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# Above ground biomass and water use efficiency of crops at shallow water tables in a temperate climate

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## Abstract

The objective of the paper was to quantify the water use efficiency (WUE) of different crops on lowland soils. This is relevant to agriculture for effective growing of bioenergy plants and sequestering carbon in plant biomass and soils.

On two groundwater lysimeter stations in the vicinity of Berlin, Germany, a long-term study has been conducted. Above ground biomass, evapotranspiration (ET), proportion of subirrigated water and water use efficiency have been measured on soils of different texture.

To quantify the effect of different water tables on crop biomass, additionally plant biomass production has been measured on surrounding farm plots.

The climate was characterized by a mean temperature of 9.4 °C and an annual precipitation of 500–600 mm during the period of study.

Subirrigation water requirements strongly depended on water table depths, crops and soil texture and showed a large variability between different years due to weather conditions. Spring barley consumed 10–60 mm of groundwater, winter wheat 20–250 mm, pasture and meadow grasses 80–300 mm, maize 100–400 mm, reed canary grass 400–900 mm, sedges 600–1000 mm and common reed 700–1200 mm. The ET in terms of the crop coefficient coincided with common recommendations, except from wetland plants, where it was higher than those. ET and above ground biomass were clearly crop-specific correlated. Plant type associated with appropriate water table depth, fertilization level and soil fertility were crucial factors of WUE. Results showed possible high dry matter biomass at all water table levels,

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but increasing WUE with deeper water tables when growing arable crops. Maize had the highest WUE with 4–6 g dry matter per l of water, followed by winter wheat, with a WUE of about 3. Wetland plants also produced high amounts of biomass but consumed more water. Their WUE was less than 1.5.

Field plots had lower drainage and subirrigation intensity than lysimeters and thus indicated both waterlogging and drought stress. This resulted in significant and strong correlations between groundwater table and biomass of arable crops. As in lysimeters, the highest WUE occurred with the highest crop biomass, it may be concluded that in field situations, highest WUE can be achieved with controlling an optimum range of water table. Crops of highest WUE, maize and winter wheat, had optimum water tables in the range of 80–160 cm on soils of higher water storage capacity. Grassland required water tables less than 80 cm. Creating rewetted areas of water tables less than 20 cm would mean a very low efficiency of water use.

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*Keywords:* Lowland soils; Water table; Crop yield; Evapotranspiration; Water use efficiency; Subirrigation

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## 1. Introduction

Lowland areas of shallow water tables are important human and wildlife habitats and play a crucial role in the energy cycle of the world. In Europe, many of those areas are drained and used for agriculture. In North-Eastern Germany, lowlands of shallow water table cover about 15–20% of the region. Strategies for their optimum use, maintenance or restoration require knowledge on water consumption and water use efficiency (WUE) of plants and sites. This is based on two main economical and environmental issues relevant to farmers:

- (i) growing of bioenergy plants;
- (ii) growing and sequestering carbon in plant biomass and soils.

Both issues will help to mitigate greenhouse effects and offer new perspectives for agriculture in Europe. Possible options range from intensive arable land use growing most effective crops to completely rewetting those areas. Rewetting of drained lowland sites would provide reconversion of soils to carbon sinks (Succow and Joosten, 2001). This would require very shallow water tables. Decisions on the most effective land use are closely related to potentialities of water table management, based on balancing of water and nutrients according to evapotranspiration and water use efficiency.

The aim of our study was to quantify the relationships between water table depths, crop biomass and water use efficiency of different soils and plants. Those data are of crucial interest for water management planning and scenarios in agricultural landscapes. The following main questions should be answered:

- Which crop, soil and hydrological factors are most important for water consumption and WUE?
- What proportion of groundwater is required for crops at different water tables?

Lysimeter and field experiments had to be conducted to get quantifiable results for answering these questions.

## 2. Materials and methods

### 2.1. Sites, meteorological and soil data

The long-term lysimeter and field study has been conducted in two lowland regions in the vicinity of Berlin, Germany, since 1975. At the Paulinenaue (P) site, located within the lowland region of the Havel River, about 60 km North-West of Berlin, lysimeter trials have been performed. At the Seelow (S) site, within the lowland region of the Oder River, about 65 km east of Berlin, both lysimeter experiments and additional soil and water management studies of adjacent farm or natural sites have been realized. At the P site, typical lowland soils are fens and humic sandy gley soils (Behrendt et al., 2000), whereas loamy, clayey and sandy gley soils are dominant at the S site (Mueller, 1988). All mineral soils are Gleysols, peat soils are Eutric Histosols (ISSS-ISRIC-FAO, 1998).

Soils and groundwater regime in terms of mean water tables of the farm plots surrounding the lysimeter site were the same. Lysimeters reflected the typical site conditions. However, there has been a difference between lysimeters and most field plots. Each lysimeter had a fast response to drainage and subirrigation situations as the plant root zone was closely located to the drainage and subirrigation tube (Fig. 1). Also, lateral fluxes did not occur. This could not be provided at the field plots in the same manner. Consequently, at same soils and similar mean water tables, both wetness and drought were more probable to occur on field plots than on lysimeters.

Meteorological data were recorded by automatic stations directly at the sites. Precipitation ( $P$ ) was measured at the soil surface since 1992 considering that standard measurements at 1 m height underestimate precipitation by about 10% (Kessler and de Raad, 1974; Richter, 1995). This value had been confirmed for both study sites. Measurements before 1992 were performed at 1 m height and thus upgraded by 10%.

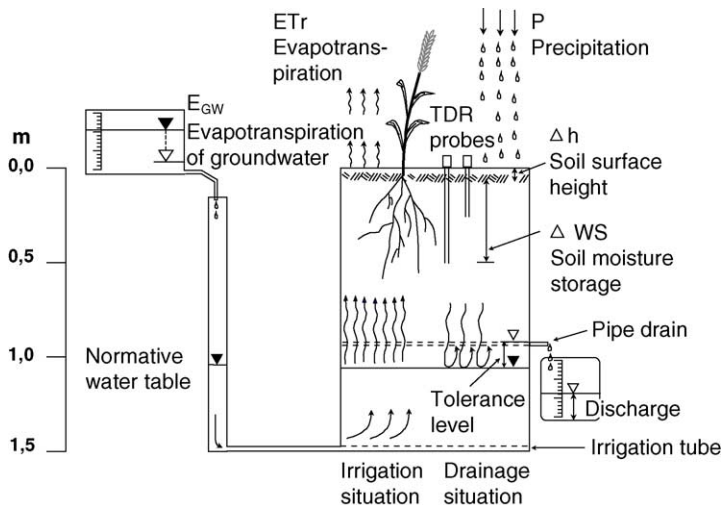


Fig. 1. Water balancing by groundwater lysimeters.

Table 1  
Average meteorological conditions (mm)

Month	<i>P</i> Seelow	<i>P</i> Paulinenaue	ET <sub>0</sub> PM grass	ET <sub>0</sub> Turc, mod. by Wendling
April	33	31	76	90
May	54	35	106	119
June	54	54	112	121
July	57	63	116	122
August	54	68	109	117
September	49	72	65	73
Vegetation period April–September	301	323	584	642
October	41	40	39	47
November	35	49	17	22
December	37	54	14	19
January	32	48	17	22
February	27	39	24	33
March	29	40	44	58
Total year	502	593	739	843

*P*: precipitation measured at soil surface; ET<sub>0</sub> PM grass: FAO Penman–Monteith grass reference ET (Allen et al., 1994b).

Temperature, global radiation and air humidity were measured to calculate the reference evapotranspiration (ET<sub>0</sub>). The method of Turc (modified by Wendling, 2001) and the FAO grass reference evapotranspiration are reliable methods of the ET<sub>0</sub> in the study region (DVWK, 1996; Wendling, 2001).

Table 1 shows conditions of precipitation and reference evapotranspiration as an average of the period from 1992 to 2003 indicating a distinct and increasing climatic deficit of water balance during the vegetation period in the study region. The Seelow site belongs to the sites with the least precipitation in Germany. The reference evapotranspiration did not differ between both locations and is at a very high level compared with other locations in Germany. The FAO Penman–Monteith grass reference evapotranspiration (ET<sub>0</sub> PM) was used as a reference basis for assessing ET of crops.

Parameters of soil type, texture, density and hydrological behaviour like pore size distribution and conductivity of soils have been measured in the laboratory and in the fields (Schindler et al., 1985, 2003).

## 2.2. Lysimeter construction and balancing of evapotranspiration

Construction and management of the lysimeters on both sites are illustrated in Fig. 1. The lysimeters are 1.5 m deep and have a surface of 1 m<sup>2</sup> (P site) or 2 m<sup>2</sup> (S site). At the P site, all 60 available lysimeters are monolith profiles. It had been planned to analyse two different crops (grassland and maize), two different soils substrates (peat and humic sand) and two different water table classes (shallow and deep) for the experiment. However, an orthogonal design was unrealistic due to further significant factors like fertilization, cultivars or soils. As the lysimeter station has been engaged with different experiments (Behrendt, 1995; Behrendt et al., 2001), only 4–12 lysimeters a year were available for this study. About one to three lysimeters had to be excluded from the analysis due to failure by

water table control or pests. Over several years, the remaining number of lysimeters was sufficient to provide statistical reliable information on water consumption and crop yield. This number of lysimeters will be indicated in the tables in Section 3.

At the S site, 16 lysimeters were available from 1975 to 1979 and 10 lysimeters from 1993 to 2002. All of them were filled with typical soils of the region, two lysimeters with each soil type. Investigation of the hydraulic behavior (Schindler, 1980) had shown no significant differences to a monolith. The bulk density was comparable with the field sites. All lysimeters of this site were uniformly managed in one rotation a year (Mueller et al., 2001).

During the vegetation period, relative constant water tables at different depths were maintained. About the same water tables were controlled during the winter period. To keep the water table constant, the groundwater supply has been provided by a recorded recharge from tanks, controlled by floating or syphon systems. Discharges after rains were measured by drain outflow from the lysimeters. The tolerance level of the water table and thus the discharge rate was adapted to the regional discharge. Considering the total vegetation period from April to September/October or even the total year and shallow water tables, the soil water storage becomes negligible. With arable crops and water tables deeper than 50 cm, the soil water content has been weekly measured by TDR probes since 1992. At swelling/shrinking clay and peat soils, the changes of the soil surface level were recorded and considered as soil moisture changes.

The real evapotranspiration was calculated based on Eq. (1) (Fig. 1):

$$ET_r \text{ (mm)} = P - D + E_{GW} + WS \quad (1)$$

where  $ET_r$  is the real evapotranspiration,  $P$  the precipitation, measured at the soil surface by rain gauges,  $D$  the discharge of percolated rainwater from the lysimeters,  $E_{GW}$  the evapotranspiration of subirrigated groundwater, recharged to keep the water table constant and  $WS$  is the change of soil moisture storage (depletion = positive values, increase after rain = negative values).

### 2.3. Field studies

In the vicinity of the lysimeter site S, field studies about the relationship between plant biomass and soil water regime have been conducted. This was useful because the limited number of lysimeters did not provide information on the relationship between water table and crop biomass in single years. Also, the possible subtle difference in the soil drainage status between lysimeters and particular field plots indicated the usefulness of those investigations.

Soil stratification and topsoil texture were estimated at each reference plot (Boden, 1994). Soil properties like water holding capacity and cation exchange capacity (CEC) had been measured at about 40 reference profiles and then regionalized (Mueller et al., 1982). The water table was measured using an array of observation wells (Tille, 1988; Tille and Mueller, 1992). Crop biomass was estimated at reference points with a size of 2 m<sup>2</sup>. Biomass harvests were provided in the years 1979 to 1988, 1990, 1991, 1993, 1994, 1998, 2001 and 2002 on 25–240 plots a year. Main crops were winter wheat (9 years, 1235 plots total), maize (7 years, 470 plots total) and meadow grassland (2 years, 67 plots total).

Representative samples of the harvested green biomass (15–30 a crop and year) were oven dried to estimate the dry matter biomass of the total population.

#### 2.4. Plants and crops grown on lysimeters

On peat and humic sandy soils (P site), typical crops are meadow and pasture grasses and maize for silage. On mineral lowland soils (S site), winter wheat, spring barley, maize for silage and field fodder crops are typical (Table 2). The number of years the crops were grown ranged from three to eight for most crops. Exceptions were spring barley and timothy appearing only two times and sunflowers, which were grown by now in 1 year only.

To minimize the “oasis and clothesline effects” of lysimeters, same crops were grown within and 1 m around the lysimeters. Permanent grasses, which have a high evapotranspiration regime, surrounded the area.

Groundwater levels were crop-specifically adjusted and fertilizers were applied according to the estimated nutrient demand of the plants (Table 2). Fertilization was not a variable in our study but differed from year to year. All crops were uniformly fertilized

Table 2  
Plants and crops grown on lysimeters

Crop/plant	Years	Water table (cm)	Nitrogen (kg ha <sup>-1</sup> )	Mean sowing date	Months of highest water demand	Harvesting date or period
Winter wheat ( <i>Triticum</i> sp.)	4	60–140	100–150	October 20	June	July 25
Spring barley ( <i>Hordeum vulgare</i> )	2	60–120	30–50	April 1	June	July 20
Maize ( <i>Zea mays</i> )	8	40–140	90–130	May 5	August	September 15
Red clover ( <i>Trifolium pratense</i> )	4	50–80	50–80	April 1	June–August	May
Alfalfa ( <i>Medicago</i> sp.)	4	60–130	40–70	April 1	June–August	May, 30–September 5
Italian ryegrass ( <i>Lolium multiflorum</i> ssp. <i>westerwoldicum</i> )	3	50–90	90–200	April 1	June–August	May 30–September 25
Sunflower	1	60–80	80	April 1	Aug	September 20
Perennial ryegrass ( <i>Lolium perenne</i> )	4	50–100	60–180	April 1	June–August	June 5–September 20
Timothy ( <i>Phleum pratense</i> )	2	55–110	80–180	April 1	June–August	June 5–September 20
Grass mixtures	8	30–100	60–180	April 1	June–August	June 5–September 20
Reed canary grass ( <i>Phalaris arundinacea</i> )	3	0–90	30–100	April 1	June–August	June 10–September 10
Sedge species ( <i>Carex</i> sp.)	5	–10–10	0		June–August	June 15–September 25
Common reed ( <i>Phragmites australis</i> )	5	–10–10	0		June–August	June 15–September 25

every year based on the nutrient status and the expected biomass level of the dominant soils in the region (peat soils at P site and clay soils at S site). Since soils and weather varied, a variability in biomass and water consumption between the different lysimeters has been created.

Within the indicated range of water tables, the lower values are the limit, within cereals, maize, clover and alfalfa can be grown before getting damaged because of a lack of air leading to a limited root development and reduced plant growth. Perennial fodder crops, grassland and pasture grasses were cut two to three times a year. At harvesting of grasses and cereals, a stubble height of about 20 mm was kept; at harvesting of maize and reed, the stubble height was about 80 mm.

### 2.5. Calculation of water use efficiency

In this study, WUE is the harvested total dry matter biomass (above ground dry matter) divided by the evapotranspiration. To minimize possible errors of the water balance comparing different crops, soils and water tables, and to enable a comparison of WUE with other data, three periods were considered:

- (i) the period from April to September (main vegetation period);
- (ii) the period from April to October (vegetation period of grass);
- (iii) the total year.

### 2.6. Statistical data analysis

Exploratory and statistical data analyses were performed using the statistical package SPSS PC+ (SPSS Inc., 1993). The main methods applied were stratification of data, computing confidence intervals of means and statistical comparison of means and regression analyses between plant biomass and most relevant site and management parameters.

## 3. Results

### 3.1. Site factors and above ground biomass

Plant biomass was dependent on appropriate soil structure and nutrient conditions, in particular on appropriate soil aeration for root growth and sufficient soil water availability in the vegetation period. The type of crop or vegetation had also a different adaptability to the water and air relationship within the soil profile.

Table 3 shows significant correlation coefficients between biomass and site factors. Distinct differences both between lysimeters and adjacent areas and between groups of crops are recognizable. Wetland vegetation (*Phragmites*, *Carex* sp.) grew up to water tables at the soil surface and even at slightly ponding conditions. The biomass was correlated with the total ET and with the component of groundwater recharge, in particular. Meadow and pasture grasses showed significant correlations with the ET and groundwater recharge as

Table 3

List of significant correlations between above ground biomass and site factors

Site factors	Correlation coefficients (Spearman)							
	Lysimeters					Adjacent fields		
	Wetland vegetation (n = 56)	Meadow and pasture grassland (n = 147)	Maize (n = 106)	Arable fodder crops (n = 73)	Winter wheat (n = 42)	Riverine grassland, unfertilized (n = 67)	Maize (n = 470)	Winter wheat (n = 1235)
Depth of water table	n.s.	n.s.	-0.38 <sup>a</sup>	n.s.	n.s.	-0.34 <sup>a</sup>	0.44 <sup>a</sup>	0.36 <sup>a</sup>
CEC topsoil	n.s.	0.51 <sup>a</sup>	0.32 <sup>a</sup>	0.30 <sup>a</sup>	0.40 <sup>a</sup>	n.s.	n.s.	0.21 <sup>a</sup>
Topsoil water storage capacity	n.s.	0.47 <sup>a</sup>	0.25 <sup>a</sup>	0.27 <sup>a</sup>	0.41 <sup>a</sup>	n.s.	n.s.	0.12 <sup>a</sup>
Nitrogen fertilization	n.s.	0.26 <sup>a</sup>	n.s.	0.28 <sup>b</sup>	0.62 <sup>a</sup>	n.s.	n.s.	0.52 <sup>a</sup>
ET <sub>r</sub> April–September	0.73 <sup>a</sup>	0.59 <sup>a</sup>	0.74 <sup>a</sup>	0.50 <sup>a</sup>	n.s.	n.m.	n.m.	n.m.
Groundwater recharge	0.73 <sup>a</sup>	0.30 <sup>a</sup>	0.70 <sup>a</sup>	0.35 <sup>a</sup>	n.s.	n.m.	n.m.	n.m.
Discharge	n.s.	n.s.	-0.20 <sup>b</sup>	n.s.	-0.55 <sup>a</sup>	n.m.	n.m.	n.m.
Soil water deficit September	n.s.	0.38 <sup>a</sup>	n.s.	n.s.	0.43 <sup>a</sup>	n.m.	n.m.	n.m.

n.s., not significant; n.m., not measured.

<sup>a</sup> Significant at 0.01 level.<sup>b</sup> Significant at 0.05 level.

well as with soil fertility and management factors. Topsoil quality (cation exchange capacity, water storage capacity and soil water depletion status) and nitrogen fertilization were important. Maize and arable fodder crops (Alfalfa, red clover and Italian ryegrass) also had a significant response to both water and soil factors. The variability of the fertilization level of maize was low and thus a significant correlation did not occur. Winter wheat required a deep rooting zone with adequate storage capacity of water and nutrients and was susceptible to lack of nitrogen. Lysimeters of sandy or shallow soils had more discharge of water and leaching of nutrients. This led to very low biomass.

Fig. 2 shows the relationship between water table and crop biomass of grasses, maize and winter wheat both of lysimeters and of adjacent fields. Data are the average of 3–6 years (exception Alluvial meadow grassland plots 2 years only) during the last 15 years.

In the field scale, the water table depth was significantly correlated with biomass. For the biomass production of wheat, nitrogen fertilization and topsoil storage parameters were most important; this corresponds with the lysimeter results. Grassland grew well at shallow water tables both in lysimeters and in the field scale. The decline of biomass with deeper water tables was significant and due to the shallow root system of most species and limited capillary water supply of layered soil profiles typical in lowlands. The higher the soil water status, the higher was the plant biomass of the adapted grass species. Stands of reed canary grass (*Phalaris arundinacea*) produced high biomass at shallow fluctuating water tables. In Fig. 2, the latter is expressed by the mean water table from 1990 to 2001. However, further site characteristics as relief position, flooding frequency and soil texture have been intercorrelated with the mean water table depth.

Maize had an optimum water table of about 60 cm in the lysimeters and 120 cm in the field. As lysimeters had a fast reacting water table controlling system and no surface or

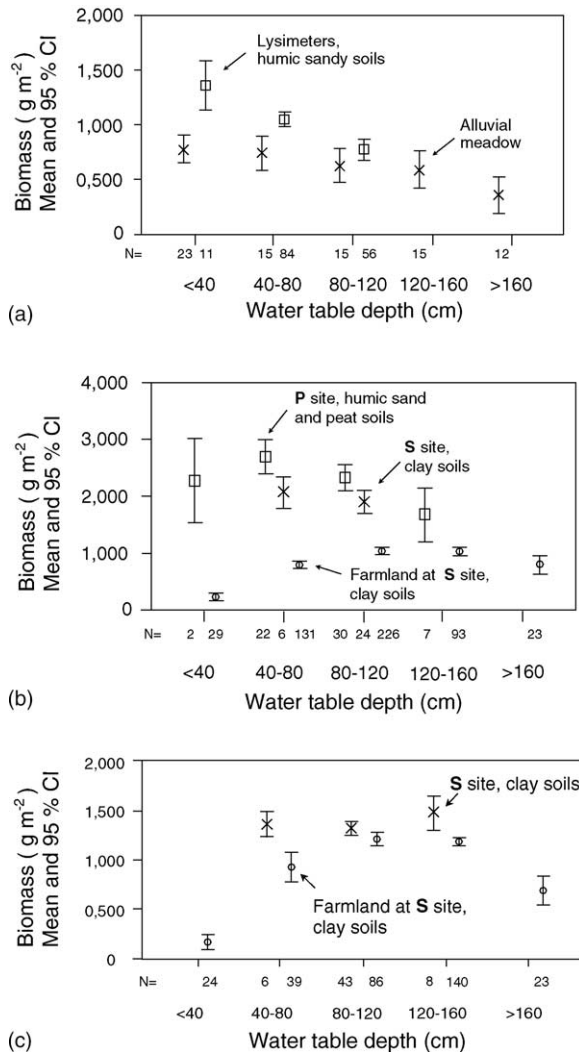


Fig. 2. Above ground biomass related to the depth of water table in lysimeters and in the field scale. (a) Grasses, alluvial meadow of the Oder River, (b) maize (*Zea maize*) and (c) Winter wheat (*Triticum* sp.).

lateral recharges, distinct waterlogging did not occur with late sown and medium deep rooting crops like maize. A high biomass production took place at relatively shallow water tables. In the field scale, the rates of the removal of excessive water and of the water supply of the roots were important as they can be very different from field section to field section.

The optimum of winter wheat in the field was between 120 and 140 cm, and it showed a slight tendency to prefer deeper water tables in the lysimeter. In contrast to maize, the biomass level was lower and did not differ much between lysimeters and fields. Winter

wheat is an autumn sown deep rooting crop and suffered from stagnant water during the winter period both in the field and in the lysimeters if the water table was shallower than 100 cm.

### 3.2. Evapotranspiration and crop coefficients in the vegetation period

In the temperate but relatively dry region of North-East Germany, the evapotranspiration exceeded the available rainfall in the vegetation period considerably. Consequently, either a high soil water storage capacity or a groundwater storage or additional recharge was required for cropping.

Table 4 shows averaged balanced values of  $ET_r$  according to Eq. (1) for different groups of crops or plants and water tables. The water consumption of most arable crops and grasses amounted to 300–600 mm during the vegetation period with increasing values at shallower water tables. The ratio of  $ET_r$  and  $ET_0$  (crop coefficient) was lower than 1 of most arable and grassland crops considering the total vegetation period. This indicates that the water supply was mainly not optimal either in general like on sandy soils or not in all stages of the vegetation period. However, during periods of most intensive growth, the coefficients in many cases considerably exceeded the value of 1 ( $ET_0$  PM). The crop coefficient in the month with the highest water demand ( $C_{\text{mid stage}}$ ) can be estimated by the regression:

$$C_{\text{mid stage}} = 0.18 + 1.22C_{\text{April–September}} \quad (n = 36, B = 0.91, S.E. = 0.15)$$

Reed canary grass, sedges and common reed had very high evapotranspiration rates and crop coefficients higher than 1.

A main reason for the large standard deviation of the  $ET_r$  between and within the groups of Table 4 was the very different level of biomass. Fig. 3 indicates higher crop coefficients with higher biomass of all crops and groups of crops, respectively. Arable fodder crops and maize revealed strongest increase of crop coefficients with biomass level.

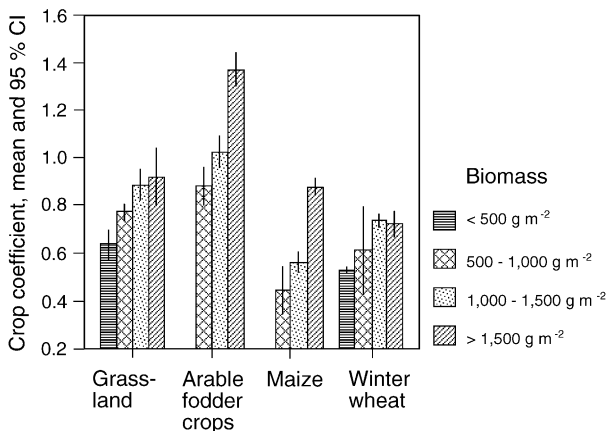


Fig. 3. Crop coefficients of grasses, arable fodder crops, maize and winter wheat in dependence on the biomass level.

Table 4  
Evapotranspiration ( $ET_r$ ) and crop coefficients ( $C_c$ ) of different arable and grass plants in the vegetation period of April–September

Crop	Water table range and mean (cm)	Soil <sup>a</sup>	Number of years/lysimeters	$ET_r^b$ April–September (mm)	$C_c^c$ April–September
Winter wheat	70–85 (79)	C	3/6	442 (31)	0.77
	85–130 (99)	C	4/27	416 (38)	0.72
	70–130 (120)	S	2/3	324 (17)	0.56
Spring barley	80–100 (90)	C	2/8	295 (25)	0.51
	80–100 (90)	S	2/4	229 (35)	0.39
Maize	50–80 (66)	C	4/9	457 (86)	0.83
	80–100 (86)	C	4/14	441 (65)	0.80
	40–60 (47)	P	4/13	536 (90)	0.94
	60–80 (70)	P	4/7	547 (99)	0.97
	80–110 (92)	P	4/12	469 (70)	0.86
	90–150 (140)	PSC	3/4	321 (16)	0.56
	80–100 (92)	S	3/11	310 (53)	0.53
80–100 (89)	S/L	3/8	457 (94)	0.81	
Alfalfa	50–80 (65)	C/L	3/7	521 (23)	0.99
	80–130 (108)	C/L	3/6	478 (118)	0.90
Red clover	40–70 (56)	C/L	3/9	589 (127)	1.13
	70–110 (99)	C/L	3/7	452 (56)	0.86
Italian ryegrass	50–70 (54)	C	3/6	497 (65)	0.99
	70–100 (78)	C	3/10	436 (29)	0.87
Sunflower	60–80 (67)	C	1/4	454 (13)	0.81
	60–80 (76)	S	1/2	446 (6)	0.73
Perennial ryegrass	55–80 (65)	C	3/12	364 (59)	0.66
	70–90 (81)	P	5/15	505 (54)	0.89
	90–120 (100)	P	2/3	347 (76)	0.65
	60–90 (74)	S	3/6	336 (53)	0.61
Grass mixtures	85–95 (90)	L/C	6/24	411 (55)	0.73
	85–95 (92)	S	3/6	373 (42)	0.65
	40–50 (42)	P	6/16	491 (46)	0.83
	50–75 (69)	P	6/17	482 (34)	0.86
	75–110 (98)	P	4/11	446 (42)	0.78
Timothy	50–80 (60)	P	2/4	460 (68)	0.86
	80–110 (100)	P	2/4	410 (55)	0.78
Reed canary grass	20–40 (30)	P	1/1	934 (–)	1.46
	30–60 (50)	HS	3/6	761 (143)	1.40
	90	HS	3/5	672 (96)	1.24
Sedge species	–10–20 (9)	P, HS	5/18	938 (109)	1.65
Common reed	–10–20 (2)	P, HS	5/18	1044 (311)	1.83

<sup>a</sup> Soil texture: C, clay (Mollic Gleysol); S, sand (Dystric Gleysol); L, loam (Eutric Gleysol); P, peat (Eutric Histosol); HS, humic sand (Mollic Gleysol); PSC, peat with sand cover (Eutric Gleysol).

<sup>b</sup> Standard deviation in parenthesis.

<sup>c</sup> Crop coefficient  $C_c$ :  $ET_r/ET_0$  ( $ET_0$ : FAO Penman–Monteith grass reference ET, Allen et al., 1994b).

3.3. Consumption of groundwater

Considering different crops/plants and depths of water table, the sources of consumed water were different (Fig. 4). Rainfall, which was stored in the soil profile, was the main source of  $ET_r$  during the vegetation period of arable crops.

The locally available water for  $ET_r$  (effective rainfall,  $P-D$ ) was about 85% of the total rainfall in the vegetation period. Discharge occurred mainly after rainstorms

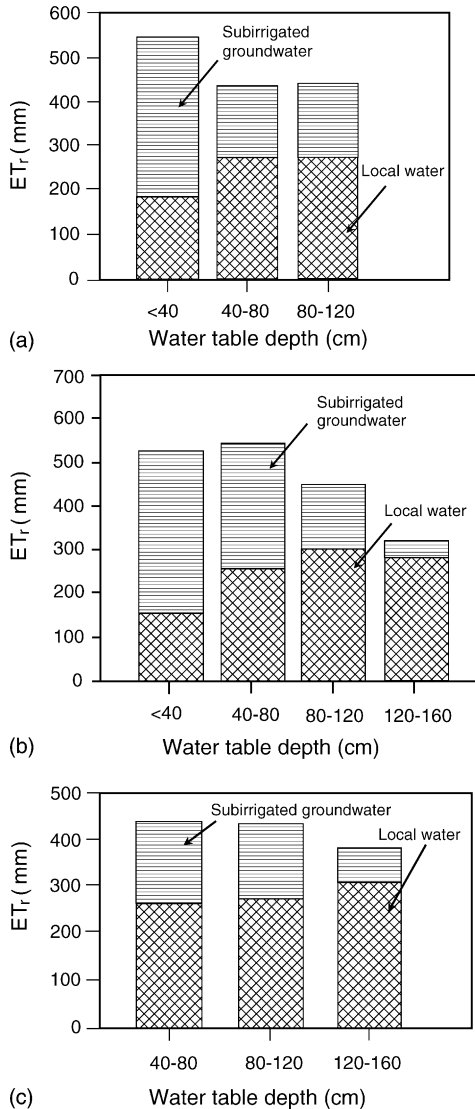


Fig. 4. Proportion of local and subirrigated water at  $ET$  in dependence on the water table (a) grasses, (b) maize and (c) winter wheat.

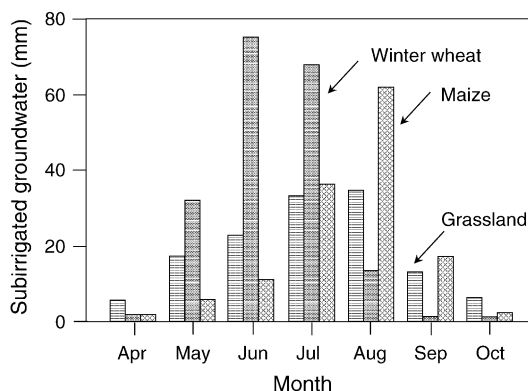


Fig. 5. Monthly groundwater recharges of grasses, maize and winter wheat.

in May and depended on soil texture and the tolerance level indicated in Fig. 1. In Fig. 4, it is recognizable that the effective rainfall was lower at very shallow water tables, as due to the limited soil water storage capacity, more water and nutrients were drained off.

An additional water source was groundwater recharge. At shallow water tables or with deep rooting crops and unlimited groundwater supply, the proportion of groundwater at the total ET became very important to dominant. This was typical for wetland plants and for maize at shallow or medium water tables (Fig. 4).

The consumption of groundwater varied between crops both in the total amount and in the period. Spring barley consumed 10–60 mm of groundwater, winter wheat 20–250 mm, pasture and meadow grasses 80–300 mm, maize 100–400 mm, reed canary grass 400–900 mm, sedges 600–1000 mm and common reed 700–1200 mm.

Fig. 5 indicates the monthly amount of subirrigation of some crops. In some cases, as for grasses and plants growing at shallow water tables, for soils of high conductivity and for shallow rooting crops, the temporal variation of subirrigation water requirements coincided approximately with  $ET_r$ . As shown in Fig. 5, the deep rooting winter wheat had a significant delay in groundwater recharge, since in May it is first using the available soil water of the root zone. Later, though the wheat was in the stage of yellow ripe in the mid of July, some recharge occurred to compensate the exhausted soil water storage. This “post-harvest groundwater consumption” amounted to 20–80 mm for winter wheat on clay soils.

Maize and sunflowers had their main growth in the warmer month of July and August and thus a later subirrigation water demand.

### 3.4. Water use efficiency

WUE was a reliable indicator of crop matter production related to water consumption. In general, highest WUE occurred with highest biomass, but was very plant-specific. Thus, the water table and the corresponding cropping regime were most important. Fig. 6 shows

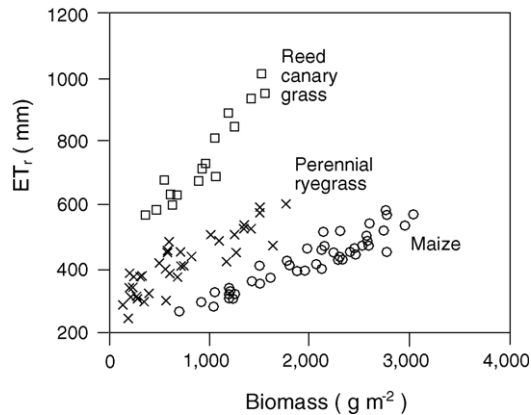


Fig. 6. Relationship between crop biomass and  $ET_r$  of maize, perennial ryegrass and reed canary grass.

the relationship between three different types of grasses all grown at relatively shallow water tables. Maize, perennial ryegrass and reed canary grass indicated different slopes of the hypothetical curve. Maize showed only slightly increased  $ET_r$  with higher biomass, whilst reed canary grass required much more water per unit of biomass. All plants have in common that they displayed highest WUE at highest biomass, mainly with a linear correlation. Maize was the most productive crop, producing the highest biomass and having the highest WUE.

Since there was no great difference in the water consumption between maize and wheat (Table 4), the significant higher WUE of maize was the result of higher biomass. Soil texture and structure had also significant effects on WUE. On clay soils, the crop biomass and WUE were slightly lower than on peat or humic sand soils.

Winter wheat, as a potentially very deep rooting crop, suffered from wetness in the lysimeters in some years during winter and had thus limited biomass and significantly lower WUE than maize. Spring barley had insufficient biomass production due to the short vegetation period and the continentally influenced climate.

Arable fodder crops (alfalfa, red clover and Italian ryegrass) had a WUE in the range of 1.8–2.7 (April–September). In all cases, there was a tendency of higher WUE at deeper water tables. All arable crops showed a tendency to suffer from wetness at water tables shallower than 80 cm. Italian ryegrass had a higher biomass and WUE than alfalfa and clover, but higher fertilizer rates were required (Table 2).

Plants of grassland peat sites had a WUE in the range of 1.6–2.8. Species of meadow and pasture grasses and grass mixtures showed a tendency to higher WUE at medium water tables of 55–75 cm. The very low WUE of wetland plants (<1.5) was due to extremely high water consumption, whilst the biomass was very high too.

In case of including longer periods, with a certain  $ET_r$  but low to none biomass production in the period of consideration, the WUE decreased. Referring to the total year the WUE values are about 15–20% lower as compared to the vegetation period of April–September (Table 5).

Table 5  
Crop biomass and WUE of different crops, soils and time spans

Crop	Water table range (cm)	Soil <sup>a</sup>	Biomass (g m <sup>-2</sup> )	WUE (g l <sup>-1</sup> )		
				April–September	April–October	Total year
Winter wheat	70–85	C	1362	3.1	2.8	2.5
	85–130	C	1420	3.4	3.1	2.8
	70–130	S	552	1.7	1.5	1.3
Spring barley	80–100	C	641	2.2	1.9	1.7
	80–100	S	414	1.8	1.5	1.3
Maize	50–80	C	1712	3.7	3.4	3.1
	80–100	C	1973	4.5	4.1	3.7
	40–60	P	2904	5.4	5.0	4.7
	60–80	P	3120	5.6	5.2	4.9
	80–110	P	2419	5.1	4.7	4.4
	90–150	PSC	1365	4.2	3.7	3.4
	80–100	S	1165	3.7	3.3	2.9
Alfalfa	80–100	S/L	2540	5.2	4.8	4.5
	50–80	C/L	962	1.8	1.7	1.6
Red clover	80–130	C/L	1034	2.2	2.0	1.8
	40–70	C/L	1084	1.9	1.7	1.6
Italian ryegrass	70–110	C/L	997	2.2	2.0	1.9
	50–70	C	1172	2.4	2.2	2.0
Sunflower	70–100	C	1004	2.7	2.1	1.9
	60–80	C	474	1.0	0.9	0.8
Perennial ryegrass	60–80	S	443	1.0	0.9	0.8
	55–80	C	502	1.4	1.2	1.0
Grass mixtures	70–90	P	1217	2.4	2.2	2.0
	90–120	P	581	1.6	1.5	1.3
	60–90	S	264	0.8	0.7	0.6
	85–95	L/C	670	1.6	1.4	1.3
Timothy	85–95	S	590	1.6	1.4	1.3
	40–50	P	976	2.0	1.9	1.7
	50–75	P	1149	2.4	2.2	2.0
	75–110	P	1230	2.8	2.6	2.4
	50–80	P	1228	2.7	2.5	2.3
Reed canary grass	80–110	P	1108	2.6	2.4	2.2
	20–40	P	1410	1.5	1.4	1.4
	30–60	HS	1048	1.4	1.3	1.2
Sedge species	90	HS	758	1.1	1.0	1.0
	–10–20	P, HS	1392	1.5	1.4	1.4
Common reed	–10–20	P, HS	1434	1.4	1.3	1.3

<sup>a</sup> Soil texture: C, clay; S, silt; L, loam, P, peat, HS, humic sand; PSC: peat with sand cover.

## 4. Discussion

### 4.1. Biomass as influenced by site factors

Results show that the water table is the best measure for controlling both biomass production and water use efficiency at comparable climatic and soil conditions. Compared with soils of deep water tables in the same region (Schindler et al., 2001; Guenther, 2003), the crop biomass in the lowland soils under study is lower and had a higher variability. This was mainly due to temporary wetness after rainstorms, which are unavoidable and mean an increase of water table and hampering the root activity due to the lack of oxygen in the root zone. At clay soils and water tables shallower than 90 cm, the lack of air limited the plant development and crop yield significantly in this geographical region (Tille and Mueller, 1992) but in other regions too (Kalita and Kanwar, 1992). Loam and clay soils were most sensitive because of their low drainable porosity after durable wetting. At shallow water tables, the storage capacity of those soils was very low and rain may lead to a high increase of the water table (Gerla, 1992). Thus, optimum conditions for crop development are not as reliable to manage as on sites with deeper water table and the biomass level remained lower and the variability higher than on deeper drained sites.

In the lysimeter experiments, water tables were kept at a constant level, whereas in the field, water tables fluctuate more or less. However, lysimeter experiments of Scholz and Hoelzel (1978) with constant and fluctuating water tables showed no significant differences of crop biomass and ET of grassland.

Adapting crops and plants to the different site conditions would be an appropriate strategy to benefit from the natural resources. However, the spatial variability of soil texture and water regime is so big in many cases that compromises between adapting and controlling strategies are necessary.

The results for sandy soils are valid for typical medium to fine textured sands. Suitable water tables for arable crops on sandy soils varied strongly in dependence on texture of sands, ranging from 40 cm with coarse sands to 100 cm with fine sands (Thihatmer, 1976).

It has been confirmed that fertilization reduces the negative effects of waterlogging and enhances the plant dry matter production (Huang et al., 1995; Ogola et al., 2002). The relatively low influence of N-fertilizer on biomass level and water consumption in our study can be explained by high N-potentials in the soil and groundwater (Mueller et al., 2001).

### 4.2. Evapotranspiration, crop coefficients and subirrigation rates

Evaluating the evapotranspiration data of lysimeters, two main sources of error may be important: (a) the changed soil structure, soil hydrological properties and root development in lysimeters and (b) the possible increased evapotranspiration by advective exchange of energy (oasis and clothesline effects). Becker (1994) analyzed the effect of soil structure disturbances on the water balance and showed that the latter was very small with shallow water tables whilst the oasis effect may have a considerable impact on the magnitude of ET. Overestimations of ET due to oasis and clothesline effects are typical for most lysimeter experiments and for shallow water tables, in particular.

Behrendt et al., 2000, estimated the oasis effect of the groundwater lysimeters at Paulinenaue site by applying the “bring-back method” by about 15% at high water tables. This value seems to be realistic for both sites under study.

For most crops, the evapotranspiration in terms of crop coefficients agrees with general recommendation values (Allen et al., 1998); our findings for the ET of wetland plants exceed these recommendations.

However, the environment and the biomass level should also be taken into consideration. Assuming a crop coefficient of 1.2 of a reed stand (Allen et al., 1998) would mean an ET of 700 mm over the vegetation period. At an average biomass of  $1.53 \text{ kg m}^{-2}$ , there would be a WUE of 2.2 which seems to be unlikely high for a wetland plant.

In North-East Germany, wetland vegetation forms relatively small belts around small lakes and kettles in many cases, e.g. oasis and clothesline effects are also probable to occur in the landscape. At least for those areas, the measured ET data of wetland vegetation seem to be realistic. Allen et al. (1994a) found larger ET with decreasing wetland size too.

Further on, it is likely that the common use of not upgraded precipitation data from rain gauges of 1 m height has lead to an underestimation of the ET of 10% or more by many authors.

Our results revealed a significant correlation between ET and biomass level. Crop coefficients should be considered as biomass-dependent.

#### 4.3. *Magnitude and variability of water use efficiency*

WUE may vary both spatially and temporarily, and is influenced by crops, soil conditions, agricultural practices including fertilization and atmospheric factors (Hatfield et al., 2001; Cox et al., 2002). The stochastic course of weather from April to June had a crucial effect on crop development and water use efficiency and may explain the large variability of data.

Maize had significantly higher WUE than wheat and all further crops. This was due to high biomass but no excessive ET. Possible causes for this are the C4-metabolism and the effective stemflow water use. But the main reason was that maize did not, in contrast to wheat, suffer from wetness in well-drained lysimeters. On field plots of clay soils, maize also suffered from wetness and the differences in the WUE between maize and wheat were small.

In agreement with Kang et al., 2001, the proportion of groundwater evapotranspiration in this relatively dry region was mainly influenced by water table depths. Considering interception, which is completely included in the proportion of “local water” evapotranspiration, the proportion of groundwater ET became even more dominant. With deeper water tables, the soil storage capacity of water and nutrients became very important. In coincidence with Kang et al. (2002), we found that WUE was higher under limited irrigation conditions, e.g. at deeper water tables under deep rooting crops as wheat and alfalfa or at medium to deep water tables under maize.

Crops on deep clay and peat soils showed highest water and nitrogen use efficiency and required relatively low amounts of subirrigation water. Sandy soils required relatively high subirrigation rates but showed an ineffective use of water and nitrogen and, thus, a low biomass level (Mueller et al., 2001).

Our findings confirmed results of [Mundel \(1994\)](#), who found linear correlations between crop biomass and evapotranspiration of different grasses, WUE rates between 1 and 3 and highest WUE with highest biomass.

Crop coefficients lower than 1 in most cases indicate that the common assumption of “unlimited water supply” of crops grown at shallow water tables was only valid at very high crop biomass or at water tables less than 40 cm and wetland vegetation.

## 5. Conclusions

- Lowland soils are fertile and can provide high crop biomass by using water table control. Potential consumption of groundwater (subirrigation rate) depended mainly on water tables, crops grown and crop biomass achieved.
- In lysimeter experiments, arable crops as winter wheat grown on clay soils required 20–250 mm, maize required 100–400 mm and further arable fodder crops had requirements of about 60–200 mm of subirrigated water within the period from April to September. Pasture and meadow grasses grown on peat and humic sand soils consumed 80–300 mm of groundwater and wetland plants had highest recharges of 400–1200 mm.
- Crop coefficients were significantly dependent on the biomass level and should thus considered biomass-dependent.
- Maize was the plant of highest biomass and highest water use efficiency in this study ( $WUE > 4$ ) and thus a favourable bioenergy plant. On mineral lowland soils winter wheat provided acceptable biomass and water use efficiency at deeper water tables of 100–140 cm ( $WUE > 3$ ). Arable fodder crops had WUE in the range of 1.5–2.8. Grassland on peat sites was characterized by WUE of 1.8–2.7, and wetland plants had very low WUE of less than 1.5.
- Main arable crops as winter wheat and maize had optimum water tables in the range of 80–160 cm (maize 80–120 cm, wheat 120–140 cm) on soils of higher water storage capacity in the field. Meadow grassland required water tables less than 80 cm. Creating and maintaining rewetted areas (water table less than 20 cm) would require high amounts of recharge water. Biomass from wetlands would be produced by very low efficiency of water use.

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