Energy crop water and nutrient use efficiency

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Content

Preface

The aim of this work was to collect and present current knowledge on two important aspects of energy crops production: the efficiency of energy crop water and nutrient use. For water use specifically, the aim was furthermore to test the suitability of the Swedish COUP-model (previously SOIL) for modelling willow water use under Danish conditions, and to evaluate the need for additional knowledge and model improvements.

It is our belief that these matters are not only of scientific interest but will become of key importance to the decisions on overall feasibility and acceptability of dedicated crop production for energy purposes.

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Summary and conclusions

The access and availability of clean water resources for drinking, irrigation etc. is a major global issue, which has to be addressed as seriously as the climate and energy problem. Any crop uses water for its growth, and energy crops often have a high water use due to their long growing season and deep rooting system. Therefore, aspects of energy crop water use can mean the life or death to the introduction of dedicated crops for energy utilisation.

The values of energy crop water use efficiency (WUE) collected in this report vary between 0.3 and 14.2 g biomass per kg water used. The WUE of common agricultural crops lies within this range as well. The high variation is due to varying definition of the WUE term, to high impact of environmental conditions and to genotypic variation. The most obvious difference between plant groups is between plants of the C_3 and the C_4 photosynthetic pathway: under optimum temperature conditions WUE of the C_4 plants is about twice as high as that of C_3 plants.

Nutrient use efficiency (NUE) is important as well but is a question of process optimisation rather than a determinant matter to the whole energy crop concept. One aspect of nutrient use, which can be an important positive driver for the introduction of energy crops, is that the perennial crops have a very low loss of nutrients to the environment. Accordingly, perennial energy crops can be used to process wastewater and sludge, as riparian buffer zones and to protect important drinking water resources, provided that the precipitation surplus is high enough to secure proper refill of aquifers.

The collected values of nutrient (N, P and K) use efficiency (NUE) vary with a factor of about 20. Energy crops generally have a higher NUE than common agricultural crops because crops with a high lignocellulosic content and a low ash content are chosen for energy purposes. Furthermore, energy crops are usually harvested when the nutrients have been retranslocated or leached from the crop. Woody crops and some C_4 grasses have the highest NUE values.

In order to properly evaluate energy crop resource efficiency and environmental impact at a practical scale and not as hitherto at the single plant level, we propose that WUE and NUE should be recalculated on a commercial crop scale. WUE of energy crops needs to be calculated from the harvestable biomass (instead of maximum biomass) and from the total annual evapotranspiration from the field. To evaluate energy crop nutrient efficiency, losses from the system should be included in the calculation of NUE instead of just the nutrient removal with biomass.

The application of the COUP (previously SOIL) model for simulating the water use of two willow clones over three years worked satisfactorily. However, the model requires site-specific information particularly on soil hydraulic parameters, which is not always available. A simpler soil model approach would facilitate water balance simulations on a routine basis for several potential energy crop sites. There was a difference in water use between the clones related to rust induced leaf fall in autumn, root development, and to apparently different minimum stomatal resistance. Fertilising the crop increased water use but differences in water use could not be detected between fertiliser levels. The total crop evaporation often exceeded reference evaporation (Penman), in some periods with about 100%.

There are so far no specific models for other energy crops e.g. miscanthus, *Arundo donax* and cynara. Models that can compare a range of crops are needed to assist in the choice of the most suitable crop for specific conditions of climate, soil and demand for groundwater recharge.

1 The importance of energy crop water and nutrient use

1.1 Water use

The production and use of crops only or mainly for energy conversion is still under development, and the efficiency and sustainability of the concept is still under discussion. Energy crops are supposed to combat the depletion of fossil energy resources and the rise in atmospheric CO_2-concentration. However, the production of energy crops touches on another major global environmental problem, namely the availability and quality of water for drinking and for irrigation of food crops for a rising world population (Wallace, 2000). Therefore, a good knowledge of the process efficiency of turning water and CO_2 into biomass is crucial in order to evaluate whether the use of energy crops is compatible with the increasing pressure on the water resources.

Water availability may influence the choice of technology when the world will increase its renewable energy contribution over the coming decades. Even though photovoltaic conversion of the sun's energy into electricity is still far from as economically competitive as biomass conversion, the PV-technology has the advantage of converting solar energy without any loss of water.

Knowledge on energy crop water use is important as well for more local decisions and for technical optimisations:

- The selection of an energy crop for a specific region must be based on an evaluation of the crop water demand in comparison with local climatic conditions. Often, water is the main yield-limiting factor.
- Annual water use and WUE can be important selection criteria in breeding programmes to improve water restricted yield and to produce a range of varieties adapted to a range of precipitation regimes.

1.2 Nutrient use

The efficient use of nutrients in the production of energy crops is important to minimise the input need. Furthermore, a high nutrient content of energy crops is a negative quality parameter in combustion as it raises the amount of ash to be handled, reduces biomass energy content, and can give rise to harmful emissions e.g. NO_x (e.g. Lewandowski & Kicherer, 1997; Obernberger et al., 1997).

In some cases crops with a low NUE are preferable if removal of excess nutrients is aimed at. This is the case when energy crops are used as riparian buffer strips or for the treatment of wastewater or sludge (e.g. Geber, 2000).

Another important aspect in the growing of energy crops is the loss of nutrients from production systems to the environment. Energy crops are introduced with an environmental rationale of reducing greenhouse gas outlets, and it will hardly be tolerated that the concept in turn creates other environmental problems such as eutrophication. On the other hand, if energy crops with a substantially lower loss of nutrients than conventional agricultural crops are available, they may be used for the protection of drinking water resources. Another possible utilisation of energy crops may be to process ‘dirty’ nutrients i.e. nutrients in sewage water or sludge, which may contain contamination that makes them questionable for use in food or feed production.

2 Water Use Efficiency – WUE

2.1 Definition

A review of WUE is complicated by the numerous ways of calculating the value in different studies. First of all must be mentioned that Stanhill (1986) and Monteith (1993) have stated that the term WUE is erroneous, as plants do loose water rather than use it as a raw material for the production of biomass. Therefore, terms such as ‘biomass water ratio’ (Monteith, 1993) and ‘transpiration efficiency’ (Byrd & May, 2000) are sometimes used instead of WUE. However, we prefer to use WUE in this report, as it still is the most well known term. The definition of WUE is:

WUE: Dry matter production/water loss (g/kg)

Dry matter production can be measured at the level of
- total crop
- above ground crop
- single leaves

Water loss can be defined as
- transpiration
- transpiration + soil evaporation
- transpiration + soil evaporation + interception loss

The time scale of measurement is important as well. Short time measurements during daytime do not include the respiration losses during the night or the seasonal differences that are included when WUE is calculated for a whole growing season.

The water loss from plants is highly dependent on the vapour pressure deficit gradient between the inside of the leaf and the ambient atmosphere. Therefore, WUE values measured under different climatic conditions may be ‘normalised’ for better comparisons (Tanner & Sinclair, 1983).

Normalised WUE: WUE multiplied by the saturation vapour pressure deficit of the air (g kPa/kg)

Lindroth & Cienciala (1996) measured WUE of willow at a range of vapour pressure deficits (Fig. 1), and for vapour pressure deficits of up to about 1 kPa a normalisation would appear to work well. At higher vapour pressure deficits, normalised values could be too far increased.

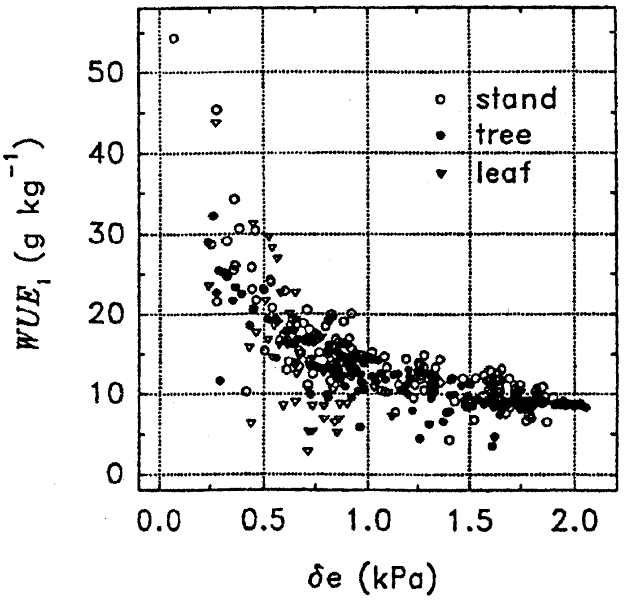


Figure 1. Instantaneous water use efficiency (WUE_I) versus vapour pressure deficit at leaf, tree and stand level. From Lindroth & Cienciala (1996).

2.2 Reported values

Table 1. Values of WUE (g dry matter/ kg water) of energy crops and of some common forest trees and agricultural crops. Grouped according to level of biomass determination, water use determination and to normalisation.

Evapotranspiration, above-ground biomass

Miscanthus	7.8-9.5 g/kg	(Beale et al., 1999)
Spartina	5.1-8.2 g/kg	(Beale et al., 1999)
Cynara	3.1-5.5 g/kg	(calculated from Fernandez et al., 1996)
Miscanthus	3.4-4.1 g/kg	(Uffe Jørgensen, unpublished)
Willow (*Salix*)	3.0-3.7 g/kg	(Lindroth et al., 1994)
Maize (*Zea*)	3.0 g/kg	(Howell et al., 1988)
Willow (*Salix*) stems only	2.2-2.9 g/kg	(calculated from Lindroth et al., 1994)
Willow (*Salix*) stems only 2. rotation	1.7-1.9 g/kg	(chapter 4.7)
Willow (*Salix*) stems only 1. rotation	0.3-1.7 g/kg	(calculated from Mortensen et al., 1998)

Evapotranspiration, above-ground biomass, normalised

Miscanthus	9.0-10.7 g kPa/kg	(Beale et al., 1999)
Maize (*Zea*)	8.5 g kPa/kg	(Howell et al., 1988)
Spartina	5.9-8.1 g kPa/kg	(Beale et al., 1999)

Transpiration only, aboveground biomass

Beets (*Beta*)	6.1 g/kg	(De Wit, 1958)
Beech (*Fagus*)	5.9 g/kg	(Polster, 1950)
Pseudotsuga	5.8 g/kg	(Polster, 1950)
Willow (*Salix*)	4.1-5.5 g/kg	(Lindroth et al., 1994)
Salix + *Alnus* + *Betula*	4.8 g/kg	(Grip et al., 1984)
Barley (*Hordeum*)	4.2-4.8 g/kg	(Jørgensen, 1991a)

Spruce (*Picea*)	4.3 g/kg	(Polster, 1950)
Peas (*Pisum)*	3-4.3 g/kg	(Jørgensen, 1991b)
Miscanthus	2.2-4.1	(Clifton-Brown & Lewandowski, 2000)
Larch (*Larix*)	4.0 g/kg	(Polster, 1950)
Peas (*Pisum)*	3.4 g/kg	(De Wit, 1958)
14 C_4 plants	3.1 +/- 0.3 g/kg	(Stanhill, 1986)
Pine (*Pinus*)	3.3 g/kg	(Polster, 1950)
Birch (*Betula*)	3.1 g/kg	(Polster, 1950)
Oak (*Quercus*)	2.9 g/kg	(Polster, 1950)
Oats (*Avena)*	2.6 g/kg	(De Wit, 1958)
51 C_3 plants	1.6 +/- 0.4 g/kg	(Stanhill, 1986)
Transpiration only, total biomass		
Miscanthus	11.5-14.2 g/kg	(Clifton-Brown & Lewandowski, 2000)
Switchgrass (*Panicum*)	3.5-10.0 g/kg	(Byrd & May, 2000)
Willow (*Salix*)	6.3 g/kg	(Lindroth & Cienciala, 1996)
Maize (*Zea*)	2.0-5.4 g/kg	(Tanner & Sinclair, 1983)
Alfalfa (*Medicago*)	4.1 g/kg	(Tanner & Sinclair, 1983)
Transpiration only, total biomass, normalised		
Maize (*Zea*)	8.2-12.0 g kPa/kg	(Tanner & Sinclair, 1983)
Maize (*Zea*)	10.7 g kPa/kg	(Howell et al., 1988)
Miscanthus	6.6 kPa/kg	(Clifton-Brown & Lewandowski, 2000)
Alfalfa (*Medicago*)	4.3 g/kg	(Tanner & Sinclair, 1983)

2.3 Discussion

The data in Table 1 are very scattered, which is in part due to the different environmental conditions of the studies and the different methods of calculation. However, under idealised conditions WUE of C_4 crops are about twice that of C_3 crops (Squire, 1990) due to their higher efficiency of photosynthetic conversion. This seems to be in line with the main tendency of the data in Table 1, where the C_4 crops maize, miscanthus, switchgrass and spartina most often have the highest WUE values. Stanhill (1986) compared WUE of 14 C_4 crops with that of 51 C_3 crops grown in the semi-arid climate of Colorado and found the mean C_4 WUE to be exactly the double of the mean C_3 WUE.

However, temperature affects the photosynthetic processes considerably, and C_4 crops are not suited for very cool regions. Miscanthus is a C_4 crop adapted to rather cool conditions (Beale & Long, 1995) and it has shown a very high WUE in Southern UK (Beale et al., 1999 (Table 1)) but under cooler conditions in Denmark the values were considerably lower (Uffe Jørgensen, unpublished (Table 1)), which can be explained by the reduced radiation use efficiency in Denmark (Vargas et al., 2001).

The importance of normalisation of WUE is exemplified by the Tanner & Sinclair (1983) data for maize and alfalfa presented without and with normalisation by the saturation vapour pressure deficit in Table 1 (transpiration only, total biomass). Without normalisation the two crops exhibit about similar WUE but with normalisation the value of the C_4 crop is about twice that of the C_3 crop.

From a plant physiological point of view the calculation of WUE from total biomass production and from transpired water only is often the most important value. However, to evaluate the efficiency of energy crop production aboveground biomass at the optimal harvest time and total annual evapotranspiration from the field is a more relevant value (however, total biomass production may be of interest for the calculation of total carbon mitigation potential including sequestration in soil organic matter). WUE based on harvestable biomass for energy and total annual evapotranspiration is very seldom presented, as most often the above-ground biomass used for calculation includes leaves in woody crops (e.g. Lindroth et al., 1994) and fresh grass during summer in grass crops (e.g. Beale et al., 1999).

The only WUE value in Table 1 that is based on harvestable biomass for energy and total annual evapotranspiration is that of willow calculated from Mortensen et al. (1998). The value of about 1 g/kg is low because it is measured during the less productive first harvest cycle and with low-productive old willow clones, but also because it only includes the harvestable biomass and includes total annual evapotranspiration. When subtracting the willow leaf fraction in the WUE calculation of Lindroth et al. (1994) (which still only includes growing period evapotranspiration), values of about 2.5 g/kg are obtained (Table 1).

Due to the high impact of the atmospheric saturation deficit on WUE (Fig. 1), the development of strategies to produce energy crops at low saturation deficits may be considered. A macro-climatic strategy may be to site the cropping areas in regions of low saturation deficit (Wallace, 2000) or, in Mediterranean climates, to use crops that have their main production period during the cool winter and spring periods. The latter strategy is possible with the thistle-like crop *Cynara cardunculus,* which can produce c. 20 t DM in areas with annual rainfalls of about 400 mm (Fernandez et al., 1996; Venendaal et al., 1997).

A microclimatic strategy to reduce the saturation deficit of the air surrounding the crop may be to introduce agro-forestry systems. An elevated tree canopy (to produce high value timber) can alter not only the humidity but also the radiation and temperature around an understorey crop (Wallace & Verhoef, 2000). Simulations have shown that agroforestry systems can improve WUE but the total water use of the system may increase as well, and this may limit the use of the system in areas of limited water resources.

3 Nutrient Use Efficiency – NUE

3.1 Definition

Several methods of expressing crop NUE have been evaluated by Gourley et al. (1994). They conclude that the single-value terms for NUE most often presented are not good indicators of efficient production at low nutrient input. The commonly used definition of NUE shown below is merely the inverse of biomass nutrient concentration and will give very high values in nutrient deficient crops with very low yields. Furthermore, it does not take into account losses from the production system, which can vary a lot (Jørgensen & Hansen, 1998). However, the data we present in this report are calculated according to this simple definition of NUE, as other data are very scarce.

NUE: Dry matter production/nutrient content (g/g)

NUE can be determined for any nutrient of interest at the level of:

- Leaves
- Above-ground crop
- Total crop

Time of NUE-determination is for a whole crop usually the time of commercial harvest.

3.2 Reported values

Table 2. Nutrient use efficiencies (g dry matter/ g nutrient) of some energy crops, forest trees, and of conventional agricultural crops. Calculated for the aboveground material at harvest. Values are shown for the 3 macro-nutrients N, P and K.

	N	**P**	**K**	
Forest wood chips	143-1000	5000	250-2000	(Sander, 1997)
Miscanthus	135-704	526-5000	78-556	(Lewandowski et al., 2001)
Poplar (*Populus*)	145-370	1000-2000	256-370	(Jug et al., 1999)
Cereal straw	67-333	500-3333	53-500	(Sander, 1997)
Spartina	310	2530	670	(Beale & Long, 1997)
Willow & poplar	104-269	831-2201	197-706	(Adegbidi et al., 2001)
Willow (*Salix*)	152-244	909-1429	323-500	(Jug et al., 1999)
Eucalypt 8y	219	3477	427	(Lodhiyal & Lodhiyal, 1997)
Miscanthus	200	1580	80	(Beale & Long, 1997)
Miscanthus	145-182	-	97-385	(Jørgensen, 1997)
Hemp (*Cannabis sativa*)	169-179	909-1111	91	(Flengmark, 2000)
Poplar (*Populus*)4y	174	1566	318	(Lodhiyal & Lodhiyal, 1997)
Poplar (*Populus*)9y	169	1496	318	(Lodhiyal & Lodhiyal, 1997)
Pine (*Pinus*)100y	129	1130	219	(Lodhiyal & Lodhiyal, 1997)
Maize (*Zea*)	66-111	333-556	86-161	(Beale & Long, 1997)
Rye (*Secale)* whole crop	107-109	-	97-105	(Jørgensen, 2000)
Reed Canary grass (*Phalaris)*	101	-	909	(Mortensen & Jørgensen, 2000)
Wheat (*Triticum*) whole crop	83-87	-	117-133	(Jørgensen, 2000)
Reed Canary grass (*Phalaris)*	43-78	278-385	40-76	(Geber, 2000)
Potatoes (*Solanum*)	73	358	53	(Beale & Long, 1997)
Ryegrass (*Lolium*)	63	333	56	(Beale & Long, 1997)

3.3 Discussion

In general the trees and lignocellulosic grass crops selected for combustion purpose have a higher NUE than common food and feed crops (Table 1). Crops for energy are often harvested after senescence and retranslocation and/or leaching of nutrients from the crop, and unlike food crops, storage organs are most often not harvested for energy. The importance of harvest time on biomass nutrient concentration (the inverse of NUE) appears from Figure 2. Miscanthus can be harvested from late November onwards, in which period N-concentration did not change much but the K-concentration was reduced about eight times from November to April in some genotypes.

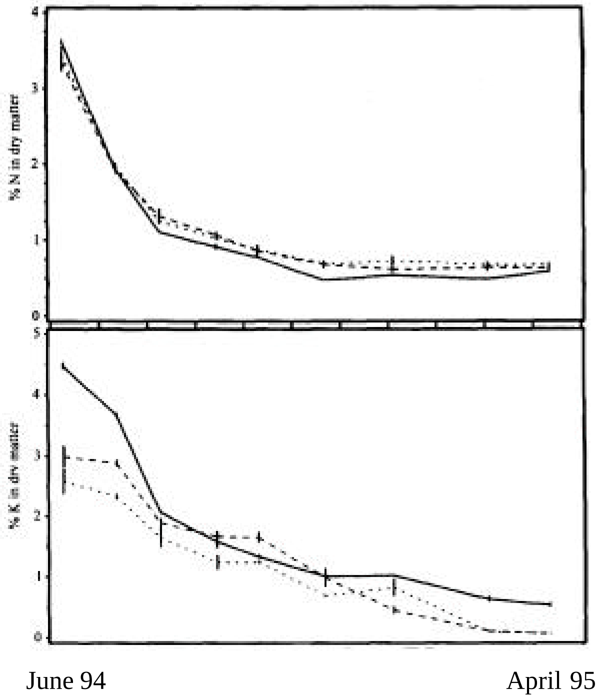


Figure 2. The concentration of N and K during the growing season and the following winter in three *Miscanthus* genotypes (From Jørgensen, 1997).

In woody crops NUE depends significantly of the length of the harvest cycle which changes the ratio between nutrient-rich bark and the stem-wood. Adegbidi et al. (2001) found an increase in NUE of N, P, K and Mg in two willow clones from annual harvesting to a 3-year rotation. However, Lodhiyal & Lodhiyal (1997) only found increased NUE$_P$ when increasing poplar rotation from 1 to 4 years.

NUE can vary a great deal between genera but variation can be just as high within one genus (Table 1). The highest NUE$_N$ in Table 1 (704 g g^{-1}) was recorded for *Miscanthus sacchariflorus* grown in Portugal and harvested in spring, but the value of a *Miscanthus sinensis* genotype at the same site was about four times lower (Lewandowski et al., 2001).

From a theoretical point of view the photosynthetic pathway of C_4 crops is more efficient in its use of N than the C_3-pathway (Long, 1983). However, tree crops that store low-nutrient lignocellulosic material in the trunk and only have a low fraction of nutrient rich bark and leaves can have very high NUE values as well.

NUE is a good measure of the ability of a crop to produce a feedstock with low removal of essential nutrients. However, a low NUE value does not per se mean that the whole production system is efficient, as NUE does not take any account of losses from the system. Especially nitrogen can easily be lost as gaseous NO_x or leached as nitrate, and all nutrients can be lost by surface run-off. In our opinion, evaluation of energy crop system efficiency of nutrient use should therefore preferably be based on a value that includes total removals from the system:

$$NUE_{system}: \textit{Dry matter production/(nutrient content + losses)}$$

Often soil nutrient content changes during a production period, but this change does not need to be included in the NUE_{system} calculation, as it can be considered as a reversible process and not a loss. When it is possible to recycle ashes from biomass combustion to the energy crop fields, the amount of nutrients recycled could possibly be deducted from the denominator of the NUE_{system}. Green biomass can be used for biogas production, which does not give as high an energy yield as combustion (Sander, 2000) but has the advantage of leaving all nutrients (even nitrogen) in the degassed liquid for potential recycling. Such a system could have potentially very high NUE_{system} values.

4 Modelling willow water use

4.1 Choice of model

The model used for water balance calculations is the Swedish COUP model (previously SOIL). It is a well-documented (Jansson, 2000; Lewan, 1993; Persson and Lindroth, 1994) one-dimensional model for calculating the water balance of cropped or bare soils (Lewan, 1993; Heidmann et al., 2000; Schelde et al., 1998). Persson and Lindroth (1994), Persson (1995) and Persson (1997) applied the model to willow stands in various parts of Sweden and used the model for comparing the water use of willow and agricultural crops. The model parameterisation reported by Persson (1995; 1997) served as a reference parameterisation for the present analysis of willow water use.

The COUP model is based on two coupled differential equations describing water and heat flows (derived from Fourier's and Darcy's laws respectively) in a one-dimensional soil profile. The model requires daily or hourly meteorological data and parameter values for soil and plant properties (soil water retention characteristics, hydraulic conductivity functions, root depth and leaf area development) as input. Evapotranspiration is calculated using the Penman-Monteith equation and plant water uptake is distributed over the soil layers in the root zone according to a specified root distribution. Snow dynamics, soil frost and percolation to the groundwater are also simulated.

4.2 Materials

The willow stand subject to water balance investigations was a Salix plot trial at Research Centre Foulum, Denmark. The trial was planted in 1993 with the two *Salix viminalis* clones 78-112 and 78-183 (Mortensen et al., 1998). Plot size is 12.1 x 13.2 m. Data analysed here are from 1997-1999 (1st-3rd year after harvest during winter 1996-97).

Experimental factors, apart from genotype, were row distance and fertiliser level. Double rows with 75 cm internal distance were planted with 126 cm and 260 cm between double rows, respectively. Four levels of fertiliser were applied in 1997 and in 1998: 0, 75 N in NPK, 75 N in manure and 150 kg N/ha in manure. In 1999 no fertiliser was applied.

4.3 Measured canopy development

Canopy development was monitored via remote sensing using hand-held equipment (Thomsen et al. 1997) during the three growing seasons. The simple ratio (RVI) is the ratio between canopy spectral reflectance (ρ) in the near infrared (NIR) spectrum and in the red (RED) spectrum:

$$\mathrm{RVI} = \rho_{\mathrm{NIR}}/\rho_{\mathrm{RED}} \tag{1}$$

RVI is closely correlated to the chlorophyll concentration of the canopy and thus to the actively transpiring and green leaf area. Heidmann et al. (2000) showed that a near-linear transformation of measured RVI into green leaf area index was applicable for successfully simulating the water balance of a winter wheat crop. We took a similar approach and converted the measured development of RVI to green leaf area . A conversion factor of 0.2 was calculated based on a set of 5 concurrent measurements of canopy RVI and leaf area index (LAI) using a LAI-2000 instrument (Li-Cor, NE, USA) during May – August 1998. At one occasion these measurements were supplemented by destructive measurements of leaf area, which indicated that LAI-2000 measurements underestimated LAI by 25 %. This finding was accounted for in the conversion factor between RVI and LAI.

RVI was measured in 9 plots during 1997 and in all 24 plots during 1998-99. During 1998 and 1999 measurements were made 2-3 times a month between April and October. During 1997 measurements were only complete from April through July.

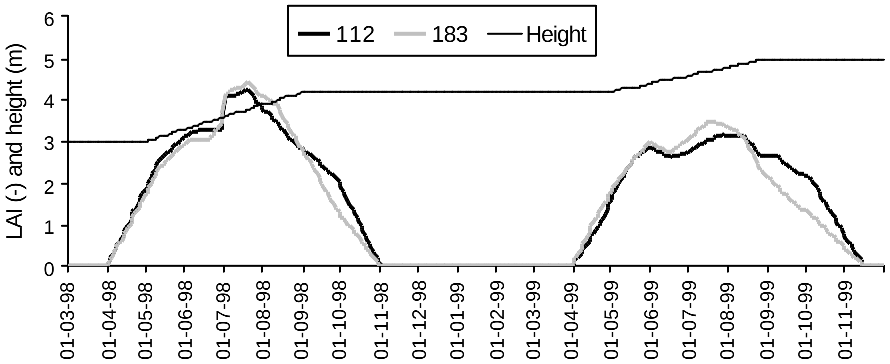


Figure 3. Development of leaf area index (LAI) during 1998 and 1999 for clones 112 and 183, used as input for simulation of willow water balance. Also shown is the estimated canopy height (common height development for both clones).

Analysis of RVI measurements showed no clear effect of row distance on canopy greenness. There was a fertilisation effect causing the unfertilised plots to be less green than fertilised plots, but differences between fertilised plots could not be distinguished. The clearest effect was related to clone type: the development of the two clones differed somewhat towards the end of the growing seasons of 1998 and 1999 when clone 183 senesced earlier than clone 112 (Figure 3). This was probably due to clone 183 being more severely attacked by rust than clone 112 in the autumn.

Development of canopy height was not measured on a regular basis during the experiment but was estimated based on the length of harvested stems at the end of the experiment (Figure 3).

4.4 Measured soil water content

Soil water content was measured using the TDR (Time Domain Reflectometry) technique (Topp et al. 1980). Measurements of depth-integrated water content using vertically installed probes were made at the depths 0-50 cm, 0-100 cm and 0-150 cm during 1998-1999. During 1997 the measurements were made in the depth intervals 0-20 cm, 0-50 cm and 0-100 cm and in a different subset of plots compared to the plots monitored during 1998-1999. TDR was measured on a regular basis (once or twice a month) during the three growing seasons in a limited number of plots. TDR measurements in 1997 were made in four plots representing a subset of treatments. In 1998-99 measurements were made in eight plots representing nearly all treatments. The measurements were not replicated.

Analysis (inspection of seasonal development of soil water content during 1998 and 1999) of TDR data representing different treatments showed that there was no clear effect of row distance on Willow water use. This was probably due to a) all TDR data analysed here represent measurements made in-between the double rows in each plot where root density can be assumed to be maximal regardless of row distance and b) the canopy of the present stand in its second rotation tended to cover the whole gap between rows, thus minimising effects of row distance on water use. We found that fertilisation treatment was evident in the TDR data since unfertilised plots showed (slightly) less water consumption compared with fertilised plots. Finally, the most significant difference in water use, considering TDR measurements only, was related to clone type. Clone number 112 appeared to consume more water from the top 100 cm or 150 cm of the root zone compared with clone 183.

4.5 Model parameterisation

The model parameterisation reported by Persson (1995; 1997) served as a reference for modelling the Foulum willow stands. Site-specific parameters required for simulations were soil hydraulic parameters, canopy development in terms of seasonal LAI and canopy height, and root depth.

Soil hydraulic properties (pF curves) had not been measured in the willow plot. However, soil texture had earlier been analysed in the experimental area. The local soil texture was compared with the reported texture of Foulum soil analysed by Jacobsen (1989) and Andersen (1986). The texture of the upper 80 cm soil in the willow plots compared reasonably to the reported texture of Jacobsen (1989) so the corresponding pF-curves were adopted for our site-specific parameterisation. Below 80 cm the clay content in the willow plots was much higher than that of Jacobsen (1989) and therefore the hydraulic properties of a deep soil layer from Andersen (1986) with a higher clay content were adopted.

The (saturated) hydraulic conductivity as a function of depth had not been measured and was estimated from Schjønning (1992) using soil analyses originating from two sites not far from the willow plots at Foulum.
The modelled soil profile was divided into 12 compartments with compartment size increasing from 4 cm at the soil surface to 80 cm at a depth of 3.5 m where a unit-gradient gravitational water flow from the soil profile was assumed.

Canopy development (leaf area index, LAI) was estimated from the RVI measurements as already described in section 4.3. For the modelling, canopy development was averaged across row distances and N-treatments (excluding the unfertilised plots) so separate developments for the two clones 112 and 183 resulted.

Root depth was estimated from Mortensen et al. (1998). They estimated – from a number of rather variable observations of root depth – that the maximum root depth at Foulum was 115-125 cm inside the double rows. From the data available, the model root distribution was assumed to decrease exponentially with depth and root depths were set to 115 cm for clone 183 and 125 cm for clone 112. The differentiation between clones was due to differences observed in the TDR measurements. In the depth interval 100-150 cm, TDR-estimated water content (by subtracting measurements in intervals 0-150 cm and 0-100 cm) was almost constant during the growing season for clone 183 while a limited water extraction was observed for clone 112.

Meteorological data for driving the water balance model were supplied from the Foulum climate station. Daily values of global radiation, precipitation, mean air temperature, mean air humidity, and wind speed at 10 m height were input to the model.

Canopy stomatal resistance (r_c) was calculated using the Lohammar equation (Lindroth 1985; Persson and Lindroth, 1994) that combines a minimum stomatal resistance (r_{smin}) with functions taking into account the influence of light (global radiation, R) and vapour pressure deficit (D) on the actual stomatal resistance:

$$r_c = \frac{r_{s\min}}{LAI} \frac{R + R_0}{R} \left(1 + D/a\right) \tag{2}$$

R_0 represents half-light saturation in the light response and a represents the vapour pressure deficit corresponding to a 50 % closure of stomata. R_0, a and r_{smin} are plant-specific parameters with reference values for willow (following Persson, 1997) of 11.8 MJ m^{-2} d^{-1}, 1318 Pa, and 67 s m^{-1}, respectively.

4.5.1 Model calibration, 1998-1999.

The two growing seasons of 1998-1999 were selected for model calibration since the measured data (RVI, soil water content) were most comprehensive during this period. The water balances of clones 112 and 183 were simulated separately. The model simulations were evaluated by comparing observed (TDR) and simulated soil water content in the root zone. For consistency with the estimated canopy development we calculated the mean TDR water content for each clone using data from all fertilised plots.

Calibration of the model resulted in three major changes compared with the preliminary model parameterisation: soil properties, water stress threshold and canopy stomatal resistance were modified.

4.5.1.1 Soil properties

The soil properties had been adopted from previous studies on soils originating from the Foulum area; however, they did not describe the specific soil at the willow plots very well. Generally, the measured soil water content during the winter and early spring period when the soil is not short of water (soil at field capacity, pF2) was higher than the simulated depth-integrated soil water content. This indicated that the soil at the willow plots had a better water holding capacity than that of the adopted soil profile. A better agreement between model and observations was obtained by letting a model soil layer at 50 cm depth, having a relatively high water holding capacity at pF 2.0, span a greater depth interval than first estimated.

4.5.1.2 Critical threshold for soil water uptake

The modifications of the critical threshold for soil water uptake (ψ_c) are possibly inter-related with the soil hydraulic properties described above. The parameter ψ_c is the critical value of the soil water potential when root water uptake is reduced compared with the atmospheric demand for evaporation as calculated from the Penman-Monteith equation. The value of ψ_c is used to quantify the ability of the plants to exhaust the soil water storage during dry periods. For the Foulum application we found that ψ_c of clone 112 (3000 hPa) and 183 (2000 hPa) represent a relatively dry soil, and thus indicate a higher drought-tolerance, compared with previous model applications ($\psi_{c\text{-reference}}$ = 200-1000 hPa ; Persson, 1995). However, it is difficult to decide if the apparent resistance to drought counterbalances an effect of incomplete parameterisation of the soil in the root zone. More water may in fact have been easily available to the Foulum willow roots than what is available according to the present soil parameterisation.

4.5.1.3 Canopy stomatal resistance

We found that the difference in water use as reflected in the TDR observations could not be accounted for by differences in canopy development (early senescence of clone 183 compared with clone 112) and root depth (125 cm for clone 112 and 115 cm for clone 115). The different amounts of water extracted from the root zone were thus attributed to differences in plant physiology, reflected in the canopy stomatal resistance: clone 183 has a higher resistance to transpiration than clone 112.
The Lohammar equation (eq.2) contains three parameters that may be varied. We decided to retain the stress-related parameters (a and R_0) at their

reference values since the present dataset was not comprehensive enough for a detailed analysis of the light- and vapour pressure-response of willow. Consequently, the differences in canopy stomatal difference were expressed in the minimum stomatal resistance (r_{smin}; reference value 67 s m^{-1}) alone. We found that r_{smin}=50 s m^{-1} for clone 112 and r_{smin}=110 s m^{-1} for clone 183 provided transpiration amounts that resulted in good agreement between observed and simulated water content in the root zone for both clones (see Fig. 4)

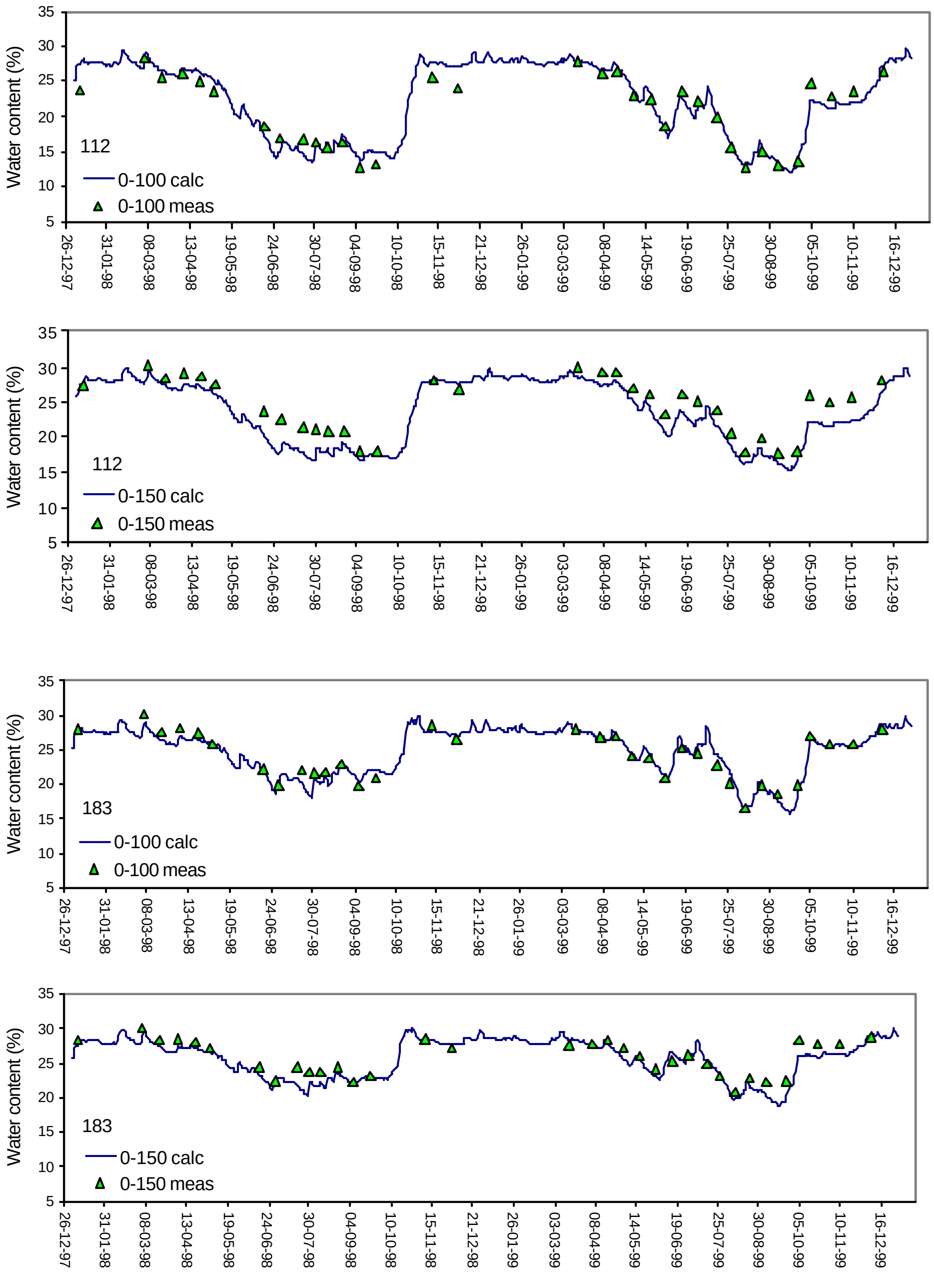


Figure 4. Result of the COUP model calibration to a Foulum willow stand during 1998 and 1999. Model calculated soil water content in the 0-100 cm and 0-150 cm depth intervals is shown together with TDR measured soil water content in the same intervals. The TDR values represent the mean of observations in all fertilised plots for each of the two clones, 112 (3 plots) and 183 (3 plots). Results for done 112 are shown in the two upper panels and results for done 183 are in the two lower panels.

4.6 Model validation

After model calibration, using data from the 1998 and 1999 seasons, the model parameterisation was validated by applying the model to the 1997 season.
The canopy development during 1997 was calculated from the RVI measurements during the first half of the season and estimated from the experiences from 1998-99 for the rest of the season. Due to the lack of measurements during the late season, the estimated canopy development did not account for any difference between clones.

The TDR data to be compared with the simulated soil water content were again calculated as the mean water content of fertilised plots for each clone. Due to the limited number of inter-row observation points during 1997 this meant that the water content representing clone 112 was the mean of observations in two plots, while the water content representing clone 183 was from observations in a single plot.

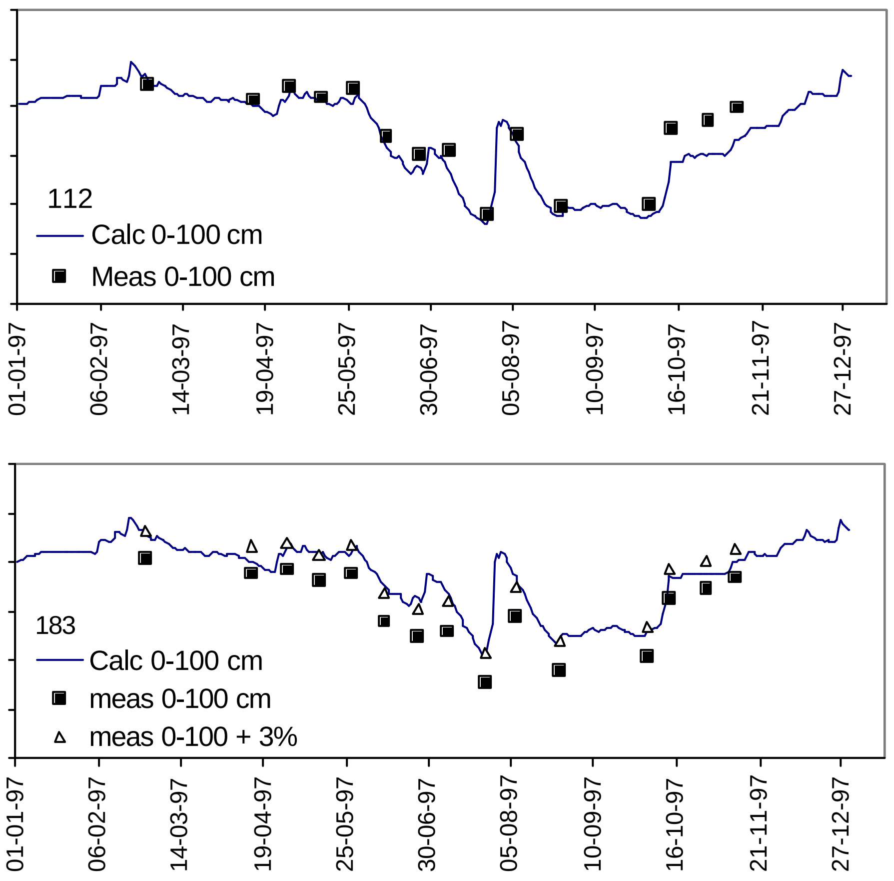


Figure 5. Model validation: application of the calibrated COUP model to the 1997 growing season. Model calculated soil water content in the 0-100 cm depth interval is shown together with TDR measured soil water content in the same interval. The TDR values are the mean of observations in fertilised plots for each of the two clones, 112 (2 plots) and 183 (1 plot). For clone 183, a tentative increase of measured soil water content by 3 % (vol.) is shown together with the actual measurements.

Figure 5 shows the result of the 1997 model application. Generally, the simulated water extraction from the 0-100 cm interval agrees with observations. The problem with regard to the limited number of TDR observations was evident for clone 183. The soil in the experimental area is very variable, and the soil of the single plot representing clone 183 obviously holds less water (lower field capacity) than found when averaging the water content of several plots (Fig. 4). In Figure 5 the observed water content values for clone 183 have been tentatively increased by 3 % (vol.) in order to illustrate that the simulated rate of water extraction is similar to the observed rate of water extraction.

In conclusion, the model test on the 1997 season provides confidence that the model has been adequately parameterised.

4.7 Total water use, yield and WUE

The willows were harvested in the winter 1999/00. Measured dry matter yields are coupled with the model calculated total transpiration and total evaporation over the three years growing period to calculate WUE (Table 3). Clone 112 that used most water also produced the highest yield but anyway had the lowest WUE. In the first rotation, which had more dry summers the two clones yielded similarly at Foulum. At a coarse sandy soil at Jyndevad the yield of clone 183 was significantly higher than that of clone 112 in both rotations. At this soil clone 112 suffered in dry periods and whole shoots wilted. Accordingly, the choice of optimum plant material when establishing a new energy crop site seems to be crucial for success. The knowledge in this area is however still very limited.

Table 3. Accumulated water use and dry matter yield over the harvest cycle 1997-1999 for willow clones at Foulum. Yields are the mean of all fertilised treatments. Water use is output from the COUP-modelling.

	Clone 112	Clone 183
Total transpiration (mm)	1047	785
Total evaporation (mm)	1589	1336
Dry matter yield (ton/ha)	27.4	24.9
WUE (transpiration) g/kg	2.6	3.2
WUE (evaporation) g/kg	1.7	1.9

4.8 Discussion

The result of the calibration was good when considering the 0-100 cm depth interval, covering most of the root zone (see Fig. 4). For both clones, however, the water extraction in the 100-150 cm interval tended to be slightly overestimated, particularly during 1998. This may indicate that root depth was not constant over the 1998 and 1999 seasons and that the depth of active roots was more shallow than found by Mortensen et al. (1998).

While the soil water extraction in the 0-100 cm compartment was well estimated by the model, the simulated extraction in the 0-50 cm interval tended to be underestimated and the extraction in the 50-100 cm interval to be correspondingly overestimated. This indicates that the actual root density was even higher in the top 0-50 cm than given by the exponentially decreasing root density assumed in the model.

Both of the above indications show a need to examine the willow root density with depth in more detail in order to improve the modelling.

We found it somewhat difficult to represent the local soil in the willow plots using the available pF-curves. The soil in the willow plots is very variable and measured water contents vary correspondingly. For water balance studies in experiments including measurement of soil water content using TDR, we suggest a) to obtain site-specific detailed pF curves or b) to apply a simpler model based on the concepts of plant available water within the limits of 'water content at field capacity (FC)' and 'water content at wilting point (WP)' (Thomsen et al., 1997). FC and WP may be obtained for specific fields or plots from time series of soil water content, including both winter time conditions (FC) and dry summer conditions (WP). The simpler model approach is more flexible for soil parameterisation.

The total evaporation of willow was high compared with reference evaporation. We compared daily totals of evaporation (E_{total}, soil evaporation + transpiration + interception loss) to the daily estimates of reference evaporation (E_{ref}) from the climate station at Research Centre Foulum. E_{ref} is calculated using a 'modified Penman' equation (Mikkelsen and Olesen, 1991) and represents the maximum evaporation from a clipped grass cover that is not short of water. The ratio E_{total}/E_{ref} may be interpreted as a 'crop coefficient' (FAO, 1998) for willow.

Figure 6 shows the E_{total}/E_{ref} ratio for the two clones and for the three seasons. Only months with a significant contribution of transpiration to E_{total} are shown. Figure 6 shows that a) E_{total} of clone 112 was typically higher than E_{total} of clone 183, b) the ratio often exceeded 1.0, particularly during 1998, and c) the ratio was typically less than 1.0 during the early growing season when LAI is small.

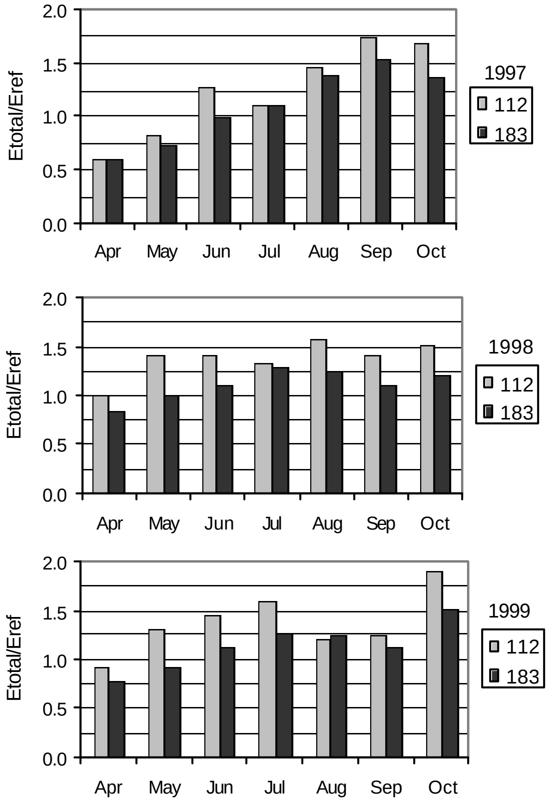


Figure 6. Monthly means of the ratio E_{total}/E_{ref} (evaporation ratio or willow crop coefficient) for each clone and growing season. E_{total} is the sum of model calculated transpiration, interception loss and soil evaporation. E_{ref} represents the evaporation from a clipped grass surface not short of water and has been calculated using a modified Penman equation (Mikkelsen and Olesen 1991).

There are two major reasons for E_{total} exceeding E_{ref} . Firstly, a willow stand forms a rough canopy so the aerodynamic resistance to evaporation is smaller compared with a grass canopy. This means that evaporation of intercepted water is very efficient and often leaves (solar) energy for subsequent transpiration from the canopy. During periods with frequent rain events the evaporation of intercepted water on the willow canopy contributes significantly to the total evaporation. The growing seasons of 1998 and 1999 were very wet with frequent rain, and this explains why both clones (112, 183) display values of E_{total}/E_{ref} well above 1.0 during several months.

Secondly, the large roughness of willow (compared with grass) contributes to enhanced transpiration. In addition, the simulated canopy stomatal resistance of clone 112 was found to be low, typically 35-50 s m^{-1} during May-August in the absence of soil water stress. These values are smaller than the canopy resistance suggested for grass for reference evaporation calculations using a Penman-Monteith approach (70 s m^{-1}; FAO, 1998; Allen et al., 1994). This caused transpiration of clone 112 to exceed E_{ref} on many occasions (days). The simulated canopy stomatal resistance of clone 183 was typically 70-90 s m^{-1} during May-August under no-stress conditions. These values are in the same range as the above mentioned resistance used for grass, and the transpiration of clone 183 was only rarely found to exceed E_{ref} .

Clone 112 experienced soil water stress sooner than clone 183 due to its higher transpiration. Effects of soil water stress caused the ratio E_{total}/E_{ref} for clone 112 to become equal to or lower than the ratio for clone 183 in July and August 1997, in July 1998 and in August and September 1999 (Figure 6 and Figure 7).

Figure 7 shows in more detail some of the behaviour explained above. The figure shows precipitation and the two evaporation ratios on individual days during mid-July to mid-August 1999. High values of E_{total}/E_{ref} (above 1.5) occur on rainy days while the ratio is between 1.0 and 1.5 on dry days. The evaporation ratio of 112 exceeds that of 183, except towards the end of the dry period when soil water stress significantly reduced the transpiration of clone 112. Clone 183, being more restrictive with regard to water use, only experienced little soil water stress during this period.

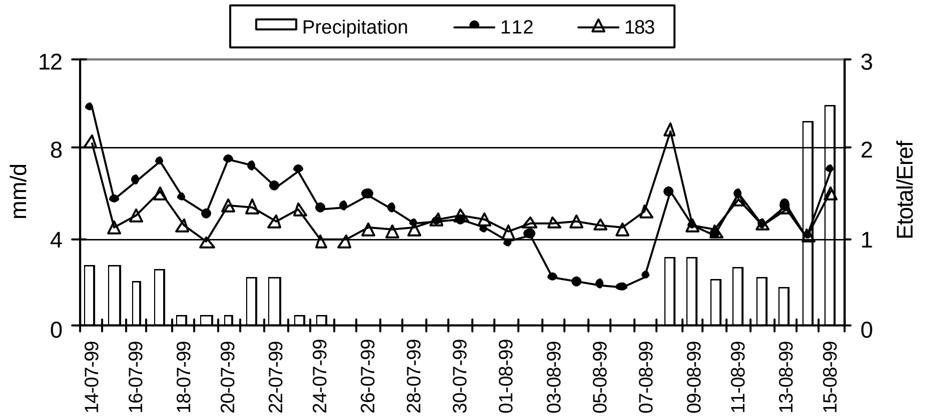


Figure 7. Precipitation (bars) and evaporation ratio E_{total}/E_{ref} (lines with symbols) for each clone during the period mid-July to mid-August 1999. High values of E_{total}/E_{ref} occur on rainy days and are due to efficient evaporation of intercepted water on the willow canopy compared to a reference grass surface. Low values of E_{total}/E_{ref} are due to soil water stress limiting transpiration of clone 112 towards the end of the dry period.

The evaporation ratios or crop coefficients found in this study agree with the findings of Persson and Lindroth (1994). They found mean weekly values of crop coefficients for willow that varied from 0.7-1.0 during the early season and reached 1.2-1.6 at midseason and about 2 at late season. The highest values were associated with abundance of precipitation and with a high leaf area index.

5 Implications of energy crop water and nutrient use on regional choice of crops, on breeding and on possible new energy crop applications

5.1 Choice of energy crops for specific regions

It is very important to evaluate energy crop water use before the planting of large commercial areas. The long growing period of the perennial crops causes a high annual water demand, which even in humid climates often exceeds the available water from soil and precipitation during the growing season. Consequently perennial crops may limit aquifer recharge and alternatively an annual crop with a lower annual water use can be chosen (Jørgensen & Mortensen, 2000).

Willow water use often exceeds Penman open water evaporation (Persson & Lindroth, 1994) and has been determined as a major yield-limiting factor in Sweden (Persson, 1995; Lindroth & Båth, 1999). The annual dry matter yield of 10 t/ha often used in economic calculations in Sweden (Danfors et al., 1998) was not likely to be obtained in the driest parts of southern Sweden, while in the wettest regions a potential yield of about 16 t/ha was estimated (Lindroth & Båth, 1999). These calculations were based on the willow plant material available in the late 1980s and early 1990s, which may allow a potential yield increase in new-bred material if their potentially higher yields are caused by a higher WUE.

The potentially two times higher WUE of C_4 crops compared to C_3 crops (Stanhill, 1986) allows for a doubling of water-restricted yield by choosing C_4 energy crops (Samson & Chen, 1996). This will, however, only be valid in areas where the C_4 photosynthesis is not restricted by temperature. The late sprouting of C_4 crops due to their high temperature demand furthermore restricts their annual water use. In Denmark willow comes into leaf during April, and miscanthus about one month later. During summer the miscanthus crop consequently depletes soil water content less than willow (Jørgensen & Mortensen, 2000). In Denmark miscanthus has therefore been selected for planting from spring 2001 on the ‘Renewable Energy Island’, Samsø, where precipitation is low compared with the rest of the country.

5.2 Breeding efforts with regard to WUE and NUE

Poplar and willow species are often riverbank species, and can exhibit a very high water use even when grown as field crops (Persson & Lindroth, 1994; Hall et al., 1998). However, within the genera significant variation exists as reported by Blake & Tschaplinski (1984) who showed that within poplar WUE could vary by a factor of two. The difference was, at least partly, explained by a lack of stomatal response upon environmental conditions of the species with the lowest WUE.

In the early screening and breeding efforts on energy crops the main focus was on aspects such as potential productivity, disease and frost resistance, coppicing and resprouting ability (Hall & Hanna, 1995; Zsuffa, 1995). However, more recently it has been acknowledged that water will very often under practical conditions be the most important yield-limiting factor (e.g. Lindroth & Båth, 1999), and WUE aspects have been included in current breeding efforts (e.g. Clifton-Brown & Lewandowski, 2000; Nordh & Christersson, 2000). Similarly, aspects of NUE have been focused on recently in the screening and breeding of energy crops, but often with the main goal of improving combustion quality by limiting the mineral content of the feedstock (e.g. Jørgensen, 1997; Lewandowski et al., 2001).

WUE is under limited water availability in the selection nursery well correlated with yield (McLauglin et al., 1997). However, in humid climates and on young crops more specific methods may be necessary to select for high WUE. Carbon isotope discrimination is related to WUE within C_3 plants (e.g. Hubick et al., 1988) and integrates well over seasonal differences. A simpler method of measuring leaf Relative Water Retention Capacity (RWR) of willow during stress has proved to correlate well with drought stress yield response and carbon isotope discrimination values, and is now introduces in the breeding programme at the company Svalöf Weibull in Sweden (Nils-Ove Bertholdsson, pers. comm.).

5.3 Additional outputs from energy crop production: Protection of ground water resources, riparian buffer strips, sewage water and sludge treatment.

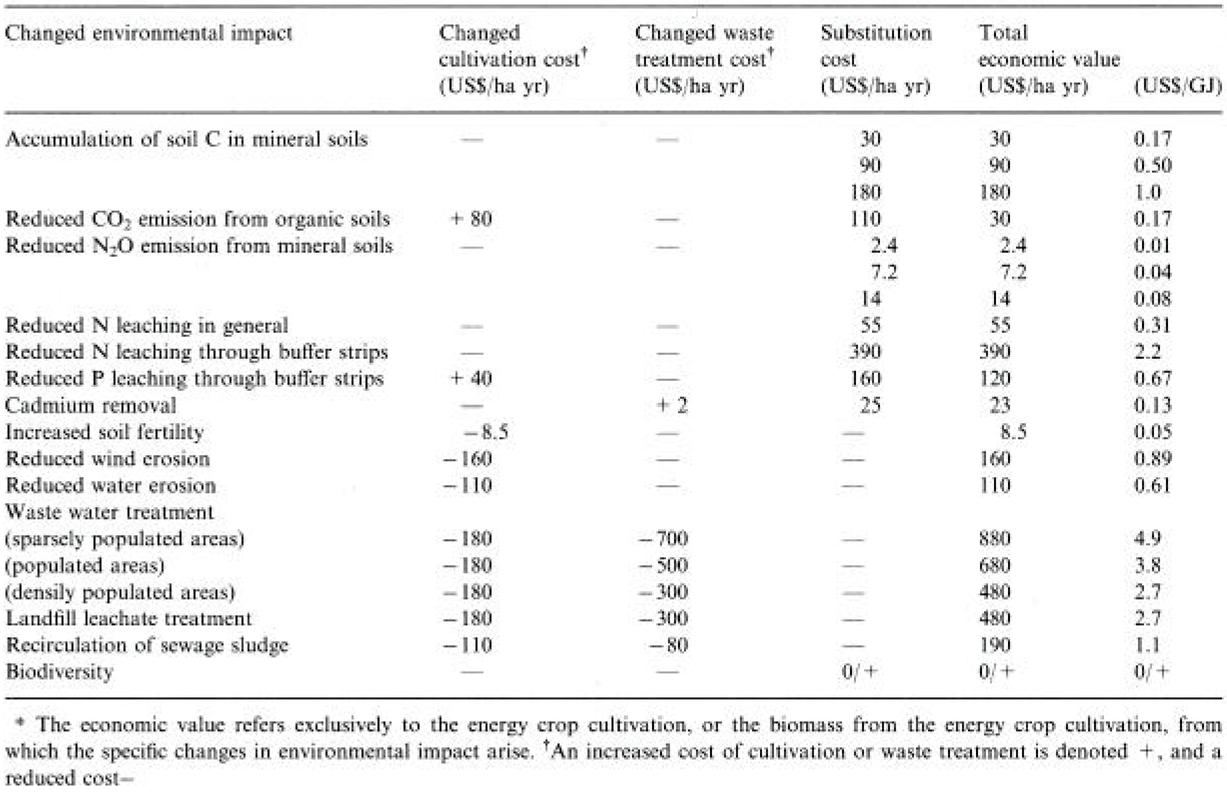
Perennial crops are usually efficient at taking up nitrate due to their long growing season and the permanent and deep root system. The absence of tillage in an established perennial crop will furthermore reduce mineralisation. Consequently leaching is very limited (Jørgensen & Mortensen, 1997; Aronsson et al., 2000) apart from during the establishment period (Christian, 1998; Mortensen et al., 1998). Low nitrate leaching has been measured in fertilised crops irrespective of the nutrient source being mineral fertiliser, sewage sludge or animal manure (Jørgensen & Mortensen, 2000). Additionally, the permanent soil cover in perennial crops can reduce surface run-off of soil, nutrients and organic material (Schultz et al, 1995; Lee et al., 2000).

The low losses from perennial energy crops combined with the often high NUE values (Table 2) imply that they will exhibit high NUE_{system} values as well. The difference to NUE_{system} values of annual crops, which can cause high N-leaching (Jørgensen & Hansen, 1998) and high surface run-off, can be expected to be even higher than the difference within the traditional NUE values (table 2). This high efficiency is why perennial energy crops have often been used as test crops for the safe treatment of solid and liquid wastes (e.g. Polglase & Tunningley, 1996; Perttu & Obarska-Pempkowiak, 1998), for riparian buffer strips (Lee et al., 2000) and for the protection of groundwater quality (Jørgensen & Mortensen, 1997, 2000). Some of these applications are now used on a commercial scale (e.g. Hasselgren, 1998; Baker et al., 2000) but still only to a limited extent.

The high water use of willow and poplar compared to most other crops (Persson & Lindroth, 1994; Hall et al., 1998) makes the crops suitable for planting on sanitary landfills to minimise leachate discharge (Ettala, 1998) along with an uptake of surplus nutrients (Hasselgren, 1998). Similar principles are employed in vegetation filters for wastewater treatment (Aronsson & Perttu, 2000; Geber, 2000). In both cases gaseous nitrogen loss may play a significant role in the N-turnover due to the reducing conditions in the wet soils and the high input of energy-rich carbon-compounds from the wastes and from the crops.

Recently some of the above uses of energy crops, additional to their production of biomass, have been evaluated in economic terms (Jørgensen & Mortensen, 1997; Rosenqvist et al., 1997; Börjesson, 1999; Turhollow, 2001). Often the expected economic benefits from the environmental applications are substantial (Table 4), and this may be a motivator in the push for the future development of energy crops. However, such new applications of crops for energy *and* for environmental protection require a long implementation period as several technical and non-technical barriers hamper the shift of technology.

Table 4. Economic value of various environmental effects (several of which relate to water and nutrient use) of growing perennial energy crops, and of possible new environmental applications of energy crops under Swedish conditions. From Börjesson (1999).



Changed environmental impact	Changed cultivation cost[†] (US$/ha yr)	Changed waste treatment cost[†] (US$/ha yr)	Substitution cost (US$/ha yr)	Total economic value (US$/ha yr)	(US$/GJ)
Accumulation of soil C in mineral soils	—	—	30	30	0.17
			90	90	0.50
			180	180	1.0
Reduced CO_2 emission from organic soils	+ 80	—	110	30	0.17
Reduced N_2O emission from mineral soils	—	—	2.4	2.4	0.01
			7.2	7.2	0.04
			14	14	0.08
Reduced N leaching in general	—	—	55	55	0.31
Reduced N leaching through buffer strips	—	—	390	390	2.2
Reduced P leaching through buffer strips	+ 40	—	160	120	0.67
Cadmium removal	—	+ 2	25	23	0.13
Increased soil fertility	− 8.5	—	—	8.5	0.05
Reduced wind erosion	− 160	—	—	160	0.89
Reduced water erosion	− 110	—	—	110	0.61
Waste water treatment					
(sparsely populated areas)	− 180	− 700	—	880	4.9
(populated areas)	− 180	− 500	—	680	3.8
(densily populated areas)	− 180	− 300	—	480	2.7
Landfill leachate treatment	− 180	− 300	—	480	2.7
Recirculation of sewage sludge	− 110	− 80	—	190	1.1
Biodiversity	—	—	0/ +	0/ +	0/ +

[*] The economic value refers exclusively to the energy crop cultivation, or the biomass from the energy crop cultivation, from which the specific changes in environmental impact arise. [†]An increased cost of cultivation or waste treatment is denoted +, and a reduced cost−

6 Research and development demands

Some of the gaps of knowledge apparent from the above analysis, which need to be addressed in future research and in collaborative actions such as the IEA Bioenergy, are:

- Knowledge of energy crop water use is often limited or lacking. As crop water use is crucial to yield potential and to the overall hydrology of a catchment area, better data are needed. The good knowledge on willow water use is an exception.
- Improvement/development of energy crop water balance models. The COUP (previously SOIL) model is adequate for simulating the water use of willow; however, it requires site-specific information particularly on soil hydraulic parameters, which is not always available. A simpler soil model approach would facilitate water balance simulations on a routine basis for several potential energy crop sites. Genotype-specific simulations are, in any case, difficult as clones appear to have significantly different minimum stomatal resistance, leading to differences in the annual transpiration.
- There are so far no specific models for e.g. miscanthus, *Arundo donax*, Cynara etc. Models that can compare a range of crops are needed to assist in the choice of the most suitable crop for specific conditions of climate, soil and demand for groundwater recharge.
- There is a need to calculate WUE with an applied energy crop system approach: WUE should be calculated from the harvestable biomass (instead of maximum biomass) and from the total annual evapotranspiration of the field (instead of growing season values only).
- There is a need to evaluate energy crop nutrient efficiency with increased focus on the environmental impact of the production system: emissions (gaseous, leaching and run-off) from the system should be included in the calculation of NUE instead of just including the nutrient removal with biomass.
- Water use can in many areas be a determinant factor for the introduction of energy crops, and future analyses of energy crop potential should seriously address this matter. The often high water use of perennial crops may limit groundwater recharge, while in areas of surplus precipitation the good quality of water leaving the root zone of perennial crops can improve the aquatic environment.

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