 % of fine root biomass of nine-year-old poplars was found in the top 15 cm of soil, the coppiced trees at Swanbourne had a relatively uniform distribution of root length to a depth of 2.0 m. Some variation of root length density with depth was found, however, and as observed by Puri et al., root length density was high at the top of the profile; it then diminished with depth to 1.2 m, below which there was a second proliferation of roots until 1.8 m, where root length density again decreased. The proliferation of roots below 1.2 m suggests that conditions for root growth in this region were good, as roots of *Populus* species have been found by others to proliferate at depth where resources are available for uptake (Friend et al., 1991).

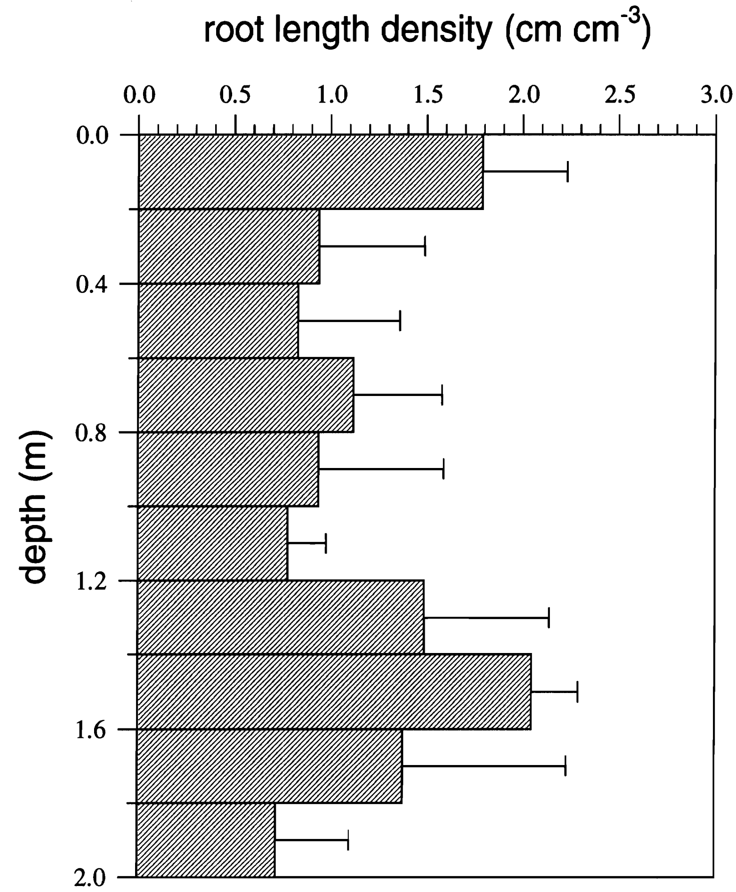


Fig. 3.31 Root length density beneath the three-year coppice (two-year old shoots on nine-year old stools in 1995) at Swanbourne (n=3). Error bars show 1 standard error.

Analysis of isotopic profiles. The disappearance of the saturated zone from the soil profile in the early summer lessened the usefulness of using isotopic profiles in soil to establish the sources of water taken up by the trees. This technique uses the naturally-occurring variation in isotopic ratios to differentiate among water sources. At Swanbourne, where the perched water table is thought to be due largely to winter rainfall, successful application of technique requires that summer rainfall infiltrating into the soil surface has a different isotopic ratio from winter rainfall. With a general absence of summer rainfall in 1995 and the rapid dry-down of the saturated zone in the early summer, isotopic ratios were unlikely to demonstrate definitively whether or not the coppiced trees were able to exploit water in the water table without also referring to other information about soil water status at the site.

Figure 3.32 shows the profile of the mean $\delta^{18}O$ value at the site on 10 May, the first day on which samples were collected and which was before the water table disappeared. As is often found (Allison et al., 1983), water near the soil surface was enriched in ^{18}O as a result of evaporation, and $\delta^{18}O$ values decreased roughly exponentially with depth. The $\delta^{18}O$ value for water sampled from the saturated zone matched the values for water in soil from the same depths. The values for water in the xylem of the twigs on this day were intermediate to the

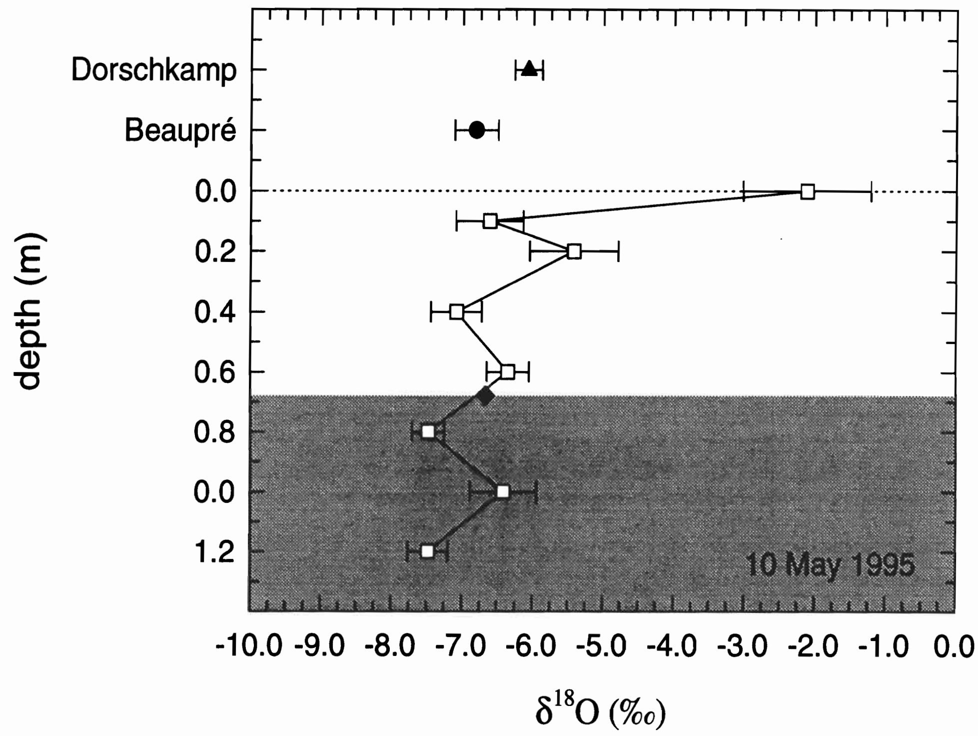


Figure 3.32 The $\delta^{18}O$ profile for soil water (□) (n=4) beneath the three-year coppice (two-year old shoots on nine-year old stools in 1995) at Swanbourne on 10 May, 1995. Also shown are the $\delta^{18}O$ values for xylem water from Beaupré (●) and Dorschkamp (▴) twigs (n=4) and the value for water from the saturated zone (♦) (n=1), the approximate extent of which is indicated by the shaded area. Error bars show ±1 standard error.

values at the surface and in the saturated zone, indicating that the trees were using water from a range of soil depths (Ehleringer and Dawson, 1992); the $\delta^{18}O$ value for Beaupré suggests the trees were extracting water largely from below 0.4 m and the value for Dorschkamp suggests that these trees were also utilizing some water from above 0.4 m. Changes in soil water content with time leading up to 10 May also indicate there was some extraction of water from the top 0.4 m (Fig. 3.35).

By 28 June, the saturated zone beneath the three-year coppice had become unsaturated. Values of $\delta^{18}O$ for water in the twigs were slightly lower than any of the values for soil water (Fig. 3.33), which were almost uniform between 0.4 and 1.2 m, suggesting that the trees were using water from some unidentified deeper source. It is also possible, however, that apparent differences in $\delta^{18}O$ values between plant water and soil water at 0.4 m and below reflect variability in the data, because there is no reason to suspect that $\delta^{18}O$ values for soil water are more negative below 1.2 m. It is probable, therefore, that the data indicates the trees were using water from 0.4 m and below, which is also suggested by the reduction in soil water content from the surface to a depth of 1.2 m between June 1 and 28 June (Fig. 3.35). Such drying of the soil could also have resulted from drainage, as the soil water potential decreased between 0.8 and 2.4 m on 28 June (Fig. 3.36) and so the dry-down of the perched water table probably occurred as a result of both uptake by the trees and drainage.

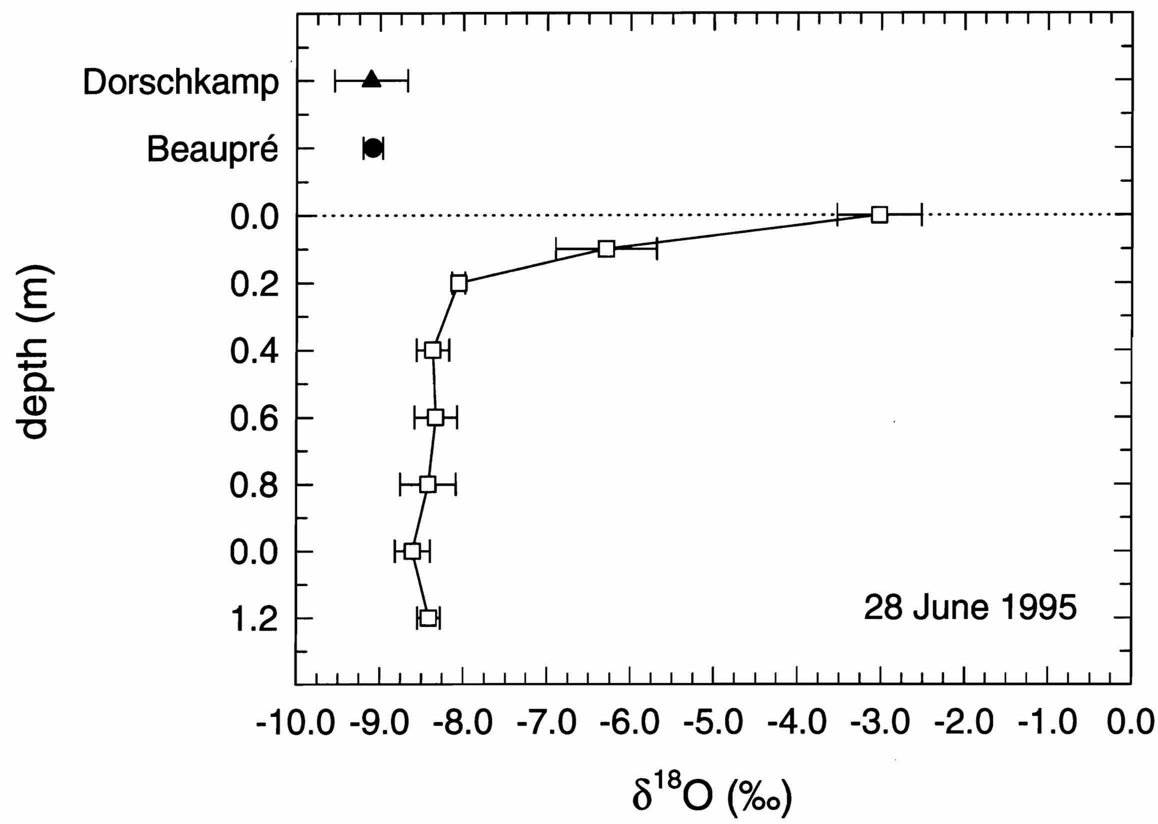


Fig. 3.33 The $\delta^{18}O$ profile for soil water (□) (n=4) beneath the three-year coppice (two-year old shoots on nine-year old stools in 1995) and the $\delta^{18}O$ values for xylem water from Beaupré (●) and Dorschkamp (▲) twigs (n=4) at Swanbourne on 28 June, 1995. Error bars show ±1 standard error.

The surface layers of the soil profile had become more moist by 14 September following rainfall at the end of the very dry summer period, although the water table was still absent. Comparison of soil water profiles between 28 June and 14 September (Fig. 3.35) shows that drying of the soil occurred down to 2.0 m, indicating that the trees had used water from the whole soil profile. The isotopic composition of xylem water from the twigs suggests, however, that on 14 September, the top 0.4 m of the soil profile was contributing at least a small amount of water to transpiration by the trees, particularly by the Dorschkamp trees (Fig. 3.34). Thus, it appears that the trees were able to exploit the rainwater that re-wet the soil surface at the end of the summer, despite any damage to the active root system near the soil surface that may have been caused by severe drying of the soil over the summer.

The root length profile for the poplar coppice at Swanbourne suggests that the trees there were able to extract water from the whole soil profile, at least to a depth of 2 m. Changes in soil water contents over the summer of 1995 and the information derived from $\delta^{18}O$ values for water in twigs and the soil profile showed that the trees extracted water from all depths down to 2 m at some point during the summer. Isotopic ratios for water in the soil and twigs in the early summer suggested that the trees were obtaining at least a portion of their water from the saturated zone, so that uptake by the trees probably contributed to the rapid dry-down of the

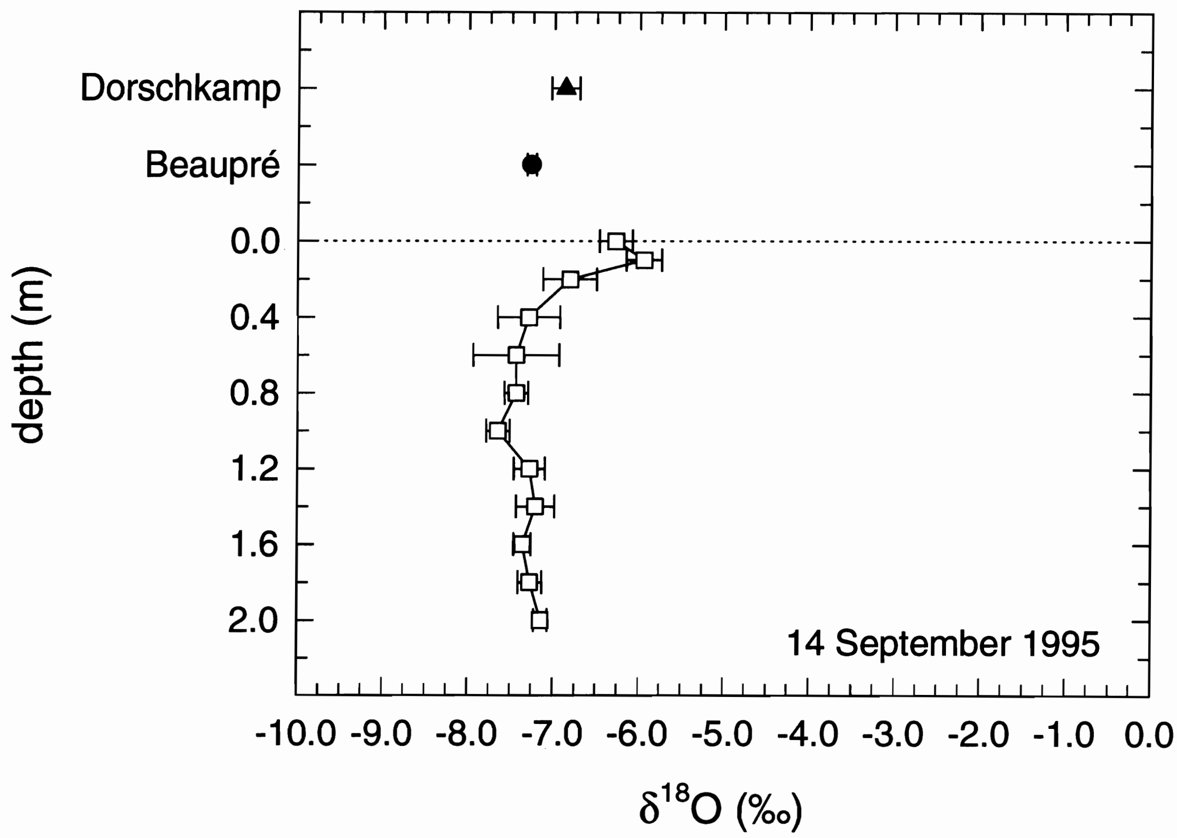


Fig. 3.34 The $\delta^{18}O$ profile for soil water (□) (n=4) beneath the three-year coppice (two-year old shoots on nine-year old stools in 1995) and the $\delta^{18}O$ values for xylem water from Beaupré (●) and Dorschkamp (▲) twigs (n=4) at Swanbourne on 14 September, 1995. Error bars show ±1 standard error.

perched water table during the first half of the summer. At the end of the dry period over the summer, when the soil surface was re-hydrated by rainfall, the trees began to extract water from close to the surface. Thus, the poplar trees at Swanbourne were able to adapt to changing soil water availability, utilising water from saturated or unsaturated zones.

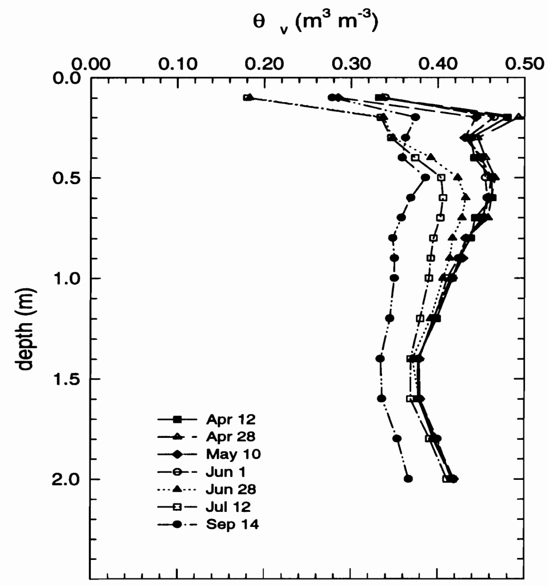


Fig. 3.35 Profiles of volumetric soil water content (θ_v) beneath the three-year coppice (two-year old shoots on nine-year old stools in 1995) at Swanbourne 1995.

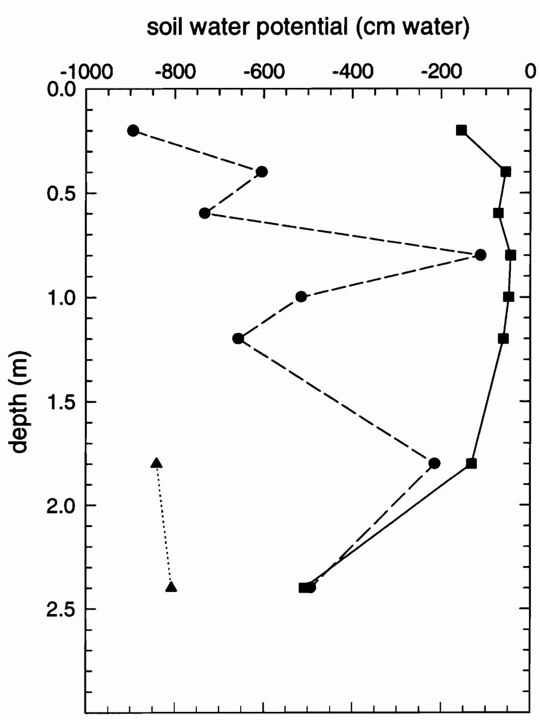


Fig. 3.36 Profiles of soil water potential beneath the two-year old shoots on nine year old stools at Swanbourne on 10 May (■), 28 June (●) and 14 September (▲), 1995. Missing data on 14 September occurred because of cavitation in some tensiometers.

3.2 MEASUREMENTS AT HUNSTRETE (KNOWLE FARM)

3.2.1 Site description and equipment layout

The layout of the coppice plantations at Hunstrete are shown in Fig. 3.37. The topography is undulating and the fields that have been planted to poplar are surrounded by woodland and pasture and on a gentle, less than 10%, north-facing slope. In all 10 ha were planted in three blocks in three successive years starting in 1992 mainly with poplar clones, Beaupré and Boelare (*P. trichocarpa* x *deltoides*) and some Trichobel (*P.* x *trichocarpa*). In addition there are a few rows of three willow clones Germany (*Salix burjatica*), Q83 (*S. triandra* x *viminalis*) and Dasyclados (*S. caprea* x *cinerea* x *viminalis*). The soil at Hunstrete differs between the lower and upper parts of the slope. At the bottom it is a freely draining sandy loam overlying red soft calcareous sandstone that contrasts with the clay at Swanbourne. Nearer the top of the slope it has a larger clay content and is subject to cracking in the summer.

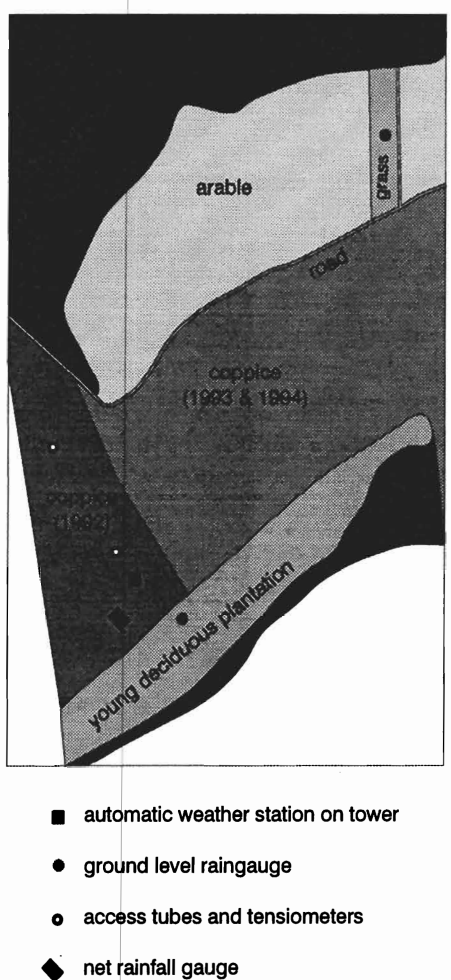


Fig. 3.37 Map of the coppice plantation at Hunstrete

3.2.2 Measurements

The disposition of the equipment at Hunstrete is also shown in Fig. 3.37. Two logged ground-level raingauges were installed, one 0.1 mm (connected to an AWS) and one 0.2 mm tipping bucket with a separate logger. With the exception of the raingauges the equipment was installed in a twenty-row block of Beaupré planted in 1992 and in the third year of coppice growth. This block was separated from a block of Boelare to the south west by a single row of willow and, on its north eastern edge, next to a block of Trichobel which also contained a double row of willow (Fig. 3.38). All of these clones had three-year old shoots on four-year old stools. The net-rainfall gauge and AWS were installed in April. As at Swanbourne in 1993 and 1994, there were three intensive data collection campaigns over the summer of 1995 when sap flow and stomatal conductances were measured and canopy surveys made. The timing of the different measurements during the summer are shown in Fig. 3.39 together with the measured leaf area index and soil water deficit (see Sections 3.2.2.2 and 3.2.2.5).

3.2.2.1 *Weather*

As at Swanbourne meteorological variables were measured using the AWS on top of a tower (Fig. 3.40). However the trees were taller at Hunstrete and two extra sections of tower were required to ensure that the weather station and solar panels, required to charge the batteries

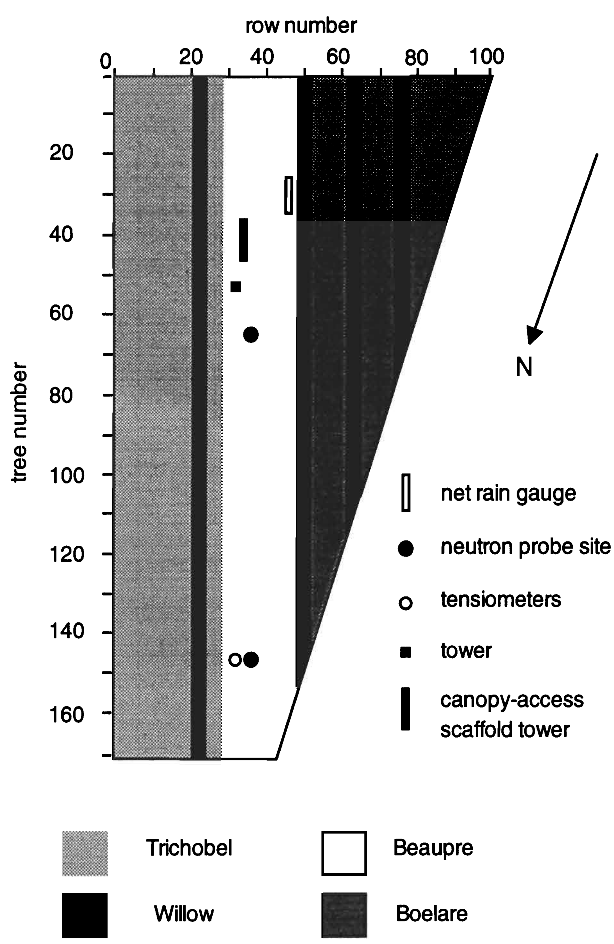


Fig. 3.38 Detailed map showing the position of the different pieces of equipment within the 1992 Beaupré plot at Hunstrete

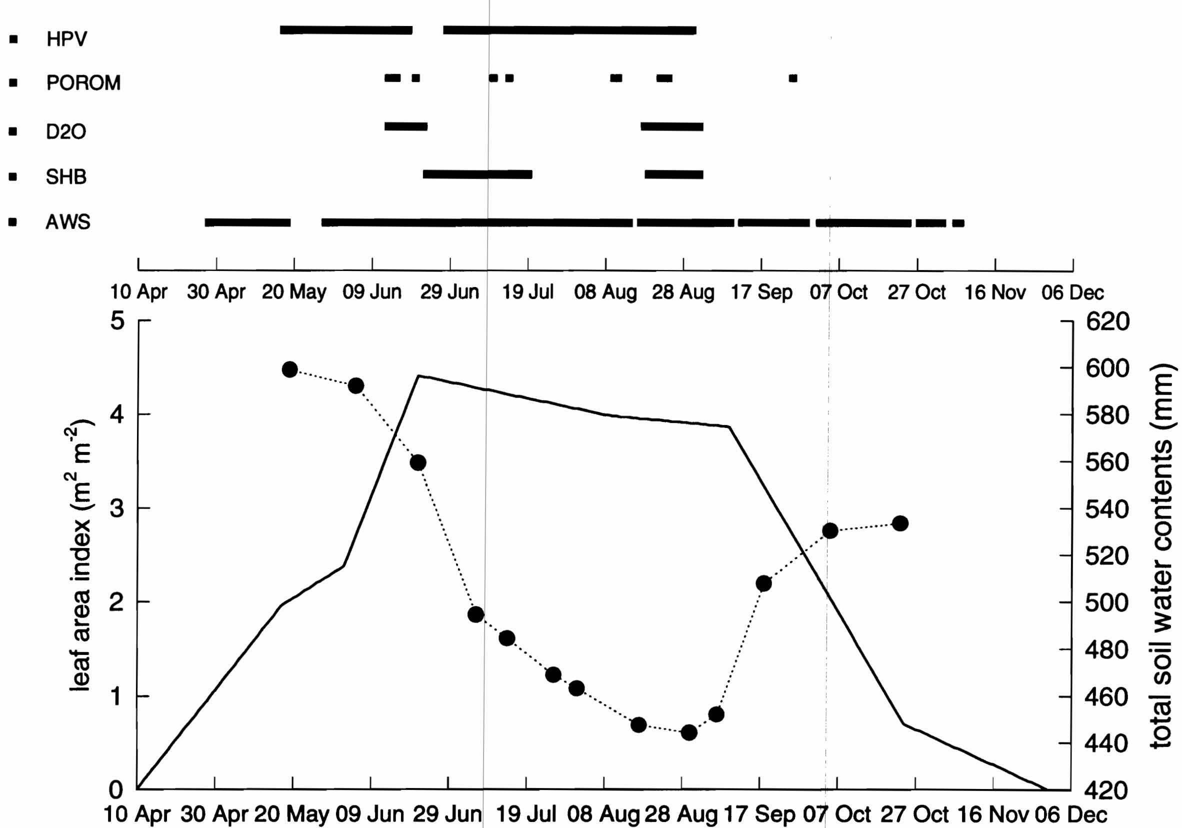


Fig. 3.39 The timing of the differnt measurements made on the coppice at Hunstrete during the summer of 1995. Also shown is the development of the leaf area index and the soil moisture deficit (dotted curve).

for the sap flow gauges, were sufficiently above the canopy. The AWS was at a height of 9.6 m above the ground. Meteorological variables were logged (Model CR10, Campbell Scientific Ltd, Loughborough) at ten-minute intervals by the AWS and data collection continued throughout the summer and autumn until the tower had to be dismantled prior to harvesting of the coppice. Sensors on the AWS measured incoming solar radiation, net-radiation, temperature (wet and dry bulb), windspeed and direction, and rainfall. In addition a tipping bucket flowmeter that measured the runoff from a nearby plastic-sheet net-rainfall gauge (Section 3.2.2.6) was also connected to the AWS.

Two ground-level tipping-bucket raingauges were installed (Fig. 3.41): one about 20m south of the plantation and connected to the AWS, the other about 500 m to the west and logged independently (Rainlog, model DDL 04, Didcot Instrument Co. Ltd, Abingdon). The raingauge closest to the plantation was calibrated as giving one tip per 0.092 mm of rainfall and the more distant raingauge as giving one tip per 0.22 mm of rainfall. In addition to these a plastic funnel was supported on the tower 6 m above the canopy to collect rain that was fed into the AWS raingauge. Placing the funnel well above the canopy in this way minimises the effects of turbulence on the rainfall measurement. The calibration factor of the AWS raingauge was 0.21 mm.

A summary of the weather recorded by the AWS and the mean daily Penman potential evaporation estimate, based on 24 hour data, are tabulated in Table 3.6. Because of problems with the logging system the record of the weather contains a few short periods with data

Fig. 3.40 The tower-mounted automatic weather station over the Beaupré coppice. The net radiometers on booms, anemometer and wind vane, funnel for the raingauge and solar panels are all visible.

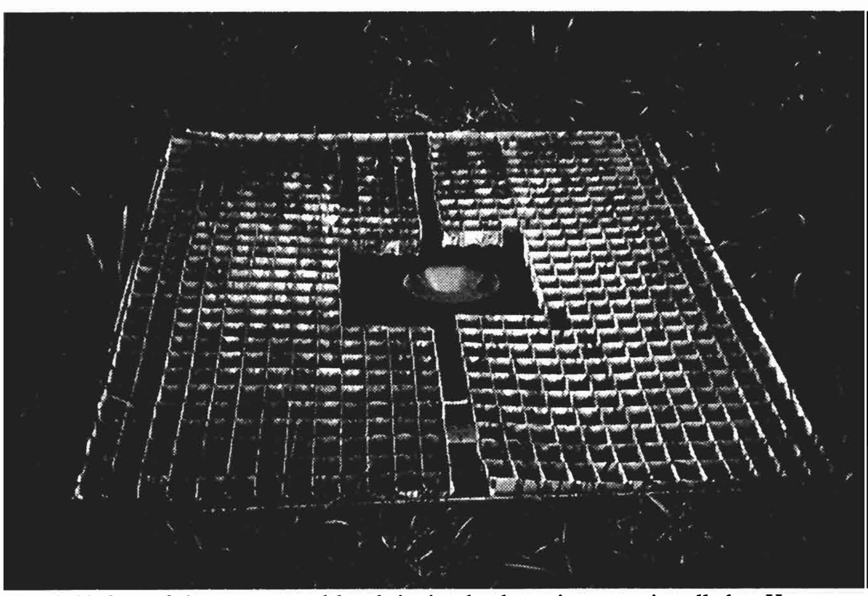


Fig. 3.41 One of the two ground-level tipping bucket raingauges installed at Hunstrete. This one was located about 20 m from the southern edge of the (1992) Beaupré plantation.

missing: the recovery rate was 91% between 18 April, when the AWS was installed, and 31 October, and 97% between 9 June and 2 September. Data from an AWS operated by the Institute of Hydrology at Alhampton (Nat. Grid Ref. ST362135), Somerset, 27 km south of Hunstrete, were used to infill using regression relationships between the two data sets. The two groundlevel raingauges were in good agreement and indicated that for the period of measurement there was little spatial variation at the site. The best estimate of the rainfall was taken as that from the AWS gauge. For the few periods when the AWS was non-operational the rainfall recorded by the independently logged raingauge were used.

The summer of 1995 was exceptionally hot and dry; the rainfall recorded at the site was less than half the long-term (1961-1990) mean rainfall (from Met. Office records) for June to August inclusive of 192 mm. This made it possible to collect data from SRC under severe water stress.

Table 3.6 Summary of the weather at Hunstrete between 9 June and 2 September 1995

variable	minimum	maximum	mean	$\sigma^{\dagger}$	total
solar rad. (MJ m^{-2})					1510
air temp. (°C)	4.2	32.4	17.0	4.4	
humidity deficit (g kg^{-1})	0	24.3	3.6	4.1	
windspeed (ms^{-1})	0	6.8	1.9	1.1	
rainfall (mm)					78.5
Penman E_T (mm day^{-1})	0.9	6.9	3.8	1.4	

† one standard deviation

3.2.2.2 *Stem and leaf surveys*

Surveys of stem diameters and leaf areas were made through the summer of 1995 on the three-year shoots on the four-year old stools. Measurements of the stem diameter distribution of the Beaupré were made on 26 April, 17 May, 2 June, 13 June, 22 August, 25 September and 24 October and of the willow on 7 July. Single stems (from different stools) were chosen to represent the diameter classes which contributed significantly to the total stem cross-sectional area of the rows. To estimate the leaf area the stratified sampling procedure used at Swanbourne was followed, but unlike Swanbourne where the stems were shorter, the selected stems were felled before the leaves were harvested and the total area measured of the leaves from each stem with the leaf area machine (Model 3100, LI-COR Inc., Lincoln, NE, USA) and this area plotted against stem diameter. Leaves were collected from the three-year old Beaupré shoots on 17 May, 2 June, 21 June, 9 August, 9 September and 24 October and from the willow on 21 July. The relationships differ from those for the trees at Swanbourne in that the best fits were obtained when the leaf areas were plotted against stem cross-sectional area rather than stem diameter. Also, unlike Swanbourne, there do appear to be distinct relationships for different times in the summer for the Beaupré but also some commonality between some consecutive surveys as shown in Table 3.7 which summarise the parameters of the regression equations from the six surveys. For the first five surveys the relationship is linear, i.e.

$$L = a + bs \tag{5,1}$$

for the sixth survey, after significant leaf fall the best fitting relationship was:

$$L = a + b\ln^2(s) \tag{5,2}$$

Table 3.7 Parameters for the equations relating leaf area to stem cross-sectional area for Beaupré and Germany (willow) at Hunstrete

clone	survey dates	intercept (a)	coefficient (b)	r^2
Beaupré	17 May 95	-0.2511	0.0018	0.869
Beaupré	2 and 21 June 95	-0.257	0.0032	0.938
Beaupré	9 Aug. 95 and 9 Sep. 95	-0.3227	0.0026	0.902
Beaupré	24 October 95	-0.6766	0.026	0.328
Germany	21 July 95	-0.2321	0.0012	0.913

3.2.2.3 *Transpiration*

Transpiration from coppice trees at Hunstrete was measured using stem heat balance (SHB) sap flow gauges, as had been done at Swanbourne in 1993 and 1994. In addition two further techniques were introduced: deuterium tracing and heat pulse velocity (HPV). There were two main reasons for supplementing the stem heat balance measurements. Firstly, at Swanbourne, very high transpiration rates had been measured using the heat balance gauges. The two additional methods both work on different principles, so provided a means of independently verifying the heat balance results. Secondly, the trees in the Hunstrete coppice were generally larger than those studied previously at Swanbourne, as they were in their third year of growth, and each stool had fewer stems. The SHB sap flow gauges ranged in size from 16 to 35 mm diameters, but a significant proportion of the stems were outside this range (up to 60 mm). Neither the deuterium tracing nor heat pulse velocity techniques are subject to any upper limitation on stem diameter, so they could be used to sample the larger stems.

Fig. 3.42 A 50 mm Dynagage™ with polythene shelter and heat pulse velocity system installed on a stem of Beaupré.

The measurements made with each of the three methods are described below in separate sub-sections. These are followed by a comparison of the results from the three methods.

Stem heat balance. Transpiration from poplar (Beaupré) and willow (Germany) was measured using the Dynagage™ stem heat balance (SHB) gauges described in Section 3.1.2.3, using the same approach as adopted at Swanbourne. Measurements were made over two periods, for both Beaupré (28 June to 19 July and 19 August to 19 September) and willow (10 June to 10 July and 19 August to 16 September), of sap flow in a sample of individual stems, and these data were scaled up to give transpiration on a land-area basis using Equation 3.6 (Section 3.1.2.3), stem diameter distributions, and relationships between leaf area and stem cross-sectional area (Equations 3.7 and 3.8). The large size of the Beaupré stems meant that only 35-mm sap flow gauges (able to operate on stems to a maximum diameter of 42 mm) could be used, limiting the sample to the four gauges available (though during the first measurement period, a 50-mm diameter gauge (see Fig. 3.42) was borrowed from another project). The willow stools were highly multi-stemmed, with smaller stems, which were in the correct diameter range to use 16-mm, 19-mm and 25-mm gauges, of which a total of 16 were deployed.

During the second measurement period for Beaupré, three of the four SHB gauges did not function properly. The fault was not discovered until the data were analysed, and cannot be corrected retrospectively. The faulty gauges were omitted from further analysis, so the transpiration values for this period are based on the data from a single gauge, and should be viewed with caution.

The daily transpiration rates measured for Beaupré and willow are shown in Fig. 3.43a. During early June, when only willow transpiration was measured, the rates were fairly low, at 2 to 5 mm day^{-1}, due to low evaporative demand caused by cloudy weather. This is indicated by the transpiration ratios (Fig. 3.43b) over the same period, which were greater than one, indicating that Penman potential, E_T was low and always exceeded by transpiration. As June progressed, the weather became hot and sunny, and transpiration rates increased, until rates of 8 to 10 mm day^{-1} were observed at the end of June for both Beaupré and willow. The effect of rainfall can be seen clearly in Fig. 3.43c: the low daily transpiration on 17 June was caused by a rain event with associated humid and cloudy conditions, which reduced E_T; similarly the succession of wet days from 10 to 19 July suppressed transpiration rates. The sudden drop in both Beaupré and willow transpiration on 1 July was caused by a marked change in meteorological conditions from a very hot, dry spell, associated with a stable high pressure system, to cooler and cloudy weather. The transpiration ratios observed for both clones during the first measurement period show no clear trend, remaining between one and two, but varying far less than the observed transpiration rates. During this period there was a plentiful supply of soil water, and the transpiration from the trees appears to have been controlled by the level of evaporative demand, as indicated by E_T.

During the second measuring period, the situation was very different. The period began during a drought, which ended on 23 August, after 21 days without rain. Both the Beaupré and willow were visibly water-stressed, and very low stomatal conductances were observed (see Section 3.2.2.5). This was reflected by transpiration ratios of well below one, indicating that the trees could not meet the evaporative demand, resulting in the rather low transpiration rates of 1 to 3 mm day^{-1}, despite sunny and warm weather. Through the end of August and beginning of September the transpiration ratio increased, suggesting that the trees were regaining physiological activity as a result of the improved soil water status. There was heavy rainfall during the beginning of September, which recharged the soil profile, relieving the water stress suffered by the trees (indicated by transpiration ratios greater than one observed for willow at the end of the second measuring period). The transpiration rates remained low however, because of the reduction in evaporative demand, caused by the change to cloudy and cooler weather.

Heat pulse velocity. The heat pulse velocity (HPV) method measures the rate of sap flow by timing how long it takes short pulses of heat to travel over a known distance in the stem. The pulses of heat (typically one second duration, every 15 minutes) are provided by an electrically-powered line heater, in the form of a metal probe, which is implanted radially into a small hole drilled in the stem. Two temperature sensing probes, one 10 mm above (downstream) and one 5 mm below (upstream) are also implanted, parallel with, and to the same depth as the heater probe. The temperature probes are used to monitor stem temperature after the heat pulse is released, as it is propagated upwards by the sap stream. The lower

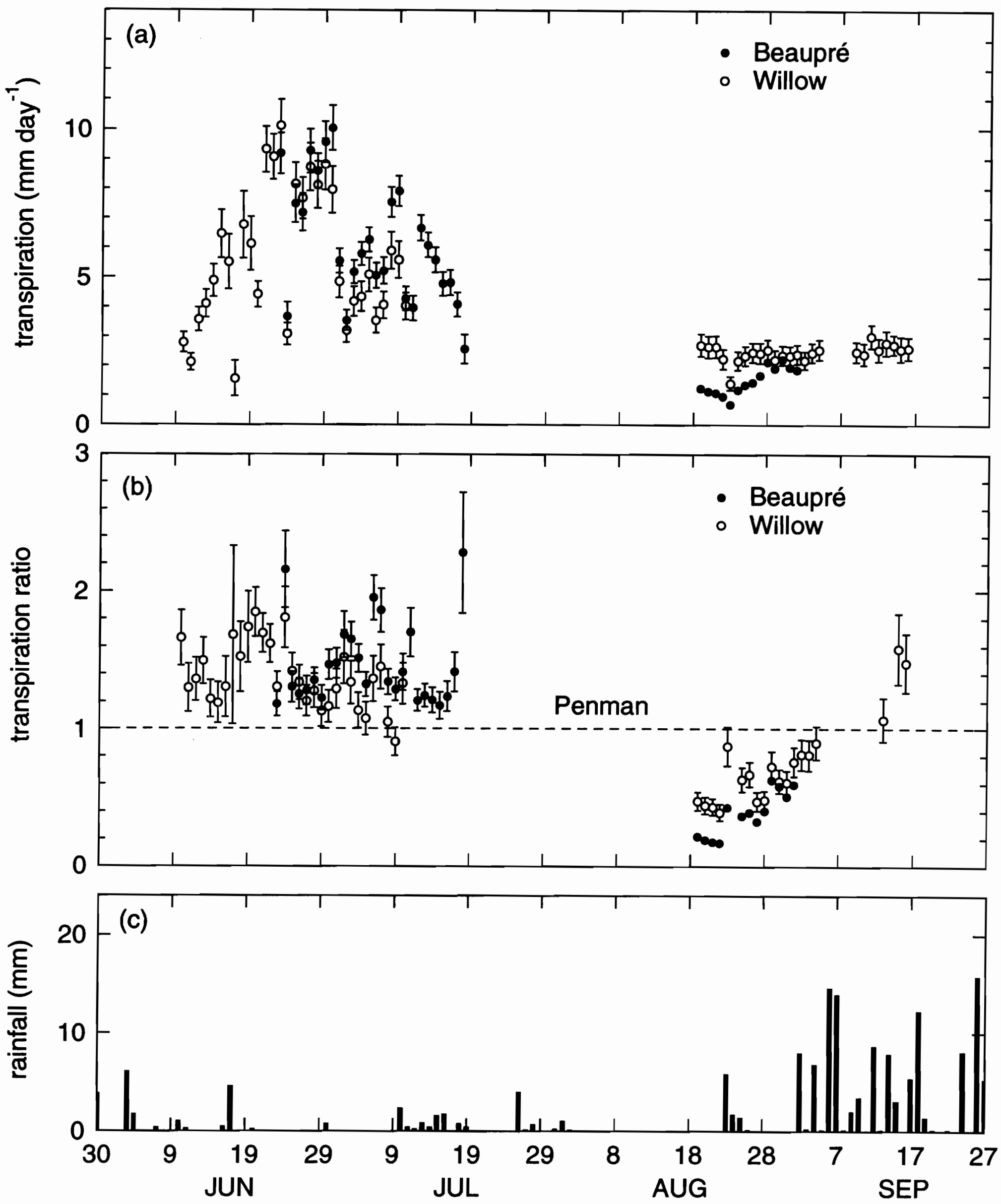


Fig. 3.43 (a) Daily transpiration rates and (b), transpiration ratios (transpiration divided by Penman E_T) measured for Beaupré and willow, summer 1995; (c) rainfall.

(upstream) probe is needed to compensate for the fact that as well as being carried upward by the moving sap stream, the pulse also spreads out, both upstream and downstream, because of heat conduction in the static wood. Although the pulse spreads, it remains symmetrical. This means that when both temperature sensors reach the same temperature after release of the pulse, the peak (i.e. centre) of the pulse must be exactly halfway between them, i.e. (10-5)/2 = 2.5 mm downstream of the heater. In this way it is possible to determine the speed of the heat pulse, from the time between releasing the pulse and the measurement of zero temperature difference between the probes, divided by the distance of travel (2.5 mm). The release and detection of the heat pulses, together with data storage, are provided by an automatic data logger (model Custom HP1, HortResearch, Palmerston North, New Zealand). The technique is described fully by Edwards and Warwick (1984).

Fig. 3.44 Three of the four probesets of the HPV system installed in different quadrants of a Beaupré stem.

Each probeset (one heater and two temperature sensors) measures HPV at one depth in the stem. As the sap velocity tends to be higher near the outside of the stem, and low or zero, near the centre, velocity must be measured at several depths, so that the radial variation is properly sampled. The datalogger is able to operate four probesets, allowing sap velocity to be measured at four different radial depths, one in each quadrant of the circumference (see Fig. 3.44).

Two HPV dataloggers were available for use at Hunstrete, allowing two trees to be monitored simultaneously. During 1995, measurements were made on a total of five Beaupré trees, for different periods through the growing season. The raw measurements of HPV at four depths per tree were converted to sap velocity using the correction described by Marshall (1958). This correction is needed to account for the difference in the specific heat capacity of wood and sap. A further correction (Swanson and Whitfield, 1981) was made to account for the narrow zone of zero flow around the heater and temperature sensors caused by wounding. The sap velocities were then integrated over the whole cross-sectional area of the stem, using the step integration method of Hatton et al. (1990), to determine the sap flow rate (g s^{-1}). These rates, measured at 15-minute frequency, were summed to obtain daily totals (kg day^{-1}).

Some previous studies using the HPV technique have indicated that for certain tree species, the measurements should be calibrated to ensure absolute accuracy. This is normally required for species where the xylem vessels conducting water through the wood have large diameters and are widely separated. Measurements made on some wood samples extracted from Beaupré stems by coring, showed that the dry wood had a high air fraction, probably indicating large diameter vessels and therefore suggesting that calibration might be necessary. Calibration is normally achieved by installing the HPV system in a cut tree stem, with its end immersed in water, and determining the true rate of sap flow from the rate of weight loss. This method of calibration was beyond our resources, so we adopted the simpler approach of calibrating

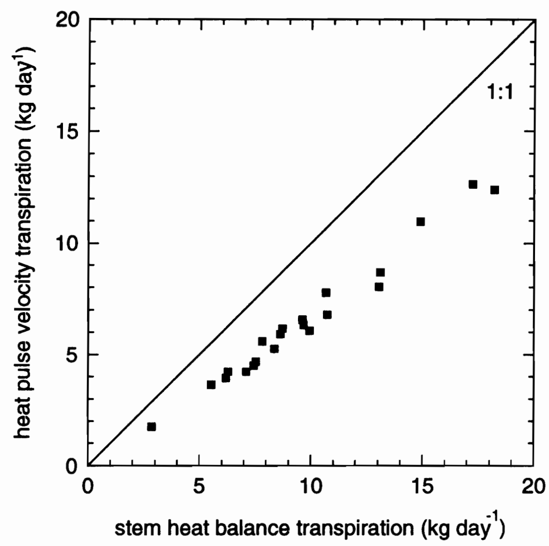


Fig. 3.45 Scatter diagram of the daily sap flow measured by the heat pulse velocity system plotted against the daily sap flow measured by the stem heat balance gauge.

against a large sap flow gauge, as SHB is an absolute method, where no calibration is required. To perform the calibration, an HPV system and a 50-mm diameter sap flow gauge were mounted on the same Beaupré stem (Fig. 3.42), and sap flow was recorded for 3 weeks.

The calibration results are shown in Fig. 3.45 as a scatter diagram of daily sap flow measured by HPV against sap flow measured by the SHB gauge. There was a good linear relationship between the measurements from the two instruments (slope = 0.678, r^2 = 0.996), though the points fall below the 1:1 line. To correct the HPV measurements it is necessary to multiply them by the reciprocal of the slope, which is 1.47. This correction factor agrees well with those determined for other species with large vessels: Green and Clothier (1988) measured a factor of 1.6 for kiwifruit and Smith (1995) found 1.62 for neem trees. The factor of 1.47 was

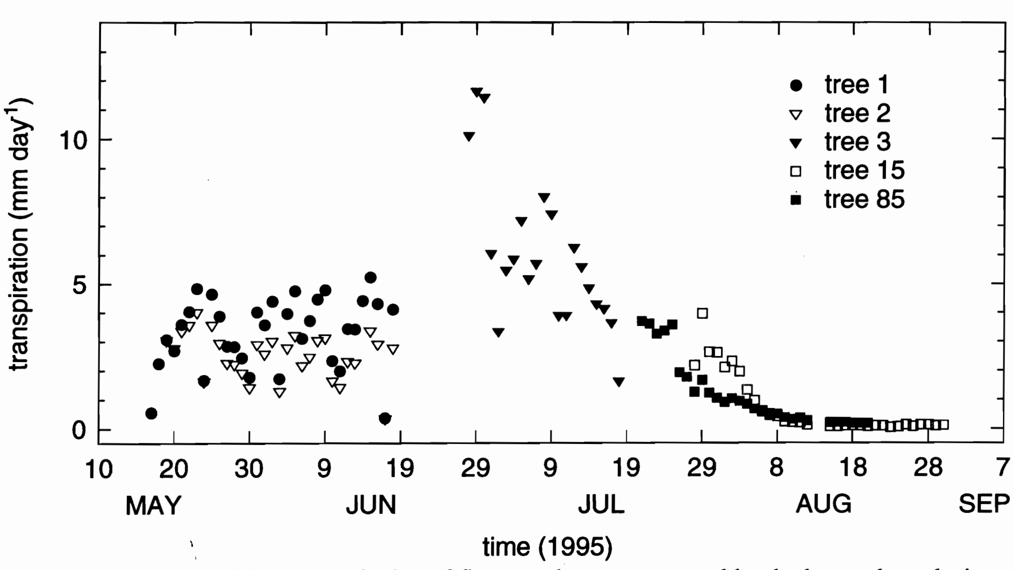


Fig. 3.46 Time series of daily transpiration of five sample trees measured by the heat pulse velocity system.

used to correct the sap flow rates measured by HPV for all five sample trees. Finally, these corrected sap flow rates were then scaled to estimate transpiration on a land area basis (mm water day^{-1}) using exactly the same procedure as for the stem heat balance measurements (see Section 3.1.2.3).

The use of an empirical calibration against SHB measurements clearly compromises the HPV method as a fully independent measurement of the absolute transpiration rates. Despite this fact, the HPV measurements allowed improved sampling of sap flow (by increasing the number of stems sampled, and providing measurements on stems too big to be monitored with 35-mm SHB gages) and temporal extrapolation outside the SHB measurement periods.

The daily transpiration rates observed through the summer for the five trees monitored by HPV are shown in Fig. 3.46. In the earlier (May-June) and later (August-September) periods of the summer, when HPV measurements were made simultaneously on two stems, the measured transpiration rates, scaled to a land area basis, agreed well with one another. A comparison of the HPV measurements with the other sap flow methods is made in the Section 'Comparison of methods' below.

Deuterium Tracing (D_2O) at Hunstrete. In this method of estimating transpiration, which is based on the 'total counts' method of Hull (1958), a known quantity of deuterium is injected into the stem of a tree and samples of transpired water collected over a period of time from bags placed at different positions around the tree canopy (Calder et al., 1986; Calder, 1991; Calder et al., 1992).

Consideration of the conservation of mass gives the basic equation as:

$$M = F \int_0^\infty C dt$$

where:

M is the total mass of the deuterium that is injected,
F is the 'measured flow rate' and
C is the concentration of the tracer in the transpired samples.

For practical considerations the equation is rewritten in the finite difference form where:

$$F = \frac{M}{\sum_{i=1}^{i=T} C_i \, \Delta t_i}$$

and where:

C_i is the concentration in the ith time increment which is measured from the collected transpirate,
Δt_i is the duration of the ith time increment and
T is the last time increment in which the deuterium was present.

All methods used to estimate transpiration, at both Swanbourne and Hunstrete, operate over different time and space scales. Although both the heat pulse velocity, the stem heat balance and the deuterium tracing methods give estimates of transpiration from single trees, the deuterium tracing method complements the other two as it also gives an estimate at low flow rates which the other two cannot.

During 1995 two deuterium tracing experiments were carried out at Hunstrete; the first

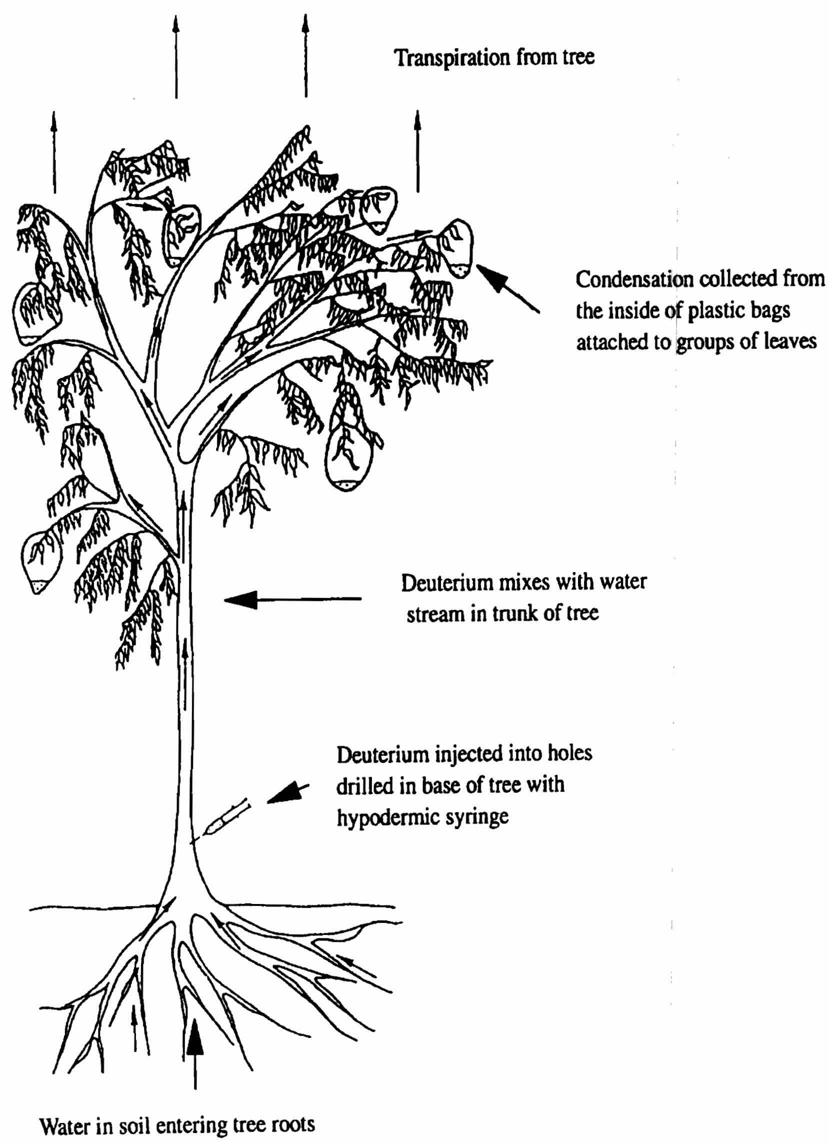


Fig. 3.47 Schematic diagram of the deuterium tracing method

between 13 - 22 June and the second between 18 - 31 August. The first experiment, which coincided with a number of relatively wet days, was designed primarily to determine the mass of deuterium that should be injected into different size stems to give large enough signals for the sample analysis by mass spectrometry. Ideally the deuterium should be injected instantaneously and from past experience a mass of between 1 and 6 gm is regarded as an appropriate amount for trees of the size found at Hunstrete. The results from this experiment are shown in Table 3.8. It is possible that Stem 93 did not have sufficient deuterium injected, to give an adequate signal, as reflected in the lower transpiration rate compared to Stems 9 and 11. However there may be other reasons attributable to this difference which cannot be explained.

The second experiment, which made use of the knowledge gained from the first, was designed to make estimates of transpiration from selected stems of Beaupré, Trichobel and willow and coincided with transpiration estimates being made on a number of stems by individual sap flow gauges and the heat pulse velocity system.

In the first experiment known masses of deuterium, see Table 3.8, were injected into 4 or 5, 4 mm diameter holes that were drilled into three different sized stems at an approximate angle of 45° above the horizontal just above the ground surface, see Fig. 3.47. The time of injection and the time taken for the deuterium to be absorbed were recorded for each stem injected. Absorption times ranged from a few minutes up to about half an hour depending upon the amount of deuterium to be injected and the prevailing climatic conditions at the time of injection. Once all the deuterium for each stem had been injected the holes were quickly sealed with, commercially available, grafting wax to minimise the possibility of air entering the stem. For convenience each stem was divided into three equal layers and three clear polythene bags per layer were then attached, each containing several mature leaves, to collect the transpirate. Samples of known volume were collected, where possible, on a daily basis until the 22 June 1995. On occasions some bags, usually those attached to leaves in the lowest canopy layer, did not contain any transpirate. Equal volume samples from each of the remaining three bags per layer were taken and thoroughly mixed to provide one sample per layer per day. The concentration of the deuterium, within the transpired water, was then analysed using a mass spectrometer (FISONS VG-Micromass 602E). The results from the top and middle layers of each of the three stems are shown in Fig. 3.48.

Table 3.8 Summary of the first D_2O campaign

Tree	Stem diameter at 1 m height (mm)	Mass of D_2O injected (gm)	Mean flow rate ($m^3\ day^{-1}$)	Mean transpiration rate ($mm\ day^{-1}$)
Beaupré # 9	41.2	2.9582	0.0058	6.408
Beaupré # 11	39.9	6.0989	0.0057	6.743
Beaupré # 93	39.8	0.9999	0.0039	4.639

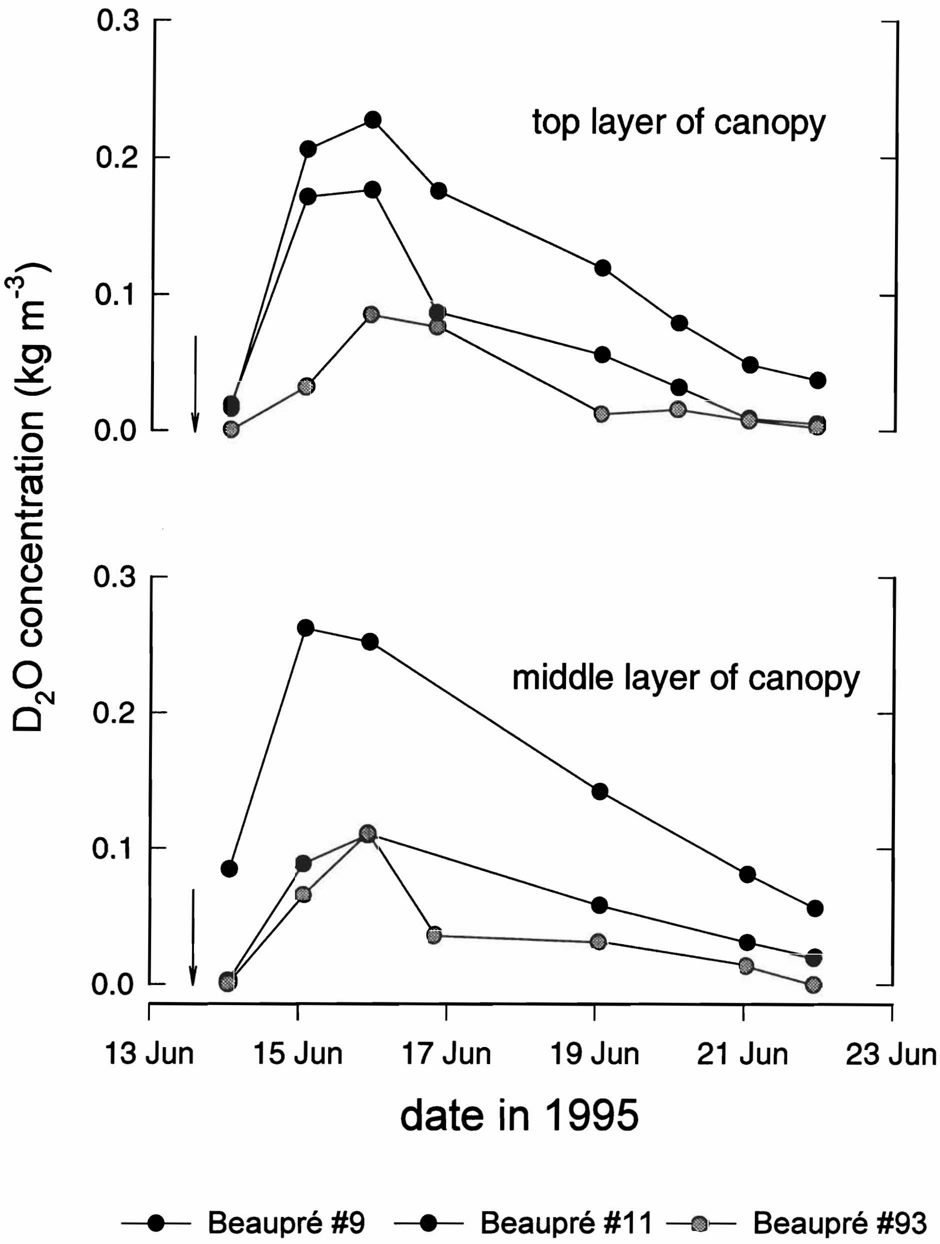


Fig. 3.48 The change with time in the concentration ("break through curve") of D_2O in collected transpirate from two canopy layers of three Beaupré trees. Arrows show time of injection.

The different volumes of deuterium injected into the different stems are clearly reflected in the maximum values of the concentration in both layers of the canopy, particularly so for the top layer. The smaller distance travelled by the deuterium to the middle part of the canopy is also seen by the difference in the timing of the maximum concentration for the two layers. For Stem 11 it is possible that not all of the deuterium had passed through as the concentration did not return to the background levels exhibited by Stems 9 and 93. The mean flow rates ($m^3 day^{-1}$) for each stem were then scaled using Equation 3.6 to give a mean transpiration rate for each stem for the measurement period, (see Table 3.8). The mean transpiration rate from the three stems is 5.93 mm day^{-1}. This is not an unreasonable figure as the leaf area for each

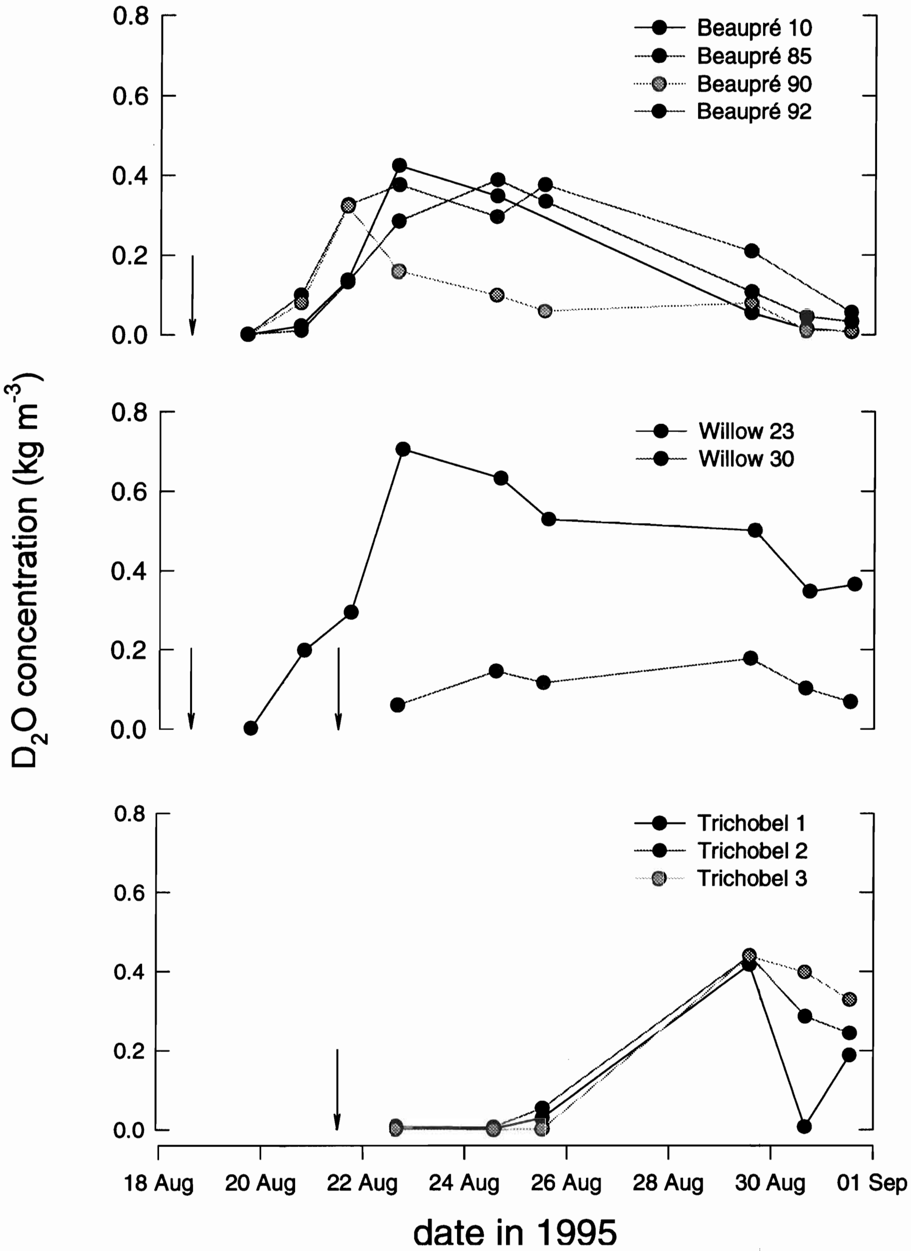


Fig. 3.49 The change with time in the concentration ("break through curve") of D_2O in collected transpirate from three varieties at the end of the drought of 1995. Arrows show time of injection.

stem was approaching its maximum, the climate was favourable and there was plenty of available water in the soil as shown by the soil water observations in Section 3.2.2.5 and also it agrees with the heat pulse velocity measurements.

In the second campaign from, 18 - 31 August 1995, which occurred during a period of water stress for the trees, as shown by the soil water observations in Section 3.2.2.5, similar masses of deuterium were injected into stems of different diameters in the Beaupré, Trichobel and willow, see Table 3.9. The methodology used was exactly the same as for the first experiment.

However it soon became evident that none of the leaves were transpiring in the lower layer and that very few leaves were transpiring in the middle layer either. As a consequence samples were only collected from the top layer for analysis and the results are shown in Fig. 3.49 and Table 3.9.

During the campaign rainfall was recorded on the 23 to 26 August and although this does not appear to have had any impact on the response of either the Beaupré or the willow stems it does for the Trichobel. Quite clearly, at the beginning of the campaign, the Trichobel were suffering from water stress as none of them were transpiring, as evidenced by the lack of any deuterium in the samples of 24 and 25 August in Fig. 3.49, but shortly after the rain they did start to transpire.

Figure 3.49 shows that the Beaupré responded in a similar way to each other, with the exception of Stem 90 although its mean transpiration rate for the period was very similar to that of the others. It may be that because Stem 90 was significantly larger than the other three stems that the bulk of the deuterium passed through it that much quicker, although all four stems seem to return to the same background level at the same time. It is also evident that the maximum concentration for all four stems was the same and that it was reached at the same time, about four days after injection. This would seem to indicate that all four stems were responding in a similar manner to the prevailing climatic and soil water conditions. Equation 3.6 was used to scale the mean flow rates (m^3 day^{-1}) to give mean transpiration rates (mm day^{-1}) and these are shown in Table 3.9.

There is no consistent pattern in the data from the two willow stems (Fig. 3.49). Stem 23 shows a maximum concentration four days after injection, the same as the Beaupré, but at a much higher value and clearly shows that by the end of the campaign not all of the deuterium had passed through the stem. Extrapolating the concentration curve downwards, to get an estimate of the flow rate, indicated that the concentration would have returned to background level about 14 days after the injection. The flow rate estimated as a result of this procedure will be an underestimate. Stem 30 was injected three days after Stem 23 and the deuterium concentration was lower. It is possible that the peak was missed as samples were not taken between the 25 and 29 August. However, it does return to the same background level as that shown by the four Beaupré stems which would indicate that all of the deuterium had passed through the stem.

The Trichobel stems responded to the rainfall of the 24 and 25 August but because no samples were taken between the 25 and 29 August it is likely that the concentration peak was missed. Clearly, as the concentrations at the end of the experiment had not returned to background levels, it is unlikely that all of the deuterium has passed through the stems. As with willow Stem 23 (Fig. 3.49) the concentration curves for the three Trichobel stems were extrapolated downwards to get an estimate of their flow rates. The extremely low value for the Trichobel Stem 1 on the 31 August (Fig. 3.49), was probably caused by an error in the sampling. The extrapolated mean flow rates of the three Trichobel stems, Table 3.9, are not too dissimilar to that of the four Beaupré stems and assuming that the leaf area indices were similar it would be anticipated that the mean transpiration rates would also be similar. However, as no individual leaf area surveys were carried out for the Trichobel (or the willow) it is not possible to give any estimates for the mean transpiration rates on a ground or leaf area basis. This is indicated by the n/a in Table 3.9.

Table 3.9 Summary of the second D_2O campaign

Tree	Injection date	Stem diameter at 1 m height (mm)	Mass of D_2O injected (g)	Flow rate (m^3 day^{-1})	Transpiration rate (mm day^{-1})
Beaupré 10	18 August	50.25	2.4489	0.0016	1.287
Beaupré 85	18 August	49.25	2.6920	0.0011	0.892
Beaupré 90	18 August	57.25	2.6685	0.0023	1.431
Beaupré 92	18 August	46.25	2.1491	0.0012	1.166
Willow 23	18 August	44.0	2.7560	0.0005	n/a
Willow 30	21 August	26.0	2.3382	0.0018	n/a
Trichobel 1	21 August	34.1	2.9438	0.0016	n/a
Trichobel 2	21 August	27.9	2.7330	0.0011	n/a
Trichobel 3	21 August	38.0	2.9323	0.0012	n/a

Comparison of methods. To compare the absolute values of the daily transpiration rates measured with the SHB, deuterium tracing and HPV methods, all the data are plotted against time for the 1995 growing season in Fig. 3.50. The measurements made by the three techniques show the same general pattern, although it should be noted that the HPV results are not fully independent of the SHB measurements, some of which were used for calibration. It is, however, encouraging that there is good agreement between the SHB and deuterium tracing methods, which work on entirely different principles, and are therefore completely independent. During May and early June, transpiration ranged between 0 and 5 mm day^{-1}, as the evaporative demand was relatively low, and the canopy leaf area was expanding. During the second half of June and the first half of July, very high transpiration rates of up to 12 mm day^{-1} were measured with the SHB and HPV methods. This period was characterised by high evaporative demand due to fine weather, good supplies of soil water, and maximum leaf area, so the high transpiration rates are credible. Through the remainder of July and August, transpiration declined steadily, as soil water was depleted during an extended dry period, and the trees experienced extreme water stress. All three techniques recorded low transpiration rates of 0.2 to 2 mm day^{-1} in mid-August but those recorded by the HPV method are subject to larger uncertainty due to the failure of the method (the travel time of the heat pulse exceeds the logging interval) at very low flow rates.

The consistency observed between the measurements made with three different methods of measuring tree water use gives confidence in the accuracy of the data, and therefore provides a solid foundation for the development of a simulation model, reported in Section 3.3.1.

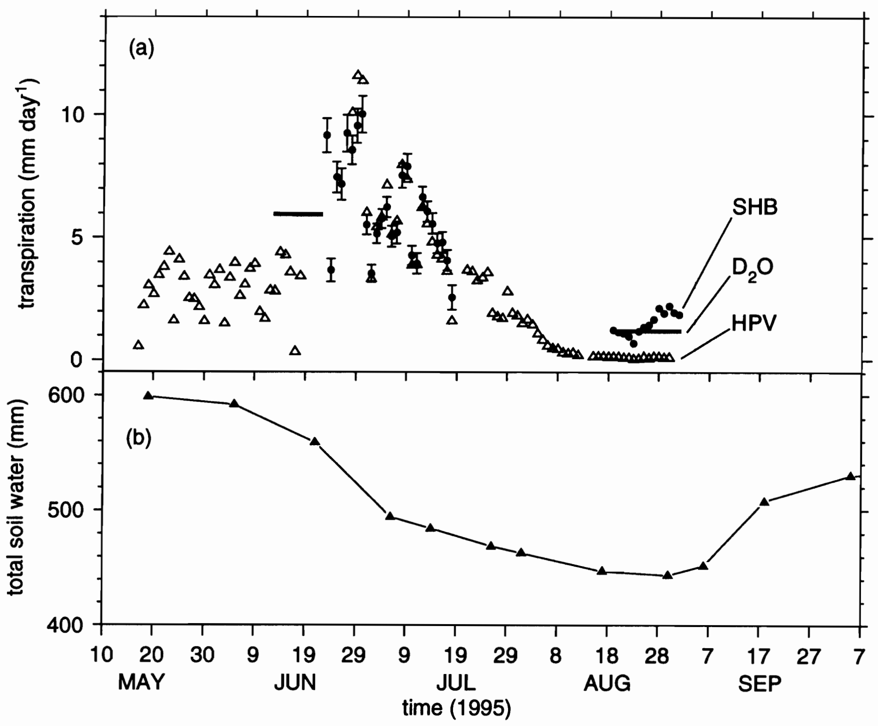


Fig. 3.50 Daily transpiration during the summer of 1995 from Beaupré (three-year old shoots on four-year old stools) measured using the SHB, HPV and deuterium tracing techniques.

3.2.2.4 *Stomatal conductance*

The leaf stomatal conductance of Beaupré at Hunstrete was measured on 11 days during 1995, using a diffusion porometer (model AP4, Delta-T, Burwell, Cambs.). At the start of the season, the Beaupré stems were more than 5 metres high, so it was necessary to construct a canopy access scaffold tower (see Fig. 3.51). The scaffold tower had three storeys, so that measurements could be made on leaves at any height in the canopy. Fig. 3.52 shows porometer measurements being made from the topmost storey of the tower.

The sampling procedure was similar to that used at Swanbourne (see Section 3.1.2.6). Measurements were made on four sample trees, two next to the scaffold tower and two within reach of the meteorological instrument tower (shown in Fig. 3.40). The canopy was subdivided into three layers: upper (topmost 1.5 m); middle (1.5 m to 3.0 m from top of canopy); and lower (3 m from top of canopy to ground level). This was necessary as there is normally vertical variation in leaf conductance, which must be taken into account when calculating the canopy conductance, required when the Penman-Monteith equation is used to model transpiration (see Section 4). At each sampling time, measurements were made on both surfaces of four leaves in each of the three canopy layers, giving a total of 96 observations at each sampling time. After some time, it became apparent that the conductances measured in the upper and middle layers were much higher than in the lower layer (confirming the same finding made at Swanbourne in 1994, see Fig. 3.53). As the upper and middle layers were therefore involved in most of the transpiration, the sampling pattern was adjusted accordingly: after 9 August, seven upper, four middle and one lower leaf were measured on each tree at

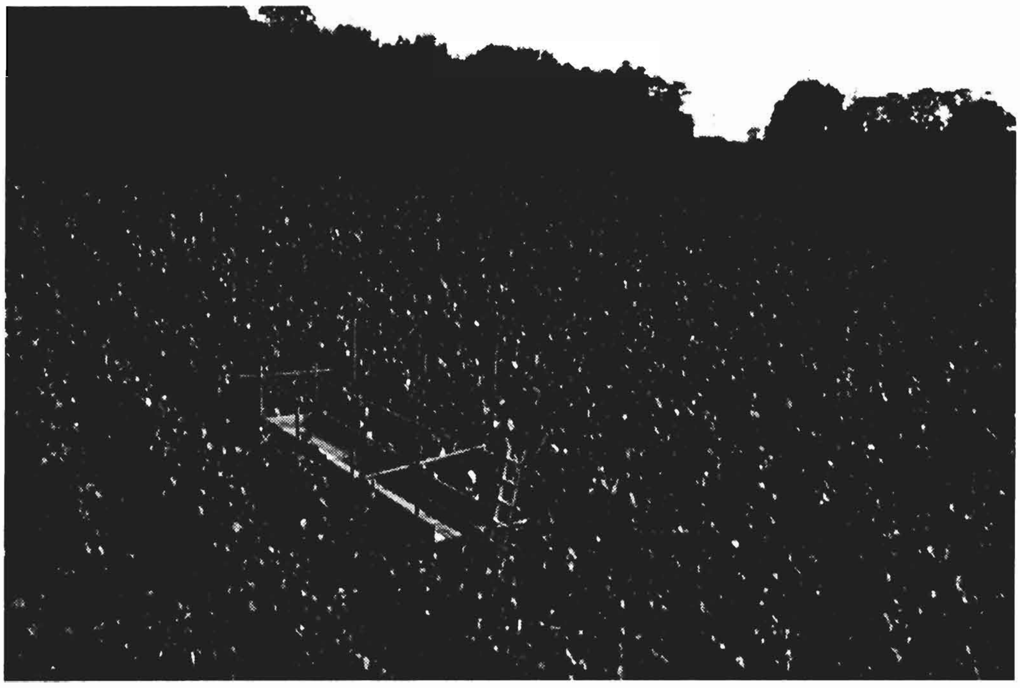


Fig. 3.51 The canopy access scaffold tower used for gaining access for making measurements on the leaves at three different levels within the (1992) Beaupré canopy.

Fig. 3.52 Porometry measurements of the stomatal conductance in progress.

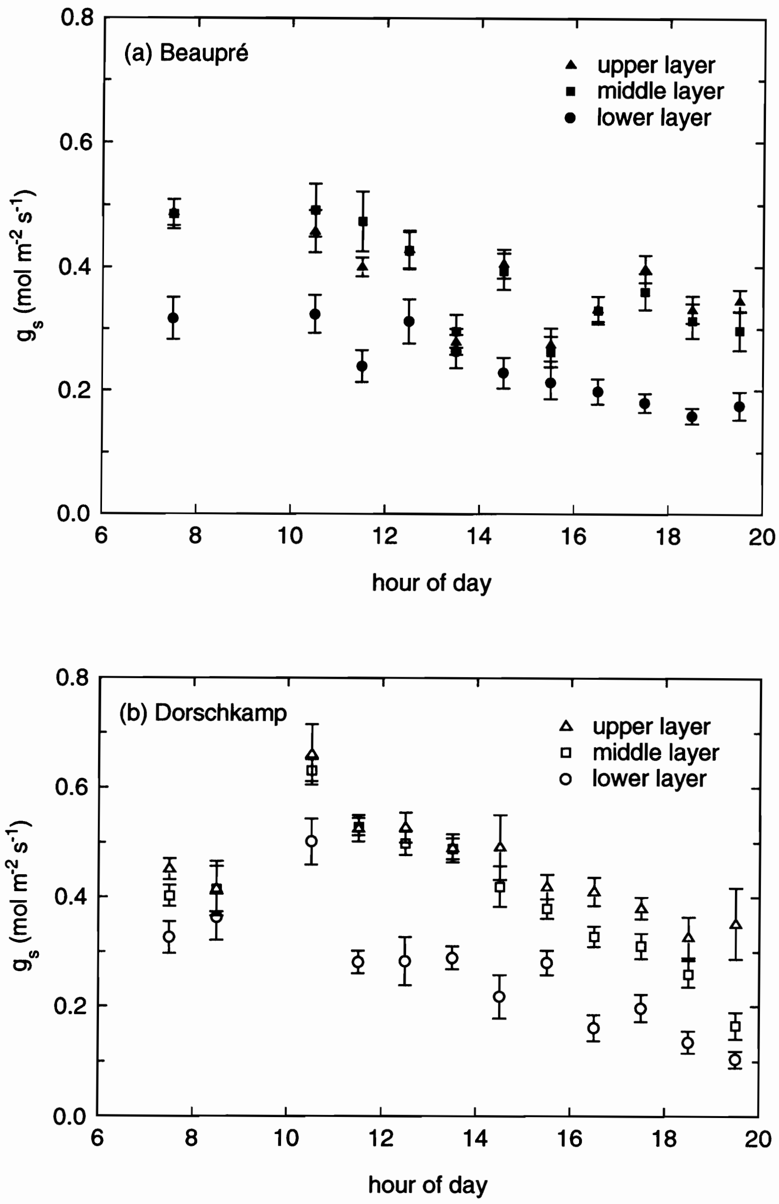


Fig. 3.53 Diurnal variation in mean leaf stomatal conductance for each canopy layer (bars show standard errors) observed at Swanbourne over the 1994 growing season.

each sampling time. As before, the sampling pattern was repeated (2 to 7 times) on each measurement day, to allow for any diurnal variation in conductance.

For each leaf sampled, the upper and lower surface conductances were summed to obtain total leaf conductance. The leaf conductances observed at each sampling time for the upper layer of all trees have been averaged, and are shown plotted against specific humidity deficit and solar radiation in Fig. 3.54. The observed conductances were generally high, lying in exactly the same range as found for Beaupré at Swanbourne in 1994 (Fig. 3.55). As before, no

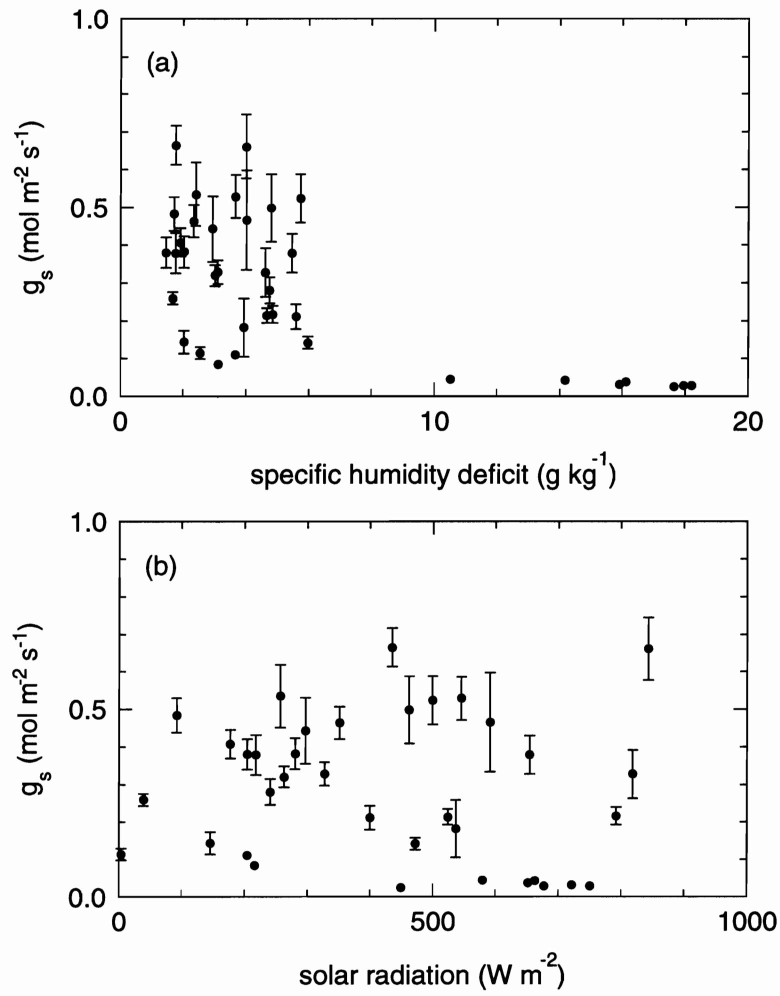


Fig. 3.54 Variation in leaf stomatal conductance of Beaupré at Hunstrete in 1995 as a function of (a) specific humidity deficit of the atmosphere, and (b) solar radiation.

response to solar radiation was observed (Fig 3.54b). Figure 3.54a shows that in the range of 0 to 10 g kg^{-1} specific humidity deficit, there was no evidence of a response to humidity (decreasing conductance with increasing deficit), as was also observed at Swanbourne in 1994 (see Fig. 3.55). However, at Hunstrete some deficits occurred that were much larger than those recorded at Swanbourne, and over these higher values, conductance was close to zero. This might indicate a stomatal closing response which only begins to operate at very high humidities. It is more likely however, that the very low conductances were related to severe soil water stress. From Fig. 3.56, where conductance and soil water content are both plotted against the same time scale, it can be seen that the very low conductances all coincide with the very low soil water content, that was observed during the August drought period.

The stomatal conductance measurements made at both Hunstrete and Swanbourne show that Beaupré does not respond to humidity or solar radiation, but has a strong response to soil water status which does not begin to operate until a large deficit is reached. This relatively simple pattern of response has been utilised for development of the poplar coppice water use model described in Section 4.

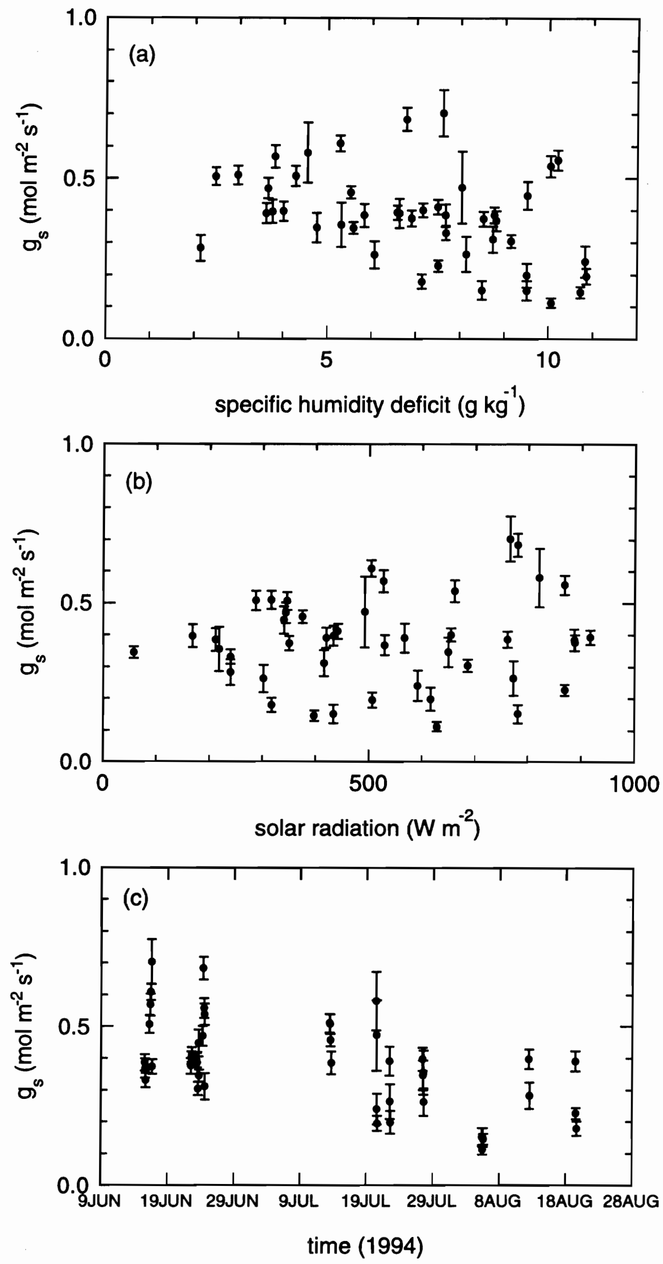


Fig. 3.55 Variation in leaf stomatal conductance of Beaupré as a function of (a) specific humidity deficit of the atmosphere, (b) solar radiation and (c) day of 1994 at Swanbourne.

3.2.2.5 *Soil water content and soil water potential*

A total of 8 neutron probe access tubes were installed, in two groups of 4 tubes (see Fig. 3.38), one close to the foot of the slope (Lower Plot), and the other up the slope (Upper Plot) near to the tower and the area in which the direct measurements of the sap flow were conducted (Section 3.2.2.3). The first access Tubes (1 and 2) were installed at the Lower Plot in July 1994. These could be read to a depth of 2.8 m. In May 1995, six more tubes were installed, two (3 and 4) close to the initial pair, and four (5 - 8) in a group at the Upper Plot. The maximum observation depth in the newer tubes ranged from 2.0 - 2.4 m. Measurements were made at 0.1 m intervals between 0.1 m and 2.0 m, and at 0.2 m intervals below 2 m depth. Observations were generally made bi-monthly, and occasionally weekly. No

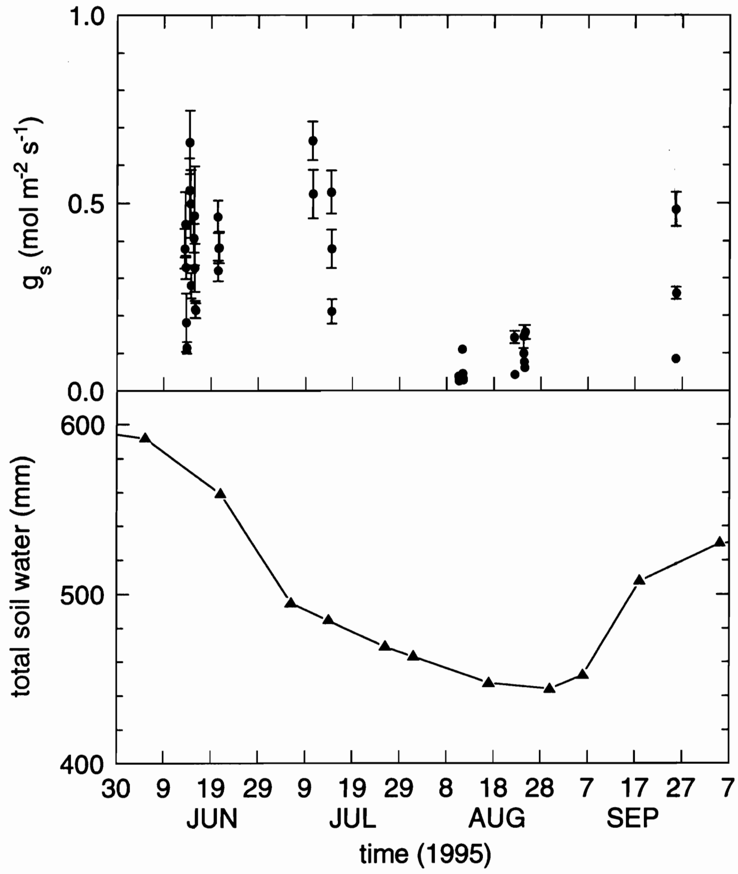


Fig. 3.56 The decrease with time during late summer of 1995 of the stomatal conductance coinciding with increasing soil water deficit

observations were made between December 1994 and March 1995.

A group of seven puncture tensiometers were also installed at the Lower Plot. The depths were 0.2, 0.4, 0.6, 0.8, 1.0, 1.2 and 1.8 m. These were read at the same time as the access tubes.

The soil profiles at the Upper and Lower Plots were not the same. The soil profiles at all 4 tubes in the upper group (T5 to T8) were clayey and very similar, but at the Lower Plot, the soil was very sandy and red. There were differences within the Lower Plot. The depth of Tubes 3 and 4 was limited to 2.4 m by a weathered sandstone layer, but there was no equivalent layer in Tubes 1 and 2, slightly down the slope. This was associated with marked differences in soil water uptake between the tubes.

The data from the four tubes at the Upper Plot (whose data can be compared with the results of the detailed transpiration studies carried out in 1995) are discussed first, concentrating in particular on the very dry period between 5 June and 30 August.

The study period was exceptional for its sustained very hot and dry weather. There was only 33.8 mm of rain and the Penman E_T evaporation was estimated to be 326 mm (24h basis) and 394 mm (daylight hours basis), equivalent to 3.8 and 4.6 mm day^{-1} respectively.

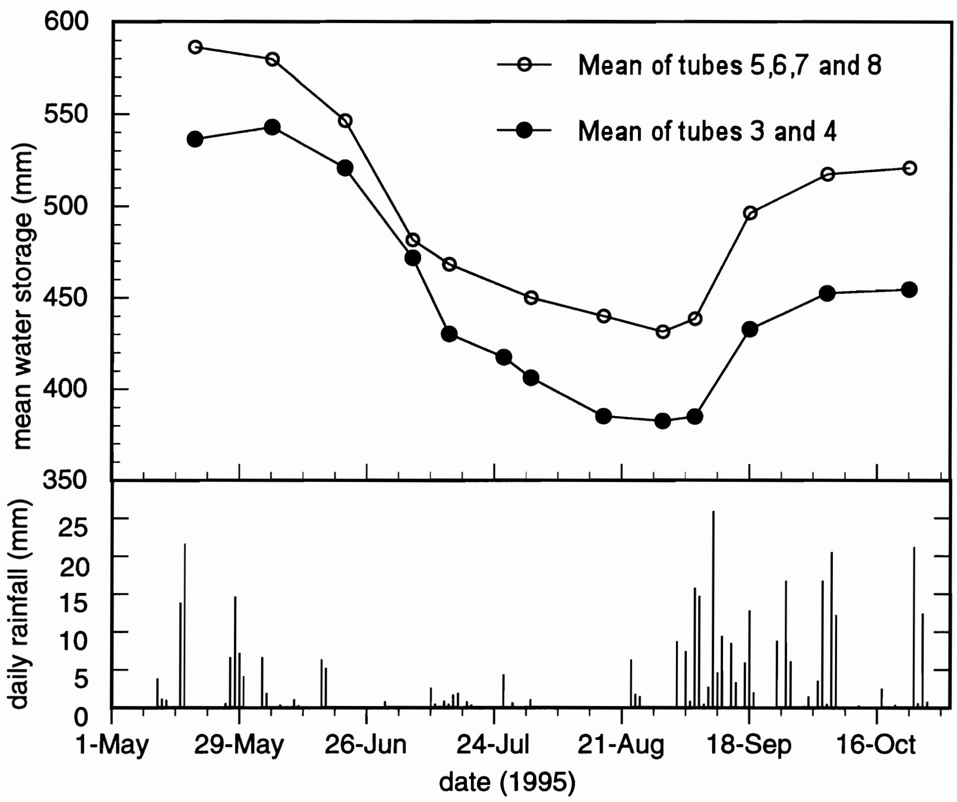


Fig. 3.57 The change in time of the mean soil water storage at the Upper Plot (Tubes 5 to 8) and at Tubes 3 and 4, Lower Plot, Hunstrete

Upper Plot. Figure 3.57 shows the mean water storage to a depth of 2.0 m of the 4 Upper Plot tubes (expressed as a depth of water, in mm) between 19 May and 23 October 1995. It can be seen that the rate of soil water depletion was highest in late June and decreased abruptly in early July. It continued to decrease until the end of August. During August, the rate of soil water depletion was only about 0.7 mm day^{-1}. The soil water store began to refill in September. The mean maximum depletion, between 5 June and 30 August was 148 mm, with a standard deviation of 11.2 mm. The largest depletion of 165 mm occurred at Tube 8 and the smallest, 135 mm, at Tube 5. The differences between the tubes did not appear to be related to the position of the tubes in relation to the trees.

In Fig. 3.58, the data are displayed as the mean storage of the four tubes within each of four successive layers of 0.5 m thickness. At this Upper Plot, the maximum rate of depletion (root uptake) in the top 3 layers was between 21 June and 6 July. Although the uptake rate from the upper 0.5 m layer decreased sharply, it did not cease. Uptake continued at a decreased rate until the end of August. Table 3.10 shows the depletion (mm) between 5 June and 30 August in each of the four layers, and expressed as a percentage of the total. It can be seen that over half of the uptake was from the top 0.5 m and there was almost none from below 1.5 m.

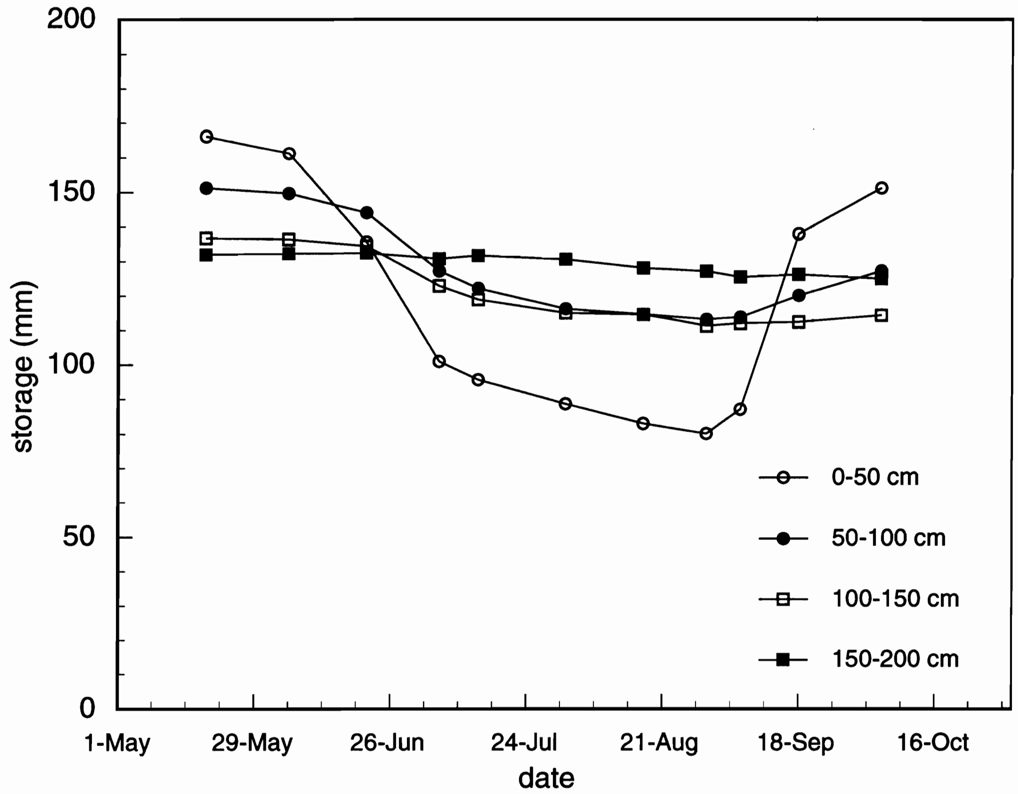


Fig. 3.58 The change in time of water storage in four soil layers beneath Beaupré coppice at the Upper Plot at Hunstrete

Table 3.10 Upper plot: soil moisture depletion in successive 0.5 m layers between 5 June and 30 August

layer	depth (m)	depletion (mm)	% of total
1	0 - 0.5	81.1	55
2	0.5 - 1.0	36.5	25
3	1.0 - 1.5	25.2	17
4	1.5 - 2.0	5.1	3
total (to 2.0m)		147.9	100

Figure 3.59 shows profiles of water content through the study period. These show the distribution of water content changes with depth. The lack of change of water content below 1.6 m can be clearly seen (all profiles converge) and this implies that root penetration is severely impeded at this depth. The contrast between this and the Lower Plot will be seen later.

Lower Plot. The longer run of data from Tubes 1 and 2 at the Lower Plot allows some comparisons of soil water response between the summers of 1994 and 1995. Results from 1995 are discussed first, and comparisons made with the Upper Plot.

The storage to a depth of 2.0 m is shown in Fig. 3.60 for each of the tubes. There was a marked difference between the tubes, in contrast to the behaviour at the Upper Plot. The pattern of storage changes and the total depletion for Tubes 3 and 4 were very similar to the Upper Plot, with maximum storage changes of 146 mm and 141 mm respectively. The maximum change at Tube 2 could not be determined as observations were not made at the driest time. In Tube 1, the maximum change was 218 mm, which is 63 mm more than the mean at the Upper Plot. There was also a large amount of uptake from below 2.0 m at the latter tube. In view of the different behaviour in the tubes, the results from Tube 1 and from 3 and 4 will be discussed separately.

The distribution of these changes with depth in Tubes 3 and 4 can be seen in Fig. 3.61, which shows the storage in four successive 0.5 m layers and a final layer of 0.4 m thickness. Table 3.11 shows the depletion between 5 June and 30 August in the same layers.

Table 3.11 Lower plot, Tubes 3 & 4: soil moisture depletion in successive 0.5 m layers between 5 June and 30 August

layer	depth (m)	depletion (mm)	% of total
1	0 - 0.5	54.2	36
2	0.5 - 1.0	26.7	18
3	1.0 - 1.5	36.7	24
4	1.5 - 2.0	26.0	17
5	2.0 - 2.4	7.6	5
total (to 2.0m)		151.2	100

It can be seen that the peak rate of depletion occurred in the top 3 layers at the same time as at the Upper Plot. However, there was less uptake from the top layer and more uptake from below 1.5 m. The relatively high rates of depletion in the layers below 1.5 m in May - June imply that some slow drainage was still occurring at this time, but there was significant uptake in August in the 1.5 - 2.0 m layer.

Figure 3.62 shows the storage in 4 successive 0.5 m layers and a final layer of 0.8 m thickness for Tube 1. At this location, the pattern of soil water uptake with time is very different to Tubes 3 and 4. In April, there is a very large decrease in storage in the layer between 2.0 and 2.8 m. This is probably the result of the fall of a water table from the base of the measured profile.

Of particular note in Fig. 3.62 are the very large changes of storage below a depth of 1.5 m. The maximum rate of depletion in the upper layer was highest in June and as the summer

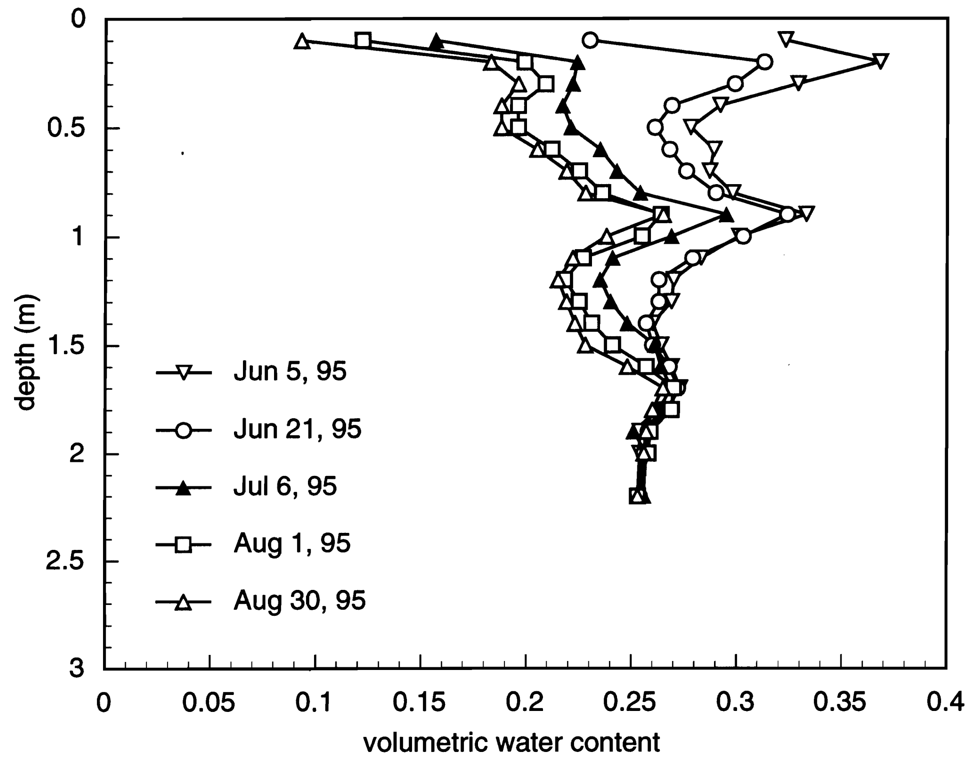


Fig. 3.59 Profiles of the mean volumetric water content with depth for Tubes 5 to 8 on five dates in 1995

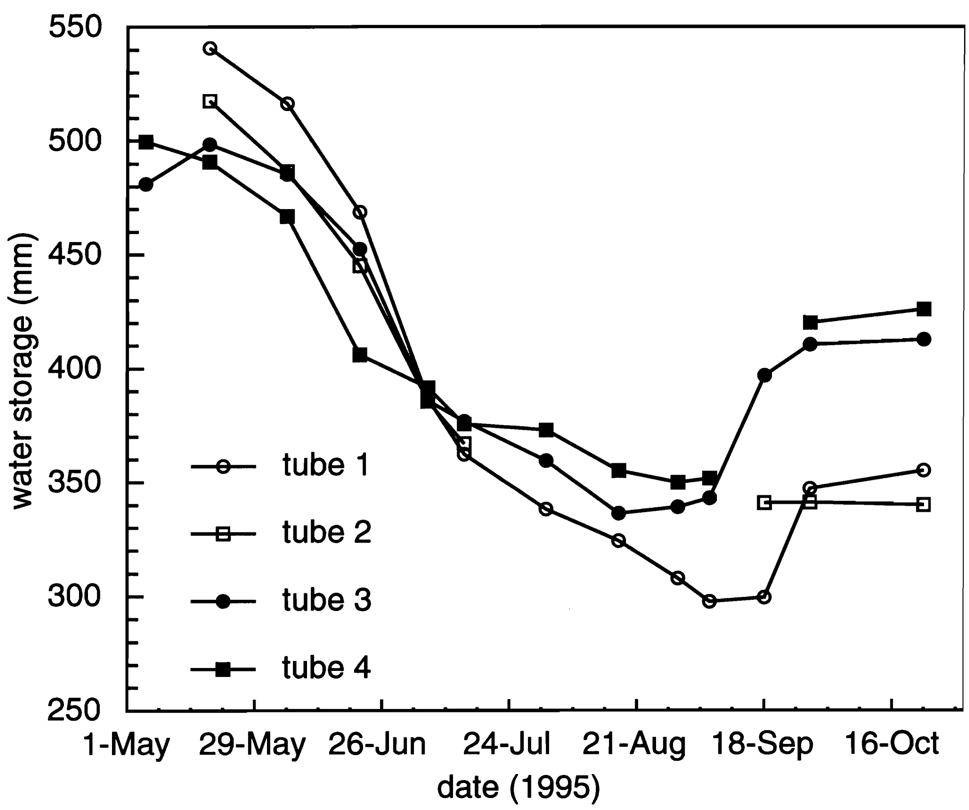


Fig. 3.60 The change in the soil water storage to a depth of 2m with time for Tubes 1 to 4 at the Lower Plot, Hunstrete.

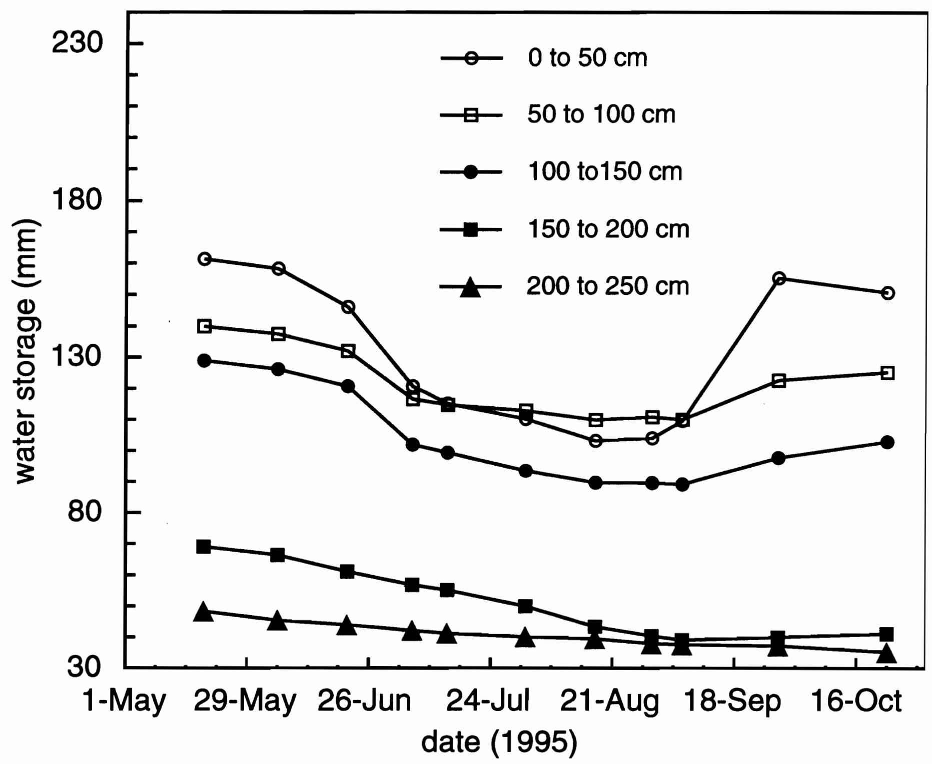


Fig. 3.61 The change with time in the mean soil water storage for Tubes 3 and 4 in five layers at the Lower Plot, Hunstrete.

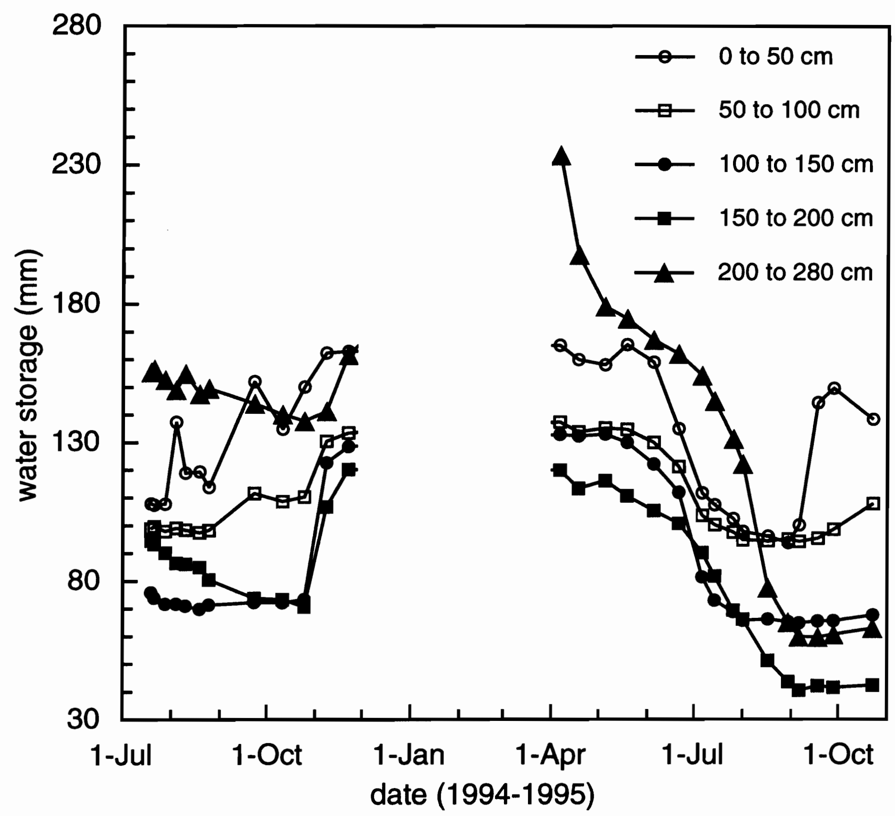


Fig. 3.62 The change with time in the soil water storage for Tube 1 in five layers at the Lower Plot, Hunstrete.

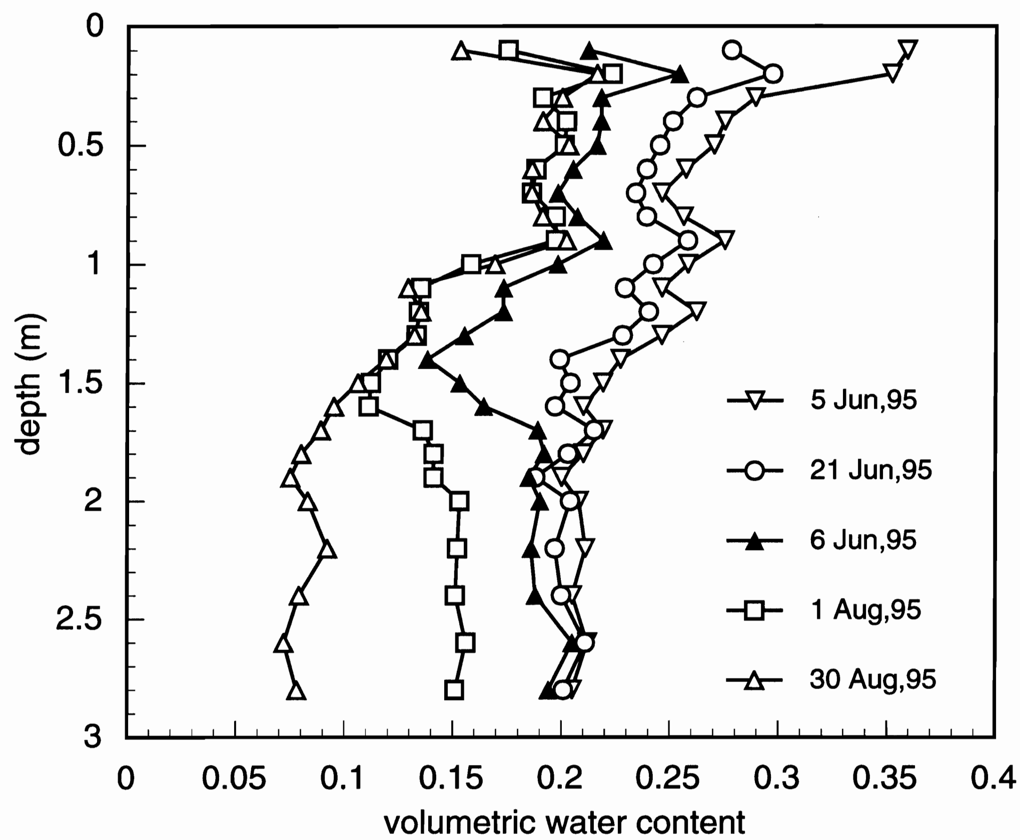


Fig. 3.63 Profiles of the volumetric water content with depth for Tube 1 on five dates in 1995.

progressed the zone of maximum depletion rate moved progressively down the profile. In the 1.5 - 2.0 m layer, the highest rate was during July and below 2.0 m it was in the first 2 weeks of August.

Table 3.12 shows the soil water depletion between 5 June and 30 August in four successive 0.5 m layers and a fifth layer of 0.8 m thickness. This shows that half of the total depletion occurred in the layers below 1.5 m and Fig. 3.63 shows that most of this occurred after the depletion in the top 1.5 m had almost ceased. The total measured depletion at this location was 321mm, but it would appear likely that this is an under-estimate of the total uptake because there is evidence of significant water content changes below this depth (see below).

Figure 3.63 shows profiles of water content between 5 June and 30 August. These data further illustrate the very large amount of uptake in the zone below 1.5 m (at the Upper Plot there was virtually none), particularly during August. During the whole of this month, it can also be seen that there was no further decrease in storage in the upper 1.5 m.

There were very large water content changes at the maximum depth of measurement. Normally, at the bottom of the rooting zone, successive water content profiles through a dry period tend to converge as the uptake decreases with depth, as occurs at the Upper Plot. There is no evidence of this in the profiles shown. This strongly implies that there was significant uptake from below a depth of 2.8 m at this location.

There is a strong contrast in the amount of uptake from depth in 1994 and 1995. This can

Table 3.12 Lower plot, Tube 1: soil moisture depletion in successive 0.5 m layers and a final, 0.8 m layer, between 5 June and 30 August

layer	depth (m)	depletion (mm)	% of total
1	0 - 0.5	65.2	20
2	0.5 - 1.0	34.9	11
3	1.0 - 1.5	56.9	18
4	1.5 - 2.0	61.8	19
5	2.0 - 2.8	102.2	32
total (to 2.8m)		321.0	100

be seen from Fig. 3.63. The minimum storage observed in the 0.5 m layers to 1.5 m depth were very similar in the two years, but uptake from the 1.5 - 2.0 m and 2.0 - 2.8 m layers was 36 mm and 85 mm respectively, greater in 1995 than 1994. These results show that given favourable soil conditions, Beaupré is able to take up water from great depth to sustain transpiration in very dry summers.

The differences in the behaviour of the soil water reservoir between the tubes at the Lower Plot appears to be because the small area covered by the tubes falls almost exactly on a soil/geological transition on the slope. Examination of the geological map for the area indicates that the slope at the site cuts across 3 different formations, the Blue Lias at the top, the Penarth beds further down, and the Mercia mudstones at the base. There are also two parallel faults running down the slope. As a result, it is likely that there will be fairly abrupt transitions in the soil profile, particularly at depth.

Tensiometer data. In unsaturated soil, the rate of water movement is determined by the gradient of total hydraulic potential and by the unsaturated hydraulic conductivity. The gradient (whether positive or negative) determines the direction of water movement. Profiles of total hydraulic potential from the tensiometers are shown in Fig. 3.64 and 3.65 for the periods from 18 April to 5 June and from 5 June to 14 July 1995. The weekly regime of observations is close to the limit in terms of obtaining reliable data, but the results confirm the soil water data obtained using the neutron probe.

In April and early May, there was an upward gradient from a depth of 0.4 m and a downward gradient below. The point at which the gradient reverses is known as the 'Zero Flux Plane' (ZFP), and separates the zone in which water movement is upward, supplying evaporation, from that in which movement is downward, ie draining from the soil profile. This ZFP was eliminated by 35 mm of rain on 16 and 17 May and the profile for 19 May shows saturated conditions at 0.4 m and 0.8 m.

After 19 May, the profile dried progressively, with the ZFP reaching at least 1.2 m by 21 June. The data from 14 July show potentials at the limit of tensiometer measurements indicating that there has been uptake to beyond 1.8 m depth.

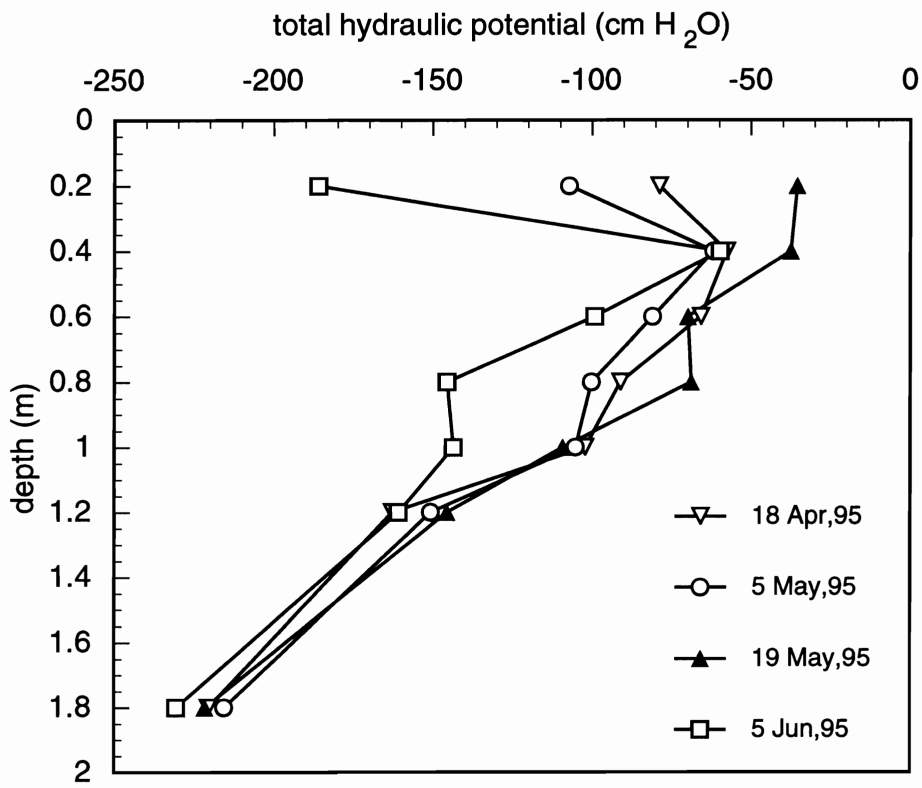


Fig. 3.64 Profiles of the total hydraulic potential at the Lower Plot, Hunstrete, on five dates in 1995.

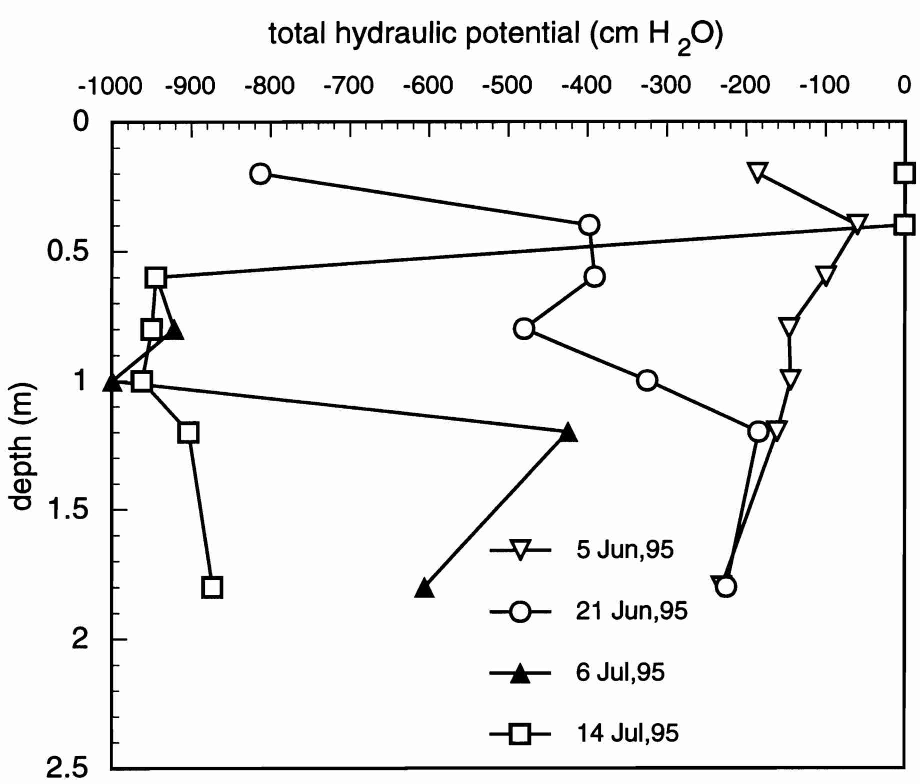


Fig. 3.65 Profiles of the total hydraulic potential at the Lower Plot, Hunstrete, on five dates in 1995.

Evaporation estimated from the soil water balance. The mean evaporation rate for the periods between soil water observations was calculated using the water balance. The evaporation rates are shown in Fig. 3.66 together with the Penman estimates of potential evaporation rate (24 h basis) for the same periods. For much of the summer the evaporation rates determined from the soil water balance are less than the rates given by the sap flow gauges. Subsequent excavation at the Upper Plot showed that ribbon-like roots were growing down wet fissures in the compact clay. It therefore is probable that the soil water depletion determined from the neutron probe measurements is underestimated as a result of the trees extracting water below the depth of the access tubes. It is also possible that the depth of the soil was greater under the trees that were gauged for sap-flow measurements.

The soil water balance estimates were below the Penman rates in mid-June. At the Lower Plot, the water balance estimates were similar to, or higher than the Penman estimates until the latter part of August, when they fell below. However, this is the time when uptake from below the maximum depth of measurement would have been taking place. It appears likely that transpiration may have been sustained at close to the potential rate throughout the summer.

At the Upper Plot, the water balance estimates declined very sharply below the Penman estimates after 6 July reaching only 0.7 mm day^{-1} in the first half of August. Later in August, the rate increased to about 1.4 mm day^{-1}, but much of the increase in evaporation was as a

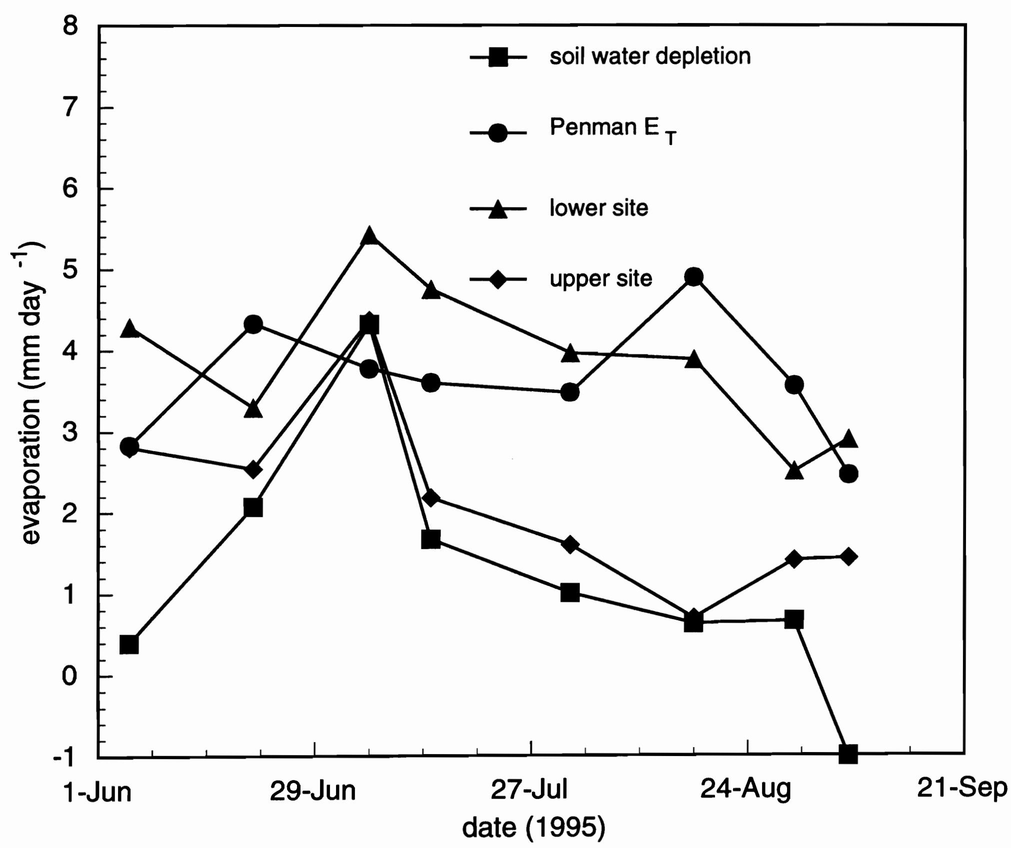


Fig. 3.66 Evaporation rates estimated from the soil water balance at the Upper and Lower Plots. Penman E_T and the soil water depletion are also plotted.

result of rainfall. The underlying soil water depletion rate was still about 0.7 mm day^{-1}.

Summary. At the Upper Plot, between 5 June and 30 August when there was only 34 mm of rain, the mean soil water storage change in the 2.0 m profile was 148 mm, with a standard deviation of 11 mm. There did not appear to be a correlation between the depletion and the position of the access tubes in relation to the trees. The soil water profiles indicated that there was no uptake from below 1.6 m depth at the Upper Plot; 55% of the total uptake came from the top 0.5 m layer and 80% from the top metre.

In the exceptional summer studied, the evaporation from the Upper Plot was severely limited by soil water availability. The depletion rate decreased abruptly in early July, after about 100 mm of water had been taken up, implying a root constant of about 100 mm. At this plot, rooting was almost certainly restricted by unfavourable mechanical conditions at depth. In more 'normal' years, there would have been sufficient rainfall to sustain transpiration rates close to potential for most of the summer. The soil water balance data from the Upper Plot gave evaporation estimates significantly lower than those obtained from the direct measurements of sap flow (Section 3.2.2.3) probably as a result of the trees extracting water from below the depth of the access tubes, or possibly because the depth of the soil was greater under the trees that were gauged.

At the Lower Plot, there were marked differences in uptake between the total amount of uptake and its distribution with depth at the different tube locations. At Tubes 3 and 4, furthest upslope in the group, the total change to a depth of 2.4 m was 151 mm, which was very similar to the Upper Plot. The distribution of uptake was more evenly spread with depth, with only 54% coming from the top metre. In August, the rate of soil water depletion had decreased to only about 0.6 mm day^{-1}. The most downslope of the Lower Plot tubes, Tube 1, showed much larger changes than the other tubes. The change in the 2 m profile was 218 mm. Over the full measured profile to 2.8 m the total storage change was 321 m. Below a depth of 2 m, most of the uptake took place in August, when the mean rate of depletion for the month was 2.9 mm day^{-1}. In the first 16 days of the month, the rate was 3.8 mm day^{-1}, falling to 1.8 mm day^{-1} over the next 13 days. There were strong indications that uptake took place from below 2.8 m, possibly from as deep as 3.5 m. There was little uptake from below 1.5 m in 1994, but this was not such a dry summer, and there was no need for the trees to exploit reserves of water at depth. Subsequent excavation at the site of Tube 1 at the Lower Plot revealed poplar roots at the lowest level attainable (3 m) by the excavator.

The data from one of the tubes at the Lower Plot appeared to indicate that uptake from the measured profile was not limited by soil water availability until mid August. It seems likely however that uptake from even deeper layers meant that evaporation was probably not limited by soil water availability. Given favourable conditions for root growth, it appears that these trees can exploit water from considerable depth to sustain transpiration even under the extreme conditions observed in 1995.

3.2.2.6 *Interception loss*

The interception loss is that component of the precipitation which is intercepted by the vegetation and evaporated back into the atmosphere without ever reaching the soil. Its magnitude is dependent upon meteorological conditions, in particular the rainfall regime, and characteristics of the vegetation viz. the storage capacity, the amount of water left on the canopy after drainage from it has ceased, and aerodynamic roughness. The aerodynamic roughness of a vegetation canopy is quantified by the aerodynamic resistance parameter, r_a, such that a small r_a is associated with a rough canopy. The aerodynamic roughness governs the rate at which water vapour is transferred from the surface of the liquid water on the vegetation into the air above the canopy. The wind interacting with an aerodynamically rough canopy generates turbulence which results in a more efficient transfer. The aerodynamic roughness is determined primarily by the height of the vegetation, but also by its density. SRC has the potential for relatively high interception loss, compared to conventional agricultural crops, given its height (typically 5 to 6 m) and large leaf area.

Interception loss is in principle straightforward to measure as the difference between the gross precipitation falling on the vegetation and the net precipitation reaching the soil beneath the vegetation. To obtain an accurate estimate, adequate sampling is required of both the gross and net rainfall. Rainfall, particularly during the summer when high intensity rainfall from convective storms is common, is spatially variable and a network of gauges is desirable.

In addition to sampling errors, systematic errors are also associated with measurement of the gross rainfall. The chief of these is undercatching due to air turbulence around the gauges. This can be generated by the effects on the wind field of nearby natural or artificial structures and the gauges themselves. Systematic errors can also arise from splash into and out of the gauges. These errors can be reduced through the use of ground level raingauges with splash grids (see Fig. 3.41).

The measurement of net rainfall amounts to a sampling problem. This can be tackled using one of two methods: (i) a large array of collectors is placed beneath the tree canopy to collect the throughfall and water flowing down the stems is sampled separately, again using a large number of collectors; (ii) a large polythene sheet is placed beneath the canopy and sealed to the stems of the trees so that it collects both stem flow and throughfall. If the first method is used a large number of collectors is needed to obtain adequate sampling of the throughfall making the method labour intensive. This number can be reduced if the collectors are randomly relocated at regular intervals but this makes the method even more labour intensive and there is still the requirement to measure adequately the stem flow which for coppice is likely to be a larger component of the net rainfall than in standard forest.

The use of the large polythene sheet method Calder and Rosier (1976) facilitates the collection of throughfall and stem flow over a large area and allows the runoff to be metered using tipping bucket flowmeters so that high time resolution data can be collected automatically. It is also far less labour intensive once it has been installed. However care must be taken to ensure that the polythene sheet is attached to the tree stems in a water tight manner and regular checks made to ensure that there are no leaks.

The polythene sheet method was used at Hunstrete. Because of the multiple stems of the

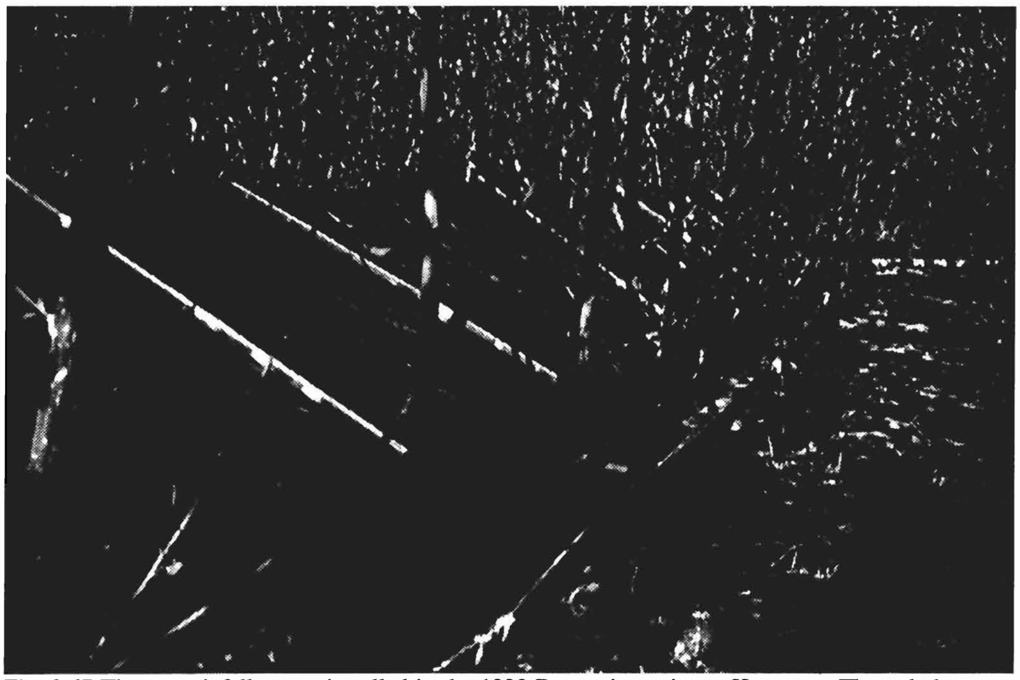


Fig. 3.67 The net-rainfall gauge installed in the 1992 Beaupré coppice at Hunstrete. The polythene sheet and wooden fixing battens and the plastic gutter are all visible.

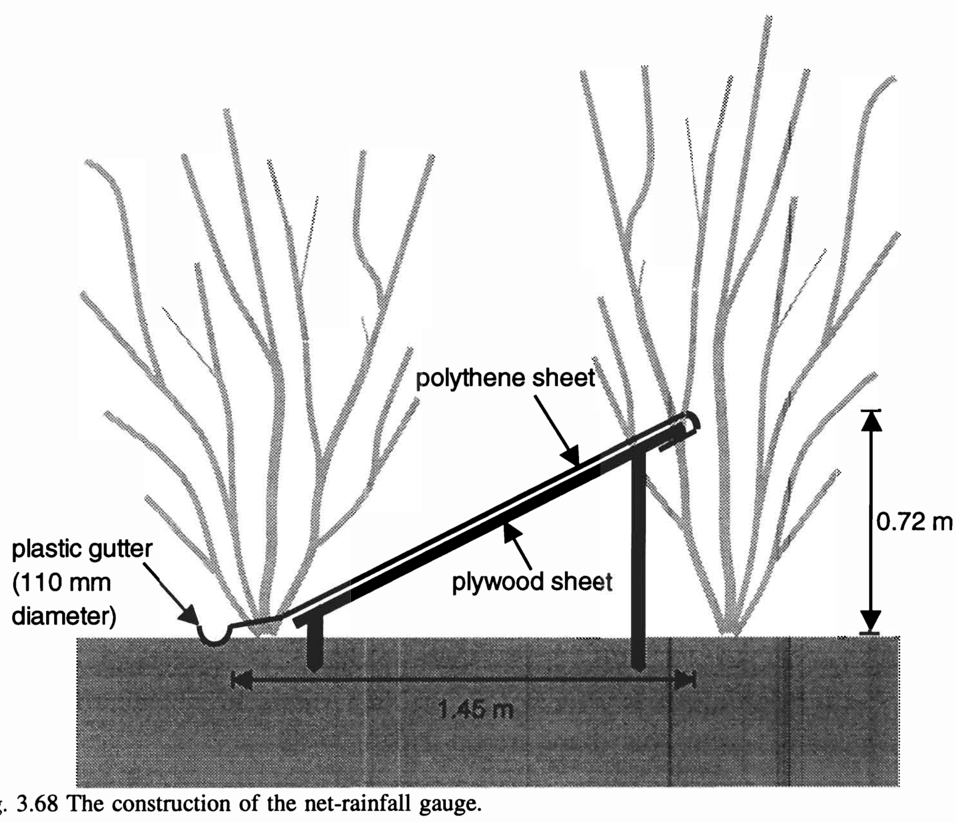


Fig. 3.68 The construction of the net-rainfall gauge.

coppice a modification of the standard design Calder and Rosier (1976) was used. The gauge, shown in the photograph in Fig. 3.67 and as a cross-sectional diagram in Fig. 3.68, was located (see Fig. 3.38) towards the southern edge of the plantation where advantage could be taken of the steeper hillslope with the rows aligned up the slope. The gauge was placed between two rows of Beaupré and incorporated 83 stems of 25 stools of one row, thereby collecting the stem flow of one row and the throughfall beneath two rows.

Lengths of plastic gutter were connected together and laid in a shallow trench down the full length of the sampled area so that the gutter was less than 10 cm from the bases of the stools. On the other side of the stools sheets of plywood placed between two rows, with one edge adjacent to the bases of one of the rows, were supported at about 25° by vertical pieces of square-section sawn timber driven into the soil. Heavy gauge polythene was fastened to the plywood by wooden battens and to the bases of the stools below the point at which the stems forked. Electrical insulation tape was used to wrap around the polythene and secure it to the stems. A much smaller separate sheet of polythene overlapped the edge of the gutter and wrapped around the stools from that side and extended beneath the large sheet to close the gap in the large sheet, caused by the inclusion of the stems. Where necessary gaps between the stems were infilled with glazier's putty. The whole area of the join was sealed using a flexible, bitumen-based compound "Liquid Felt" (manufactured by Aquaflex Ltd) to make the joins waterproof. This proved to be sufficiently flexible not to crack as the stems moved and increased in diameter over the growing season. Runoff from the sheet was collected by the plastic gutter and channelled into a 110 mm plastic pipe which conveyed it to a large tipping bucket flowmeter Calder and Kidd (1978). Checks were made at regular (usually fortnightly) intervals for leaks throughout the period of operation of the sheet and any breaks in the seals were repaired.

The net rainfall gauge was installed over three days, 16-18 May 1995. Dynamic calibration of the tipping bucket flowmeter gave a volume of 1.29. 10^{-3} m^3 per tip and a tipping time of 0.55 s. Tips from the flowmeter were recorded, via a 150 m cable, by the logger monitoring the AWS. The sheet was 21.9 m long and 1.65 m across covering a ground area of 31.8 m^2 which resulted in each tip of the flowmeter corresponding to a depth increment over the area of the sheet of 0.0407 mm. Measured volumes of water were applied to the sheet using either watering cans or a knapsack agricultural sprayer at different times through the summer to detect leaks and to establish the amount of water required to wet the sheet. No leaks were detected and the amount of water required to wet the sheet remained constant at about 0.06 mm depth. The recorded net rainfall was increased by this figure for each rainfall event that was followed by thirty minutes or more without rain to allow for evaporation from the sheet.

The net rainfall recorded during the period when the coppice was in leaf in 1995 is shown as a cumulative graph together with the gross rainfall in Fig. 3.69. The graph shows that most of the rainfall during the growing season fell during September. The total gross and net rainfall measured over the period 18 May to 20 October was 268.7 mm and 212.5 mm respectively, i.e. an interception loss of 56.2 mm or 21% of the gross rainfall. Intermittent problems with the logging system became more frequent towards the end of the summer and into the Autumn and resulted in no useful data being collected between 8 November and 22 December 1995.

A small amount of data have been collected since then and these are plotted in Fig.3.70.

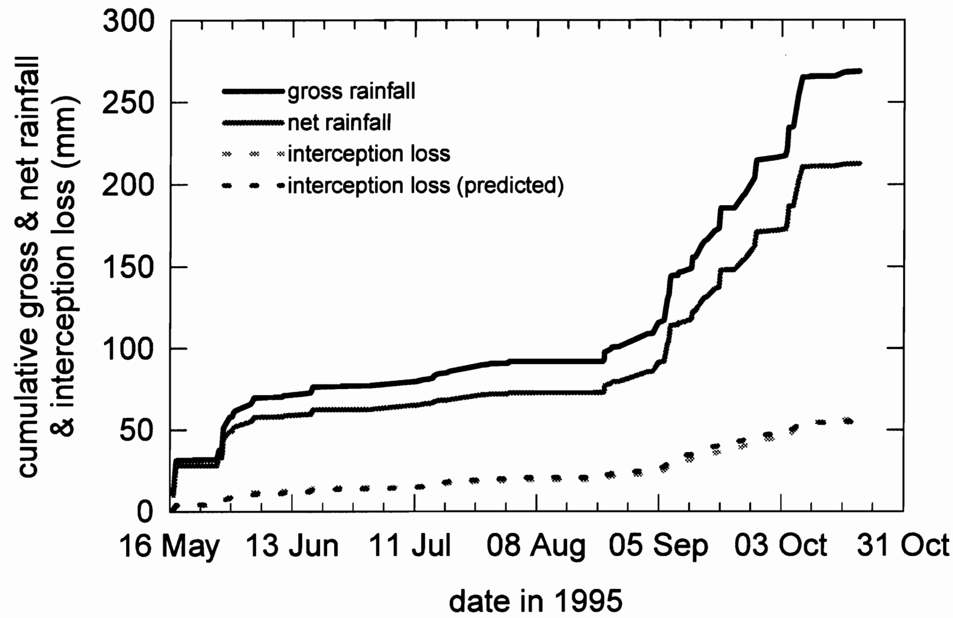


Fig. 3.69 Cumulative net rainfall, beneath three-year old shoots on four-year old stools of Beaupré, cumulative gross rainfall and the cumulative interception loss at Hunstrete

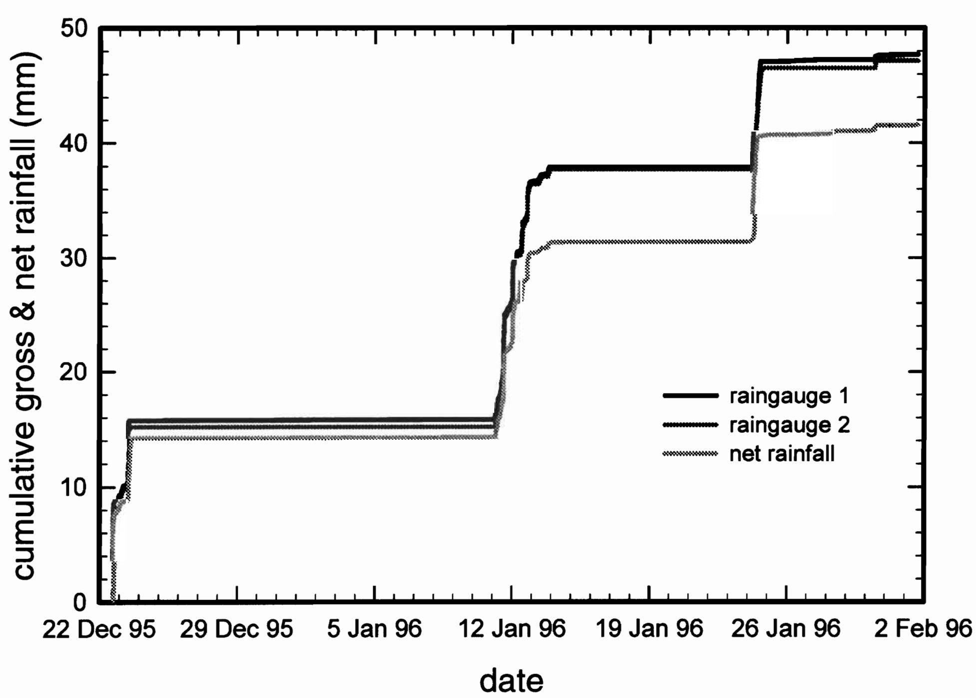


Fig. 3.70 Cumulative net rainfall beneath unfoliated three-year old shoots on four-year old stools of Beaupré, cumulative gross rainfall and the cumulative interception loss.

Between 25 December and 31 December the raingauges froze and some precipitation was not recorded. Because of the small sample size the interception loss from unfoliated coppice indicated by these data carries large uncertainties.

The interception loss measured for the poplar coppice at Hunstrete is well within the range of reported interception losses from mature broadleaf forest in leaf which ranges from 8% for ash Harding et al., (1992), to 36% for hornbeam Leyton et al., (1967) (see Hall and Roberts (1990) for a review) and similar to the 24% measured by Harding et al., (1992) from 21m-tall beech in Hampshire. However, given that the coppice was less than one third of the height of the beech it is perhaps surprising that the interception loss is so similar.

To find an explanation for the high interception loss several tests were performed on the net rainfall gauge to ensure that there were no leaks which would result in the net rainfall being underestimated and therefore the interception loss overestimated. These tests, that were additional to the regular checks and test made through the summer, all proved negative.

We also measured the canopy storage capacity of the coppice. A representative poplar stem was harvested and placed in a container of water, to prevent the leaves from wilting, on a logged electronic balance. A wooden frame held the stem vertical. We then used the knapsack sprayer to spray water onto the leaves and branches of the sample from the scaffold walkway (Section 3.2.2.4). Spraying was continued until the balance recorded a more or less constant mass. The storage capacity was taken as the mass recorded once drainage was seen to have stopped. After repeating this several times the stem was removed and the leaves harvested and their area measured using a leaf area machine (Section 3.2.2.2). These measurements yielded a specific storage capacity (depth of stored water per unit area of leaf) of about 0.1 mm m^{-2}. This figure was confirmed by laboratory measurements on individual leaves. It is lower than the 0.27 mm m^{-2} reported Harding et al., (1992) for the beech which had a similar leaf area to the coppice. However our measurements were made at the end of the season when the leaves may have become less water retentive with ageing.

If indeed the canopy capacity is small, it would appear that the coppice must have a low aerodynamic resistance to explain the high interception loss. It is possible that because the canopy density of SRC is high, a large leaf area in a small depth of canopy, there is better coupling between the lowest leaves and the air above the canopy than there is in the much deeper canopy of mature beech forest. Further consideration of the canopy capacity and r_a is given in the following Section 4. However further studies are needed before the mechanisms that explain the high interception loss from coppice are identified clearly.

3.3 MODELS AND MODELLING

To maximise the utility of the measurements from Swanbourne and Hunstrete mathematical models have been developed to estimate SRC water use that incorporate the results and relationships that were derived from those measurements. Mathematical models in themselves produce new insights and also, by incorporating the results of process studies, allow predictions to be made for situations different from those in which the original measurements were made.

The basis for all models of crop water use is the water balance equation:

$$P = E + D + Q + \Delta\Theta \tag{3.9}$$

where P is the precipitation, E is the evaporation, (the sum of the transpiration, T, and the interception loss, I), D is the drainage, Q is the runoff and $\Delta\Theta$ is the change in the soil water storage. In the models described here it is assumed, unless stated otherwise, that drainage and runoff are zero when there is a soil water deficit. Models work sequentially through the data calculating the different terms in the water balance at particular moments in time. The frequency of these time steps is usually determined by the periodicity of the input data. Using the subscript i to denote the ith time step, then when there is a soil water deficit the evaporation at time step i is given by,

$$E_i = T_i + I_i = P_i + \delta\theta_i - \delta\theta_{i-1} \tag{3.10}$$

where $\delta\theta_i$, and $\delta\theta_{i-1}$, are the soil water deficits at time steps i and i-1 respectively. When the soil water store is full it is assumed that any additional precipitation results in drainage from the soil to underlying groundwater or surface runoff to streams or both. Which of these routes is dominant will depend upon the soil type. For heavy clays runoff will dominate whereas for sandy soils drainage will dominate. In the models used here these routes are not separated but both considered as drainage. The drainage[4] at a time step i is equated to the negative of the excess soil water at the previous time step i - 1. So, $D_i = -\delta\theta_{i-1}$.

Two main models have been developed: WUCOP, (Water Use of Coppiced Poplar) a fairly detailed process-based model that operates on a ten-minute time step, and SIMWUCOP (Simplified Model of the Water Use of Coppiced Poplar) that operates on a daily time step. The data requirements of the two models are different. WUCOP requires ten-minute values of solar and net radiation, dry and wet-bulb temperature, windspeed and rainfall, whereas SIMWUCOP requires just daily values of rainfall and Penman E_T.

[4]In some soils there can be significant drainage even when there is a soil water deficit. Chalk soils are an example of this and to model the drainage from these correctly it is necessary to use an additional drainage function as discussed in Section 3.3.2.1.

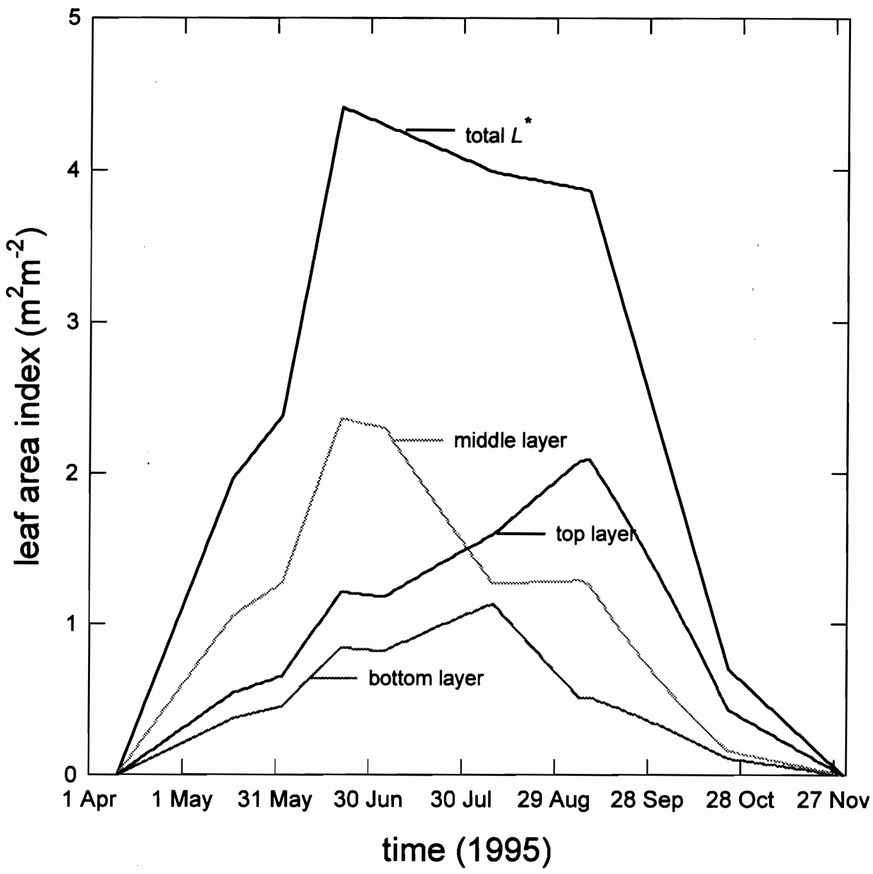


Fig. 3.71 Total leaf area index (L^*, m^2 m^{-2}) and leaf area index for the three canopy layers of Beaupré at Hunstrete

The sequence of calculations at each time step is the same for both models and uses Equations 3.9 and 3.10. At each time step the first operation is to equate the estimate drainage to the absolute value of soil water deficit calculated at the previous time step if that deficit was negative, i.e. if $\delta\theta_{i-1} < 0$ then $D_i = -\delta\theta_{i-1}$ (see above). If the deficit was negative it is then reset to zero, i.e. $\delta\theta_{i-1} = 0$. The transpiration is then calculated with due account being taken of any reduction in transpiration caused by rain water on the canopy. Next the interception loss is calculated. The new soil water deficit is then calculated from these values of transpiration and interception loss and the rainfall using Equation 3.10. Running totals are kept of the water balance components.

With appropriate parameter values, WUCOP produced estimates of the water use of the three-year Beaupré coppice at Hunstrete in summer 1995, in good agreement with measurements. The transpiration estimates produced by WUCOP were used as the basis for the calibration of SIMWUCOP. This model was derived to make it possible to compare the water use of SRC with other crops using data sets extending over several years and consequently different climatic conditions. These models and their operation are described in more detail in Sections 3.3.1 and 3.3.2.

3.3.1 Process-based model of SRC water use (WUCOP)

Figure 3.74 shows the framework of the model and how it is derived from the results of the measurements made at Hunstrete (Section 3.2.2). The various components of the model and the inter-relationship between them shown in Fig. 3.74 are discussed in the following sections.

3.3.1.1 *Description of the model*

At the heart of this model is the calculation of the evaporation from the SRC. It is expedient to calculate the evaporation from a stand of vegetation as the sum of the transpiration and the interception loss. A relatively simple, physically-based equation able to calculate the evaporation either through the stomata or from surface water, usually rainfall or dew, is used for this purpose. This treats the vegetation as a single homogeneous surface and consequently is sometimes referred to as the "big leaf model", but more frequently as the Penman-Monteith equation (Monteith, 1965). It has been extensively tried and tested over the years. The evaporation rate, E, is given in mm of water per second by:

$$E = \frac{\Delta' A + \rho c_p D / r_a}{\lambda \Delta' + c_p (1 + r_s / r_a)} \tag{3.11}$$

where: A is the energy available for evaporating water and warming the air and is estimated as the difference between R_n, the net radiation, and G, the soil heat flux; c_p is the specific heat of air at constant pressure; D is the above-canopy specific humidity deficit of the air; Δ' is rate of change of saturated specific humidity with air temperature; λ is the latent heat of vaporisation of water and ρ is the density of air. All of these meteorological variables are measured directly by, or derived from measurements made by, the AWS (see section 3.1.2.1 and 3.2.2.1). The two resistances, r_a, the aerodynamic resistance to water vapour transfer and r_s, the surface resistance, are parameters that quantify the efficiency with which water vapour is transferred from the leaf surface to the bulk atmosphere and from the leaf interior through the stomata to the leaf surface. These had to be determined for the coppice.

Transpiration. When the vegetation canopy is dry the surface resistance can be approximated by the bulk stomatal resistance, r_c, and the formula (Equation 3.11) then provides an estimate of the transpiration rate. The bulk stomatal resistance can be derived from measurements of stomatal conductance and leaf area using the relationship,

$$r_c = g_c^{-1} = \left(\sum_{j=1}^{3} g_{s,j} L_j \right)^{-1} \tag{3.12}$$

where the bulk stomatal or canopy conductance, g_c, which inverted gives the bulk stomatal resistance, is calculated as the sum of the mean leaf stomatal resistances for each canopy layer, $g_{s,j}$ weighted by the leaf area index of that layer, L_j. The changing leaf area indices of

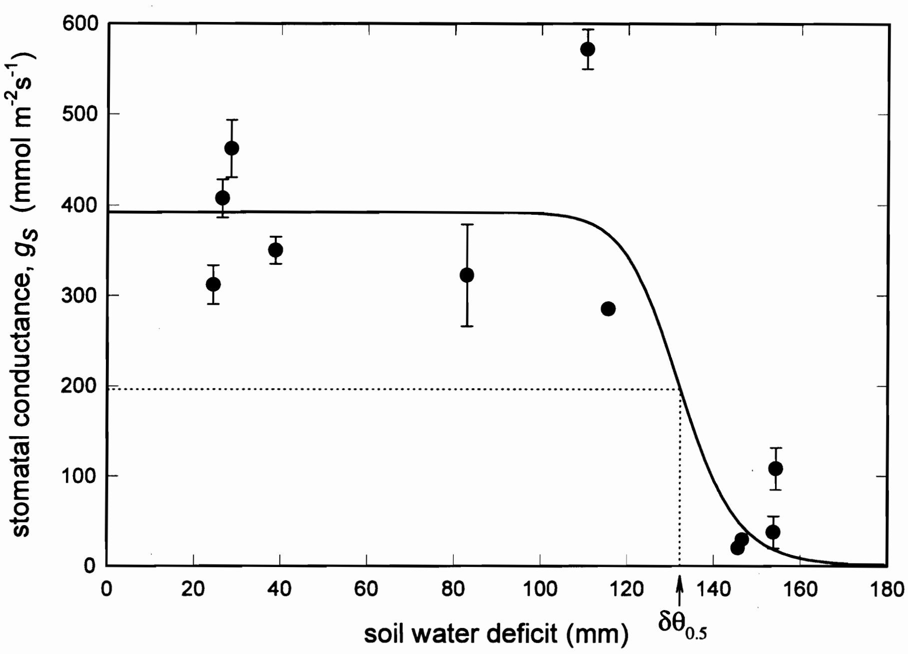


Fig. 3.72 The relationship between the leaf stomatal conductance and the soil water deficit for leaves of the middle canopy layer

the different layers of the canopy through the summer (Fig. 3.71) were interpolated between the leaf area and stem diameter measurements made on six occasions through the summer using the procedure described in Section 3.2.2.2.

To obtain estimates of transpiration for periods when there are no measurements of stomatal conductance available it is necessary to have a means of calculating g_s. Because the results of the conductance measurements showed that g_s for both Beaupré and Dorschkamp clones is insensitive to variations in the meteorological variables, estimating g_s can be simplified to determining the relationship between g_s and $\delta\theta$, the soil water deficit, to which it is sensitive, at least for Beaupré. The soil water deficit is in turn calculated as part of the water balance (Equation 3.10). Figure 3.72 shows the relationship between measured stomatal conductance of leaves in the middle layer of the canopy, and the soil water deficit determined from measurements of soil water storage made with the neutron probe (see Section 3.2.2.5). The simple function

$$g_s = g_{s,\max}\left(1 + \left(\frac{\delta\theta}{\delta\theta_{0.5}}\right)^b\right)^{-1}, \qquad (3.13)$$

was fitted to these data using commercial software (TableCurve™ 2D, Jandel Scientific GmbH, Erkrath, Germany). $g_{s,max}$, is the mean stomatal conductance that prevails when the trees are not short of water, $\delta\theta_{0.5}$ is the soil water deficit when the stomatal conductance is reduced to 50% of $g_{s,max}$ and b is a parameter that relates to the rate of decrease of g_s with increasing $\delta\theta$. Similar graphs and $g_s(\delta\theta)$ functions were derived for the leaves of the top and bottom canopy layers. The parameter values for all three functions are given in Table 3.13.

Table 3.13 Parameters for the equation relating stomatal conductance g_s for leaves within three canopy layers to the soil water deficit $\delta\theta$

	$g_{s,max}$ (mmol m^{-2} s^{-1})	$\delta\theta_{0.5}$† (mm)	b
upper layer	437	239 (135)	21
middle layer	392	239 (132)	20
bottom layer	217	239 (126)	11

† the fitted values (in parentheses) were all replaced by 239 for the reasons given in Section 3.3.1.3.

Thus it was possible to calculate r_s from Equations 3.12 and 3.13 and the leaf area index. To model the nighttime stomatal closure, r_s is put equal to the 500 s m^{-1} or the value calculated from Equation 3.12, whichever is larger, for times when the solar radiation is less than 2 W m^{-2}.

The other parameter required for use in Equation 3.11, the aerodynamic resistance (r_a), is difficult to measure directly and is often approximated by a formula that gives the aerodynamic resistance to momentum transfer as a function of the windspeed. However by making simultaneous measurements of the transpiration rate, leaf temperatures and windspeed we were able to determine the aerodynamic resistance to water vapour transfer as a function of wind speed. The data and fitted curve,

$$r_a = 26u^{-0.53} \tag{3.14}$$

are shown in Fig. 3.73 and details of the theory and methodology are given in Appendix A. The measurements were obtained between 19 August and 1 September 1995 but the resultant function was used to calculate r_a over the whole data set (10 April to 30 November 1995).

Having obtained expressions for r_s and r_a Equation 3.11 was used to estimate the transpiration rate from meteorological data and estimates of the soil water deficit.

Interception loss. When the vegetation is wet the surface resistance, r_s, equals zero as evaporation takes place from the surface of the water on the leaves instead of from the interior of the cavity inside the stomatal pores. In this situation, and with r_a estimated from the windspeed using Equation 3.14, Equation 3.11 provides an estimate of the rate of evaporation of water on the surface of the vegetation which integrated over time gives the interception loss. This integration is performed in an interception model of which there are many of widely varying complexity. In this application a well established, physically-based, analytical model (Gash, 1979; Gash et al., 1995) was used.

The Gash model calculates the interception loss as the sum of the loss from small storms,

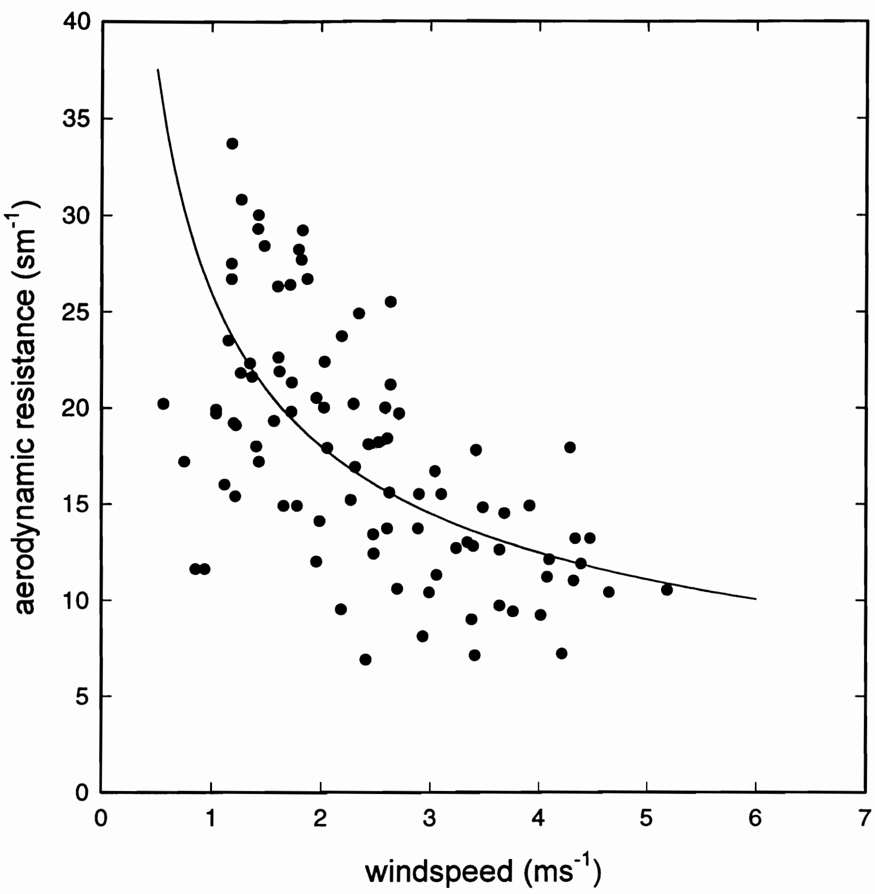


Fig. 3.73 The aerodynamic resistance to water vapour transfer versus windspeed, for three-year old shoots of Beaupré with the fitted curve $r_a = 26\ u^{-0.53}$

which is just equal to that fraction of the rain falling on the vegetation, and from storms large enough to saturate the canopy. The interception loss from the large storms is calculated as the sum of the loss occurring as the rain wets the canopy, the loss following saturation until cessation of rainfall and the loss after rain ceases.

As used in this application the model requires values to be assigned to three parameters: r_a; S, the canopy storage capacity; and p the free throughfall coefficient, the fraction of the rainfall that reaches the soil without touching the vegetation. Equation 3.14 defines r_a, but see Section 3.3.1.3. S was calculated from the leaf area of the canopy multiplied by the specific storage capacity that was measured as described in Section 3.2.2.6. It was assumed that the specific storage capacity remained constant through the summer. To be able to estimate p through the growth season we derived the relationship with leaf area index, L^*,

$$p = (1.008 - 0.2222(L^*)^{0.5})^2 \quad , \tag{3.15}$$

using the results of Chen et al., (1993) who used a fractal approach to model the canopy structure of poplar. An estimate of p calculated from this formula was within about 10% of

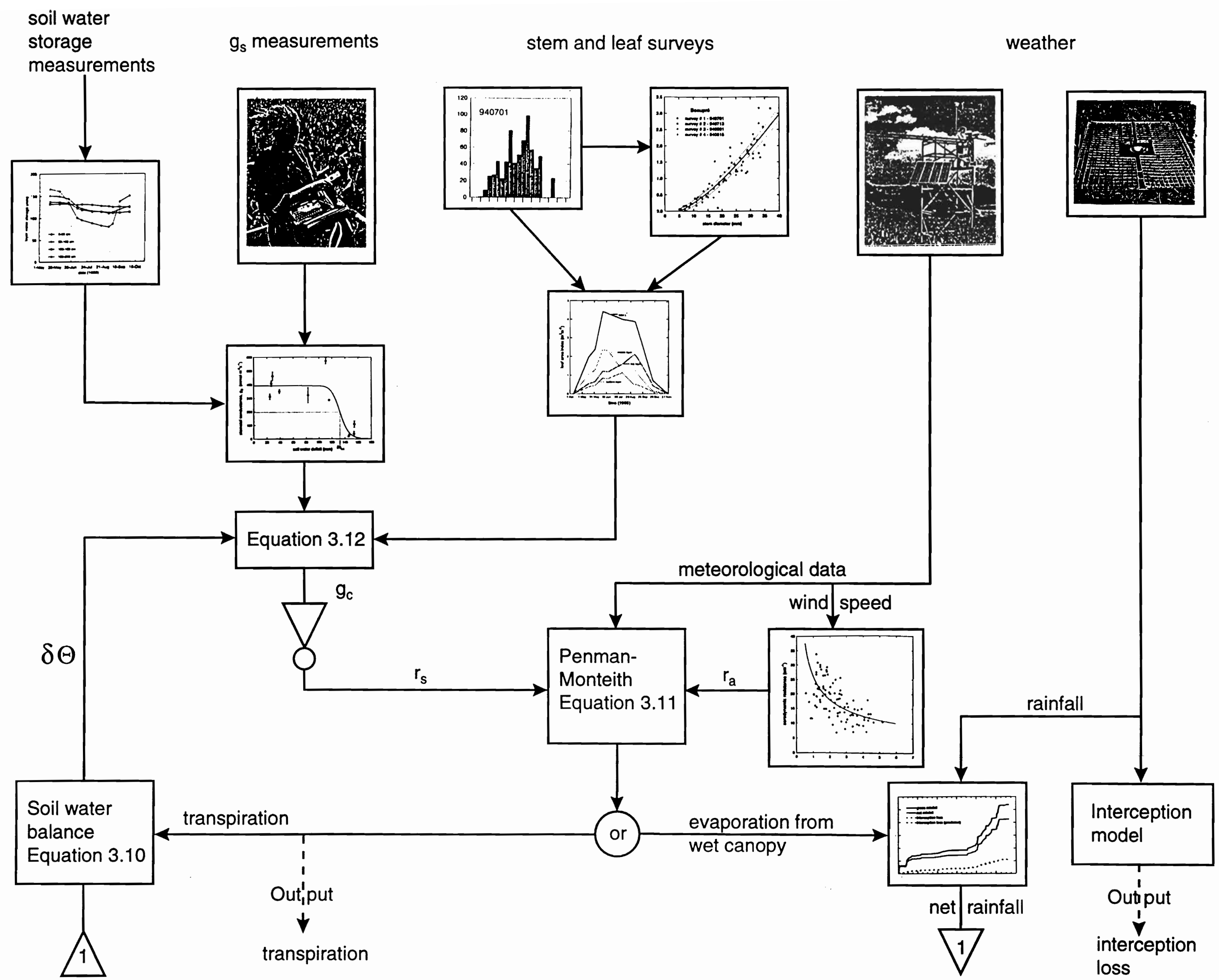


Fig. 3.74 Flowchart showing the logic of the WUCOP

an estimate calculated from 100 readings of canopy cover made with an anascope[5] at the net raingauge plot.

A requirement of the Gash model is that the mean evaporation rate, $\bar{E}$, and rainfall rate, $\bar{P}$, from a saturated canopy are calculated. This is achieved by assuming the canopy is saturated for those hours in which the rainfall exceeds 0.5 mm. $\bar{E}$ is then calculated for those hours using Equation 3.11. Having determined these values the amount of rain needed to achieve canopy saturation, P'_G, is calculated. Once representative values for these state variables have been calculated the model can be used to estimate the interception loss from this type of vegetation from estimates of rainfall alone, if required.

3.3.1.2 *Operation of the model*

The weather data from the AWS provide the basic inputs for the Penman-Monteith equation together with the derived resistances (see above). The estimated evaporation rates give either transpiration rates on a ground area basis or, when the coppice canopy is wet during and after rainfall, used to estimate the interception loss rate. This in turn is used to determine the drying of the canopy, which affects the total calculated transpiration, and summed to give the interception loss. The difference between the rainfall and interception loss gives the net rainfall that reaches the soil. The rainfall, transpiration and interception loss are used in Equation (3.10) to calculate the change in the soil water deficit.

The WUCOP model was operated on a ten-minute time step using data from the AWS at Hunstrete and the optimal estimates of rainfall from the raingauge network. To investigate the possible water use from coppiced poplar with unlimited water availability, e.g. growing along a river bank or under irrigation, the model was also operated with the dependence of the stomatal conductance upon the soil water storage removed, i.e. Equation 3.13 became $g_s = g_{s,max}$.

The evaporation from one-year old Beaupré coppice was also simulated. The model parameter values were adjusted on the basis of a stem and leaf survey made on 24 October 1995 on coppice planted in 1994 (see Fig. 3.37). Because there had been no measurements of stomatal conductance or soil water storage made on these trees it was necessary to make some large assumptions viz., the leaf stomatal conductance of the one-year old shoots on two-year old stools was the same as for the three-year old shoots on four-year old stools and had the same dependence on the soil water deficit. On the basis of these assumptions the parameter $g_{s,max}$ was put to 350 mmol m^{-2} s^{-1}, equal to the mean of the values for the different layers of the three-year old shoots and the value of $\delta\theta_{0.5}$ was put to 130 mm to reflect the shallower root system. It was also assumed that the maximum value of L^* was reached on the same date as on the three-year old shoots. The value of L^* calculated from the survey was 0.94. To allow for the shortness of the one-year old shoots the r_a coefficient was increased by 120%. This corresponds to the percentage increase for the shorter shoots over the three-year old shoots

[5]A simple manual instrument comprising a gimbal mounted mirror with sights that allows the canopy to be viewed perpendicularly above the instrument.

predicted by equations governing the aerodynamic resistance to momentum transfer.

In addition to the Hunstrete data the model was also operated using the 1994 data from Swanbourne. To allow for the younger, and therefore shorter, shoots of both Beaupré and Dorschkamp clones at Swanbourne the aerodynamic resistance coefficient was increased by 50% and 90% respectively following the procedure described above. To simulate transpiration from the Dorschkamp the value of $g_{s,max}$ in Equation 3.13 was increased in accord with the higher stomatal conductances of the Dorschkamp measured in 1994. The leaf area index, L^*, at Swanbourne was modelled using the mean of the values measured there in 1994 but with the timing of the increase and decrease in L^* taken from the more frequently measured Hunstrete data.

The results of all the model runs are described below.

3.3.1.3 *Model estimates of interception loss, transpiration and evaporation*

Estimated interception loss. The interception loss predicted by the Gash model, incorporating the canopy capacity and aerodynamic resistance function (Equation 3.14) derived from our measurements (see Section 3.3.1.2 and Appendix A), was significantly less than the observed interception loss; the difference between the measured gross and net rainfall (see Section 3.2.2.6). A possible explanation concerns the aerodynamic resistance. This is dependent upon the area of the surface from which water is evaporating. The function that we derived was obtained from dry, transpiring leaves. However, the surface area from which surface water evaporates is considerably larger; water is stored on both sides of the leaves, the leaf petioles and the branches and shoots of the coppiced trees. Consequently the aerodynamic resistance function that we derived is likely to overestimate significantly the aerodynamic resistance from the wet trees. This would result in the predicted rate of interception loss being underestimated which in turn would result in an underestimate of the total interception loss. It is also possible that the specific canopy capacity we used is too small: we measured it at the end of the summer when ageing of the leaves may have caused a reduction in their water retention characteristics.

To achieve agreement between the predicted and observed interception loss (see Fig. 3.69), the windspeed coefficient in Equation 3.14 was reduced from 26 to 8 and this value used subsequently.

Estimated transpiration. The estimated transpiration was in good agreement with that calculated from measurements of the sap flow rates (see Section 3.2.2.3), using the SHB, HPV, and deuterium tracing methods, for the period at the start of the summer until about the first week in July. However after that time the model estimates were much lower than the measurements. The reason for this disagreement lies in the calculation of the stomatal conductance from the function based upon the soil water deficit (Equation 3.13). As discussed in Section 3.2.2.5, a soil water balance calculation produced estimates of the coppice water use that were less than those obtained from the direct sap flow measurements. It was suggested that either the trees were accessing water below the lowest depth reached by the neutron probe access tubes, or that the soil was deeper beneath the gauged trees than at the

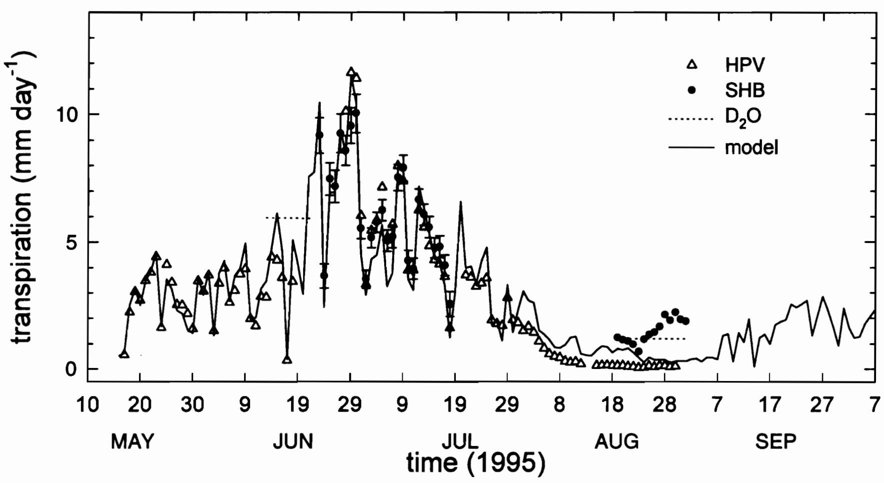


Fig. 3.75 Transpiration predicted by the WUCOP model and transpiration measured with heat pulse velocity (HPV), stem heat balance (SHB) and deuterium tracing methods (D_2O)

access tube Upper Plot. The sap flow measurements indicated that the soil water available to the trees was more than that indicated by the neutron probe measurements. In consequence the apparent value of the soil water deficit at which the stomatal conductance rapidly declines is significantly less than the true value. This causes the model to simulate a reduction in transpiration too soon and produces the disagreement with the measured transpiration rates.

Better agreement was achieved when $\delta\theta_{0.5}$, the parameter in Equation 3.13 which determines the point at which the modelled stomatal conductance declines, was increased to 239 mm for all canopy layers. Figure 3.75 shows the model-estimated and measured transpiration during the summer of 1995 at Hunstrete from three-year old coppiced Beaupré. Agreement is generally good. It is poorest at the end of the drought period when 9.6 mm of rain which fell on 23-25 August, caused an increase in the transpiration of the trees, indicated by the measurements from the SHB gauges, which was not simulated by the model. The trees, it would appear, rapidly respond to an increase in the available water in the soil surface layers. With the simple, single-store soil-water model used here this effect cannot be simulated and there is potential for improving the model in this respect. Notwithstanding, the agreement between the measurements and the simulated transpiration values is encouraging.

Cumulative evaporation. Over the period when there were measurements the accumulated transpiration simulated by the model was 313 mm compared to 310 mm which was the total of the mean of the SHB and HPV measurements. And over the entire period for which the necessary data were available for the model to be operated the total simulated transpiration and interception loss were 425 mm and 72 mm respectively. It can be expected that in more typical summers with more frequent and plentiful rain the ratio of the transpiration to interception loss would not be so large.

Figure 3.76 shows cumulative simulated interception loss and transpiration. In so far as the model is an accurate simulation of the behaviour of the trees these results show that during late spring the transpiration rate was about equal to E_T but as the tree canopy developed the transpiration rate exceeded E_T. This continued until about 20 July when the trees responded

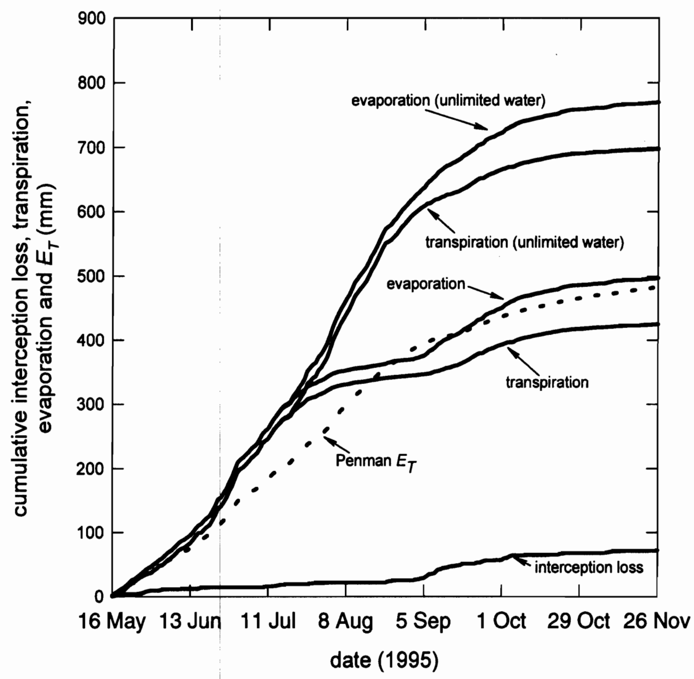


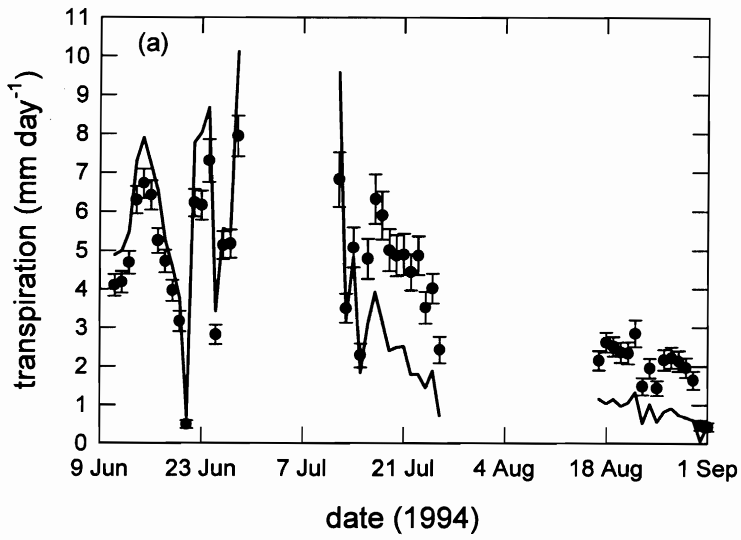
Fig. 3.76 Cumulative evaporation, transpiration and interception loss predicted by the WUCOP model for Hunstrete

to the large and increasing soil water deficit by closing their stomata and the transpiration rate fell to values much lower than E_T by mid-August. After rainfall at the end of August and early September the transpiration rate increased again to equal E_T after which senescence and leaf fall caused transpiration to cease.

For the case of unlimited soil water, also plotted in Fig. 3.76, the transpiration rate continues at an even higher rate during late July and early August in response to the very high atmospheric demand associated with hot, dry and sometimes windy weather. Under these circumstances the total transpiration and evaporation are 700 and 772 mm respectively over the simulation period.

The estimated transpiration from the one-year old Beaupré was 222 mm compared with 402 mm from the three-year old Beaupré over the period 16 May to 20 October. The interception loss estimated for the one-year old shoots on two-year old stools over the same period was 33 mm, about 12% of the rainfall compared to 54 mm from the three-year old shoots on four-year old stools.

The results of operating the model on the 1994 Swanbourne data are shown in Fig. 3.77. Agreement between the simulated and measured transpiration from the Beaupré (Fig. 3.77a) during the first campaign is good. For the second and third campaigns the model simulates well the general transpiration response but systematically underestimates the magnitude. This



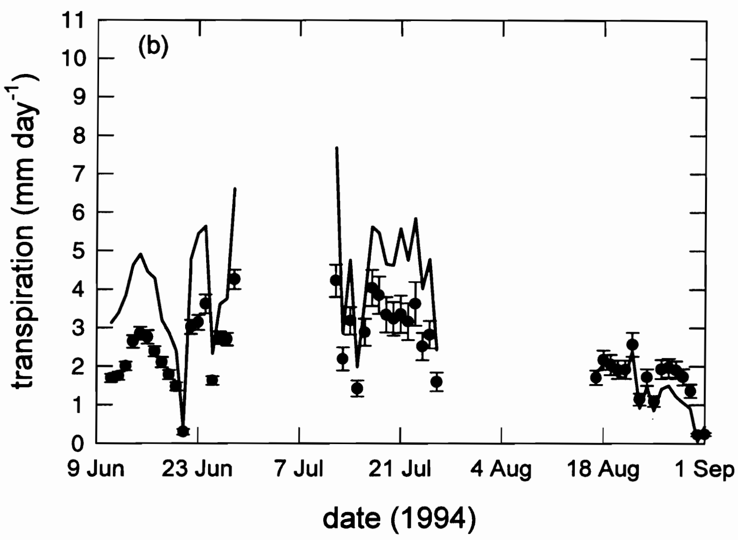


Fig. 3.77 (a) The transpiration predicted (solid line) by the WUCOP model with measurements from the SHB system for Beaupré at Swanbourne, (b) the same as (a) but for Dorschkamp

underestimate implies that the value of $\delta\theta_{0.5}$, appropriate for the Hunstrete site, is too small for the trees at Swanbourne. This in turn implies a greater store of groundwater available to the trees. This could be caused by deeper rooting, to be expected with the older trees, or, when the perched water table was present, lateral movement of soil water from the adjacent field into the rooting zone of the coppice plantation, or both.

There is reasonable agreement between the transpiration simulated and measured from the Dorschkamp during the last campaign of 1994 (Fig. 3.77b) and, as with the Beaupré, in the general transpiration response. However the model systematically overestimates the transpiration, contrary to the results from the Beaupré. Although the different height of the Dorschkamp shoots was allowed for by increasing the windspeed coefficient in the r_a function it was not possible to modify the model to allow for sheltering effects arising from interclonal competition. This was a marked feature of the Swanbourne site and is partly visible in Fig.

3.2 and is probably the reason for the lower transpiration from the Dorschkamp.

3.3.2 Simulation of comparative water use

The WUCOP model is able to provide realistic estimates of coppice water use when suitable data are available. However it requires detailed data of a high time resolution which are usually only available from research sites. To be able to simulate the water use for a wide range of sites and for general operational use, models with a simpler data requirement are needed. Also for our specific purpose, to examine how the water use of SRC compares with that of conventional agricultural crops and plantation forestry, within the resources of the project, simple models with the same basic structure and data requirement were needed. Similarity of function between the models is necessary to reduce artificial differences arising from model differences. To this end SIMWUCOP and the other models described below were developed to work on daily values of rainfall and E_T. Because of the larger degree of empiricism in these models there is more uncertainty in their estimates and care must be exercised in extending their use beyond their calibration ranges.

3.3.2.1 *Description of the model SIMWUCOP*

Transpiration and soil evaporation. Daily estimates of transpiration from WUCOP for the period when there was a full canopy were used to calibrate a function giving the potential daily transpiration, T (mm), as a function of the daily E_T estimate:

$$T = k_T E_T \left(1 + \left(\frac{\delta\theta}{\delta\theta_{0.5}}\right)^b\right)^{-1} , \qquad (3.16)$$

where k_T = 1.62 and b = 15.6 are constants. The effect on the water use of SRC of different soils or rooting depths is simulated by altering the magnitude of $\delta\theta_{0.5}$. The value of 239 mm optimised for this parameter in the stomatal conductance function (Equation 3.13) for the soil at the Upper Plot at Hunstrete should be appropriate for modelling clay soils such as that at Swanbourne.

Equation 3.15 yields an estimate of the transpiration from an SRC canopy at maximum L^* on dry days. To allow for the reduction in transpiration due to water on the leaves on rain days and for the lower L^* in spring, early summer and autumn this function is multiplied by two additional factors.

To allow for the effect of the changing leaf area at the start and end of the summer the normalised leaf area factor is used. This increases linearly from 0 on 10 April to 1 on 29 June, is kept at 1 for dates between 29 June and 9 September and then decreased linearly to 0 on 1 November.

To allow for the reduction in transpiration on rain days the wet canopy factor, the fraction of the day that the canopy is wet, is introduced.

The model also simulates evaporation from the soil which makes a significant contribution to the total evaporation during the unleafed period. The algorithm suggested by Doorenbos and Pruitt (1984) was followed in which the evaporation rate from bare soil is dependent upon the evaporative demand and the time since rainfall. For the foliated period the soil evaporation is reduced exponentially as the leaf area increases in accord with Beer's law (Monteith, 1973). This is assumed to approximate the reduction in the radiation, which is available for driving the soil evaporation, as a result of attenuation by the canopy.

Thus the daily transpiration, T_D, from the coppice is estimated by SIMWUCOP as

$$T_D = k_T E_T \left(1 + \left(\frac{\delta\theta}{\delta\theta_{0.5}}\right)^b\right)^{-1} L_N(1 - t_R) + E_S e^{-0.7L}, \tag{3.17}$$

where L_N is the normalised leaf area factor, t_R is the fraction of the day that the canopy is wet during and after rainfall, E_S is the soil evaporation and L is the leaf area which has a maximum value of 4.5 m^2. The value of t_R is calculated from the rainfall divided by the mean rainfall rate, calculated for example from the Gash model, and multiplied by 1.5. This factor of 1.5 is introduced on the basis that on average the canopy remains wet for 1.5 times the rainfall duration.

Interception loss. As in WUCOP, the Gash model of interception loss was used but operated on a daily time step. The model has been shown to work well using a daily time step, for which it was originally developed, by numerous studies worldwide. The free throughfall coefficient, *p,* was calculated as a function of the leaf area in the same way as for WUCOP and the same values used for the mean evaporation rate $\bar{E}$, and rainfall rate, $\bar{P}$ during saturated canopy conditions. During the unleafed period the canopy capacity was set at a constant value of 0.05 mm.

Drainage. For simulating the water use of SRC growing on most soils it is adequate to assume that there is no drainage as long as there is a soil water deficit. However it was found necessary by Harding et al (1992) to include a drainage function that simulated drainage from chalk soils when there was a deficit. This function

$$D = k_D \exp(-K\delta\theta) \tag{3.18}$$

where k_D and K are empirical parameters, has been included in SIMWUCOP to allow a more accurate estimate of the drainage when simulating SRC growing on chalk soils.

3.3.2.2 *Modelling the water use of agricultural crops and trees*

A common model based upon the daily E_T value was used for estimating the water use of grass pasture, spring barley, wheat, potatoes and sugar beet. An important component in simulating the annual water use of each of these crops is the evaporation from bare soil. As in SIMWUCOP the method of Doorenbos and Pruitt (1984) was followed. This component probably represents one of the largest uncertainties in these models. However this uncertainty is much less important when comparing the water use of different crops against each other because the soil evaporation algorithm is common to all except the conventional forestry trees.

Transpiration from the agricultural crops was estimated using the structure of the model of Lhomme and Katerji (1990). This model uses E_T multiplied by seasonally varying crop and available water factors to allow for the growth of the crop above and below ground. To simulate the effects of soil water stress in clay soils an exponential function (Calder et al., 1983), where $\delta\theta$, is the soil water deficit and k_w a root constant, was included viz:

$$f(\delta\theta) = 1 \qquad \text{for } \delta\theta \le k_w$$

$$f(\delta\theta) = 1.9\exp\left(-0.65\frac{\delta\theta}{k_w}\right) \qquad \text{for } \delta\theta > k_w. \tag{3.19}$$

In addition a simple interception model is also incorporated that allows for changing leaf area index through the growing season.

Transpiration and interception loss from mature ash and beech forest was estimated using the models described by Harding et al. (1992). The transpiration models are based on empirical functions of E_T, and also use Equation 3.18 for simulating the effects of soil water deficits in clay soils. The drainage function for chalk soils, Equation 3.17, was also included. The ash transpiration model implicitly includes an understorey component that continues for all months except December and January. An allowance for evaporation from the beech litter layer was added to the original model. Evaporation from litter was equated to the E_T value for rain days and to $0.5E_T$ for the day following rainfall. On all other days the evaporation from the litter was assumed to be zero. Evaporation from the litter layer during the foliated periods was attenuated by the same exponential function of leaf area used in SIMWUCOP to model soil evaporation beneath coppice.

A very simple model was used for pine transpiration in which E_T is multiplied by a crop factor and the soil stress (Equation 3.18) and drainage functions (Equation 3.17) for clay and chalk respectively. Calder (1986) gives the crop factor as 0.9 on the basis of studies in the uplands of Britain. However we found it necessary to use a value of 0.8 to give realistic annual transpiration for the south of England.

The models used to simulate interception loss from the ash, beech and pine (see Harding et al., 1992 and Calder, 1986 for details), are simpler and more empirical than the Gash model used in SIMWUCOP, but do provide good estimates of the interception loss on a long term basis. However, the interception loss from unfoliated ash is probably an overestimate; the unavailability of parameter values for ash necessitated the use of parameters for unfoliated beech instead.

Model parameters. The values of the parameters used for the different land uses are given in Table 3.14. The entry for the root constant for the SRC is actually the value of parameter $\delta\theta_{0.5}$. In addition to these dominant parameters other parameters in the models determined the timing of the days of emergence, full canopy cover, maturity and harvest.

Table 3.14 Parameter values for the ten different land uses modelled

	root constant k_w for clay (mm)	root constant k_w for chalk (mm)	crop factor	crop factor post mature
SRC (poplar)	(239)†	∞	-	-
ash	200	∞	-	-
beech	200	∞	-	-
pine	200	∞	0.8	-
grass	75	160	1	1
barley	80	160	1.05	.25
wheat	80	160	1.05	.25
potatoes	100	200	1.05	.7
sugar beet	200	400	1.2	.9
bare soil	25	25	-	-

† $\delta\theta$

3.3.2.3 *Operation of the models*

To validate the performance of the SIMWUCOP model it was operated on a set of daily E_T and rainfall values generated from the Hunstrete AWS and raingauge data collected during the summer of 1995. The coppice transpiration estimated by SIMWUCOP was 390 mm compared with 402 given by the WUCOP model over the same period and the interception loss was 60 mm compared to 67 mm. Given the differences between the models and input data this level of agreement is reasonable and indicates that coppice water use estimated for other input data by SIMWUCOP will be consistent with estimates that would have been produced by WUCOP were the appropriate data available.

A seventeen-year record of daily E_T values, calculated using data from a climatological station in the Grendon Underwood catchment, Buckinghamshire (Nat. Grid Ref. SP678215), and daily rainfall for the area, derived from Meteorological Office records, was used to investigate the effects of different climatic conditions on the water use of SRC using SIMWUCOP. The models of crop and tree water use were also operated with this data set to allow comparison of water use and drainage. The models were operated for two soil types viz., clay and chalk.

Although it is unlikely that SRC will often be planted on chalk soils this simulation indicates what effects a soil of greater water availability has on the absolute and comparative water use of SRC. On the basis of the findings of Harding et al. (1992) the model parameters for trees on chalk soils were adjusted to simulate unlimited water availability.

These simple crop water use models were also operated on the Hunstrete data to provide estimates of crop and tree water use for comparison with that of SRC. The results of the simulation assuming unlimited water availability for the SRC can be taken as the an estimate of the evaporation that would occur if the trees were growing along the banks of the stream at Hunstrete. It also provides an upper limit of the evaporation of the trees growing around Tube 1 at the Lower Plot (see Section 3.2.2.5) where the soil is deep and of light texture.

3.3.2.4 *Comparative water use of SRC, agricultural crops and conventional forestry*

SIMWUCOP was calibrated using data from WUCOP that in turn was derived using data collected from three-year old shoots on four-year old stools. Consequently the results of the simulations that are described below represent the largest differences in water use compared to the agricultural crops expected during the first rotation. Given suitable data for one and two-year old shoots it would be possible to adjust the parameters to allow SIMWUCOP to calculate the water use for these younger shoots. We would expect the increase in water use with increasing age of the shoots to become less so that that the increase from one to two year-old shoots would be greater than the increase from two to three-year old shoots and so on.

Hunstrete data. The results of operating the simple models using the Hunstrete daily data are given in Table 3.15 and plotted in Fig 3.78. Immediately apparent is the high potential evaporation over the period reflecting the extreme summer of 1995. Over this period the evaporation from the deep-rooted crops exceeded the rainfall. For the clay soil simulation the evaporation from the pine is highest followed by that from beet and coppice. The evaporation from the beet is high and should be regarded with caution. This may be an example of the simple crop water use model failing to correctly simulate the crop for an extreme data set. The root factor used for the beet may be too large or the soil water stress function could be inappropriate for beet.

The estimated evaporation for the same vegetation covers growing on a chalk soil are all higher but that of the coppice increased the most. The different type of soil used in the simulation had the smallest effect on the evaporation from the ash, beech and pine in that order. The reason for the extremely large evaporation from the coppice for this simulation, seen in Fig. 3.78b, is the high transpiration from the simulated poplar in mid-August. With the unlimited available water in this simulation there is no reduction in g_s and the poplar is able to transpire at the rates dictated by the atmospheric demand. Figure 3.78b also shows the significantly increased transpiration during mid to late summer by the grass compared to the simulation for grass growing on a clay soil.

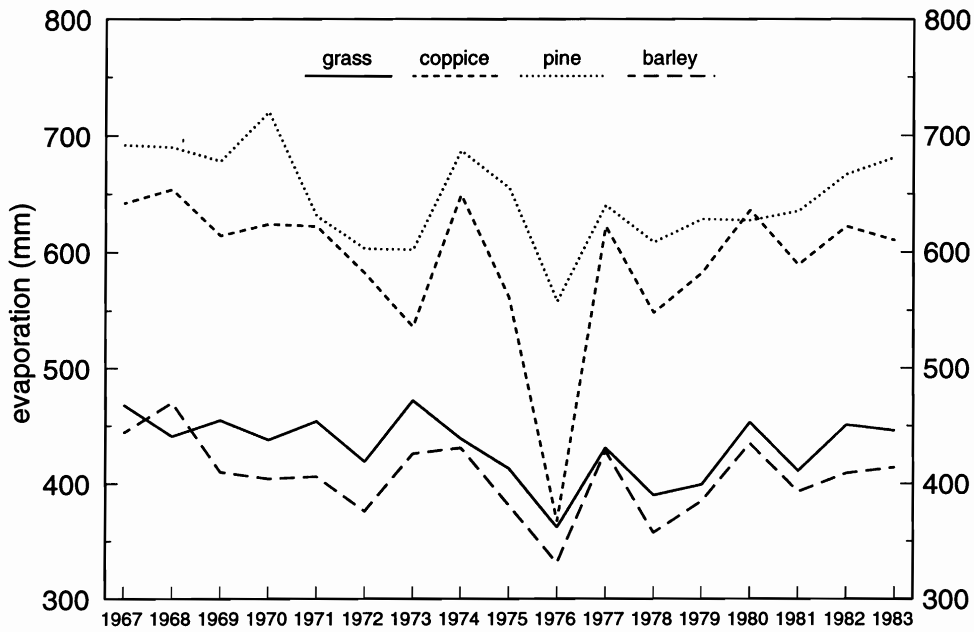


Fig. 3.78 Evaporation predicted for SRC, grass, barley and pine using the SIMWUCOP model

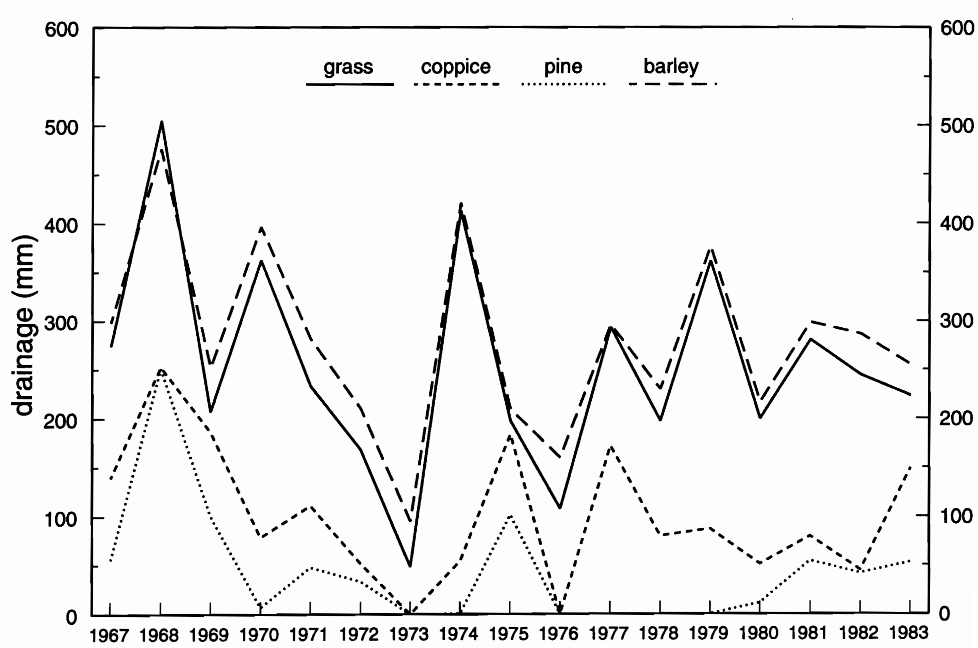


Fig. 3.79 Drainage predicted for SRC, grass, barley and pine using the SIMWUCOP model

Table 3.15 Simulated evaporation totals (10 April 1995 to 30 November 1995) for trees, crops and bare soil at Hunstrete

	EVAPORATION (mm)											
	E_T	rain	coppice	grass	ash	beech	pine	barley	wheat	potatoes	sugar beet	soil
clay	587	434	523	405	478	486	598	343	353	390	550	326
chalk	587	434	812	507	497	506	627	377	389	438	599	326

Long term data: Grendon Underwood. Table 3.16 gives the annual evaporation for trees, crops, grass and bare soil predicted by the SIMWUCOP model for a clay soil using the data from Grendon Underwood. The highest evaporation predicted is from pine and the lowest from bare soil. Evaporation from poplar coppice is second only to the pine. Evaporation from all tree types is higher than from crops except for sugar beet. Evaporation from potatoes, winter wheat and barley are similar. Estimated evaporation, using the same E_T and rainfall but with parameters for a chalk soil, are higher for all vegetation covers. Using the chalk soil parameters the ranking of crops for evaporation remains the same except for the coppice and pine; the coppice water use for this soil exceeds that from the pine.

The annual evaporation for coppice, grass, barley and pine are plotted as a time series in Fig. 3.79. There are two noteworthy features of the SRC evaporation. In 1976 the coppice evaporation is much lower than the other coppice values and reaches the level of the evaporation from grass. This is a consequence of the hot dry summer of 1975 being followed by a dry winter. The simulated transpiration of the coppice in 1975 resulted in a large soil water deficit which was not fully removed by winter rainfall. Once transpiration resumed in the hot, dry summer of 1976 the point at which the stomata close in response to soil water deficit was soon reached so that transpiration almost stopped. In 1980 the simulated coppice evaporation was higher than that from the pine. This was the result of rainfall during much of the summer maintaining soil water levels sufficiently to allow the poplar coppice to transpire at the rate set by atmospheric demand. At the same time the rainfall was not sufficiently high to allow the interception loss from the pine to compensate for the higher coppice transpiration.

Table 3.17 gives estimates of the annual drainage from the same vegetation covers and bare soil as Table 3.16. As expected, the amount of drainage reflects the annual rainfall : drainage is least in the driest years. For a clay soil the smallest drainage is under the pine and for several years is zero or negligible. Drainage is also predicted to be low from poplar coppice and zero in the driest years 1976 and 1973. As expected drainage is highest from bare soil. Under the crops, except for sugar beet, it is at least double that under the pine and coppice. With a chalk soil, drainage under the pine and the coppice are about the same. 3.80. This graph highlights the greater variability of the drainage compared to the evaporation reflecting The annual drainage from coppice, grass, barley and pine are plotted as a time series in Fig. the variation in annual rainfall.

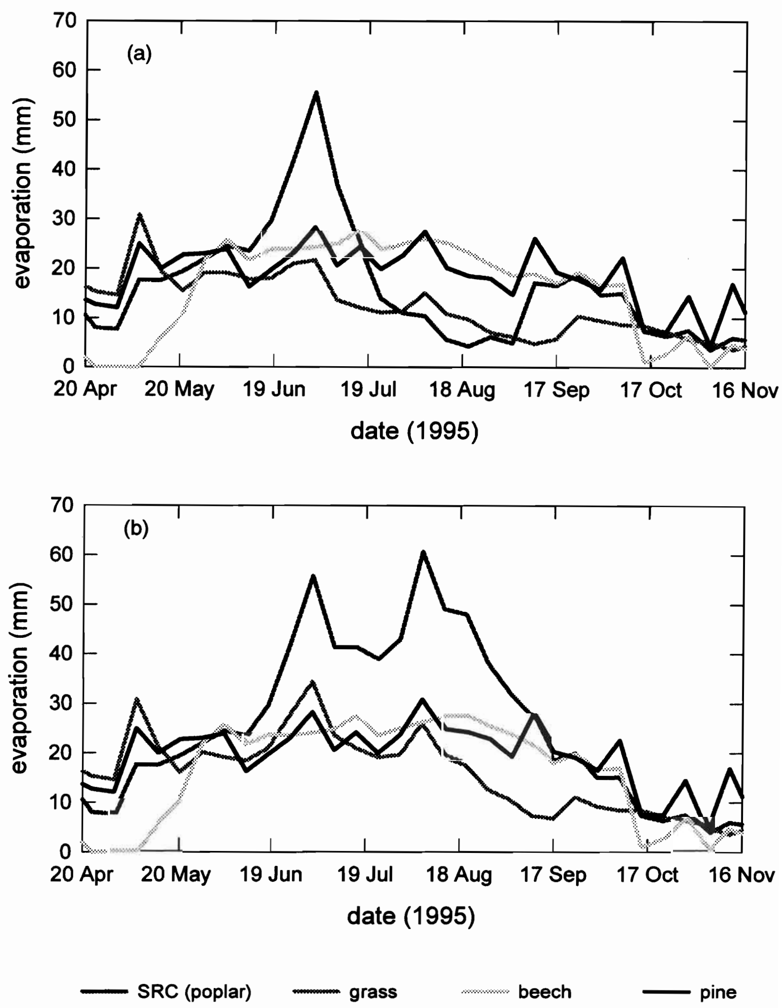


Fig 3.80 The evaporation predicted for SRC, grass, beech and pine at Hunstrete using the SIMWUCOP model

Table 3.16 Annual evaporation from trees, crops and bare soil calculated using Grendon Underwood data and assuming a clay soil. Average annual evaporation for the same on clay and chalk soils.

			EVAPORATION (mm)									
	E_T	rain	coppice	grass	ash	beech	pine	barley	wheat	potatoes	sugar beet	soil
1967	495	746	642	468	491	509	692	444	423	464	556	399
1968	441	942	654	441	449	491	690	470	471	468	519	375
1969	511	662	614	455	497	514	678	410	425	436	562	378
1970	503	800	624	438	509	547	720	404	400	425	492	408
1971	464	687	622	454	453	474	631	406	433	431	493	359
1972	448	587	582	419	441	468	603	376	373	404	479	353
1973	493	522	536	472	465	489	602	426	418	450	513	368
1974	461	852	649	439	461	496	687	431	441	451	514	372
1975	518	596	561	413	505	518	655	381	382	412	563	373
1976	545	506	367	362	473	439	558	331	338	355	395	346
1977	444	703	622	431	459	488	640	428	429	435	457	332
1978	448	588	548	390	454	492	608	357	360	381	479	351
1979	417	760	582	399	432	474	628	385	388	365	468	329
1980	463	651	636	453	452	473	627	435	437	397	480	370
1981	444	692	589	411	453	486	635	393	399	402	511	349
1982	485	694	622	451	477	496	667	409	425	408	524	389
1983	507	669	610	446	492	531	681	414	418	437	567	412
Clay	476	686	592	432	468	493	647	406	409	419	504	368
Chalk	476	686	676	467	471	499	654	426	433	436	509	368

Table 3.18 presents model estimates of annual evaporation for groups of years of differing rainfall totals with a clay soil assumed. Years were grouped into those with rainfall above 700 mm, between 600 and 700 mm and years with rainfall below 600 mm. There is a larger fall in annual evaporation from coppice with decreasing annual rainfall than for the other trees. The effect of dry years on the evaporation from ash and beech is small. However the evaporation from pine and coppice are still the highest annual totals in all years. Evaporation for crops also falls in dry years but the decreases are also smaller than those estimated for coppice and pine.

In Table 3.19 are shown the annual drainage values in the same groups of years of differing rainfall as in Table 3.18. In the driest group of years the drainage falls below 100 mm. When run for a chalk soil the model predicted (not shown) that drainage below coppice would be slightly less than that below pine.

Table 3.17 Annual drainage from trees, crops and bare soil calculated using Grendon Underwood data and assuming a clay soil. Average annual drainage for the same on clay and chalk soils.

			DRAINAGE (mm)									
	E_T	rain	coppice	grass	ash	beech	pine	barley	wheat	potatoes	sugar beet	soil
1967	495	746	139	274	252	234	56	298	319	279	187	343
1968	441	942	253	505	496	454	251	476	475	478	427	571
1969	511	662	186	207	172	240	101	252	237	226	205	284
1970	503	800	79	362	284	161	7	397	400	375	203	392
1971	464	687	111	233	234	218	48	281	255	257	208	328
1972	448	587	52	168	146	183	33	210	214	182	139	234
1973	493	522	0	48	57	16	0	95	103	71	0	154
1974	461	852	54	413	391	302	0	421	411	401	300	480
1975	518	596	184	197	178	237	101	209	209	203	202	217
1976	545	506	0	108	0	0	0	160	152	111	0	145
1977	444	703	172	293	190	136	0	296	295	289	188	392
1978	448	588	80	197	167	205	0	230	227	206	198	236
1979	417	760	87	362	296	164	0	376	373	396	203	432
1980	463	651	51	199	199	178	11	217	215	255	172	282
1981	444	692	80	280	240	234	54	299	293	290	189	343
1982	485	694	45	244	218	171	41	286	270	287	162	306
1983	507	669	149	223	189	245	53	255	251	232	206	257
Clay	476	686	101	254	218	199	45	280	276	267	188	317
Chalk	476	686	71	221	234	201	80	260	253	250	184	317

Table 3.20 shows the annual transpiration and interception totals for the tree covers in years with annual rainfall a) above 700 mm b) between 600 and 700 mm and c) rainfall below 600 mm. For pine, ash and beech transpiration is predicted to be largely unaffected in the years of lower rainfall and reduced evaporation in those years is a function of a reduction in interception. On the other hand the fall in evaporation of the poplar coppice in the intermediate and driest years is a consequence of a reduction in both interception and transpiration. High estimated evaporation for the coppice is due to the transpiration which is the highest of any trees or crops.

Comparison of the transpiration estimates from trees in Table 3.20 with the values in Table 3.22 indicates that the model estimates are in general agreement with the published values.

Table 3.18 Predicted average annual evaporation under different land uses for three classes of annual rainfall: (a) above 700 mm (b) between 600 and 700 mm and (c) below 600 mm. Soil type is clay.

			EVAPORATION (mm)									
	E_T	rain	coppice	grass	ash	beech	pine	barley	wheat	potatoes	sugar beet	soil
(a)	460	801	629	436	467	501	676	427	425	435	501	369
(b)	479	676	615	445	471	496	653	411	523	418	523	376
(c)	490	560	519	411	467	481	605	374	374	400	486	358

Table 3.19 Predicted average annual drainage under different land uses for three classes of annual rainfall: (a) above 700 mm (b) between 600 and 700 mm and (c) below 600 mm. Soil type is clay.

			DRAINAGE (mm)									
	E_T	rain	coppice	grass	ash	beech	pine	barley	wheat	potatoes	sugar beet	soil
(a)	460	801	131	368	318	242	52	377	379	370	251	435
(b)	479	676	104	231	209	214	51	265	253	258	191	300
(c)	490	560	63	144	110	128	27	181	181	155	108	197

Table 3.20 Predicted average annual transpiration (*T*) and interception (*I*) from trees on a clay soil grouped by rainfall: (a) rainfall above 700 mm, (b) between 600 to 700 mm and (c) below 600 mm.

		coppice		ash		beech		pine	
	rain	*T*	*I*	*T*	*I*	*T*	*I*	*T*	*I*
(a)	801	525	104	345	122	376	125	361	315
(b)	676	527	89	360	111	387	108	379	274
(c)	560	448	71	368	100	390	91	372	233

(a) Averages of 1967, 1968, 1970, 1974, 1977, 1979
(b) Averages of 1969, 1971, 1980, 1981, 1982, 1983
(c) Averages of 1972, 1973, 1975, 1976, 1978

Table 3.21 Annual transpiration for four crops using Grendon Underwood climatological data and assumed to be growing on a clay soil

Year	barley	wheat	potatoes	sugar beet
1967	304	291	280	309
1968	266	289	233	268
1969	296	320	284	352
1970	268	269	247	277
1971	270	313	269	284
1972	260	261	247	283
1973	299	302	296	304
1974	264	286	226	255
1975	285	298	261	350
1976	241	268	233	309
1977	314	286	243	239
1978	281	265	242	300
1979	299	282	218	282
1980	304	285	197	273
1981	301	274	237	285
1982	306	294	216	284
1983	322	301	261	335
	287	287	246	293

The evaporation values given in Table 3.16 for barley, wheat, potatoes and sugar beet include, as well as interception losses, losses due to soil evaporation following harvest and before the next crop emerges. The transpiration estimates for the crops in Table 3.21 include only associated soil evaporation during the growth period of the crop. The averages suggest that transpiration is least from the potatoes but about the same for the other crops. It is possible to compare these values with the published values in Table 3.22 which generally do not include the soil evaporation from the non-growing periods. This comparison indicates that the model estimates of crop transpiration are realistic.

3.4 SUMMARY OF THE RESULTS OF THE STUDY OF THE WATER USE OF SRC

Measurements were made of transpiration, using a suite of methods, interception loss and additional supportive measurements including meteorology, soil water status and rooting. Transpiration was measured from three-year old shoots on seven-year old stools and two-year-old shoots on eight-year old stools of Beaupré and Dorschkamp clones on the heavy clay site at Swanbourne and from three-year old shoots on four-year stools of Beaupré and willow (Germany clone) on a clayey loam site at Hunstrete. Interception loss was measured during the leafed period at Hunstrete from the three-year old Beaupré. This programme of measurements was augmented by modelling studies. Both measurements and modelling results provided objective support for the commonly held belief that poplar and willow can be large water consumers.

3.4.1 Comparative water use

When incorporated into models the findings from the measurement programme resulted in estimates of evaporation that generally agreed well with the measurements. The evaporation from SRC estimated by the SIMWUCOP model is higher than all of the other land uses modelled with the exception of pine forest on a clay soil (see Table 3.16). Measurements made over several years by the Institute of Hydrology in both the mid-Wales catchments and at Thetford Forest confirm that evaporation from coniferous forest is as high as the model estimates for pine. However, the high evaporation losses predicted for the coppice and pine using the Grendon Underwood climate data are the consequence of different processes. For the pine plantation interception losses occur throughout the year, whereas in coppice, high transpiration rates in the growing season assume the greater importance. On the basis of the figures in Tables 3.16 and 3.20 it is possible to calculate that on average the water use of pine will exceed that of SRC growing on clay at locations where the annual rainfall exceeds about 480 mm, i.e. the whole country, and that it will exceed that of SRC growing on chalk where the annual rainfall exceeds about 770 mm.

The comparative modelling was carried out to examine the size of the differences between crops and the influence of soil type and climate. No judgement was made on the likelihood of particular crops being grown on the soil types chosen and with the simple models used, the degree of uncertainty in the crop/soil parameters makes it impossible to define the soil types precisely. "Clay" and "chalk" represent a range of soils more accurately labelled clayey loams and calcareous loams. In particular the clay category includes the soils at both Swanbourne and Hunstrete (Upper Plot). The chalk category can be regarded as representing situations with unlimited water availability for the tree crops. Harding et al. (1992) found no reduction in transpiration from ash and beech growing on chalk soils when there were large (> 400 mm) soil water deficits. Other situations that this simulation may represent would be riparian and irrigated plantations.

On average (see Table 3.16) the simulated annual evaporation from the poplar SRC exceeds that from other crops by an amount that ranges from 88 mm for sugar beet on a clayey soil to 250 mm for barley on a chalk soil. The high evaporation from SRC results from its high transpiration rate.

3.4.1.1 *Transpiration*

Annual transpiration values for a range of crops and trees taken from the literature are listed in Table 3.22.

Transpiration from SRC, both measured and estimated from models, is higher than all other vegetation covers (see Tables 3.16 and 3.22). The high transpiration rates measured from the coppice when soil water was not limiting were the consequence of high stomatal conductances rather than because of high L^*. Although the L^* of the poplar coppice reached 4.8 at Swanbourne and 4.4 at Hunstrete, values in this range are commonly observed in forest, crop and grassland communities and are often exceeded. Hall and Roberts (1990) show the range

Table 3.22 Annual transpiration of different vegetation covers

Species	Country	Year	Transpiration ($mm\ y^{-1}$)	Remarks	Forest age (years)	Reference
Short-Rotation Coppice						
Willow	Sweden	1980	481	(transpiration + soil evaporation)	2	Grip *et al.* (1989)
	Sweden	1985-	445	(transpiration + soil evaporation May to Oct.)	2	Persson & Lindroth (1994)
		1988	306		6	Persson (1995)
Crops						
Barley	Rothamsted, UK		288	(irrigated)		Day *et al.* (1978)
	"		204	(non-irrigated)		
Spring barley	Denmark	1976	250			Aslyng and Hansen (1982)
grass	Denmark	1976	290			"
	"	1968-1976	353			"
Oats	Germany	1976	229			Ehlers (1989)
		1977	275			
		1982	368			
		1983	316			
Potatoes	Reading, UK		301	(irrigated)		Asfary et al (1983)
			213	(unirrigated)		"
	Holland		287			Feddes *et al.* (1988)
Sugar beet	Broom's Barn, UK		385	(irrigated)		Brown *et al.* (1987)
"	"		290	(non-irrigated)		"
Fodder beet	Denmark		390	(irrigated)		Aslyng and Hansen (1982)
			355	(unirrigated)		"
Winter wheat	Rothamsted, UK		340	(irrigated)		Weir & Barraclough (1986)
"	"		223	(droughted)		"
Winter wheat	Nottingham, UK		244	200 kg N ha^{-1}		Scott *et al.* (1994)
"	"		229	100 kg N ha^{-1}		"
"	"		192	0 Nitrogen		"

Species	Country	Year	Transpiration (mm y^{-1})	Remarks	Forest age (years)	Reference
Broadleaves						
Ash	Hants, UK	1989	407			Roberts and Rosier (1994)
Ash	Northants	1990	294			Roberts and Rosier (1996)
Beech	Belgium		344			Schnock (1971)
Beech	Hants, UK	1989	393			Roberts and Rosier (1994)
Beech	France	1971	288			Chassagneux & Choisnel (1987)
Beech	Germany	1970	283		100	Kiese (1972)
Sweet Chestnut (coppice)	France	1987	275		12	Bobay (1990)
Oak (sessile)	Germany	1968 &	342		18	Brechtel (1976)
		1969	298		54	"
			342		165	"
Oak (sessile)	UK	320				IH (unpublished)
Oak	Denmark	1976-1983	293		70	Rasmussen & Rasmussen (1984)
Oak	France	1992	301		32	Breda et al. (1993)
		(droughted)	151		"	"
Oak	France	1981	340		120	Nizinski & Saugier (1989)
		1982	241		"	"
		1983	284		"	"
Oak/Beech	Holland	1984	267		100	Bouten *et al.* (1992)
		1986	362		"	"
		1987	239		"	"
Conifers						
Norway spruce	Germany		362			Tajchman (1971)
Norway spruce	Germany		279			Brechtel (1976)
Norway spruce	UK		290			Calder (1977)
			340			
			330			
Sitka spruce	UK		340			Law (1956)
Scots pine	Germany		327			Brechtel (1976)
Scots pine	UK		353			Gash and Stewart (1977)
Scots pine	UK		427			Rutter (1968)

of L^* of broadleaf woodlands in Europe[6]. There are two features of the stomatal conductance of the coppice which result in the high transpiration rates. Firstly the maximum g_s is as high as has been observed over many types of vegetation (Korner et al., 1979) and is only exceeded in a few isolated cases e.g *Tectona* (Teak) and *Gmelina* plantations in Nigeria (Grace et al., 1982). Secondly, g_s of poplar coppice is insensitive to increasing air humidity deficit. In many species, including temperate woody species, stomatal closure has been shown to be associated with increasing dryness of the atmosphere which occurs routinely from morning into mid-afternoon and will be particularly marked on days which are hot and sunny. In the poplar coppice no such relationship of g_s with deficit was observed thereby allowing high atmospheric humidity deficits to sustain high transpiration rates through open stomata. Such hot and dry conditions were particularly prevalent in the summer of 1995.

3.4.1.2 *Interception loss*

The magnitude of interception loss from poplar coppice in leaf was measured as 21% of rainfall, and the SIMWUCOP simulations indicated an annual interception loss (including the unleafed period) of about 14%. Both figures are within the ranges for broadleaved woodland. Equipment problems prevented the collection of sufficient data to allow the a firm figure to be assigned to the interception loss from unleafed coppice. The small sample recorded indicates a value of about 16% which if representative of the long term value is high for an unleafed tree stand. However the measurements were made after much of the surrounding coppice had been harvest in November 1995 and it is expected that the loss figure is enhanced by elevated evaporation rates due to edge effects. It is also likely that there was increased evaporation from the polythene-sheet net-rainfall gauge that would result in the interception loss being overestimated.

3.4.2 Effect of stool and stem age

The characteristics of the Swanbourne site and the harvesting timetable prevented differences in the water use arising from different rotation periods from being identified. Transpiration is likely to increase with increasing age of the trees as the root system develops and a greater store of soil water becomes available. However the rate of this root development is likely to be dependent upon the physical characteristics of the soil. In some locations where the soil is light textured this development may be rapid but at others it may take longer, resulting in a gradual increase in transpiration with time. There is some evidence that the root system of poplar coppice becomes established in a short time. Soil water measurements from Hunstrete (Tube 1 at the Lower Plot) suggested that after only four years growth (three-years coppiced growth) Beaupré roots had reached a depth in excess of 2.8 m. This was subsequently confirmed when a pit was excavated at the Lower Plot and roots identified as poplar were found at 2.95 m depth.

Transpiration rates measured at Swanbourne from three-year old shoots on seven-year old

[6]Whereas the tree L^* of some forests may be lower this is often supplemented by the foliage of a shrub or understorey layer. A number of studies have shown that this understorey can contribute substantially to total forest transpiration (Roberts et al., 1980; Roberts and Rosier, 1994)

stools in 1993 were higher than rates measured in 1994 from two-year shoots on eight-year old stools. The transpiration rates from the three-year old shoots would be expected to be larger as a result of their larger leaf area and taller shoots. However at this site the higher rates from the older shoots would have been enhanced by more water being available to them as a result of the higher rainfall in 1993 and as a result of the water table being nearer the surface for more of the year at their lower elevation.

It is expected that the evaporation from coppice in its first year of growth after harvesting will be reduced due to a lower leaf area and shorter shoots. Measurements of the leaf stomatal conductance of one-year old shoots were not made. However it is probable that they are similar to the leaf stomatal conductances of two and three-year old shoots that we have measured. We estimated, using the WUCOP model and some major assumptions, that the evaporation from one-year old shoots was about 55% of that from three-year old shoots. However the difference in evaporation from one and three-year old shoots on stools of greater age, with an established root system and therefore greater available water, is likely to be less.

3.4.3 Clonal differences

The measured transpiration rates from three-year old shoots on seven-year old stools in the coppiced Beaupré and Dorschkamp at Swanbourne in 1993 were very similar. However at the end of the summer transpiration from the Dorschkamp was slightly higher than from the Beaupré (see Fig. 3.11). In 1994 there were significant differences in the transpiration rates from two-year shoots on the eight-year old stools of these two clones (see Fig. 3.12) with the transpiration from the Beaupré exceeding that from the Dorschkamp. This difference reflected the lower L^* in Dorschkamp as the stomatal conductances of the two clones were very similar. The lower L^* was mainly caused by interclonal competition for light which in the longer rotation coppice had more time to develop. The five-year coppice was at a slightly higher elevation than the three-year coppice so the perched water table was present for less time. Thus it is possible that the Beaupré is better able to exploit available water than Dorschkamp but further research would be needed to establish a clear difference in the water use between these two clones.

Deuterium tracing measurements at Hunstrete during August 1995 indicated that the sap flow rates in Beaupré, Trichobel and Germany (willow) were all low. However given the drought conditions this is not surprising. There did appear to be a difference between the Trichobel and the other two clones in that prior to rainfall on 23 to 26 August, when there was small but measurable sap flow in the Beaupré and willow, none was detectable in the Trichobel with the deuterium tracing method. After the rainfall the Trichobel did start to transpire at a measurable rate. It was also visually observed that there was large leaf fall from the willow during the drought period and that leaf fall from the Beaupré was less and that from the Trichobel the least. These differences suggest clonal differences in water conservation strategies e.g. the Trichobel stomatal response to drying soil may be greater than for Beaupré, making it possible for Trichobel to maintain a higher leaf area, ready for the end of the drought. There are reports of varying degrees of leaf shedding by different poplar clones as a means of avoiding dehydration when droughted (Blake and Tschaplinski, 1992). Any reduction in the photosynthetic material tends to reduce the carbon assimilation, with consequent reduction in yield. It is not possible without detailed plant physiological studies to identify firmly the drought avoidance mechanisms exhibited by the different clones.

3.4.4 Root characteristics

Our measurements indicate that at Swanbourne the roots of poplar SRC extended throughout the soil profile (see Fig. 3.31) and that, although there was a maximum in the root length density in the depth range 1.4 to 1.6 m, the distribution was fairly uniform with depth. This contrasts with what is usually observed in trees and crops. For example, Heilman et al.(1994) found root length densities of around 6 cm cm^{-3} in the surface soil, declining to about 1 cm cm^{-3} at 2.5 m in a poplar SRC. They also estimated the below-ground biomass as between 34% and 42% of the above ground biomass. The surface density measured by Heilman et al is almost three times the surface density measured at Swanbourne. These authors did however observe concentrations of roots at certain points in the profile which were associated with differences in soil density. The soil profile at Swanbourne is variable with lenses of sand and gravel in the clay which may account for the small differences in root density distribution. It is interesting to note that the depth range at which the maximum root density was found coincided with the layer in which the soil water storage was the greatest (see Fig. 3.23).

Pits excavated at Hunstrete in spring 1996 revealed that the roots grew down fissures in the hard clay layers (Upper Plot) in which there was water, probably due to capillarity, and that in the sandy soil (Lower Plot) they achieved depths of at least 2.9 m in four years of growth since planting.

The picture that emerges from measurements at Swanbourne and Hunstrete (see Sections 3.1.2.6 and 3.2.2.3) is one of a very efficient root system that is able to adapt to the soil in which the coppice is growing. It would appear able to extract water from depth, below 2.9 m in sandy soil at Hunstrete after four years of growth; able to extract water from the saturated zone, as evidenced by the $\delta^{18}O$ measurements at Swanbourne, and able to extract water from the surface soil after it has been rewetted following drought, as evidenced by the $\delta^{18}O$ at Swanbourne and from the sap flow measurements at Hunstrete.

3.4.5 Willow

At Hunstrete, in addition to the poplar, the sap flow was also measured in willow shoots. However because there are only a few rows of willow planted in single or at most double rows within the poplar plantation, measurements of soil water depletion could not be used to determine the water use of the willow specifically. The effect of interspecies competition on the transpiration rates also raises doubts about the validity of comparing the transpiration rates for the two species derived from the sap flow measurements. However it should still be valid to use the willow transpiration estimates for the different times in the summer to study the effect on transpiration rates of the soil water deficit. Measurements of sap flow in willow (clone Germany) shoots using sixteen Dynamax™ gauges were made from 10 June to 10 July and 19 August to 16 September and using the deuterium tracing technique over the period 18 August to 1 September.

Although there are the uncertainties arising from the isolation of the rows of willow in the poplar plantation, the rates of sap flow in the willow did appear to be high; of the same magnitude as those measured from the poplar. At the start of the summer these rates exceeded the Penman E_T rate (Fig. 3.43). Over the period 10 June to 10 July the mean daily transpiration rate for the willow was 6 ± 2.3 mm and for the poplar 6.7 ± 2.1 mm compared with a mean E_T of 4.8 ± 2 mm. During the second measurement campaign in August the mean daily transpiration of the willow was lower at 2.4 ± 0.3 mm whereas that from poplar was 1.5 ± 0.5 mm; both below the mean daily E_T of 4.4 ± 1.4 mm. The reduction in transpiration between the two periods was probably the result of a reduction in leaf area and stomatal conductance in response to drought stress. Certainly there was a large leaf fall from the willow. However we did not make stomatal conductance measurements on the willow preferring to concentrate resources on measuring the stomatal conductance of the poplar. It is therefore unknown whether there was a similar response function of stomatal conductance to the increasing soil water deficit as seen in the poplar.

Without basic information on the physiological and abiotic controls of transpiration (e.g. the stomatal response to soil water deficit, the development of leaf area during the summer, an aerodynamic resistance function, required in the Penman-Monteith equation), there was no advantage to be gained in simulating the water use of the willow using the WUCOP and SIMWUCOP models. The uncertainties and caveats that would be associated with the model estimates would make them of less value than conclusions that can be drawn from the measurements that were made at Hunstrete and from the results of studies in Scandinavia.

There has been extensive work, measurements and modelling, on the water use of willow done in Sweden. The results of this work, almost entirely on irrigated coppice, are in agreement with the high sap flow rates that we measured at the start of the summer when the trees were not stressed. Lindroth and Iritz (1993) reported that transpiration from willow (*Salix viminalis*) was higher than the net radiation for much of the growing season (July to October inclusive) as we have observed. Although the absolute values of the willow transpiration at Hunstrete must be treated with caution (see above). Ettala (1988) reported a total water use (May to September 1986 inclusive) of 362 - 480 mm for unirrgated coppiced willow on a landfill site in Finland. This compares with the water use given by Persson and Lindroth (1994) of 416 - 584 mm (May - October inclusive) for irrigated willow coppice. Iritz and Lindroth (1993) found that transpiration occurred from willow at night and could account for 30 % of the daytime transpiration on occasions. Persson (1995) gave the six-year mean daily water use from willow SRC growing at a Swedish site with annual rainfall of 442 to 596 mm during the growing season as 2.3 mm compared with 2.4 mm for spruce, 1.9 mm for grass ley and 1.6 mm for barley. This accords well with the comparison we give in section 3.3.2.4. for poplar SRC in which we found the same ranking. But Persson and Lindroth (1994) indicated that the simulated water use of willow SRC exceeded the water use from mature coniferous forest in Sweden. In their simulation, that gave good agreement between predicted and observed daily evaporation, the canopy resistance values were typically 30 - 50 sm^{-1}. These are very similar to the poplar SRC values calculated in the WUCOP model (Section 3.3.1.1, Equation. 3.12). However the function that we empirically derived for r_a for poplar SRC, results in lower values than the function for r_a used by Persson and Lindroth. This would suggest that evaporation rates from willow may be less than from poplar.

There is evidence of a stomatal response in willow to atmospheric humidity deficit. Cienciala and Lindroth (1995) obtained good agreement between modelled and measured stomatal conductance of *Salix viminalis* as a function of solar radiation and atmospheric humidity deficit. This stomatal response could result in reduced transpiration and the postponement of dehydration of the trees in drought conditions but it would also result in lowered biomass production through reduced CO_2 fixation.

On the basis of these studies and our own findings, we expect that the total water use of willow SRC is unlikely to be *significantly* different from that of poplar but may be slightly less. The transpiration in an average summer may be a little lower as a result of the stomatal response to atmospheric humidity deficit but in very dry summers such as 1995 this response may result in the willow having a larger soil water store available later in summer so that transpiration continues over a longer period.

Larsson (1981) reported that the specific canopy storage for *S. viminalis* is 0.2 mm m^{-2} leaf area; slightly less than the 0.27 mm m^{-2} found for beech and ash by Harding et al. (1992) but more than the 0.1 mm m^{-2} that we measured for Beaupré. The interception loss for foliated willow SRC given in the literature (Grip et al., 1989; Andersson, 1986; Halldin, 1989; Grip, 1981; Ettala, 1988; Persson and Lindroth, 1994) ranges from 11% to 38% and encompasses the 21% that we measured for poplar at Hunstrete.

3.4.6 Hydrological implications

The average annual drainage values predicted by the SIMWUCOP model and listed in Table 3.17 have been recast (Table 3.23) to show the average annual reduction in drainage caused by replacing various crops with SRC. The average reduction in drainage increases with rainfall for conversion from all crops except pine and beech (Table 3.19): a consequence of their high interception loss.

Table 3.23 The average reduction in annual drainage (runoff and deep percolation) (mm) expected when land use is changed from different agricultural crops to poplar SRC (mean annual rainfall 686 mm)

	grass	barley	wheat	potatoes	sugar beet	bare soil
clay	153	179	175	166	87	216
chalk	150	189	182	179	113	246

The higher average water use and lower drainage from SRC compared to agricultural crops implies that any change in land use from crops to SRC will result in a reduced catchment water yield. The size of this reduction will depend on rainfall and the percentage of the catchment converted to SRC. At Swanbourne the model predicted that annual drainage from SRC will be 150 mm less than from pasture. In areas where the rainfall is less, transpiration will be reduced due to soil water deficits so the reduction in drainage will be less. The reduction in drainage for the drier parts of the country can be estimated from the model predictions in Table 3.19. These estimates represent the largest possible reductions in drainage as coppice growth will be less vigorous in the drier parts of the country. The average drainage in the five driest years (Table 3.19, row c) for coppice and pasture suggests a reduction in drainage of about 80 mm in parts of the country with an annual rainfall of 560 mm. This potential reduction, when taken in conjunction with information on the effective precipitation (see Fig. 1.1), implies that, for much of the east of England, the net recharge and runoff from grassland catchments wholly converted to SRC will be reduced on average by at least 50%. In some areas the reduction in drainage will be near to 100%. The reduction in drainage for agricultural crops would be greater, except for sugar beet. To determine more accurately the drainage for any particular location would require the SIMWUCOP model to be operated using meteorological data for that location. Improvement of the model predictions for the dry areas would require further measurements on SRC, e.g. development of leaf area and depth of rooting zone, growing in those areas to allow the model to be calibrated accordingly.

The figures in Table 3.23 show virtually no difference in the reduction in drainage between chalk and clay soils. The drainage is more variable between years than the evaporation because of its dependence upon the rainfall which is more variable than E_T. Thus average drainage values should be considered with caution. Annual drainage figures will often depart significantly from the mean: the standard error of the mean drainage (63 mm) for the five driest years referred to above is 34 mm.

The dominance of transpiration over interception loss from SRC results in the drainage from coppice increasing more with increasing annual rainfall than does drainage from pine (see Table 3.19) which has a more uniformly high water use. The dominance of transpiration also results in evaporation from SRC being greatest in those years when there are regular periods of rain throughout the summer so that there is no reduction in transpiration due to soil water stress. An example of this was 1980 (see Fig. 3.79).

If SRC is planted on a deep soil then the vigorous rooting of poplar may result in the trees annually extending their roots to extract the water from deeper soil levels. Such 'mining' for water has been observed in eucalypts in India. If it occurred the annual water use may exceed the annual rainfall and if this continued over a number of years then large soil water deficits would develop. Once the SRC was removed these deficits could take several years to replenish and would result in the continued reduction of runoff and aquifer recharge for that period.

On a seasonal basis the highest risk of water shortage associated with SRC occurs during the summer when transpiration is highest and there are fewer rain days. At this time the smaller catchments will be at greater risk due to their smaller potential for storage. There is the possibility of springs and ephemeral streams drying up, sooner and for longer, and small scale domestic supplies being adversely affected.

There may also be a reduction in the peak flows especially during the summer. The large soil water deficits that can develop beneath SRC especially on deep soils will result in a storage buffer for high intensity summer rainfall.

During the first year of coppice growth after harvesting, the smaller L^* and shorter shoots will result in higher r_s and r_a respectively, and therefore lower evaporation rates. From the viewpoint of conserving water it would therefore be of benefit to grow SRC with as short a rotation period as possible.

Enhanced evaporation occurs at the edge of blocks of tall vegetation due to various processes including increased air turbulence and L^*. To reduce this enhancement of evaporation requires that the total length of plantation edge per land area is minimised. Therefore for water conservation it would be best for extensive areas of coppice to be planted in a few large blocks rather than many small ones. However this is probably a small effect.

The effect on crops planted on land that has been used for SRC should be small where there has been sufficient winter rainfall to recharge the top layers of the soil between removal of the SRC and planting of the crop. If planting of the crops follows a dry winter then the top soil layers would not be adequately recharged and the crop development would be adversely affected and, if a dry summer followed, the yield of the crops would be reduced.

4. WATER QUALITY AND SRC

The review in Section 2 showed that as far as groundwater quality is concerned, the principal impact of SRC is likely to focus on its effect on nitrate leaching. This is likely to be low under most management practices but it is not clear how low this might be and to what extent the SRC can reduce nitrate leaching from reasonably fertile agricultural land or land which has been fertilised with sewage sludge or inorganic fertilisers. The aims of this study are to investigate these effects.

4.1 SITE SELECTION

No long-term SRC sites could be located which overlie important UK aquifers. This may be because of the tendency to locate SRC on wetter soils whereas the unconfined parts of the major UK aquifers tend to be overlain by well-drained soils. Most SRC plantations in the UK have also been established since 1986. Therefore it was also not possible to carry out detailed unsaturated zone investigations using deep cored boreholes as in past studies of nitrate leaching (Foster et al., 1986). Rather we have focused on shallow profiles. These will only reflect recent outputs, typically over the last 1-2 years.

The following points were considered during site selection:

- age and type of SRC (poplar or willow)
- type of soil, drainage and underlying geology
- range of previous land use, fertiliser history and sludge treatment
- range of 'treatments' available on a particular site
- amount of ancillary information available

Six sites were selected for study (Fig. 4.1). Since many of these sites were SRC trial sites, there were often several treatments available at each site. The aim of the water quality studies was to cover the above factors in as broad a way as possible so as to obtain an early indication of the major factors influencing nitrate leaching. At this stage, this was thought to be preferable to a fully replicated experiment at one or two sites.

A summary of the main characteristics of the sites is given in Table 4.1.

In order to reduce the number of variables, it was decided to sample the same poplar and willow clones at all sites. The poplar clone, Beaupré, and the willow clone, Bowles Hybrid, were selected since at the beginning of this study they appeared to be relatively high yielding clones that would be representative of those likely to be planted. These two clones were available at all sites except Swanbourne (no willow was grown), Downham Market (Trichobel was substituted for Beaupré) and North Norfolk (no poplar).

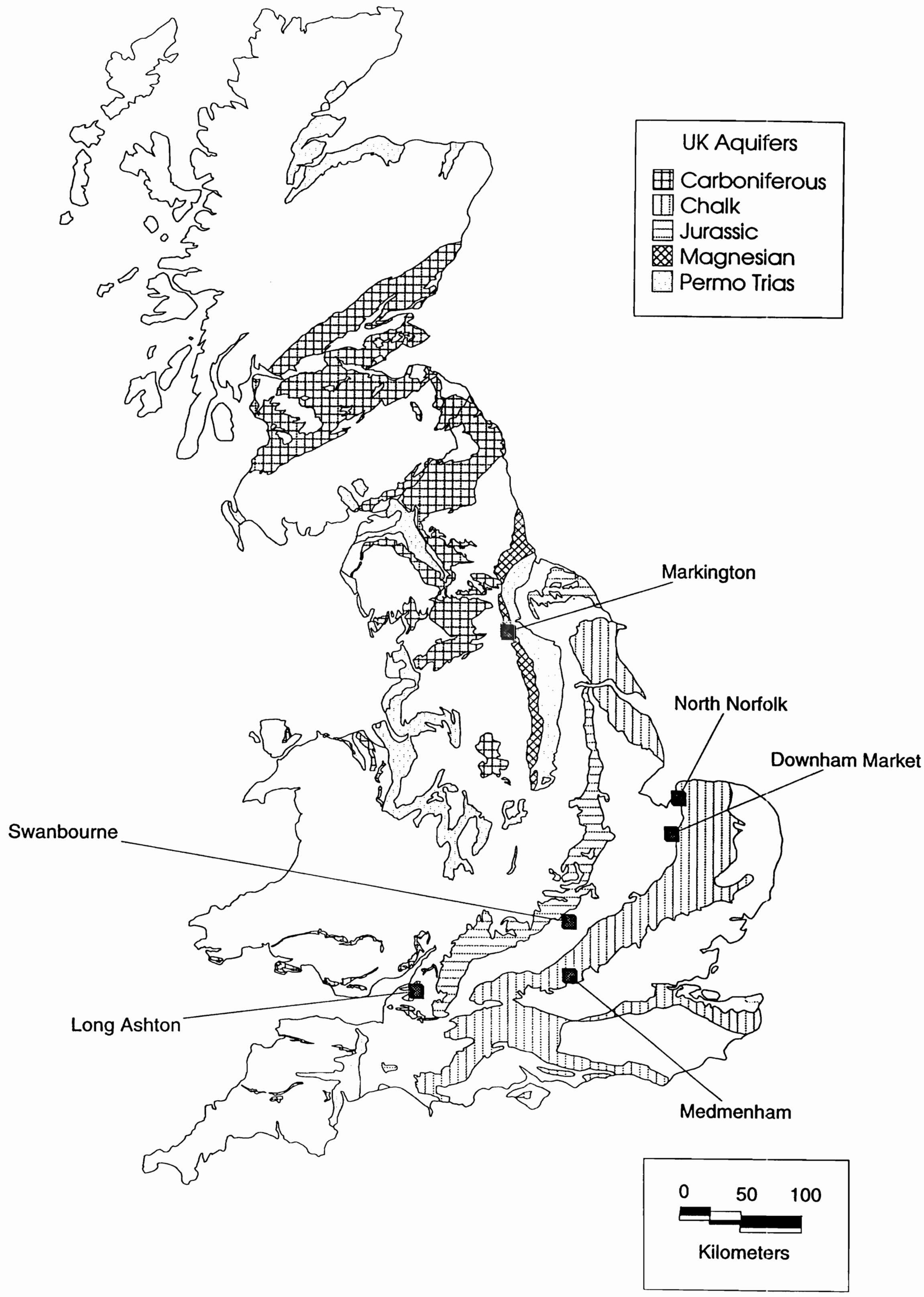


Fig. 4.1 Map showing the principal UK aquifers and the location of the six SRC sites studied in the water quality investigations. In the areas not underlain by aquifers, excess rainfall will be diverted to local streams and rivers.

Table 4.1. Principal characteristics of the SRC sites sampled

Site	Grid Reference	Type of coppice and size (ha)	Date coppice established	Date sampled	Treatments	Precipitation (Effective precipitation) 1961-1990 (mm a^{-1})	Previous land use	Soil type and geology
Swanbourne, Bucks	SP 795 281	Poplar 0.8 ha	1987	May 93 June 94	NPK fert. Mar 89 NPKMg fert. May 91	659 (173)	Permanent pasture	Clay loam over Oxford Clay
Medmenham, Berks	SU 804 838	Poplar, willow 6 ha	1992	June 93 Jan 94	Sewage sludge May 93	678 (177)	Arable	Brown earths over alluvial sands and gravels
Long Ashton, Bristol	ST 557 701	Poplar, willow	1986	Mar 94	Fertilizer	855 (324)	Permanent pasture	Stony clay loam over Permo-Triassic Sandstone and alluvium
Markington, N Yorks	SE 290 663	Poplar, willow 34 ha	1988 (control) 1991 (sludge)	Mar 94 Jan 95	Sewage sludge Mar 93, Apr 94	1194 (707)	Arable	Medium loam in glacial till over Permian-Lower Magnesian Lst
Downham Market, Norfolk	TF 628 007	Poplar, willow 1.6 ha	1990	June 95	None	570 (90)	Arable	Sandy loam over Lower Greensand
North Norfolk	Confidential	Willow 4 ha	1994	Nov 95	Sewage sludge Mar 95	585 (98)	Set-aside	Sandy loam

The Precipitation and Effective precipitation are based on MORECS (Meteorological Office) data for the nearest 10 km grid square.

4.2 SOIL SAMPLING AND LABORATORY ANALYSES

4.2.1 Soil sampling and extractions

Samples were obtained by taking cored samples at various locations representative of the plot being investigated. Late winter/early Spring was preferred so that the subsoil samples would be more representative of the water draining from the plot. 50 mm diameter cores were obtained using an Edelman-type hand auger (Eijkelkamp, The Netherlands). Where possible, cores were obtained down to approximately 1.7 m below ground surface. In most cases, the samples consisted of profiles and the depth interval was normally 15 cm. The profiles were sited mid-row in both directions. The samples were bulked over this depth interval but they were not bulked between different profiles. However, at Swanbourne bulked samples from 15 shallow cores sampled over a whole treatment (row) were obtained in order to compare the results of a bulked sample with those from a corresponding profile sample. This was only feasible for relatively shallow samples, i.e. above 45 cm. The bulked sample will be more representative of the treatment as a whole and so the difference between the results from the bulked sample and the profile sample gives an indication of how representative the profile samples are.

The maximum number of samples that could be processed in one batch was 50-60. This meant that the maximum number of profiles that could be sampled in one visit was normally 5-6 depending on the depth achieved. The samples were stored cool and extracted within two days of sampling in order to minimize any mineralisation effects. The soils were not air-dried but were disaggregated and thoroughly mixed. Two approaches were used: either (i) the interstitial water was extracted by high speed centrifugation (14000 rpm) (Kinniburgh and Miles, 1983), or (ii) a 2 M KCl extract was prepared by adding 10 g of field moist sample to 50 ml of 2 M KCl (early measurements used 100 ml 0.01 M $CaCl_2$ plus 50 g of field-moist soil).

Method (i) gives samples which should be representative of the mobile pore water whereas Method (ii) will extract both soluble and KCl-exchangeable ions. After correction for dilution, the extraction method should give similar results to the pore water method providing that there are no exchangeable ions. This should be true for nitrate and but will not be true for most other solutes.

An advantage of the centrifugation method is that it can give an estimate of the pore water concentration of all solutes including ammonium, calcium and trace metals; a disadvantage is that it is relatively time consuming to do and the yields of water can be low. It also does not include exchangeable ions which can be a disadvantage. For nitrogen species, the KCl extraction method has the advantage that it will extract both nitrate-N and exchangeable ammonium-N. This is useful since most of the soil ammonium will not be in the pore water but will be in exchangeable form which will ultimately be oxidized to soluble nitrate. It is therefore useful to see if NH_4^+ concentrations vary.

A disadvantage of the KCl extraction method is that it is not as sensitive to nitrate as the centrifugation method because of the dilution of the native nitrate with the large volume of 2 M KCl extractant solution. This was only significant where soil solution nitrate concentrations were less than 1 mg NO_3-N l^{-1}, i.e. very low.

4.2.2 Sample depth

We attempted to auger to between 1.7-2.0 m depth on all occasions but were sometimes prevented from doing so by large stones or a collapsing hole (when below the water table). The aim was to sample below the rooting zone. Initially we had thought that the rooting depth of SRC was dominated by horizontal roots between 5-20 cm below the surface combined with occasional 'sinker' roots to explore greater depths (Dickmann and Pregitzer, 1992).

However, root sampling at Swanbourne, one of the sites sampled in the water quality investigations, showed that the root distribution in terms of the root density found was remarkably uniform throughout the top 2 m (Section 3.1.2.6), and additional evidence (Section 3.1.2.5 and 3.1.2.6) suggested that water uptake took place from below 2 m. Therefore our initial assumption that most of the water and nutrients would be taken up in the top metre may be wrong. The net result of this is that nitrate concentrations below 1 m are likely to give an *upper* limit to the concentration of nitrate leaching to greater depths.

4.2.3 Analytical methods

The solutions were analyzed by automated colorimetry (nitrate, nitrite, chloride and ammonium) and ICP-OES (cations) using standard procedures (Kinniburgh and Miles, 1983).

Nitrate was measured with the sulphanilimide-N-(1-naphthyl)-ethylene diamine hydrochloride method using a copperized cadmium column for reduction. Nitrite was determined similarly without the reduction step. Ammonium was determined using the indophenol blue method. An ARL 34000C ICP-OES was used for the major and minor cations in displaced soil solutions.

4.3 RESULTS OF THE FIELD INVESTIGATIONS

The results of the fieldwork at the six sites are reviewed below. For each site, a description of the site and samples collected (with plan) is followed by a discussion of the main findings. This discussion is supported by a summary table of the nitrate and ammonium concentration in the profiles, averaged across replicate samples where appropriate. These contents are expressed on a gravimetric basis (mg N kg^{-1} dry soil) so that they can be compared with each other. The pore water nitrate profiles are also plotted; in this case, the concentrations are expressed on a mg l^{-1} basis in order to relate them to concentrations in surface and groundwaters (the EU Drinking Water limit is currently set at 11.3 mg NO_3-N l^{-1}). These two ways of expressing nitrate content are related through the moisture content of the sample.

The raw data on which these tables and figures are based are given in Appendix B.

4.3.1 Swanbourne

4.3.1.1 *Site and sampling*

The Swanbourne coppice plantation is located on a clay loam soil overlying the Oxford Clay near Thame. The site consists of a 1.82 ha poplar plantation which has been planted on former permanent pasture (Fig. 4.2). It is surrounded by permanent pasture. There is a gentle slope with a small 'valley' running through the centre of the plantation. The depth to water table varies significantly with season and position within the plot. In winter, there is a perched water table at 50 cm depth or less below ground level on the downhill side of the

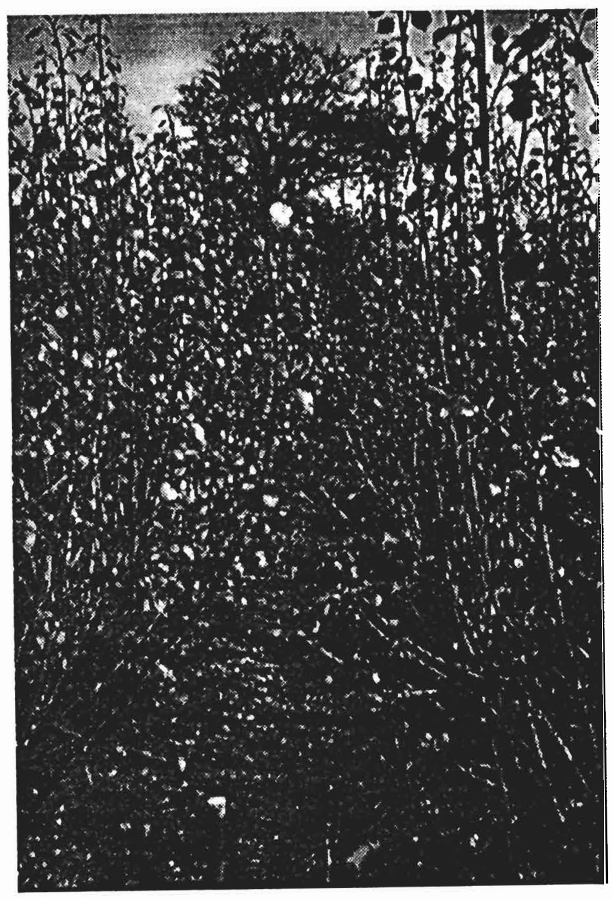


Fig. 4.2 Close-up view of the poplar (*Beaupré*) SRC trials at Swanbourne. The spacing between the rows is 1.5 m. Soil profiles were taken mid-row. A piezometer which was used in the water use studies is just visible in the foreground.

plantation. The water table is lower on the uphill side. The ETSU trials consist of a screening trial and a production trial based on six poplar clones.

The trees in the plantation are aligned in rows, each row corresponding to one of six clones. The rows are further grouped into 3 and 5 year cutting cycles and with or without fertiliser. NPK fertiliser was applied during March 1989 at a rate of 80:40:40 kg ha^{-1}. It was applied over half of the plantation. Further fertiliser was applied in May 1991 after the 3 year old shoots had been harvested in February 1991. This was applied at the rate of 72:108:108:102 kg ha^{-1} NPKMg. The 5 year old shoots had been harvested in the Spring of 1993 and had only just begun to reshoot when the first profiles were sampled in May 1993.

The soil profiles were chosen to compare fertilised (Rows 35 and 55) and unfertilised (row 20) plots and to compare both of these with a control profile in the adjacent permanent grassland (Fig. 4.3). The 'No fertiliser' plot was not sampled in May 1993 because of problems with the auger. It was not possible to sample to the maximum depth in January 1994 because of the high water table. Further fertiliser was applied in July 1994.

4.3.1.2 *Results*

An initial test was undertaken to compare the ability of 0.01 M $CaCl_2$ (50 g/100 ml) and 2 M KCl (10 g/50 ml) to displace nitrate from soil. The results of a comparison of two methods and of soil water displaced by centrifugation are shown in Table 4.2. The nitrate concentrations based on the centrifuged pore water and 2 M KCl extracts methods generally agreed well, and were consistently greater than those based on the $CaCl_2$ extract. The larger solution/soil ratio with the KCl extract may have enabled better dispersion of the clay to take place and thereby more efficient extraction. The KCl extract was also more effective at displacing NH_4^+ because of its higher cation concentration. In view of these results, the KCl method was adopted as the standard method for future sampling. It is widely used for estimating soil mineral nitrogen status in agricultural studies.

The nitrate profiles in May 1993 and January 1994 are shown in Fig. 4.4. Nitrate-N concentrations were higher in the top soil than the subsoil at both times but the concentrations were low, approximately 8 mg NO_3-N l^{-1} and less than 3 mg NO_3-N l^{-1}, respectively. There were no clear differences between fertilised and unfertilised plots, or between the control plot and the SRC plots. The lack of a 'fertiliser' effect is perhaps not surprising because of the relatively small amounts of fertiliser added and the fact that the last treatment with fertiliser had been applied more than two years previously. Nitrate concentrations below 1 m were consistently higher during January 1994 than in May 1993 in both coppice and control.

A groundwater sample taken from a depth of 0.90 m below ground level in January 1994 had a concentration of 4.6 mg NO_3-N l^{-1} and 0.04 mg NH_4-N l^{-1}. The nitrate concentration was slightly greater than the concentrations found in the other soil samples from a similar depth and probably reflects a contribution from the drainage from the grazed pasture immediately upgradient of the plantation.

The NH_4-N content of the soil was generally less than that of NO_3-N in both topsoil and subsoil and there was no clear fertiliser effect (Table 4.3).

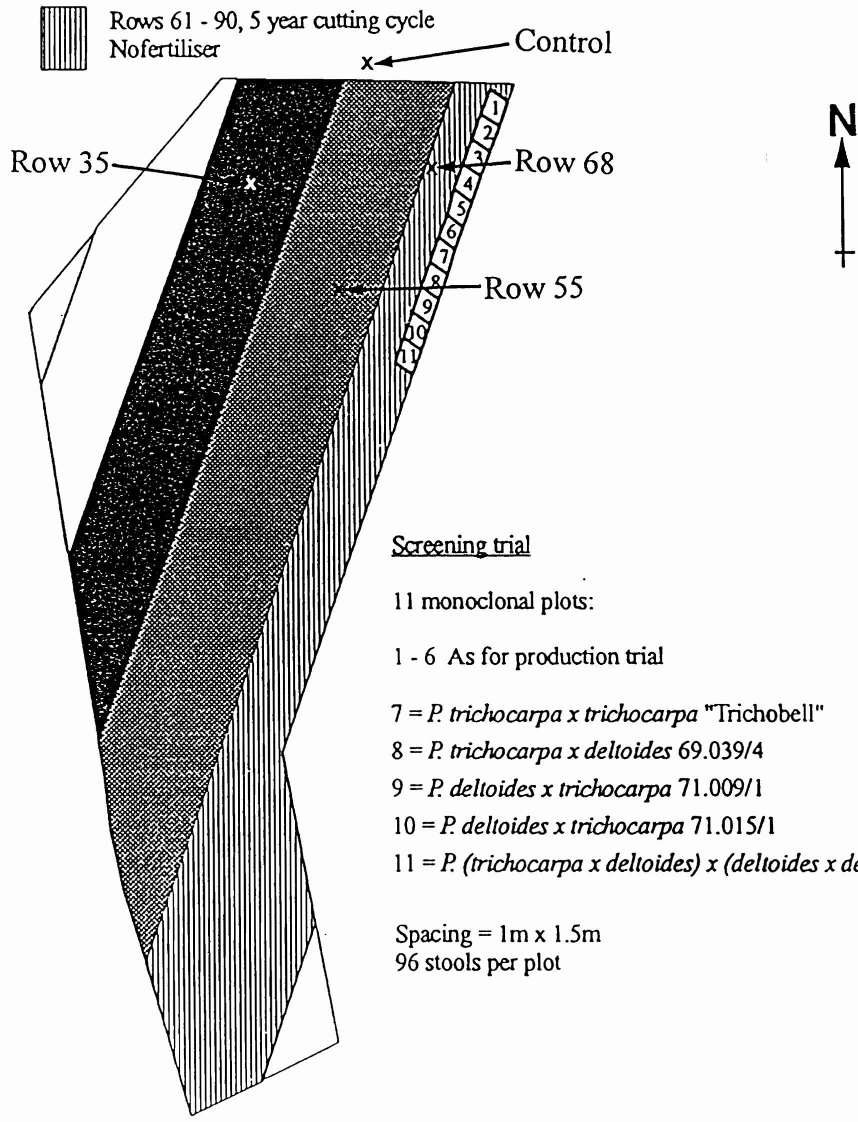
Swanbourne SRC

- Rows 1 - 28, 3 year cutting cycle
  Nofertiliser
- Rows 29 - 46, 3 year cutting cycle
  Fertiliser
- Rows 47 - 60, 5 year cutting cycle
  Fertiliser
- Rows 61 - 90, 5 year cutting cycle
  Nofertiliser

Rows are monoclonal and include six clones:

1 = *P. trichocarpa x deltoides* "Rap" (yellow)
2 = *P. trichocarpa* "Fritzi-Pauley" (white)
3 = *P. deltoides x nigra* "Dorschkamp" (green)
4 = *P. trichocarpa x deltoides* "Beaupre" (red)
5 = *P. trichocarpa x deltoides* "Boelare" (orange)
6 = *P. (trichocarpa x deltoides) x deltoides* 75.028/3 (blue)

Spacing = 1m x 1.5m



Screening trial

11 monoclonal plots:

1 - 6 As for production trial

7 = *P. trichocarpa x trichocarpa* "Trichobell"
8 = *P. trichocarpa x deltoides* 69.039/4
9 = *P. deltoides x trichocarpa* 71.009/1
10 = *P. deltoides x trichocarpa* 71.015/1
11 = *P. (trichocarpa x deltoides) x (deltoides x deltoides)* 76.028/5

Spacing = 1m x 1.5m
96 stools per plot

Fig. 4.3 Plan of the Swanbourne SRC trials showing the approximate location of the soil sample points (marked with a cross). The figure is based on the plan of the Swanbourne trial given by Mitchell et al. (1995).

Table 4.2. A comparison of three methods for estimating the pore water nitrate concentration in bulked soil samples from the Swanbourne poplar (Beaupré) plantation

Treatment	Depth of sample (cm)	NO_3-N (mg l^{-1})		
		Centrifuged pore water	0.01 M $CaCl_2$ extract	2 M KCl extract
Fert. Row 55	0-15	7.0	3.6	6.5
	15-30	7.2	5.0	8.6
Fert. Row 35	0-15	4.8	4.0	4.7
	15-30	7.6	4.0	6.0
No fert. Row 20	0-15	5.0	3.7	4.1
	15-30	7.2	4.2	5.6

Each value is the average of duplicate determinations.

4.3.2 Medmenham

4.3.2.1 *Site and sampling*

A large experimental plantation (approximately 2.2 ha) of willow and poplar was established in March 1992 in a field adjacent to WRc Medmenham in Berkshire. The plantation, formerly an arable field, overlies the Chalk and is in the River Thames floodplain. It is prone to surface flooding in the winter and tends to have a high groundwater table. The soil is a mixture of alluvial sand and clays with sands being dominant. Gravel at depth sometimes limited the depth to which augering was possible. The soil texture varied appreciably within the field.

The plantation was established primarily to assess the value of anaerobically digested sewage sludge as a fertiliser for SRC. The plantation consists of three sets of trials, A, B and C. Trial A was sampled in this study. The Bowles Hybrid (willow, Replicate 1) and Beaupré (poplar, Replicate 3) plots were sampled (Fig. 4.5). Sludge application rates on Trial A varied from 0-172 m^3 ha^{-1}, the highest rate being equivalent to approximately 111 kg N ha^{-1} (Riddell-Black, 1995). The anaerobically digested sludge was applied in May 1993. Sampling was carried out in June 1993 and January 1994 by which time the trees were 1.5-1.75 m high. Only the zero and the highest (172 m^3 ha^{-1}) sludge application plots were sampled. The highest application rate was equivalent to a uniform application of 17 mm of water. The control profile was from a nearby weed-free gangway between the sub-plots.

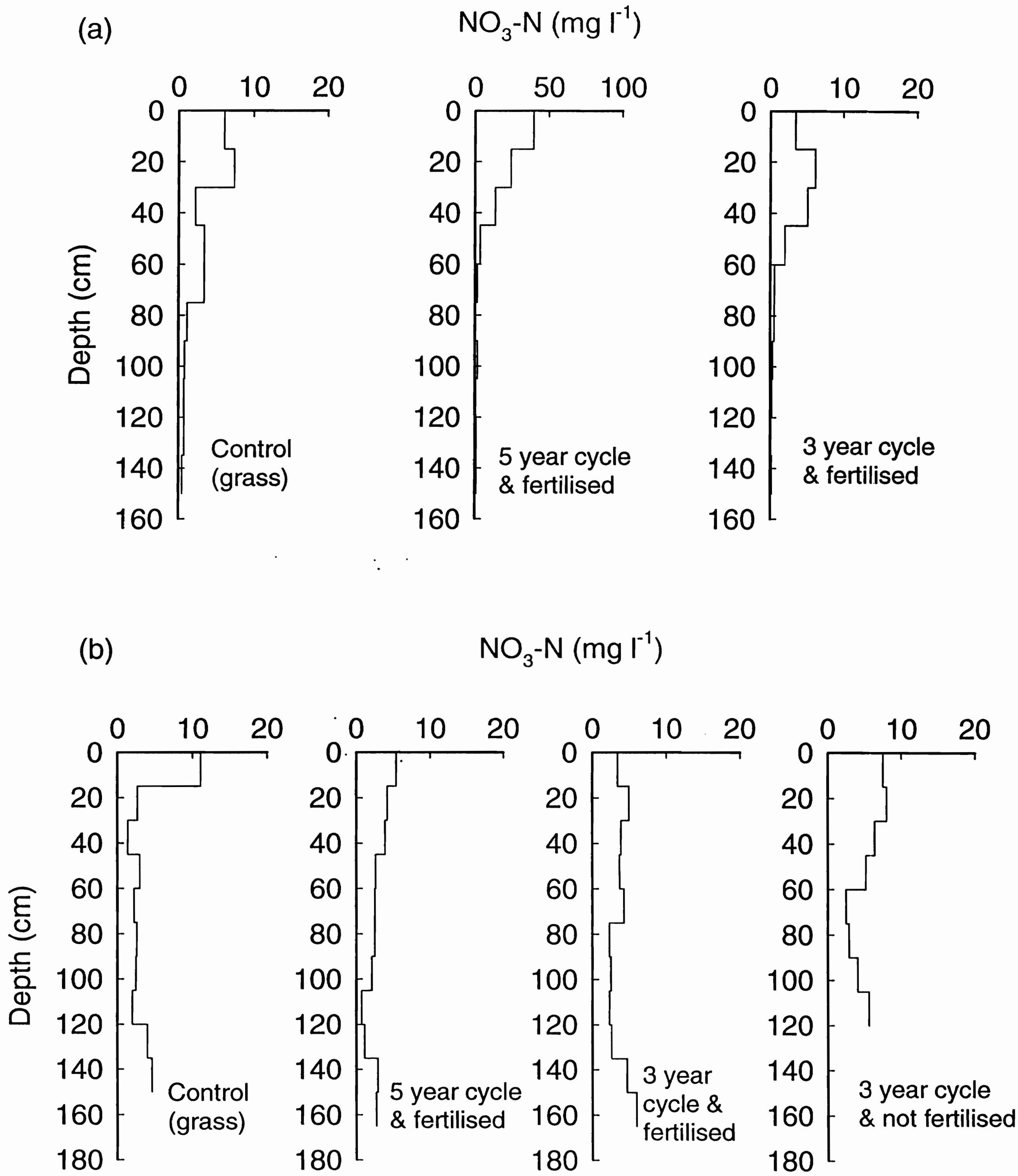


Fig. 4.4 Average pore water nitrate profiles at the Swanbourne SRC site in (a) May 1993 and (b) January 1994. Note the different concentration scale used for the '5 year cycle & fertilised' plot in May 1993.

Table 4.3. Summary of soil nitrate and ammonium data from the Swanbourne SRC 3 and 5 year cutting cycle plots. Results are expressed in terms of mg of nitrogen per kg dry soil. Fertiliser had been applied on the fertilised plots in 1989 (80:40:40 kg ha^{-1} NPK) and again in 1991 (72:108:108:102 kg ha^{-1} NPKMg)

	Sampling May 93			Sampling January 94							
	Control (grass)	5 year/ fertilised	3 year/ fertilised	Control (grass)		5 year/fertilised		3 year/fertilised		3 year/unfertilised	
Sample Depth (cm)	NO_3-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
0-15	2.5	10	1.1	7.1	1.6	1.9	0.41	1.4	0.89	2.9	1.3
15-30	2.9	6.2	2.1	1.3	0.41	1.6	0.81	1.9	1.2	3.0	2.0
30-45	0.72	2.9	1.4	0.59	0.52	1.1	0.32	1.6	1.4	1.5	1.6
45-60	0.66	1.1	0.48	1.4	0.57	0.73	0.13	0.90	0.49	1.2	0.90
60-75	0.60	0.50	0.16	0.86	0.28	0.74	0.13	1.0	0.39	0.74	0.95
75-90	0.34	0.14	0.13	0.73	0.19	0.73	0.10	0.50	0.09	0.87	1.1
90-105	0.22	0.43	0.08	0.82	0.23	0.60	0.17	0.57	0.13	-	-
105-120	0.16	0.13	0.05	0.60	0.18	0.65	0.18	0.58	0.13	-	-
120-135	0.19	0.21	0.03	-	-	0.71	0.28	0.73	0.21	-	-
135-150	0.11	0.21	0.05	-	-	-	-	-	-	-	-

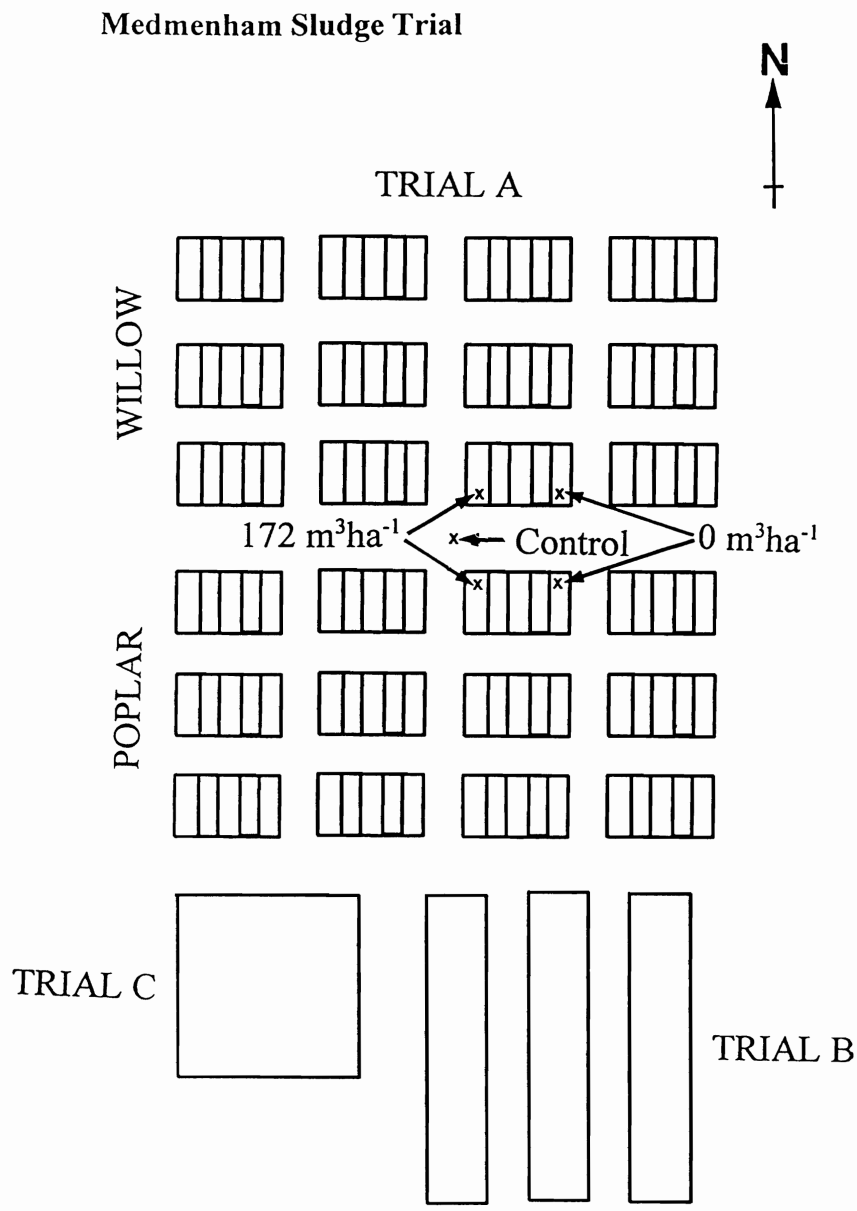


Fig. 4.5 Plan of the Medmenham SRC Westfield trials showing the approximate location of the soil sample points (marked with a cross).

4.3.2.2 *Results*

The most notable feature of the profiles (Fig. 4.6) was the extremely high nitrate concentration (50-350 mg NO_3-N l^{-1}) in the topsoil of the sludged plots when sampled in June 1993. Sludge residue was still visible on the soil surface since it had only been applied a month before.

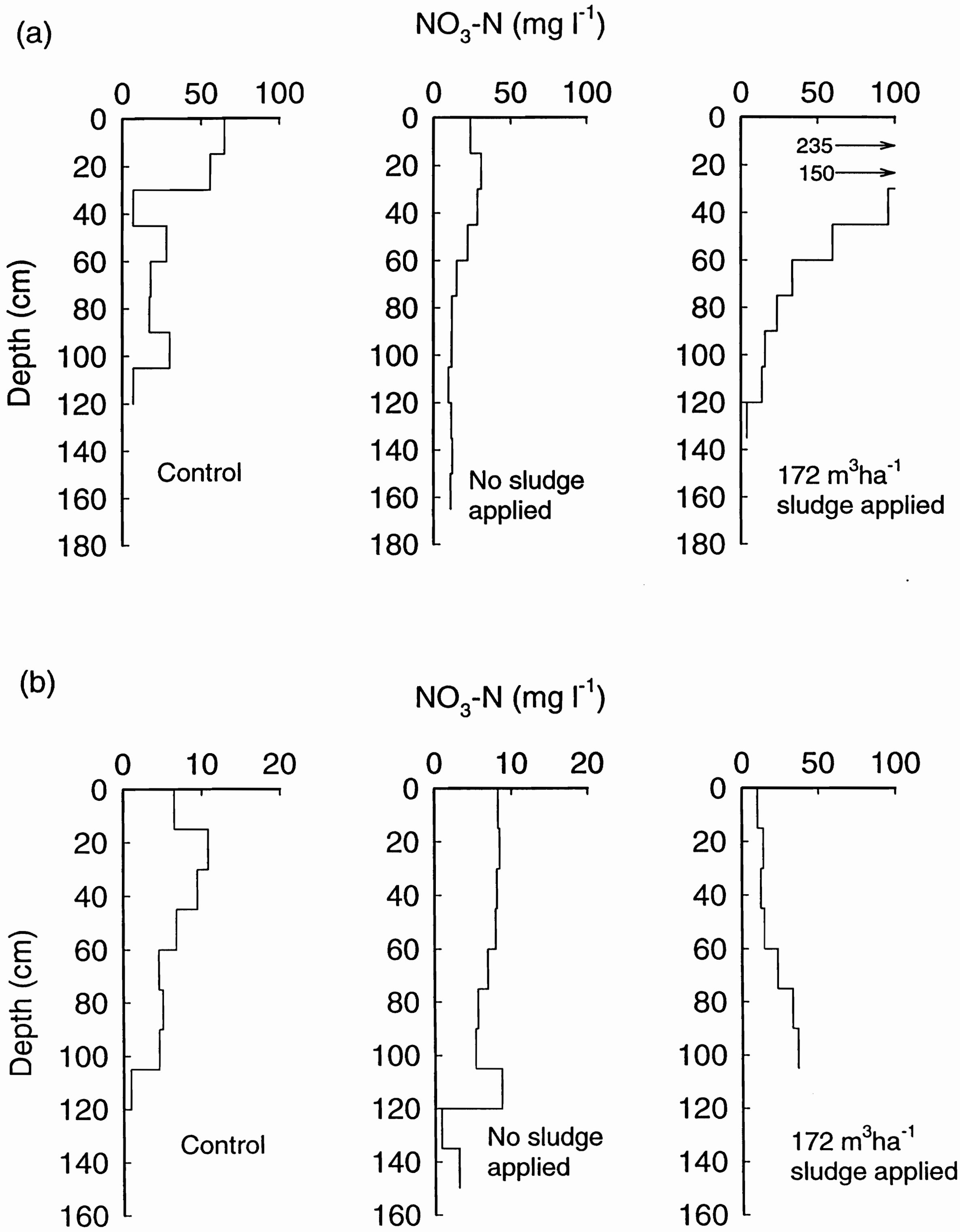
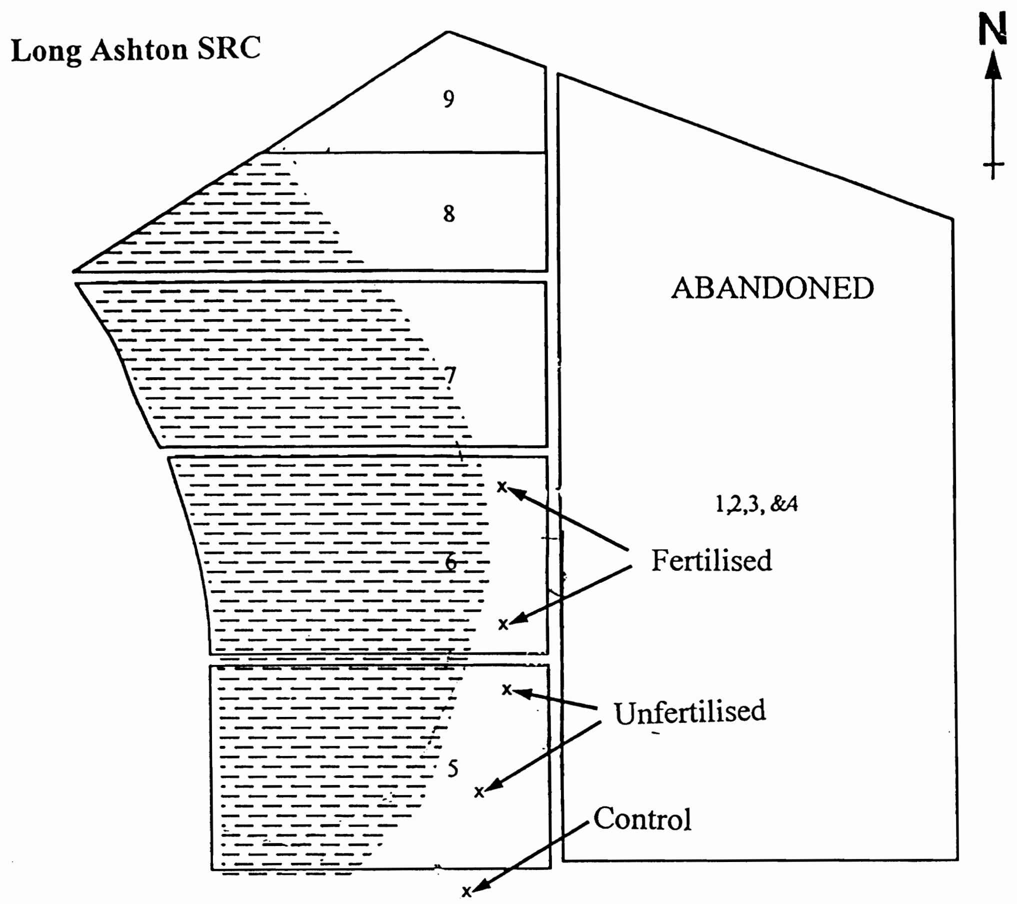


Fig. 4.6 Average pore water nitrate profiles at Medmenham in (a) June 1993 and (b) January 1994. Note the different concentration scales used for the 'Control, June 1993' and the 'sludge applied, January 1994' profiles.



Plots 1-4: Abandonned *S. burjatica* "Korso" plots.
Currently being reclaimed.

Spacing = 1m x 1m

Plot 5: *S. viminalis* "Bowles Hybrid"
2 year cutting cycle, no fertiliser

Plot 6: *S. viminalis* "Bowles Hybrid"
2 year cutting cycle, fertiliser

= Poor Growth

Plot 7: *S. viminalis* "Bowles Hybrid"
4 year cutting cycle, fertiliser

Plot 8: *S. viminalis* "Bowles Hybrid"
4 year cutting cycle, no fertiliser

Plots 9: *S. burjatica* "Korso"
4 year cutting cycle, no fertiliser

Fig. 4.7 Plan of the Long Ashton SRC Pearce's field site showing the approximate location of the soil sample points (marked with a cross). Note plots 1-4 were abandoned and the area of poor growth.

Table 4.4. Summary of soil nitrate and ammonium data from the Medmenham site showing the effect of sludge on soil nitrogen contents beneath poplar and willow. Up to 172 m^3 ha^{-1} of sewage sludge had been applied to the sludged plots in May 1993

	Sampling June 93					Sampling January 94									
	Control (between plots)	Willow no sludge	Poplar no sludge	Willow sludge	Poplar sludge	Control (between plots)		Willow no sludge		Poplar no sludge		Willow sludge		Poplar sludge	
Sample Depth (cm)	NO_3-N mg l^{-1}	NO_3-N mg l^{-1}	NO_3-N mg l^{-1}	NO_3-N mg l^{-1}	NO_3-N mg l^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}	NO_3-N mg kg^{-1}	NH_4-N mg kg^{-1}
0-15	65	22	26	350	120	2.0	0.34	2.7	0.33	1.8	0.39	4.1	0.42	2.9	0.48
15-30	56	17	45	180	120	3.3	0.41	2.6	0.33	1.8	0.45	4.9	0.34	4.1	0.68
30-45	47	14	43	96	95	2.0	0.37	2.4	0.25	1.3	0.25	3.5	0.33	2.6	0.31
45-60	28	7.4	33	53	67	1.4	0.19	2.4	0.26	1.3	0.25	5.1	0.33	2.0	0.48
60-75	18	6.4	24	20	48	1.0	0.19	2.8	0.39	0.76	0.19	13	0.21	-	-
75-90	17	7.6	17	23	25	1.2	0.19	2.5	0.45	0.38	0.19	17	0.20	-	-
90-105	30	16	7.8	11	20	1.2	0.19	3.0	1.4	0.18	0.18	21	0.21	-	-
105-120	27	13	6.6	9.5	18	1.2	0.24	4.8	0.67	0.39	0.19	-	-	-	-
120-135	-	16	6.9	14	-	-	-	-	-	0.19	0.13	-	-	-	-
135-150	-	15	9.5	-	-	-	-	-	-	0.61	0.18	-	-	-	-

4.3.3 Long Ashton

4.3.3.1 *Site and sampling*

A short rotation coppice plantation was established in the Spring of 1986 near to Long Ashton Research Station on a 1.86 ha trial which was previously used as permanent pasture. Two clones of willow were on trial, Bowles Hybrid and Korso, both at 1 m x 1 m spacing. The Bowles Hybrid plots chosen for sampling had a cutting cycle of two years. The trial is on a stony, clay loam overlying red mudstone. The trial was divided into various plots (Fig. 4.7).

Two profiles were obtained from Plot 5 which had had no fertiliser applied, and two profiles were obtained from Plot 6 which had been fertilised. Fertiliser had been applied in June 1987 at a rate of 60:30:80 kg ha^{-1} NPK in accordance with standard fertiliser recommendations for SRC. A second fertilizer application to Plot 6 was made in Spring 1992.

When the site was sampled in May 1994 it was evident that many trees had been damaged by rust, canker and beetles and some trees had died. Plot 6 had particularly poor growth in places. Sampling therefore concentrated on the more productive parts of the trial.

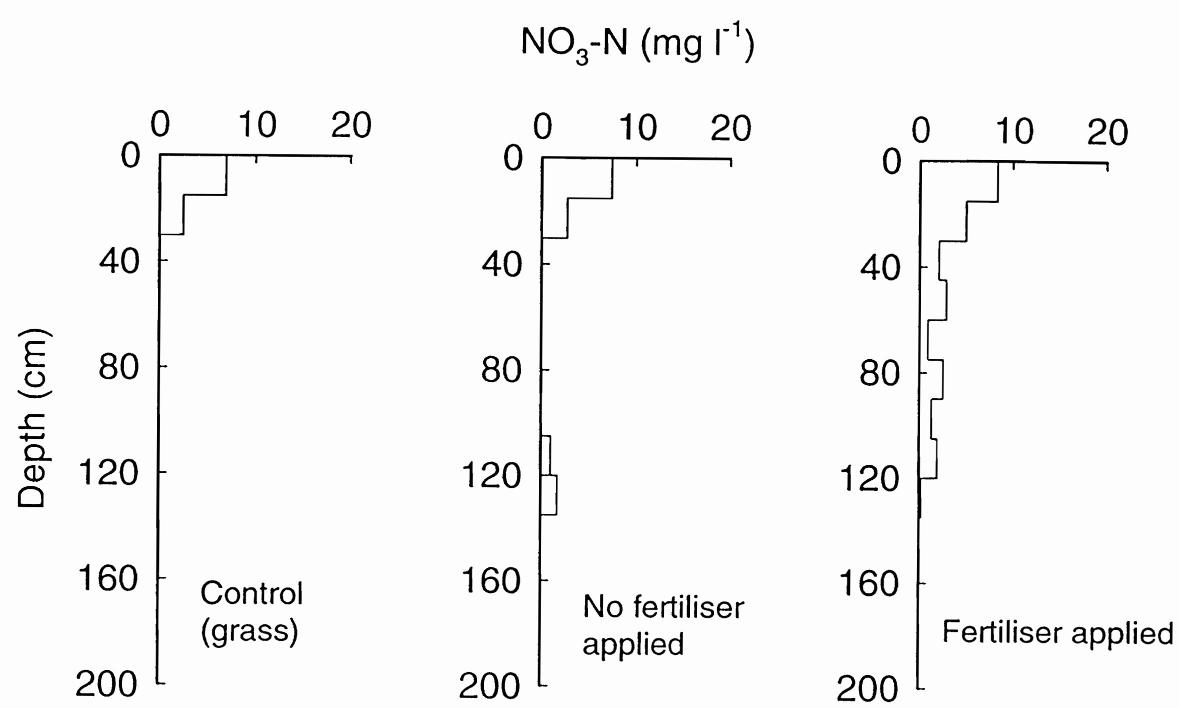


Fig. 4.8 Average pore water nitrate profiles at Long Ashton near Bristol during May 1994.

A control profile was sampled from an adjacent grassed area.

4.3.3.2 *Results*

The results from the duplicate profiles under willow were averaged. Agreement between the individual profiles was good. The average nitrate profiles (Fig. 4.8) show a small amount of nitrate-N (up to 8 mg NO_3-N l^{-1} in the top 20 cm with concentrations mostly of less than 1 mg l^{-1} below that. The plot to which fertiliser had been applied showed slightly higher concentrations of nitrate but the concentrations were still low, mostly less than 3 mg NO_3-N l^{-1} at depth. Clearly nitrate leaching from this site is very low.

Table 4.5. Summary of soil nitrate and ammonium data from the Long Ashton SRC site. Plots were on a two year cutting cycle and were sampled in duplicate. Fertiliser had been applied to the fertilised plots in 1990 at a rate of 60:30:80 kg ha^{-1} NPK

	Sampling May 94					
	Control (grass between plots)		No fertiliser		Fertiliser	
Sample Depth (cm)	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
0-15	3.9	1.8	4.3	1.4	5.2	1.1
15-30	1.2	0.84	1.2	1.0	2.4	0.63
30-45	<0.07	0.58	<0.07	0.44	0.85	0.40
45-60	<0.07	0.59	<0.08	0.75	1.3	0.45
60-75	<0.08	0.38	<0.08	0.35	0.43	0.43
75-90	<0.08	0.39	<0.08	0.35	1.19	0.39
90-105	<0.08	0.38	<0.08	0.35	0.62	0.35
105-120	<0.07	0.22	0.47	0.42	0.97	0.31
120-135	<0.08	0.31	0.82	0.38	0.08	0.19
135-150	<0.08	0.31	<0.08	0.31	<0.08	0.23
150-165	<0.08	0.31	<0.07	0.58	<0.07	0.87
165-180	<0.07	0.30	<0.07	0.78	<0.07	2.7

Nitrite was not detectable in any of the samples. Ammonium-N concentrations were generally less than those for nitrate-N on a weight basis (Table 4.5). An exception was the high concentration of NH_4-N at the base of the 'Fertiliser' profile. The reason for this anomaly is not known.

4.3.4 Markington

4.3.4.1 *Site and sampling*

The Markington site consists of a large area of commercial SRC and is also the site of some ETSU-supported and 'Club'-supported trials (the 'Club' is a consortium of water industry interests) (Fig. 4.9). Samples were taken from both the commercial plantation and the 'Club' plots. The Club trials are based on a 0.90 ha plantation which was established in 1988 for an annual crop of cuttings. This continued until 1991 when the trials began. The primary aim of the trials was to explore the potential of using willow and poplar clones in a more northerly latitude. They were also used to investigate the response of SRC to a range of sewage sludge applications. The soil type is a medium loam overlying glacial till and Permian-Lower Magnesian limestone. The previous land use was arable. Bowles Hybrid willow was selected in all cases.

Liquid digested sludge was applied to the trial plots in April 1991 and March 1993 at four rates covering the range 0-150 m^3 ha^{-1} on both occasions. The 150 m^3 ha^{-1} application was equivalent to applications of 213 kg N ha^{-1} and 164 kg N ha^{-1} in 1991 and 1993, respectively. No further sludge applications were made.

Six profiles were sampled during March 1994, some 12 months after the second sludge application (Fig. 4.10). Three of these profiles were from an established commercial willow plot. These profiles were taken 7 m apart and willow trees were approximately 6 m high. This plot had never received fertiliser. The remaining three profiles were from the Club trial plots. Two of these were from the highest sludge treatment (150 m^3 ha^{-1}) and the other was for the next highest treatment (100 m^3 ha^{-1}). The trees had been harvested just before sampling.

The site was revisited in January 1995 and this time profiles were only taken from the Club plots. The plots were being harvested at this time with the trees having reached a height of approximately 2 metres. Eight profiles were sampled, two from each of the 0, 50, 100 and 150 m^3 ha^{-1} plots. The stony ground meant that it was difficult to auger below 90 cm.

4.3.4.2 *Results*

The March 1994 sampling showed that the three nitrate profiles from the established commercial plots had small accumulations (5-10 mg NO_3-N l^{-1}) of nitrate in the top soil (0-30 cm) but below that nitrate concentrations in the subsoil were very low. At 1 m depth, the average nitrate concentration was less than 1 mg NO_3-N l^{-1} (Fig. 4.11). This is probably typical of an established SRC site in this area in which there have been no additions of fertilizer or sewage sludge.

In contrast, the sewage sludge-treated plots had nitrate concentrations in the range 6-26 mg NO_3-N l^{-1} over their depth. The highest concentrations were found in the plot with the greatest (150 m^3 ha^{-1}) sludge application but the data did not provide clear evidence of the expected 'dose-response' relationship. Nitrite was not detected in any of the samples and ammonium concentrations were mostly in the range 0.2-0.5 mg kg^{-1} (Table 4.6). There was

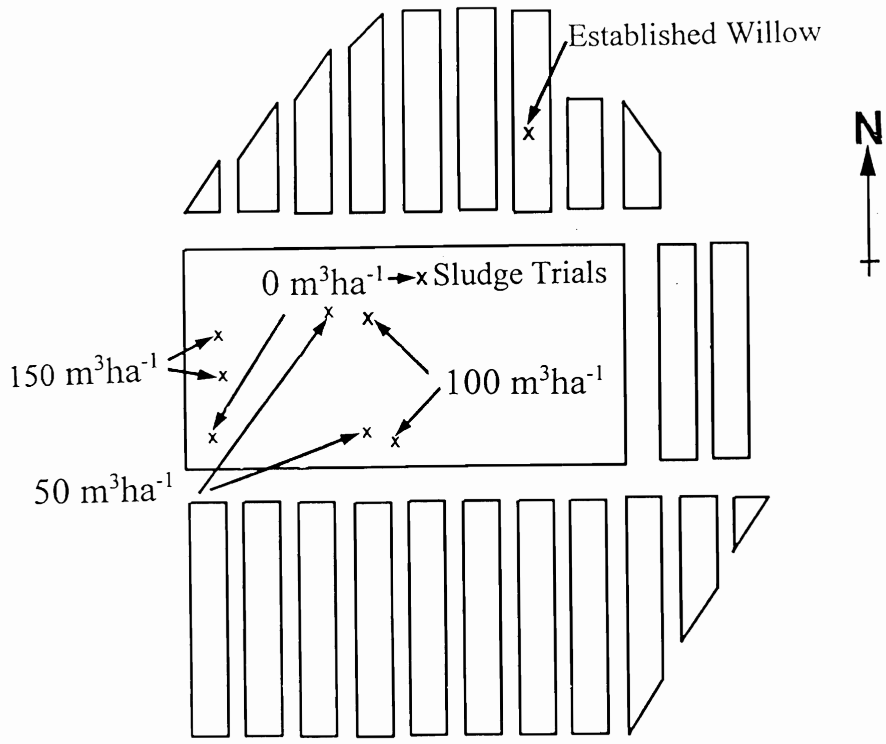


Fig. 4.9 Plan of the Markington SRC Pond field trials showing the approximate location of the soil sample points (marked with a cross).

no increase in the NH_4-N contents of the sludged profiles compared with the 'no sludge' profile.

In the March 1994 sampling, it was noted that the zero sludge site contained a considerably higher concentration of nitrate compared with the established willow plots especially below 40 cm, i.e. 8 mg NO_3-N l^{-1} compared with less than 2 mg NO_3-N l^{-1}. The reasons for this are unknown but may be due, in part at least, to the release of nitrogen from dead roots following harvest in February 1994.

The repeat sampling of the sludge-treated plots in January 1995 showed considerably lower nitrate concentrations than previously. The highest nitrate concentrations were found at depths of 15-45 cm but these averaged less than 10 mg NO_3-N l^{-1}. Although there was considerable variation between the duplicate profiles, a trend of increasing soil nitrate concentration with increasing sludge application can be seen (Fig. 4.11). The nitrate concentrations below 75 cm were mostly below 2 mg NO_3-N l^{-1}. It appears that nearly two years after the sludge had been applied there was little nitrate being leached from any of the treatments.

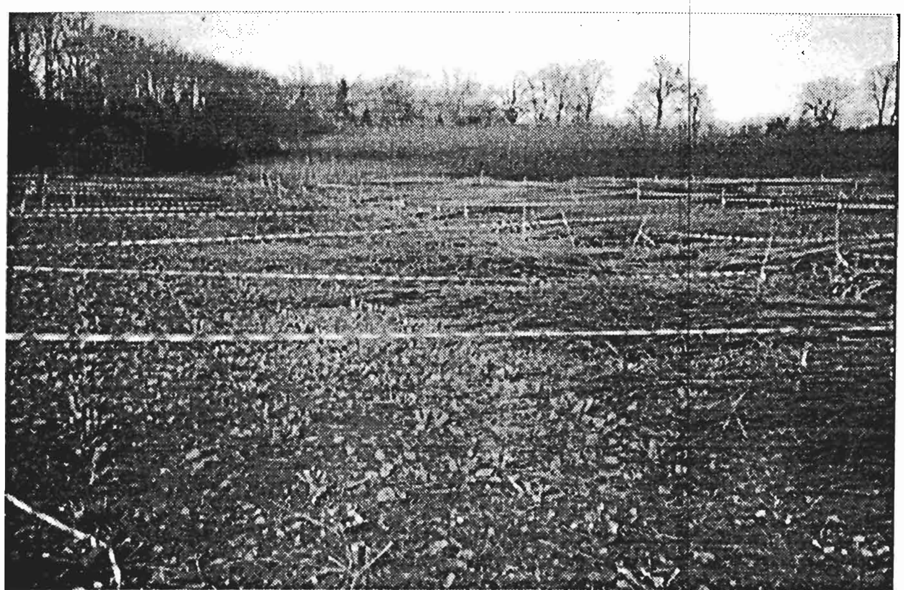


Fig. 4.10 General view of the SRC trial plots at Markington, near Harrogate, North Yorkshire during March 1994. The SRC in the foreground had just been harvested and the harvested material can be seen laid out in each plot prior to weighing. The striped tape was used to separate the plots. Mature SRC can be seen in the background.

4.3.5 Downham Market

4.3.5.1 *Site and sampling*

Downham Market is currently the site for an ETSU trial examining the effects of spacing on crop growth. The trees were planted in March 1993 on a sandy loam soil overlying the Lower Greensand and are poplar (Boelare and Trichobel) and willow (Bowles Hybrid and Dascyclados) with spacings varying between 0.8 and 1.5 metres. The trial was divided into 8 subplots (Fig. 4.12). The Bowles Hybrid and Trichobel plots were sampled. The land was previously arable with a variety of crops. The trial covers approximately 1.6 ha. No fertiliser had been applied.

Growth in parts of the plantation was very poor, especially on the poplar plots. The reason for this is unknown. In the worst affected areas, growth of the coppice had been almost completely stopped and the ground was bare (even the weeds were affected). The 1.0 m x 1.0 m spacing plots were chosen for soil sampling in the willows but the 1.15 m x 1.15 m plots were chosen for the poplars because of the poor growth in the 1.0 m x 1.0 m poplar plots.

Six profiles were sampled in June 1995. These were for a grassland control site adjacent to the SRC plots, and a willow and poplar plot, each in duplicate. Only areas where growth was good were sampled. The sandy soil and lack of large stones meant that profiles down to 2 m were possible. In addition, two bulked topsoil (0-15 cm) samples were taken from the 'poor

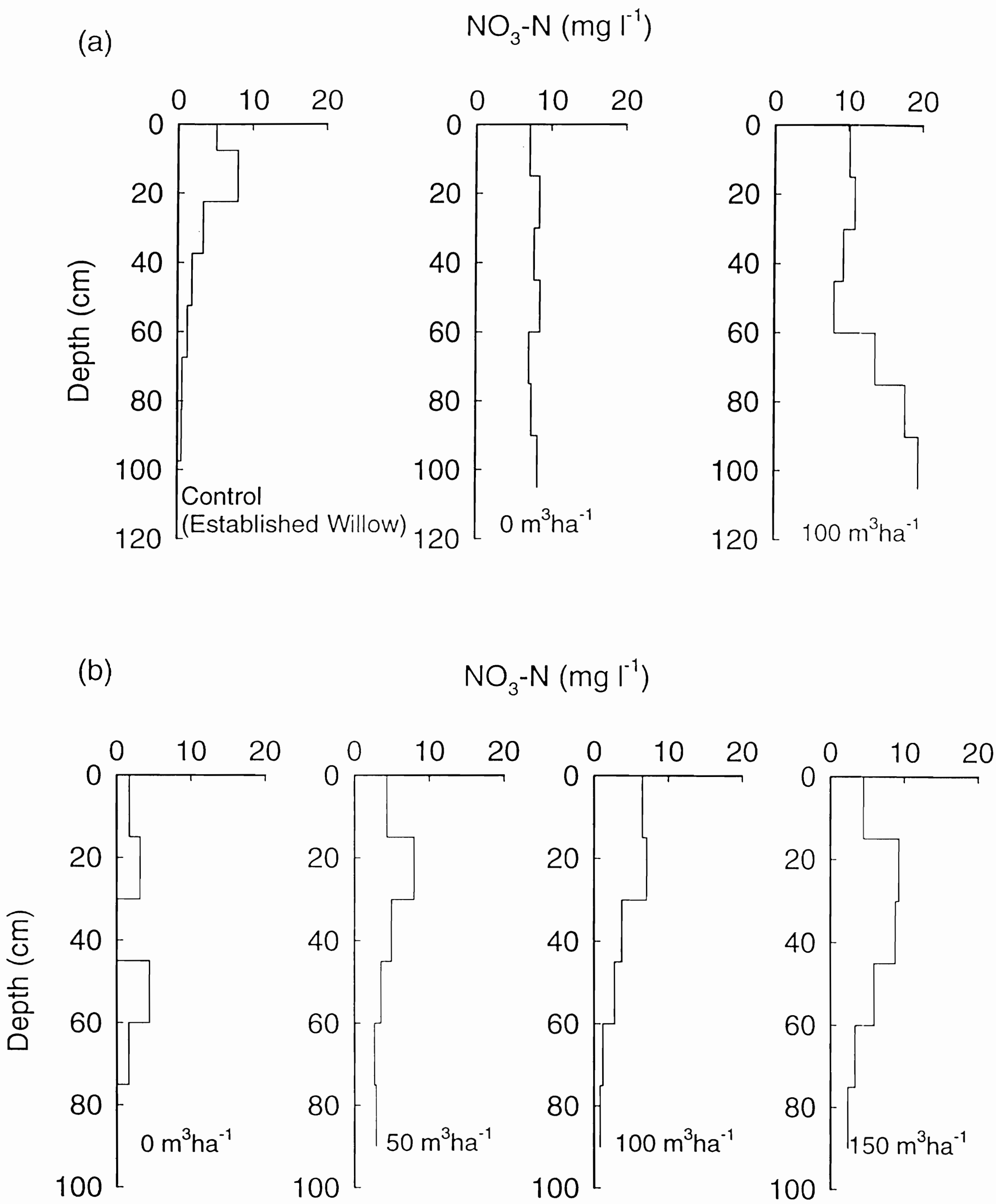


Fig. 4.11 Average pore water nitrate profiles at the Markington SRC site in (a) March 1994 and (b) January 1995.

Table 4.6. Summary of soil nitrate and ammonium data from the 'Club' trial plots at Markington. Sewage sludge had been applied to the willow in early 1994 at rates ranging from 0 to 150 m^3 ha^{-1}. Results are expressed in terms of the average of duplicate profiles

	Sampling March 94				Sampling January 95							
	No Sludge		100 m^{3}ha^{-1} sludge		No Sludge		50 m^{3}ha^{-1} sludge		100 m^{3}ha^{-1} sludge		150 m^{3}ha^{-1} sludge	
Sample Depth (cm)	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
0-15	1.8	0.32	2.5	0.83	0.42	0.74	1.1	0.48	1.6	0.09	1.1	0.23
15-30	1.6	0.30	2.2	0.65	0.65	0.86	1.8	0.19	1.4	0.09	1.9	0.25
30-45	1.5	0.49	1.8	0.55	<0.08	0.54	0.91	0.33	0.70	<0.06	1.5	0.05
45-60	1.7	0.31	1.7	0.59	0.83	0.43	0.68	0.18	0.55	0.28	1.1	0.27
60-75	1.4	0.25	3.6	0.45	0.31	0.28	0.49	0.21	0.25	0.06	0.72	0.33
75-90	1.6	0.19	4.9	0.26	<0.08	0.25	0.56	0..19	0.19	<0.03	0.59	0.28
90-105	1.5	0.06	4.8	0.13	-	-	-	-	-	-	-	-

Downham Market Spacing Trial

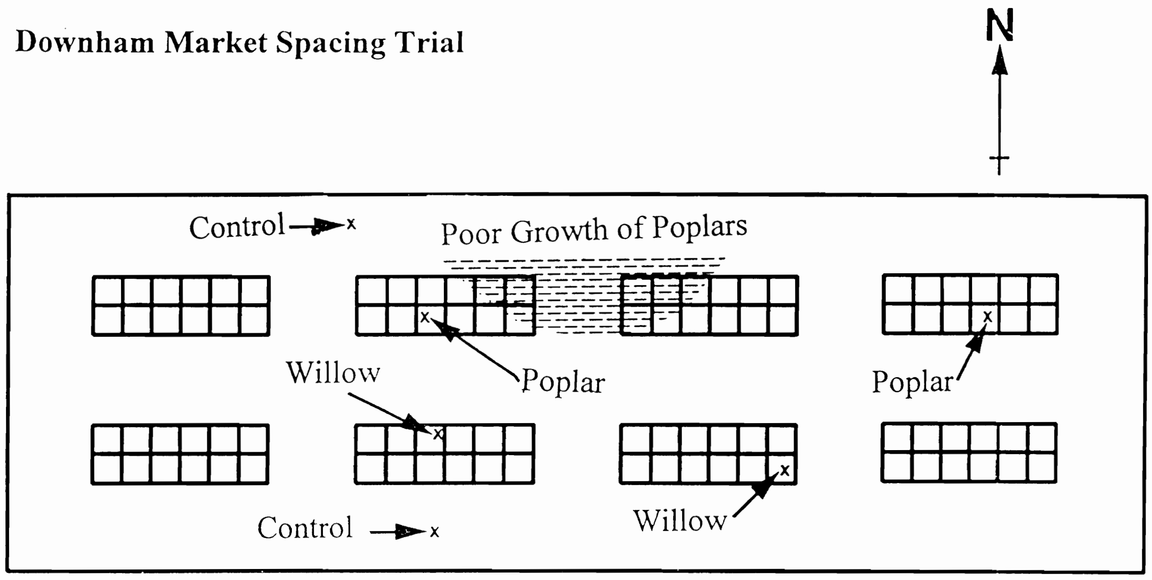


Fig. 4.12 Simplified plan of the Downham Market SRC trials showing the approximate location of the soil sample points (marked with a cross). Note the area of poor growth.

growth' areas in order to see if there was anything different in the mineral status of this soil that might be responsible for the poor growth.

4.3.5.2 *Results*

The shapes of the nitrate profiles for all three plots were broadly similar (Fig. 4.13) with a small accumulation of nitrate in the topsoil (5-10 mg NO_3-N l^{-1}) then a dip to about <3 mg NO_3-N l^{-1} followed by an increase below about 1 m to 15-20 mg NO_3-N l^{-1}. There was no marked difference between the control plot (grass) and the SRC plots, or between the willow and poplar plots.

The top metre of soil probably represents about the last 3 years of net water inputs assuming piston flow. The residual nitrate below this depth may reflect the legacy from the previous arable land that has been leached during the early life of the SRC crop.

A comprehensive inorganic soil solution analysis (including ICP-OES analysis) of the topsoil was performed on the bulked topsoil from the poor growth parts of the plot and compared with a sample from the normal growth areas. No significant differences were seen which could explain the poor growth.

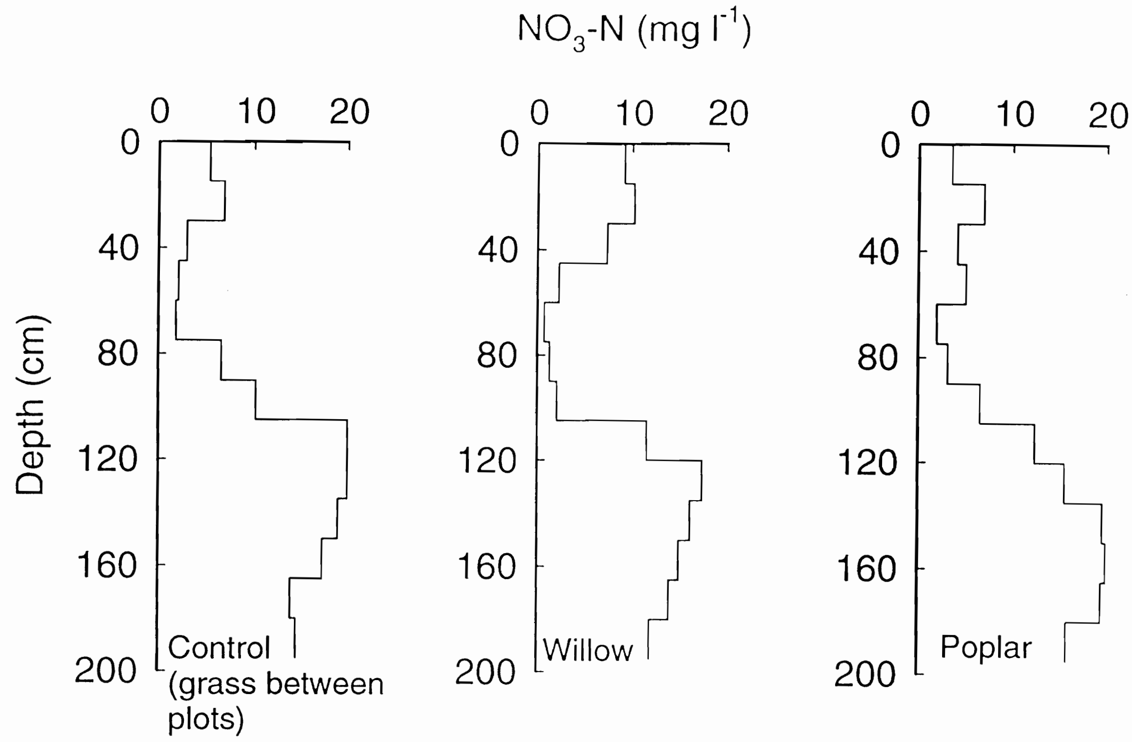


Fig. 4.13 Average pore water nitrate profiles at the Downham Market SRC site, Norfolk in June 1995.

Concentrations of ammonium were uniformally low at this site, mostly less than the detection limit of about 0.1 mg kg^{-1} NH_4-N (Table 4.7).

4.3.6 North Norfolk

4.3.6.1 *Site and sampling*

The North Norfolk site is a trial SRC plantation of approximately 4 ha in size and is situated on a sandy loam soil overlying the Lower Greensand. The site was established in 1994 and had previously been set-aside.

The site was established to determine the impact of sewage sludge on the growth of various mixes of ten willow clones. Digested sewage sludge was applied uniformly to approximately three quarters of the plantation by rain gun in April 1995. The plantation was arranged in 7 blocks (Fig. 4.14).

Table 4.7. Summary of soil nitrate and ammonium data from the ETSU spacing trial at Downham Market. Results are expressed in terms of the average of duplicate samples

	Sampling June 95					
	Control (grass adjacent to plot)		Willow		Poplar	
Sample Depth (cm)	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
0-15	0.69	0.03	0.86	0.08	0.46	0.41
15-30	0.89	0.06	0.97	0.06	0.79	<0.11
30-45	0.41	<0.12	0.76	0.03	0.52	<0.11
45-60	0.33	0.12	0.26	<0.11	0.47	<0.11
60-75	0.33	<0.12	0.09	<0.11	0.33	<0.12
75-90	1.3	<0.12	0.17	<0.12	0.81	<0.12
90-105	2.2	<0.12	0.33	<0.12	1.3	<0.12
105-120	3.9	0.15	2.2	<0.12	2.4	<0.12
120-135	3.6	<0.12	3.5	<0.12	3.2	<0.12
135-150	3.3	<0.12	3.1	<0.12	4.2	<0.12
150-165	3.1	0.03	2.9	<0.12	4.4	<0.12
165-180	2.7	<0.12	2.9	<0.12	4.5	<0.13
180-195	2.9	<0.12	2.5	<0.12	4.0	<0.13

Five profiles were sampled in late November 1995 some seven months after the sludge application. Three profiles were from the Mix 2 plot in Block 3. These included both sludged and unsludged plots. Duplicate profiles were obtained from the sludged and unsludged parts of the trial. A control profile was sampled from the access corridor between the sludged and unsludged plots.

4.3.6.2 *Results*

The most surprising feature of the nitrate profiles (Fig. 4.15) was the very high concentration of nitrate in the control profile - more than 80 mg NO_3-N l^{-1} at depth of between 30-45 cm and concentrations continued to be greater than 30 mg NO_3-N l^{-1} down to the base of the profile at 130-150 cm. Such high concentrations are unlikely to have been due to 'natural' background concentrations but are almost certainly due to some form of sludge contamination.

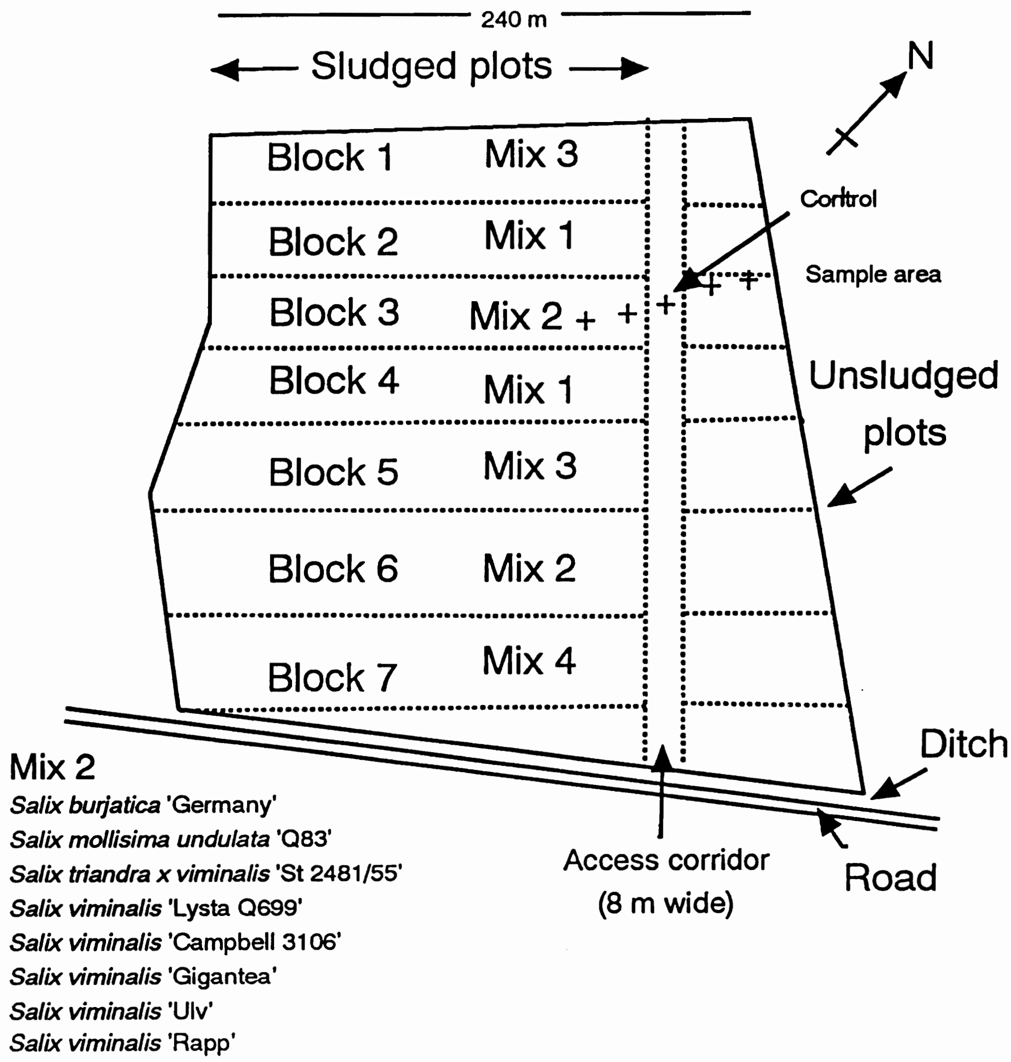


Fig. 4.14 Plan of the North Norfolk SRC site showing the approximate location of the soil sample points (marked with a cross). The sludged plots are on the western side of the Access corridor.

The profile was situated close to the sludged SRC plots and, for example, may have been close to the site from where the sludge tanker had been operating. In retrospect, this was not a good choice of 'control' site. This control site is therefore not considered to be representative of a normal, unfertilised, unsludged area and has been disregarded in subsequent analyses.

The nitrate profiles from the sludged and unsludged plots are broadly similar in that they show

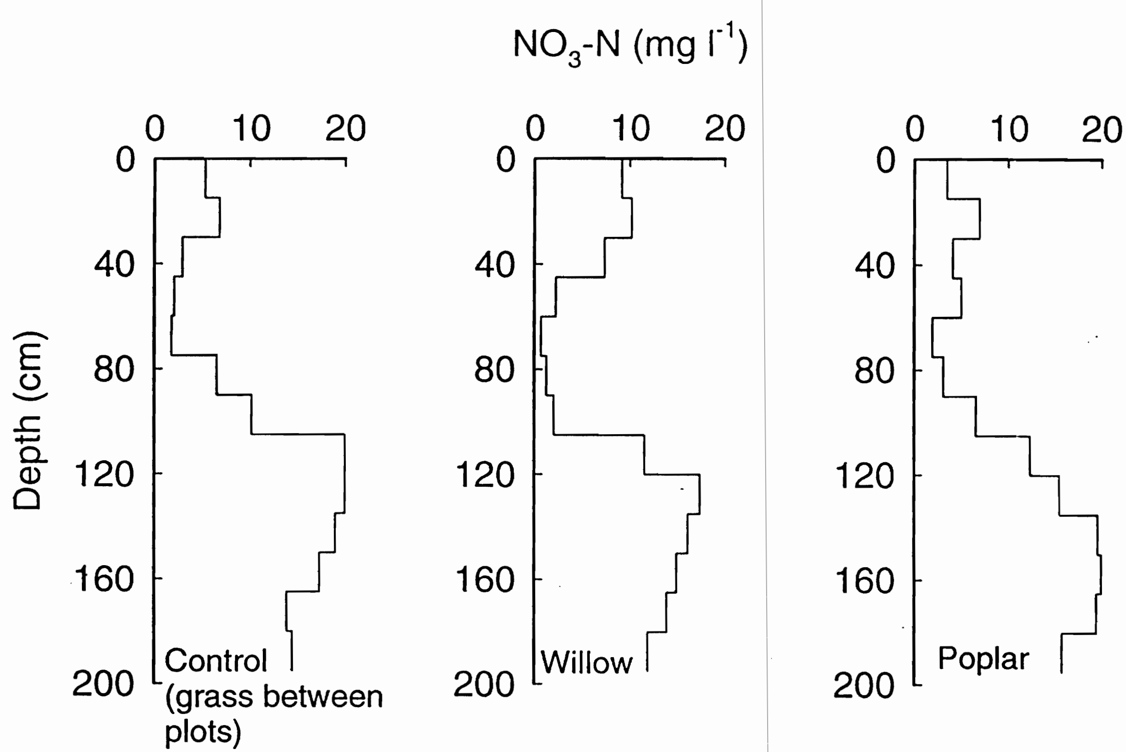


Fig. 4.15 Average pore water nitrate profiles at the North Norfolk SRC site in November, 1995. Note the different concentration scales used for the 'Sludge' and 'No sludge' plots.

a low concentration in the top 30 cm and then a broad peak of 15-25 mg NO_3-N l^{-1} down to 90 cm. Nitrate concentrations in the sludged plots were somewhat greater than in the unsludged plots; on average this difference was about 25%.

NH_4-N concentrations were generally much lower than NO_3-N concentrations (Table 4.8).

Table 4.8. Summary of soil nitrate and ammonium data from a SRC site in North Norfolk sampled in November 1995. Sewage sludge had been applied in April 1995. Results are expressed in terms of the average of duplicate samples

	Sampling November 95					
	Control (bare soil between plots)		Unsludged		Sludged	
Sample Depth (cm)	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})	NO_3-N (mg kg^{-1})	NH_4-N (mg kg^{-1})
0-15	1.3	0.57	1.2	0.24	1.2	0.23
15-30	2.6	0.29	1.4	0.17	1.1	0.29
30-45	7.5	0.22	2.5	0.11	1.7	0.22
45-60	6.1	0.17	2.6	0.11	2.6	0.14
60-75	5.5	0.27	2.3	0.17	3.0	0.16
75-90	4.3	0.27	1.9	0.14	2.0	0.22
90-105	2.8	0.11	0.96	0.13	1.1	0.14
105-120	3.7	0.11	0.92	0.10	1.4	0.16
120-135	4.7	0.06	1.2	0.11	0.98	0.14
135-150	3.6	<0.06	1.7	0.06	1.2	0.11

4.4 THE USE OF COMPUTER MODELS TO PREDICT THE IMPACT OF SRC ON NITRATE LEACHING

Although under ideal conditions, field observations can provide estimates of the overall amount of nitrate leaching that is currently taking place, or has taken place in the recent past, they cannot usually provide quantitative answers to what might happen if the land use changed in a significant way or what effect long-term changes in climate might have. There are so many interacting factors governing nitrate leaching that process-based computer models provide the only realistic and cost-effective way of gaining insight into those questions. While such models are in many ways highly idealised, and are certainly not perfect, they do allow the most critical processes and parameters to be identified and enable simulations to be made which can evaluate the impact of changes in which just one or two factors are changed at a time. Once the most important effects have been identified, the effort can then be directed towards improving estimates of critical parameters either through improved modelling or through further field data collection. A number of dynamic nutrient models has been developed for arable crops but to our knowledge, these have not yet been applied to SRC.

Broadly speaking, predictions of nitrate leaching can be approached in two ways: if only a qualitative indication of the likely impact is required then a satisfactory sensitivity analysis can be achieved using a one dimensional (1D) transport model, i.e. assume that flow of water and nitrate is vertically downwards. Such models could answer questions such as 'If I replace wheat with SRC, what will the change in nitrate leaching be? (approximately)'. The answer would be something like 'it will change from being in the range ... kg N ha^{-1} a^{-1} to ... kg N ha^{-1} a^{-1}'. The mixing of the SRC-derived groundwater with the rest of the groundwater then becomes a critical issue.

However, if more quantitative details of the impact of a specific plantation or plantations is required then a more complete regional or catchment model is needed. This must incorporate a N submodel as well as a water flow model. Such a model could then answer questions such as 'How will a 10 ha SRC plantation at ... affect the nitrate concentration in stream ... at time ... or in borehole source ... at time ...'.

Both of these types of models already exist but clearly the regional models are more demanding in terms of data requirements and computation. Good regional models include 3D submodels for water movement through the soil and unsaturated zones and a saturated flow model for groundwater flow. In practice, there are many uncertainties in both the model structure and the calibration data which means that such predictions also carry a large uncertainty.

There are a large number of 1D nitrogen leaching models for use with agricultural crops and there is in principle no reason why these models could not be adapted for SRC providing that the various crop-specific model parameters could be estimated.

A recent EC program '*Nitrate in Soils*' (Thomasson et al., 1991) reviewed various aspects of soil nitrate leaching models. Five popular models, namely ANIMO, DAISY, EPIC, RENLEM and SWATNIT were compared. An important difference between an SRC-specific nitrate model and these agricultural models would be that atmospheric inputs and the cycling of N through leaf fall and root exudates will be a relatively important component of a SRC model. It is quite likely that denitrification could also be important for SRC, especially if SRC were preferentially grown in wetter areas.

All of these models allow for the mineralisation of soil organic matter but only some include added organic manures. There are other models for the mineralisation of such manures, and even for the volatilisation of ammonia from the manures when surface applied. The SUNDIAL model (J. Smith, personal communication, 1996) is a dynamic organic matter and N model developed at IACR (Rothamsted) and is designed for helping advisers to make arable crop fertiliser recommendations. SUNDIAL includes all of the major processes that control N dynamics and is centred around a description of the mineralisation of various types of organic matter. It can in principle estimate the extent of nitrate leaching under various cropping and management scenarios. It has not yet been used specifically for estimating the impact of sewage sludge on nitrate leaching although there is in principle no reason why it should not be able to do given the correct calibration data. It includes two relatively simple models for 1D (vertical) water movement, including the SLIM model, but is not yet linked to a regional hydrological model. SUNDIAL would probably be the best model for modelling the N dynamics of SRC crops.

The two variants of the SHE (Systeme Hydrologique European) model now known as SHETRAN (UK) (Lunn and Mackay, 1994) and SHE (DK) (Storm et al., 1991) are examples of advanced regional models. SHETRAN (UK) developed in Britain incorporates the EPIC model for plant uptake and decay and is interfaced to a decision support system. SHE (DK) has been developed in Denmark and incorporates the DAISY rootzone model for the simulation of the transport and transformations of N.

An important but difficult aspect of all regional models is defining the 'initial conditions', i.e. the amount and type of N everywhere in the catchment before the start of a simulation run. Where there are deep unsaturated zones, a not uncommon feature in Britain, the nitrate at depth can reflect changes that took place at the surface up to 30 or more years previously and so the unsaturated zone will reflect the changes that have occurred over this order of timescale. These initial conditions need to be defined. The simplest way of doing this is to attempt to simulate them using the model itself. However, in order that the final simulation is not too sensitive to this initialization process, long simulations are required and these are computationally expensive.

Lunn and Mackay (1994) simplified this process by using a moving point model which was run on a series of representative soils to establish representative unsaturated zone nitrate profiles. These were then transferred to the larger SHETRAN (UK) model which was then used for simulating the possible impact of various land use changes on the nitrate concentrations in surface and groundwaters.

In conclusion, models already exist that could provide estimates of the impact of SRC on water quality at both a local scale and on a regional scale. Initially, the lack of suitable calibration data would probably limit their usefulness but at least they provide a rational framework for planning and interpreting field experiments, and can only improve as the knowledge of the underlying processes improves.

4.5 SUMMARY OF THE WATER QUALITY RESULTS

It is likely that the most important impact of SRC on water quality will be its impact on nitrate leaching although other issues such as pesticide leaching and acidification could be locally significant. Clearly the scale of any such impacts will be related to the scale of planting and if only a small part of a catchment is planted, the impacts are likely to be correspondingly small. However, if a reduction in nitrate leaching were of principal concern, then the particular location of SRC could also play a role, e.g. the use of buffer strips or shelterbelts close to rivers, or of plantations in Nitrate Vulnerable Zones or in groundwater protection zones close to groundwater pumping stations. Of course any such benefit from the anticipated reduction in nitrate leaching would have to be offset against any disbenefit from the likely reduction in surface water runoff or groundwater recharge.

This study therefore concentrated on the impact of SRC on nitrate leaching. A summary of the sampling programme and the main results for soil nitrate and ammonium concentrations from the six sites is given in Table 4.9 and the average concentrations of nitrate are plotted in Fig. 4.16. In both cases, it is reasonable to assume that most of the nitrate below 105 cm will eventually be lost to the groundwater. The data have been divided into their main treatments, i.e. all of the data from the various rates of sludge application have been combined to give a single average value. Simple averages were taken, i.e. the moisture contents of each sample have not been considered. If the volumetric moisture contents are reasonably similar within and between the replicate profiles, these averages will be directly related to the amount of nitrate in each profile. This is a reasonable assumption in most cases.

The pore water nitrate concentrations in Table 4.9 are expressed in terms of mg NO_3-N l^{-1} whereas the ammonium concentrations are expressed in terms of mg N kg^{-1} since most of the ammonium was present in the adsorbed phase. The percentage of the extracted N present as NH_4^+ is given in the final columns of Table 4.9.

The concentration of nitrate and ammonium passing through a soil profile is dependent on a wide variety of factors. Some of these are related to the soil and site, some to crop, and some to climate. In addition, the effects of fertiliser and sewage sludge application are superimposed on these factors. We have not attempted to carry out a N mass balance at any of the sites. At best, this is a very demanding task and at worst, is practically impossible given present knowledge and techniques. For example, atmospheric N inputs are likely to be significant but there is very little data which would enable us to quantify this at a particular site and over the lifetime of the crop. It would also be difficult to quantify experimentally.

Similarly, denitrification could be important at some of the wetter and less well-drained sites (e.g. Swanbourne and Medmenham) but is difficult to quantify. Rather we have looked at quite a broad range of sites to see if the major factors likely to be of importance could be identified. Below we summarize our principal findings.

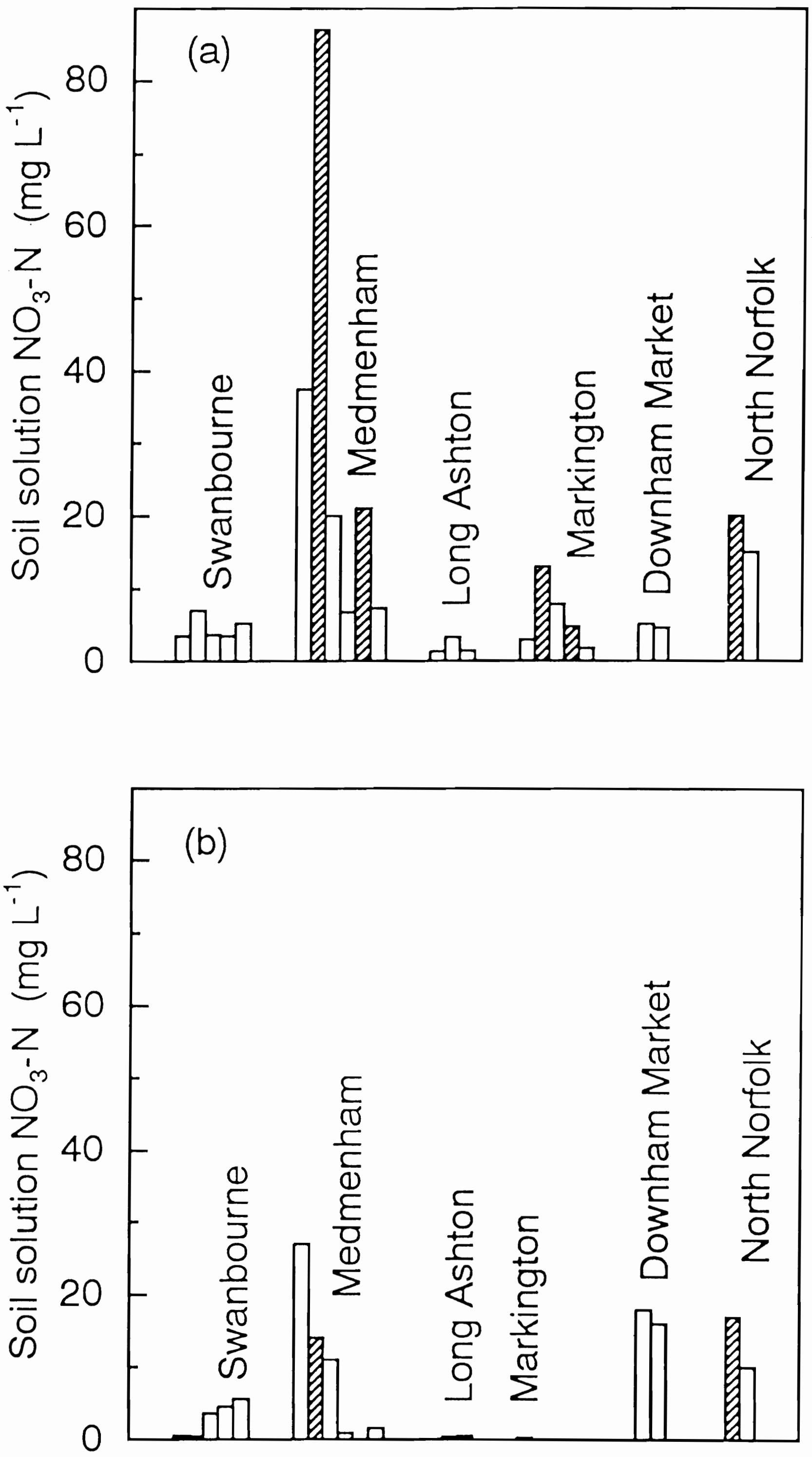


Fig. 4.16 Summary of average NO_3-N concentrations in the pore water for the six SRC sites sampled: (a) 0-1.05 m, and (b) below 1.05 m. Each bar represents a different time or treatment. The shaded bars are for treatments to which sewage sludge had been applied.

Table 4.9. Summary statistics for the pore water soil nitrate concentration and the soil ammonium content for the six sites expressed in terms of the mean and range (in parentheses)

Site	Samples Taken	Date Visited	Treatment (date)	NO_3-N in top 105 cm (mg l^{-1})	NH_4-N in top 105 cm (mg kg^{-1})	NO_3-N below 105 cm (mg l^{-1})	NH_4-N below 105 cm (mg kg^{-1})	% of total N as NH_4-N in top 105 cm	% of total N as NH_4-N below 105 cm
Swanbourne Soil: Clay loam	7 profiles sampled to 150 cm & 8 bulked samples to 30 cm	19-5-93	Control (grass)	3.5 (0.8-7.4) n=7		0.58 0.42-0.74 n=4			
			Fertiliser (March '89) (rows 35+55)	7.0 (0.35-40) n=16		0.49 (0.11-0.94) n=6			
		12-1-94	Control (grass)	3.7 (1.4-11.1) n=7	0.54 (0.19-1.6) n=7	2.0 n=1	0.19 n=1	23	24
			Fertiliser (rows 35+55)	3.5 (2.1-5.4) n=14	0.48 (0.09-1.4) n=14	2.6 (2.3-2.8) n=4	0.20 (0.13-0.28) n=4	31	25
			No Fertiliser (row 20)	5.2 (2.5-8.0) n=7	1.3 (0.90-2.0) n=7	5.6 n=1	2.0 n=1	43	51

Table 4.9 (contd.)

Site	Samples Taken	Date Visited	Treatment (date)	NO_3-N in top 105 cm (mg l^{-1})	NH_4-N in top 105 cm (mg kg^{-1})	NO_3-N below 105 cm (mg l^{-1})	NH_4-N below 105 cm (mg kg^{-1})	% of total N as NH_4-N in top 105 cm	% of total N as NH_4-N below 105 cm
Medmenham Soil: Sandy/clay loam	10 profiles sampled to 150 cm	17-6-93	Control (bare soil)	37.3 (17-65) n=7		27 n=1			
			Sludge (May '93)	87 (11-350) n=14		14 (9.5-18) n=7			
			No Sludge	20 (6.4-45) n=14		11 (6.6-16) n=7			
		27-1-94	Control (bare soil)	6.8 (4.5-11) n=7	0.27 (0.19-0.41) n=7	0.92 n=1	0.24 n=1	13	17
			Sludge	21 (8.0-62) n=14	0.40 (0.20-0.68) n=14			6.0	
			No Sludge	7.3 (0.96-11) n=14	0.38 (0.18-1.4) n=14	1.6 (0.84-3.1) n=4	0.29 (0.13-0.67) n=4	17	16

Table 4.9 (contd.)

Site	Samples Taken	Date Visited	Treatment (date)	NO_3-N in top 105 cm (mg l^{-1})	NH_4-N in top 105 cm (mg kg^{-1})	NO_3-N below 105 cm (mg l^{-1})	NH_4-N below 105 cm (mg kg^{-1})	% of total N as NH_4-N in top 105 cm	% of total N as NH_4-N below 105 cm
Long Ashton Soil: Stony clay loam	5 profiles augered to 180 cm	5-5-94	Control (grass)	1.3 (<0.15-6.9) n=7	0.71 (0.37-1.8) n=7	<0.15 n=5	0.29 (0.21-0.31) n=5	49	100
			Fertiliser	3.3 (<0.15-12) n=14	0.54 (0.31-1.4) n=14	0.45 (<0.15-2.8) n=10	0.85 (0.15-4.2) n=10	24	80
			No Fertiliser	1.4 (<0.15-9.6) n=14	0.66 (0.23-1.7) n=14	0.55 (<0.15-3.5) n=10	0.49 (0.22-1.19) n=10	46	64
Markington Soil: Medium loam	3 profiles sampled to 105 cm & 8 profiles sampled to 90 cm	1-3-94	Control (commercial willow)	3.0 (<0.27-12) n=21	0.46 (0.18-1.2) n=21	<0.29 n=1	0.25 n=1	39	100
			Sludge (January '94)	13 (5.9-26) n=14	0.49 (0.06-1.0) n=14			14	
			No sludge	7.8 (7.1-8.5) n=7	0.27 (0.06-49) n=7			15	
		24-1-95	Sludge	4.8 (<0.30-16) n=33	0.21 (<0.06-0.77) n=33			17	
			No sludge	1.8 (<0.30-8.8) n=12	0.52 (0.18-1.5) n=12			58	

Table 4.9 (contd.)

Site	Samples Taken	Date Visited	Treatment (date)	NO_3-N in top 105 cm (mg l^{-1})	NH_4-N in top 105 cm (mg kg^{-1})	NO_3-N below 105 cm (mg l^{-1})	NH_4-N below 105 cm (mg kg^{-1})	% of total N as NH_4-N in top 105 cm	% of total N as NH_4-N below 105 cm
Downham Market Soil: Sandy loam	6 profiles sampled to 195 cm	15-6-95	Control (grass)	5.1 (1.8-10.2) n=7	0.03 (<0.01-0.12) n=7	18 (14-21) n=6	0.03 (<0.01-0.15) n=6	3.2	1.0
			None	4.6 (0.69-10) n=14	0.04 (<0.01-0.41) n=14	16 (12-21) n=12	<0.12 n=12	6.4	0
North Norfolk Soil: Sandy loam	5 profiles sampled to 150 cm	29-11-95	Control (bare soil)	51 (10-84) n=7	0.27 (0.11-0.57) n=7	45 (40-51) n=3	0.09 (<0.06-0.11)	6.0	0.9
			Sludge (April '95)	20 (6.8-53) n=14	0.20 (0.11-0.34) n=14	17 (12-24) n=6	0.14 (0.05-0.22) n=6	9.8	10
			No sludge	15 (2.9-27) n=14	0.15 (0.11-0.24) n=14	10 (2.6-17) n=6	0.09 (0.05-0.13) n=6	7.8	6.6

4.5.1 Differences between willow and poplar

Comparisons could be made at all sites except Swanbourne (only poplar) and North Norfolk (only willow).

There were no sufficiently large and consistent differences in the nitrate or ammonium concentrations below willow and poplar that could be attributed to a pure species effect (all other things being equal).

The offtake of nitrogen in the crop is directly related to the dry matter yield and the nitrogen content of the dried material. Therefore, all other things being equal, the greater the dry matter yield, the greater the offtake of nitrogen and the less the anticipated nitrate leaching. Therefore yield differences between tree species (e.g. willow versus poplar) and between high and low yielding clones might be expected to be reflected in the amount of nitrate leaching. However such differences were not detected in the present results. It would need a well replicated trial to determine any such differences, and both nitrate concentrations and water fluxes would need to be measured.

4.5.2 Established crop with minimal inputs

The nutrient balances in the first few years of SRC growth are likely to be atypical of those of long term production because of the legacy of fertility inherited from the previous land use, the lack of a well developed root system, and any effects created by the disturbance during clearing and planting especially if old pastures are converted to SRC (Rushton, 1993). The sites with the longest history of SRC were Swanbourne, Long Ashton and Markington (commercial production site), and each had unfertilised plots. The average NO_3-N concentrations for these plots below 1.05 m were: Long Ashton, <1; Markington, <1, and Swanbourne, 2-5, all in mg NO_3-N l^{-1}. The relatively high Swanbourne figure may have been affected by the downslope flow of nitrate from outside of the plot, or from high rates of mineralisation in the old pasture soil.

These results suggest that under established coppice, nitrate leaching is very low and is comparable to what might be expected under unfertilised grassland. The N offtake in the stems would be useful for estimating the sustainability of production under low N inputs.

4.5.3 Fertilisers

None of the sites studied had had fertilizers applied during the period of the study or in the year before the study began. Therefore it was not possible to monitor the fate of fertilizer nitrogen in the year following application when losses are expected to be greatest. Modest applications of fertiliser at Swanbourne and Long Ashton did not appear to increase the nitrate concentrations at depth. These were about 2-5 mg NO_3-N l^{-1} at Swanbourne and <1 mg NO_3-N l^{-1} at Long Ashton. However, the lack of a residue is likely to have been in part because the fertilisers had been applied at least two years before sampling and so any excess fertiliser N will have already been leached out of the soil by the time of sampling. Swedish experience in which recently established short rotation willow had been fertilized for two years with up to 150 kg N ha^{-1} showed that the shallow groundwater beneath the plots usually contained less than 1 mg l^{-1} NO_3-N (Bergström and Johansson, 1992). Bergström and Johansson (1992) suggested that this nitrate concentration was much lower than on comparably fertilised arable fields because of the ability of the root systems of trees to take up nitrogen from the subsoil, especially in the second year of growth. It is also possible that there may have been some denitrification in the less well drained parts of the profile.

Although detailed studies tracking the fate of fertilizer nitrogen in a SRC crop are lacking, it is unlikely that regular 'maintenance' applications of fertiliser nitrogen will lead to an environmentally significant increase in nitrate leaching. In any case, the evidence in the UK to date does not provide strong evidence for an economic yield increase with nitrogen fertilization, and so large applications of N fertilizer are unlikely. Nitrogen fertilizers will probably best be applied in the later stages of the life of the coppice when any legacy of nitrogen derived from the earlier land use will have been depleted. A well-developed root system at this stage should minimize any nitrate leaching. Nitrogen uptake from deep roots would be particularly significant in reducing nitrate leaching.

4.5.4 Sewage sludge

Anaerobically digested sewage sludge had been applied at the Medmenham, Markington and North Norfolk sites. However, the Medmenham and North Norfolk sites were sites where sewage sludge had been applied to a crop that was only 1-2 years old and so our results from these sites may not be representative of sludge applications to more established crops. Liquid digested sludge differs from inorganic fertilisers in the form of N applied and in its mode of delivery, i.e. it is delivered with water. It is also more difficult to spread evenly and so there is the possibility of some rapid preferential leaching through cracks.

Application rates of nitrogen in the sludge ranged from zero up towards the maximum rates recommended by the Code of Good Agricultural Practice for the Protection of Water, i.e. 250 kg N ha^{-1} a^{-1} (MAFF, 1991). We did not have enough replication to establish a clear dose-response relationship for any of the sites but the indications are clear from all three sites that the sludge increased nitrate concentrations in the topsoil and that at least some of this increase led to increased nitrate concentrations at depth. This would indicate that some loss of the sludge N to groundwater was occurring. This is not surprising since the quantities of nitrogen applied exceed the crop requirement which is likely to be on the order of 70 kg N ha^{-1} a^{-1} or less.

At Markington, although the sludge applications appeared to increase the rate of nitrate leaching in both the first and second years after application, the concentrations of nitrate leaching two years (21 months) after the second application were low and well within the drinking water limit of 50 mg l^{-1} nitrate (11.3 mg l^{-1} NO_3-N).

We did not have enough samples at different times to follow the downward migration of the nitrate front from the sludge applications and so cannot calculate the additional nitrate flux to groundwater. As expected, most of the leaching seems to occur in the first year after application - the potential for long term release of nitrogen from liquid digested sludges is relatively low (Smith, 1996) - and a detailed analysis of the leaching loss would require an estimate of water movement through the profile during this first year.

4.5.5 The legacy of soil nitrogen from agricultural land

In the early stages of growth of SRC, it is reasonable to expect that the inherent fertility of the soil could play an important role in controlling the extent of nitrate leaching. We have examined our data to see to what extent this might be true.

The Medmenham and North Norfolk sites were the sites that had been planted two or fewer years before our first sampling. Nitrate leaching from the sludge treatment plots at these sites is expected to be dominated by the impact of the sludge application and so the zero sludge and control plots were examined.

At Medmenham, the nitrate concentration in the control plot (bare soil in the corridor between plots) and the zero sludge sites averaged 37 mg NO_3-N l^{-1} in the top 45 cm in June 1993. This reflects a 'fertile' soil containing a considerable amount of mineralised N (we have assumed that the zero sludge and control plots were not cross-contaminated with sludge). The return sampling to Medmenham in January 1994 showed a much lower concentration of nitrate (c. 7-11 mg NO_3-N l^{-1}) in the top 45 cm reflecting the combined effects of crop uptake, slow down in mineralisation, dilution by low nitrate rainfall, and possibly denitrification.

At the North Norfolk site, the 'control' site had probably received a spillage of sewage sludge during sludge application and so could not be used. The 'no sludge' profiles sampled in November 1995 showed nitrate concentrations of about 10 mg NO_3-N l^{-1} in the topsoil and a peak of 20-30 mg NO_3-N l^{-1} between 30-80 cm. Such high concentrations of nitrate could well indicate a legacy from an earlier arable history (before set-aside). The low rate of recharge at this rather 'dry' site would tend to increase nitrate concentrations through evaporative concentration but the slower rate of movement of water and its dissolved nutrients through the root zone should give a greater opportunity for plant uptake.

In conclusion, while there does seem to be a 'legacy' at recently established sites, some form of longer term monitoring is necessary to see how the soil nitrate concentrations at depth change over the establishment phase. In practice, the legacy effect - the store of mineralisable N inherited from the previous land use - is difficult to separate from the establishment effect - low nutrient uptake because of sparse root development.

There will also be a legacy after the growth of SRC. If it is assumed that some form of maintenance application of mineral fertilisers has been used over the life of the coppice in order to maintain adequate supplies of Mg, P and K, then there should be no serious mineral deficiencies. It is likely that the growth of SRC will lead to the slow buildup of the soil organic matter content. This should be beneficial for future crops in terms of its contribution to improving the soil structure and moisture retention. It will also provide a store of organic nitrogen which will be slowly mineralized. Providing that the land is cropped this should be seen as an asset rather than a liability and should not lead to any deterioration in water quality.

4.5.6 Climate and nitrate leaching

Climate affects the rate of nutrient (including nitrate) leaching through its effect on: (i) coppice growth rates (and hence nutrient uptake rates); (ii) the amount of water available for leaching (the 'effective' rainfall) and so the extent of dilution of leached chemicals; (iii) the rates of various biological transformations such as nitrification and denitrification, and (iv) the input of nutrients through wet and dry deposition. The overall relationship between nitrate leaching and effective rainfall is complex since there are likely to be strong interactions between the two. There were too few data in the present study to separate out detailed differences due to climatic effects or the sensitivity of nitrate leaching to individual climatic factors. This is best understood by modelling as discussed in Section 4.4.

The climate at the six SRC sites studied varied considerably. Most factors would favour low nitrate concentrations in the more northerly climates, namely: greater effective rainfall, a colder climate and hence a slower rate of nitrification, and possibly a less polluted atmosphere with consequent lower rates of ammonium deposition. On the other hand, all other things being equal, denitrification is favoured by higher temperatures. Of these effects, the variation in effective rainfall is likely to be most important. For example, the long-term average effective rainfall based on the Meteorological Office's MORECS system varies from about 100 mm a^{-1} at the Downham Market and North Norfolk sites to more than 700 mm a^{-1} at Markington (Table 4.1). These data are for short grass and so the effective rainfall under SRC is likely to be even less than this perhaps by 150 mm a^{-1} or more in the wetter parts of the UK (rainfall greater than 700 mm a^{-1}) to 80 mm a^{-1} or so in the driest parts of the UK (Section 3.4.6). If these figures are correct, then recharge could potentially be reduced to practically zero by SRC in the driest parts of the UK. This means that even quite small fluxes of nitrate leaching could lead to relatively high concentrations of nitrate in the small amount of water draining from the land (Fig. 4.17). For example, if the amount of nitrate leached was equivalent to 5 kg N ha^{-1} a^{-1}, then an effective rainfall of 50 mm a^{-1} would give a final nitrate concentration of 10 mg l^{-1} NO_3-N or very close to the current UK drinking water limit. Also, for a given flux of N leaching, the average groundwater nitrate concentration leaching from the Downham Market site will be some ten times greater than from the Markington site.

We have combined estimates of the likely effective rainfall with the average pore water concentration of nitrate below 1 m to give estimates of the steady state rate of nitrate leaching at the six sites studied (Table 4.10). The effective rainfall or drainage under SRC was estimated by reducing the MORECS estimate for grass by between 80 and 150 mm a^{-1}. We have omitted the sludged plots from these calculations since we do not have enough data to estimate the quantity of nitrate leached from the pulse of nitrate produced by the sludge application. It appears from the results in Table 4.10 that as a generalization the rate of nitrate leaching under established SRC is likely to be less than 15 kg N ha^{-1} a^{-1} and quite likely to be less than 5 kg N ha^{-1} a^{-1} in the drier parts of the country. There are large uncertainties in both the average nitrate concentration below 1 m and in the effective rainfall but the overall conclusion is that nitrogen losses from SRC are indeed likely to be small. These estimates are probably upper estimates since root uptake of nitrate and denitrification might be occurring below the deepest sample. The denitrification loss is likely to be greatest on wetter soils. However, it is clear from Fig. 4.17 that when the effective rainfall is less than 100 mm a^{-1}, even low rates of nitrate leaching can lead to concentrations of nitrate in the drainage water that exceed the current drinking water limit.

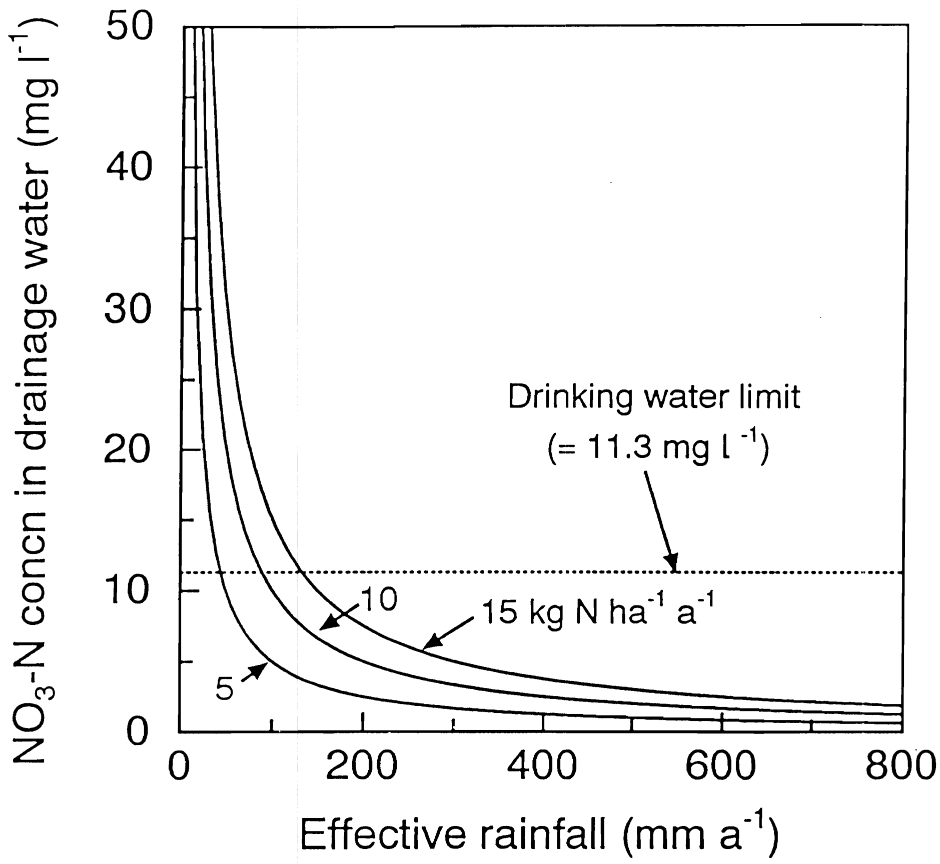


Fig. 4.17. Average nitrate-N concentration in the drainage water as a function of effective rainfall. Curves are shown for nitrogen leaching fluxes of 5, 10 and 15 kg N ha^{-1} a^{-1}.

Table 4.10. Approximate nitrate leaching fluxes at the six SRC sites based on the concentration of nitrate in the subsoil pore water and the estimated effective rainfall at each site.

Site	Average NO_3-N concentration in soil water below 1 m (mg l^{-1})	MORECS long term effective rainfall for the nearest MORECS 10 km square (mm a^{-1})	Estimated range of effective rainfall under SRC (mm a^{-1})	Nitrate leaching (kg N ha^{-1} a^{-1})
Swanbourne	2.9	173	20-90	0.6-3
Medmenham	6.3	177	30-100	2-7
Long Ashton	0.5	324	170-240	1-2
Markington	2.0 (below 0.6 m)	707	560-630	11-13
Downham Market	17	90	<20	<3
North Norfolk	10	98	<30	<3

Data are for plots to which no sewage sludge had been applied

5. CONCLUSIONS

5.1 WATER QUANTITY

An array of measurement techniques was successfully employed on SRC of different clones at two sites in southern England to quantify the water use. In particular, the stem heat balance method proved successful in providing continuous measurements of the sap flow rate within the coppice shoots during three summers. The rates of sap flow were verified using the heat pulse velocity and deuterium tracing methods at Hunstrete. These sap flow rates when scaled up using the results of stem diameter and leaf area surveys provided direct estimates of the transpiration rates on a ground area basis.

Additional data were collected and analysed e.g. weather, stomatal conductances, soil water storage and potential, gross and net rainfall, that have allowed the processes controlling the water use to be more fully understood. The information from these process studies have been incorporated into mathematical models of SRC water use. The modelling studies have supported the results of the measurement programme and made it possible to compare the water use of SRC with other crops.

The presence of a perched water table at the Swanbourne site prevented differences in water use between coppice on different harvesting cycles from being determined and increased the degree of uncertainty in estimates of the water use calculated from the soil water balance. However its presence did give an incentive and opportunity to use the experimental $\delta^{18}O$ tracing technique to determine the sources of water used by the coppice. The move to Hunstrete during the second year of the project made it possible to determine the transpiration of poplar and willow SRC subject to drought stress and to measure the interception loss from poplar SRC. The different methods used to determine the transpiration from sap flow measurements gave consistent results. These were used as a validation data set for a physically-based model incorporating the results of measurements of stomatal conductance as a function of soil water deficit.

The consistent results from the measurements and from the model give confidence in drawing the following conclusions:

Water use of SRC

- The water use of poplar SRC (Beaupré, *Populus trichocarpa* x *deltoides*; Dorschkamp, *P. deltoides* x *nigra*) is high; higher than all the major agricultural crops and broadleaved trees and second only to pine forest. Our measurements on the willow clone Germany (*Salix burjatica*) gave no indication of significantly lower water use. Scandinavian work on willow (*S. viminalis* and *S. aquatica*) suggests similarly high water use.

- The high water use of SRC results from its high transpiration, typically 500 mm a year, compared with 350 and 390 mm a year for conventional ash and beech forest respectively.

- The high transpiration from poplar (Beaupré and Dorschkamp) SRC is due to high stomatal conductances with an absence of response to atmospheric humidity deficits and a delayed (but large) response to soil water deficits.

- The interception loss from poplar SRC over the growing season is about 21% of the rainfall. The annual interception loss, including the unleafed period, is about 14% of the annual rainfall (estimated by the SIMWUCOP model). These values are typical of conventional broadleaved woodland.

- The poplar root system is efficient and appears to adapt well to the soil in which the SRC grows. It would appear able to extract water from depth, able to extract water from the saturated zone and able to extract water from the surface soil after it has been rewetted following drought.

Hydrological implications

The hydrological implications of these results are:

- Extensive plantation of SRC will result in reduced stream flows and reduced peak flows except in the unlikely event of the conversion of coniferous forest. The size of the reduction will be dependent upon the rainfall and the land use that the SRC replaces. For most agricultural crops the reduction will be greater than for pasture.

- Large scale conversion of catchments in the driest parts of the country will result in the annual net recharge to aquifers and drainage to rivers and streams being reduced by up to 80 mm where a grassland catchment is wholly converted to SRC. The reduction may persist for some time after removal of the SRC in some atypical locations where there has been mining of water by the trees.

- During the summer SRC may cause springs and ephemeral streams to dry up sooner and for longer.

- In dry summers when there is a significant soil water deficit at the start, such as 1976, the water use of poplar SRC will be much less than that of coniferous forest and similar to grassland.

5.2 WATER QUALITY

The amount of nitrate leaching beneath SRC is likely to be the most important water quality issue. Although the quantity of nitrate leaching reflects a large number of site- and time-specific factors and the amount of data available is relatively small, the following conclusions can be made:

- Although atmospheric nitrogen fluxes to SRC are likely to be smaller than to a mature deciduous woodland, nitrogen inputs are likely to be substantial and so use of nitrogen fertilisers for SRC may not be required.

- In the wetter parts of Britain, the average concentration of nitrate draining from beneath established SRC plantations with minimal or no fertiliser inputs is likely to be less than 3 mg l^{-1} NO_3-N and quite possibly less than 1 mg l^{-1} NO_3-N.

- In the drier, south eastern part of Britain, the nitrate concentration in the drainage water is critically dependent on the effective rainfall. The effective rainfall is likely to be less than 150 mm a^{-1} and so even low rates of nitrate leaching could give rise to nitrate concentrations close to or exceeding the 11.3 mg l^{-1} NO_3-N limit for drinking water.

- Where there is a legacy of nitrate or mineralizable nitrogen from the previous land use, a newly established SRC plantation does not appear to be able to reduce the nitrate leaching to low levels in the first few years.

- Sewage sludge applications at rates within the current Codes of Practice give rise to a measurable increase in nitrate leaching but the effect from single applications appears to be short-lived and the amount of nitrate leaching could well be less than from land under intensive agriculture.

5.3 FUTURE DEVELOPMENTS

Biomass production from SRC is showing promise as an alternative fuel source but high water use is at present an inevitable feature of SRC. In our studies we have identified high, and for much of the time fairly constant, stomatal conductances as the reason for the sustained high transpiration rates. However, because of the important role stomata have in regulating entry of CO_2 into leaves the high stomatal conductances are, together with other, internal, leaf physiological characteristics, necessary for high rates of dry matter production.

As well as short rotation coppice there is a substantial interest in the use of temperate grasses with the C_4 photosynthesis pathway as a source of biofuels. The water use by such vegetation during their growth period has been studied at the University of Essex by C.V. Beale and S.P. Long (personal communication, 1996). These studies involved *Miscanthus x giganteus* and *Spartina cynosuroides* in irrigated and unirrigated plots. The highest evaporation rates were 509 mm for irrigated *Miscanthus* and 461 mm from *S. cynosuroides*. Unirrigated, these species evaporated between 310 and 327 mm. Although the water use with irrigation is similar to the water use by SRC, the production of dry matter is substantially larger. Dry matter production was around 18 tons ha^{-1} in *Spartina* irrespective of the irrigation treatment while *Miscanthus* had a dry matter production of 24 tons ha^{-1} when unirrigated and 30 tons ha^{-1} with irrigation. In contrast dry matter production of a broad range of willow and poplar cultivars at different sites across the UK ranged from 1.8 to 6.95 tons ha^{-1} for willow and 2 to 9.8 tons ha^{-1} for poplar (Mitchell et al., 1995).

High productivity is required if poplar SRC is to become a profitable alternative crop for farmers. To this end breeding programmes to enhance Water Use Efficiency (WUE) by clonal selection would be of great benefit. According to Dickmann et al. (1992) genetic variation within the genus is large and, compared to other tree taxa, genetic improvement using conventional and molecular techniques are easy. There is plenty of scope for future work in this area but also in determining the effects of environmental factors, e.g. drought, temperature, atmospheric humidity, on WUE.

The low rates of nitrate leaching found under SRC make it an attractive crop for Nitrate Sensitive Areas (NSAs) or for groundwater protection zones around water supply boreholes. However, for the SRC plantation to make a substantial improvement in the overall quality of the groundwater it must make up a significant proportion of the catchment. These are precisely the conditions under which reduced groundwater recharge could become significant and so the benefits of improved water quality will have to be carefully matched against the reduction in water yield that can be expected. Clearly in terms of water resources, SRC is most attractive for the wetter, western parts of Britain where the relative reduction in groundwater recharge or river flow would be of least concern.

6. RECOMMENDATIONS

- Unless it is part of a sewage recycling scheme, extensive plantation of SRC should be in the wetter parts of the country where the high water consumption of the SRC will not have potentially serious consequences for the water resources. In these areas, and where the radiation is not limiting, the plentiful supply of rain should produce high yields. In the drier parts of the country, only a small proportion of a catchment should be planted.

- Recharge and runoff is increased by using a shorter rotation period. The practice of staggering the harvest times would therefore be hydrologically beneficial.

- If large areas are to be planted then the evaporation will be reduced if plantations are in a few large blocks rather than many small blocks.

- Measurements on the growth and water use of SRC in the driest parts of the country should be made to allow the SIMWUCOP model to be calibrated for less vigorous coppice. Water use models could be incorporated into a GIS to produce maps of reduction in drainage. It would also be possible using information on the WUE to produce maps giving the potential biomass yield.

- Growers of SRC should be encouraged not to use nitrogen fertilisers unless the indications are that they definitely increase yield, and even then, only modest rates of fertiliser should be applied.

- If sewage sludge applications to SRC are to be widely used, a 'dose-response' relationship between the rate of sewage sludge application and the amount of nitrate leaching needs to be established at a few key sites. This will require continuous monitoring for at least two years after the last sludge application.

- Where there is less than 100 mm a^{-1} of effective precipitation, the concentration of nitrate in the drainage (recharge) water becomes very sensitive to the actual amount of drainage and even quite small rates of nitrate leaching (in terms of kg N ha^{-1} a^{-1}) can lead to high concentrations of nitrate in the drainage water. Therefore the concentrations of nitrate in the drainage water from well established (5 years or more old) SRC sites in the drier parts of eastern England need to be monitored closely. The long term rate of recharge should be estimated independently from physical measurements or by using the chloride mass balance approach.

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APPENDIX A

Determination of the aerodynamic resistance, r_a

Estimation of the evaporation rates from vegetation in dry and wet conditions using the Penman-Monteith equation, the basis for the models used in this work, (Section 3.3.1) requires values for the aerodynamic resistance, r_a. This parameter quantifies the resistance experienced by water vapour when transported from the vegetation surface into the atmosphere. In wet conditions the evaporation rate is particularly sensitive to its value. There are theoretical reasons to expect the value to be different for dry and wet canopies and there is evidence to support this from our measurements (Section 3.3.1.3). It is generally difficult to determine r_a and is often approximated by a formula that gives the aerodynamic resistance to momentum transfer as a function of the windspeed. Through this analogy the r_a to water vapour transfer is also expected to be a function of the windspeed.

If for some periods the evaporation rates are known then r_a can be determined by inversion of the Penman-Monteith equation. However in addition to the weather variables this also requires that the surface resistance is known. In wet conditions it is zero and the problem is simplified a little. However to determine the appropriate value of r_a for transpiration estimates (dry conditions) it will be necessary to have values for the surface resistance. The surface resistance is often approximated by the bulk stomatal resistance (Section 3.3.1.1) that can be derived from the stomatal conductance (g_s) and leaf area measurements. However to obtain a reasonable number of estimates of r_a would require more values of g_s than we were able to collect. Fortunately it is possible to derive an expression for r_a that does not require the surface resistance to be known. Instead it requires measurements of the leaf surface temperature. Through the use of automatically logged thermocouples it was possible to collect enough of these data to be able to determine r_a over several weeks over a range of windspeeds (Fig. 3.73) so that we were able to obtain the function given as Equation 3.14.

The derivation of the necessary expression for r_a follows.

The evaporation rate, E (mm s^{-1}), is given by the Penman-Monteith formula:

$$\boldsymbol{E} = \frac{\Delta' A + \rho c_p D / r_a}{\lambda \Delta' + c_p (1 + r_s / r_a)} \tag{A1}$$

where: A is the energy available for evaporating water and warming the air and is estimated as the difference between R_n, the net radiation, and G, the soil heat flux; c_p is the specific heat of air at constant pressure; D is the above-canopy specific humidity deficit of the air, i.e. the difference between q', the *saturated* specific humidity of the air at the air temperature and q, the specific humidity of the air; Δ' is rate of change of saturated specific humidity with air temperature; λ is the latent heat of vaporisation of water and ρ is the density of air; r_s is the surface resistance.

The basic flux-gradient relationship for water vapour gives the evaporation rate, λE, as,

$$E = \frac{\rho(q_s' - q)}{r_a + r_s} \tag{A2}$$

where q_s' is the saturated specific humidity at the surface temperature of the leaf.

Rearranging Equation A2 and substituting for r_s in Equation A1 gives after some manipulation

$$r_a = \frac{\rho c_p[D - (q_s' - q)]}{\Delta'(\lambda E - A)} \tag{A3}$$

which can be simplified to give

$$r_a = \frac{\rho c_p(q_s' - q')}{\Delta'[(R_n - G) - \lambda E]} \tag{A4}$$

We used Equation (A4) to determine r_a for a range of windspeeds (Fig. 3.73) by measuring the leaf surface temperature so that q_s' could be calculated, in addition to the weather variables and the transpiration rate. G was estimated from R_n.

APPENDIX B

This Appendix contains a complete listing of all the nitrogen data collected from the six field sites visited as part of the water quality investigations. The data are based on both neutral salt extractions and analyses of porewaters displaced by high speed centrifugation. It also contains associated data for the moisture content (expressed in terms of g kg^{-1} dry weight of soil) and porewater yield where appropriate. The sites visited were: Swanbourne (Buckinghamshire); Medmenham (Berkshire); Markington (North Yorkshire); Long Ashton (Bristol); Downham Market (Norfolk); and North Norfolk. Data for porewater concentrations of selected cations are also given for the Medmenham site and for the top 30 cm of soil at Downham Market. Porewater data for chloride concentrations from the North Norfolk site are also given.

APPENDIX B

CONTENTS

B1. Soil nitrate for various treatments at Swanbourne extracted by 0.01M $CaCl_2$ and expressed as an equivalent soil solution concentration (19/5/93).

	Control		5 year cycle/fertilizer		3 year cycle/fertiliser	
Sample Depth (cm)	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**
0-15	359	6.1	241	40	220	3.5
15-30	346	7.4	237	24	235	6.2
30-45	290	2.3	200	14	205	5.1
45-60	181	3.4	274	3.3	181	2.0
60-75	165	3.4	273	1.7	204	0.6
75-90	269	1.1	253	0.5	189	0.5
90-105	253	0.8	229	1.7	172	0.4
105-120	210	0.7	225	0.6	178	0.2
120-135	236	0.6	218	0.9	186	0.1
135-150	219	0.5	208	0.9	194	0.2

B2. Nitrate concentrations in the bulked soils from Swanbourne extracted by 0.01M $CaCl_2$ and expressed as an equivalent soil solution concentration (19/5/93).

	Control		5 year cycle/fertiliser		5 year cycle/no fertiliser		3 year cycle/fertiliser	
Sample Depth (cm)	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**
0-25	408	12	276	20	257	7.3	267	13
25-50	315	7.7	253	10.3	208	5.3	231	6.1

B3. Soil nitrate for various treatments at Swanbourne extracted by 2M KCl and expressed as an equivalent soil solution concentration (12/1/94).

	Control				5 year/fertiliser				3 year/fertiliser				3 year/ no fertiliser			
Sample Depth (cm)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)
0-15	595	5.6	<0.1	<0.05	330	5.4	<0.1	<0.05	385	3.4	<0.1	<0.05	365	7.5	<0.1	<0.05
15-30	451	2.7	<0.1	<0.05	352	4.2	<0.1	<0.05	352	5.0	<0.1	<0.05	356	8.0	<0.1	<0.05
30-45	399	1.4	<0.1	<0.05	258	3.9	<0.1	<0.05	392	3.9	<0.1	<0.05	231	6.4	<0.1	<0.05
45-60	437	3.0	<0.1	<0.05	274	2.6	<0.1	<0.05	234	3.7	<0.1	<0.05	224	5.2	<0.1	<0.05
60-75	365	2.3	<0.1	<0.05	285	2.5	<0.1	<0.05	228	4.3	<0.1	<0.05	287	2.5	<0.1	<0.05
75-90	269	2.6	<0.1	<0.05	276	2.6	<0.1	<0.05	206	2.3	<0.1	<0.05	285	2.9	<0.1	<0.05
90-105	310	2.5	<0.1	<0.05	281	2.1	<0.1	<0.05	218	2.5	<0.1	<0.05	-	-	-	-
105-120	282	2.1	<0.1	<0.05	253	2.5	<0.1	<0.05	241	2.3	<0.1	<0.05	-	-	-	-
120-135	-	-	-	-	242	2.8	<0.1	<0.05	272	2.6	<0.1	<0.05	-	-	-	-

B4. Comparison of nitrogen species extracted by 2M KCl and 0.01M $CaCl_2$ and displaced in the soil solution by high speed centrifugation on bulked samples from Swanbourne (12/1/94).

	2M KCl				0.01M $CaCl_2$				Centrifuged Porewater			
Sample Depth (cm)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Yield (%)	NO_3-N ($mg\ l^{-1}$)	NO_2-N ($mg\ l^{-1}$)	NH_4-N ($mg\ l^{-1}$)
	Control				Control					Control		
0-15	558	4.1	<0.1	1.3	-	-	-	-	-	-	-	-
15-30	532	4.6	<0.1	0.8	-	-	-	-	-	-	-	-
	5 year fertilised				5 year fertilised					5 year fertilised		
0-15	358	6.5	<0.1	1.1	358	3.6	<0.1	0.2	27	7.0	0.01	0.1
15-30	326	8.6	<0.1	0.9	326	5.0	0.1	0.5	24	7.2	0.01	0.1
	3 year fertilised				3 year fertilised					3 year fertilised		
0-15	405	4.7	<0.1	0.8	405	4.0	0.1	0.1	17	4.8	0.02	0.2
15-30	365	6.0	<0.1	2.0	365	4.0	0.1	0.2	15	7.6	0.03	0.1
	3 year not fertilised				3 year not fertilised					3 year not fertilised		
0-15	395	4.1	<0.1	1.2	395	3.7	<0.1	0.3	18	5.0	0.01	0.1
15-30	315	5.6	<0.1	2.0	315	4.3	0.1	0.4	17	7.2	0.03	0.1

B5. Soil solution chemistry at Swanbourne (19/5/93)

Sample	Depth (cm)	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
		mg l^{-1}							µg l^{-1}								
Outside Coppice	0-25	18.5	1	58.5	3.8	39.5	19	4.3	167	145	<15	550	185	20	45	45	250
Outside Coppice	25-50	15.5	1	46.1	3.6	42	12.5	4.1	144	40	20	650	330	10	75	75	450
Row 55	0-25	18	6.5	73.5	6.8	71	29	7.1	198	460	<15	400	185	130	40	40	300
Row 55	25-50	21.5	3	63	6.3	79.5	17	7.3	195	145	<15	550	1170	45	45	45	1200
Row 68	0-25	20.5	14.5	49	4.2	66	10.5	5.6	148	425	15	450	520	75	120	120	300
Row 68	25-50	18.5	9	44.8	3.5	59	8	5.7	121	280	15	550	170	120	80	80	250
Row 35	0-25	16.5	3	53.5	3.8	48	19	5.1	141	395	<15	500	95	15	90	90	200
Row 35	25-50	13.5	2.5	54	5.5	81.5	9	4.6	171	120	<15	400	400	20	50	50	650

P_{total} < 1.0 mg l^{-1} for all samples

B6. Soil solution nitrate concentrations from profiles beneath various treatments at the WRc Medmenham trial site (17/6/93).

	Control			Willow (172 m^3ha^{-1} sludge)			Willow (no sludge)			Poplar (172 m^3ha^{-1} sludge)			Poplar (no sludge)		
Sample Depth (cm)	**Moisture ($g\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**
0-15	292	18	65	339	16	350	264	16	22	318	20	120	240	21	26
15-30	255	5	56	278	14	180	254	20	17	315	17	120	222	17	45
30-45	206	9	47	264	20	96	220	18	14	239	6	95	201	16	43
45-60	190	10	28	284	19	53	236	2	7.4	227	6	67	186	13	33
60-75	208	20	18	273	24	20	262	2	6.4	207	6	48	178	17	24
75-90	233	41	17	262	34	23	241	6	7.6	188	13	25	142	16	17
90-105	206	53	30	214	50	11	107	12	16	218	17	20	201	28	7.8
105-120	164	66	27	267	49	9.5	81	20	13	287	23	18	102	24	6.6
120-135	-	-	-	297	48	14	77	42	16	-	-	-	141	27	6.9
135-150	-	-	-	-	-	-	88	38	15	-	-	-	186	39	9.5
150-165	-	-	-	-	-	-	-	-	-	-	-	-	174	58	11

B7. Nitrate concentrations 2M KCl extractions from profiles beneath various treatments at the WRc Medmenham trial site (26/1/94).

	Control			Willow (172 m^3ha^{-1} sludge)			Willow (no sludge)			Poplar (172 m^3ha^{-1} sludge)			Poplar (no sludge)		
Sample Depth (cm)	Moisture (g kg^{-1})	NO_3-N (mg l^{-1})	NH_4-N (mg kg^{-1})	Moisture (g kg^{-1})	NO_3-N (mg l^{-1})	NH_4-N (mg kg^{-1})	Moisture (g kg^{-1})	NO_3-N (mg l^{-1})	NH_4-N (mg kg^{-1})	Moisture (g kg^{-1})	NO_3-N (mg l^{-1})	NH_4-N (mg kg^{-1})	Moisture (g kg^{-1})	NO_3-N (mg l^{-1})	NH_4-N (mg kg^{-1})
0-15	303	6.5	0.3	329	12	0.4	274	9.5	0.3	312	8.8	0.5	247	7.1	0.4
15-30	293	11	0.4	309	15	0.3	259	9.7	0.3	292	14	0.7	235	7.4	0.5
30-45	205	9.4	0.4	252	13	0.3	219	11	0.3	216	12	0.3	214	5.7	0.3
45-60	206	6.8	0.2	276	18	0.3	237	9.9	0.3	163	12	0.5	213	6.0	0.3
60-75	217	4.5	0.2	312	39	0.2	240	11	0.4	-	-	-	224	3.3	0.2
75-90	235	5.0	0.2	292	55	0.2	249	9.5	0.5	-	-	-	216	1.7	0.2
90-105	249	4.5	0.2	317	62	0.2	297	9.6	1.4	-	-	-	184	1.0	0.2
105-120	182	0.9	0.2	-	-	-	289	16	0.7	-	-	-	238	1.6	0.2
120-135	-	-	-	-	-	-	-	-	-	-	-	-	218	0.8	0.1
135-150	-	-	-	-	-	-	-	-	-	-	-	-	189	3.1	0.2

B8. Soil solution nitrate concentrations from profiles beneath various treatments at the WRc Medmenham trial site.

	Control				Willow (172 $m^3 ha^{-1}$ sludge)				Willow (no sludge)			
Sample Depth (cm)	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Yield (%)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**
0-15	17	10	0.01	0.02	22	19	0.02	<0.02	14	13	0.05	0.02
15-30	18	20	0.08	0.08	17	27	0.06	<0.02	29	18	0.04	0.02
30-45	24	14	0.03	<0.02	15	21	0.03	0.13	22	18	0.02	0.04
45-60	26	7.5	0.03	<0.02	23	26	0.03	<0.02	10	18	0.05	<0.2
60-75	28	5.4	0.01	<0.02	23	47	0.08	0.08	10	17	0.05	<0.2
75-90	53	4.2	0.02	<0.02	35	64	0.09	0.07	10	27	0.08	1.5
90-105	55	3.9	0.01	<0.02	54	66	0.13	0.08	15	20	0.03	0.04
105-120	17	3.0	0.01	<0.02	-	-	-	-	18	23	0.02	<0.02

B9. Soil solution chemistry at WRc Medmenham (26/1/94).

Control Site

Depth	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
(cm)	mg l^{-1}							µg l^{-1}								
0-15	15	4.2	140	4.8	61	65	7.6	260	390	12	420	1400	200	30	190	240
15-30	23	4.2	110	4.3	44	56	8.5	210	400	24	960	390	18	54	640	660
30-45	14	2.4	110	3.8	40	47	6.1	200	320	15	540	27	<1	36	130	270
45-60	18	1.8	83	2.7	25	28	5.5	170	640	24	1000	48	6	54	110	1100
60-75	16	14	96	2.4	23	18	3.4	180	380	18	540	<20	<1	<20	90	360
75-90	14	<0.6	110	2.2	30	17	2.1	190	130	<3	300	<20	<1	<20	39	<120
90-105	18	<0.6	150	3.8	54	30	2.9	300	300	<3	270	<20	<1	<20	<20	<120
105-120	16	0.9	120	3.5	48	27	2.5	270	93	9	270	<20	<1	30	<20	<120

Soil solution chemistry at WRc Medmenham (26/1/94).

Willow with 172 m^3ha^{-1} sludge applied.

Depth	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
(cm)	mg l^{-1}							µg l^{-1}								
0-15	43	13	570	18	200	350	6.0	930	670	<3	420	<20	24	42	120	<120
15-30	25	7.2	300	11	92	180	4.6	540	560	<3	480	<20	12	40	100	<120
30-45	19	2.4	190	7.0	50	96	3.3	320	300	<3	420	<20	6	36	72	<120
45-60	17	1.2	130	5.0	35	53	2.8	220	340	<3	420	<20	3	27	63	<120
60-75	16	0.9	100	3.2	42	20	2.0	180	400	9	360	<20	3	<24	63	<120
75-90	15	0.9	110	3.4	50	23	2.0	200	210	12	210	<20	3	<24	42	<120
90-105	17	1.2	110	3.4	58	11	2.5	220	110	12	270	<20	<1	<24	27	<120
105-120	17	1.5	100	4.5	58	9.5	2.9	300	78	12	180	<20	<1	<24	30	<120
120-135	15	2.1	120	4.3	59	14	2.4	280	93	15	210	<20	<1	<24	24	<120

Soil solution chemistry at WRc Medmenham (26/1/94).

Willow with no sludge applied.

Depth	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
(cm)	mg l^{-1}							µg l^{-1}								
0-15	11	16	49	5.3	41	22	6.5	110	240	15	420	120	9	57	99	150
15-30	13	18	30	3.6	32	17	5.6	69	200	12	450	180	6	33	90	<120
30-45	16	18	21	2.7	25	14	6.4	49	130	24	720	480	12	<48	160	420
45-60	17	23	35	4.9	26	7.4	24	86	200	48	1300	2300	530	120	230	13000
60-75	n/s	n/s	n/s	n/s	n/s	6.4	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s
75-90	20	3.0	73	3.3	76	7.6	4.2	130	200	24	720	940	30	<48	84	840
90-105	19	3.0	75	2.9	68	16	2.8	130	110	<18	540	1700	210	54	72	360
105-120	23	7.8	58	2.7	54	13	4.1	110	140	<18	840	60	<1	60	78	<240
120-135	20	5.1	72	2.7	58	16	3.3	130	120	<3	600	<18	<1	36	27	<120
135-150	20	4.5	73	2.5	57	15	3.2	130	93	<3	600	<18	<1	33	24	<120

Soil solution chemistry at WRc Medmenham (26/1/94).

Poplar with 172 m^3ha^{-1} sludge applied.

Depth	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
(cm)	mg l^{-1}							µg l^{-1}								
0-15	13	12	190	11	47	120	7.6	410	290	12	300	27	12	<24	87	120
15-30	14	6.9	190	10	47	120	8.1	390	360	15	330	280	18	30	72	240
30-45	15	4.8	160	7.9	37	95	9.4	340	340	<18	360	2600	160	48	150	1500
45-60	20	3.6	110	4.7	24	67	7.7	240	290	<18	720	1700	84	<96	170	1200
60-75	n/s	n/s	n/s	n/s	n/s	48	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s	n/s
75-90	17	1.2	57	1.5	26	25	4.9	120	200	<18	660	2100	130	<48	84	1300
90-105	14	1.2	66	1.4	47	20	2.8	140	87	<9	420	500	27	<24	33	300
105-120	14	2.4	100	2.1	57	18	2.5	210	160	<9	300	39	9	27	42	<120

Soil solution chemistry at WRc Medmenham (26/1/94).

Poplar with no sludge applied.

Depth	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
(cm)	mg l^{-1}							µg l^{-1}								
0-15	9.6	25	56	5.2	34	26	5.3	100	250	<3	330	54	<1	36	39	<120
15-30	15	42	78	8.8	38	45	5.5	140	520	9	540	<18	<3	51	45	<120
30-45	16	50	64	6.9	34	43	3.5	130	450	<3	540	<18	<1	60	33	<120
45-60	19	50	48	4.3	29	33	2.9	110	390	<3	660	<18	<1	39	45	<120
60-75	16	42	49	3.3	33	24	2.5	110	290	<3	570	<18	<1	27	39	<120
75-90	15	31	58	3.2	40	17	2.5	110	230	<3	570	<18	<1	33	36	<120
90-105	12	32	82	4.4	65	7.8	2.1	150	230	12	300	<18	3	30	39	<120
105-120	15	24	74	3.5	71	6.6	1.9	150	200	9	540	<18	<1	30	33	<120
120-135	12	26	77	4.5	66	6.9	1.9	150	220	9	390	<18	<1	<24	39	<120
135-150	14	22	94	6.1	72	9.5	2.1	170	160	9	270	<18	<1	<24	51	120
150-165	14	17	89	5.4	73	11	2.6	160	110	12	270	<18	<1	<24	42	<120

B10. Soil nitrate for various treatments at Long Ashton extracted by 2M KCl and expressed as an equivalent soil solution concentration (5/5/94).

	Control			Fertiliser			Fertiliser			No Fertiiser			No Fertiliser		
Sample Depth (cm)	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**
0-15	538	6.9	1.8	616	12	1.4	482	5.1	0.9	524	5.2	1.1	549	9.6	1.7
15-30	441	2.5	0.8	466	9.1	0.6	348	1.0	0.7	376	1.1	0.6	407	4.3	1.4
30-45	372	<0.2	0.6	395	4.2	0.4	372	<0.2	0.4	385	<0.2	0.5	386	<0.2	0.4
45-60	388	<0.2	0.6	445	3.9	0.5	396	1.9	0.4	439	<0.2	0.4	400	<0.2	1.1
60-75	446	<0.2	0.4	474	1.9	0.5	468	<0.2	0.4	465	<0.2	0.2	488	<0.2	0.5
75-90	451	<0.2	0.4	450	5.2	0.5	466	<0.2	0.3	424	<0.2	0.4	493	<0.2	0.3
90-105	431	<0.2	0.4	463	2.7	0.3	450	<0.2	0.4	432	<0.2	0.3	469	<0.2	0.4
105-120	374	<0.2	0.2	514	1.2	0.3	441	2.8	0.3	422	<0.2	0.5	470	2.0	0.4
120-135	470	<0.2	0.3	424	<0.2	0.2	426	0.5	0.2	410	<0.2	0.2	462	3.5	0.5
135-150	476	<0.2	0.3	448	<0.2	0.2	422	<0.2	0.3	434	<0.2	0.3	480	<0.2	0.3
150-165	474	<0.2	0.3	433	<0.2	1.4	388	<0.2	0.4	400	<0.2	0.3	421	<0.2	0.8
165-180	406	<0.2	0.3	404	<0.2	4.2	350	<0.2	1.1	382	<0.2	0.4	404	<0.2	1.2

B11. Nitrogen species extracted by 2M KCl for the 1/3/94 sampling at Markington.

	No Sludge Applied				100 m^3ha^{-1} sludge applied				100 m^3ha^{-1} sludge applied			
Sample Depth (cm)	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**	**Moisture ($g\ kg^{-1}$)**	**NO_3-N ($mg\ l^{-1}$)**	**NO_2-N ($mg\ l^{-1}$)**	**NH_4-N ($mg\ kg^{-1}$)**
0-15	245	7.1	<0.1	0.3	236	13	<0.1	0.6	235	7.4	<0.1	1.0
15-30	182	8.4	<0.2	0.3	191	14	<0.2	0.7	198	8.2	<0.2	0.6
30-45	184	7.7	<0.2	0.5	190	12	<0.2	0.5	179	7.3	<0.2	0.6
45-60	188	8.5	<0.2	0.3	201	11	<0.2	0.5	193	5.9	<0.2	0.7
60-75	194	7.1	<0.2	0.3	267	19	<0.1	0.5	225	8.7	<0.1	0.4
75-90	214	7.4	<0.1	0.2	283	25	0.1	0.3	231	11	<0.1	0.2
90-105	179	8.2	<0.2	0.1	239	26	<0.1	0.1	202	13	<0.2	0.2

B12. Nitrogen species extracted by 2M KCl for plots from Markington (22/1/95).

Sample Depth (cm)	No sludge applied			50 m^3ha^{-1} sludge applied			100 m^3ha^{-1} sludge applied			150 m^3ha^{-1} sludge applied		
	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)	Moisture ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N ($mg\ kg^{-1}$)
1st Block												
0-15	239	2.9	1.2	249	6.3	0.2	236	8.1	0.1	242	7.7	0.2
15-30	238	2.6	1.5	223	12	0.3	197	6.4	<0.1	198	15	0.3
30-45	174	<0.3	0.9	180	9.2	0.6	175	4.4	<0.1	161	16	0.2
45-60	195	<0.3	0.6	196	7.0	0.3	198	3.6	0.1	172	11	0.3
60-75	205	3.2	0.4	191	5.3	0.2	204	2.4	0.1	212	6.0	0.3
75-90	190	<0.3	0.2	198	5.7	0.1	220	1.7	<0.1	248	4.8	0.3
2nd Block												
0-15	199	0.6	0.3	237	2.4	0.8	257	4.9	0.1	248	1.3	0.3
15-30	173	3.7	0.2	227	4.1	0.1	192	7.8	0.3	214	3.1	0.2
30-45	164	<0.3	0.2	186	0.6	0.1	188	3.2	<0.1	169	1.7	<0.1
45-60	188	8.8	0.3	190	<0.3	0.1	186	1.9	0.4	176	1.0	0.2
60-75	200	<0.3	0.2	188	<0.3	0.3	-	-	-	154	0.8	0.4
75-90	194	<0.3	0.3	202	<0.3	0.3	-	-	-	158	<0.4	0.3

B13. Soil nitrate concentrations for poplar and willow at Downham Market extracted by 2M KCl (15/6/95).

	Control 1			Control 2			Poplar 1			Poplar 2			Willow 1			Willow 2		
Sample Depth (cm)	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$	Moist. ($g\ kg^{-1}$)	NO_3-N ($mg\ l^{-1}$)	NH_4-N $mg\ kg^{-1}$
0-15	121	6.0	0.2	138	4.5	<0.1	132	3.9	0.9	120	3.3	<0.1	91	13	0.2	97	5.6	<0.1
15-30	118	7.1	0.2	139	6.6	<0.1	121	7.0	<0.1	101	7.1	0.1	93	15	0.2	96	5.7	<0.1
30-45	134	3.0	<0.1	143	2.8	<0.1	132	2.6	<0.1	116	5.8	<0.1	100	9.3	0.2	102	5.4	<0.1
45-60	137	2.5	0.1	179	1.7	0.1	127	0.9	<0.1	88	9.3	<0.1	100	2.8	<0.1	129	1.8	<0.1
60-75	175	2.4	<0.1	189	1.3	<0.1	174	3.0	<0.1	125	0.9	<0.1	120	1.9	<0.1	117	<0.5	<0.1
75-90	191	9.0	<0.1	191	4.1	<0.1	189	6.0	<0.1	168	0.4	<0.1	135	2.9	<0.1	144	<0.4	<0.1
90-105	201	11	<0.1	206	9.4	0.1	187	13	<0.1	184	<0.3	<0.1	158	4.4	<0.1	197	<0.3	<0.1
105-120	189	21	0.1	178	20	0.2	170	18	<0.1	223	6.6	<0.1	179	13	<0.1	183	11	<0.1
120-135	201	21	<0.1	140	20	<0.1	184	20	<0.1	222	12	<0.1	197	20	<0.1	188	15	<0.1
135-150	194	22	0.1	137	16	<0.1	205	19	0.1	210	20	<0.1	177	17	<0.1	189	15	<0.1
150-165	202	19	0.2	140	16	<0.1	211	18	<0.1	200	23	<0.1	176	16	<0.1	196	14	<0.1
165-180	215	15	<0.1	160	13	<0.1	207	16	<0.1	236	23	<0.1	202	15	0.1	196	12	<0.1
180-195	208	19	<0.1	169	10	<0.1	198	15	<0.1	278	17	<0.1	204	13	<0.1	205	11	<0.1

B14. **Porewater chemistry at Downham Market for top the 15 cm of soil including the region of poor growth (15/6/95).**

Site	Na	K	Ca	Mg	SO_4	NO_3-N	Si	Sr	Ba	Li	B	Fe	Mn	Cu	Zn	Al
	mg l^{-1}							µg l^{-1}								
Control 1	18	1.8	38	1.6	26	2.0	5.0	90	180	<3	680	45	1	<8	16	<40
Control 2	11	2.3	46	1.6	39	<0.4	5.1	94	210	<3	570	49	3	9	21	<40
Poor Growth	18	2.4	51	1.2	39	<0.4	6.0	110	210	<3	880	32	9	17	27	50
Poor Growth	19	2.1	50	1.5	39	0.4	7.1	110	190	<3	100	27	9	16	24	<40
Poplar 1	14	2.5	33	1.1	32	2.7	4.6	71	150	<3	630	75	8	16	26	50
Poplar 2	19	2.1	37	1.2	34	<0.4	5.4	64	170	<3	1000	46	11	20	37	40
Willow 1	43	4.0	67	2.5	43	n/s	6.9	140	190	<15	1900	55	5	<40	45	<200
Willow 2	26	2.5	51	2.5	37	1.8	5.3	110	180	<15	1100	70	<5	<40	45	<200

B15. Soil solution chemistry at the North Norfolk site (29/11/95).

Sample Depth (cm)	Control			Unsludged			Unsludged			Sludged			Sludged		
	Yield (%)	NO_3-N (mg l^{-1})	Cl (mg l^{-1})	Yield (%)	NO_3-N (mg l^{-1})	Cl (mg l^{-1})	Yield (%)	NO_3-N (mg l^{-1})	Cl (mg l^{-1})	Yield (%)	NO_3-N (mg l^{-1})	Cl (mg l^{-1})	Yield (%)	NO_3-N (mg l^{-1})	Cl (mg l^{-1})
0-15	40	6.3	19	32	8.7	34	31	6.4	13	32	9.5	16	43	8.8	16
15-30	37	24	21	24	7.4	63	25	11	12	28	11	13	30	15	13
30-45	37	91	40	28	15	180	24	21	24	34	15	25	28	68	55
45-60	39	100	42	24	25	190	28	34	36	27	20	40	26	42	39
60-75	39	92	39	27	26	41	30	28	31	34	19	33	36	60	53
75-90	40	76	33	19	15	42	28	23	32	32	16	27	18	49	31
90-105	36	58	22	8.2	8.7	57	5.4	17	40	n/s	n/s	n/s	6.0	29	48
105-120	62	46	20	11	5.9	45	4.7	4.6	35	9.8	12	84	3.2	27	51
120-135	33	50	22	23	9.3	48	n/s	n/s	n/s	n/s	n/s	n/s	6.1	28	45
135-150	34	48	21	21	22	45	7.4	6.4	15	11	18	57	7.6	35	42

B16. Nitrogen species extracted by 2M KCl at the North Norfolk site (29/11/95).

	Control			Unsludged			Unsludged			Sludged			Sludged		
Sample Depth (cm)	**Moist. (g kg^{-1})**	**NO_3-N (mg l^{-1})**	**NH_4-N mg kg^{-1}**	**Moist. (g kg^{-1})**	**NO_3-N (mg l^{-1})**	**NH_4-N mg kg^{-1}**	**Moist. (g kg^{-1})**	**NO_3-N (mg l^{-1})**	**NH_4-N mg kg^{-1}**	**Moist. (g kg^{-1})**	**NO_3-N (mg l^{-1})**	**NH_4-N mg kg^{-1}**	**Moist. (g kg^{-1})**	**NO_3-N (mg l^{-1})**	**NH_4-N mg kg^{-1}**
0-15	124	10	0.57	138	8.6	0.23	155	7.8	0.24	118	8.5	0.34	121	11	0.11
15-30	119	22	0.29	134	9.8	0.17	144	9.5	0.18	120	11.2	0.34	112	8.0	0.23
30-45	88	84	0.22	113	27	0.11	118	17	0.11	97	6.8	0.22	99	28	0.22
45-60	85	71	0.17	122	23	0.11	101	22	0.11	81	12	0.16	99	42	0.11
60-75	76	71	0.27	133	21	0.17	92	18	0.17	80	17	0.22	87	53	0.11
75-90	69	62	0.27	133	15	0.17	96	18	0.11	68	14	0.16	66	45	0.27
90-105	66	42	0.11	313	2.9	0.14	104	9.1	0.11	72	12	0.11	89	15	0.17
105-120	71	51	0.11	235	2.6	0.06	274	4.2	0.13	55	12	0.11	87	24	0.22
120-135	104	44	0.06	125	11.3	0.11	63	14	0.11	53	12	0.05	89	15	0.22
135-150	88	40	<0.06	140	16.7	0.06	75	12	0.05	47	19	0.11	72	22	0.11