

Managing the drought

A review of the evidence of the benefits of native trees species for shelter on the water regime of pasture and arable crops

Harper Adams University College

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Aerial view of arable farmland in Hampshire complete with hedges and trees © Peter Dean / Agriculture Images

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Slage machinery in Dorset © Peter Dean/Agriculture Images

Contents

Executive summary	6
I UK agriculture and Climate change	9
1.1 Introduction	9
1.2 Current UK water shortages	9
1.3 Climate change predictions and UK agriculture	10
1.4 Food Security	10
2 Aim of review and methodology	10
3 Crop water use	11
3.1 Introduction	11
3.2 Evapotranspiration	11
3.3 Factors affecting evapotranspiration	11
4 Shelterbelts	17
4.1 Introduction	17
4.2 Shelterbelt types	17
4.3 Shelterbelt design	17
4.4 Farm shelter audit	20
5 Microclimate and tree crop interactions	21
5.1 Introduction	21
5.2 Microclimate and soil moisture	21
5.3 Plant structure	22
5.4 Tree crop environment	22
5.5 Computer modelling	24
5.6 Previous review findings	25
6 UK Evidence	26
6.1 Introduction	26
6.2 Lack of UK evidence	26
6.3 Shelterbelt studies	28
6.4 Agroforestry studies	29
6.5 Computer modelling	31
7 European Evidence	33
7.1 Introduction	33
7.2 Shelterbelt studies	33
7.3 Agroforestry studies	35
8 Temperate zone Evidence	37
8.1 Introduction	37
8.2 North America	37
8.3 New Zealand and Australia	39
9 Discussion	41
9.1 Benefits of shelter	41
9.2 Shelterbelts in the UK	42
9.3 Benefits of shelter on the water regime of crops	42
10 References	44
11 Appendix	50

Executive summary

1. Climate change scenarios suggest that the UK will experience extremes of weather with drier hotter summers and wetter winters. Water is already over abstracted in large areas of southern England. Climate change scenarios predict this will get worse. Water shortages in the UK and overseas may increase the level and volatility of food prices. To maintain current levels of agricultural production and ensure food security water needs to be used more efficiently.
2. The review assesses the benefits of native tree species for shelter on the water regime of pasture and crops. It draws on evidence from the UK, Europe and other temperate zones. Before the evidence is presented overviews are given of evapotranspiration, shelterbelt design and crop microclimate.
3. Evapotranspiration is the process by which water is lost from the agricultural environment. It is a combination of both evaporation from the soil surface and crop transpiration. Crop transpiration is the process by which water is lost as vapour from plant tissues through small openings on the plant leaf. The rate of evapotranspiration is controlled by solar radiation, temperature, wind speed and humidity. The energy to vaporise water from the plant and soil surface is provided by solar radiation and to a lesser extent temperature. As evapotranspiration occurs humidity levels increase around the soil or leaf surface. As the air becomes saturated the process slows down unless water vapour is removed. The replacement rate is dependent on wind speed and turbulence. Faster wind speeds will transfer larger amounts of dry air over the soil or leaf surface and therefore remove saturated air more quickly from evaporative zones, thus increasing evapotranspiration rates. Water for transpiration is supplied from soil water. When levels of available soil water drop below a certain value the crop is water-stressed and the lack of water results in a reduction in transpiration and ultimately crop yield. Vegetation and cultivation practices can also impact evapotranspiration rates.
4. Trees planted on farms can be used for fuel, shelter, sport, landscape enhancement and to encourage biodiversity. Trees can shelter buildings, crops and animals from wind, sun, rain and snow. Shelterbelts alter the speed and direction of wind. Porosity and height are the main factors that determine the level of protection given by a shelterbelt. A dense shelterbelt provides a small area of intense shelter. A shelterbelt of less than 40 per cent porosity will reduce wind speeds by as much as 90 per cent and protect an area up to 10 times the height of the shelter. Shelterbelt height determines the extent of cover: the taller the shelter, the larger the area of cover. Tall shelterbelts with an optimum porosity of between 40–60 per cent protect an area up to 30 times the height of the shelterbelt creating shelter suitable for crops. The shelterbelt should be as tall as local conditions allow. Agri-Food Canada recommend shelterbelt trees that at maturity reach 15m in height. A detailed farm audit can identify the areas in most need of shelter. Shelterbelts composed of native deciduous trees are a good choice as they are well adapted to local conditions and have a leafless period which allows pasture to recover in winter from the adverse effects of shading.
5. The effect of shelter on crop production is a result of multiple interacting factors. Shelterbelts modify the crop microclimate by reducing wind speeds and increasing daytime temperatures. Lower wind speeds increase the level of humidity around the transpiring plant surface slowing evapotranspiration. Increased daytime temperature provides more energy to drive evapotranspiration. Reductions in wind speed can increase vegetative growth. A well watered crop protected by shelter may use the same amount of water as a non-sheltered crop, but would have increased photosynthesis rates and therefore increased water use efficiency. Shelter can reduce mechanical damage of crops. The introduction of trees into the crop environment can modify soil structure, therefore impacting crop water regimes. However, trees can shade crops and compete for water and nutrients, reducing crop yields adjacent to shelter. These yield reductions are dependent on shelterbelt species, crop type and local conditions. Yield reductions typically occur up to a distance of 1-2H from the shelterbelt, where H represents the height of the shelterbelt.

6. A UK study using artificial shelters showed yield increases of wheat and barley in the years when the weather was hot and dry. Another UK study showed that artificial shelter reduced mechanical damage of plants, potentially reducing water loss from damaged tissue. Yields of wheat next to boundary hedges (within 9m of the shelter) can be halved due to tree shading as found by a UK study. Soil infiltration rates can be increased up to 5m from deciduous shelterbelts as demonstrated at Pontbren, Wales. Agroforestry experiments conducted in the UK have demonstrated that crops and native deciduous trees can be grown together while still maintaining good economic returns. Careful selection of trees, such as choosing deciduous trees over conifers, can reduce the negative effects of shelter.
7. Farmers in drier parts of Europe are more likely to plant trees for water conservation. A study in Italy showed that a shelterbelt of 40 per cent porosity could increase rain-fed durum wheat yields and reduce evapotranspiration rates by 16 per cent at a distance of 4.7H (H represents height of shelter) from the shelterbelt. Reductions in evapotranspiration rates due to shelter were measured up to a distance of 12.7H from the shelterbelt. Yield increases were measured up to 18H from the shelterbelt. Likewise, a study in the Austrian basin showed that evapotranspiration rates of alfalfa were lower at a distance of 20m from an 8m hedge, compared to 80m from the hedge. A study in Denmark observed no yield increase with a shelterbelt of a hazel coppice, but the barley crop was not water stressed. Vegetative growth was enhanced in the study, but this did not transform into greater grain yields. In Poland large networks of shelterbelts act as water pumps cooling the air of large areas of the landscape. Trees, due to high rates of evapotranspiration, humidify the air reducing crop evapotranspiration rates in adjoining fields.
8. Trees are used as shelter in Canada, USA, Australia, New Zealand, China, Argentina and many developing countries. The Agri-Food Canada website states that shelterbelts can increase wheat yields by 3.5 per cent and that figure is greater in drier years. Two Canadian studies showed that shelterbelts increase overall crop yields, despite an area of reduced yield directly next to the shelter. One study reported that sheltered crop evapotranspiration rates were 75 per cent of non-sheltered crops at a distance of 1H (H represents height of shelter) from a shelterbelt. Pruning of tree roots can reduce yield losses next to shelter. Due to inconsistencies in wind direction yield increases were not observed in an Australian shelterbelt study.
9. Shelter for livestock on Scottish farms is being promoted by the Forestry Commission and Quality Meat Scotland. Shelterbelts with a porosity of 40-60 per cent can have a beneficial effect on crop yields providing an area of shelter with reduced wind speeds of up to a distance of 30H (H represents height of shelter) from the shelterbelt. Crops and trees will compete for water and light; this effect frequently disappears within a distance of about 1 to 2H from the shelterbelt. The distance of 1.5 to 9H from the shelterbelt is the area which has the greatest increase in crop yields. These distances can vary with year, crop, soil type, shelterbelt design, stage of crop development and geography. The benefits of shelterbelts become more pronounced when the plants are water stressed and wind direction is consistent. The evidence in this review suggests that under the right conditions native tree shelterbelts could enable UK crops to use water more efficiently. Shelterbelts can be viewed as an insurance policy. They may not provide yield increases every year, but they can buffer crop production when extreme weather events strike.



Bumblebee on a goat willow catkin: WTPL/John Duncan

I UK agriculture and climate change

I.1 Introduction

Climate change scenarios suggest that the UK will experience more extremes of weather with drier hotter summers and wetter winters. Since agricultural land covers 75 per cent of the UK this is an area of concern, as it faces the agricultural sector with the challenge of operating within an increasingly unpredictable natural environment (Knox *et al.*, 2010). Trees have the capacity to stabilise and buffer agricultural production from these climatic extremes (Herzog, 2000). They have been used throughout history to provide shelter to crops, animals, soils and buildings and to reduce the risk of floods (Nisbet *et al.*, 2011). These benefits have been recognised by governments since the mid-1400s, when the Scottish parliament encouraged the planting of wind breaks to protect agricultural land (Brandle *et al.*, 2004). Currently shelter belts, hedges and small areas of forests are scattered throughout the landscape, providing shelter to arable and pasture farming. Trees are now needed even more to help UK agriculture adapt to climate change (FAO, 1989).

This introductory section will examine the current and predicted water shortages facing UK agriculture and the implications for food security. The UK needs to consider all strategies that can increase efficiencies in water use including the beneficial role of shelter provided by trees.

I.2 Current UK water shortages

In the last 50 years the amount of water abstracted from UK sources has increased (Charlton *et al.*, 2010; Weatherhead and Howden, 2009). Large parts of southern England are currently over-abstracted (Charlton *et al.*, 2010). These areas are permanently under water stress with reduced levels of soil water available for crop growth. The UK has already experienced severe drought conditions such as those of 1976 and 2003 brought on by hot, dry summers. The cool, dry winters in combination with hot, dry summers in the mid 1980s and late 90s resulted in water supplies being put under severe stress (Charlton *et al.*, 2010).

Currently, agriculture accounts for 1-2 per cent of UK water use, 40 per cent of which is used for crop irrigation. However, this figure is misleading as there are large regional differences in water use within the UK. For example, during the summer months, the agricultural sector accounts for 16 per cent of water use in eastern England (Thompson *et al.*, 2007). The Anglian region is the largest abstractor of water for crop irrigation. In this area potatoes and vegetables for human consumption are the largest recipients of irrigation water (DEFRA, 2011). Currently, 55 per cent of their production takes place in areas considered as over-abstracted (Knox *et al.*, 2010).

Water shortages create challenges for farmers trying to ensure optimum quality and yields and may be a condition of winning contracts with certain supermarkets (Weatherhead and Howden, 2009; DEFRA, 2011). Crop quality is dependent on the timing and volume of water applications. In the drought of 1995 the yield and quality of potatoes, sugar beet and field vegetable crops were reduced due to irrigation restrictions. Farmers bought extra animal feed to supplement drought-induced reductions in pasture yield (Charlton *et al.*, 2010).

1.3 Climate change predictions and UK agriculture

Farming will face a challenging future. Water shortages are predicted to get more acute, exacerbated by legislative restrictions (e.g. the 2003 Water Act in the UK) (Morrison *et al.*, 2008). UKCP09 climate change scenarios predict that temperatures will increase in the UK, particularly in summer. In summer southern England is predicted to have an average increase in temperature of 4°C, whilst the Scottish islands will warm by an average of 2.5°C. The far south of England is expected to experience summer droughts, as there will be a 40 per cent reduction in rainfall and a decrease in humidity of about 9 per cent. In winter the western side of the UK is predicted to get 33 per cent more rain (Murphy *et al.*, 2009). No projections were made for snow fall. There is projected to be very little change in wind speed (DEFRA, 2010a).

The effects of climate change could be more marked than the averages suggest. Different land use, topography and soils will generate variability in water quality and quantity (Weatherhead and Howden, 2009). Irrigation is likely to become more important, with existing irrigated crops requiring more water. Rain-fed crops such as wheat are likely to be under increasing levels of water stress with less available soil water. To maintain current livestock stocking levels, grass may have to be irrigated. Crop production could move north, where water will be more available. The price of water for agricultural production is predicted to increase under climate change predictions. Farmers will be under increasing pressure to maintain current production levels (Charlton *et al.*, 2010; Knox *et al.*, 2010).

1.4 Food Security

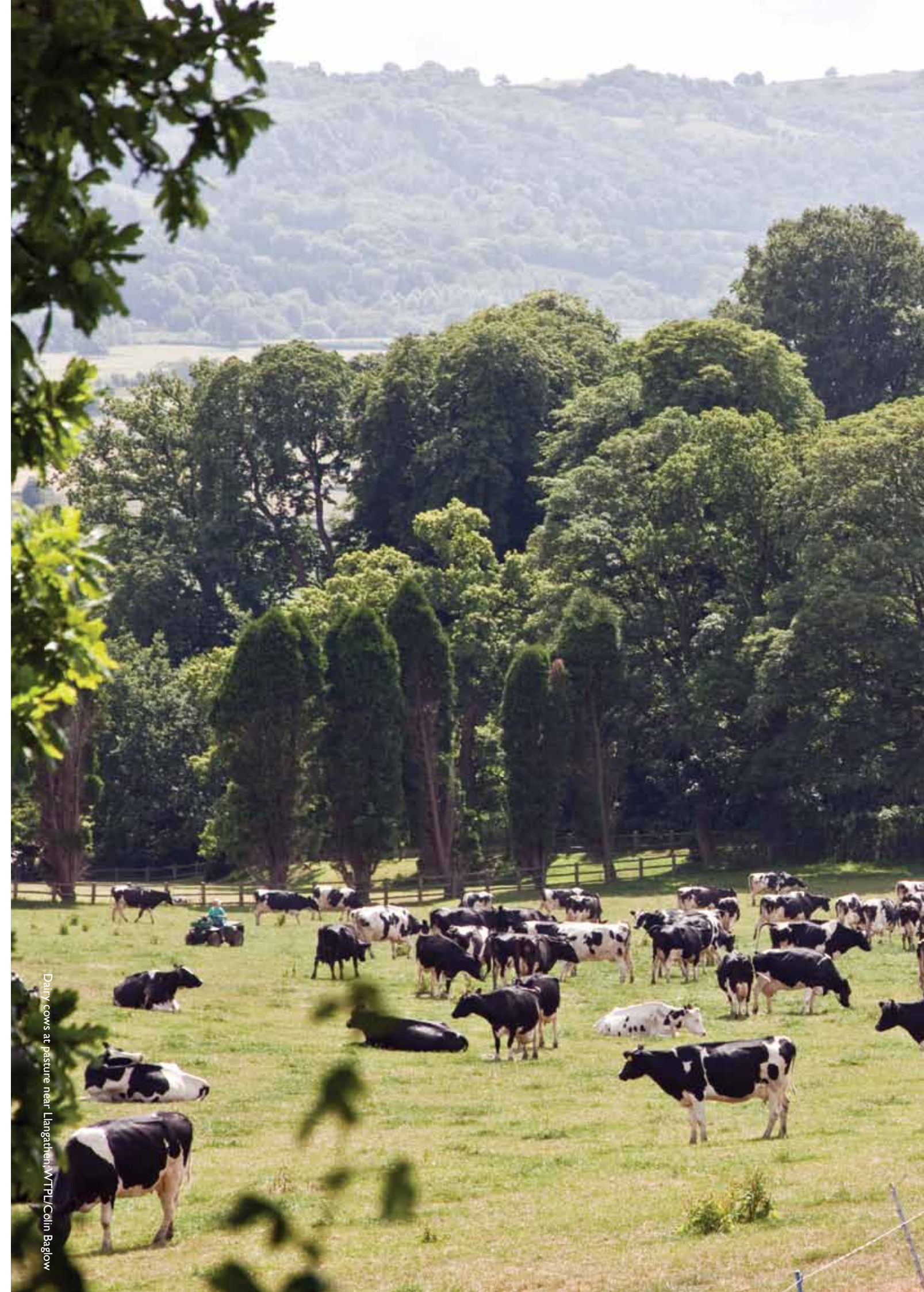
There will be less available water under climate change scenarios. This has the potential to increase the level and volatility of food prices. This is significant, as the UK is an importer of 'virtual water', relying heavily on imports of agricultural products. Extreme weather events may create disruptions in food production and distribution. Agricultural production needs to be maintained at current levels to ensure UK food security. To ensure this water needs to be used more efficiently by crops (Thompson *et al.*, 2007; DEFRA, 2010b). Irrigation may not be a viable answer to climate change if constraints are placed on UK agricultural water usage (Weatherhead and Howden, 2009).

2 Aim of review and methodology

UK agriculture derives many benefits from native trees. They may help UK agriculture adapt to current and future water shortages. This review will present evidence to suggest that shelterbelts composed of native trees species can have a beneficial effect on the water regime of pasture and arable crops.

The report is divided into two main sections. The first section is theoretical. It describes evapotranspiration, the process by which water is lost from the crop environment, then gives a description of shelterbelt design and finishes, and then describes the mechanism by which shelterbelts modify the crop microclimate to increase crop water use efficiency. The second section introduces evidence to suggest that native trees may help UK agriculture adapt to current and future water shortages. It draws on evidence from agricultural systems of the UK, Europe and other temperate zones. Despite the lack of UK research in this field, evidence from comparable countries can provide valuable insight into the potential of trees to combat the adverse effects of climate change.

The literature search for the review was conducted by predefining keywords and using them to search the online database Google Scholar. Other online databases were searched using a subset of keywords. Keywords and all search sources for the literature review can be found in Appendix I. Peer reviewed, grey literature and government reports were all considered relevant.



Dairy cows at pasture near Langgathen, WTP/Colin Baglow

3 Crop water use

3.1 Introduction

UK agriculture is facing water shortages. By targeting the mechanism by which water is lost from crops, water savings can be made. This section of the report covers the fundamentals of crop water loss through the process of evapotranspiration. The rate of evapotranspiration is driven by climatic conditions, vegetation and soil type. By favourably modifying these climatic conditions, crop water savings can be made.

3.2 Evapotranspiration

Evapotranspiration is the process by which water is lost from the agricultural environment. It is a combination of both evaporation from the soil surface (evaporation) and crop transpiration.

Crop transpiration is the process by which water is lost as vapour from plant tissues through small openings on the plant leaf called stomata. Stomata control the rate of evapotranspiration by modifying their aperture size (Allen *et al.*, 1998). Water for transpiration is supplied from soil water. Water is taken up through the roots, transported through the plant and lost at the leaf surface by transpiration. These losses are considerable, with over 90 per cent of water taken up by plants lost through transpiration (Morrison *et al.*, 2008). The two processes involved in evapotranspiration occur at the same time.

Before a crop creates a full canopy much of the water loss comes from evaporation from the soil. As the plant canopy increases then the loss from transpiration becomes dominant (Allen *et al.*, 1998).

3.3 Factors affecting evapotranspiration

The weather parameters that affect the rate of evapotranspiration are solar radiation, temperature, wind speed and humidity. Soil type, organic matter content, soil water content and soil structure plus cultivation type and depth all contribute to the amount of water available for plant root uptake and thus affect the rate of evapotranspiration. Evapotranspiration rates also vary with vegetation type, density, developmental stage, leaf surface roughness and reflective capacity, rooting depth, density and root architecture.

3.3.1 Climatic conditions

The climatic factors involved with evapotranspiration are those which provide energy for the vaporisation of water and those that remove water vapour.

Vapour generation (Solar radiation and air temperature)

The energy to vaporise the water from the plant and soil surface is provided by solar radiation. The amount of energy available in radiation depends on latitude, season and weather. Solar radiation levels at the plant and soil surface will be lower on cloudy days. As the crop grows it shades the soil resulting in less radiation reaching the ground. Therefore, as the plant grows soil evaporation decreases and crop transpiration increases. The air temperature surrounding the crop drives evapotranspiration to a lesser extent. As weather becomes warmer and less overcast evapotranspiration and crop water requirements increase (Allen *et al.*, 1998).



Vapour removal (Vapour pressure humidity and wind speed)

As evapotranspiration proceeds humidity levels (vapour pressure) increase around the soil or leaf surface. As the air becomes saturated the process slows down unless the water vapour is removed. The replacement rate is dependent on wind speed and turbulence. Faster wind speeds will transfer larger amounts of dry air over the soil or leaf surface and therefore increase evapotranspiration rates. In hot dry conditions variations in wind speed can result in large variations in evapotranspiration rate, as compared to cooler weather conditions (Allen *et al.*, 1998). Any mechanism that reduces wind speed will also reduce evapotranspiration rates. Shelterbelts of trees can reduce wind speeds and offer the potential to reduce the evapotranspiration rates.

3.3.2 Soil water content

Rainfall, irrigation and capillary rise of groundwater all add water to the soil root zone. Soil evaporation, crop transpiration, run-off and drainage remove water from the root zone.

How water is added to the soil

As water is applied to soil in the form of snow, rain or irrigation, it is absorbed by the ground if the soil water is lower than field capacity. This process is called infiltration. The rate of infiltration depends on soil texture; it is faster for sandier, coarse-textured soils and slower for fine-textured clay soils. Water infiltrates faster when the soil is dry and not compact. When water is first applied to dry soils it infiltrates easily, but as the soil becomes wet, the infiltration rate decreases as the soil pores fill with water. Once the soil pores are filled with water and there is no air left in the soil it becomes saturated. Some of this water moves downwards under gravity and as these pores become saturated the water moves beyond the root zone to deeper soil layers. These layers may be permanently saturated and form the water table. When all drainage ceases the soil is said to be at field capacity, an optimum state for plant growth. As the soil begins to dry the ground water can move upwards through small pores (capillars) this process is called capillary rise. This rise can be extensive, up to 2m in clay, but is relatively small, 50cm, in sands. For crop production, capillary rise is not considered as a useful water source except for particular situations. Infiltration and soil water holding capacity can be increased by cultural practices that favourably modify the soil structure or increase the organic matter content of the soil. Trees through root exploration modify soil structure and therefore offer the potential to increase soil infiltration rates (Allen *et al.*, 1998; Brouwer *et al.*, 1985)

How water is removed from soil

Water stored in the soil is used by plant roots. Near to the surface it is also evaporated from the topsoil. Too much soil water can result in waterlogging which damages roots and inhibits plant respiration. As soil dries water becomes more strongly bound to the soil matrix and becomes less easily available to the crop. Evaporation rates then decline as there is not enough water to supply the evaporative process. When contents of available water fall below a crop-specific critical value the crop becomes water-stressed and the lack of water results in a reduction in transpiration and thus productivity. The total water content in the soil is the difference between permanent wilting point (point where the plant wilting is irrecoverable) and the 'field capacity' of that soil. The term 'soil moisture deficit', SMD, is used to quantify the amount of water needed to raise the soil water content back to field capacity. Therefore the soil moisture deficit can exert a controlling effect on the rate of evapotranspiration (Allen *et al.*, 1998).

3.3.3 Vegetation type

During rainfall water is lost through evaporation from the branches and leaves of trees due to their height and rough aerodynamic profile, a process called interception. Interception rates vary amongst deciduous trees. Ash and birch lose about 11 per cent of water through interception as compared to about 15 per cent

for the heavier canopies of oak or beech. Trees growing on chalk based soils may be able to maintain water uptake during periods of drought, by capillary rise of otherwise unavailable water (Nisbet, 2005).

Evapotranspiration rates of arable crops are higher than those of most trees, however yearly average rates are lower due to the short cycle of crops (Nisbet, 2005). The annual evaporation losses for arable crops are 370–430mm, as compared to 400–640 mm a year for deciduous trees. These figures are based on the land surface receiving 1000 mm annual rainfall (Nisbet, 2005). Crop type, variety and development stage area all factors which will affect evapotranspiration rates. Differences are a result of variations in crop height, root depth and leaf anatomy. Variations in rates of evapotranspiration of a crop at the same developmental stage within a field are low (Allen *et al.*, 1998; Blyth *et al.*, 2006).

3.3.4 Measuring evapotranspiration

Evapotranspiration can be measured in the field with lysimeters, or calculated using the Penman-Monteith equation using weather data. A lysimeter is an isolated tank filled with moist soil in which a crop is grown. The rate of evapotranspiration is measured by the change in mass of the lysimeter. The vegetation inside and outside the lysimeter should be identical (height and leaf area). The Penman-Monteith equation is based on a wide range of climatic and location data and can then be modified with crop-specific details. Daily mean temperature, wind speed, relative humidity and solar radiation are all parameters used in the calculation. Therefore, if wind speed alone is reduced the Penman-Monteith will calculate a lower rate of evapotranspiration (Allen *et al.*, 1998; Cleugh, 1998). However, the reduction of wind speed may also affect the temperature and relative humidity around the crop canopy and thus the effect of wind speed cannot be considered in isolation.

3.4 Mechanisms to reduce crop water loss

As discussed in the introductory section, large areas of southern England are expected to become hotter and drier. Knox *et al.* (2010) used UK climate change data generated for 2050 (UK Climate Impacts Programme) to model rainfall, evapotranspiration and soil moisture deficit under climate change scenarios. Knox *et al.* (2010) calculated that by 2050 there would be a 20-30 per cent increase in aridity in summer (April to September) assuming current summer evapotranspiration rates of 3mm/day. This has serious implications for UK agriculture as it will need to improve its crop water use efficiency to maintain current production levels. Improvements in crop drought resistance and agricultural practice will increase crop water use efficiencies.

3.4.1 The crop

Conventional breeding programmes can be used to select water-efficient crops that are drought resistant. Cultivars that give higher yields under conditions of water stress should be selected. Antitranspirants sprayed onto wheat leaves to cover stomata at the drought sensitive stage may produce water savings (Kettlewell, 2010). Trials could be established in southern England to investigate the viability of growing Mediterranean crops more suited to hotter climates, such as olives and apricots (Thompson *et al.*, 2007; Charlton *et al.*, 2010).

3.4.2 Agricultural management

Improvements in irrigation use and scheduling will produce water savings. Measures to reduce soil compaction can also significantly enhance soil water content (Thompson *et al.*, 2007). Mediterranean studies suggest that by combining both crop breeding programmes with improvements in agricultural husbandry water savings can be made (Morrison *et al.*, 2008).

4 Shelterbelts

4.1 Introduction

Traditionally trees have been used to shelter buildings, crops and animals from wind, sun, rain and snow. The UK is a windy country, so by reducing wind speeds shelterbelts offer the potential to improve agricultural production (Gardiner, 2004). Under climate change predictions evapotranspiration will increase, thus the shelter offered by trees may be beneficial for reduced water use.

This section introduces the different shelter formations trees can provide, how shelterbelts work and factors such as height and porosity that determine their usage. The benefits derived from shelterbelts can be maximised if a detailed farm audit is done to find areas of most need on a farm.

4.2 Shelterbelt types

Trees are used for a variety of purposes on a farm. The combination of agriculture and forestry is termed agroforestry. By combining the two systems ecological and economic benefits can be gained (Sinclair, 1999).

Trees can be planted in different configurations to provide shelter. Vigjak *et al.* (2003) describe a system devised by Drachenfels that divided shelter into the following six categories of hedgerow, hedge, line of coniferous trees, single line of deciduous trees, multiple lines of deciduous or mixed trees and small wood. This review will use the term shelterbelt to encompass all forms. However, Gardiner *et al.* (2006) preferred the term shelter wood suggesting that trees are not always in a linear formation that a shelterbelt may imply.

4.3 Shelterbelt design

Shelterbelts alter the speed and direction of wind (Brandle *et al.*, 2004). A shelterbelt obstructs the flow of air upwind (windward) and downwind (leeward). As wind approaches the shelterbelt it can flow in three directions, either through the shelterbelt, around the sides or upwards (Cleugh, 1998).

Above the shelterbelt there is increased turbulence and wind speed - this is called the displacement zone. The shelterbelt creates an area of high pressure and turbulence on the windward side which is one of the factors forcing the air upwards. On the lee side there is an area of low pressure. If the shelterbelt is dense enough on the lee side, the air stagnates resulting in increased turbulence.

The area either side of the shelterbelt containing turbulent air is termed the cavity zone. Beyond the cavity zone on the leeward side the faster moving air from the displacement zone combines with the slower moving air flowing through the shelterbelt to create the wake zone. Eventually downwind of the barrier the effects of the wind break are lost and the wake zone ends (Brandle *et al.*, 2004; Gardiner, 2004; Gardiner *et al.*, 2006). Cleugh and Hughes (2002) substantiated the existence of these zones by wind tunnel experiments. Figure 1 shows the different shelterbelt zones and effects on wind speed and turbulence.



Shelterbelt protecting young crops: Andy Tryner

4.3.1 Shelterbelt performance

The effects of shelterbelts are measured in H , where H is the height of the shelterbelt. This review will use the H notation to describe the results of shelterbelt experiments. The upward movement of air can create a region of reduced wind speed on the windward side from 2 to $5H$ from the shelterbelt. A larger area of reduced wind speed is created on the leeward side which can range from 10 to $30H$. These distances are modified by the porosity and height of the shelterbelt. Other factors such as length, width, orientation and surrounding landscape will all effect the size of the area protected (Brandle *et al.*, 2004; Gardiner, 2004; Gardiner *et al.*, 2006).

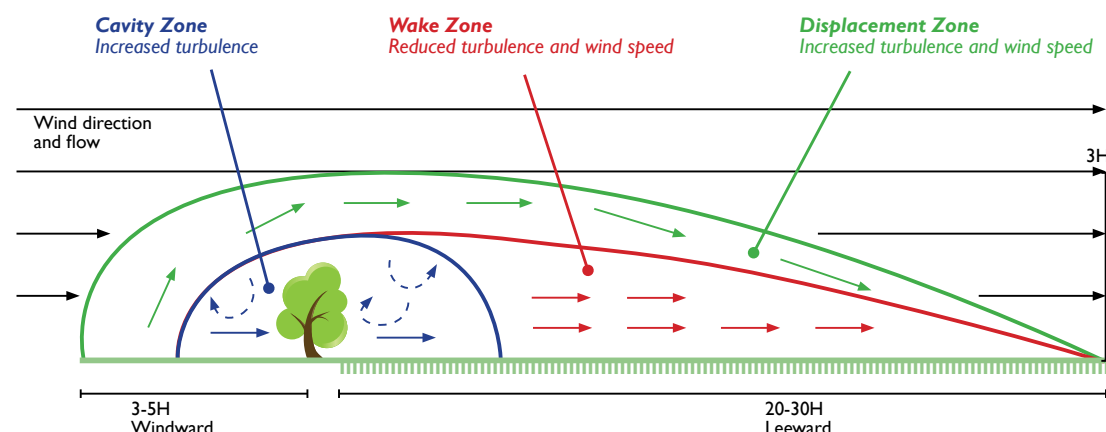


Figure 1

Wind speed and turbulence in shelterbelt zones. Source: after Gardiner *et al.* 2006.

4.3.2 Porosity

Porosity is how easily wind can flow through the shelterbelt. It influences the level of protection provided to the leeward side of the shelterbelt. In general, the less porous the shelterbelt the more intense but shorter the protection. Porosity is affected by tree density, species and the time of year. If the shelter is too dense it can increase turbulence in the cavity zone, resulting in increased wind speed (Gardiner, 2004; Gardiner *et al.*, 2006).

Optical porosity has traditionally been used to give an estimate of the porosity of shelterbelts (Cleugh, 1998). More recently aerodynamic porosity has been used to measure porosity as the shelterbelt can be considered as a three-dimensional structure. Nelmes *et al.* (2001) measured wind speed upwind and downwind of different types of shelter. They produced a calculation that could assess the effectiveness of different shelters giving an indication of aerodynamic porosity. Brandle *et al.* (2004) concluded that although optical porosity can overestimate aerodynamic porosity, optical porosity was still a valid indicator of shelter performance. Porosity is a key measurement for modelling programmes, but can be particularly difficult to assess for wide rows of deciduous trees (Vigiak *et al.*, 2003). Deciduous trees will keep 60 per cent of their sheltering effect in winter which is enough to provide adequate shelter (Palmer *et al.*, 1997).

4.3.3 Height

Shelterbelt height determines the extent of cover; the taller the shelter the larger the area of cover. It is normally measured from the centre of the shelterbelt (Gardiner, 2004; Gardiner *et al.*, 2006). The shelterbelt should be as tall as local conditions allow, Agri-Food Canada recommend shelterbelt trees that at maturity reach 15m in height (AAFC, not datedb).

4.3.4 Width

Width is important because it affects porosity. Porosity can be decreased by adding another row of trees to the shelterbelt. In windy locations the addition of another row of trees to a shelterbelt can ensure that the shelterbelt has the desired height as the most windward row of trees is often stunted. However, wider groups of trees tend not to provide large areas of shelter and take up more space. Clear objectives need to be set for the shelterbelt, which will then drive shelterbelt design, for example whether the wood will be used for timber or fuel (Gardiner, 2004; Gardiner *et al.*, 2006; QMS, 2011a).

4.3.5 Length

To reduce the effects of wind flow around the ends of the shelterbelt, it is recommended that the length of the shelterbelt should be at least ten times the height. This results in an area of cover the shape of a triangle with the edges of the covered area returning to the local wind speed quicker than the centre (Figure 2) (Gardiner, 2004; Gardiner *et al.*, 2006).

An opening in the shelterbelt can result in increased wind speeds which has the same effect as the edge of a shelterbelt. If an opening is needed for access then it should be angled into the shelterbelt (Gardiner, 2004; Gardiner *et al.*, 2006).

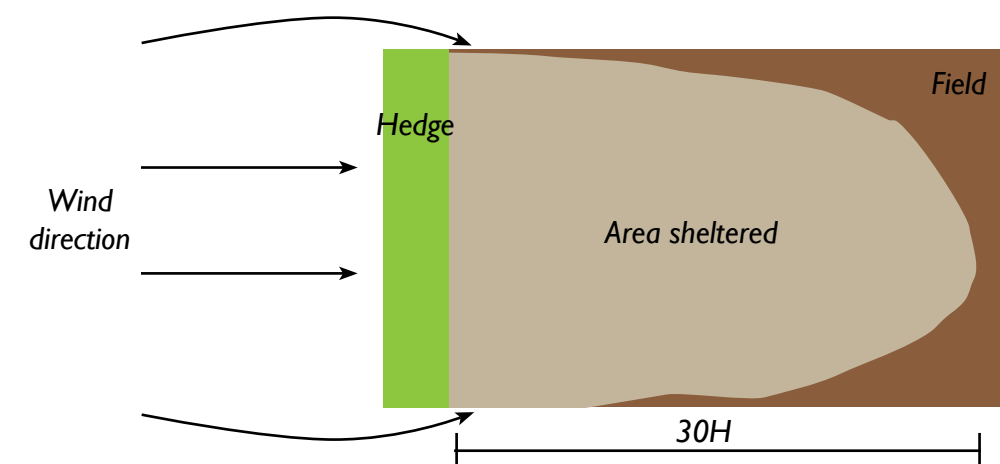


Figure 2

Area of shelter behind a shelterbelt. Source: after Gardiner *et al.* 2006.

4.3.6 Orientation

Orientation of the shelterbelt is important as it affects the area covered. The greatest cover is when the wind hits the shelterbelt at right angles, but is reduced when this angle is decreased. If the wind does not hit at right angles then the porosity of the shelterbelt decreases and the area of cover is decreased. This effect is more pronounced with wider shelter belts (Gardiner, 2004; Gardiner *et al.*, 2006).

4.3.7 Air turbulence and surrounding area

Weather, topography and the surrounding vegetation all affect air turbulence. To manage gusts around hills, shelterbelts may be needed on more than one side. Wind tunnels can be formed between lines of trees or valleys. Thus, the local area should be considered when designing shelterbelts (Nelmes *et al.*, 2001; RHS, not dated).

Shelterbelt networks impact air turbulence. Shelterbelt systems can slow down the average wind speed of a whole region. Increased roughness of vegetation can create turbulence, for example a sugar beet crop is not as rough as grass and thus creates less air turbulence (Vigiak *et al.*, 2003; Tuzet and Wilson, 2007).

4.4 Farm shelter audit

4.4.1 Match porosity to use

It is important to be clear on the objectives of a shelterbelt. A dense, low porosity shelterbelt provides a small area of intense shelter. A shelterbelt of less than 40 per cent porosity will reduce wind speeds by as much as 90 per cent and protect an area up to ten times the height of the shelter. They are suitable for protecting buildings and young livestock. Tall shelterbelts of 40–60 per cent porosity protect an area up to 30 times the height of the shelterbelt creating suitable shelter for crops. Hybrid shelterbelts which are dense at the base and more porous at the top can perform two functions. They provide a wide area of shelter, but at the base a very sheltered area. Very porous shelterbelts of more than 60 per cent porosity can increase wind speeds. Porosity can be increased by thinning and pruning the trees and reducing the width of the shelterbelt. Porosity can be reduced by under-planting, fencing and straw bales (Palmer *et al.*, 1997; Gardiner, 2004; Gardiner *et al.*, 2006).

4.4.2 Farm shelter audits

A farm shelter audit was created by the Forestry Commission and SAC (Scottish Agricultural College). It provides a framework with which to advise farmers on the creation of shelter around a farm. Trees can be of benefit to farmers, but only in the right location and layout. The farm shelter audit consists of three steps. The first step involves gathering information to establish the potential benefits and assess existing shelter effectiveness. Information is gathered on farm size, existing boundaries, activities taking place in each field and direction of problem winds. Local weather conditions are considered such as location of frost pockets, frequency of droughts and soil erosion problems etc. Shelterbelts should face the prevailing wind, often from the south-west in the UK, but colder winds can come from the north east (RHS, not dated). Further information on wind speed directions can be gained from the governmental wind speed database (DECC, not dated). Once all this information is gathered recommendations can be given as to whether shelter would be beneficial and if so what type (Hislop *et al.*, 1999; QMS, 2010).

If shelterbelts are to be planted the amount of land available and the ultimate use of the trees needs to be considered. Hedges do not take much space and can be thinned to desired porosity (QMS, 2010). Altitude, hydrology, soil type and pH are all important factors to consider in the species selection of the shelterbelt. Native trees already growing in the area are often a good choice (QMS, 2011a; QMS, 2011b). The Woodland Trust can provide guidance on tree and site selection (The Woodland Trust, not dated; Forestry Commission, not dated).

5 Microclimate and tree crop interactions

5.1 Introduction

As discussed in Section 3, solar radiation, temperature, humidity and wind speed all affect the rate of evapotranspiration. The previous section described how shelterbelts can reduce wind speed (Gardiner, 2004). This reduction in wind speed can improve the crop microclimate and make the crop more efficient in its water use. This section will examine the effect a shelterbelt has on crop water use including both beneficial and negative effects.

5.2 Microclimate and soil moisture

5.2.1 Wind speed and humidity

In the wake zone of a shelterbelt the movement of air is slowed above the crop canopy. This reduces the rate of water vapour removal from the crop surface, resulting in the build-up of a moisture layer around the crop. The air becomes more humid and the rate of evapotranspiration declines. Shelterbelts also slow the transfer of heat (heat advection) to the crop. Shelterbelts reduce the amount of hot air moving over the transpiring crop surface and thus the rate of evapotranspiration. Reductions in wind speed can occur up to 30H from the shelterbelt (Kort, 1988; Gardiner, 2004.)

5.2.2 Temperature

In the wake zone of the shelterbelt daily air temperatures can increase by as much as 4°C due to reductions in wind speed, which results in higher leaf surface temperatures. This increases transpiration, photosynthesis and respiration. At night, temperatures can be reduced by up to 1°C due to air not mixing resulting in reduced respiration and increasing growth overall (Kort, 1988; Brandle *et al.*, 2004).

Using wind tunnels, Cleugh and Hughs (2002) confirmed that wind speed reductions occurred up to 30H downwind of a shelterbelt, whereas the temperature effect was up to 10H. They found that at 20H wind speed could be 80 per cent of the upwind value. Figure 3 summarises the main climatic effects on each shelter zone.

5.2.3 Soil water and irrigation

Reductions in wind speed reduce soil moisture evaporation rates and can improve the distribution of irrigation water. However, increased soil moisture can drive evapotranspiration, as there is more water available to the plant to transpire (Davis and Norman 1988; Dicky, 1988).

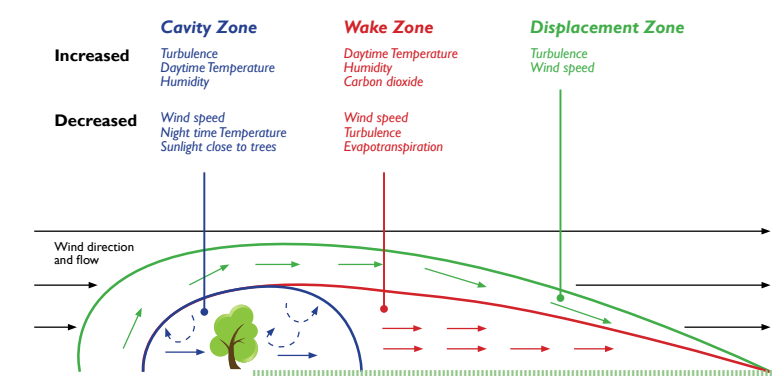


Figure 3

Shelterbelt zones and microclimate: source after Gardiner *et al.* (2006).

5.2.4 Water use efficiency

Shelterbelts can reduce evapotranspiration rates by increasing humidity levels and decreasing heat advection. Evapotranspiration rates in the lee of a shelterbelt can increase as daytime air temperatures are higher. The overall net effect on evapotranspiration is determined by such factors as light, temperature and moisture stress acting on stomatal aperture size. Stomata in sheltered plants may stay more open, which allows more carbon dioxide exchange, resulting in increased photosynthesis and growth rates. Thus, when comparing evapotranspiration rates net gains in biomass should be considered. The comparison of the ratios can give an indication of crop water use efficiency (Nuberg, 1998; Davis and Norman, 1988).

5.3 Plant structure

5.3.1 Plant growth

Increases in photosynthetic rate will occur up to about 30°C. This results in longer growing season and a greater growth rate. Plants growing within shelter are often more luxuriant and can have a larger leaf area index than those in exposed areas. However, this greater leaf area index can increase transpiration losses. Furthermore, increased temperatures in sheltered areas can reduce the length of developmental stages, thus reducing time for photosynthesis. Increased growth may not equate to larger grain yields. Crops grown for biomass may yield greater returns than those harvested for grain.

(Allen *et al.*, 1988; Kort, 1988; Cleugh, 1998). Cleugh (1998) concluded that a well-watered crop protected by shelter would use the same amount of water as a non-sheltered crop, but would have increased photosynthesis rates and increased water use efficiency.

5.3.2 Mechanical

Plants growing in sheltered areas experience less wind damage. If plants have wind damage they can lose water from the damaged tissues (Grace, 1988). Cleugh and Hughes (2002) found using wind tunnels that the benefits of shelter extended 30H from the shelterbelt, whereas those for temperature extended to about 10H. From this they concluded that the benefits of reduced mechanical damage would extend longer than those of improved microclimate. Those benefits can start from the initial sowing of the crop. Seeds that are planted at shallow depth are less likely to be blown out of the soil. A shelterbelt can protect seedlings from sand blasting by soil particles as the crop grows plants will be less likely to be knocked against each. Wind can also increase lodging and thus crop damage.

Horticultural products respond particularly well to shelter as fruits will be produced earlier and are less prone to damage (Nuberg, 1998; Cleugh, 1998; Baldwin, 1988).

5.4 Tree crop environment

Living shelters also have an impact on the crop environment. Tree root growth can improve soil structure aiding water infiltration and reducing water run-off. Tree transpiration can create a moisture blanket over crops reducing crop transpiration. However, trees can compete with crops for water and reduce photosynthetic rates by shading crops.

5.4.1 Tree crop interactions

Species compete if they are in the same environment and have the same requirements for resources. Trees modify the amount of light, water and nutrients available for crop growth. This zone of interaction can extend up to a distance of about 1H to 2H from the shelterbelt (Nuberg, 1998). Plants can coexist if the biomass gains are greater than if they are grown separately (Jose *et al.*, 2004; Kort, 1988).

Competition for water

The highest density of tree and crop roots occurs in the top 30 cm of soil (Jose *et al.*, 2004). Lack of deep ploughing before tree planting, compact soils and low soil water moisture will all encourage competition between crops and tree roots. Competition for water and nutrients will be reduced if there is spatial separation of tree and crop roots (Jose *et al.*, 2004).

Shading effect of trees

Shading reduces the amount of solar radiation the understorey crop receives, which can slow down the rate of photosynthesis and transpiration (Benavides, 2009; Jose *et al.*, 2004). The orientation and crown density of the shelterbelt will influence the degree of shading. Shelters running north-south minimise the effect of shading (Natural England, 2008). Young ash and sycamore do not heavily shade crops, as they grow initially upwards and only develop their branches horizontally as they mature (Hein and Spiecker, 2008). Deciduous trees do not have a detrimental effect on pasture production until there is 85 per cent canopy cover as compared to 67 per cent for conifers. The leafless period of deciduous trees enables pastures to recover from the adverse effects of shade and can encourage pasture growth in spring. Pruning of lower tree branches reduces the effect of shading and results in knot-free timber (Sharrow, 1999; Benavides *et al.*, 2009).

5.4.2 Water infiltration

Tree root exploration and increased litter inputs can improve soil organic matter and thus infiltration rates and water holding capacity. Animals congregating by a shelterbelt can increase soil compaction and reduce soil infiltration rates. Trees can prevent water reaching the crop through canopy interception; the amount of rain intercepted is dependent on tree density and crown size. Under heavy rainfall conditions this can prevent the impact of raindrops on the ground damaging soil structure. Shelterbelts can create rainshadows which can extend 1H on the lee side of the shelterbelt (Bird, 1998; Riha and McIntyre, 1999; Jose *et al.*, 2004; Chandler and Chappell, 2008).

5.4.3 Hydraulic lift

Due to their deep roots, trees can intercept water unavailable to shallower rooting crops through hydraulic lift. This is the movement of water from more moist soil layers to drier soil layers via plant roots. Water lifted by plant roots is released at night when transpiration ceases, this water becomes available during the day for transpiration. An experiment over five days showed that a mature 20m tall maple tree can lift about 102l of water a night (the review did not state in which season the experiment was conducted). The water added to the upper soil layers accounted for 25 per cent of the transpiration losses (Caldwell *et al.*, 1998). If tree roots access water below the crop rooting zone, then tree crop water competition will be reduced (List and White, 2008). Whether the water lifted by trees becomes available to the crop is not known (Jose *et al.*, 2004).

5.4.4 Tree transpiration

As the wind passes through shelterbelts, the water vapour generated by tree transpiration humidifies the air. Moisture blankets can develop over the crop canopy, resulting in reduced rates of crop transpiration.

5.4.5 Allelopathy, nutrient cycling, insects and pathogens

Trees and crops will compete for nutrients. Due to their deeper roots, trees can access nutrients at greater depths and may reduce nutrient leaching. Tree litter on the ground can buffer against soil water losses. Tree roots can exude toxins that reduce plant growth; this process is termed allelopathy. Insects, pollen and pathogens use wind as transport, thus shelter will modify these pathways. In orchards there are often increased numbers of insects which aids pollination. However, the reduction in wind speed can result in pests and pathogens being deposited on the lee side of the shelterbelt. Modification of humidity levels can also impact fungal diseases (Bird, 1998; Eichhorn *et al.*, 2006; Cleugh, 1998; Jose *et al.*, 2004; Kort, 1988).

5.5 Computer modelling

Table 1 summarises some of the advantages and disadvantages of shelterbelts. Computer models can help unravel the complexities of crop shelterbelt interactions. By modifying climatic parameters such as rainfall and temperature the potential benefits of shelterbelts could be predicted under climate change scenarios. However, computer models are prone to being over simplified (Mize *et al.*, 2008b; Palma *et al.*, 2007; Jose *et al.*, 2004).

Advantages	Disadvantages
Reduction in soil evaporation and plant transpiration	Trees compete with crops for light, water, and nutrients resulting in reduced crop yields close to shelterbelts
Increased air temperature resulting in improved crop germination and growth	Increase in lodging in the cavity zone
Extension of growing season due to increased soil and air temperatures	Reduction in pollination for some crops
Control of snow drifting, spray drift and irrigation water	Land taken out of production and added cost of establishment and maintenance.
Reduced mechanical damage leading to less water loss from plant tissues	Potential of water logging of soil close to low porous shelter belts
Reduction of crop lodging	
Reduction of soil erosion	
Increased soil organic matter and nutrient recycling from leaf litter	
Mineralization of soil nitrogen encouraged	
Reduction of soil acidification for certain soils	
Increased pollination for some crops	

Table 1

Advantages and disadvantages of shelter: source Gardiner, 2004.



Farmland at Hucking Estate: WTPU/Nicholas Spurling

5.6 Previous review findings

The most tangible benefit that shelterbelts bring is increased yield. As this section has demonstrated the exact benefit a shelterbelt provides may be harder to determine. There are a number of reviews that cover this topic in more detail. Kort (1988) and Nuberg (1998) looked at the effect of shelter on arable crop yields, whilst Bird (1998) reviewed the literature for the effect of shelter on pasture. These reviews concluded that a large number of studies have shown improved growth and yield over a range of climates and soils, although the results were variable depending on crop, weather, year shelterbelt type and soil. Yield increases are more consistent for vegetables as detailed in the review of Baldwin (1988). Kort (1988) noted that quantitative comparisons between studies were difficult as many parameters were not recorded. Often it was not clear if the land taken out of production for the shelterbelt was deducted from the yield calculations (Cleugh, 1998). Shelterbelt studies should have detailed microclimate measurements at varying distance from the shelterbelt (Grace, 1988; Nuberg, 1998). The next three sections will review the evidence for the benefits of native trees species for shelter on the water regime of pasture and arable crops.

6 UK evidence

6.1 Introduction

Trees planted on farms can be used for fuel, shelter, sport, landscape enhancement and to encourage biodiversity. Trees were planted in large parks to enhance the aesthetic appeal of the landscape (Sibbald, 2001). Woodland edges can provide habitats for game hunting. Farmers can diversify their income by producing timber which can be sold or used for fencing and fuel (The Woodland Trust, not datedb). Until 1989, Bryant and May intercropped poplar with crops for match stick production; when the trees became larger the understorey was replaced with pasture (Lawson, et al, 2004; Sibbald et al., 2001).

Shelter can have a number of purposes. Trees such as poplars or alders have been planted to provide shelter to orchards in Kent (Natural England, not dated). Breadalbane Farm Forestry and Glensaugh run silvopasture demonstration sites (Breadalbane, not dated; Glensaugh, not dated). The Forestry Commission and Quality Meat Scotland have a current initiative promoting farm woodlands to provide shelter to livestock (QMS, 2010; QMS, 2011a; QMS 2011b).

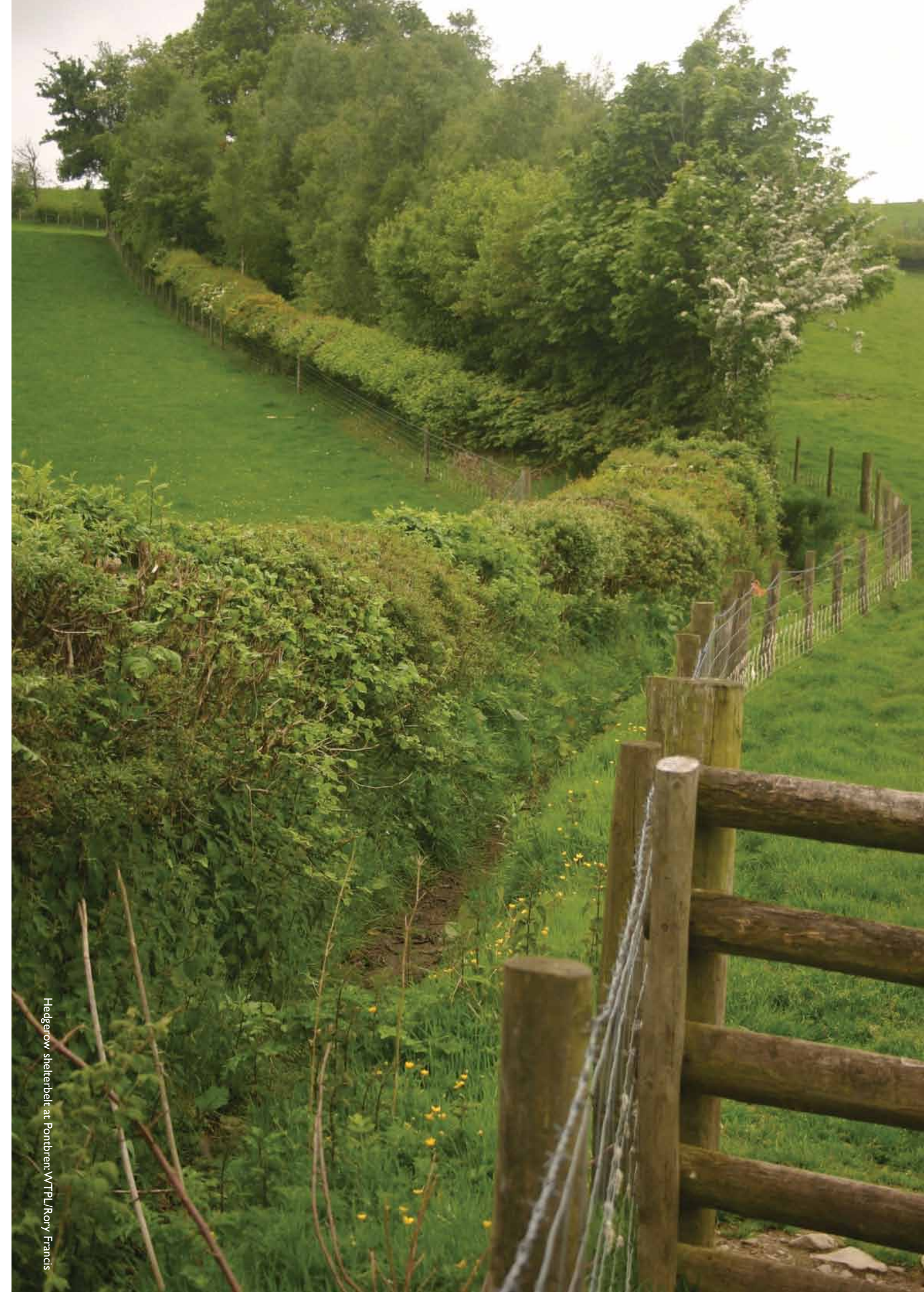
Hedges to define boundaries of fields and to prevent movement of livestock have a long tradition in the English landscape. Many hedges are very old. In Devon, it is believed that over a quarter of the hedges are more than 800 years old (Hedgelink, 2009). Hedges were planted to shelter horticultural crops in coastal areas such as Cornwall, Isle of Scilly, or in exposed regions such as the Wirral, South Hampshire and West Sussex (Hooper and Holdgate, 1968). Oak and ash are the most common hedgerow trees, but beech can also be found. For example, in the 19th century beech hedgerows were planted at Exmoor. In 1998, a survey showed that less than 1 per cent of hedgerows were younger than four years old, highlighting the need to encourage new plantings (Natural England, 2008).

6.2 Lack of UK evidence

There has been very little UK research on the benefits of shelter to crops and pasture. Bird (1998) commented that there was a lack of research globally on the benefits of shelter on pasture growth. Bird (1998) cited only one UK study, that of Russell and Grace (1979). Likewise, Nuberg (1998) in a review of the literature on the benefits of shelter to arable crops mentions only one UK study, that of Hough and Cooper (1988). Kort (1988) reviewed 50 years of shelter literature and made no mention of any UK research.

Caborn (1955) pioneered UK shelter research, studying the microclimate of Scottish shelterbelts. These shelterbelts planted in the 19th Century have become neglected (Hislop et al., 1997). In the 1970s there was a series of shelter symposiums organised by MAFF (Gloyne, 1976). Gloyne (1976) reports on the work of Alcock who found that shelter provided early grazing of pasture in Welsh hills. He cites the work of Drew who showed that shelter aided carrot germination as sand blasting was reduced. Horticultural produce in the UK also prospers under shelter. For example, Gloyne (1976) reported that strawberries were grown successfully in Scotland when sheltered.

Two UK studies have examined the effect of artificial shelter on pasture and crop growth. UK agroforestry initiatives have demonstrated that trees intercropped with pasture or arable crops can yield good economic returns. The following section will present the findings of these studies.



Hedgerow shelterbelt at Pontbren; WTP/LRory Francis

6.3 Shelterbelt studies

6.3.1 Arable

Hough and Cooper (1988) conducted experiments in north-east England examining the effect of artificial shelter on yields of spring barley, winter wheat and winter barley. The shelter had a porosity of 50 per cent, and was 0.9m tall and 80m long. Measurements were made behind the shelter at various distances in plots up to 20m or 30m from the shelter. Sheltered crops were taller and yielded more grains than non-sheltered crops for the first two years. In the third year results were inconclusive. The authors attributed these results to climatic conditions. In the first two years there were periods of dry windy weather for several weeks before anthesis, whereas in the third season it was wet with mild winds until anthesis.

Assuming the benefits of shelterbelts extend up to 30H into the field, then it could be hypothesised that a 5m hedge of 50 per cent porosity angled against the predominant winds could afford protection of up to 150m into a field. Likewise a 10m high shelterbelt could protect an area up to 300m long. These values are absolute maximums and would need to be substantiated by further field experiments.

The authors suggested that the beneficial effect of shelter was to reduce evapotranspiration. Using the Penman-Monteith equation they calculated that shelter would decrease transpiration by 10 per cent. They suggested that during drier periods the soil moisture levels may be higher under sheltered treatments. They supported this by field observations, noting that after light rain fall the sheltered top soil was not as dry as the unsheltered top soil.

Sparkes *et al.* (1998) investigated the effect of field margins on crop yield. Over five years, field margins of commercial farms growing sugar beet, wheat and barley were studied. They found that there was a reduction in yield at the edge of the field and this was most pronounced for sugar beet (mean reduction 26 per cent) and least for cereals (mean reduction 7 per cent). Yield reductions did not extend further than 20m from the field margin. They attributed these losses to soil compaction from machinery as it turned. When hedges were part of the field margins yield losses were greater due to shading. Areas shaded by trees produced 4.4 t ha⁻¹ of wheat as compared to non shaded areas which produced 8.1 t ha⁻¹. Yields of wheat were halved within 9m of the hedge and the grain contained slightly more moisture. The authors suggested that the area within 20m of the hedge was a good candidate for set-aside.

Wilcox *et al.* (2000) studied the effect of crop margins bordered with 1.5 to 2m high hedges on arable crop yields at Shropshire (Harper Adams), Hampshire and Leicestershire. Yields were reduced up to 30m into the field at one site, but this could not be attributed solely to the presence of weeds. The authors concluded that yield reductions were site dependent and could be due to presence of weeds, seed bed quality and soil compaction. They made no comment on the effect of the hedge.

6.3.2 Pasture

Russell and Grace (1979) conducted an experiment over three years in Scotland on the effect of artificial shelter on pasture yield. Wind speeds were reduced by 27 per cent which resulted in increases in dry matter yield in the re-growth period, but not in spring. However, they could not attribute the increases to leaf water potential but did not rule it out as a possibility. They concluded that the most likely explanation was that sheltered conditions reduced leaf damage, which can increase evapotranspiration losses.

A study at Pontbren showed that deciduous tree shelterbelts planted on grazed lands could reduce flood risk (Bird *et al.*, 2003; Carroll *et al.*, 2006). Within two years of planting infiltration rates were higher than non-sheltered areas up to 5m from shelter. Infiltration rates were up to 60 times higher than non-tree planted areas.

6.4 Agroforestry studies

UK agriculture may in dry windy conditions benefit from shelter, but yields may be reduced at field margins. The effect of shelterbelts on crop yield is a balance between positive and negative interactions. There are a number of agroforestry experiments that have examined these interactions. These are relevant as the findings can give insight to how shelterbelts may compete with crops. Most of the experiments were part of two UK initiatives that investigated yields of tree/pasture (Silvopastoral national network) and tree/arable systems (SAFE : Silvoarable Agroforestry for Europe) (Agroforestry Forum, not dated). The trees were planted in alleys and at various levels of spacing.

6.4.1 Pasture

Shading

Northern European agricultural production is largely limited by light and southern European agricultural production by water (Eichhorn *et al.*, 2006). Bergez *et al.* (1997) conducted an experiment at three sites in the UK to examine the effect of tree shading on pasture production. Light levels were measured under the stands of eight year old sycamore, ash and larch trees. The light levels intercepted by the tree canopies were quite low; on average tree shading reduced the amount of light reaching the sward by 8 per cent.

The introduction of trees did not reduce the animal carrying capacity of the pasture.

The authors suggested a number of explanations for this result some of which were: maximum sward growth occurred before the leaves of the tree were fully expanded; shelter afforded by trees may have conserved sward soil water moisture; livestock had reduced energy expenditure due to shelter.

McEvoy and McAdams (2008) conducted an experiment in Northern Ireland examining the effect of sheep grazing on ash and oak pastures. Prior to the introduction of sheep, swards were taller under ash than oak pastures. These results could be explained by the fact that ash leaves are only fully expanded after 70 per cent of pasture growth has occurred and their canopies are smaller than oak (QMS, 2010).



Silvopastoral farming system at Loughall. © Paul Burgess

Root competition

Trees occupy the same competitive root space as crops. However, when confronted with competition tree and crop roots can change their behaviour. Campbell *et al.* (1994) studied root competition of wild cherry trees inter cropped with pasture at a site in Scotland under varying levels of N application. The study showed that grass was more competitive than trees. Only under hot dry conditions and at the highest applications of nitrogen did water limit tree growth.

Dawson *et al.* (2001) using the same study site as Campbell a few years later studied the distribution of tree and grass roots. Tree roots avoided the top 5cm of soil which was occupied by grass roots. Tree roots were only found in the top 5cm of soil if grass growth was suppressed by herbicide treatment.

Soil properties

As discussed earlier Carroll *et al.* (2006) found that shelterbelts increased infiltration rates. Parkinson *et al.* (1998) studied the hydrology of an ash agroforestry site in Devon. Water drained quicker from the soil in the alley cropped site than the site without trees. The authors suggested that this was due to enhanced soil macroporosity created by tree root exploration.

Microclimate study

A series of microclimate measurements were made at a conifer agroforestry site in Scotland (Sibbald *et al.*, 1991; Sibbald and Griffith, 1992; Sibbald *et al.*, 1994; Greens *et al.*, 1995). Some general principles can be gained from these experiments which can have some extrapolation to native deciduous trees. Wind speed reduction was measured at different densities of conifer planting. Wind speed was measured 2m above the ground and was found to be 46 per cent, 29 per cent and 16 per cent in the wide, medium and narrow plots, respectively (Greens *et al.*, 1995). At the greatest tree density, grass meristem temperature was reduced (Sibbald and Griffith, 1992). Herbage yield declined with tree density. Yield reductions were not significant if the trees were less than 8m tall and at a spacing of more than 6m. The authors suggested that trees may promote some out of season pasture growth (Sibbald *et al.*, 1991). As part of the same study it was found that the horizontal projection of tree crowns gave a good indication of herbage yield (Sibbald *et al.*, 1994).

6.4.2 Arable

Agroforestry experiments that have mixed trees and arable have focused on the yield of both crop and tree. There has been a large focus on poplar trees which are fast growing and produce marketable timber relatively quickly (Burgess *et al.*, 2003; Burgess *et al.*, 2005).

Nutrient inputs

Ranasinghe and Mayhead (1990) studied the effect of inter cropping poplars and beans as compared to a poplar control. They found that even at two years old the greatest tree growth was at the widest spacing. There were higher levels of nitrogen in the poplars grown with beans as compared to the control. At the end of the second year bean growth was reduced within 25cm of the tree due to reduced light and moisture. The authors concluded that the poplars had benefited from growing next to the beans due to the increased N levels.

Park *et al.* (1994) investigated soil properties of arable inter-cropped with four year old poplars. They found that within 1m of the tree, there was more organic matter and soil invertebrates. The authors concluded that poplars were unlikely to have a detrimental effect on soil organic matter.



Silvopasture barley farming system: © Paul Burgess

Effects of water competition and shading

Burgess *et al.* (2003, 2005) conducted a large scale agroforestry study using young poplar trees. Poplars were inter-cropped with various arable crops and growth rates were compared to a poplar fallow control. Arable crops caused a reduction in tree growth as compared to the control. The poplar and arable treatment had a greater soil water deficit than the control suggesting that water was limiting tree growth. Crop yield was reduced by 10 per cent, due to either shading, competition for water, weeds or slug damage. Trees had the greatest effect on break crops and the least effect on winter cereals suggesting that shading was limiting crop growth. The yield of inter cropped mustard and beans was about 80 per cent as compared to pure arable field, whereas, inter cropped winter wheat yields were about 93 per cent of the arable field. Winter crops finish much of their development before tree leaves emerge, therefore avoiding the adverse effects of shading. Burgess *et al.* (2005) reported that high pruning of poplars minimized the effect of shading on crop growth.

6.5 Computer modelling

Part of the SAFE project was to develop a computer model to predict yields of both crops and trees over time (Van der Werf *et al.*, 2007). The experimental data to validate the model was derived from the poplar experiments reported by Burgess *et al.* (2003). The model consists of seven equations to express tree biomass, tree leaf area, number of shoots per tree, crop biomass, crop leaf area index, soil water content and heat sum. The model takes as daily input parameters temperature, radiation and precipitation. Planting densities, soil parameters and initial biomasses of tree and crop can also be specified as parameters. The authors did not indicate if wind speed was also an input. For the first 12 years the model generally matched the experimental results.

7 European Evidence

7.1 Introduction

Many examples of traditional agricultural practices that grew crops and trees together have now fallen out of practice in Europe (Eichhorn *et al.*, 2006). At one time large areas of central Europe had fruit and nut silvoarable systems (Sinclair, 1999). Since Roman times, pigs have been released into beech and oak woodlands to eat acorns and beech mast, a practice called pannage. In northern Europe mature woodlands provided shelter to livestock in winter (Smith, 2010).

Shelterbelts are found on the Jutland plains of Denmark and the steppes of Russia and Ukraine (Hislop and Claridge, 2000). Hedgerows still cover many areas of Europe such as in the Rhone Valley, where a series of hedges have been planted for water conservation. A 50m hedgerow can store between 150 and 375 cubic metres of water, which can be released during dry periods. In north West France, hedges were removed from the bocage region which resulted in soil erosion. Regulations now stipulate that hedges have to be planted in these areas (Merot, 1999; Hedgelink, 2009).

Farmers in drier parts of Europe are more likely to plant trees (Dupraz *et al.*, 2005). Three million hectares of mainly oak mixed with pastures or crops cover parts of Spain and Portugal, a practice called dehesa (Lawson *et al.*, 2004). The dehesa provide shelter for livestock and the wood is used for timber. In Italy olives and vines are inter cropped with cereals.

7.2 Shelterbelt studies

7.2.1 Microclimate

Campi *et al.* (2009) conducted a three year study of rain fed durum wheat growing in Italy. A 3m high cypress shelterbelt sheltered the crop from the prevailing winds. Trees were 20 years old and had a porosity of 40 per cent. Wind speed was reduced at a distance of 12.7H from the shelterbelt and temperature was increased up to a distance of 4.7H from the shelterbelt. Evapotranspiration was reduced up to a distance of 12.7H from the shelterbelt. The greatest efficiency in water use was found at 2.7H and at 4.7H the evapotranspiration rate was 16 per cent lower than unsheltered areas. Yields were increased within a distance of 18H of the shelterbelt. The authors suggested that shelterbelts could be considered as an agricultural practice for sustainability.

Foerid *et al.* (2002) conducted a study in Denmark of a four year old hazel coppice shelterbelt growing with barley. The shelterbelt reduced winds by about 50 per cent. Generally air and soil temperature were increased close to the shelterbelt during the day and slightly decreased at night. Soil moisture and humidity were slightly higher nearer the shelterbelt. The authors stated that water was never limiting. Light levels were reduced by about 10 per cent. Barley growth was slightly reduced close to the shelterbelt and the authors suggested this was due to evening shading. Anthesis and crop development were slightly earlier closer to the shelterbelt due to increased temperatures. The computer model Sirius was run with crop growth and climatic data. The model validated that temperature and light levels accounted for these results. The authors did not report on overall barley yields.

Jossart *et al.* (1998) studied a short rotation willow coppice grown with maize in Belgium. Shelter had an effect on the speed of maize development, but not yield. These studies show that bioenergy crops can be grown within an arable crop system.



Trees providing a windbreak in Denmark © Poul H. Hansen/Stock

Orfanus and Eitzinger (2010) studied the effect of soil texture and 8m hedge shelter on the growth of alfalfa in one of the windiest and driest parts of central Europe, the Austrian basin. Evapotranspiration was significantly lower at 20m (2.5H) from the hedge than at 80m (10H) due to reduced wind speed. Sandy soil had to have 8 per cent more water compared to clay soils to eliminate plant water stress. They concluded that hedges can save almost 2000 m³ ha⁻¹ of water due to reductions in wind speed (presumably over a year).

7.2.2 Large scale effects of shelterbelts

Ryszkowski and Kędziora (1987, 2008) studied the effects of deciduous and conifer shelterbelts on the hydrology and energy fluxes of large areas of the Turew landscape in Poland. They showed that the structure of the vegetation is very important for energy balances and thus evapotranspiration rates. The total energy in a landscape is affected by the incoming solar radiation and the reflection of that energy from vegetative surfaces. Mixtures of cereals, row crops and shelterbelts reflected the lowest amount of radiation, whereas meadows reflected the most. Wheat fields used three times more energy heating air than shelterbelts.

Shelterbelts had the highest rates of evaporation and meadows had the lowest. Shelterbelts evaporated more water and used 40 per cent more energy for evapotranspiration than wheat. Shelterbelts acted as water pumps humidifying and cooling the landscape resulting in lower crop evapotranspiration losses in adjoining fields. The authors estimated that landscapes with a 20 per cent cover of deciduous shelterbelts could conserve considerable amounts of water and this effect would be most pronounced under hot dry conditions. These findings are in agreement with the study of the water balances of the steppes of Northern Caucasus by Lazarev (2006). They showed that shelterbelts increased rainfall by 22 per cent and reduced soil water run-off. Soil water evaporation from bare soil was reduced by 34 per cent. They estimated that the annual water input into the soil increased by 3.5 times. These studies show that shelterbelts can have a profound impact on water regimes.

Hedges in Brittany can also have a big impact on hydrology. Viaud *et al.* (2005) showed that hedges could increase annual evapotranspiration rates from 5 to 30 per cent. The groundwater table was lowered suggesting that hedge roots were able to uptake water from this resource.



Landscape of Brittany: © Pere Sanz/Stock

7.3 Agroforestry studies

Balandier *et al.* (2008) studied ten year old cherry trees inter-cropped with pasture in the Auvergne, France. Tree and grass roots avoided the same competitive space. Grass roots occupied the upper 20cm layers and tree roots the lower 20-80cm layers. Trees grown with grass were more water stressed, possibly due to grass roots extracting water from the top 20cm of topsoil as it fell as rain.

De Montard *et al.* (1999) studied the effect of competition for light, water and nitrogen between hazel and cocksfoot growing in Clermont Ferrand, France. Hazel was very water stressed when grown with cocksfoot. However, cocksfoot growth was not limited by shading and during wet windy periods it benefited from the presence of trees. After four years of planting, grass roots were confined to the top 0.2m of soil. The authors suggested this was due to the hazel drying lower levels of soil and therefore the grass avoided that soil layer. Picon-Cochard *et al.* (2001) also found that walnut seedling growth was inhibited by presence of grass, whereas the grass was not affected by the presence of the walnut.



Silvopastoral system: © Paul Burgess

7.3.1 Studies reported in literature reviews

Nuberg (1998) cited work from Germany, Norway, Czechoslovakia, Ukraine and Russia in a review of the effects of shelter on arable yields. Pretzschel (in German) studied the effect of shelterbelts on the productivity of arable crops over six years. The study found that the benefits of shelter depended on the crop. Potatoes responded well to shelter with a yield increase of 29.7 per cent, whereas barley mixed with oats had the least yield increase. Nuberg (1998) also cited an experiment by Miloserdov (in Russian) conducted in the Ukraine. An analysis of 25 years of data showed that shelterbelts increased barley yields. The effect was most marked in dry years when net revenues were increased by 27–52 per cent. Another Ukrainian study by Tkach (in Russian) showed that particularly in windy years shelter increased the yield of wheat.

Kort (1988) after reviewing 50 years of research concluded that shelterbelts increased yields. Included in that review were studies from Germany, Denmark, Poland, Ukraine and Russia. Most of the studies reported an area of reduced growth between 0.5H and 1.5H from the shelterbelt, but these losses were compensated for by increased yield in the area between about 1.5H – 7H. Kort (1988) stated that yield reductions were dependant on the competitiveness of the tree and the crop.

Bird (1998) found that there was a lack of research on the effects of shelter on pasture. Only two western European studies were cited, that of Russell and Grace from the UK and a study by Alterna (in Dutch) from the Netherlands. Alterna found that pasture yields were reduced by 10 per cent either side of a shelterbelt comprised of oak and birch. The authors attributed this loss to animal poaching and tree pasture competition.

8 Temperate zone evidence

8.1 Introduction

Shelterbelts can be found in Canada, USA, Australia, New Zealand, China, Argentina and many developing countries (Campi *et al.*, 2009). National Shelterbelt programmes have been set up in Canada, USA, China and Australia to promote tree planting (Brandle *et al.*, 2004). The Agriculture and Agri-Food Canada Prairie Shelterbelt Program has created a large network of shelterbelts across the prairies of Canada. The shelterbelt programme is one of the longest running government programmes. Since 1901, 600 million tree seedlings have been grown and given to 700,000 farms (AAFC, not dated a; AAFC, not datedb; Wiseman *et al.*, 2009).

This section will look at evidence from other temperate zones for the beneficial effects of shelterbelts on the water regime of pasture and arable crops. It will examine evidence from North American prairies, silvopastoral systems of New Zealand and the shelterbelts of temperate Australia.

8.2 North America

8.2.1 Canada

The Agri-Food Canada Prairie Shelterbelt website states that shelterbelts on the prairies can increase wheat yields by 3.5 per cent and that yield increases are higher in drier years. The site recommends that shelterbelts should only take up 5 per cent of land and that trees should be selected with upright growth to avoid sprawling branches (AAFC, not dateda).

Kowalchuk and Jong (1995) studied the effect of a shelterbelt comprising green ash and maple on yields of wheat, barley at a site in Saskatoon, Canada. Yield increases were most pronounced when water supply was low. The shelterbelt reduced yields up to 2H into the field, but in seasons when water was not limiting this zone was smaller. Increased yields were observed between 2H and 4H into the field. Wind speed was reduced by 40 per cent at 1H and the evapotranspiration rate was 75 per cent of the non-sheltered site at the same distance. The authors concluded that increased yields were due to reductions in crop evapotranspiration rates.

Pelton (1967) studied the effect of a 2.5m high artificial shelter of 45 per cent porosity on yields of wheat. The fence reduced wind speed by between 15 per cent and 50 per cent and resulted in reductions in evapotranspiration of between 12 per cent to 23 per cent. Yields were increased from between 23 per cent to 43 per cent. The beneficial effects were strongest up to a distance of 10H from the shelter. The authors noted that yield increases were highly variable from year to year.

Bayou (1997) studied the effect of a hedge on the microclimate of a field. The study found that microclimate was not consistently modified by the hedge due to variability in hedge porosity. The author suggested that management programmes should be in place to ensure that hedgerows have the optimum porosity to maximise the benefits of shelter.



Windbreaks sheltering crops in New Zealand: © Andrew Simpson/Stock

8.2.2 USA

In the prairies of the USA, shelterbelts were planted to reduce wind erosion (Mize *et al.*, 2008a). Bates conducted pioneering research into the effects of shelterbelts on microclimate and crop yields in Nebraska in 1911. He found that up to 12H from the shelterbelt there was a reduction in water loss of 12-36 per cent (Bird, 1998).

Asse and Sidway (1974) studied tall wheat grass barriers sheltering wheat in Montana. They found that wheat growth benefited most from shelter in dry years suggesting that shelter benefits were not just restricted to snow capture, but also included reductions in crop evapotranspiration rates.

Lyles *et al.* (1984) studied the effect of root pruning on wheat next to a shelter of deciduous trees in Kansas. Wheat yields in the 0.5h to 2H zone were 1.6 times higher in the pruned site as compared to the non-pruned site. Soil water content was lower nearer the shelterbelt for the non-pruned site and this effect was strongest in summer and autumn. The study suggested that root pruning can reduce water competition between the crop and tree shelter. Hou *et al.* (2003) studied the effect of root pruning on yields of soya beans next to a shelter of either conifer or deciduous trees in Nebraska. Soil water content was higher at 0.75H in the pruned treatment, as compared to the non-pruned treatment. The increases in yield at the pruned site was matched by an increase in soil water content. After 1H from the shelter there was no difference between treatments. Both studies suggest that the observed reductions in yield were due to competition for water.

Shelterbelts can also reduce water loss from spray irrigation and therefore increase crop water efficiency (Bird, 1998). Dicky (1988) in the USA reported that shelterbelts reduced irrigation water losses by as much as 42 per cent.

Gillespie *et al.* (2000) studied maize growing with black walnut or red oak. When maize and tree roots were isolated, there was no reduction in maize yield. The authors concluded that shading had no negative effect on maize production.

A computer model called the Erosion-Productivity Impact Calculator (EPIC) was developed in Nebraska by Easterling (1997). Simulations demonstrated that shelter gave the most benefit to crops when conditions are hot and windy. The authors suggested that shelterbelts could help combat the adverse effects of climate change.



Harvesting wheat in Whitman County © Phil Augustavoi/Stock

8.3 New Zealand and Australia

8.3.1 New Zealand

New Zealand has a tradition of mixed tree pasture systems as it is a windy country (Benavides *et al.*, 2009; Mead, 1995). Bird (1998) compiled a literature review of the effect of shelter on pasture production citing two New Zealand studies. One was the work of Radcliffe who studied the effect on the growth rate of pasture of a shelterbelt comprised of pine and cedar. Pasture production at 3H to 5H from the shelterbelt was 6.5t as compared to a midfield value of 4t. Yield was 3.6t at 0.3H from the shelterbelt. The shelterbelt resulted in a 60 per cent increase in pasture production which the authors concluded was due to reduced evapotranspiration rates. Bird (1998) also reports on the work of Hawke and Tomblason who found pasture growth was increased at 0.7H from the shelterbelt, possibly due to nutrient transfer from grazing animals.

Wall *et al.* (2010) and Wall (2006) looked at the viability of growing poplars in pastures under New Zealand conditions. If canopy closure was prevented from getting more than 30-40 per cent then pasture production could be maintained to 75 per cent of that of open pasture. The authors suggested that if pruning and thinning was maintained, then the negative effects of shading could be reduced. Poplar trees also increased the soil pH, therefore exerting a beneficial effect on nutrient cycling.

8.3.2 Australia

Australia is a country that suffers from extremes of weather conditions with severe droughts. Shelterbelts offer the potential to alleviate this water stress, however wind speeds are not as strong or in such a consistent direction as New Zealand. Oliver *et al.* (2005) cites Australian studies that have shown a positive effect of shelter on yields. One study by Bicknell showed yield increases in lupins and oats in the lee of a pine shelterbelt. Bird (1998) reported on the work of Lynch and Donnelly which demonstrated that artificial shelter could increase pasture production due to reduced evapotranspiration rates.

The National Windbreaks programme was started to address the lack of shelterbelt research in Australia. Some yield increase was demonstrated, but results were not convincing as wind direction was inconsistent resulting in fields not always being sheltered. A significant yield increase was only demonstrated when wind direction was consistent. Shelterbelts had no effect on ground water levels. The authors concluded that shelterbelts were only appropriate for certain sites (Cleugh *et al.*, 2002; Sudmeyer and Scott, 2002).

Nuberg and Mylius (2002) studied wheat growing near Adelaide with an artificial shelterbelt. Sheltered plants were 7 per cent more efficient in water use. Early in the season less water was lost from the soil in the sheltered site. Sheltered wheat conserved water early in the growing season and was more efficient in biomass production, but some of the saved water was used to support the extra biomass. There was no overall increase in grain yield under sheltered conditions. The authors commented that for farmers growing biomass crops shelter could be advantageous.

A large scale study in southern Australia looked at 32 different tree formations to investigate whether it was better to integrate, or separate trees for water resource management (Oliver *et al.*, 2005). Climatic effects had a large effect on results; some years it was better to have trees mixed with crops whilst other years not. A combination of factors could make the inter cropping more productive such as access to perched water tables, fields with consistent wind directions, trees aged less than ten years and low rainfall (less than 400mm).

9 Discussion

9.1 Benefits of shelter

Studies in Europe and other temperate zones have shown that shelterbelts can reduce wind speeds up to 30H from the shelterbelt. Crops and trees compete for water and light. This effect frequently disappears at a distance of 1 to 2H from the shelter belt, at which point yield increases may occur. The area at a distance of 1.5 to 9 times the height of the shelterbelt produces the greatest yield increases. Therefore based on these values it can be hypothesised that a 10m high shelterbelt of between 40-60 per cent porosity could reduce wind speeds over an area of 300m from the shelter. Yield reductions due to tree crop competition could be confined to within about 15m of the shelterbelt. The area between 15 and 90m from the shelter could have the greatest crop yields.

The effects of shelter can vary with year, crop, soil type, shelterbelt design, stage of crop development and geography (Kort, 1988; Bird, 1998). Bird (1998) stated that finding the particular factor which produced the yield increase can be difficult and quoted Davis and Norman (1988) who stated that 'shelter has multiple, interacting effects on crop processes which almost defy explanation'.

This review has presented evidence from temperate agricultural systems which suggest that shelterbelts can have a positive effect on water regimes. This effect is more pronounced under hot, dry conditions. Shelter can also effect plant growth sometimes increasing crop biomass or reducing mechanical damage. However, the introduction of trees into an agricultural system can result in competition for resources.

9.1.1 Shelterbelt and crop water regime

Farmers in drier areas of Europe are more inclined to plant trees (Dupraz *et al.*, 2005). Herzog (2000) stated that agricultural production was limited in northern Europe by light and in southern Europe by water. However, under climate change scenarios parts of northern Europe will experience water shortages. It has already been suggested that Mediterranean crop trials could start in southern England (Thompson *et al.*, 2007).

A study in Italy by Campi *et al.* (2009) showed that a shelterbelt could reduce rain fed durum wheat evapotranspiration rates and increase yields up to 12H from shelter. Likewise, Orfanus and Eitzinger (2010) found that in one of the driest parts of central Europe, evapotranspiration rates of alfalfa were reduced at 20m from an 8m high hedge. Canadian studies have also shown that shelterbelts can reduce crop evapotranspiration losses and increase crop yields (Pelton 1967; Kowalchuk and Jong, 1995).

The benefits of shelterbelts become more pronounced when the plants are water stressed and wind direction is consistent. Shelter induced yield increases of wheat and barley were only observed in the UK in the years when the weather was hot and dry (Hough and Cooper, 1988). Asse and Sidway (1974) also found that wheat growth benefited most from shelter in the drier years.

In contrast, a study in Denmark by Foerid *et al.* (2002) observed no yield increase with a shelterbelt of a hazel coppice, but the barley crop was not water stressed. In Australia shelterbelts have been used to protect crops against drought. Despite the hot conditions a study in Australia showed no positive effect of shelter on crop growth, as a result of inconsistent wind direction (Cleugh *et al.*, 2002; Sudmeyer and Scott, 2002).



Large networks of shelterbelts can also reduce evapotranspiration rates of crops by modifying local air humidity. In Poland large networks of shelterbelts act as water pumps cooling the air. Trees have high evapotranspiration rates, which humidify the environment reducing evapotranspiration crop losses (Ryszkowski and Kędziora, 2008). Shelterbelts can also exert a beneficial effect on soil structure increasing soil infiltration rates as demonstrated at Pontbren, Wales (Carroll *et al.*, 2006). Within two years of tree planting soil water infiltration rates were increased.

Foerid *et al.* (2002) in Denmark and Nuberg and Mylius (2002) in Australia both found that shelterbelts increased the amount of biomass produced by a crop. However, in both cases this did not result in higher grain yields. Shelter can also reduce mechanical damage to plants, reducing water loss from damaged tissue (Russell and Grace, 1979).

9.1.2 Tree crop interactions

Agroforestry experiments conducted in the UK have demonstrated that crops and native deciduous trees can be grown together and that by judicious mixing of crop and trees, economic returns can be maintained. (Sibbald *et al.*, 2001; Burgess *et al.*, 2005). Bergez *et al.* (1997) found that the introduction of trees into grazed pastures did not reduce the animal carrying capacity of the field. However, Sparkes *et al.* (1998) found that crop yields were reduced near the field edge due to shading. Careful selection of trees can reduce the negative effects of shelter. Deciduous trees are better than conifers as they have a leafless period which allows pastures to recover in winter from the adverse effects of shading.

Trees and crops can avoid being in the same competitive rooting space (De Montard *et al.*, 1998; Balandier *et al.*, 1994; Dawson *et al.*, 2004). Studies in the USA have shown that the zone of reduced yield next to a shelterbelt can be decreased by pruning tree roots (Lyles *et al.*, 1984; Hou *et al.*, (2003).

9.2 Shelterbelts in the UK

Shelterbelts laid out in the 19th century in Scotland have been neglected and their management for multiple purposes has resulted in them losing their effectiveness (Palmer *et al.*, 1997). A new initiative between the Forestry Commission and Quality Meat Scotland is now promoting the use of shelterbelts on Scottish farms. Livestock derive benefit from shelter gaining relief from cold winters and hot summers (QMS, 2010; QMS, 2011a; QMS, 2011b).

Shelterbelts can provide many ecosystem functions reducing the risk of soil erosion, water logging and flooding (Nisbet *et al.*, 2011). In addition, they can increase biodiversity, promote crop pollination from insects and improve the aesthetic value of landscapes. They can produce timber to supplement farm income and reduce green house gas emissions (Cleugh *et al.*, 2002). An environmental stewardship scheme report found that hedges provided 19 ecosystem functions (DEFRA, 2009).

9.3 Benefits of shelter on the water regime of crops

The evidence in this review suggests that under the right conditions shelterbelts can enable crops to use water more efficiently. Table 2 summarizes some of the observed effects of shelter. In the UK there has been little research covering the benefits of shelterbelts on crop water regimes. However, studies from drier parts of the world have shown that shelterbelts are beneficial when wind direction is consistent and water is limiting to plant growth. To be effective shelterbelts should be of the correct porosity and have a suitable tree crop mix. Shelterbelts composed of native deciduous trees are a good choice as they are well adapted to local conditions and have a leafless period which can reduce the negative impacts of shading on crop growth.

Based on the evidence presented in this review shelterbelts could counteract the negative effects of heat waves and droughts that climate change scenarios suggest. Shelterbelts can be viewed as an insurance policy, they may not provide yield increases every year, but they can buffer crop production when extreme weather events strike (Sudmeyer *et al.*, 2007). Droughts are predicted to become more common place in the UK and shelterbelts could have a beneficial effect on the water regimes of crops and pastures. As Caborn wrote in 1955 “From this evidence it should be apparent that there is a place in the rural economy for shelter-belts both on arable and hill farms” this is even more relevant today when considering the threats to UK food security from climate change.

Author	Country	Tree/Crop/Formation	Effect of shelter
Orfanus and Eitzinger (2010)	Austria and Slovakia	Hedge/Pasture/Shelter	Evapotranspiration rate reduced
Campi <i>et al.</i> (2009)	Italy	Conifer/Arable/Shelter	Evapotranspiration rate reduced
Kowalchuk and Jong, (1995)	Canada	Deciduous/Arable/Shelter	Evapotranspiration rate reduced
Pelton (1967)	Canada	Artificial/Arable/Shelter	Evapotranspiration rate reduced
Ryszkowski and Kędziora (2008)	Poland	Deciduous/Arable/Shelter Deciduous/Pasture/shelter and some conifers	Air humidified Less energy available to drive ET
Hough and Cooper (1988)	UK	Artificial/Arable/Shelter	In drier years yield increase
Asse and Sidway (1974)	USA	Tall wheat/Arable/Shelter	In drier years yield increase
Nuberg and Mylius (2002)	Australia	Artificial/Arable/Shelter	Increase in water efficiency, but not grain yield
Foerid <i>et al.</i> (2002)	Denmark	Deciduous/Arable/Shelter	Earlier anthesis, increase biomass, but not grain yield
Russell and Grace (1979)	UK	Artificial/Pasture/Shelter	Reduced mechanical damage Yield increase regrowth period
Carroll <i>et al.</i> (2006)	UK	Deciduous/Pasture/Shelter	Soil infiltration rates increased
Dawson <i>et al.</i> (2001)	UK	Artificial/Pasture/Alley	Roots avoided same competitive space
Balandier <i>et al.</i> (2008)	France	Deciduous/Pasture/Alley	Roots avoided same competitive space
De Montard <i>et al.</i> (1999)	France	Deciduous/Pasture/Alley	Roots avoided same competitive space
Hou <i>et al.</i> (2003)	USA	Deciduous/Arable/Shelter	Root pruning increased yield, and soil water content
Lyles <i>et al.</i> (1984)	USA	Deciduous/Arable/Shelter	Root pruning increased yield
Bergez <i>et al.</i> (1997)	UK	Deciduous/Pasture/Alley	8 year old trees incepted 8% of the light

Table 2
Main conclusions from the major shelter studies found in the literature.

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Appendix

General	Wind speed	Microclimate	Tree/crop
Agroforestry	Shelter	Microclimate	Water competition
Silvopasture	Wind speed attenuation	Evapotranspiration	Water uptake
Silvoarable	Wind speed reduction	Soil evaporation	Water requirements
Tree-Pasture	Wind break	Plant transpiration	Water use
Tree-arable	Shelterbelt	Shading Light interception	Water regime
Forest edge	Wind Shelter	Heat advection	Tree placement
Hedgerow	Wind flow	Radiation	Tree density
Orchard	Aerodynamics	Air/Soil temperature	Tree spacing
Field margin		Vapour pressure deficit	Tree age
Agroecosystem		Humidity	Root length
Parkland		Vapour transfer	Root architecture
Temperate			
Native broadleaved			
Deciduous			
Irrigation			
Drought			
Climate change			
Precipitation			
UK			
England			
Wales			
Scotland			
Britain			
Ireland			
Europe			
Canada			
USA			
New Zealand			

Table 1
Keywords used in literature search.

Databases	Websites
Google Scholar	Forestry Commission/Forestry Research
Web of Science	The Woodland Trust
PhD theses UK thesis	Centre for Ecology and Hydrology
Science Direct	Natural England
Open fields	Countryside Council for Wales
IngentaConnect	Scottish Natural heritage
Oalster	ADAS
Cam Abstracts	Farm woodland forum
	Campaign for the farmed environment
	Scottish Environment Agency
	European Environment Agency
	National Farmers Union
	RSPB
	Shropshire Hills

Table 2
Literature sources.



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