REPORT PREPARED FOR THE ENVIRONMENT AGENCY 10th July 2007:

THE BENEFITS AND NEGATIVE IMPACTS OF BIOMASS CROPS ON RESOURCE PROTECTION

1. Contributors (alphabetical order)

Rothamsted Research, Harpenden, Hertfordshire
Richard Bromilow, Angela Karp, Andrew Riche, Goetz Richter, Chris Watts, Andrew Whitmore

Centre for Ecology and Hydrology, Wallingford
Jon Finch, Mark Robinson

2. Aim of Report

To identify existing knowledge and knowledge gaps on the benefits and negative impacts of biomass crops on resource protection. The study focuses on enabling land to be targeted for biomass crops and on identifying practices that are sustainable to resource management. This will provide supporting evidence for Natural England and the Forestry Commission to decide on suitable land for energy grant aids.

3. Executive summary

This report is a brief synopsis of the current state of knowledge on the positive and negative impacts of Miscanthus and SRC willow on resources. Gaps of knowledge are also highlighted. The report addresses a number of questions regarding nutrients (nitrogen and phosphorus), pesticides, water and soils. The main findings are summarised below:

1. Growing perennial energy crops instead of annual food crops reduces the risk of water pollution through leaching and runoff.

2. The nitrogen (N) budget for Miscanthus is as follows:
- N-requirements in the first year may not exceed 100 kg N ha^{-1} (uptake capacity).
- Currently, under UK growing conditions N fertilizer and is not usually applied during or after establishment.
- N fertilizer is not required on fertile soils, but may be needed on low-fertility soils.
- Most N is stored in the roots and rhizomes (2/3rds) which is important for re-growth.
- On average, 60 kg N ha^{-1} is returned to the soil as litter which is slowly mineralised and may change the overall humus quality and retard later release.
- 90 kg N ha^{-1} could be exported with the biomass at harvest (assuming yields of 15 tDM ha^{-1})
- Nitrate leaching is reported to be negligible unless mineral soil N exceeds 100 kg N ha^{-1} in the establishment year. However, if grassland was converted to Miscanthus, then nitrate leaching and nitrous oxide emissions could be significant.

3. In willows the N budget is as follows:
- Currently, under UK growing conditions, N fertlizer is not usually applied during or after establishment. However, some growers apply waste treatments, e.g. sewage sludge.
- Once willows have an established root system the uptake capacity is well above 100 kg N ha^{-1}.
- Between 100 and 185 kg N ha^{-1} is taken up without nitrate leaching.

- Nitrate leaching may occur in the establishment year.
- N-leaching is estimated to be 30-50% lower than in cereal production.

4. A difference at present between Miscanthus and willow biomass crops is that, whilst for Miscanthus there is currently only one main variety grown in the UK, there are several varieties of SRC willow. Willow varieties show wide genetic variation for water-use and nutrient-use efficiency and perform differently in different environments.

5. More research is needed on the recommended applications of N in different regions (and for different varieties), as this will vary depending on genotype, N availability in the soil and aerial deposition. More research is also required on levels of nitrous oxide emissions.

6. There is a paucity of data on using energy crops as pesticide buffers and sinks. However, we do not think that this is a topic worthy of further investigation as we believe it is unlikely that biomass crops could be used as pesticide sinks. Ground water quality (in terms of pesticides) is also unlikely to be affected by biomass crops.

7. Soil types:

- SRC and Miscanthus are grown successfully on a wide range of UK and European soil types with an optimum pH range between 5.5 and 7.5.
- Highest yields from biomass crops are associated with deep well aerated soils with a good supply of moisture and no impedance to root growth within the upper 40 cm horizon.
- Energy crops have a high demand on water and in drier areas (<800 mm annual rainfall) soil hydraulic properties, particularly the ability to store water with an unimpeded deep rooting zone become increasingly important.
- High water demand can also limit deep percolation. This can offer environmental benefits or risks depending on the situation.
- Greater crop cover of established energy crops during their growing season and a mulch of senescent leaves over winter provide protection to the soil from the destabilising effects of raindrop impact.
- A combination of high root mass and the lack of annual tillage is linked to increased levels of soil organic carbon over time compared with arable cropping, which in turn have measurable benefits to soil physical quality and biodiversity.
- UK trials suggest that newly established Miscanthus rhizomes are capable of withstanding soil temperatures below -3.5℃. Willow is normally planted soon after harvest in winter but cuttings can be stored for several months at -2 to -4˚C. In the absence of water stress, canopy emergence depends on the accumulation of thermal time above a temperature threshold: 5˚C

8. Impacts of harvesting:

- Harvesting of SRC and Miscanthus frequently coincides with wet weather and high soil water content. Under these conditions, compaction, puddling and rutting are particularly likely.
- Attempts to remediate damaged soil by deep cultivation had no effect on yield. Direct mechanical damage to the stools by wheeling significantly impacted on subsequent SRC yields.
- Mechanical removal techniques for SRC were expensive and damaged the soil, particularly in terms of surface soil removal. Soil adhering to the ‘root plates’ following removal prevents their use as biomass. Killing stools with glyphosate and waiting for them to rot reduces the flexibility of land use.
- Research is needed to develop more benign methods of stool removal and also to investigate the long term effect of growing perennial biomass crops on the physical properties of soil.

- Reverting Miscanthus fields to other crops appears to be non-problematic; however, the effects on nitrogen and carbon cycling need to be investigated
- Further research is needed to investigate the effects on N and C cycling of converting grassland to biomass cropping and to develop methodologies for minimizing any negative impacts

9. As competition for land use is likely to become more intense, there is a need for research into N-requirement and nutrient cycling in relation to growing Miscanthus and SRC willow in low-input systems/low fertility soils.

10. Biomass crops can be used as buffers to restrict run-off but this will be very site-specific as several factors will influence their effectiveness. Where the main purpose of the buffer strip is sediment removal, a width of 15 m may be sufficient on slopes of 0-5%.

11. Surface water quality could be improved by buffer strips of biomass crops grown between conventional crops and water courses. In practice we expect that 10m -15m wide of buffer would be sufficient for filtering.

12. As a C_4 crop, Miscanthus has higher water use efficiency than SRC willow but is relatively cold tolerant, unlike other C_4 plants, and therefore able to be productive over a longer growing season in the UK. Little data are currently available on transpiration rates of Miscanthus but SRC willows have higher transpiration rates than most annual arable crops. Overall, evidence suggests that water use of SRC willow is equivalent to woodland and Miscanthus is equivalent to grassland. However, if a significant area of arable crops were replaced by energy crops, negative impacts on water availability are to be expected.

13. There is scope for using strategically placed floodplain woodland to alleviate downstream flooding; however, more data are required on how effective biomass crops might be in this regard.

4. Full report

4.1. Background

The UK and EU Government policies for decreasing reliance on fossil fuels and reducing greenhouse gas (GHG) emissions, particularly the renewable obligations for electricity (ROCs http://www.restats.org.uk/renewables_obligations.html) and transport fuels (RTFO: http://www.dft.gov.uk/pgr/roads/environment/rtfo/), present challenging targets for bioenergy production. EU targets equate to 20% of all energy (heat/electricity/transport fuels) from renewables by 2020 and 10% of transport fuels from biofuels by 2020. Increased production of bioenergy from optimised feedstock derived from crops will need to be significantly boosted within a short time frame to meet these targets.

In comparison with conventional arable crops which require high input agriculture, perennial biomass crops, such as Miscanthus and short rotation coppice (SRC) willow do not require annual cultivation and are fast growing with the potential to produce high biomass yields from low fertiliser and pesticide requirements. As a result, life cycle analyses (LCA) indicate that higher energy savings and greater GHG reductions can be achieved through bioenergy production from perennial biomass crops in comparison with annual arable crops such as oil seed rape and wheat. However these might not be the only benefits that accrue from a land-use change to perennial biomass crops, since the lower input agriculture could also result in reduced erosion and nutrient leaching. Furthermore, energy crop systems can also be used to purify waste and act as riparian buffers or phytoremediation agents.

This report briefly reviews the state of knowledge on these environmental benefits, whilst also identifying possible negative impacts of converting arable or grassland to biomass crops. Gaps of knowledge are also identified. The report is divided into three main sections which consider energy crops as a nutrient sink, in relation to their impacts on soils and in relation to their impacts on water. The report finishes with a consideration of some and general issues. In each section, specific questions raised by the Environment Agency have been addressed.

4.2. Biomass crops as a sink

1. *How can each crop be used as a **nitrate** sink? How much nutrients will they soak up. What area of crop is needed as a buffer? What will be the expected improvement on surface and ground water quality. (Note include ploughing up of grassland)*

2. *How can each crop be used as a **Phosphate** sink? How much nutrients will they soak up. What area of crop is needed as a buffer ?What will be the improvement on surface and ground water quality*

3. *How can each crop be used as a **pesticide** sink? What area of crop is needed as a buffer? What will be the improvement on surface and ground water quality?*

4. *What are the **savings in leached pollutants** (nutrients and soil) over and above the arable / grass crops that they replace*

Nitrate and phosphate sink

Biomass crops generally have higher nitrogen use efficiencies compared with annual food crops because they remobilise their nitrogen at the end of the growing season and store it 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 (Long, 1983). 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 (Börjesson, 1999). Nutrient use differs somewhat between Miscanthus and SRC willow.

Miscanthus

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 as, to date, most experimental and commercial crops have been grown on reasonable quality soils. First year growth of Miscanthus is slow and sparse, and applying N fertilizer can have the disadvantage of promoting weed growth. At Rothamsted there has been no effect of N-dose (applied at 60 and 120 kg ha^{-1} per year) compared with the control in an experiment planted in 1993 and still running (Christian *et al*, unpublished). However, the site had a high N supply as it was in long-term grassland until 1988. Supporting this, data from 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).

Other research has shown that *M. sinensis* (a related species) grown in solution culture needs a sustained N supply during the establishment phase, which affects N in the rhizomes and subsequently yields in the second year (Wiesler *et al.*, 1997). There may be a preference for ammonium N (Holme, 1998). In the field *Miscanthus x giganteus* took up more than 100 kg N ha^{-1} in the first year but only 20 % from applied N fertiliser (Christian *et al.*, 1997), after 3 years more than 300 kg N ha^{-1} had been taken up (Christian *et al.*, 2006). Another 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).

Further evidence from field experiments is mixed and could be related to the general fertility status of the sites. Recent UK data from one year, from an on-going experiment on low fertility sandy soil has shown an N-dose effect (Yates, unpublished) in *Miscanthus x giganteus*. Further research on this experiment will provide a clear indication of the nitrogen requirement of Miscanthus on poor soils. Similarly, on different soils in the Czech Republic, N had little (< 20%) or no yield effect on high and intermediate fertility soils while it tripled yields on a low fertility soil (Strasil, 1999). While results for potential production (irrigated) of *Miscanthus x giganteus* in Greece show no response to N (Danalatos *et al.*, 2007), similar experiments in Italy resulted in a yield increase between 25 and 40 % in response to 50 and 100 kg N ha^{-1}, again, with irrigation (Cosentino *et al.*, 2007). In another study in Italy, the average N response ranged from 37 to 50 kg biomass per kg^{-1} N ha^{-1} applied, and the energy gain from 200 kg N ha^{-1} was 100 GJ ha^{-1} compared to a gain of 250 GJ ha^{-1} from irrigation (Ercoli *et al.*, 1999). However, the yield without any N fertilizer appears to have been about 18 tDM ha^{-1}, greater than is expected in the UK. More research is needed on the recommended applications of N in different regions of the UK, as this will vary depending on N availability in the soil and aerial deposition.

Based on yields between 15 and 25 tDM ha^{-1}, between 90 and 150 kg N ha^{-1} will be exported. A similar amount can be stored in the soil-rhizome system. Heavy metals can reduce the N-uptake and translocation rates (Arduini *et al.*, 2006). By the winter, most N remains in litter, roots and rhizomes, and after three years more than 200 of the 330 kg N ha^{-1} N-uptake can be found in the soil-root-rhizome system (Christian *et al.*, 2006). Studies have shown that over three years, and over different soils, the below-ground biomass (rhizomes, roots) averaged from 15 and 5.4 t DM ha^{-1} (before sprouting) with N concentrations of 11.3 and 12.5 g kg^{-1} respectively (Kahle *et al.*, 2001), which adds 240 kg N ha^{-1} stored in the system. Litter of 4.5 tDM ha^{-1} due to pre-harvest losses during winter (26% of above-ground biomass) adds another 60 kg N ha^{-1} to the soil organic matter (Kahle *et al.*, 2001). A C/N ratio of 36 to 40 would cause mineralization rates to be low. Other studies have shown that the turnover time of the organic matter increases with length of time under Miscanthus cultivation (Foereid *et al.*, 2004).

Less data are available on phosphorus. In established Miscanthus in the UK around 11 kg of phosphorus are removed in the aerial biomass at harvest (Defra, 2001).

Willow

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 (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 $N0_3$-N l^{-1}) irrigation was 6 mm in excess of transpiration, however, all of 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).

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).

Unlike Miscanthus, which is a relatively new crop, SRC willow varieties have been selected and grown commercially for almost 20 years and a wide range of genotypes exist. Weih and Nordh (2002) characterised 14 clones of willow in terms of relative growth rate, total biomass production, 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 indicates that it will be important to select optimal clones for growing in the different environmental conditions associated with specific regions of the UK.

Pesticide sinks

No data could be found on energy crops in relation to pesticides, for example, whether or not there are reduced risks of water pollution by pesticides in perennial energy crops cultivation compared with annual food crop production. Current practice is to apply very few pesticides to Miscanthus and SRC; weed control is important during establishment, but in subsequent years one herbicide at most would be the only application. Fungicides and insecticides are not expected to be used. With SRC in particular the height of the crop can prevent applications being possible.

We believe it is unlikely that biomass crops could be used as pesticide sinks; most UK soils contain extremely low levels of mobile pesticides as they are mostly degraded with small amounts washed out by rainfall within the crop year or soon after. Therefore the likelihood of significant levels of soluble pre-existing residues is very small.

Ground water quality (in terms of pesticides) is also unlikely to be affected by biomass crops for the same reason, and because below ground lateral flow rarely occurs. Ground water quality in terms of nitrates is likely to improve (see below).

Various studies have shown the benefits of grassed strips used as pesticide buffers (e.g. Lacas *et al*., 2005). Surface water quality could be improved by buffer strips of biomass crops grown between conventional crops (receiving pesticides) and water courses; some pesticide residues, both those held in solution and those bound to organic and inorganic soil particles, would get filtered out by the standing biomass, improving the water quality. However, if large amounts of pesticide were taken up by the buffer strip, it may become important to consider the subsequent fate of the residues in the biomass during the conversion process. It is extremely unlikely to be a problem, unless used in a small scale industrial plant where the contaminated biomass represents a significant proportion of the processed feedstock. Miscanthus crops usually have a dense layer of leaf litter on the soil surface which would also filter water before it infiltrated the soil. The width of the buffer would be determined by the likely amount of filtering required and the area of biomass crop required to make the crop economically viable. In practice we expect that 10m wide of buffer would be sufficient for filtering. In summary, the filtering effect, although a potential benefit is unlikely to be of useful significance.

<u>Savings in leached nutrients</u>

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. Leaching losses for a grass/clover ley, fertilized in spring with 75 kg N ha^{-1} were reported to be 0.14 to 5.4 kg N ha^{-1} (Armstrong *et al*., 1983); for unfertilized grass on heavy clay Catt *et al*., (1992) measured losses between 1.3 and 2.1 kg N ha^{-1}. In comparison, Goss *et al*., reported 8 year average losses from winter arable crops as 38 kg N ha yr^{-1}. N-leaching under *Miscanthus x giganteus* was also found to be negligible in another study (Beale and Long, 1997).

Swedish studies estimate nitrogen leaching from SRC 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).

Effects of planting biomass crops into ex-grassland

If grassland were ploughed up to provide land for biomass crops, there would be an excess of N in the soil; the crop's N requirements would be supplied to excess, and it is likely that nitrate leaching and nitrous oxide emissions would increase. Current IPCC methodology (Houghton *et al.*, 1997) suggests that 1.25% of mineral N from whatever source will be emitted from soil as nitrous oxide (N_2O). On this basis, and using data from Whitmore *et al.* (1992), ploughing out grassland will increase N_2O emissions by 48 kg N ha^{-1} over 20 years which has a greenhouse gas equivalence to almost 14 tonnes of CO_2. This suggests that fossil fuel savings from the first two or three years of biomass production on ploughed-up grassland will be offset by the enhanced emission of N_2O unless the CO_2 emitted can be recaptured at conversion.

Whitmore (1992) estimated that up to half of any losses of N on ploughing up grassland will occur in 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 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.

Whitmore's 1992 study could be re-worked to express the effect locally and nationally of replacing grassland now with energy crops on the potential for nitrate leaching. Since the losses are greatest immediately after ploughing and since energy crops take two or three years to reach their maximum growth rate, planting energy crops in old grassland could lead to very large losses of nitrate.

4.3. Biomass crop impacts on soils

5. *Which **soil / land types** are suitable for biomass crops and which types are more prone to **erosion***

SRC is grown successfully on a wide range of UK and European soil types (from sands to heavy clays and within a pH in the range 5.5 to 7.0 (Ledin and Willebrand, 1996; Armstrong, 1999). Similarly, Miscanthus is also grown on a wide range of lowland soils ranging from clays to silts and loams (Bullard and Kirkpatrick, 1997). Miscanthus is also tolerant of a wide range of pH including chalk soils (Defra, 2001) but the optimum is between 5.5 and 7.5. Highest yields from biomass crops are associated with deep well aerated soils with a good supply of moisture and no impedance to root growth within the upper 40 cm horizon. Miscanthus may extract water from 2 m depth and SRC from up to 3 m although the majority of roots are in the top 40 cm.

Soil water

Energy crops have a high demand on water (Beale *et al.*, 1999; Stephens *et al.*, 2001) and yields are significantly reduced by water stress (Clifton-Brown and Lewandowski 2000, Stephens *et al.*, 2001). However, permanently waterlogged sites should be avoided as it limits rooting depth (Ledin and Willebrand, 1996; Crow and Houston, 2004). In areas where average annual rainfall is greater than 800 mm, the nature of the soil type has little impact on the water use of energy crops. In drier areas, soil hydraulic properties, particularly the ability to store water with an unimpeded rooting zone become increasingly important. High permeability and limited water storage make light (sandy) shallow soils and some chalk soils vulnerable to water limitations.

High levels of rainfall interception and evaporation from the leaves (20 to 30%) (Riche and Christian, 1998), together with 400-500 mm transpiration can build up a soil water deficit greater than 250 mm (Stephens *et al.*, 2001) during the growing season and in drier regions there may be insufficient rainfall during the winter months to rewet the soil to field capacity. High water demand can also limit deep percolation below the root zone which can be a major disadvantage in areas with low rainfall leading to reduced aquifer recharge (Finch, 2000) and planting of bioenergy crops upstream of sensitive habitats such as wetlands could also present a significant environmental risk. However, planting energy crops on soils prone to flood may be beneficial by increasing the soils ability to absorb rainfall. Similarly, reclaimed industrial sites could benefit by reducing the leaching of pollutants (Steer and Barker, 1997; Aronsson *et al*, 2000; Kahle *et al.*, 2002).

Soil quality

The cover of established energy crops (from late spring to early winter) and a mulch of senescent leaves over winter will substantially reduce raindrop energy, the major driver in destabilising surface soils. This should reduce the risk of soil crusting, improve infiltration and significantly reduce runoff and water erosion. Water and wind erosion are potential risks mainly during establishment when there are large areas of open ground with little or no cover. Soils at risk to water erosion can be on any sloping land (generally slopes steeper than 5%) particularly weakly structured sandy and silty soils with low organic carbon. Compacted wheelways can be a major source of runoff and erosion on sloping land particularly if crops are planted up and down slopes (see research on arable tramlines). Soils most prone to wind erosion are light sandy soils and organic soils, and these could benefit from perennial bioenergy crops used as wind breaks.

There are two factors that are likely to lead to increased amounts of soil organic matter under energy crops. Firstly perennial crops deposit more carbon in the soil as roots and root exudates than annual crops (Riche and Christian, 2001). Secondly, the absence of tillage is likely to slow the decomposition of organic matter. This more stable uncultivated soil environment can also benefit biodiversity (Bullard *et al.*, 1996). Carbon sequestration is most likely on soils whose carbon content has been depleted to relatively low levels due to previous management practices. Kahle (2001) measured significant increases in soil organic carbon on a number of central European soils under Miscanthus and this was also linked to improved soil physical and chemical characteristics potentially reducing the risk of erosion. Benefits included; improved aggregate stability, greater cation exchange capacity, porosity and water retention while the overall soil bulk density was lower. However, any increase in soil organic carbon is likely to be slow (Hansen, 2004) and is also reversible if the land is returned to arable cropping.

Soil temperature

Soil temperature can have an impact on the establishment of biomass crops. Clifton-Brown and Lewandowski (2000) report losses of Miscanthus rhizomes in the first years after establishment if soil temperatures fall bellow -3.5˚C. However, in the UK, ADAS trials at seven sites have not reported this when temperatures have fallen below this threshold.

Willows for SRC are planted as either cuttings or rods taken from 1 year old material. These should be harvested between December and March and should be planted straight away but ideally after the last frost. However, cuttings or rods can be safely stored for several months at between -2 and -4˚C. In the absence of water stress canopy emergence depends on the accumulation of thermal time above a temperature threshold: 5˚C (Cannell et al., 1987). In the UK the duration of the growing season, hence biomass production is closely related to latitude and altitude (Cannell et al., 1987). Establishment of energy crops on waterlogged clays can be slow as they tend to remain colder until later in the spring.

6. *What are the impacts of **establishing and harvesting** biomass crops? What can be done to mitigate the impacts through improved practice and targeting land use. Will the root mats support heavy machinery and not produce long term compaction?*

The establishment of Bioenergy crops requires deeply cultivated weed free seedbeds. Direct drilling of SRC into sprayed off grassland may result in problems of pests. These exposed seedbeds with little crop cover can be vulnerable to water erosion especially light sandy soils on slopes.

Harvesting of SRC and Miscanthus frequently coincides with wet weather and high soil water content (Wall and Deboys, 1997). Under these conditions, compaction, puddling and rutting are particularly likely given the high axle loads of harvesting machinery and associated equipment (Kofman and Spinelli, 1997) leading to increased soil strength, density, reduced water-holding capacity, reduced infiltration and a small reduction in yield (Souch *et al*., 2003). These authors also found that roots did not penetrate the areas of greatest compaction and were thus found in reduced numbers in the upper 0.3 m of the soil. However, it is likely that once established the dense root mat of SRC, and the rhizome, root and litter layer of miscanthus would help to protect the soil from compaction by providing mechanical support for vehicles although surface damage will still dramatically reduce infiltration and increase runoff. Attempts to remediate damaged soil by deep cultivation had no effect on yield (Souch *et al*., 2003). Direct mechanical damage to the stools by wheeling significantly impacted on subsequent yields. It is also recommended, that the practice of staggering harvest times within a catchment be adopted so that the variation in the gross annual water use of an area planted with SRC is reduced.

Removal of Miscanthus can be done by spraying off re-growth and ploughing out or rotorvating the rhizomes. This is likely to result in the similar flush of nitrate and rapid loss of soil organic carbon experienced when ploughing-out any grassland. Limited trials showed that it is possible to remove SRC stools but that none of the chosen mechanical removal techniques adequately addressed the problem of quickly returning the land to arable cultivation (Dti, 2003). All removal techniques were expensive and damaged the soil, particularly in terms of surface soil removal. The quantity of soil adhering to the 'root plates' following removal probably prevents their use as biomass. Killing stools with glyphosate and waiting for them to rot before removal or cultivation is a cheaper option. However, this reduces the flexibility of land use until the stools are rotted.

The removal of both crops is another area where new research is needed. Removal systems need to be developed to optimize the crop's full life cycle analysis (LCA), and to determine the subsequent fate of the increased soil C and N contents.

7. *How can each crop be used as buffer to **sediment**? How much sediment will they trap? What area of crop is needed as a buffer? What will be the improvement on surface and ground water quality?*

8. *How can biomass prevent **run-off** from intensive rainfall events. How much crop is needed for attenuation*

In addressing the above, and the questions in Section 4.4, there are a number of caveats:

i) A lot of these issues will be very site specific.
ii) The crop must be capable of coping with different degrees of aggradation or submergence by trapped sediment.
iii) The crop properties will influence the trapping efficiency – dense ground cover is more effective than woodland with little undergrowth and bare soil or litter; rigid woody vegetation will have a greater hydraulic resistance than vegetation with flexible stems.
iv) The period of ploughing and establishment will be a time of increased erosion potential and limited filtering capacity.

The following is also assumed:

a) The questions refer to sediment in dispersed overland flow *from upslope* rather than overbank river flooding.
b) Buffer strips are defined as the area of crop located between a source of contamination and a water body.

A buffer strip favours the settling out of soil particles by restricting the flow of surface runoff and increasing the water infiltration rate. Their effectiveness depends upon site conditions: buffers are most effective as sedimentation and filtration areas when water flow is shallow and slow moving. Several factors may affect the buffer's effectiveness; local topographic conditions or farming practices, such as tillage, may concentrate water flow which may in turn significantly reduce the effectiveness of the buffer as a filter. As far as practical, water should be encouraged to fan out rather than be allowed to enter the buffer zone in a concentrated flow. As the slope, intensity of land use, or total area of the land upslope increases, or as soil permeability decreases, a wider buffer zone is required.

According to Welsch (1991) the total width of the buffer strip depends in large part on its major functions and the slope and use of the adjacent land. Summarizing the work of others Welsch suggests that buffer strip widths could be 30 – 50 m. Where the major purpose of the buffer strip is sediment removal from surface runoff, a width of 15 m may be sufficient on slopes of 0-5%. Price *et al*., (2004) provide a table of grass filter strip widths for different slopes and sediment loadings in overland flow.

The UK Forestry Commission's guidelines recommend a buffer zone of about 10-times the width of the receiving watercourse for fine material in surface water to be filtered out by short vegetation before entering a watercourse. Irish Forestry recommendations (Mulqueen *et al*., 1999) follow closely the Forestry Commission guidelines and also advocate the use of sedimentation for settling out sediment before waters reach a watercourse.

Buffer strips are unlikely to be effective in removing nitrates from surface water due to the very high solubility of nitrate. However, they may be effective in filtering phosphate out of surface water flowing through the strip, but we have found no evidence to directly support this. The efficiency of nutrient retention in the buffer strips depends on water flow pathways controlling the transport of nutrients through the landscape and the composition and width of the riparian zones. Plant biomass (sum of above- and below-ground biomass) of riparian and wetland communities accumulates up to 700 kg N ha^{-1} and up to 60 kg P ha^{-1} during the growth season. Harvesting of riparian herbaceous communities may remove 20-30% of nutrient input (Mander *et al*. 1995). Perennial energy crops could be used as vegetation filters decreasing runoff and leaching if they are established between open streams and food crops cultivations.

4.4. Biomass crop impacts on water

9. *What are the **water requirements** of biomass crops? Will they impact on **wetlands** or head waters within a catchment? Will it be economical to irrigate?*

A high yield is required for a biomass crop to be economically viable. However, it is generally considered that a high yield is associated with a high water use and research has tended to confirm this hypothesis. Measurements of the transpiration of poplar SRC in the UK (Hall *et a*l., 1998, and Allen *et al*., 1999) and a modelling study in Belgium (Deckmyn *et al*., 2004) have shown that transpiration rates from poplar SRC are high, mainly because it has a limited ability to modify the transpiration rate in response to atmospheric demand or soil water stress. A similar situation, although less marked, has been found for SRC willow. Studies in Sweden (e.g. Iritz *et al*., 2001, Cienciala and Lindroth, 1995) and the UK (e.g. Hall *et al*., 1998, Finch *et al*., 2004) have demonstrated high transpiration rates although these are limited by soil water stress and atmospheric demand more than is the case for poplar. Both poplar and willow SRC are deeper rooting (2 m or more) than conventional crops and thus are able to support higher transpiration rates through periods of drought. In addition, interception losses are also higher than for “conventional” crops (Persson, 1997).

Less information is available about Miscanthus, which is a more recent biomass crop. Miscanthus uses the C_4 photosynthetic pathway and so it had been anticipated that it would have a higher water efficiency than C_3 species but, unlike most other C_4 species, it is able to remain productive in the cool temperate climate of northern Europe due to increased tolerance of low temperatures, thereby prolonging the growing season. There is very little information about transpiration rates in the literature, although there are a number of studies of water use efficiency which confirm that it is comparable to other C_4 crops. Finch *et al*., 2004, used a combination of measurements and modelling to quantify the evaporation from Miscanthus and concluded that although the rates were high, on an annual basis they were comparable to permanent grassland. Riche and Christian (2001) have shown that interception losses are high whilst Foti *et al*., 2003, have shown that transpiration is affected by soil water stress. A rooting depth of up to 2.5 m is given by Neukirchen *et al*., 1999, which is in agreement with measurements of soil water content (Finch *et al*., 2004). Thus it would seem likely that the evaporative losses from Miscanthus are significantly greater than those for annual crops in the UK.

Finch *et al*., 2004, provide an extensive analysis of the evaporative losses from SRC and Miscanthus for England and Wales. They concluded that the annual evaporative losses due to poplar SRC would be high whilst those for willow SRC would be comparable to existing broadleaf woodland, those for Miscanthus would be comparable to existing permanent grassland. They point out that, when considering the hydrological implications, there is no simple answer as it depends on which biomass crop replaces which land cover as well as the nature of the soil and climate at the location. It is also necessary to consider the time scale of interest because, although the crops are perennial, evaporation during the winter is minimal due to the absence of leaves, whilst high evaporation rates occur during spring and summer. Also, the biomass crops have rooting depths much greater than annual crops or permanent grass and so can support higher evaporation rates during drought by extracting soil water from greater depths. In the case of SRC it is also necessary to consider which year of the coppicing cycle the crop is in, i.e. evaporative losses will be least in the year after harvest and be greatest in the year preceding harvest, given the same weather.

Currently, biomass crops are a minor component of the agricultural landscape and how this will change in future will depend predominantly on farmers' perceptions, the economics of the crops and the nature of the market (e.g. whether it is being grown for use in centralised electricity generation or for heating) - it is generally assumed that the crops will not replace woodland nor the "high value" crops grown on agricultural grade 1 and 2 soils. Hence it is unclear how the evaporation rates of biomass crops will affect any given catchment other than in general terms. Were biomass crops to become a major component of the land cover of a catchment, particularly if they replaced annual crops, then the available water resource is likely to diminish, which might be significant in areas with a low average annual rainfall.

Biomass crops are able to maintain transpiration from groundwater in riparian conditions, although it appears that root growth is restricted in saturated conditions. Thus these crops can extract water from groundwater when the opportunity occurs. Depending on what land cover the crop replaces, the high evaporation rates of these biomass crops could have a detrimental effect on a wetland either directly, when planted in the wetland, or indirectly, when the biomass crops are planted close enough to a wetland to modify the subsurface flow. The relative sizes and positions of the biomass crop planting and the wetland will be important.

The current assumption is that biomass crops will not be irrigated in the UK because it would be uneconomic to do so. This is based on the current and future yield and value of these crops. Inevitably there is significant uncertainty about the value of these crops as it will depend on the policy of the UK government, the global market for bioenergy and the technology for energy conversion.

10. *What areas of **flood plain** are suitable for planting biomass? What will be the impact on **water flows** when rivers are in flood? Will these be positive or negative? What will be the impact of this for down stream receptors? What will be the impact on the crop during flooding? What areas of flood plain are suitable for planting biomass?*

Work by the Forestry Commission suggests there is evidence that floodplain forests could have an important role to play in ameliorating downstream flooding. This is based on woodland's greater hydraulic roughness compared to other vegetation types, which acts to slow flows down, enhancing flood storage and thus potentially reducing flood peaks (Thomas and Nisbet, 2007). One and two-dimensional models were used to simulate a 2.2 km reach of river in south-west England for a 1 in 100 year flood using different roughness parameters. Both models predicted a reduction in water velocity within the woodland, increasing water level by up to 27 cm and creating a backwater effect that extended nearly 400 m upstream. Flood storage increased by 15 and 71%, while flood peak travel time was increased. The results suggest that there is scope for using strategically placed floodplain woodland to alleviate downstream flooding.

4.5. General

11. *How sensitive are the assumptions used to answer the above questions to* ***changes in significant price signals****, such as the price of wood, and plant for various production processes?*

Currently, biomass crops are only just economic even with subsidies, e.g. planting grants. Studies in Sweden and Northern Ireland have shown that economics can be substantially improved for SRC if it is combined with waste treatment (Rosenqvist and Dawson, 2005).

Influential price signals are likely to come from three directions: (1) demand for food and consequent changes in the price of agricultural products, (2) demand for biomass, and (3) the price of alternative renewable energy supplies.

Agricultural product prices, e.g. wheat, have fluctuated widely in recent years, and this variability seems likely to continue. For instance, it seems likely that the price of UK wheat in the autumn of 2007 will be around twice what it was only a few years previously. This price increase is due to many factors, such as unfavourable growing conditions in other countries, and the demand for agricultural feedstocks for the fast growing ethanol production industry. There is wide debate as to whether the prices will remain high. However, as long as there seems the prospect that prices will remain higher than the past few years, we would expect that growers with land well suited to cereal production will be reluctant to establish low-return, long term biomass crops. At the same time, due to the ROCs and RTFO, we believe there will be an increasing demand for biomass feedstock. Therefore it would seem likely that the biomass crops will compete for land in less favourable cereal growing areas, including competing with grassland. This emphasizes the need for research into growing Miscanthus and SRC in such areas; investigating the effects on N and C cycling of converting grassland to biomass cropping, and developing methodologies for minimizing any negative impacts.

Within the renewables energy market, biomass competes on two fronts: renewable electricity and renewable transport fuels production. For renewable electricity, biomass competes with several technologies: wind, solar, wave, tidal etc. The proposed banding of the ROCs is likely to raise demand for biomass for co-firing, however in the long term, if demand for land for food production increases, the other technologies may become a cheaper option than biomass for electricity production, reducing demand for biomass for this use.

Agricultural feedstocks for both first and second generation transport fuels offer the only viable route for large scale renewable transport fuel production for current engine technologies. Because of this, it may be that UK land used for renewable fuel production is concentrated on this end-use rather than for electricity production. If this is the case, it remains to be seen whether second generation fuels are produced in preference to first generation. And if second generation fuels are produced, then large scale plantings of dedicated biomass crops such as SRC willow and Miscanthus will be required.

In summary, we believe the scope of this last question is beyond the expertise of the authors, however it bolsters our view that new research into the impacts of establishing and growing biomass crops in marginal cereal growing areas and in ex-grassland is essential in order to fully understand the implications on full LCA, and how the production systems can be optimized for minimal environmental impact in the broadest sense.

4.6. References

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