ENGLISH HERITAGE

# Miscanthus, short-rotation coppice and the historic environment

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# 1 Introduction

The land cover of England is the result of a combination of natural and physical processes and the influence of external drivers that have changed over timescales of decades, centuries and millennia. These processes and influences are still shaping our land cover and will continue to do so in the future. Outside urban areas, the land cover is predominantly influenced by agriculture and changes can happen over short time scales, as rapidly as from year to year, as farmers respond to economic pressures and market opportunities. Since the World Wars, agriculture has essentially been synonymous with food production but, at the end of the twentieth century, low profit margins from food crops, coupled with concerns over oil supplies, resulted in an increasing interest in non-food crops, particularly those that could be used as feedstocks for energy. Non-food crops, specifically grown for energy production, are called biomass crops and include grasses and trees which would be a significant change in land-use from arable agriculture. This has raised concern about the lack of knowledge on possible impacts of such a potentially large-scale land cover change, for example on water, biodiversity and the historic environment. This report describes a literature review of the aspects that are likely to be relevant to the preservation of the historic environment, of the two biomass crops commercially grown in England: short rotation coppice willow and *Miscanthus*. As such, it mainly considers the subsurface environment and makes comparisons with other, selected rural land covers: conventional crops, grassland and woodland. The report is structured to represent the major issues that have been considered:

- The current and future scale and distribution of biomass plantings;
- Impacts of mechanical operations;
- Soil water content;
- Soil chemistry and water quality

These are discussed in detail in the relevant sections and an extended summary is included which omits the discussion of the evidence base.

# 2 Extended Summary

## *2.1 Background*

Short rotation coppice (SRC) willow and *Miscanthus* are classed as biomass crops – grown with the primary objective of harvesting and using virtually all the above ground growth (the biomass) for energy or other non-food uses. There are a number of potential uses but the current dominant driver is to use the biomass as a feedstock for energy production. In terms of their management and crop cycle they are very different to conventional crops – see section 2.3.

Interest in biomass crops, in the UK, began during the oil crisis of the 1970's and was driven by a rise in fossil fuel prices. Initially, this interest focussed on short rotation coppice (SRC), especially willow which had been the subject of research previously. Although market interest in biomass subsequently decreased, with the fall in oil prices, research continued so that, when farmers were searching for alternative crops in the 1990's, there was a body of knowledge about biomass crops that could be drawn on. SRC willow and *Miscanthus*, a semi –temperate grass, have emerged as the preferred dedicated biomass crops in the UK. The recent interest in biomass crops is driven dominantly by: as sources of alternative incomes for landowners, as a means of climate change mitigation; as security of energy supply.

The anticipated end-uses of biomass crops have increased over the last 20 years. Originally, they were seen as being used in direct combustion, for heat and/or electricity generation. Direct combustion for heat is still the most thermally efficient method but is not widely used in the UK. Thermal conversion to produce electricity is done on a large scale, either in dedicated plants or mixed with coal (co-firing). However, most of the biomass used in these plants is currently imported. In the future, it is expected that biomass crops will be used as feedstock to produce biofuels, using so called second generation processes, but this technology is not currently operational commercially.

Three key attributes are required from a biomass crop in order for it to be cost effective:

- High output
- Low input
- Harvested material suitable for end use

In practice, high output is synonymous with high yield because there is little variation in the calorific content per unit dry matter between the dominant crops. A low input is required to minimise the initial and recurrent costs. As a result, perennial crops, with an economic life time of about two decades, tend to be preferred over annual crops in order to reduce establishment costs. In addition, efficient recycling of nutrients, low incidence of diseases and insect pests, and low weed control requirements also reduce input costs. Finally, an end product that has low water content and low concentrations of elements that could be detrimental to the processes used for energy production is required.

## *2.2 Summary of the issues relevant to the historic environment*

The table below draws together the information reviewed with respect to different issues (rooting depth, soil compaction etc.) into a simple classification which depicts whether a change from a conventional land cover to either of the biomass crops is neutral, positive or negative for a given issue. It is an approximation based on the overall findings, which for many issues are in need of further study. As such it should be used with extreme caution and only with reference to the section dealing in detail with the issue concerned.

| | SRC willow as compared with: | | | *Miscanthus* as compared with: | | |
|---|---|---|---|---|---|---|
| | arable crops | grassland | woodland | arable crops | grassland | woodland |
| Rooting depth | | 3.1.3 | | | 3.1.3 | |
| Crop establishment | | 4.1.1 | | | 4.1.1 | |
| Crop removal | | 4.1.4 | | | 4.1.4 | |
| Soil compaction | | 4.1.6 | | | 4.1.6 | |
| Soil erosion | | 4.1.7 | | | 4.1.7 | |
| Soil water content | | 4.2 | | | 4.2 | |
| Soil water quality | | 4.3.1.2 | | | 4.3.2.2 | |
| Soil chemistry | | 4.3.1.1 | | | 4.3.2.1 | |

Negative - significant issue for consideration if replaced by the biomass crop

Neutral - no significant change anticipated if replaced by the biomass crop

Positive – significant improvement if replaced by the biomass crop

**Table 1 Comparison of the issues which might impact on the historical environment of SRC willow and *Miscanthus* with other land covers. The red blocks highlight potential issues for concern. The numbers in the cell are the Sections in this report which discuss that issue. NOTE this table only gives indicative classifications and readers must refer to the details in the relevant text.**

## 2.3 The characteristics of SRC willow and Miscanthus

Compared to conventional agricultural crops, these crops:

- are perennial and likely to be *in situ* for around 20 years; there are no annual cultivations;
- have relatively low plant population densities;
- are usually harvested later – in the winter or spring;
- are taller, up to 3 m for *Miscanthus* and 8 m for SRC willow, for a large part of the year
- are deeper rooting, potentially in excess of 2 m;
- less mechanical operations are required.

Willow uses the $C_3$ photosynthetic pathway (as do the vast majority of plants in the UK). It is usually planted in the spring. The plants are cut back at the end of the first year to stimulate coppicing, i.e. the production of more branches at ground level. The first harvest is then taken three years after cutback, i.e. four years after planting. Harvests are subsequently taken at regular intervals, generally every three years, the rotation period. A leaf litter layer accumulates, due to leaf fall in the autumn, which helps to recycle nutrients. Herbicides are often required in the establishment year, and again after cutback and each harvest. Fertilizers can also be applied after each harvest, when the crop is short enough for conventional application equipment to be used.

*Miscanthus* has the $C_4$ photosynthetic pathway (generally found in tropical or semi-tropical grasses) but it can grow more efficiently at low temperatures than most other $C_4$ plants. It is a rhizomatous grass; the rhizomes are the below ground storage and perennating organ. The hybrid of *Miscanthus* grown for biomass, *Miscanthus x giganteus*, is a naturally occurring inter-specific hybrid which does not set fertile seed and so has to be multiplied vegetatively. The usual method of propagation is to use pieces of rhizome, harvested from crops two – three years old, which are usually planted in March – April. At the end of the first year there is insufficient growth for economic harvesting, so the aerial biomass is mown and left in the field. This starts the build up of a layer of mulch on the soil which is added to in subsequent years by the *Miscanthus* leaves which drop off in the late summer and autumn before each harvest. The mulch helps to suppress weed growth and conserve water. The first proper harvest is taken at the end of the second year, and the crop is then harvested annually, usually around March. Herbicides are used at establishment, and occasionally in mature crops. Most commercial crops currently receive no fertilizer.

Both biomass crops are established with a relatively wide spacing between plants and rows when compared with conventional agricultural crops. In the case of *Miscanthus*, the rhizomes spread slowly so the rows ultimately disappear and a uniform stand results.

Both crops are deeper rooting than conventional crops, which can cause concern to growers as the roots may block field drains, where these are present. It is thought that this is more likely to occur with willow. The rooting depths of the biomass crops are, however, comparable to those of trees.

## 2.4 The scale and distribution of biomass crop plantings - current and future

In England, the Energy Crops Scheme, which started in 2001, pays a planting grant to growers of *Miscanthus* and SRC. The current areas planted under this Scheme are scattered throughout England but they are more common in the South West and the East Midlands. Some crops were planted before the Scheme started, notably about 2000 ha of SRC for the ARBRE project, in Yorkshire, in the late nineties. Some *Miscanthus* was also established prior to the Scheme starting and, since 2001, some crops have been planted outside of the Scheme, usually because they were grown for uses other than energy, e.g. *Miscanthus* for rhizome production and horse bedding. So in total, there is likely to currently be around 10 000 ha of dedicated biomass crops in England, approximately two thirds of which is *Miscanthus* (*cf* 3,700,000 ha of cropped land in England)

It is very difficult to estimate the future scale of biomass crops as it will be influenced by a number of factors, e.g. the profit margins of conventional crops; the price of fossil fuels; regulatory schemes promoting renewable energy; farmers perceptions etc. A number of these factors are global and so not easily predicted as they, in turn, reflect global economic and political conditions.

There are currently, in 2009, three drivers suppressing the uptake of biomass crops. Firstly, although the profit margins from food crops have declined since the peak in 2008, higher profit margins on conventional crops reduces the farmer’s interest in planting biomass crops.

Secondly, the EU has reduced the requirement for set-aside to 0%, because of high grain prices and low grain stocks This affects the planting of biomass crops because the regulations allowed the planting of non-food crops on set-aside. Thirdly, there was a temporary disincentive because the re-writing of the Energy Crops Scheme took longer than expected.

In contrast, there are two favourable factors encouraging the market for biomass crops. Firstly, the prices of fossil fuels reached all time highs in 2008 and, although they subsequently fell significantly as a result of the downturn in the global economy, higher prices are anticipated to be the norm in the longer term, encouraging the search for cheaper alternatives. Secondly, the proposed changes to the Renewables Obligations should increase both the demand and price of biomass. In the long term, the development of second generation biofuels, which use ligno-cellulose as a feedstock, will increase demand for biomass crops.

In the longer term, the UK Government's Biomass Strategy has identified that up to 350 000 ha may be used for biomass crops by 2020. Although this is now interpreted as an aspiration rather than a target, it indicates the scale of planting required to meet the Government's objectives.

Just as it is difficult to predict the scaling of planting, it is also difficult to predict where it will be grown as this is likely to be influenced by the end use of the crop. Where the use is small scale, e.g. for an office or school, the planting will be small scale and the distribution close to the user; a few fields near the locality will be sufficient. In contrast, where the use is large scale, e.g. a dedicated biomass power station, the plantings are likely to be clustered around farm businesses that have decide to plant a significant proportion of their land with biomass, in a region around the user. In the longer term, the development of very large scale demand, e.g. a biorefinery producing biofuels, may result in the catchment for feed stocks being substantial, probably including imports from outside the UK.

The nature of the landscape will also influence the distribution of biomass crops. Currently, most biomass crops have been established on arable land but, future planting may replace grassland. In addition there are constraints in terms of: the soil type, climate and the efficiency of mechanical operations. In particular low temperatures or, to a lesser extent, low summer rainfall may restrict the yield and thus make it unprofitable to grow biomass crops in particular areas.

Future climate change may have an impact on the choice of where biomass crops are planted, although there is a complex interplay of a number of factors so it is difficult to currently form any specific conclusions. Factors that may have an effect are:

- Higher levels of atmospheric $CO_2$ acting to "fertilise" the crops;
- Increased concentrations of ozone in the lower atmosphere may result in crop damage;
- Predicted increases in average temperatures will extend the growing season and may also allow the crops to be grown in areas which were previously too cold;
- A decrease in summer rainfall may result in growth being limited even more by water availability, particularly in areas of low summer rainfall.

## 2.5 Subsurface impacts of mechanical operations

Due to their perennial habit, subsurface mechanical operations for biomass crops only occur prior to establishment and during plantation removal. An exception is the production of

*Miscanthus* rhizomes, for planting material, which are obtained from crops that have been grown for three years, usually with a higher planting density than biomass production crops. The rhizomes are harvested using one or two passes of a rotary tiller to break up the rhizomes, with pieces then lifted using a stone picker or a bulb/potato harvester, and so the mechanical operations are within the depth of normal mechanical operations for conventional crops.

The operations required for planting SRC willow and *Miscanthus* are fairly similar to each other. Planting takes place in Spring; between February and June are the maximal though, for best results, between March and May is preferred. Preparation before planting could include removal of large stones to facilitate machinery operations, but this is rarely if ever done in the UK. Occasionally, where appropriate, the soil is subsoiled to 35-40cm before planting, e.g. to remove a plough pan which can limit growth. The soil is then ploughed 20-30cm deep in autumn using standard farm equipment and left to overwinter to aid breakdown of soil by frost. Shortly before planting both crops, the land is cultivated to produce a fine tilth. These soil tillage requirements are typical of most agricultural crops, and where the crops are being grown on arable or non-permanent grassland, it is most likely that similar operations would have been carried out many times previously for the other crops. *Miscanthus* rhizomes are planted fairly shallow, 5- 20cm, as emergence from deeper planted rhizomes takes longer reducing the establishment and survival rates. Planting of SRC willows generally uses semi-automatic step planters which cut rods of willow into cuttings, 18-25 cm long, which are inserted into the soil vertically, before firming the surrounding soil.

Thus the mechanical operations required for planting biomass crops do not differ significantly from those required for conventional crops.

In contrast, plantation removal is not usually required for conventional crops; even in the rare case of removal of woodland, e.g. for habitat restoration, passive methods are used. In general, a biomass crop plantation will be removed at the end of its economic life, which is anticipated to be about 20 years. However, it could occur earlier for a number of reasons, e.g. poor productivity, economics or plant breeding improvements. In the case of *Miscanthus* the procedure is comparatively simple as it involves the application of a post emergence herbicide in the spring, followed by ploughing or rotovation which is unlikely to be to a depth greater than 30 cm and thus comparable in depth to ploughing for a conventional crop.

The removal of SRC willow is a more complex matter and the method used tends to reflect the age of the plantation. Plantations under two years old are removed by the plants being ploughed back into the soil using a conventional plough. Plantations that have undergone one or two harvest rotations can be removed in a similar manner to that used with *Miscanthus*, i.e. application of a post emergence herbicide in the spring, followed by ploughing. The application of a herbicide in the spring is also used for removing mature plantations, but there are a number of options for removing the stump. Ploughing may be used but the timing of this will depend on the size and decay rate of the stump; it could be up to three seasons after the application of the herbicide. Mulching the soil and stump/root material decreases the time taken to convert the land for establishing another crop. It might be possible to use a tractor driven mulcher to a depth of 4-7 cm. Older plantations can be mulched to up to 90 cm depth using one or two passes of a modified peat cutter to reduce the biomass to wood chips, however we have not known of this being done in the UK. Complete removal of the stumps is possible, using a bucket attached to a digger to lever the stumps out, followed by cultivating to remove the finer roots. However, this method is also expensive and can adversely affect the soil structure and so is likely to be used rarely. Thus the removal of mature SRC willow plantations could involve mechanical operations to a depth of 90 cm, substantially deeper than any mechanical operation generally associated with a conventional crop although comparable to some used in forestry.

## 2.6 Soil compaction and erosion

Soil compaction usually affects just the topsoil, but in some circumstances may also affect the subsoil. Compaction increases soil bulk density and has a negative effect on the number and volume of pores and associated organisms. Furthermore, water and air permeability is decreased and there is a greater root penetration resistance. Consequently soil compaction from machinery can affect the entire soil system. Although there are few studies focussing on biomass crops, comparisons can be made between the pressure exerted by conventional equipment and equipment used for biomass crops, and hence predictions of effects can be made.

The number of vehicle passes that a field receives coupled with the weight and pressure exerted from a pass are key factors in understanding likely soil compaction and its extent in a field. A pass of machinery counts as one vehicle moving over the soil, i.e. a tractor and trailer constitutes two passes.

Wheels ruts are the most common form of damage and source of compaction. They are caused by soil being pushed out and up from underneath wheels, causing increased soil density under the rut. Soils with greater clay content suffer deeper ruts. The exposing of the lower soil increases risks of soil erosion, which is more likely to occur on steeper slopes.

The amount of soil water is the most important factor determining the soil compaction process and the soil water content should be below the plastic limit to prevent long term damage. During the winter months a general increase in water content leads to a reduction in the number of working days available.

Once the SRC crop is established, the dominant mechanical operation is harvesting. The two types of harvester, used for SRC willow in the UK, both require tractors and trailers to collect the crop from the harvesters and it is possible that several tractors and trailers may follow a harvester. Studies have concluded that the harvesters cause minimal ground damage but the tractors and trailers cause rutting which can be significant in wet conditions. It should be noted that harvesting generally occurs every third year.

In contrast, the harvesting of *Miscanthus* is more typical of a conventional crop, due to the annual cycle and the lack of definable rows. The limited data available suggests that the harvesting machinery does not affect the soil. It is speculated that the increasing levels of soil organic matter, coupled with the production of a root and rhizome mat, may help prevent soil damage.

Conventional, annual, crops allow the grower the opportunity to sub-soil to remove the effects of compaction. This option is not available with biomass crops but the available evidence suggests that soil compaction is less of an issue with biomass crops due to the reduced number of mechanical operations.

In the UK, the average annual amount of soil formation is over an order of magnitude less than the average erosion rate of cropland. This is dominantly because removing the ground cover, thus exposing bare ground to the environment, increases the risk of sediment loss through water and wind erosion. It should be noted that soil erosion can result in deposition elsewhere, increasing the soil depth. Soil type and location affect the amount of sediment loss, but in general, processes removing the finer soil particles reduce soil depth and increase bulk density. During biomass crop production the highest risks of soil erosion occur during establishment, harvesting and final plantation removal. For up to 24 months during establishment, and dependent on the removal method used, up to another 24 months at the end of the plantation lifetime, soil erosion is likely to be high at vulnerable sites. Harvest erosion losses occur across a much more restricted time frame than with conventional crops. There is very little information about soil erosion rates for biomass crops but what there is suggests that the rates are significantly less than those for arable crops and may be comparable with those from grassland. They appear to be higher than those associated with undisturbed forest but comparable to those for harvested forests, although they may be lower during the establishment phase.

## 2.7 Soil water content

The soil water content is a complex function of: the rates of precipitation and irrigation; the rates of evaporation (dominantly determined by the vegetation structure), the root depth and density; and the soil hydraulic properties. In England the dominant factor determining the seasonal evaporation rates is the amount of downward solar radiation at the land surface; so evaporation rates are at their lowest during the winter and highest during the summer. An exception to this can occur with coniferous woodland as the greater aerodynamic roughness can result in evaporation rates during the winter that are comparable to those in summer. In contrast the average monthly precipitation rates are either higher in winter, mainly in the west of the country, or similar throughout the year. The balance between these rates means that soil water deficits (which are defined as water contents less than the water content at which drainage ceases) are very rare in winter. So, for a change in land cover at a specific location (i.e. with a defined soil and climate) the major factors determining the extent of soil water deficits are the evaporation rates during the summer and the rooting depth and density. Most vegetation roots down to a depth of at least 0.8 m, so soil water deficits can be anticipated to a depth of at least 1 m, allowing for a capillary fringe, in virtually all conditions except where the water table is shallower than this depth, e.g. close to a permanent body of water. Thus, in the context of this report, changes between vegetation types with shallow rooting depths and those with deep rooting depths is important. Both SRC willow and *Miscanthus* have rooting depths of up to 2.5 m, i.e. deeper than grass and most agricultural crops (exceptions are maize, which can develop roots down to 2 m and oilseed rape which can root down to 1.5 m)

Although *Miscanthus* is a cold tolerant $C_4$ plant, for growth, it needs temperatures a few degrees higher than those for the vast majority of other vegetation in England (an exception is maize which is also a $C_4$ plant, but not cold tolerant). Thus the period when it has a well developed green canopy, and thus evaporation rates are highest, starts later than most other vegetation and will stop earlier in the autumn; except for annual crops most of which will have started to senesce earlier. A further factor to consider is that, on average, plants with the $C_4$ photosynthetic pathway use half the water per unit biomass increase compared to those that use the $C_3$ photosynthetic pathway. So *Miscanthus* has average evaporation rates during the growing season which are comparable to those of woodlands but higher than those of grass or cereals. It is assisted in maintaining these evaporation rates by its rooting depth, potentially up to 2.5 m. As a consequence, *Miscanthus* replacing conventional crops and grassland is, in most situations and for average weather conditions, likely to result in greater soil water deficits extending to greater depths.

The situation for SRC willow is similar to that for *Miscanthus*, i.e. replacing conventional crops and grassland is, in most situations and for average weather conditions, likely to result in greater soil water deficits extending to greater depths, although there are differences in detail. SRC willow has a root depth similar to *Miscanthus* but its growing season is longer although this is counter balanced by slightly lower evaporation rates during this period. There is a complication in the form of the three year rotation as, for the same weather, the evaporation rates differ in each successive year as the crop grows.

## 2.8 Soil chemistry and water quality

Because SRC willow varieties have been selected and grown commercially for at least 20 years, there is a reasonable body of research available, although much focuses on the issues of leaching of fertilisers. In terms of soil chemistry, there are reports of low to moderate uptake of metal pollutants and this seems to be linked to the effects of dissolved organic carbon (DOC) mobilising the pollutants and so increasing the uptake. Increases in soil carbon are reported but micronutrients, such as boron, might be depleted. The leaching of nitrogen and phosphorus is reported to be lower than from grain crops, ca 30-50%. In part this seems to be because smaller amounts of fertiliser need to be applied due, in part, to nitrogen in the leaves being re-distributed to perennating organs, such as stems and roots, in the autumn. In addition, leaf fall will act to recycle nutrients in the soil. The result is that, although some nutrients are lost at harvest, this can be made good with modest applications of fertiliser.

In comparison, there is relatively little information about *Miscanthus*. So far, studies have focussed on the issues of soil carbon and nitrogen and phosphorus in fertilisers. In the UK, commercial practice is generally not to apply fertilisers and the current evidence suggests that aerial deposition of nitrogen is sufficient to meet the plants needs. As a consequence, it is thought that rates of nitrate leaching below *Miscanthus* crops, will be low, probably comparable to extensively managed grasslands, rather than arable crops.

There is concern that, were grassland to be ploughed up for biomass crops, the supply of nitrogen from mineralization would exceed the crop's requirements resulting in an increase in nitrate leaching, particularly in the first five years.

Biomass crops generally have higher nutrient use efficiencies compared with annual food crops because they remobilise nutrients at the end of the growing season and store them in vegetative structures until next year's growth. In addition, the $C_4$ photosynthetic pathway of *Miscanthus* is more nitrogen-use efficient than the $C_3$ pathway of conventional UK crops. Growing perennial energy crops instead of annual food crops reduces the risk of water pollution through leaching and runoff, due to reduced input of fertiliser, longer growing season, soil cover all year round and a more extensive root system. Nutrient use differs somewhat between *Miscanthus* and SRC willow, with willow appearing to require more. Nitrate and phosphorus leaching could be reduced under perennial biomass crops relative to arable and indeed these crops have been suggested to remove nutrients from polluted water or metals from polluted land. Soil pH appears to become slightly more acidic under energy crops than arable crops and there is an increase in soil carbon content with an increase or improvement in associated soil properties such as cation exchange capacity, hydraulic conductivity and aggregate stability.

## 2.9 Recommendations

- This report should be updated in about 3-5 years time to take advantage of information that becomes available and thus reduce uncertainties;
- A study should be carried out into the impacts of commercial machinery, for biomass crops, operating in commercial fields;
- A study, involving numerical modelling, should be carried out to allow a comparison of the developments of soil water deficits under different land covers, for a variety of soils and climatic conditions found in England, to inform those interested in the historic environment;
- A study should be made of the soil chemistry and water quality issues that are relevant to the historic environment, under biomass crops and, if there is a lack of information, other land covers.

# 3 Background

Interest in biomass crops, in the UK, began during the oil crisis of the 1970's and was driven by the rise in fossil fuel prices. In the case of coppice willow, there has been active research programmes since the 1920's, at Long Ashton Research Station, Somerset, primarily due to the importance of willow for basket making. By the 70's, as other materials became available, the basket-making industry reduced in size to a specialist craft industry. However, the ability of willow to produce high yields from low inputs and the suitability of the wood for use as a biomass fuel had become recognised.

Subsequently, as the oil price came down, the interest in biomass diminished, but the research was continued. By the early 1990's farmers and growers were keen to have alternative profitable uses for their land, as a result of reducing income from conventional arable crops and the introduction across the EU of compulsory set-aside. Simultaneously, there were governmental incentive schemes for renewable energy projects (e.g. Non Fossil Fuel Objectives, NFFO's). The result was that interest in biomass crops revived, and along with willow, *Miscanthus* grass was identified as an ideal plant for biomass production in temperate climates. At the same time, non-food uses of conventional crops were developed, e.g. enabling oilseed rape to be grown for industrial lubricant uses on set-aside land.

Through the nineties, as concerns about climate change grew, biomass energy systems were seen not only as a source of alternative income for landowners, but also as one route for climate change mitigation. These two drivers for growing biomass continued into the 2000's. Most recently, the rise in fuel use in the transport sector has led to concerns over future supplies of liquid transport fuels and a push for substituting these with biological alternatives. In the US, fuel security has been a primary driver and has led to the rapid expansion of bio-ethanol refineries. In the EU the main driver is climate change, as the transport sector is currently the only one with rising greenhouse gas emissions.

There can be confusion between the terms biomass, biofuel and bioenergy. Throughout this report we adhere to the commonly used definitions: biomass refers to crops producing high yields of ligno-cellulosic material. The term biofuels refers to the production of liquid transport fuels, for example, bioethanol or biodiesel. Bioenergy covers both these systems, and also renewable energy systems such as anaerobic digestion of plant and animal wastes, i.e. it is derived from recently living organisms or their metabolic by-products.

Through the 1970's and 80's, the expected end-use for biomass was direct combustion, either for heat or for electricity production from steam turbines. However, a wide range of end-uses and conversion processes is now envisaged. Direct combustion for heat is still the most thermally efficient process, but it is not yet widely used in the UK. Thermal conversion to produce electricity is deployed on a large scale in the UK at a few dedicated generation plants, and also through co-firing at most coal fired power stations.

There are several technologies for generating renewable electricity, for example wind, tidal, wave, but currently only crops provide alternatives for liquid transport fuels. "First generation" renewable transport fuels use seed from oilseed crops as a feedstock for bio-diesel or grain or sugar for ethanol production as a replacement for petrol. "Second generation" transport fuels will use biomass crops as the feedstock, which will either be processed to fuels via biological conversion, though breakdown of the lignocellulose followed by saccharification, or thermal conversion, though gasification and the production of synthetic hydrocarbon fuels from the syngas. Life cycle analysis of second generation transport fuels shows them to have higher energy savings and significantly lower green house gas emissions associated with their production than first generation fuels.

Other sources of plant biomass include forestry, and potentially algae, however these are not considered in this report.

### 3.1 What are biomass crops?

During the 1990's over thirty plant species were evaluated at Rothamsted Research to determine their suitability as biomass crops. Based on the results, together with those from trials conducted by others in similar temperate climates, three grass and two woody species were identified as having potential: *Miscanthus* (*Miscanthus x giganteus*), switchgrass (*Panicum virgatum*), reed-canary grass (*Phalaris arundinacea*), and the two woody species, both grown as short rotation coppice (SRC), willow (*Salix spp*.) and poplar (*Populus spp*.).

Currently, in the UK, only *Miscanthus* and SRC willow are commercially produced (Figure 1), with insignificant areas of the other crops grown. A total of 1,671 ha of willow and 5,772 ha of *Miscanthus* has been planted under the Energy Crops Scheme. Some areas of both crops have been established without grant aid, either because they were planted before the scheme started, or else because they did not qualify for grant for various reasons. Therefore the actual area planted is somewhat greater, possibly as much as 10,000ha. In comparison, agricultural holdings in England cover approximately 9,290,000 ha (about 71.3% of the total land area) of which crops account for about 3,700,000 ha

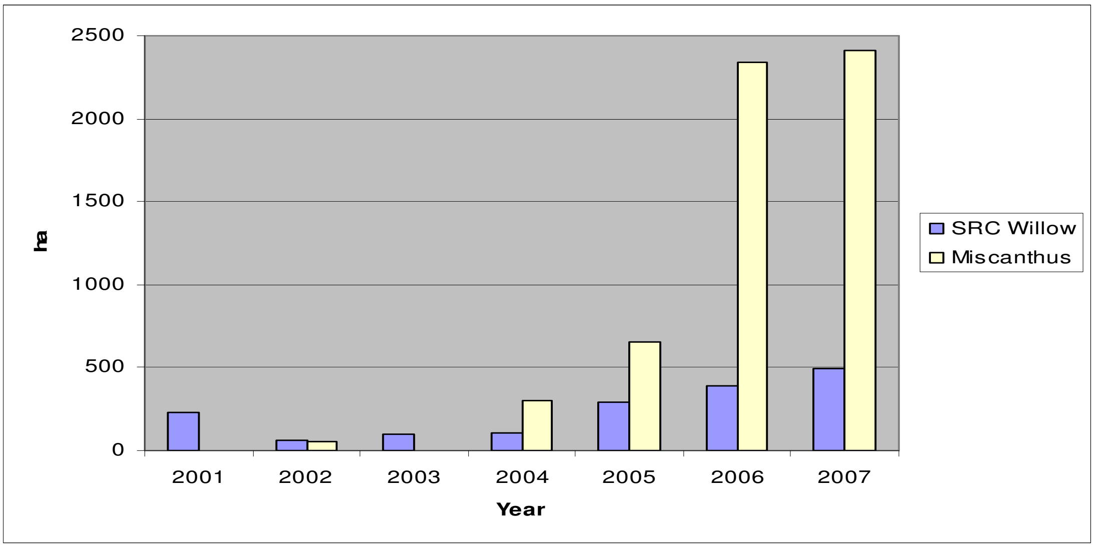


**Fig 1. Areas of *Miscanthus* and SRC willow planted in England each year, from 2001, receiving the Energy Crops Scheme planting grant.**

Plant species need to have three key attributes to be suitable for biomass cropping:

- High output
- Low input
- Harvested material suitable for end-use

In reality high output means high yield. Most if not all the varieties studied have a similar calorific content on a dry matter basis, so in order to maximise energy yield, total biomass yield needs to be high. NIAB (2007) draws together the yield data from the UK. These data give an average annual yield for *Miscanthus* of 13.1 (±3.4) t DM $ha^{-1}$ from seven sites at year three for *Miscanthus* and 10.1 (±1.5) t DM $ha^{-1}$ $yr^{-1}$ for 18 varieties of SRC willow over six years at four sites. These yields should be considered indicative as they are from trial plots with a limited spread in locations across the UK. The energy equivalent of these yields is an elusive quantity as it depends on the end use of the energy produced and the conversion process used. Nevertheless, taking the value of 1.47 $MWh_e$, used in the UK Biomass Strategy (Defra, 2007) for electricity generation from biomass crops, means that each hectare of biomass crops will produce about 17 $MWh_e$ of electricity.

**Box 1: Photosynthesis**

All plants use the process of photosynthesis to convert carbon dioxide to plant material. There are two different types of photosynthesis, commonly known as $C_3$ and $C_4$. $C_4$ plants have bio-chemical, physiological and morphological adaptations to facilitate $CO_2$ concentration in a particular site within the leaf. They can achieve higher rates of photosynthesis with less nitrogen than their $C_3$ counterparts. $C_3$ plants typically grow at lower temperatures than $C_4$ plants, and this becomes an important consideration in cooler climates where the temperatures may rarely be sufficient for the $C_4$ process. The optimum temperature for $C_3$ photosynthesis is in the range 15-30 ˚C whilst for $C_4$ it is 30-45 ˚C. Most crop plants grown in the UK are $C_3$'s; maize is the only commonly grown $C_4$. $C_4$ plants have the benefit of using nutrients, light and water more efficiently than $C_3$ plants and hence, in suitable climates, tend to have a higher yield potential. *Miscanthus* is unusual in that, despite using the $C_4$ process. its optimum temperature range seems to lie between the usual values for $C_3$ and $C_4$.

Low input is needed to maximise the energy return; a high energy yield with low energy input gives a high energy return. To achieve low input, perennial species are preferable to annual species, as there is a one off establishment cost in the plantation lifetime. It is currently expected that, for the species studied, plantations should be economically viable for at least 20 years. A further condition required to achieve low input is that species with low fertilizer requirements are very desirable because the fertilizer, especially if it is nitrogenous, has a very high energy, and consequently Greenhouse Gas (GHG), cost. It is known that *Miscanthus* belongs to a group of plants (Box 1) that uses nitrogen efficiently, however, some woody species, such as willow, are almost as good. It is also desirable to select species with low incidence of insect pest or disease susceptibility, and low weed control requirements as this minimizes the requirements for agrochemicals, which again have a significant energy and GHG cost. Low input requirements also indicate low financial growing costs.

When selecting a crop for biomass production it is important to consider the end-use. In most situations, biomass with a high dry matter/low water content is required. This reduces transport costs (as less water has to be transported), allows for easier storage, and maximises the net calorific content for most end-uses. It is also important to consider the elemental content of the biomass, and whether any undesirable elements are present, or whether their concentration is of significance.

### 3.1.1 SRC Willow

Willow is a $C_3$ plant. It is planted as stem cuttings in spring at around 15 000 plants $ha^{-1}$. The established practice is to plant a number of varieties, interspersed throughout a particular field, in order to limit the spread of disease. At the end of the first year the plants are cut back, with a tractor mower, which stimulates coppicing, i.e. the plants respond by producing more branches in the following spring. The first harvest is then taken three years after cutback, i.e. four years after planting. Harvests are subsequently taken at regular intervals – the rotation period. Willow grown for biomass is usually harvested once every three years, although some growers harvest on a two or four year rotation, Figure 2. The length of the harvest cycle depends partly on the amount of growth; where growth has been very good a shorter rotation may be used, and where growth has been poor then growers might use the longer rotation. Herbicides are required in the establishment year, and again after cutback and each harvest. Fertilizers can also be applied after each harvest. The details of the operations required including plantation removal are discussed later in this report.

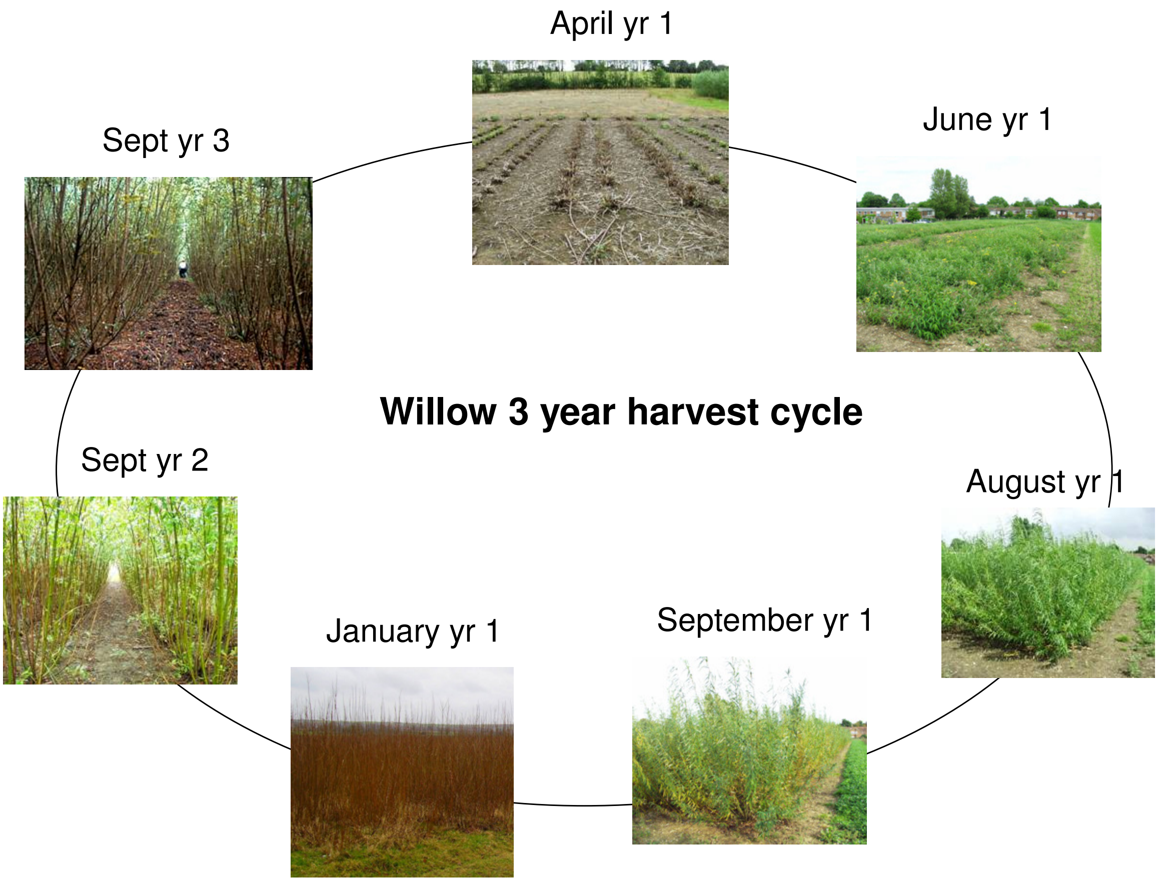


**Fig 2. The SRC willow growth cycle through a three year production period. The crop grows quickly through the year, reaching around 2m height by the end of the first year, and 5m by the end of the third year.**

### 3.1.2 *Miscanthus*

*Miscanthus* has the $C_4$ photosynthetic pathway; however, it can grow more efficiently at lower temperatures than other $C_4$ plants (Beale *et al.*, 1996). It is a rhizomatous grass, the rhizomes are the below ground storage and perennating organ. The hybrid of *Miscanthus* currently grown for biomass, *Miscanthus x giganteus*, is a naturally occurring inter-specific hybrid. Although both its parents are flowering species, producing fertile seed, *M. x giganteus* does not set fertile seed, and so has to be multiplied vegetatively. The usual method of propagation is to use pieces of rhizome, harvested from crops two to three years old. The pieces are planted at 10 000 – 20 000 $ha^{-1}$, usually in March – April. At the end of the first year after planting there is insufficient growth for economic harvesting, so the aerial biomass is mown and left in the field. This is done to add to the layer of litter and crop mulch that builds up on the soil surface, and which is added to in subsequent years by the *Miscanthus* leaves which drop off in the late summer and autumn before each harvest. The mulch helps to suppress weed growth and conserve water. The first proper harvest is taken at the end of the second year, and the crop is then harvested annually, usually around March. The oldest on-going experiment in the UK is now in its sixteenth year and shows no sign of losing vigour. It is therefore expected that crops should last at least 20 years. Herbicides are used at establishment, and occasionally in mature crops, however, most commercial crops currently receive no fertilizer.

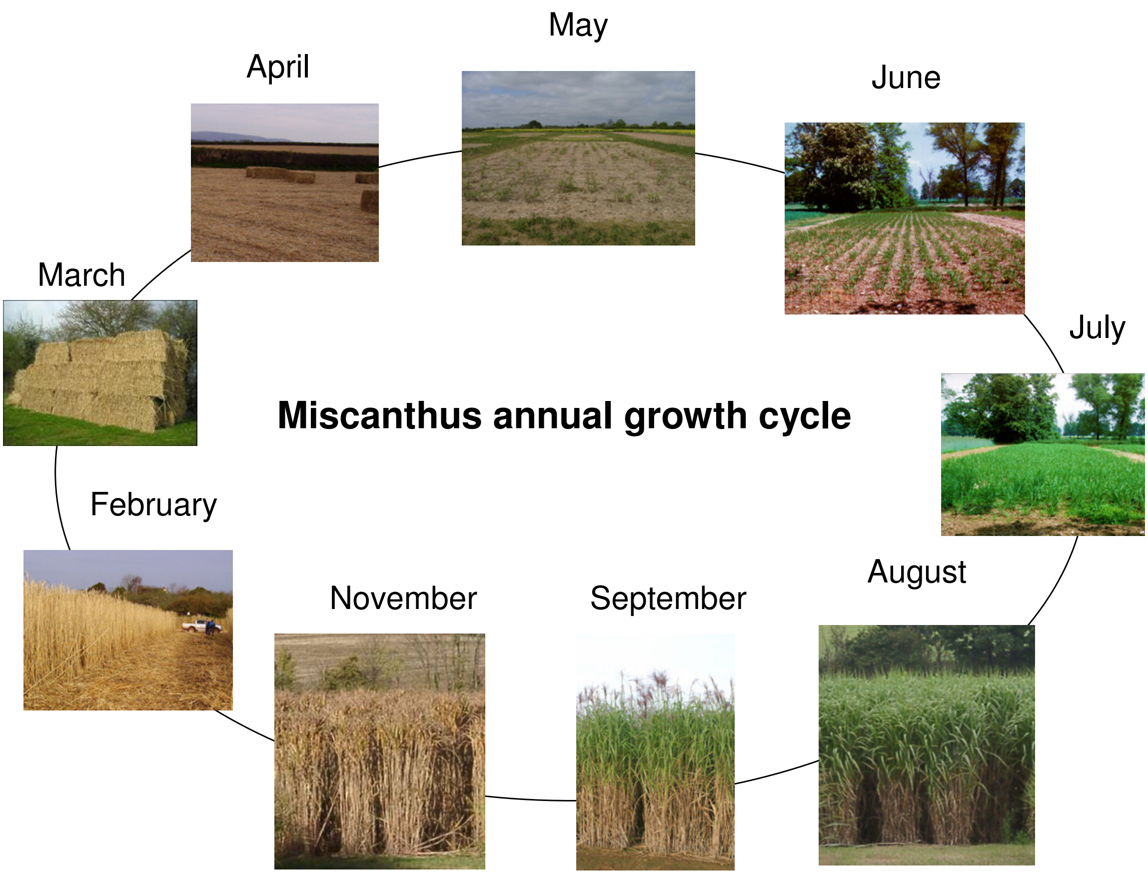


**Fig 3. The *Miscanthus* annual production cycle. The crop grows very quickly between the end of May and the middle of August, often reaching over 3m height.**

### 3.1.3 Differences between conventional and biomass crops

Compared to conventional agricultural crops, biomass crops:

- are perennial and likely to be *in situ* for around 20 years; there are no annual cultivations;

- have relatively low plant population densities;
- are usually harvested in winter or spring;
- are taller for a large part of the year;
- are deeper rooting;
- less mechanical operations are required.

All conventional UK arable crops are annual, usually autumn or spring planted and summer or autumn harvested. Most crops require some soil tillage prior to planting, although reduced and zero tillage has become more popular in recent years for combinable crops. In contrast, *Miscanthus* and SRC require tillage only for establishment and, for the lifetime of the plantation, no further soil cultivation is expected.

| Vegetation type | Maximum depth of high root density (m) | Maximum depth of roots (m) | Source |
|---|---|---|---|
| **Main agricultural crops** | | | |
| Maincrop potato | 0.7 | 1.0 | (Bailey 1990; Smit and Groenwold 2005) |
| Oilseed rape | 1.0 | 1.5 | (Bailey 1990) |
| Winter cereals, ryegrass barley | 0.8 | 1.2 | (Bailey 1990; Thorup-Kristensen 2006) |
| Winter wheat | 0.8 | 1.3 | (Gregory *et al.*, 1978) |
| Spring cereals | 0.5 | 1.2 | (Bailey 1990) |
| Onions | 0.25 | 0.6 | (Bailey 1990) |
| Peas | 0.25 | 0.7 | (Bailey 1990) |
| Sugar Beet | 1.0 | 1.6 | (Bailey 1990) |
| Strawberries | 0.45 | 0.6 | (Bailey 1990) |
| Permanent Grass | 0.5 | 0.8 | (Cranfield University 2001b) |
| **Forestry** | | | |
| Coniferous | 0.5 (about 70%) | 2.5 | (Canadell *et al.* 1996; Crow 2005, Roberts *et al.* 2006, Jackson *et al.* 1996) |
| Broadleaf | 0.5 (about 80%) | 4.0 | (Canadell *et al.* 1996; Crow 2005, Roberts *et al.* 2006, Jackson *et al.* 1996) |
| **Biomass crops** | | | |
| SRC Willow | 0.36 (70%) | 2.5<br>Long roots, deeper than 0.36, are <10mm | (Cranfield University 2001b; Crow and Houston 2004; Souch, Martin *et al.* 2004) |
| *Miscanthus* | 1.2 (75%) | 2.5 | (Riche and Christian, 2001a; Beale *et al.* 1999; Neukirchen *et al.* 1999; Cranfield University 2001b) |

**Table 2. Rooting depths of conventional UK crops and *Miscanthus* and SRC willow.**

Both *Miscanthus* and SRC are established with a relatively wide spacing between plants and rows, very different to conventional arable crops. *Miscanthus* rhizomes spread slowly, approximately 5 cm $yr^{-1}$, so the rows disappear, with time, and result in a uniform stand.

*Miscanthus* is harvested March – April. SRC willow is ideally harvested during the winter, but it is sometimes harvested at other times of the year if there has been a significant pest attack. Because of the winter or spring harvest, and because the crops are so tall, both crops can have a significant visual impact during the winter, when conventional crops are very short.

Both crops are deeper rooting than conventional crops; typical rooting depths of the crops are given in Table 2. The deep rooting habit is useful for extracting water for crop growth, but can be of concern to growers in that it is thought that the roots may block field drains. This is of particular concern with willow, where it is thought to be most likely, due to the presence of larger diameter roots (greater that 10 mm). For *Miscanthus*, the rhizomes rarely penetrate deeper than 0.2 m.

## 3.2 The scale and distribution of biomass crop plantings - current and future

In England, the Energy Crops Scheme pays a planting grant to growers of *Miscanthus* and SRC. The scheme started in 2001. The current areas of *Miscanthus* and SRC willow planted in England within the Energy Crops Scheme are shown in Figure 1. Some SRC willow was planted before the Scheme started, notably about 2000 ha of SRC for the ARBRE project in the late nineties. (The Arable Biomass Renewable Energy project was a 'flagship' project in the UK to demonstrate electricity generation from dedicated energy crops, employing the high efficiency of gasification combined cycle technology.) Other plantings are unlikely to be extensive so of the order of 3000 ha have probably been planted outside the Scheme. Some *Miscanthus* was also established prior to the scheme starting and, since 2001 some crops have been planted outside of the scheme, usually because they were grown for uses other than energy, e.g. for rhizome production or horse bedding. This is likely to be of the order of 2000 ha. So in total, there is likely to be, at the time of writing, around 10,000 ha of dedicated biomass crops in England, approximately two thirds of which is *Miscanthus*. There are also known to be only small areas of both crops in Wales and Scotland.

It is very difficult to estimate the future scale of biomass crops; at one extreme arable crop profit margins have shown large fluctuations in the past few years and when they are high the farmers' interest in growing biomass is significantly reduced. At the other end of the spectrum, large scale power generators need renewable technologies to fulfil their renewable obligations, and co-firing with biomass is one technology that works and it could provide a market for large volumes of biomass. In the future, as demand for renewable transport fuels increases, it is also possible that bio-refineries will be built that can convert biomass into synthetic diesel and petrol and, with current technology, the optimum size of a bio-refinery is generally thought to be one processing around five million tonnes of biomass per year. This clearly means that large areas of biomass crops would need to be grown to fulfil the demand.

The UK Biomass Strategy (Defra, 2007) states '*We believe there is significant potential to expand the UK supply of biomass without any detrimental effect on food supplies and in a sustainable manner by … increasing the amount of perennial energy crops produced in the UK to meet market demands – with the potential to use up to a further 350,000 hectares across the UK by 2020.*' This is now interpreted as an aspiration rather than a firm target but it indicates the scale of planting required for the Government's objectives to be attained. In any case, it is unlikely to happen without new drivers – e.g. lower incomes from conventional land uses, increased energy prices, or incentives or obligations imposed to promote the uptake of biomass crops. There are also increasing concerns over world food production and prices, and the potential conflict for land use, food or fuel is gaining recognition.

There are currently three factors suppressing the uptake of energy crops.

Firstly, and most importantly, through 2007 world prices of cereals increased dramatically. Between 2001 and mid-2006, the UK price of wheat varied between around £60 and £80 $t^{-1}$. From then on the price increased steadily, peaking at around £170 $t^{-1}$ in late summer 2007, before falling back somewhat. These high prices were driven by several factors, including drought and poor yields in some regions of the worlds, increased demand for bio-ethanol in the US and also increased demand from other regions. To an extent, the high prices were offset by increased costs of fertilisers so the profit margins were not as high as might be expected at first sight. Nevertheless, when the profit margins on food crops are high, growers are likely to be content growing crops they are used to; it is only when margins fall to near or below zero, or significantly below alternatives, that growers get interested in the alternative crops. In 2007, biomass could not compete economically with conventional arable crops but, in 2008, the situation was more advantageous.

**Box 2: Renewables Obligation**

This is the main UK incentive scheme for renewable electricity. The obligation requires licensed electricity suppliers to source a certain percentage, increasing annually, of electricity from approved renewable sources. The obligation came into effect in April 2002, and is expected to last until 2027. Each MWh of electricity produced from an approved renewable source is awarded one Renewables Obligation Certificate (ROC), and each supplier has to obtain their required number of ROC's during the year – either by buying ROC's from other suppliers, or producing their own renewable electricity. If a supplier fails to obtain sufficient ROC's they have to pay a buy-out price, the proceeds of which are distributed pro-rata between suppliers that have presented ROCs. For 2007/08 7.9% of electricity supplied has to be from a renewable source.

Secondly, as a result of the world grain stocks being at very low levels, and grain prices being high, the EU has reduced the requirement for set-aside to 0%. There is the option to re-instate set-aside at a higher level in the future, but at present this seems unlikely. This has had a negative effect on the uptake of biomass crops. Many farmers did not like leaving land fallow, and hence looked for alternative non-food uses, such as biomass, which were allowed under the regulations. With the removal of set-aside such land is again most likely to be used for food.

The third, and temporary, disincentive for biomass crops was the re-writing of the energy crops scheme. The old scheme ended in 2006 (but applications made in 2006 could cover plantings in that year and 07 and 08), and a new scheme had to be approved by the EU. This took time, and as a result there was a period of uncertainty, with the level of the grant unconfirmed. This put growers off committing land to biomass crops, especially as they would probably face a few years of negative cash flow before the yields become economic. As a result, the areas planted in 2007 and 2008 were lower than would have been the case if the grant scheme had been continued or renewed sooner.

To balance these three negative drivers, two favourable factors remain: the prices of fossil fuels reached all time highs in 2008 and, although they subsequently fell significantly as a result of the downturn in the global economy, higher prices are anticipated to be the norm in the longer term; the proposed changes to the renewables obligation (Box 2) should both increase demand and increase the price of biomass. In the case of the latter, co-firing biomass with coal can only be currently used to supply 10% of a supplier's renewables obligation, reducing to 5% for 2011-15/16 and 0% from 2016. However, from 2009 an increasing proportion of the co-fired biomass will have to come from an energy crop (25% for 09/10, 50% for 10/11 and 75% for 2011-15/16).

In addition, the proposed changes to the renewables obligation will allocate two renewables obligation certificates (ROCs) to each MWh of electricity generated from dedicated burning of biomass, and single ROCs to each MWh generated from co-firing with energy crops. The support for the largest UK source of renewable electricity, landfill gas, will reduce to 0.25 ROCs per MWh. The overall effect, if these proposals are passed, will be additional indirect support for biomass crops.

Just as it is hard to predict the uptake of biomass crops, it is also difficult to predict the distribution of plantations. Where demand is small scale, e.g. for household, office or village school heat, distribution is likely to be local and small scale; a few fields in the near locality will be sufficient and optimal. Where demand is large scale, either for dedicated biomass plants or for co-firing, then plantings are likely to be clustered across a region; the clusters are likely to centre around farm businesses that have decided to convert a significant proportion of their land to biomass production. The large scale demand points may well occur at the sites of current coal fired generators. A further development would be very large scale demand centres, e.g. a biorefinery, and for this it may well be that biomass will be transported over a longer distance, simply to get enough supply. The transport may be by rail or sea, and the biomass might be densified, e.g. by pyrolysis, to make the transportation more efficient.

A further factor that will influence the distribution of biomass crops is the land type: currently most biomass crops have been established on arable land but, with increasing arable margins, it seems likely that some might be grown on ex-grassland, if demand for biomass also increases. With higher commodity prices, income from livestock is likely to decline which may make biomass more competitive with livestock rather than with arable farming systems. Further constraints include, the crop yield (which is dominantly a function of soil and climate), factors determining access of machinery and classification of the land (e.g. as an SSSI). These issues are discussed in detail in the following paragraphs.

The best soils for biomass crops are well aerated water retentive soils (rainfall 900-1100mm), of pH 5.5-7.5 (Abrahamson, Volk *et al*. 2002; Defra 2004; DAFF 2007; DAFF 2007; Defra 2007; McCracken 2007). However, establishment has been successful on a variety of soils from sandy to heavy clay soils, although the latter has been associated with poor establishment in some cases, and caution is advised in harvesting as heavy soils are prone to damage (Hilton 2001; Defra 2004). The soil can have a great effect on the life cycle and, at least in the initial period, yields of a biomass crop. *Miscanthus* usually takes between three and five years to reach its full yield potential but full yield can be reached earlier on soils where establishment is quicker. Soils must be able to take the weight of harvesting machinery (see below). Climatic factors may need to be considered in conjunction with the soil type, i.e. sandy soils may suffer higher losses due to wind erosion, whereas heavier clay soils will be more affected by rain. The presence of drainage systems may need to be considered prior to planting, as roots will penetrate to the depth of the drains (Danfors *et al.* 1998; Defra 2004).

Site selection requirements also include sufficient access for machinery and for removing the harvested material. Biomass crops are often grown with wide un-cropped headlands (typically 8-10 m), to facilitate machinery movements (Danfors *et al*. 1998; Mitchell *et al*. 1999; Defra 2004; DAFF 2007; DAFF 2007; Defra 2007). These headlands should be planted with a cover such as grass to prevent ground damage by machinery (Danfors *et al*. 1998; Mitchell *et al*. 1999). Planting in long rows maximises machinery efficiency (Danfors *et al*. 1998). In order to qualify for the energy crops scheme, growers need to plant areas of at least 3 ha (Defra 2004; Defra 2007).

Fields that have too steep a slope are unlikely to be used because harvesting could be difficult and dangerous. Defra, 2004 recommends that, for SRC willow, the slope should be up to 7% and a maximum of 15%. Not only is machinery access related to slope but also the likelihood of soil erosion (see section 4.1.7).

The climate of a location is an important consideration in determining the yield. The average temperature has an effect through both the length of the growing season and the efficiency of photosynthesis. Thus higher latitude and topographic height may limit the yield. This is likely to have a greater impact on the yields of *Miscanthus*, due to its use of the $C_4$ photosynthetic pathway, that SRC willow. The amount of rainfall during the summer may also be important as, in areas of low summer rainfall the depletion of the amount of water stored in the soils may exceed the rate of replenishment by the rainfall such that the rate of growth becomes so limited that an economic yield can not be achieved. Currently, although there is evidence that yields may be limited by water availability in southeast England, it does not seem to be sufficient to render the yield uneconomic.

Future climate change may have an impact on the choice of where biomass crops are planted, although there is a complex interplay of a number of factors so it is difficult to reach any specific conclusions currently. There is evidence, although not conclusive, that increasing levels of atmospheric $CO_2$ act to “fertilise” the crops so that higher yields are obtained, implying that the same yield could be obtained from a smaller land area. However, increased concentrations of ozone in the lower atmosphere may mitigate this to some extent. Generally, the simulations for the future climate of England suggest an increase in the average summer and winter temperatures and an increase in winter rainfall balanced by a decrease in summer rainfall – the latter continuing a trend that has been present since the C19. The increase in temperatures will increase yields by extending the growing season. It may also allow the crops to be grown in areas which were previously too cold. However, these “gains” may be offset by the reduction in summer rainfall resulting in growth being limited by water availability. Research is ongoing to produce numerical models of crop yield that incorporate the impact of climate change.

# 4 Aspects of biomass crops relevant to the historic environment

## *4.1 Impacts of mechanical operations*

This section considers the likely impacts of the mechanical operations associated with biomass crops. The mechanical operations are discussed in relation to operations associated with conventional cropping.

In general, the machinery currently in use in the UK is either identical to, or is a modified version of, those used for conventional crops. Specialised machinery is required for harvesting because of the more substantial nature of the above ground growth but even these tend to be based on existing machinery. The major difference between biomass and conventional crops, including temporary grass, is the number of machine operations required per year. After the first year, the only operations required, for biomass crops, are the harvest and intermittent applications of fertilisers. This is very different to conventional crops where frequent applications of fertilisers, herbicides, fungicides and pesticides, combined with soil preparation and planting occurring annually or at intervals of a few years result in many more vehicle passes.

The two main impacts of vehicle movements are soil compaction and soil erosion. Both processes can reduce the depth of soil, in effect bringing the lower layers of soil closer to the surface. Erosion can also have the opposite effect, increasing the depth of soil where the eroded soil is deposited.

Due to the perennial habit of biomass crops, subsurface mechanical operations only occur prior to establishment and during plantation removal. This means that in a plantation lasting 20 years there will be 18 years of no subsurface cultivations. It is just possible that growers could use sub-soilers to alleviate particular compaction problems in growing crops; however this is very likely to be rare, particularly with regulations aimed at minimizing soil damage.

The other exception linked to the industry, is the production of *Miscanthus* rhizomes. Because the variety of *Miscanthus* grown for biomass has to be grown from pieces of rhizome, it is necessary to grow crops especially for rhizome production. These crops are usually grown for three years before harvesting the planting material, and the harvesting process involves some soil disturbance; the establishment of rhizome crops is almost identical to the establishment of a *Miscanthus* biomass crop.

The ground conditions for machinery activities differ between countries which restricts the relevance of work in other countries to conditions in the UK. In Sweden, it is often possible to work on frozen and possibly snow covered soils, minimizing the risk of soil damage and facilitating the use of heavier machinery. In milder climates such as Denmark and the UK these conditions are much less likely, and certainly cannot be relied on (Danfors and Nordén 1995; Spinelli and Kofman 1996; Danfors *et al*. 1998). Also in the UK, soils often have a higher clay content and, coupled with potentially wetter conditions, this can make harvesting more difficult.

The nature of the soil has a strong influence on when mechanical operations can be carried out. For sandy soils there are potentially more days when work can be carried out compared with clay soils. In soils exhibiting more than 15% clay, work conducted too soon after rainfall will exert severe damage to soil structure (Watts, pers. comm.)

For this report data has been collated on typical weights of the machinery associated with establishing, maintaining and harvesting, and removal of SRC and *Miscanthus* crops. There is a lack of data on the actual ground pressures that these machines will exert, and it is not possible to simply convert the weights to ground pressures. The ground pressure will depend on the size of the tyres fitted to the tractors and machinery, and also the air pressure in the tyres. To do the conversion it would be necessary to know the surface area of tyre or track in contact with the soil. Also, any soil engaging parts of any machinery used will affect the ground pressures.

### 4.1.1 Planting

Prior to planting, a number of operations are required. Some literature suggests that large stones should be removed to facilitate machinery operations (Mitchell *et al*. 1999; Abrahamson *et al*. 2002; McCracken 2007); however this is rarely if ever done in the UK. Literature also suggests that a stony site can be used but care should be taken as removal of large stones can disturb the soil leaving open areas that could increase soil erosion losses.

Occasionally, where appropriate, the soil should be subsoiled to 35-40 cm before planting (Hilton 2001; Defra 2004; Defra 2007). This may be to remove a plough pan (layer of compaction below cultivation depth) which can limit growth (Makeschin 1994). The soil is then ploughed 20-30 cm deep in autumn using standard farm equipment and left to overwinter to aid breakdown of soil by frost (Mitchell *et al*. 1999; Hilton 2001; Abrahamson *et al*. 2002; Defra 2004; Defra 2007; McCracken 2007). Shortly before planting both crops, the land should be power harrowed to produce a fine tilth (Mitchell *et al*. 1999; Defra 2004; McCracken 2007). These soil tillage requirements are typical of most agricultural crops, and where the crops are being grown on arable or non-permanent grassland, it is most likely that similar operations would have been carried out many times previously for the other crops (Danfors *et al*. 1998). *Miscanthus* rhizomes are planted fairly shallow, between 5 and 20 cm (Jorgensen 1995; Kristensen 1997; Defra 2007), as emergence from deeper planted rhizomes takes longer, reducing the establishment and survival rates (Schwarz *et al*. 1999; Nixon *et al*. 2001).

Planting takes place in spring; between February and June are possible, though for best results, from March to May is preferred. Earlier planting makes use of a longer growing season and soil moisture and produces more growth in the first year. Obtaining good first year growth is important for survival and tolerance of cold winters (Schwarz *et al*. 1999; Defra 2004; Defra 2007)

Both SRC and *Miscanthus* crops should be planted at a density of 10-20,000 plants $ha^{-1}$, though field losses may reduce the actual plants established (Danfors *et al*. 1998; Mitchell *et al*. 1999; Defra 2004; DAFF 2007; DAFF 2007; Defra 2007).

| Machinery | Timing | Yearly Max no. passes | Weight (kg) | Tractor power (kw) | Tractor weight (kg) | Total weight (kg) |
|---|---|---|---|---|---|---|
| Herbicide application – Boom sprayer | Summer/Autumn in establishment x3<br>Cutback and or Harvest | 1-2 up to 3 | 670 | 37 | 2572 | 3242 |
| Stone picker | Autumn/spring | 1 | 1200 | 34 | 2572 | 3772 |
| Subsoiler | Autumn | 1 | 1600-3700 | 45-200 | 4000-11700 | 5600-15400 |
| Plough | Autumn | 1 | 1200 | 60 | 4000 | 5200 |
| Rotary Tiller | Winter - rhizome production | 1-2 | 130-360 | 60 | 4000 | 4130 |
| Potato harvester | Winter – rhizome collection | 1 | 5440 | 100 | 5230 | 10670 |
| Harrow/disc | Spring, prior to planting | 1-2 | 2000 | 100-130 | 7850 | 9850 |
| Planter | Spring March-May | 1 | Various, up to 2000 | 75-100 | 4500-6000 | 8000 |
| Roller | Spring, post planting | 1 | 5000 | 75 | 4500 | 9500 |
| Fertiliser spreader | spring | 1-2 | 180 | 75 | 4500 | 4680 |
| Mower for cutback (SRC) | Spring after 1st years growth | 1 | 270 | 54 | 3240 | 3510 |
| Seed spreader/precision drilling (cover crop) | At end of rotation | 1 | 400-1000 | 34 | 2572 | 3572 |

**Table 3. Typical machinery used in establishing the biomass crops with their respective weights. (Data adapted from Heller *et al.* 2003 and manufacturer's specifications. The number of vehicle passes received per year is estimated; see 3.1.1 for definition of a pass.)**

#### 4.1.1.1 SRC Willow

For SRC willow, planting equipment from the Nordic countries has been introduced in the UK because the industry there is further ahead with machinery development. Willow is usually planted on twin rows of 0.75 m with 1.5 m between the twin rows. Distance between willows in the rows is usually around 0.6 m. Research has shown that good pest and disease control can be obtained by planting mixed varieties within a field. Mixtures of at least six varieties are recommended (Danfors *et al.* 1998; Mitchell *et al.* 1999; Abrahamson *et al.* 2002; Defra 2004; DAFF 2007).

Initially establishment used either a modified cabbage planter or hand planting, both of which are slow (Mitchell *et al.* 1999; Hilton 2001; Defra 2004). However, the development of semi-automatic step planters, from Scandinavia, have replaced these and become the standard. These cut 1-2 m rods of willow into cuttings of 18-25 cm which are inserted into the soil vertically, before firming the surrounding soil. The Salix Maskiner (8-10 ha/day) is capable of planting four rows at one time, the Fröbbesta Salix Planter plants just two rows (Danfors *et al.* 1998; Rushton 1999; Defra 2004) (Table 3). Both these machines have low overall weight and require low powered tractor. They can be adapted to suit the local soil conditions (Hilton 2001; Abrahamson *et al.* 2002).

An alternative design, lay-flat planters, place short rods (billets), of 5-10 cm in length, horizontally into furrows of 2-8cm depth. A machine produced by Austoft (Mitchell *et al.* 1999) that uses rods produced from their harvesting machinery is an automatic planter that works in a similar way to the lay-flat planter. These methods produce random shoots due to the placement of the billets and hence are less used. However using billets could reduce costs as less planting precision is required, and billets can be taken straight from the harvesting operation.

The site should be rolled after planting to aid weed control, though the pressure exerted should be minimal (Culshaw and Stokes 1995; Abrahamson *et al.* 2002; Defra 2004; DAFF 2007). A summary of the equipment used is given in Table 4.

| Method | Work rate ha/d | Planter weight (kg) | Tractor power (kw) | Total weight |
|---|---|---|---|---|
| Potato planter | 0.3 | 2000 | 75-100 | 6740+ |
| Manure spreader | 20-25 | 3-6000 | 75-130 | 7740+ |
| Bespoke Planter | Small 5<br>Large 10-25 | Unknown | | |
| Salix Maskiner Step Planter | 8-10 | 1400 | 75 | 6140 |

**Table 4. *Miscanthus* planting machinery and Salix Maskiner planter. (The work rates and vehicle weights were obtained from reference to agricultural machinery websites. Information related to the bespoke planters is guarded and therefore difficult to obtain. Only information relating to the willow planter shown could be found.)**

#### 4.1.1.2 *Miscanthus*

Initially planting was done with manure spreaders broadcasting the rhizomes across the land at a relatively fast and cheap rate. However the lack of uniformity in planting depth, and spacing, resulting in poor establishment, coupled with the high cost of the rhizomes, made this an unsuitable method (Hilton 2001; Defra 2007). The desired density and planting depth can be achieved through using a manually fed potato planter, but most UK fields are now established using bespoke engineered planters (Table 4). The potato planters can be very successful, and are available on some farms, but are slow and labour intensive. However the automatic design of the bespoke machinery results in lower costs and higher work rates as only a single operator is required. These bespoke designs can plant 2-6 rows depending on the machine and with a high rhizome load capacity of 5 tonnes, can plant large areas quickly. If conventional potato planters are used the crops need rolling post-planting, however the bespoke planters incorporate this rolling operation into the machine (Kristensen 1997; Lewandowski *et al.* 2000; Nixon *et al.* 2001; DAFF 2007).

### 4.1.2 Applications of herbicides and fertilisers

Before a biomass crop is established, in the autumn prior to planting, removal of the current vegetation including weeds is achieved through the application of a herbicide (typically glyphosate). Efficient weed control is vital due to the long term nature of the crops and in ensuring maximum yield at harvest (Culshaw and Stokes 1995; Danfors *et al*. 1998; Sage 1999; Abrahamson *et al*. 2002). Hence up to two applications may be required to obtain optimum weed control before ploughing later in the autumn, with a further application possible prior to planting in spring (Defra 2004; Defra 2007).

If weed control is necessary in established *Miscanthus*, herbicides should be applied after harvest when the plant is dormant. Timing this is important to ensure new shoots are not damaged (Defra 2007). In SRC willow, the applications take place after cutback and the harvests if required (Abrahamson *et al*. 2002; Defra 2004). Once both crops have matured, after the first two seasons of growth, the leaf litter and canopy cover combine to provide effective weed control (Defra 2004). Application of herbicides should not affect the soil at or below the surface.

Biomass crops typically have very low nutrient requirements. Currently, most UK *Miscanthus* receives no fertilizer, and most SRC receives sewage sludge rather than inorganic fertilizers. If biomass crops are grown on lower quality land, and if sewage sludge is not available, then inorganic fertilizers may be required for optimal production. In this case, fertilizer application may take place during the first growing season of each rotation for willow, but not within the establishment year (Abrahamson *et al*. 2002; Defra 2004).

On poor soils fertilizer may be applied to *Miscanthus* within the first two years (Defra 2007). However, once the rhizome has built up a nutrient reserve, fertiliser requirements are lowered. Application can be done using a standard spreader in late spring/early summer (Abrahamson *et al*. 2002; Heller *et al*. 2003) though more specialised equipment would be required to fertilise mature SRC crops in years two or three of the rotation (Defra 2004).

These operations do not involve subsurface disturbance and so the impacts are restricted to the passage of the farm vehicles causing soil compaction and, due to the infrequent nature of these operations, these are likely to be limited.

### 4.1.3 Harvesting and cutback

#### 4.1.3.1 SRC Willow

SRC is cutback after the first year's growth in January-February to stimulate coppicing (Defra 2004). A modified sickle-bar mower is used to cut cleanly to within 10 cm of the ground, from which 5-20 shoots per stool should emerge in the spring (Heller *et al*. 2003; McCracken 2007). A clean cut is important to avoid jagged edges that may encourage attack from pathogens (Hilton 2001).

The harvesting of SRC is carried out during the winter months, between December to March after senescence and before bud break. This occurs once in the 3-4 year cycle. Extensive trialling of harvest machinery across Europe and North America has been reviewed in a number of papers (Culshaw and Stokes 1995; Hartsough *et al*. 1996; Spinelli and Kofman 1996; Kofman and Spinelli 1997; Mitchell *et al*. 1999; Hartsough and Spinelli 2001; Hilton 2001). Harvesting methods can be grouped into: whole stem, billet, or cut and chip, and comprise both self-propelled and trailed machinery. The end use and or desired chip quality will determine which method is used. A summary of the weights and work rates of biomass crop harvesting machinery in use is presented in Table 5.

Harvesting the whole stem (up to 8m tall) produces bundles which can be stored for later use (Kofman and Spinelli 1997). In the UK whole stem harvesting is not practiced commercially. The bundles must be processed (e.g. chipped), usually after drying, before use, adding an extra handling stage. Chipping dried whole stems is prone to shattering, reducing the size and quality of the chips. Hence if this is important for the end use, this method is not advisable. (Danfors *et al*. 1998; Mitchell *et al*. 1999; Hilton 2001; Defra 2004).

| | Machinery | Rate ha/hr | Max. Number passes | Machine weight (kg) | Tractor weight |
|---|---|---|---|---|---|
| **SRC willow** | | | | | |
| Cut and chip | Forage harvester with specialist header and tractor and trailer to transport biomass | 0.64-0.72 | 3-5 | 11560<br>5590 (trailer) | 5030 |
| | Salix Maskiner Bender | 0.25-0.48 | 1 | 1250 | 4740 |
| Billet | Billet harvester with tractors and trailers to transport the biomass | Unkown | 3-5 | Unknown<br>5590 (trailer) | 5030 |
| Wholestem | Segerslätt Empire 2000 | 0.38-0.53 | 1 | Unkown | |
| ***Miscanthus*** | | | | | |
| Mow and chop | Tractor mower | | 2 | 2550 | 5030 |
| | Forage Harvester with tractor and trailer to transport biomass | | 3 | 11560<br>5590 (trailer) | 5030 |
| Mow and bale | Tractor mower<br>Baler with tractor and chaser to transport bales | 1 | 6 | 2550 (mower)<br>8440 (baler)<br>5250 (chaser) | 5030<br>5600<br>4740 |
| Mow and bundle | Agostini reed grass harvester. Reaper-binder | | 1-2 | | |

**Table 5. *Miscanthus* and SRC harvesting methods with associated machinery and weights of machinery. (Rates where given are averaged across various stand densities and soil types. The number of passes depends on the capacity of the machinery and the number of trailers following. (Danfors and Nordén 1995; Danfors *et al*. 1998; Venturi *et al*. 1998; Hartsough and Spinelli 2001; DAFF 2007))**

Billet harvesting is the mid-way between whole stem and chipping and produces rods 5-20 cm in length which are stored and dried in outside stacks (Defra 2004). Billets leave the wood with the bark which prevents rainwater from re-entering the billets. Large air spaces between the billets within the stacks facilitate increased air flow, aiding drying without decomposition, heating or fungal build up that can occur when wet chips are left in storage (Hilton 2001;

O'Sullivan 2006). As for whole stem harvesting, an extra step is added in the harvesting process by the requirement to chip the billets at a later stage. However the chip produced is uniform in shape and of high quality (O'Sullivan 2006). The Austoft 7700 is a self propelled adapted sugar cane harvester used in the UK for billet harvesting, with a tractor/trailer shuttle running alongside to collect the crop. A modified version in Scandinavia has been adapted to produce chips 3-5cm long. The billets can be used directly for planting with some planters (Culshaw and Stokes 1995; Spinelli 2003), but again, this is not practiced in the UK.
Cut and chip methods reduce the handling and transport requirements. The Salix Maskiner Bender and Claas Jaguar are two frequently used cut and chip harvesters (Hartsough and Spinelli 2001; Abrahamson *t al*. 2002; Volk *et al*. 2006). The Bender is not used in the UK and falls into a group of machines designed specially in Sweden to harvest the twin row system of willow coppice, comprising a header attached to a tractor. The Bender is row independent, and can cut across rows if required (Hartsough and Spinelli 2001; Abrahamson *et al*. 2002). The Claas Jaguar meanwhile is a converted conventional agricultural self-propelled forage harvester with a specially built SRC header; it has to be driven along rows, i.e. it is not row-independent (Culshaw and Stokes 1995; Spinelli and Kofman 1996; Abrahamson *et al*. 2002; Spinelli 2003). Both the Claas and Salix Maskiner machine can use high sided tipping trailers towed behind to collect the chips, but the Class usually delivers directly to a trailer towed alongside the harvester by a tractor. Whilst it is an advantage to use conventional equipment, it has been noted that the conversion is not necessarily cheap (Spinelli and Kofman 1996).

#### 4.1.3.2 *Miscanthus*

*Miscanthus* is harvested annually between March-May when the moisture content of the biomass is at a minimum, to maximise the quality of the product (DAFF 2007; Defra 2007). With the crop reaching a typical height of 2.5-3.5 m with rigid stems, there has been some development of adapted headers, originating from maize or grass cutters. A range of mowers have been used to harvest *Miscanthus*, and forage harvesters are also often used to cut and swath the crop (Huisman and Kortleve 1994; Reynolds *et al*. 2000; Huisman 2003; Adler *et al*. 2006). Mower-conditioners are recommended, to aid moisture loss, (by increasing surface area and air flow) and handling, through shortening the length of the stems (Huisman 2003; DAFF 2007). The swath is usually baled into large high density bales. Similar to willows, the end use dictates the harvesting process and hence machinery used. Use of the whole stems is appropriate for use as fibre material for building or textiles (Huisman and Kortleve 1994; Venturi *et al*. 1998; Lewandowski *et al*. 2000). The *Miscanthus* for this end use is bundled based on a harvester designed for reed grass (Venturi *et al*. 1998). This is rarely, if ever, done in the UK. Table 5 summarises *Miscanthus* harvesting machinery, and Table 6 summarises balers and chasers, the machines used to collect and stack the bales.

Experimental *Miscanthus* and SRC plots are often not harvested as they would be commercially; typically small horticultural scale machinery is used to cut the plots, and the biomass collected manually. Consequently, the effects of the harvesting operation on the soil cannot be accurately quantified using data from these experimental trials.

| Bale size (w by h, cm) | Baler Weight (kg) | Tractor Weight (kg) | Total weight (kg) |
|---|---|---|---|
| 130 by 120 | 8440 | 5600 | 14040 |
| 90 by 120 | 7500-9350 | 5030 | 12530+ |
| 70 by 120 | 7500-9350 | 4740 | 12240+ |
| 90 by 80 | 6600- 8300 | 4740 | 11340+ |
| Chaser (collects bales) | 5250-6850 | 4740-5030 | 9990+ |

**Table 6 *Miscanthus* balers and chaser weights with tractor required. Information from manufacturer's websites.**

### 4.1.4 Plantation Removal

Plantation removal is not a requirement for annual crops and, in forestry, it is good practice to re-establish felled areas. The suggested economic life span of *Miscanthus* and willow SRC is in the range 15 to 20 years, although up to 30 years has been mooted. For SRC, this is based on the advised 3-4 yr cycle and 6 harvests (Danfors *et al*. 1998; Mitchell *et al*. 1999; Lewandowski *et al*. 2000; Abrahamson *et al*. 2002; Defra 2004; DAFF 2007; DAFF 2007; Defra 2007). The crop may be removed before then due to: poor productivity, including pest or disease attack; economics such as the fluctuation in crop prices making agricultural crops a more viable option; or breeding improvements - new clones with greater yielding or resistance characteristics. Thus removal may be either in order to re-establish the biomass crop, or to change to a different land use (Mele *et al*. 2003; Devine *et al*. 2006; Goodlass *et al*. 2007). Either way the land will be exposed, as during establishment, to the erosive effects of wind and rain. How removal is undertaken will be related to the intended subsequent land use.

#### 4.1.4.1 SRC Willow

Whether or not, and how, SRC willow is removed is related to a number of factors (Table 7). In the UK there is very little experience of SRC plantation removal. Jonsson and Hadders, 1999, described methods based on interviews with Swedish farmers who removed crop for plantation renewal or conversion to cereal production. Young plantations under two years old are easiest to remove with stools being ploughed back into the ground with a conventional plough. As they have yet to reach first harvesting rotation, they are still small and so do not require chemical input (Jonsson and Hadders 1999). However, it would be very unusual to want to destroy such young crops. Stands that have undergone one or more harvest rotations can be removed in a similar way to *Miscanthus*, by application of glyphosate and/or ploughing out, but will take longer to decay. Stumps of this age can be 7-10 cm in diameter (Jonsson and Hadders 1999; Lamb 1999; Mitchell, *et al*. 1999).

The application of post emergence glyphosate prior to removal is common for all other techniques. After final harvest, shoots are allowed to grow to 15-20 cm followed by the application of herbicide in the spring. A second application can be applied in summer to complete stool death. Timing of ploughing to remove stumps will depend on the size and decay rate; in sycamore this can take up to three seasons (Devine *et al*. 2006). This method has been found to work for many established willow plantations (Lamb 1999; Mitchell *et al*. 1999). Methods of this nature have a time delay from final harvest to re-seeding the new crop of 18-24 months, though an earlier final harvest can be used to shorten the time taken (Jonsson and Hadders 1999; Lamb 1999; Mitchell *et al*. 1999; Defra 2004).

The use of the stump wood from biomass crops has been suggested as an additional from of biomass production. In SRC poplar where the trees develop a tap root, the larger rooting system would make this a viable option, though use of heavy machinery is required (Defra 2004; Spinelli *et al*. 2005). The technique uses a bucket attached to a digger to lever the stools out. However the machinery and time taken make this an expensive method with estimates made of ~30 hours/ha for poplar (Lamb 1999; Mitchell *et al*. 1999; Goodlass *et al*. 2007). The land is however immediately available for cultivation of the next crop. Following this procedure the land is power harrowed to remove the finer roots (Goodlass 2007).

| Factor | Effect |
|---|---|
| Age of stand | Older stools have more developed roots |
| Soil type | Heavier soils likely to be damaged more by removal. |
| Species/Clone | Different clones may produce more root biomass, also other bioenergy woody species (poplar more biomass – see section) |
| Subsequent land use | Next crop species to be grown |
| Disease control | Full removal may be required to prevent spread of fungal disease |
| Use of chemicals | Limit amount apply to land |
| Time available | The time between removal method and next crop is important for economics, and relates to climate |

**Table 7. The factors effecting removal of SRC willow from a plot (Mitchell *et al*. 1999; Hakkila 2004)**

| Method | Plantation Age | Time to next crop | Machinery | Machinery weight (kg) | Max No. passes |
|---|---|---|---|---|---|
| Herbicide only | 1-2yrs | 2-3 months | Sprayer | see Table 3 | 1 |
| Herbicide/plough | 3yrs+ | 10-14 months | Sprayer, plough | see Table 3 | 3-4 |
| Stump removal | 3+ but more 10+/older | Available immediately | Digger | | 1 |
| Topsoil mulch | 3+ | 10 months | Sprayer, Tractor trailed mulcher | 1000-2500<br>Tractor 6620-11770 | 3 |
| 90cm mulch | 10+/older plantations | Available immediately | Heavy duty mulcher | 9000-12000 | 1 |
| Fodder/cover crop | | 10-14 months | Sprayer<br>Seed drill | see Table 3 | 2 |

**Table 8. Removal methods of SRC. The age of the plantation, time to next crop, machinery used and weight, alongside maximum number of passes before ploughing for the next crop (Jonsson and Hadders 1999; Lamb 1999; Mitchell *et al*. 1999).**

Due to the small size of willow stools, it is unlikely that they could be used for biomass production (Devine *et al* 2006). Complete removal of stumps from sites could be recommended as a method to prevent fungal rot spread and also facilitating site regeneration (Hakkila 2004). However complete removal can adversely affect the soil structure, with the removal of soil organic matter (SOM), extreme soil disturbance and potentially more risk of erosion.

Mulching the soil and stump/root material decreases the time taken to convert the land to a state suitable for establishing other crops. The depth of the soil that is required to be mulched will affect the size of the machinery required. Following glyphosate application, a tractor driven mulcher can be used to mulch the top 4-7 cm of soil. This method can convert land to grassland within 10 months (Lamb 1999; Mitchell *et al.* 1999).

Older plantations, such as those over 10 years, can be mulched to up to 90 cm deep, to include the stool and majority of root matter (Jonsson and Hadders 1999). This can be achieved by one or two passes with a modified peat cutter to reduce the biomass to wood chips. This operation requires the land to be stone free to avoid machinery damage (Lamb 1999; Mitchell *et al.* 1999; Abrahamson *et al.* 2002). Similar to the stump removal, the land is immediately available for use, but the operation is expensive and can have a detrimental effect on the soil structure (Jonsson and Hadders 1999; Lamb 1999; Mitchell *et al.* 1999). A summary of removal methods is provided in Table 8.

#### 4.1.4.2 *Miscanthus*

The destruction of the rhizomes can be achieved through the application of post-emergence herbicide in the spring, followed by ploughing or rotovation (DAFF 2007; Defra 2007). Although this is a standard procedure, some resilience in rhizomes has been noted commercially. The crop may be grown to around 1.5 m tall prior to applying the herbicide, and once the crop has been killed the aerial biomass could be harvested and sold.

In one study, investigating a 10 year old *Miscanthus* stand, (Kahle *et al.* 2002) glyphosate was applied after the last harvest in July and then the crop was mulched in August. The depth was not recorded but may be assumed to be within the top 30 cm. Preparations were also made for the sowing of winter rape in August, which established identically to rape in a control plot. The conversion back to arable crops in *Miscanthus* is therefore a relatively easy transition.

### 4.1.5 *Miscanthus* rhizome production

As *Miscanthus* seeds are infertile, establishment is done either from plantlets or rhizomes (Lewandowski *et al.* 2000; DAFF 2007; Defra 2007). The more expensive plantlet establishment technique is sometimes used for experimental plots, but the main commercial propagation method uses rhizomes. Rhizomes can be divided by hand or machine, the former producing a higher multiplication (100 x) compared to the latter (50 x) (Venturi *et al.* 1998; Lewandowski *et al.* 2000).

Fields of dormant 2-3 year old plants are subjected in winter or early spring to up to two passes of a rotary tiller, with pieces lifted using a stone picker or bulb/potato harvester (Jorgensen 1995; Venturi *et al.* 1998; Lewandowski *et al.* 2000; Defra 2007). The rhizomes are usually further sorted from soil and stones on a grading line. Planting must be done as quickly as possible after division to avoid moisture loss, or else the rhizomes are put into cold storage. Viability losses occur after a few weeks with inappropriate storage (Nielsen 1987; Lewandowski *et al.* 2000; Defra 2007). The effect on the soil of these operations is not documented.

### 4.1.6 Soil compaction

Land degradation through conventional agricultural practise has received much research attention, particularly the effects on soil erosion and soil compaction. Soil compaction usually affects just the topsoil, but in some circumstances may also affect the subsoil, which carries significantly greater problems as it is more difficult to rectify. Compaction increases soil bulk density and has a negative effect on the number and volume of pores and associated organisms. Furthermore, water and air permeability is decreased and there is a greater root penetration resistance. Consequently soil compaction from machinery can affect the entire soil system. There are few studies focussing on biomass crops within these areas. However comparisons can be made between the pressure exerted by conventional equipment and equipment used for biomass crops to make predictions of possible effects.

The number of vehicle passes that a field receives coupled with the weight and pressure exerted from a pass are key factors in understanding likely soil compaction and its extent in a field. A pass of machinery counts as one vehicle moving over the soil, i.e. a tractor and trailer constitutes two passes. In widely spaced row crops such as SRC, and *Miscanthus* in its early years, the most likely route of machinery is to work up and down the rows (Rushton 1999).

Wheels ruts are the most common form of damage and source of compaction, they are caused by soil being pushed out and up from underneath wheels, causing increased soil density under the rut (Souch *et al*. 2004). On steeper slopes especially, the exposing of the lower soil increases risks of soil erosion. Soils with greater clay content suffer deeper ruts (Watts *et al*. 2005).

The soil water content is the most important factor determining the soil compaction process (Hamza and Anderson 2005). It should be below the plastic limit to prevent long term damage. During the winter months a general increase in soil water content leads to a reduction in the number of working days available (Culshaw and Stokes 1995; Nix 2006).

#### 4.1.6.1 SRC Willow

To minimize compaction, machinery with a low weight and low ground pressure should be used if possible. Once the crops have established, the harvesting equipment will be the heaviest machinery regularly in the field. One of the SRC harvesters in the UK, the Austoft, runs on caterpillar tracks, which spread the pressure over a larger surface, bringing an increased mobility with harvesting recorded on wet slopes of over 20% gradient (Hartsough *et al*. 1996; Spinelli and Kofman 1996). In contrast, the other main type of harvester used, Claas Jaguar forage harvester, cannot operate on such steep slopes. Both harvesters require tractors and trailers to collect the crop from the harvesters. Therefore whilst both harvesters have had very limited soil disturbance recorded, a small amount of rutting can be caused by the tractors and trailers (Spinelli and Kofman 1996). Confirmation of this is provided in trials by Forest Research (1998) that concluded that harvesters caused minimal ground damage. Instead the tractor and trailer units caused rutting and significantly so in wet conditions.

Alternatives to conventional trailers are possible, but tracked trailers may limit vehicle road transport, therefore wheeled trailers with low ground pressure tyres (tyres with a larger width, giving a greater surface area in contact with the soil) may be the best option to minimise compaction (Culshaw and Stokes 1995; Kofman and Spinelli 1997).

Conventional agricultural tractors can be used to haul the trailers, and again, low ground pressure tyres should be used if possible. In order to increase the speed of the harvesting process, several tractors and trailers often follow the harvester to maintain a constant supply of trailers for the harvester, however this means repeated passes will occur along the same strip of land, and should be avoided (Spinelli and Kofman 1996).

The stresses imparted from various wheeling treatments simulating harvesting machinery were measured by Watts *et al*. (2005) using sensors 30 cm below the surface of an SRC field. The experimental area was established at ~10,000 plants ha$^{-1}$. The highest recorded stresses were from a tractor pass followed by a tractor and laden trailer (total weight ~13,000 kg) with tractor ground pressure being ~200 kPa and the trailer 350 kPa.

To avoid compaction damage, ground pressure should be kept below 200 kPa in top soil and preferably below 150, but up to a maximum of 200 kPa, in subsoil (Lewandowski *et al*. 2000; Spoor *et al*. 2003). The study of Watts *et al*. (2005) found stresses at 30 cm above these limits, showing that harvesting machinery with or without the multiple passes of trailers may well cause damage. Other work has estimated that the maximal weight on tandem wheels should not exceed 8-10 tonnes (Danfors and Nordén 1995).

In contrast, Watts, *et al*. 2005 found that a caterpillar crawler tractor weighing ~8 tonnes exerted a maximum of 25 kPa at 30 cm, clearly demonstrating the advantage of tracked systems.

The extent of the compaction zone on an SRC field was assessed by Souch *et al*. (2004) investigating clay-loam and silt-loam soil. Two compaction treatments; moderate, with three passes of a seven tonne telehandler down each double row; and heavy, with three passes between and within each double row, were applied to a dry soil. The moderate treatment was meant to represent commercial passage of loads with the heavy treatment representing excessive traffic. The heavy treatment produced significant changes in soil structure, increasing soil strength and bulk density in both the sand and clay soils tested. The compacted soil formed U-shape zones up to 40 cm deep and ~30 cm wide around each rutting, covering a potentially large area. In response the trees' roots proliferated within the topsoil. In practice, the heavy treatment described is unlikely to occur. Heavy loads can be expected between the rows with the potential of forming wheel ruts, but soil within the rows is unlikely to be driven over. The telehandler used to simulate the harvesting movements is not an accurate representation of the harvesting machinery currently used, which is heavier, and there are potentially more passes. Also, some of the plantations were at densities of 8 330 and 9 660 plants ha$^{-1}$, almost half the typical 15 000 plants ha$^{-1}$. At commercial densities the compaction area and roots responses may differ. Overall due to the method used, the application of this data may be limited.

Direct wheel damage caused by driving over the stools is the biggest cause of damage to SRC willow, facilitating entry of infections into broken stumps (Danfors and Nordén 1995; Souch *et al*. 2004). As for conventional crops, care is necessary when driving within rows to avoid driving on stools, and all turning should be at the end of the rows.

#### 4.1.6.2 ***Miscanthus***

The harvesting of *Miscanthus* is more typical of a conventional arable crop due to the annual cycle and lack of definable rows in a mature plantation. Nixon and Bullard (2003) passed two harvesting machines, a John Deere mower conditioner and a Claas Rape swather, over two sites, sandy and silt-clay for spring and autumn harvest of *Miscanthus*. Autumn harvest is not commercial practice, and both machines are for cutting the crop, it would be necessary to follow with another operation to bale the crop. The penetration resistance up to 50 cm was measured for both treatments and also a control site where no passes had occurred. The penetration resistance relates to the level of compaction and bulk density. In general, both sites recorded similar results, i.e. the control plots were not significantly different from the harvested sites. The sandy soil required less force to penetrate then the clay soil, with the greatest resistances being measured during the spring harvest. The sandy site had greater resistance for both harvest dates in the top 20cm, but below this the control had greater resistance. The clay soil did not differ in regards to the depth in the soil versus the control. Therefore it appears the harvesting machinery did not negatively affect the soil structure. The full extent of the trial is not reported, including the number of passes or similar information.

Similarly Kahle *et al*. (1999) noted during their *Miscanthus* trials no negative effect was observed from harvesting machinery. However no data was recorded, their conclusions being based on observations and assumptions from bulk density measurements.

The limited data suggests that *Miscanthus* harvesting machinery does not adversely affect the soil. The increasing levels of soil organic matter coupled with the production of a root and rhizome mat may prevent soil damage in *Miscanthus* stands. Furthermore the root mat produced by these plants occurs at around 35 cm, which may influence the strength of the soil to limit damage by providing support for machinery (Souch *et al*. 2004; Watts *et al*. 2005). Direct evidence is required to support this.

#### 4.1.6.3 Comparison with conventional crops

More information is required for both biomass crops on the effect of associated machinery on the soil, including that related to the level of compaction and the number of machinery passes. The time between passes allows for soils to recover and, as noted above, consecutive passes can build up high stresses on the soil. These high pressures increase the likelihood of soil damage, which may be permanent or measurable for long periods after the original impact (Alakukku 1996). Farmers may get the opportunity to sub-soil to remove compaction in annual crops, but this is unlikely in perennial crops, especially SRC, so damage sustained may not be easily corrected. Therefore, natural alleviation by earthworms, soil cracking (drought) and roots may become the predominant form of soil conditioning (Culshaw and Stokes 1995).

Subsoil compaction e.g. a plough pan may sometimes provide a benefit by protecting the deeper parts of the sub-soil from further compaction pressures (Spoor *et al*. 2003; Schafer-Landefeld *et al*. 2004). However, plough pans may restrict root growth, and therefore remedial action may be beneficial if they remain following preparatory cultivations (Makeschin 1994).

In forestry, where heavy machinery may create large wheel ruts, foresters try to alleviate pressure through the use of brash mats. Brash is composed of the leaf litter and biomass that is not sold on commercially (Moffat *et al*. 2006). Brash mats can be strengthened through use of straw or other timber and demonstrate that the application of plant material on the ground can aid soil support (Murgatroyd and Saunders 2005). *Miscanthus*, in particular, forms a mat of litter and plant debris at the soil surface which undoubtedly aids harvesting, but the effect has not been quantified.

A direct comparison between conventional agricultural and biomass crop machinery would provide clearer information in regards to effects on soil structure. The limited studies done so far, compounded by different soil types, hampers the conclusions that can be made. Inference can currently be made from pressure data but the importance of direct comparison should not be ignored.

The technology of the machinery is constantly developing, e.g. with lighter trailers resulting in reduced ground pressure, and as the land in use for these crops increases, the number of machines available for the operations alongside the amount of investment put into the design of machinery should increase (Hilton 2001). A new review of the available machinery including relative work rates, costs and ground pressure on the soils would provide a reference point of the current situation.

Overall, the key difference between biomass and conventional crops that will have an impact at the soil surface is the harvesting. The applications of herbicides and any fertilisers are not likely to cause any different damage compared with applying them to conventional crops. The harvesting operation, on the other hand, is somewhat different from conventional arable crops, and is carried out at a different time of year. If good practise is followed, i.e. avoiding use of the machinery when ground conditions are unsuitable, it seems unlikely that significant soil disturbance will occur during the harvest of biomass crops. The fact that it is hard to carry out remedial action in biomass crops makes it important for the grower to avoid possible damage. And although the equipment used is not typical of arable farms, it is very similar to machinery used on grassland farms for silage production, a process that is common across the grassland regions of the UK.

### 4.1.7 Soil erosion

The average annual amount of soil formation is 1 Mg ha $^{-1}$ year$^{-1}$, whereas cropland has an average erosion rate of 18.1 Mg ha$^{-1}$ year$^{-1}$ (Pimentel and Krummel 1987). Subsequently soil erosion has a major effect on the productivity and sustainability of agriculture.

Removing the ground cover and exposing bare ground to the environment increases risk of sediment loss through water and wind erosion. Soil type and location will affect the amount of sediment loss, but in general processes removing the finer soil particles reduce soil depth and increase bulk density. During biomass crop production the highest risks of soil erosion occur during establishment, harvesting and final plantation removal. For up to 24 months during establishment, and dependent on the removal method used, up to another 24 months at the end of the plantation lifetime, soil erosion is likely to be high at vulnerable sites (Ranney and Mann 1994; Kort *et al*. 1998; Mitchell *et al*. 1999; Defra 2007). Harvest erosion losses occur across a much more restricted time frame.

Once a SRC plantation has reached its life span and the final harvest has been taken, keeping stumps in the ground as they decompose will maintain some soil stability. Devine *et al*. (2006) describe stump decomposition after final harvest: microbes colonised within the 1$^{st}$ year, with most of the stump broken down in the 2$^{nd}$ year leading to the stump being undetectable from the surface by the 3$^{rd}$ year. No mechanical impedance is conferred during this time.

#### 4.1.7.1 Comparison between conventional and biomass crops

Studies looking at the effect on the soil when converting to biomass crops are limited. Table 9 shows some data on soil erosion losses from different agricultural land uses. However, a number of papers have looked at erosion losses in the USA for SRC willow with rotations up to 10 years and also in the herbaceous grass switchgrass. In addition, high erosion losses for two crops were been found by Green *et al*. (1996) in a comparison of three species (corn, switchgrass and sweetgum). In this study, losses for switchgrass and sweetgum were high compared to corn production but corn and switchgrass losses reduced over the year in contrast to sweetgum. Planting fescue in the sweetgum tree plots decreased the losses to below those of the other two crops.

Thornton *et al*. (1998), measuring first year losses in corn and biomass trees, found losses within the first year of establishment were always significantly higher in the corn than in the biomass tree crops (cottonwood, sycamore and sweetgum). They found initial losses were significantly higher during the first months of establishment but, as stands established, these losses decreased very significantly to levels similar to no-till corn. Greatest losses were under tilled cotton (16.2 Mg $ha^{-1}$) in 14 months and the lowest in cottonwood (2.3 Mg $ha^{-1}$). Planting with a cover crop aided lower erosion loss in sweetgum. Hansen (1993) concluded from a study looking at poplar plantations that soil carbon loss occurred from the top 30 cm early on after planting. However as trees aged to over six years the soil carbon increased. Decreasing erosion losses after stand establishment is a general trend found in research projects (Tolbert *et al*. 1998).

| Vegetation type | Average Erosion loss Mg $ha^{-1}$ $yr^{-1}$ | Establishment year Mg $ha^{-1}$ $yr^{-1}$ | Source |
|---|---|---|---|
| Corn | 21.8 | | (Pimentel and Krummel 1987; U.S. Congress 1993) |
| Wheat | 14.0 (4% slope) | | (Pimentel and Krummel 1987; Ranney and Mann 1994) |
| Av. agricultural loss | 18.1 | | (Pimentel and Krummel 1987) |
| Pasture | 0.2 | | (Mann and Tolbert 2000) |
| Herbaceous grasses | 0.2-2.0 | | (Mann and Tolbert 2000) |
| SRC | 2-4.0 | 130 (Poplar on 13% slope) | (Pimentel and Krummel 1987; U.S. Congress 1993; Mann and Tolbert 2000; White *et al.* 1991, cited by Volk *et al.* 2002) |
| Undisturbed Forest | 0.2-4 | | (Pimentel and Krummel 1987; Mann and Tolbert 2000) |
| Harvested forest | 2-4 | 2-17 | (Pimentel and Krummel 1987) |

**Table 9. Soil erosion losses from agricultural, forestry and biomass crops.**

Pimentel and Krummel 1987 estimated an average of 2 Mg $t^{-1}$ $y^{-1}$ of soil erosion for a five year SRC field on a 5% slope, and for herbaceous perennial grasses they estimated 1 Mg $t^{-1}$ $y^{-1}$ or even as low as permanent grassland at 0.2 Mg $t^{-1}$ $y^{-1}$. Erosion rates for SRC might also be as low as grassland if it was not for the initial establishment phase (Ranney and Mann 1994). Overall, losses are significantly less for biomass crops compared to conventional agricultural crops (Table 9).

The slope of the land dramatically affects the soil erosion potential. An increase from 0-2% to 12-20% slope can produce a 20-fold increase in soil erosion (Pimentel and Krummel 1987). Whilst there is a recommended maximum slope for SRC willow of 15% no such guidance is given for *Miscanthus* other than that relating to machinery access. Clearly, if machinery is working on steeper slopes, particularly under wet conditions, the erosion losses may be increased further.

#### 4.1.7.2 Methods for alleviating soil erosion

In general, studies for both *Miscanthus* and SRC willow conclude that additions of soil organic matter bring about decreases in bulk density with increasing porosity and water retention (Kahle *et al*. 1999; Tolbert *et al*. 1999; Kahle *et al*. 2001; Kahle, *et al*. 2002; Tolbert *et al*. 2002). The extensive rooting systems and root mat that contribute to the soil organic matter, alongside the ground cover provided by the perennial crop through the rotation period, mean biomass crops can be used as an environmental tool to reduce or stabilise erosion loss (Pimentel and Krummel 1987; Kort *et al*. 1998; Borjesson 1999; Wilkinson 1999; Kuzovkina and Quigley 2005). These characteristics are also likely to promote resilience to machinery passes after establishment (Souch *et al*. 2004).

The incorporation of cover crops during establishment can be used to address the soil erosion risk. In addition cover crops can aid weed suppression and add nutrients to the soil. Malik *et al*. in two studies (2000; 2001) investigated the effect of four cover crops introduced during establishment of short-rotation woody crops (sweetgum) on erosion control and any subsequent loss in biomass yield. In these studies, ryegrass performed best, reducing erosion losses by 64% whilst decreasing biomass the least by 15% versus the control. Nyakatawa *et al*. (2006) found that planting a fescue cover crop in sweetgum significantly reduced sediment yield compared to sweetgum without cover.

On a similar idea, clover was planted into SRC willow plantations, before being destroyed and added as a green manure by Arevalo *et al*. (2005). Plots were planted at densities of ~10,500 plants $ha^{-1}$ and harvested on an annual basis. The biomass yields were higher in the covered plot versus the control in the $3^{rd}$ harvest but lower in the $1^{st}$, $2^{nd}$ and $4^{th}$. Potential biomass yield loss is the principal reason cover crops are not popular. Volk *et al*. (2002) found that a cover crop (rye grass) could be successfully incorporated without reduction in biomass yield in the first two growing seasons of SRC. However pre-emergence herbicide had to be applied immediately after planting. They concluded that a balance between above ground biomass production, weed control and cover crop is required in the management method applied.

Use of cover crops during removal is less studied as the yield of the biomass crop is not an issue. A fodder crop may be added for grazing cattle or sheep, whose trampling will facilitate stump decomposition (Mitchell *et al*. 1999). Devine *et al*. (2006) planted wheat following removal of a woody biomass crop (sycamore) before conversion to arable. The cover crop also helps weed control.

#### 4.1.7.3 Summary

Overall soil erosion risks are highest within the first two years of growth, however once the stands have established they have a stabilising effect. Initial losses may be comparable to row crops, but on average biomass crops will only produce up to 4 Mg $ha^{-1}$ $yr^{-1}$ erosion compared to 18.1 Mg $ha^{-1}$ $yr^{-1}$ for agricultural crops (Table 5).

Due to the lower erosion potential, biomass crops have been used in a number of conservation projects to restore land and as a buffer strip to reduce run-off of nitrogen and sediment

(Borjesson 1999). So far studies looking at erosion losses associated with biomass crops have been short term, up to three years after establishment. The average erosion loss remains an estimate until longer term studies have been carried out. Work is also needed to study losses associated with plantation removal. The soil type used in the studies is not always provided in the literature, which is an issue, as soil type can have a large effect. Experimentation looking at the effect of soil type in relation to establishment and removal would be useful.

## 4.2 Soil water content

The soil water content is a balance between the input (precipitation and/or irrigation) and the outputs (lateral flow, drainage and evaporation). Following a period of rainfall or irrigation, sufficient to saturate the soil, the soil drains until the water held by surface tension on the soil particles is in equilibrium with the gravitational force causing drainage, i.e. drainage ceases. It is then defined as being at field capacity. It typically takes a few days for drainage to cease. During the period of drainage, water loss can also occur through evaporation, either directly from the surface of the soil or water extracted through the vegetation's roots to support transpiration. Once drainage has stopped, soil drying continues due to evaporation, with little restriction due to the soil water content until the "critical" soil water content is reached. The amount of soil water between field capacity and the critical point is often referred to as the readily available water content. As drying continues, the evaporation rate is increasingly limited by the soil water content until a point is reached at which the evaporation rate is effectively zero. This represents a progression from the evaporation controlled by meteorological conditions to it being controlled by the soil. Soil water deficits are defined relative to the soil water content at field capacity. In practise, the amount of soil water that is available for plants does not show large differences between soil types with the exception of sandy soils, when it is less, and chalk and organic soils when it is greater.

The amount of soil water available to vegetation for transpiration depends on two factors, the hydraulic properties of the soil and the rooting depth of the vegetation. The rooting depth can change as the vegetation goes through its lifecycle - a point of particular significance for annual vegetation. The depth to which soil water deficits develop is predominantly a function of two factors: The distribution of roots with depth and the hydraulic properties of the soil. The distribution of roots with depth can be conceived of as being determined by two parameters. The first of these is the maximum rooting depth of vegetation, see Table 2, which shows significant variation between vegetation types. The second is the root length density which generally reduces with depth, approximated by an exponential function, so the soil water deficits often show a similar trend with depth. The hydraulic properties of the soil determine the thickness of a "capillary" zone in which upward movement of water develops beneath the root zone. In most soils this is very thin and often is undetectable. The exception to this is the Chalk where the capillary zone can extend for several metres. The variations in soil water content with depth are rarely reported in the literature but, in the majority of cases, they show an exponential decrease with depth, mirroring the change in root density. In England, soil water deficits usually begin to develop in the late spring, as the evaporation rate begins to exceed the precipitation rate. The drying out of the soil begins near the ground surface, where the greatest density of roots is found. As time progresses, the depth to which the soil water deficits extend deepens and the size of the soil water deficit increases in the near surface. Changes in the soil water content near the ground surface, ca 0.3 m, can be very dynamic through the summer as rainfall events wet up the soils, followed by a period of drying over several days. In the autumn, the soils begin to wet up, as the precipitation rate exceeds the evaporation rate, and this process begins from the ground surface and extends downwards. It should be noted that detectable soil water deficits do not necessarily extend to the full rooting depth of the plant. This is because, at low root densities, the amount of soil water extracted is too small to be measured (Bailey, 1990)

In this report the soil water contents and deficits are given in depths of water - mm. This is done to allow easy comparison with rainfall and evaporation. However, in the context of soil water, it should be noted that the value applies to a depth interval, which may be measured from the surface e.g. in this case of the total rooting depth. It should also be noted that the soil water contents are instantaneous values of water storage whereas rainfall and evaporation are rates and so apply to a defined interval of time. This is often a day but can also be over a more arbitrary interval, e.g. the growing season

Values of soil water deficit are rarely quoted in the literature but a surrogate can be used, the evaporation rate, and this is done in this report. The magnitude of the soil water contents, and thus of soil water deficits, is essentially determined by the balance between the input from precipitation or irrigation and the outputs due to a combination of drainage and evaporation. In England, there is a strong seasonal variation in the evaporation; being lower in winter and higher in summer. (An exception to this can occur with woodland as the greater aerodynamic roughness of the canopy can result in the evaporation rates during winter being similar to those in summer.) As a result, soil water deficits are very rare in winter but occur in most summers, except where the water table is close to the surface e.g. close to a river. They will be greater in areas of lower summer rainfall, i.e. southeast England.

The evaporation is predominantly due to three sources: interception (precipitation intercepted by plant canopies and evaporated directly, without entering the soil), evaporation from the soil and transpiration from plants. Evaporation from the soil is generally from soil water within 0.2 m of the surface and so tends to be a relatively small proportion of the total – thus the characteristics of the vegetation are mainly responsible for explaining the differences in evaporation rates and consequently the size and timing of soil water deficits. Interception is usually a small fraction of the evaporation for short vegetation but it is often a significant fraction (20-40%) of the annual evaporation from woodland.

The term “water use” is often found in the literature concerning crops. To be precise, this should really be called “water loss” as the water is not actually used in photosynthesis. The term approximates to the evaporation over a given period in the vegetation’s life cycle but it is not always clear whether a publication is defining it as transpiration alone or transpiration and interception combined. Much of the literature is more concerned with water use efficiency rather than water use *per se*. There are a number of definitions of water use efficiency but they are basically a measure of the amount of biomass accumulated by the vegetation per unit water use. Unfortunately, it is not possible to use data about water use efficiency to discuss soil water contents unless the values for the yield are given, which is rarely the case.

### 4.2.1 Conventional land use

#### 4.2.1.1 Grass

In terms of evaporation rates and soil water contents, grass is generally considered to be the simplest land cover in terms of both processes and measurements. In England, the interception rates are generally found to be comparable to the transpiration rates, significantly reducing the uncertainties. Hence grass is generally taken as the benchmark against which comparisons are made.

Finch (2000) measured the soil water contents beneath a pasture in Berkshire during 1997 and showed that there was depletion of the soil water content down to a depth of 1.2 m. The maximum total soil water deficits recorded were around 130 mm. He simulated the evaporation rate at this site, using a water balance model, for a 25 year period getting an average annual evaporation rate of 0.97 mm $d^{-1}$ and an average evaporation rate over the growing season of 1.5 mm $d^{-1}$.

Similarly, Green *et al*. (2006) made measurements under grass, in Nottinghamshire, from 1998 to 2002. They recorded soil water deficits of up to 150 mm between the surface and a depth of 2 m, a depth which would comfortably exceed the rooting depth of the grass. Calder *et al*. (2003) used these data to calibrate a model of the water balance which they then used to simulate the long term average annual evaporation rate, obtaining a value of 1.4 mm $d^{-1}$.

Finch and Harding (1998) measured the soil water contents under grass, at a riparian site in Oxfordshire during 1997. They also made direct measurements of the evaporation rates. The maximum soil water deficit measured, down to a depth of 1.5 m, was 150 mm whilst the average evaporation rate during the growing season, April to September, was 1.1 mm $d^{-1}$

Roberts and Rosier (2005a and b) measured the soil water deficits under grass, at a site in Hampshire, and also directly measured the evaporation. They recorded soil water deficits of up to 250 mm down to a depth of 7.8 m. The average evaporation was 1.6 mm $d^{-1}$ over the period March 1999 to March 2000. This work needs to be seen in context because the site was on a chalk soil, which has very anomalous hydraulic properties compared to other mineral soils. In particular more water is available to support evaporation and drainage takes much longer to cease.

#### 4.2.1.2 Winter wheat

The annual average evaporation rates of cereal crops are generally similar to those from grass but the timing within the year differs significantly. Evaporation rates are lower during the late summer and early autumn. This is a result of a reduction in photosynthesis as the crops ripen and then, following harvest, the evaporation continues at a reduced rate because evaporation is only from the soil until the new crop emerges. However, cereal crops tend to have higher evaporation rates than grass during the growing season, essentially reflecting their more vigorous growth, and soil moisture deficits extend to a greater depth due to the greater rooting depth.

Weir and Barraclough (1986) measured the soil water contents, to a depth of 2 m, beneath winter wheat at a site in the UK. Soil water deficits were observed down to depths in excess of 1.5 m. The average evaporation rate during the growing season, 24$^{th}$ March to 2$^{nd}$ August, was estimated from the water balance giving a value of 1.3 mm $d^{-1}$ for a droughted crop and 2.0 mm $d^{-1}$ for a rain fed crop.

Hall and Heaven (1970) measured soil water deficits beneath wheat in 1975. The deficits extended to greater than 1 m but not to 1.5 m.

Scott *et al* (1994) analysed data from a site in Nottinghamshire. For the growing season, April to August, they obtained average evaporation rates of 1.5 mm $d^{-1}$, when no fertiliser was applied, and 1.7 mm $d^{-1}$ when fertiliser was applied, implying that the fertiliser application promoted more vigorous growth resulting in higher evaporation rates.

#### 4.2.1.3 Potatoes

Potatoes are shallow rooting and thus are prone to reduced yield due to low rainfall during the growing period with the result that they are more likely to be irrigated.

Asfarey *et al* (1983) reported soil water deficits developed down to a depth of 0.75 m under potatoes at a site near Reading. They calculated the average evaporation rate through the growing season (mid-April to mid-August 1978), using the water balance method, to be 1.5 mm $d^{-1}$ when not irrigated and 2.3 mm $d^{-1}$ when irrigated.

Feddes *et al* (1988) in a study in the Netherlands, found that soil water deficits were limited to a depth of 0.65 m. Using a numerical model of the evaporation and soil water tested against observations, they estimated that the average transpiration rate during the growing season (mid May to mid September 1976) was 2.0 mm $d^{-1}$.

A study in Canada by Singh *et al* (1993) also estimated the average evaporation rate using a numerical model and concluded that it was 3.8 mm $d^{-1}$ (June to mid August 1988) with soil water deficits dominantly occurring at depths less than 0.6 m. It is not clear why this evaporation rate is so much higher than the rates estimated in the other studies.

#### 4.2.1.4 Broadleaf woodland

The water balance of broadleaf woodland has been the focus of numerous studies in the last two decades. The absence of leaves during the winter means that the evaporation rates during this period will be low, in terms of both transpiration and interception. However, during the summer, higher evaporation rates can be expected, partly due to the greater aerodynamic turbulence associated with the shape of the trees' canopies and partly because they are deep rooted, typically several metres, allowing them to maintain transpiration rates in low rainfall years (Herbst *et al*., 2007; Herbst *et al*. 2008). The situation can become more complex where an understory is present.

In a comparison of reported annual transpiration rates of temperate forests, Roberts (1983) pointed out that the rates showed remarkable similarity, averaging 0.91 mm $d^{-1}$. Subsequent research, summarised by Komatsu (2005), has shown that, on average, broadleaf woodlands have higher annual transpiration rates than needliferous woodland. Herbst (pers. comm.) considers that the annual transpiration rates of English broadleaf woodlands are remarkably similar, with the exception of "wet" woodlands which have higher rates. However there are differences in the seasonal transpiration rates between different species.

Finch (2000) measured the soil water contents, down to a depth of 3 m, beneath a small, mature mixed broadleaf woodland in England during 1997 and showed that there was depletion of the soil water content down to a depth of 2.1 m. The low soil water contents recorded below this depth strongly suggest that soil water deficits existed at depth prior to 1997, indicating that soil water deficits actually extended to a depth in excess of 3 m. Finch simulated the evaporation rate, using a water balance model, for a 25 year period getting an average evaporation rate of 1.6 mm $d^{-1}$.Unpublished measurements, made during the drought years 2003-5 at a site about 10 km away from that used by Finch (2000), have confirmed the development of soil water deficits at depths down to 4 m which can persist through the winter.

Green *et al*. (2006) made measurements under an oak woodland, in Nottinghamshire, from 1998 to 2002. They recorded soil water deficits, of up to 200 mm, between the surface and a depth of 2 m, which they considered corresponded to the majority of the roots. Calder *et al.* (2003) used these data to calibrate a model of the water balance which they used to simulate the long term evaporation rates. The long term average annual evaporation rate was 1.6 mm $d^{-1}$, with an average annual transpiration rate of 1.1 mm $d^{-1}$.

#### 4.2.1.5 Coniferous woodland

Concern about the possible impact of extensive planting of coniferous woodland on water resources was first raised in the 1950's with the result that there is now a significant volume of research in the UK, although much is related to sites in the uplands, i.e. high rainfall areas. The presence of leaves throughout the year will result in active transpiration through the winter, albeit at a low rate, but the major impact is through a significant loss of water due to interception from the tree canopy. In terms of soil water, these factors are unlikely to have a significant effect on the soil water content, except in low rainfall areas during winters with significantly below average rainfall. Coniferous trees tend to be shallower rooting than broadleaf trees, a typical value being around 2 m, see Table 2,. The combination of these factors leads to the conclusion that the annual evaporation rates from coniferous woodland are greater than for grass.

Law (1956) measured the water balance of Sitka Spruce in a small catchment located in Yorkshire and estimated that, over a period of one year, the average transpiration rate was 0.9 mm $d^{-1}$ whilst the average interception rate was 1.0 mm $d^{-1}$. There was little variation in the interception rate through the year but a significant difference between the winter and summer transpiration rates, the latter averaging 1.2 mm $d^{-1}$. Rutter (1968) describes measurements of transpiration of Scots Pine and reported an average annual rate of 1.2 mm $d^{-1}$.

A detailed experiment to measure the evaporation from a forest of Scots and Corsican pine in Norfolk during 1975 is described by Gash and Stewart (1977). The average interception rate over the year was 0.59 mm $d^{-1}$ whilst the average transpiration rate was 0.97 mm $d^{-1}$. The lower interception rate compared to that of Law (1956) can be attributed to lower rainfall rates and wind speeds at the site. The average summer transpiration rate was 1.7 mm $d^{-1}$. Roberts *et al.*(1982) carried out further studies and concluded that the differences in the evaporation rates of the two types of pine were minimal, which they attributed to the greater leaf area of the Corsican pine being balanced by an understory of bracken in the Scots pine.

Analysing a 30 year set of measurements of the water balances of two experimental catchments in mid-Wales, Marc and Robinson (2007) concluded that the average evaporation rate from mixed coniferous woodland was 1.6 mm $d^{-1}$. However this hides a trend of decreasing evaporation with the age of the forest.

On the continent Tajchman (1971), reported an annual average transpiration rate of 1.2 mm $d^{-1}$ and an annual average interception rate of 0.4 mm $d^{-1}$ for Norway spruce.

### 4.2.2 SRC Willow

There has been interest in the water use of SRC willow for some time. A number of studies have been carried out in the UK but there is also a significant body of work from Sweden.

Jørgensen and Schelde (2001) measured the soil water contents, over three 0.5 m intervals down to a depth of 1.5 m, under two clones (78-112 and 78-113), from 1997 to 1999 at a site in Denmark. Soil water deficits occurred throughout the period May to October inclusive. The maximum soil water deficit for clone 112, over the depth interval 0 – 1 m, was 180 mm whilst over the interval 0 – 1.5 m it was 185 mm. In comparison, the equivalent soil water deficits for clone 183 were 105 mm and 145 mm. This implies a shallower rooting depth for clone 183, possibly not much more than 1 m, but higher evaporation rates. The authors went on to use a numerical model of the land surface water balance (Gardenas and Jansson, 1995) to estimate the evaporation by calibrating the model against the measured soil water contents. The results gave an average annual evaporation rate of 1.5 mm $d^{-1}$ for clone 112 and 1.2 mm $d^{-1}$ for clone 183. The corresponding values for the average annual transpiration rate are 0.96 mm $d^{-1}$ and 0.71 mm $d^{-1}$.

The evaporation from SRC willow was estimated by Persson (1997), for a period of six years using a numerical model, for conditions in Sweden assuming a rooting depth of 1m. The model used was an earlier version of that of Gardenas and Jansson (1995). The average annual transpiration rate was estimated to be 0.84 mm $d^{-1}$, with the rate being well above this average value during the months April to October, i.e. the period with leaves.

Measurements by Linderson *et al*. (2007) of the transpiration from six SRC willow clones, at a site in southern Sweden gave an average transpiration rate of 1.3 mm $d^{-1}$ for the period May to September 2000. However there was considerable variation about this mean, covering a range of 1.0 mm $d^{-1}$ to 2.1 mm $d^{-1}$, part of which can be explained by the differences in the amount of leaves of the different clones. A similar result was obtained by Grip *et al*. (1989), who measured the evaporation of irrigated SRC willow in three stands at a site in southern Sweden in the second year of growth after harvesting. They then simulated the evaporation from the optimally irrigated SRC willow and for a more limited irrigation. In the case of the latter, the annual evaporation rate was 1.4 mm $d^{-1}$ of which 1.0 mm $d^{-1}$ was transpiration, 0.15 mm $d^{-1}$ was interception and 0.25 mm $d^{-1}$ was soil evaporation. The values of transpiration and soil evaporation must be considered to be higher than will be obtained in practice, due to the irrigation.

In the UK, ongoing measurements of the soil water content at a site in Lincolnshire (Finch pers. comm.) began in May 2006. The SRC willow is at least four years old. The maximum soil water deficit recorded during 2006 was 165 mm. The range of soil water contents recorded clearly show that soil water deficits occurred down to a depth of 1.2 m. Below this depth the soil is saturated and it is likely that the permanently waterlogged conditions have restricted root development.

At a site near Swindon, Finch *et al*. (2004) made detailed measurements of the transpiration from a number of varieties of SRC willow during the summer of 2002. These measurements were used to test and calibrate a numerical model of the land surface water balance which was then used to simulate the evaporation of SRC willow over England and Wales at a spatial scale of 1 $km^2$. For a location near Ludlow, the annual average evaporation rate, over the three year growing period, was 1.6 mm $d^{-1}$, but was composed of a rate of varying between 1.3 mm $d^{-1}$ in the first year, 1.6 mm $d^{-1}$ in the second and 1.8 mm $d^{-1}$ in the third. During the growing season, April to October incl., the three year average evaporation rate was 1.8 mm $d^{-1}$.

Cranfield University (2001a) carried out a modelling study, taking parameter values from the literature, and simulated the annual evaporation rates from SRC willow at three sites over a period of up to 30 years. The values for two of the sites, Silsoe and Selby, were similar at 1.2 mm $d^{-1}$ and 1.3 mm $d^{-1}$. However, at the third site, Cirencester, the value was much higher, at

1.6 mm $d^{-1}$. The authors speculated that this might be due to higher rainfall and/or the meteorological conditions.

### 4.2.3 *Miscanthus*

There is less information in the literature about *Miscanthus* than SRC willow because interest in this crop is much more recent. Nevertheless, there have been a number of studies in the UK. Beale *et al*. (1999) measured the soil water contents, down to a depth of 1.2 m, and the transpiration of a 3 year old crop during the growing season of 1994 at a site in Essex. They recorded the maximum soil water deficit as 108 mm, although it is likely that they did not record the soil water deficits to the full depth. The average evaporation rate over a period of 118 days, starting on 26 April, was estimated to be 2.3 mm $d^{-1}$, based on the soil water balance.

Measurements of the soil water content at a site in Somerset (Finch pers. comm.) began in May 2006 and were taken at intervals of 2-3 weeks until February 2007. The *Miscanthus* was planted in 2003 and so was in its fourth year. The range of soil water contents recorded clearly shows that soil water deficits occurred down to a depth of 1.2 m and are likely to continue beneath this. Thus, the maximum soil water deficit recorded, 140 mm is probably an underestimate. Finch *et al*. (2004) made measurements of the soil water content, down to a depth of 1.2 m during the summer of 2003 at a site near Ludlow. They also measured the sum of transpiration and soil evaporation over an area with a radius of about 100 m. The maximum soil water deficit recorded was 150 mm but the range recorded shows that soil water deficits existed to an unknown depth below the measurements. The measurements were used to test and calibrate a numerical model of the land surface water balance which was then used to simulate the evaporation of *Miscanthus* over England and Wales at a spatial scale of 1 $km^2$. The simulated annual average evaporation rate over a three year period was 1.4 mm $d^{-1}$ for the measurement site. The average rate during the growing season April to September incl. was 2.6 mm $d^{-1}$.

Cranfield University (2001a) carried out a modelling study, taking parameter values from the literature and simulated the annual evaporation from *Miscanthus* at three sites over a period of up to 30 years. The values for two of the sites, Silsoe and Selby, were similar at 1.2 mm $d^{-1}$. However, at the third site, Cirencester, the value was much higher at 1.6 mm $d^{-1}$. They speculated that this might be due to higher rainfall and/or the meteorological conditions.

Cosentino *et al*. (2007) measured the soil water contents at intervals of 0.2 m to a depth of 0.8 m under plots of *Miscanthus* in Sicily during 1994 and 1995. The measurements were made over the growing season, defined as June to November. The rainfall at the site was low during the growing season, 57 mm in 1994 and 151 mm in 1995, and two different levels of irrigation were applied. The total precipitation (rainfall + irrigation) for the first treatment was about 260 mm in 1994 and 230 mm in 1995 whilst it was 500 mm in 1994 and 400 mm in 1995 for the second treatment. The first treatment approximates to average rainfall and the second to above average rainfall during the growing season for areas of low rainfall in England. The authors give the average evaporation rate (estimated from the soil water balance) during the growing season as 2.1 mm $d^{-1}$ in 1994 and 1.9 mm $d^{-1}$ in 1995 for the first treatment and 3.1 mm $d^{-1}$ in 1994 and 2.0 mm $d^{-1}$ for the second.

Finch and Riche (2008) report measured soil water contents, from four sites in England, which show soil water deficits extending down to 1.7 m at two of the sites. At the other sites the measurements did not extend down to this depth but soil water deficits extended to the maximum depth at which measurements were made. They analysed these data to estimate evaporation rates during the summer months. There was significant variability between sites but the highest rates occurred in June, when the average rate was around 3.2 mm $d^{-1}$, which then decreased as the summer progressed, to around 1 mm $d^{-1}$ in October. The authors point out that the evaporation rates in October are probably untypical as two of the sets of measurements were made in 2003, which was one of the driest summers on record, and there was clear evidence of soil water availability limiting the transpiration rates.

It should be noted that there is a degree of confusion between the depth that the *Miscanthus* rhizomes extend down to, typically 0.2 m, and the depth to which the roots extend to, typically 2 m.

### 4.2.4 Comparison between conventional and biomass crops

Inevitably there are dangers in making generalisations, as conditions at each site will vary from the "average". Nevertheless, it is possible to establish some broad characteristics from the details given above. Soil water content, from the perspective of the historic environment, is dominantly concerned with the evaporation rates during the growing season and the availability of soil water to support these. Soil water deficits are likely to occur down to a depth of 1 m under virtually all vegetation types, except in parts of the country where the summer evaporation rates are significantly less than the rainfall rates – generally in the west of England. Amongst the conventional land uses, it is broadleaf woodland that is likely to result in the greatest soil water deficits. Although the evaporation rates are similar to the other land cover types, Table 10, they are maintained at these levels during dry summers by drawing on the greater amounts of soil water available due to the greater maximum rooting depth. The result is that, during a period of two or more winters with low rainfall, significant soil water deficits can be developed to a depth of up to 4 m. SRC willow and *Miscanthus* are significantly shallower rooted than broadleaf woodland and so soil water deficits under these will not extend to the depth that may occur under broadleaf woodland. However, the higher evaporation rates of these crops suggest that the intensity of the soil water deficits could be greater.

| Land cover | Typical growing season average evaporation rate (mm $d^{-1}$) | Maximum rooting depth (m) |
|---|---|---|
| Conventional land cover | | |
| Grass | 1.1 - 1.6 | 0.8 |
| Winter wheat | 1.3 - 1.7 | 1.2 |
| Potatoes | 1.5 - 2.3 | 1.0 |
| Broadleaf woodland | 1.5 - 1.7 | 4.0 |
| Coniferous woodland | 1.5 - 2.0 | 2.5 |
| SRC willow | 1.5 - 2.6 | 2.0 |
| *Miscanthus* | 1.8 - 2.6 | 2.5 |

**Table 10 Typical growing season evaporation rates and maximum rooting depths for SRC willow, *Miscanthus* and selected conventional land uses.**

The rooting depths of the two biomass crops are comparable to that of coniferous woodland. Although the range of evaporation rates of the two crops overlap, those of coniferous woodland tend to be lower which suggests that, although soil water deficits will extend down to about the same depth, the intensity of the soil water deficits under the biomass crops will be higher. The remaining land cover types are shallower rooting than the biomass crops whilst also having lower evaporation rates so the soil water deficits will extend to a shallower depth under these land covers. An exception to arable crops being shallower rooting than the biomass crops is maize which can have roots down to 2 m (Liedgens and Richner, 2001).

It is not practical to make any specific comments on the impact of the water table levels in wetlands were SRC willow and/or *Miscanthus* to be planted in the vicinity. This is because the result would be determined by a complex interaction of a number of factors such as: the land cover the biomass crops replaced; the average rainfall in the area; the fraction of the contributing area to flow into the wetland that was covered by the biomass crops; the amount of flow out of the wetland, *etc*. In the worse case scenario, were the whole of the contributing area to be covered with biomass crops and these replaced land covers with low evaporation rates then it would be anticipated that a lowering of the water table would occur but it is not possible to quantify how much this would be other than to carry out a detailed analysis of specific sites.

## *4.3 Soil chemistry and water quality*

### 4.3.1 SRC Willow

#### 4.3.1.1 Soil chemistry

SRC willow varieties have been selected and grown commercially for almost 20 years and a wide range of genotypes exist and so there is a reasonable amount of information in the literature. Weih and Nordh (2002) characterised 14 clones of willow in terms of relative growth rate, total biomass production, nitrogen (N)- and water-use efficiency under different irrigation and fertilisation treatments from bud break to leaf abscission. Significant differences were found in nearly all parameters measured and clones varied in response to the different experimental treatments. None of the clones was superior in terms of shoot production, N and water economy under all the treatments tested. This suggests that the industry may select optimal clones for growing in the different environmental conditions associated with specific regions of the UK.

Meers *et al*. (2007) and Maxted *et al*., (2007) report low to moderate uptake of metal pollutants by willow from soil suggesting a use in phytoremediation of lightly-polluted land, for example where contaminated sludge has been applied. Uptake varied with species and was enhanced by chelating agents (Meers *et al*., 2007). Zhao *et al*. (2007) found strongly variable and thus localised effects of dissolved organic carbon (DOC) on metal concentrations in soil columns planted with willow. DOC is able to complex heavy metals and mobilise them (e.g. de Vries *et al*., 2007). Zhao *et al*. (2007) suggest that the source of the DOC is microbial rather than plant and that mobilisation increases the uptake rather than leaching of the pollutants.

Mann and Tolbert (2000) in a review of biomass crops, especially SRC, found an increase in soil C and a reduction in sediment loss, after the initial establishment phase, as a result of an increase in aggregate stability. Although biomass crops were thought to reduce the leaching of N and P there were suggestions that micronutrients such as boron might be depleted in soil under energy crops (Mann and Tolbert, 2000). Blanquo-Canqui *et al*. (2007) also found evidence of an increase in aggregate stability in relation to increases in soil organic matter under several trees grown for fibre including poplar.

#### 4.3.1.2 Water quality

In willow, evidence suggests that N cycling is similar to poplar, where developing leaves represent a dominant sink for N during the growing season followed by a major internal redistribution of N from leaves to perennating organs such as stems and roots. During autumn, N-rich amino-acids and other mobile nutrients are transported via the phloem and are accumulated in protein-filled vacuoles in parenchyma cells of bark (Cooke and Weih 2005). Willows also lose a large fraction of the nutrients taken up during the growing season by leaf abscission in the autumn and the leaf litter quality, in terms of nutrient concentration, is a strong determinant of litter decomposition and nutrient cycling in soil (Weih and Nordh, 2002).

In a lysimeter study of the whole-season nitrogen budget of willow, during the first season in which 191 kg N $ha^{-1}$ of liquid fertilizer was applied, 98 kg N $ha^{-1}$ was taken up by plants (Aronsson, 2001). In another experiment, Mortensen *et al* (1998) concluded that 75 kg N $ha^{-1}$ could be applied to willow without a leaching hazard. In studies in which willows were used as vegetation filters to clean polluted drainage from agricultural land (10-17 mg $NO_3$-N $l^{-1}$) irrigation was 6 mm in excess of transpiration. However, all the total N delivered (185 kg $ha^{-1}$) was taken up by the crop (Elowson, 1999). Labrecque *et al.*, (1998) studied supply of N from sewage sludge (at the rates of 0 to 300 kg available N $ha^{-1}$) by monitoring growth, nutritional plant response and impact on soil. N in the leaves varied between 25 and 47 mg N $g^{-1}$ DM, with yields of 19-22 t DM $ha^{-1}$. Stem and branch nutrient concentrations suggested that N was the most limiting factor but 100 kg N $ha^{-1}$ was sufficient to ensure growth and avoid nitrate pollution (Labrecque *et al.*, 1998). A later study raised the optimum N input to 150 kg N $ha^{-1}$ (Labrecque and Teodorescu, 2001). The effect of nitrogen fertilization on accumulated stem growth over the experimental period was found to be significant only for nitrogen applied in years 2 and 3 (Alriksson *et al.*, 1997). A negative interaction coefficient between these years was interpreted as the system's ability to recycle N from roots.

Lysimeter experiments suffer from the initial conditions and at least 1/3 (69 kg N $ha^{-1}$) can be leached (Aronsson, 2001). With higher initial N, $NO_3$-N leaching loads were very high the first year after plant establishment (on average 341 kg N $ha^{-1}$ from clay and 140 kg N $ha^{-1}$ from sand lysimeters; Aronsson and Bergstrom, 2001). However, leaching loads decreased and were low or negligible during the second (43 from clay and 17 kg N $ha^{-1}$ from sand lysimeters) and third year (3 kg N $ha^{-1}$ from clay and less than 1 kg N $ha^{-1}$ from sand lysimeters; Aronsson and Bergstrom, 2001).

Leaching problems during field establishment can originate from high mineral N contents in the planting year and it has been concluded that fertilisation should be avoided in the year of planting (Mortensen *et al.*, 1998), while 75 kg N $ha^{-1}$ can be given thereafter. In studies in which 0-53 kg N $ha^{-1}$ fertiliser were applied, nitrate concentrations were found to be very low (0.5 mg $l^{-1}$; Aronsson *et al.*, 2000), a value that confirmed earlier observations (Bergstrom and Johansson, 1992). Using waste water from sewage sludge treatment imposed doses up to 320 kg N $ha^{-1}$, which resulted in leaching loads of 70-90 kg N $ha^{-1}$ from clay and sand lysimeters (Dimitriou and Aronsson, 2004).

Leaching of nitrate from crops is one of the biggest factors affecting diffuse water contamination. Nitrogen leaching from SRC has been estimated to be 30-50% lower than from grain production (Makesschin, 1994 Rijtema and de Vries 1994). This benefit will be greatest on coarse-textured sandy soils, as the nitrogen leakage from these soils is on average double that from fine textured soils (Börjesson, 1999). Good removal efficiencies of problematic landfill leachate components have been achieved in Sweden, with the nitrogen content of leachate reduced by 93% from 1600 kg N $ha^{-1}$ $yr^{-1}$ to approximately 100 kg N $ha^{-1}$ $yr^{-1}$ over a ten year period (Hasselgren, 1998).

A recent modelling study confirmed the ability of biomass crops to store carbon in soil but also the danger that these crops might use more water than current agricultural crops (García-Quijano *et al.*, 2008).

### 4.3.2 *Miscanthus*

#### 4.3.2.1 Soil Chemistry

Kahle *et al* (2002) found that the pH in the top 20cm of soil under *Miscanthus* grown for 10 years declined by about 0.25 units. There was a general increase in potassium in soils and to a lesser extent magnesium, probably as a result of the withdrawal of cations from depth and return to the surface in residues (Kahle *et al.*, 2001). These same authors found a significant increase in the cation exchange capacity (CEC), moisture retention characteristics, a widening of the soil C:N ratio and a decrease in the bulk density probably as a result of increases in organic carbon. However, since the control soils also changed in the same direction it is not clear to what extent growing *Miscanthus* has brought about the changes or whether some other factor was responsible.

Unlike poplar and willow which have been grown widely for many years, there is little literature on the use of *Miscanthus* in remediation of contaminated land. Jones *et al* (2005) discuss the merits of *Miscanthus* for phytoremediation of landfill waste. They point out that although *Miscanthus* is able to tolerate the high levels of N found in landfill leachate, most leachates contain more N than the plant will use.

Earthworm numbers halved under *Miscanthus* relative to a meadow (Kohli *et al*, 1999) apparently because of a decline in quality of the secondary plant compounds in the plant residues; the benefits to soil and water chemistry can be expected to decline in proportion. In contrast, recoveries in earthworm numbers and microfauna are quoted on transition from maize to wild-flowers (Mann and Tolbert, 2000). Earthworms promote aggregation and aeration (Six *et al*, 2004) and are thought to bring benefits to most parts of the whole soil ecosystem (Lavelle, *et al.*, 1997).

The Defra growers guide recommends that there should be a soil nitrogen supply in excess of 150 kg $ha^{-1}$ for the first two seasons but has no further recommendations. Current UK commercial practice is not to apply nitrogen fertilizer to *Miscanthus* at any stage. This is supported by various pieces of research, but might well change if crops are established on poorer soils. To date, most experimental and commercial crops have been grown on reasonable quality soils. Various experiments with *Miscanthus x giganteus* in Germany showed that although a supply of up to 150 kg N $ha^{-1}$ can increase the biomass yield (Lewandowski and Schmidt, 2006), yields of less than 20 tDM $ha^{-1}$ require less than 40 kg N $ha^{-1}yr-^{1}$; in the UK this amount is quite commonly received from aerial deposition, in addition to what is available from the soil (Goulding, 1990). The study also ignored the N cycling between rhizomes and aerial biomass which determines second year re-growth (Wiesler *et al.*, 1997).

A study evaluating 97 experiments for *Miscanthus x giganteus* (≥3 years after planting, average of 22 tDM $ha^{-1}$) showed a significant positive response to water and N (Heaton *et al.*, 2004), however under UK conditions yields are likely to be significantly less, and factors other than N, e.g. water and temperature are more likely to be limiting to growth (Lewandowski and Schmidt, 2006). The capacity to sustain uptake of N throughout the year resulting in late additional growth was reported for *M. sinensis* (Wiesler *et al.*, 1997).

Less data are available on phosphorus although Mann and Tolbert (2000) expect a reduction in P loss in biomass crops compared to other agricultural use. In established *Miscanthus* in the UK around 11 kg of phosphorus are removed in the aerial biomass at harvest (Defra, 2001).

#### 4.3.2.2 Water quality

Nitrate leaching under *Miscanthus x giganteus* receiving 0, 60 and 120 kg N $ha^{-1}yr^{-1}$ was measured over the six years following establishment at Rothamsted (Christian and Riche, 1998, Riche and Christian 2000). The treatment receiving no N fertilizer (i.e. recommended practice on fertile soils) had a mean nitrate-N concentration of 32 mg $l^{-1}$ in the drainage water over the first winter following establishment. In the subsequent five winters this concentration reduced significantly to a range of 1 to 7 mg nitrate-N $l^{-1}$. The EU limit for drinking water is 11.3 mg $l^{-1}$. The high concentration in the first winter was probably due to the site having high levels of soil nitrogen (the site was permanent grass up to 1988), and very little crop growth in the first year as the crop was established using micro-propagules, which is not commercial practice. The actual quantities leached were also very low after the establishment year, just 8 and 3 kg nitrate-N $ha^{-1}$ in the second and third winters. These low amounts are a result of the low concentrations and also the low drainage flows. As *Miscanthus* grows through the summer, and also intercepts a significant proportion of rainfall (Riche and Christian, 2000), there is usually a large soil moisture deficit by the end of the growing season, which then takes a lot of the winter to be reduced. Leaching losses were closer to those recorded under extensively managed grassland than arable land. N-leaching under *Miscanthus x giganteus* was also found to be negligible in another study (Beale and Long, 1997).

### 4.3.3 Effects of planting biomass crops into grassland

If grassland were ploughed up to provide land for biomass crops, N supply from mineralization would exceed the crop's N requirements, and it is likely that nitrate leaching and nitrous oxide emissions to the atmosphere would increase. Whitmore (1992) estimated that up to half of any losses of N on ploughing up grassland will occur during the first 5 years and more than 90% during the first 20 years. Typical soils were found to lose 4 t $ha^{-1}$ of N from organic matter altogether. The resultant concentration in natural waters is determined by the crop grown and the site, since some areas of the country receive more rainfall than others and some crops use more water in winter than others. The concentrations are likely to range from 300 mg $NO_3$-N $l^{-1}$ (at worst) to 80 (at best) directly under the ploughed land and averaged over the first 5 years. Both these concentrations are in excess of the EU limit of 11.3 mg $l^{-1}$ in natural waters.

# 5 Discussion and recommendations

Although there has been research into SRC willow for more than two decades, there is a limited amount of information available on subsurface conditions and the information that is present tends to reflect concern about soil water deficits and water quality in terms of agricultural residues. Even less information is available about *Miscanthus* as interest in it as a crop is more recent. However, some of the studies have had positive outcomes, and shown a benefit from growing biomass crops.

Soil erosion and compaction are mainly due to mechanical operations although soil compaction can result from livestock. They are two important factors when considering the impact of agriculture on soils. Soil compaction can impede water infiltration, leading to increased surface water and associated surface flows, and so can result in erosion. Both processes effectively reduce the depth of topsoil, bringing the subsoil closer to the surface. However it is in the grower's best interest to avoid soil damage that will affect crop productivity because, being perennial, there is little or no opportunity to rectify issues in the growing biomass crops. There is a degree of uncertainty in the mechanical operations as the machinery for some operations, e.g. harvesting, is still being developed but it would seem unlikely that the effect of the vehicles themselves will be significantly different to those used with conventional crops. However there is a lack of measurements on commercially used machinery operating on commercial fields.

It is unlikely that activities to prepare the soil for planting will differ significantly from those used for conventional crops, e.g. if deep ploughing is needed for biomass crops, it is likely to be needed for conventional crops. However, if previously uncultivated grassland is being converted to biomass crops, then the disturbance is likely to be greater than has previously occurred.

Once the crops have been established, being perennial, the only significant regular mechanical operation is the harvest, annually for *Miscanthus* and usually once in three or four years with SRC willow. Harvesting both crops involves several passes with relatively heavy machinery so there are risks of damage to the soil but there is little evidence to suggest that the effect will be greater than with the machinery used on conventional arable crops. It may well be less due to the development of a leaf mat on the ground surface by both crops and there is the added advantage of carrying out fewer or no operations to apply fertilisers and herbicides. Again, the situation is likely to be different if biomass crops replace uncultivated grassland.

Where biomass crops differ from conventional crops is in the need for removal of the crop at the end of its economic lifetime. In the case of *Miscanthus* the process is relatively simple and would be comparable to normal ploughing. However, SRC willow may require major mechanical operations to be used. In this, it would appear to be similar to woodland, but stumps are rarely actively removed in woodlands because, in managed woodland, it is usually re-planted whilst in other situations the stumps are usually left to rot. Because of the long economic life of SRC willow and *Miscanthus*, and the interest in planting is relatively recent, there is little experience of how, in practice, the crops are removed.

There is a reasonable amount of information on the rooting habit of biomass crops, in terms of the maximum rooting depth, root density distribution with depth, and the root diameter distribution. Both SRC willow and *Miscanthus* are significantly deeper rooting, at up to 2.5

m, than the majority of conventional crops (an exception is maize) and thus the risk of physical damage to historic remains is greatly increased, although the large majority of roots occur at depths shallower than 0.5 m. Where there is a lack of information, as there is with other plant types, is in how these parameters are modified by local conditions, e.g. permanently water logged conditions or the presence of a hard layer within the normal rooting depth.

There is no simple answer to the question of whether the biomass crops will result in greater drying out of soils as it depends on: the land cover they are being compared with, the soil type and hydrological conditions at the site, and the amount of summer rainfall. Although there is quite a bit of information in the literature, and there are a number of ongoing studies that will report shortly, it is difficult to make comparisons between these studies and with information about other land covers. The situation becomes further complicated when it comes to making guidance available for those working with the historic environment, so that it is relevant to a given site. The solution to both difficulties is to carry out a study using numerical modelling. There is sufficient information available to parameterise such a model and to carry out simulations to an appropriate accuracy. The simulations could be used to quantify the effect of the different factors. The challenge will be to identify how to distil the information in a way that is meaningful. However, a few general comments can be made. In general, both biomass crops have higher evaporation rates than “conventional” crops or grass during the summer. Combined with greater rooting depths, it is likely that soil water deficits will be more intense and extend to a greater depth. A consequence of this is that soil water deficits are probably eliminated later in the year.

In terms of soil chemistry and water quality, there is a lack of information that is directly relevant to the historic environment, mainly because research has focussed on the issue of nitrates, from the point of view of the needs of the crop and the potential for contamination. Thus there is a need for a study that addresses specifically the factors that could impact the historic environment, e.g. acidity.

The greatest uncertainty is in the future scale and distribution of biomass crops in England. Factors involved include: the prices of food and biofuels, technological advances (e.g. in converting biomass to liquid transport fuels) and policies of organisations such as the UK Government and the European Union. The situation is currently changing rapidly and it is difficult to know which changes are short term and which are longer term. As a result, there is a persuasive argument to update this report on a timescale of around 3-5 years when more information is available and general trends may be clearer.

In summary, we recommend that:

- This report should be updated in about 3-5 years time to take advantage of information that becomes available and thus reduce uncertainties;
- A study should be carried out into the impacts of commercial machinery, for biomass crops, operating in commercial fields;
- A study, involving numerical modelling, should be carried out to allow a comparison of the developments of soil water deficits under different land covers, for a variety of soils and climatic conditions found in England, to inform those interested in the historic environment;
- A study should be made of the soil chemistry and water quality issues that are relevant to the historic environment, under biomass crops and, if there is a lack of information, other land covers.

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# Annexe – list of abbreviations

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|---|---|
| ARBRE | Arable Biomass Renewable Energy |
| DAFF | Department of Agriculture, Fisheries and Forestry |
| ECS | Energy crop scheme |
| EU | European Union |
| Defra | Department for the Environment, Food and Rural Affairs |
| DM | Dry material |
| GHG | Greenhouse gas |
| MAFF | Ministry of Agriculture, Food and Fisheries |
| NFFO | Non fossil fuel objectives |
| NIAB | National Institute of Agricultural Botany |
| ROC | Renewables obligations certificate |
| SOM | Soil organic matter |
| SRC | Short rotation coppice |
| UK | United Kingdom |
| US | United States of America |