

Large carbon-sink potential by Kyoto forests in Sweden—a case study on willow plantations

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(Manuscript received 15 January 2007; in final form 21 June 2007)

ABSTRACT

Fluxes of CO₂ were measured in a 75-ha short-rotation willow plantation at Enköping, central Sweden. The plantation was irrigated with wastewater for fertilization and water-filtering purposes. The harvested biomass was used locally for combined heat and power production. The plantation was a sink of ca. 8 tonnes C ha⁻¹ during 2003, of which ca. 50% was estimated to be attributed to fertilization. Biomass increment by shoot growth was 5 tonnes C ha⁻¹ during the same year. Belowground carbon allocation was estimated to 3 tonnes C ha⁻¹ yr⁻¹ by a model that relates carbon allocation to shoot growth. Thus, the ecosystem carbon balance was closed by these estimations. The carbon uptake by the willow plantation was 5.5 times as high compared to a normally managed spruce forest, but only half as high as from an experimental, well-managed willow plantation in the same region. This illustrates the vast potential of short-rotation willow plantations for CO₂ uptake from the atmosphere.

1. Introduction

Forestry has a potential to counteract rising atmospheric CO₂ levels, both by directly acting as a CO₂ sink by carbon sequestration, and by replacement of fossil fuel by bio fuels. This has even political and economical impact, since countries (like Sweden did) may choose to account for forest management activities to fulfil their commitments under the Kyoto Protocol. Therefore, there is increasing interest in highly productive, intensive forestry such as short rotation forestry in Sweden. Currently willows (i.e. different varieties of *Salix* sp.) are commercially grown on 15 000 ha of Swedish farmland for production of fuel for district heating plants, usually combined with power generation. The combustion ashes are usually recycled to the plantations. Furthermore, willow plantations have a potential for treatment and recycling of wastewater by enhanced denitrification and by plant uptake of nitrogen and other plant nutrients in the wastewater, which in turn results in an increased growth (e.g. Aronsson and Bergström, 2001; Dimitriou and Aronsson, 2004). While the beneficial effects of fossil fuel substitution by bio-energy from willow plantations are relatively well known by

biomass inventory, less is known about the net CO₂ sink strength of short-rotation willow plantations.

The over all study was conducted in order to quantify the balance of greenhouse gases (N₂O and CO₂) and leaching of nitrogen, and thus to quantify the overall treatment efficiency and environmental impact of the system. This paper concentrates on the net ecosystem CO₂ exchange, from a 2-yr study of CO₂ fluxes and biomass production in a wastewater irrigated willow plantation in central Sweden, while N₂O fluxes and the total greenhouse gas balance will be subject of separate studies. To facilitate comparison with biomass estimates, the quantitative analyses of CO₂ fluxes were done in terms of carbon (C).

2. Material and methods

In Enköping, central Sweden (59°37'N, 17°04'E), a novel system for improved nitrogen treatment of wastewater has been adopted. The field is located on a former lake bottom with soil properties shown in Table 1. The main feature of the system is irrigation with a fraction of wastewater during summertime of a 75-ha willow plantation, divided into several fields, adjacent to the wastewater treatment plant (WWTP) (Fig. 1). The sewage sludge produced in the tertiary treatment step is dewatered by sedimentation and centrifugation. The supernatant water from this process constitutes less than 1% of the total water flow in the

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DOI: 10.1111/j.1600-0889.2007.00299.x

Table 1. Soil properties of the experimental field

	Within double row			Between double rows		
	10–15 cm	35–40 cm	55–60 cm	10–15 cm	35–40 cm	55–60 cm
Bulk density (g cm^{-3})	0.89	0.95	0.78	1.01	0.92	0.74
Porosity (%)	64.6	64.3	70.5	60.1	65.4	72.0
Water content at						
0.05 m tension (vol%)	66.8	63	65.3	64.6	62.6	65.4
1.0 m tension (vol%)	51.4	53.6	58.1	55.8	55.2	59
6.0 m tension (vol%)	44.6	47.1	53.2	49.7	48.4	54.7
Hydr. conductivity (cm d^{-1})	4	34	370	0.9	20	280
Soil organic carbon (%)	3.74		1.60			
Soil nitrogen (%)	0.36		0.21			

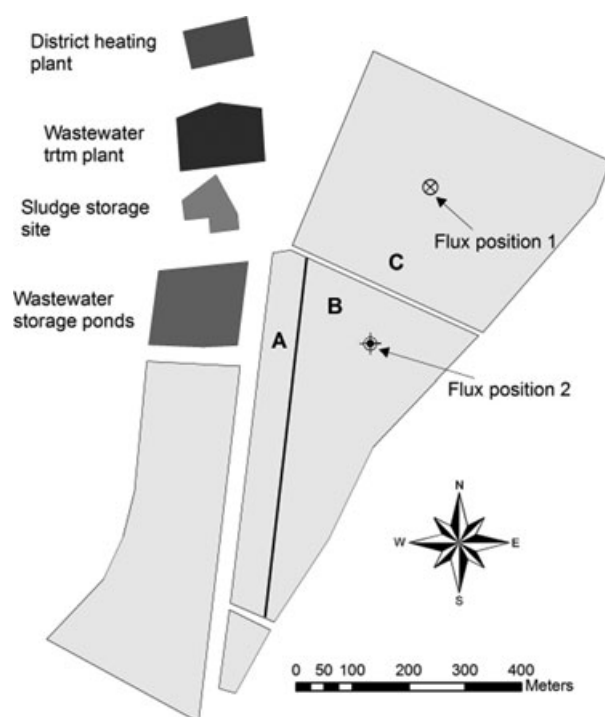


Fig. 1. Map of the Enköping willow plantation. The dominant wind direction is from southwest.

WWTP but contains approximately 25% of the nitrogen entering the WWTP. During summer, the supernatant is mixed with treated wastewater and distributed to the willow plantation by drip pipes.

The willow plantation in which the field measurements were conducted was established in May 2000 using a bred variety of willow (i.e. *Salix* spp; 'Tora') in an area with mean annual temperature of 6.0°C and precipitation of 521 mm. In July 2000, drip irrigation pipes were laid out in every double row of willows. Mechanical weeding was conducted during the first summer. In winter 2000/2001, the plants were cut back in order to promote sprouting and canopy closure. In winter

2002/2003, a 100-m wide section of the field was harvested (Fig. 2), the remaining part in January 2004. The field is tile drained with drainage pipes at approximately 60-cm depth, but the functionality of the drainage system is probably low. Field measurements started in September 2001. In the centre of a nearly quadratic 15-ha field within the 75-ha plantation, a system for meteorological measurements and groundwater pipes were installed.

In November 2001, a system for CO_2 and H_2O flux measurements was installed next to the meteorological system. During the summer of 2002, it became obvious that the willows growing south and west of the measuring systems (i.e. in the prevailing wind direction) suffered heavily from frost damages and weed competition. Therefore, in April 2003, the entire measurement system was moved 320 m southwards to another section of the large willow plantation with less plant damages and less weed competition. That field consisted of two sections of which the westernmost part (A) was planted 1 yr before the other part (B) (Fig. 1), and consequently also harvested 1 yr earlier. This was done in order to obtain data that mainly reflect processes in a reasonably well-growing willow plantation, since the very poor growth in the first field made the measurements not valid for scaling up or judgments valid for a normally growing willow plantation. A summary of the management scheme is given in Table 2.

The entire area of willows (75 ha) was very flat with less than 2 m variation in elevation. Air temperature T_a and relative humidity RH were recorded using a Rotronic MP 100A hygrometer (Rotronic AG, Bassersdorf, CH) installed in a radiation shield (R.M. Young, Traverse City, MI, USA). Wind speed and direction were recorded using a Wind Monitor (R. M. Young, Traverse City, MI, USA), and solar radiation ($0.4\text{--}1.1\ \mu\text{m}$) was recorded using a LI-200 Pyranometer (LI-COR inc, Lincoln, NE, USA). Precipitation was recorded by a rain gauge with a tipping bucket device. The instruments were connected to a CR 10 data logger (Campbell Scientific Ltd., Loughborough, UK) calculating and storing 30-min mean values. In addition, soil temperature was recorded using two Optic StowAway Temperature loggers

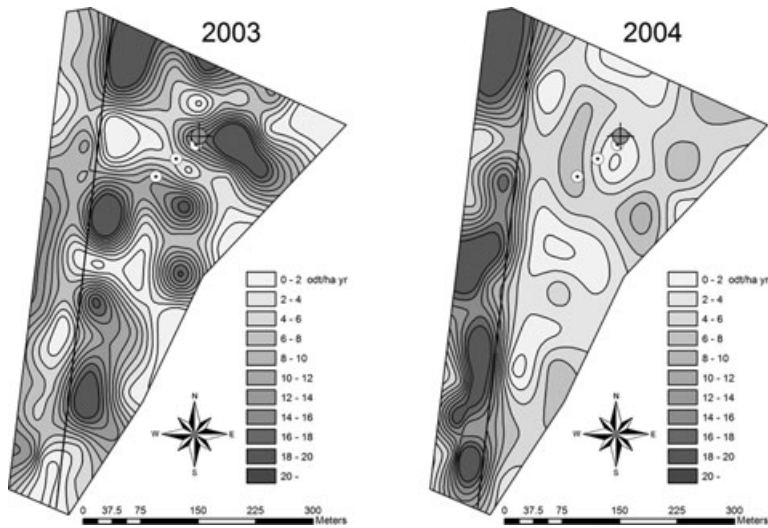


Fig. 2. Variations of biomass increment during 2003 and 2004. The black line indicates the boundary between the parts that were harvested during 2002/2003 and 2003/2004, respectively. The black cross indicates the position of the field station; the circles indicate positions of groundwater gauges.

Table 2. Management scheme of the Enköping willow plantation

Year	1999	2000	2001	2002	2003	2004
Operation	Planting area A	Planting area B and C. Cut back of area A	Cut back of area B and C		Harvest area A in January	Harvest area B and C in January
Shoot age area A (year)	0–1	0–1	1–2	2–3	0–1	1–2
Shoot age area B and C (year)		0–1	0–1	1–2	2–3	0–1
Flux measurements				Position 1	Position 2	

(Onset, Pocasset, MA) buried in the ground at 10 and 30 cm depth, respectively.

Fluxes of CO_2 and H_2O were measured by an eddy-correlation system (In Situ Flux Systems AB, Ockelbo, Sweden) based on a Solent R3 sonic anemometer (Gill Instruments, Lymington, UK) and an LI-7000 closed path infrared gas analyser (LI-COR inc, Lincoln, NE, USA). Sample air was brought to the analyser through a 6 m long HDPE-tube with a diameter of 1/4 inches. The air flow rate was 12 l min^{-1} , assuring turbulent flow through the tube. The design of the system is in principle described by Grelle and Lindroth (1996). Corrections and calculations of the fluxes were done following the Euroflux methodology (Aubinet et al., 2000). In particular, two coordinate rotations including a ‘sector fit’ were applied to align the coordinate system with the long-term mean wind vector. Furthermore, weak detrending by a digital recursive filter with a time constant of 2000 s was applied. Time lags due to signal processing and air transport through the sample tube were estimated by covariance optimization on a 30-min basis, and signal samples were shifted accordingly. High-frequency losses were corrected by empirical transfer functions applied on turbulence co-spectra that were theoretically derived based on wind speed, measuring height and atmospheric stability. The sensors were located on top of a guyed expandable aluminum tube. Because of the fast growth of the *Salix*, the height of the eddy-correlation sensors was periodically adjusted to ca. 2 m above the canopy.

The ‘source area’ or ‘footprint’, that is, the area that is represented by the measured turbulent fluxes has to be known. Therefore, the flux footprints were calculated using the footprint model by Schmid (1994). First, we verified the applicability of the parametrized version of FSAM (Mini-FSAM) by comparison with FSAM-runs on a subset of data. Then, the Mini-FSAM equations were used to calculate the dimension of the elliptical flux source area that contributes by 80% to the flux for each half hour. As the size and distance of source areas depend strongly on atmospheric stability, the results were grouped into summer and winter, separately for day and night. For each such scenario, the corresponding 30-min polygon surfaces were then successively accumulated in an array in polar coordinates representing the surface around the flux tower. The resulting frequency distributions were then averaged over all wind directions, integrated by distance, normalized and plotted as line plots (Fig. 3).

Several gaps occurred in the flux data, typically of the duration of single days. The main reasons were power failures, air pump failures, and a hard disk failure. The total fraction of gaps during the study period was 31%. These gaps were filled using a neural network with air temperature T_a , relative humidity RH , incoming shortwave radiation R_{is} , and wind speed Ws from the meteorological system as input. The network was trained with measured CO_2 fluxes from a period of 2–3 weeks before or after the gap and then used to estimate the fluxes during the gap period. To estimate the uncertainty introduced by gap-filling, 31% of the

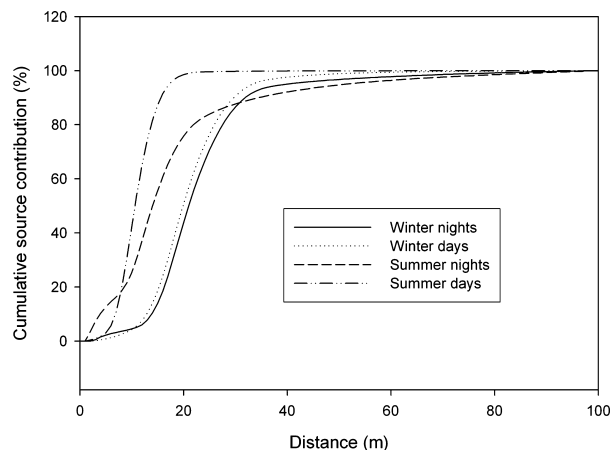


Fig. 3. Cumulative frequency distribution of flux source areas upwind of the flux tower during 2003. The values indicate the relative frequency of conditions when a surface point belonged to the area that was responsible for 80% of the observed flux.

measured flux data were removed, evenly distributed over the entire period. These artificial gaps were then filled by the neural network, and the corresponding Net Ecosystem Exchange (NEE) was compared with the NEE determined by measurements only. The difference was 0.20 tonnes C ha⁻¹ for the entire period, which corresponds to 13.5% of the measured NEE.

The annual aboveground growth of the willow plants was estimated using a combination of destructive and non-destructive measurements (Verwijst and Telenius, 1999). Biomass estimations were conducted in February 2002, in May and November 2003, and in November 2004. The diameter of each living shoot in a large number of 3-m row sections was measured at 95 cm height using a calliper. Shoots of all diameter classes (25 shoots per sampling occasion) were then harvested and dried at 80 °C until constant weight to obtain a two-parameter power function describing the relationship between shoot diameter and shoot dry weight. The average section dry weight was then used to calculate the average standing biomass of the whole field and the average growth during the last growing season. By use of ArcView Software (ESRI) maps were produced showing the smoothed spatial distribution of growth within the field for 2003 and 2004.

When modelling carbon sequestration by the willow plants, a conceptual model presented by Aronsson (2000) was adopted. According to that model, the carbon sequestration by the plants is due to (i) C-incorporation into harvestable shoots, (ii) C-incorporation into non-harvestable coarse roots and stumps and (iii) incorporation of leaf and fine-root litter-C into the pool of slow-degradable soil organic matter (humus). The C-incorporation into harvestable shoots was estimated by use of a combination of destructive and non-destructive measurements of annual shoot growth. Shoots, stumps and humus fractions were assumed to have a C proportion of 50%. The C-incorporation

into non-harvestable stumps was calculated using templates of biomass partitioning presented by Rytter (1997). Since little is known about the build-up of coarse, structural roots in short-rotation coppice systems, this C-sink was excluded. For the calculation of annual net build-in of C in humus, data from Rytter (1997) on leaf- and fine-root litter formation was used. The annual fine root growth is usually very high as compared with that of other plant compartments, but the living fine-root biomass is likely fairly constant after the first few years of plant establishment (Rytter, 1997). Thus, in this model the annual die-off of fine roots equalled the annual growth. The biomass allocation pattern varies considerably with growth conditions, for example, N availability, and is probably highly variable in a somewhat unevenly wastewater-irrigated willow plantation. This was not considered in the model. Instead the annual production of leaves, stump wood and fine roots were assumed to be a constant fraction of the shoot growth. The following equations were used for calculating the annual net C-sequestration by the plants:

$$\text{Shoot C} = \text{Shoot Growth (SG)} \times 0.50 \quad (1)$$

$$\text{Stump Growth} = 0.05 \times \text{SG} \quad (2)$$

$$\text{Stump C} = \text{Stump Growth} \times 0.50 \quad (3)$$

$$\text{Fine Root Litter} = 0.69 \times \text{SG} \quad (4)$$

$$\text{Fine Root Litter to Humus} = 0.50 \times \text{Fine Root Litter} \quad (5)$$

$$\begin{aligned} \text{Fine Root Litter C to Humus} \\ = \text{Fine Root Litter to Humus} \times 0.50 \end{aligned} \quad (6)$$

$$\text{Leaf Litter} = 0.31 \times \text{SG} \quad (7)$$

$$\text{Leaf Litter to Humus} = 0.42 \times \text{Leaf Litter} \quad (8)$$

$$\text{Leaf Litter C to Humus} = \text{Leaf Litter to Humus} \times 0.50 \quad (9)$$

By combining eqs (1)–(9), the following equation was obtained for calculating the C-sequestration (C_{SEQ}):

$$C_{\text{SEQ}} = \text{Shoot Growth} \times 0.76 \quad (10)$$

3. Results

The calculated biomass increment based on 70 sample points is shown in Fig. 2. In the part of the plantation where the equipment was installed initially the growth was very low (2.6 tonnes DM ha⁻¹) during 2002, while there was a major occurrence of weeds. After moving the station during spring 2003, the measurements represented a much better-growing *Salix* plantation. A 4.1-ha large part at the western edge of the field was harvested during winter 2002/2003, whereas the remaining part (9.8 ha)

Table 3. Budget of biomass increment and carbon storage (*nm* = not measured)

	2002	2003	2004
Shoot growth <i>Salix</i> (tonnes DM ha ⁻¹)	2.6	10.2	9.4
Estimated weed growth (tonnes DM ha ⁻¹)	3	1	1
Estimated C storage in <i>Salix</i> shoots and weeds (tonnes C ha ⁻¹)	2.8	5.6	5.2
Measured net ecosystem CO ₂ uptake (tonnes ha ⁻¹)	12.1	30.0	13.5
Measured net ecosystem C uptake (tonnes ha ⁻¹)	3.31	8.18	3.68
Litterfall (tonnes DM ha ⁻¹)	<i>nm</i>	<i>nm</i>	0.95
Calculated fertilization effect on <i>Salix</i> growth (+50%; tonnes DM ha ⁻¹)	1.87	3.75	3.48

was harvested during winter 2003/2004 (the boundary between the two parts is marked in Fig. 2).

The spatial variation of growth was rather large (Fig. 2), and even changing in time. During 2003, the average growth in the field was 10.2 tonnes DM ha⁻¹ (8.9 tonnes DM ha⁻¹ in the 4.1-ha large 1-year old part, and 10.8 tonnes DM ha⁻¹ in the 9.8-ha large 3-year old part). During 2004, the average growth was 9.4 tonnes DM ha⁻¹ (17.0 tonnes DM ha⁻¹ in the 2-year old part, and 6.3 tonnes DM ha⁻¹ in the 1-year old, harvested part).

A litterfall of 945 kg DM ha⁻¹ was measured during autumn 2004 (Table 3). The bud break after the harvest occurred late during 2004, and the leaves were yellowish until late June, which indicates problems with the photosynthesis, which may have been due to low temperatures during spring and early summer. The measured air temperature at 2 m height gave very little useful information on surface frosts. However, severe night frosts caused by radiative heat losses occurred during late spring and early summer 2004 in this part of Sweden, substantially damaging regrowing willow plantations.

During the rest of the year growth was normal and the shoots reached a height of ca. 2.6 m before the shoot elongation ceased in the beginning of September (Fig. 4).

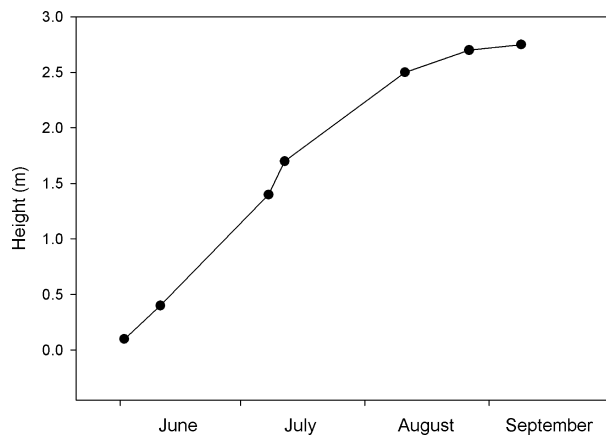


Fig. 4. Measured shoot height growth during 2004.

The estimated flux source areas were evenly distributed around the tower. Therefore, instead of a three-dimensional surface plot, a linear representation of the flux source distance from the tower was chosen, averaged over all wind directions. These flux distance frequencies were then integrated by distance to indicate the radius around the tower from within which 80% of the observed fluxes originate. Finally, the frequencies were normalized by the maximum frequency of occurrence to eliminate differences in numbers of observations (Fig. 3). The source areas are typically larger and further away from the tower during night than during day, and during wintertime as compared with summertime. The difference between night and day is much more pronounced during summertime than during wintertime. However, in all cases 75–80% of the fluxes originate from within a radius of 50 m around the tower, thus representing the willow plantation.

Measurements of net fluxes show that the willow plantation was a significant carbon sink between 2002 and 2004 (Fig. 5). The annual net uptake and the seasonal dynamics varied substantially from year to year. During 2002, the uptake was smallest, ca. 3.3 tonnes C ha⁻¹ yr⁻¹. Still, this is much compared with the relatively small shoot growth during that year. This may indicate that a part of this uptake actually was associated with the large growth of weeds during 2002. After moving the flux tower to the more productive part of the *Salix* plantation in the beginning of 2003 the measurements showed much larger uptake, 8.2 tonnes C ha⁻¹ yr⁻¹. This mainly reflects the carbon allocation in the biomass of the fast growing *Salix*. After the harvest during winter 2003/2004, the uptake related to regrowth started late in spring 2004. During that season the uptake never reached the same level as during 2003. The autumn 2004 was characterized by a considerably larger carbon loss than during the preceding years. Still, the net carbon uptake between January and November 2004 was almost as large as during 2002, ca. 2.7 tonnes C ha⁻¹.

Carbon fluxes show distinct diurnal dynamics, with a relatively small net emission during nighttime and a clear uptake during daytime (Fig. 6). The fluxes are controlled by, for example, solar radiation, air temperature, and air humidity. While the winter months are characterized by an almost constant loss

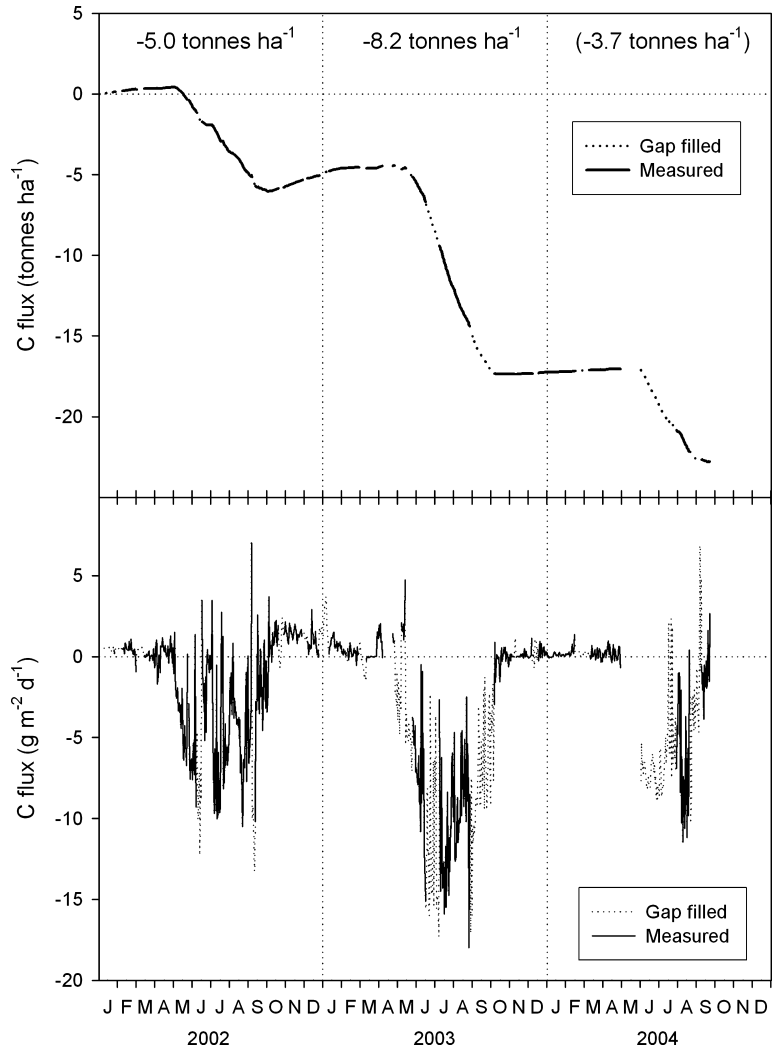


Fig. 5. Daily sums of C fluxes (bottom) and cumulative C fluxes (top) from Enköping. Negative fluxes mean uptake. The dotted lines indicate periods when gaps in the time series were filled by means of a neural network that had been trained for relationships between meteorological variables and C fluxes. The numbers in the upper plot indicate annual sums of net fluxes except for 2004, where the measurements ceased in September.

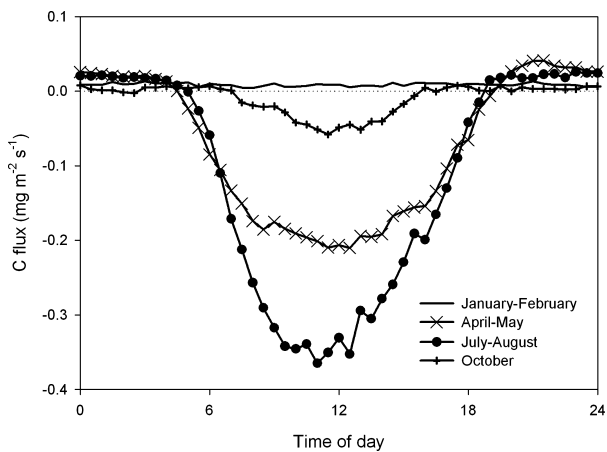


Fig. 6. Mean diurnal courses of C flux from Enköping.

of carbon, there is a strong diurnal variation during the vegetation period, because the day-and-night ecosystem respiration is more than compensated by photosynthetic uptake during the daylight hours. Naturally, the amplitude of these diurnal variations is largest in the middle of the summer.

The measured shoot growth in the field varied substantially between years and locations. The weed growth was estimated to 3 tonnes DM ha⁻¹ in the slowly growing stand around the first flux tower location during 2002, but only to 1 ton DM ha⁻¹ at the new location during 2003 and 2004. The difference between the measured carbon uptake of the ecosystem and the allocated carbon in the biomass was relatively large, in particular during 2003.

4. Discussion

Both the measured biomass increment and the net carbon uptake at the original location (Fig. 1) were low and not representative

for a conventional or wastewater-irrigated *Salix* plantation. Therefore, the flux tower was moved to a more representative part of the field during spring 2003, and the following discussion focuses on fluxes during 2003 and 2004.

Uptake of carbon leads to a downward (negative) CO₂ flux between the atmosphere and the plantation. To verify that the measured fluxes represent the willow plantation, estimations of flux source areas ('footprint analyses') were done. The results show that the measured fluxes originated from an area within a radius of 25–50 m around the tower, thus clearly representing the willow plantation (see Figs 1 and 3).

For technical reasons the data used in this study contained 31% gaps. When cumulative sums are evaluated, these gaps cannot be neglected but must be interpolated. Among many possible gap-filling techniques that often yield similar results (Falge et al., 2001) we chose a neural network, which resulted in an uncertainty of 13.5%. For analyses of light response and for bin-averaged diurnal courses, however, only measured data were used.

Part of the differences in NEE between the years may be due to stand age, associated with differences in LAI. In an established *Salix* plantation, though, LAI in mid-summer is fairly constant, except the first summer after harvest when there is a delay of around one month before canopy closure. However, during the establishment phase, which could be 1–3 yr, mid-summer LAI tends to increase over time.

There is a considerable difference between the dynamics of carbon-NEE (Fig. 5) and shoot growth as an indicator of re-growth during the summer (Fig. 4), because the measured fluxes represent the total ecosystem net uptake, while shoot growth only is one of several carbon sinks in the system. Other components of the NEE are weed growth, stump growth, and even leaf- and fine-root growth that eventually produces litter that enters the humus pool in the soil. In the only known study of carbon allocation to willow roots, Rytter (1997) studied a *S. viminalis* clone 78–183. There are no studies on clonal differences as regards carbon allocation to roots in a field situation. Rytter (1997) found variation over time in carbon allocation, at least during the first 3 yr after planting. Not much is known about differences in allocation patterns between young and mature stands of *Salix*. The calculations are valid for a mature stand assuming a constant fine-root biomass with a turnover rate according to estimates by Rytter (1997).

To understand the differences between measured fluxes and estimated aboveground biomass increment (Table 3) we used a simple model by Aronsson (2000) that relates the belowground carbon allocation in willow plantations by stump- and root-growth, leaf- and fine root-litter production to shoot growth. These budget calculations show good agreement with the measured fluxes (Table 4).

The fertilization by wastewater enhanced the growth of the willow plantation. However, in lack of a reference stand at the site the fertilizer induced growth could not be determined. Different

Table 4. Net fluxes and budget calculations

Mechanism	2003
Measured net CO ₂ -uptake (tonnes C ha ⁻¹)	-8.18
Measured shoot growth (tonnes C ha ⁻¹)	5.12
Modelled belowground C allocation (tonnes C ha ⁻¹)	2.97
Difference (tonnes C ha ⁻¹)	0.09

studies have shown that the effects can vary from 10 to 73%, and can even differ substantially between different rotations (e.g. Hofmann-Schielle et al., 1999). Little is known about the yield increase due to wastewater irrigation; in the present study we therefore assumed a growth increment of ca. 50% as an effect of wastewater irrigation, in accordance with the authors' practical experience. Thus, the fertilization effect on growth corresponded to between 1.87 and 3.75 tonnes C ha⁻¹ yr⁻¹. If we thereby only consider the carbon that is stored by aboveground woody biomass we are likely to underestimate the total C-uptake. If, on the other hand, the total C-uptake is considered, there is a potential risk for overestimation, because we do not know when the system is in equilibrium, that is, when the contribution by leaf- and fine-root-litter is balanced by decomposition of soil humus. Therefore, both components are presented (Table 5).

To put the carbon uptake into the perspective of conventional Swedish forestry, we compared the net carbon flux from Enköping between June 1 and September 15, 2003, with fluxes from two other stands in the same region and during the same time of year. One of them, the 'Model forest', was an experimental willow plantation in Uppsala, ca. 35 km NE of Enköping, planted in 1984. CO₂ fluxes were measured there by a gradient system (Lindroth and Cienciala, 1996). The other stand, 'Knottåsen', was a 30-year-old planted spruce stand in Gästrikland in central Sweden that is quite representative for conventional, managed Swedish forests in that area (Grelle et al., 2004). CO₂ fluxes at the Knottåsen site were measured with the same kind of system as was used in the Enköping plantation. In Fig. 7 the cumulative carbon fluxes during the comparison period are shown. During those 3.5 summer months, the Model forest accumulated 15.2 tonnes C ha⁻¹, while the Enköping willow plantation accumulated 7.1 tonnes C ha⁻¹. The Knottåsen spruce forest, however, accumulated only 1.3 tonnes C ha⁻¹. A small part of these differences may be attributed to differences in meteorological conditions, as these measurements were done during different years and at different locations. For comparisons of the fluxes independently of weather conditions, the daytime light response functions of ecosystems fluxes for the three sites are shown in Fig. 8. Here, data for PAR > 5 μmoles m⁻² s⁻¹ were used. For the eddy-flux measurements, data were confined to periods where the friction velocity (u_*) was above 0.2 m s⁻¹ to assure sufficient turbulent mixing. Response functions were obtained by fitting an exponential model (eqs 11) to the measured

Table 5. C-storage during 2003 in C and CO₂-equivalents

Mechanism	Tonnes C (ha ⁻¹ yr ⁻¹)	Tonnes CO ₂ -ekv. (ha ⁻¹ yr ⁻¹)
Net CO ₂ -exchange	8.2	30.0
Contribution by N-fertilization	4.0	14.9
Stem biomass	5.1	18.8
Increased stem biomass by N-fertilization	2.5	9.4

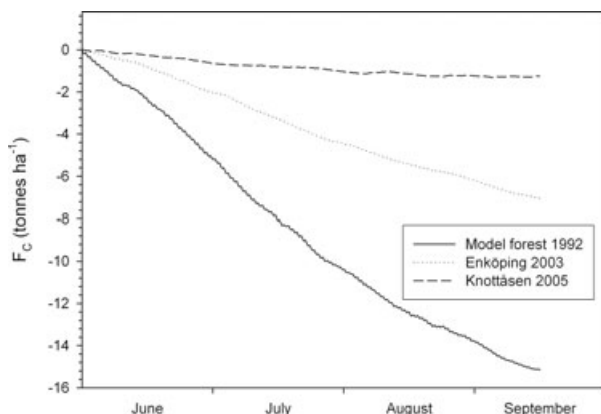


Fig. 7. Cumulative C fluxes from two short-rotation willow plantations and a 30-year-old spruce forest (Knottåsen) during summer.

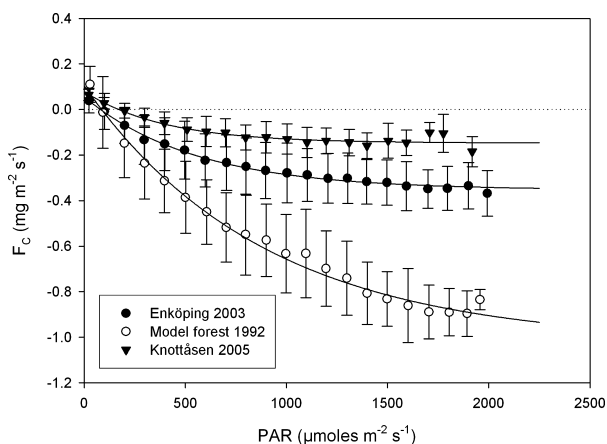


Fig. 8. Light response curves based on 30-min average ecosystem C fluxes for two short-rotation willow plantations and a 30-year-old spruce forest (Knottåsen) during summer.

daytime fluxes in terms of CO₂-C.

$$F_C = (F_{C_{\text{sat}}} + R_d) \left[1 - e^{\left(\frac{-\alpha \text{PAR}}{F_{C_{\text{sat}}} + R_d} \right)} \right] + R_d, \quad (11)$$

where F_C is net ecosystem carbon exchange ($\text{mg m}^{-2} \text{s}^{-1}$), $F_{C_{\text{sat}}}$ is saturation net ecosystem exchange ($\text{mg m}^{-2} \text{s}^{-1}$), R_d is dark respiration ($\text{mg m}^{-2} \text{s}^{-1}$), PAR is photosynthetically active radiation ($\mu\text{mol m}^{-2} \text{s}^{-1}$) and α is quantum efficiency ($\text{mg } \mu\text{mol}^{-1}$). The coefficients are given in Table 6.

Table 6. Parameters of ecosystem light response functions (eq. 11) for two willow plantations and a spruce forest (Knottåsen) during summer

	$F_{C_{\text{sat}}}$	R_d	α	R^2	N
Enköping	-0.3095	0.03709	-0.00049	0.84	2085
Model forest	-0.8228	0.06987	-0.00085	0.93	2555
Knottåsen	-0.2039	0.05296	-0.00038	0.79	1053

The dark respiration (R_d) of the Model Forest (i.e. the experimental willow plantation at Uppsala) was almost twice as high as in the Enköping plantation. However, this was more than compensated for by the quantum efficiency (α) which was almost twice as high as in Enköping, and of the saturation net ecosystem exchange ($F_{C_{\text{sat}}}$) which was almost three times as high as in Enköping. The spruce forest, on the other hand, had an only slightly lower quantum efficiency than Enköping, but a 34% lower saturation flux ($F_{C_{\text{sat}}}$), and the dark respiration was in-between that of the two willow plantations.

5. Conclusions

The comparison clearly shows the large potential of willow plantations to take up carbon from the atmosphere. Even the Enköping plantation, which in terms of growth corresponds to an ordinary commercial willow plantation, took up 5.5 times as much carbon as the spruce forest during the comparison period. The Model Forest, on the other hand, corresponds to the 'high end' of short rotation forestry, since it had been managed with an optimum of care (i.e. rigorous weeding, and irrigation and fertilization according to plant requirements), which is currently not commercially feasible. It demonstrates, however, the vast capability of short rotation forests to act as a terrestrial carbon sink.

6. Acknowledgments

This paper is based on studies financially supported mainly by the Swedish Energy Agency and its predecessor, which is gratefully acknowledged. We also want to thank Richard Childs, Herman Arosenius and the staff at the municipality of Enköping for valuable technical assistance.

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