

**ECOSYSTEM RESPIRATION OF RESTORED AND
DEGRADED FENS SITES IN THE DONAURIED,
SOUTHERN GERMANY**

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ABSTRACT

Ecosystem respiration of restored and degraded fens in the Donauried, southern Germany

by Rachel Schultz

Currently, 83% of Germany's total fen area (12,434 ha) is being managed as either drained grassland (51%) or cropland (32%), with only 3% in natural or restored status and the remaining fen area in forest (FREIBAUER et al. in prep. cited in BYRNE et al. 2004). Drained peat soils used for agricultural purposes are reported to respire 2 to 3 times the amount of carbon dioxide as mineral or sandy soils (LOHILA et al. 2003), whereas the carbon exchange for restored fen sites is relatively unknown (BYRNE et al. 2004). The main purpose of this study in the Donauried of southern Germany was to measure ecosystem respiration fluxes of CO₂ (dynamic chamber system) from three vegetation communities in a 28-year-old restored fen and two drained and cultivated sites, a grassland and a crop-rotation field in carrots. Seasonal changes in plant phenology, soil moisture, decomposition rates, and/or soil microbe growth dynamics influence ecosystem respiration rates, and the seasonal separation of R_{eco} results in a more accurate model (REICHSTEIN et al. 2005a). Accordingly, in modeling the respiration fluxes over the year using the LLOYD & TAYLOR (1994) exponential regression model, the parameters, reference respiration (R_{ref}) at 10°C air or soil temperature and the activation energy E₀, were individually fit for each measuring period at approximately 3 week intervals over the year, which did in fact provide a more accurate model in comparison to a singularly parameterized model. Green leaf area index (LAI) was positively correlated with weekly respiration fluxes in all of the sites except the carrot field site, which was only vegetated between July and October. The two sedge lawn communities in the restored wetland had a negative correlation between R_{ref} values and water table depth during the growing season whereas the large tussock sedge community and the two drained sites showed no significant relationship. The yearly flux of CO₂-C for the grassland site was significantly higher than the other sites at 1823.55-2339.78 g CO₂-C m⁻² y⁻¹ (including the model's standard error) compared with the *Carex disticha* fen site at 1084.87-1361.26, *Carex paniculata* fen site at 1244.22-1676.93, *Carex acuta* fen site at 1025.74-1270.39 and the carrot field at 958.82-1282.73g CO₂-C m⁻² y⁻¹.

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1 INTRODUCTION

1.1 Carbon dioxide respiration of degraded and restored fens

The two largest fluxes in determining the net ecosystem exchange (NEE) of carbon are gross primary productivity (GPP) and ecosystem respiration (R_{eco}) (TRUMBORE 2006). Often the definitive factor between an ecosystem being a source or a sink of carbon is the respiration flux (VALENTINI et al. 2000). Nations that have signed the Kyoto Protocol are obligated to record and reduce known sources of greenhouse gas (GHG) emissions to an agreed upon amount. This accounting process also includes the voluntary reporting of emissions from natural and managed lands, and once the process of reporting emissions based on land cover and land use is begun, it must be continued. Reporting on land cover and land use as carbon sinks in the national inventory under Article 3.4 of the Kyoto Protocol requires a preceding decision by the UNFCCC. In particular, the draining of peatlands for management including crop rotation and grassland use has been found to create strong carbon sources in European countries (Table 1-1).

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Table 1-1 Emission factors based on measured fluxes from different European fen management types modified from BYRNE et al. (2004).

Managed - types of peatlands	Emission factor			GWP 100 (CO ₂ -C Equivalents kg ha ⁻¹ yr ⁻¹)
	CO ₂ (t C ha ⁻¹ yr ⁻¹)	CH ₄ (kg C ha ⁻¹ yr ⁻¹)	N ₂ O (kg N ha ⁻¹ yr ⁻¹)	
Grassland	4.12 ^{19,24,27} (0.82 – 6.58, n=5)	0.4 ^{3,8,19,24,28,34} (-1.04 – 105, n=13)	5.05 ^{2,3,4,5,12,14,21,22,24,28,36,37} (0.30 – 38.8, n=60)	4794
Arable	4.09 ^{13,21,28} (1.09 – 10.6, n=3)	-0.2 ⁸ (-0.20, n=2)	11.61 ^{5,12,14,21,30,38} (4.0 – 56.4, n=15)	5634
Restoration	-	12.4 ³ (6.5 – 18.3, n=2)	0.64 ¹⁶ (n=1)	179 (without CO ₂ -C)

(ALM et al. 1999; AUGUSTIN 2001; AUGUSTIN et al. 1998a; AUGUSTIN et al. 1996; AUGUSTIN et al. 1998b; DÖRSCH et al. in prep.; FLESSA et al. 1998; JAAKKOLA 1985; JOOSTEN & CLARKE 2002; KASMIR KLEMEDTSSON et al. 1997; KLEMEDTSSON et al. 1997; LAINE et al. 1996; LANGENVELD et al. 1997; LUSTRA 2002; MALJANEN et al. 2001; MARTIKAINEN et al. 1993; MEYER 1999; MUNDEL 1976; NYKÄNEN et al. 1995; REGINA et al. 1996; VAN DEN POL-VAN DASSELAAR et al. 1999; VELTHOF & OENEMA 1995; WESLIEN et al. in prep.)

Restoration of fens in European countries has been increasing over the last few decades, as an indication, the German nation states with large peatland areas have published peatland conservation strategies in recent years, including fen restoration (LANDESUMWELTAMT BRANDENBURG 2004; WAGNER & WAGNER 2003). Nevertheless, this type of peatland management has received little attention as to the quantification of the effects of management on GHG emissions (Table 1-1). If this practice is to be promoted as a means of reducing GHG emissions on a large-scale basis, it is necessary to provide precise flux measurements to quantify carbon budgets. In this study, an analysis of the CO₂ respiration fluxes from restored and degraded (drained arable, drained grassland) fens is provided as a means of filling in the research gaps on this topic.

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1.2 The carbon cycle in peatlands

Peatlands by definition are ecosystems that act as a carbon sink through the accumulation of peat (carbon-rich material) over time (MITSCH & GOSSELINK 2000). This is possible due to typically low litter decomposition rates associated with the anoxic conditions accompanying high water tables. Plants and mosses utilize carbon dioxide from the atmosphere through photosynthesis, allocating part of this carbon into leaf and root material. About 50 to 70% of the assimilated carbon (GPP) is respired back into the atmosphere through growth and maintenance processes by living leaves, stems and roots, defined as autotrophic respiration (AMTHOR & BALDOCCHI 2001). Ecosystem respiration also includes heterotrophic respiration, the carbon respired through the decomposition of litter and soil organic material (SOM) by soil microbes (TRUMBORE 2006). Another categorical separation of respiratory processes is into plant (leaf and stem respiration) and soil (soil microbes and root) respiration (Figure 1-1). The following sections elaborate on the individual processes of plant and microbial respiration, as well as the factors that regulate these processes.

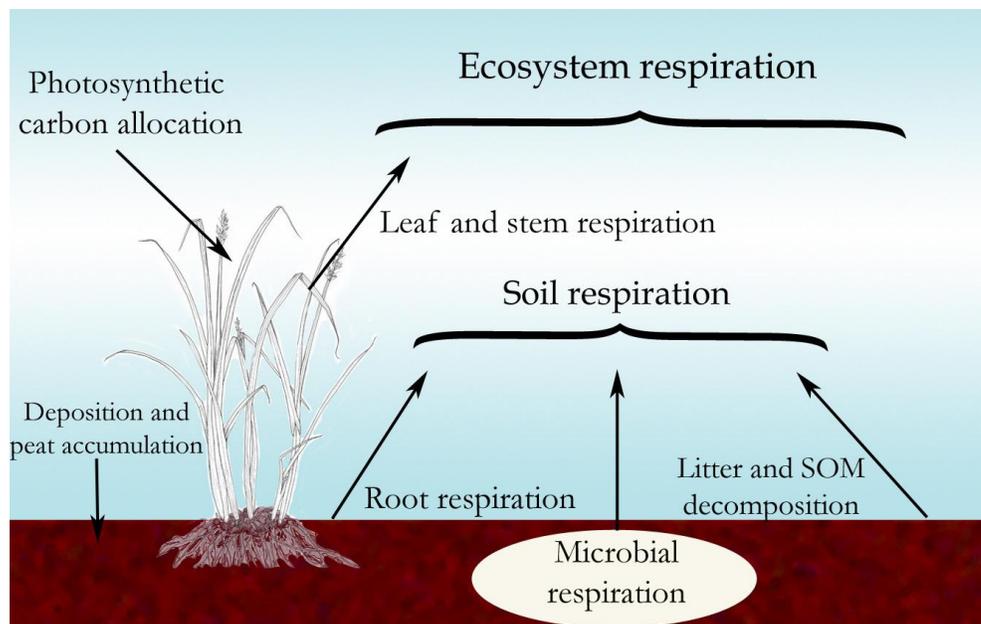


Figure 1-1. Carbon allocation is solely a product of plant photosynthesis and the accumulation of peat depends on a higher deposition of plant material than its decomposition. Respiration in fen ecosystems is the sum of plant physiological processes (autotrophic respiration) and microbial metabolic processes (heterotrophic respiration), modified from TRUMBORE (2006) with sedge sketch from UNIVERSITY OF FLORIDA (1996).

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1.2.1 PLANT PHYSIOLOGICAL ACTIVITY: AUTOTROPHIC RESPIRATION

Plant respiration creates products that are needed for basic plant function including a range of C-skeleton intermediates generated along respiration pathways, ATP, and the reductants NADH and NADPH. In a period of fast growth, respiratory products are used up more quickly, which stimulates higher respiration rates whereas older tissues have a relatively lower respiration rate. (AMTHOR & BALDOCCHI 2001).

A simplified breakdown of autotrophic respiration is represented by two components: growth and maintenance in the following model (THORNLEY 1970):

$$R_a = gB + mS,$$

in which g is the coefficient of growth respiration, including the costs of biosynthesis (B) and m is the maintenance respiration coefficient including the costs of maintenance including substrate relocation (S).

Due to the fact that leaf respiration has been primarily studied under dark conditions to remove the effect of photosynthesis on CO_2 concentration change, it has been impossible to determine the effects of light on leaf respiration (AMTHOR & BALDOCCHI 2001). However, a recent study utilizing measurement techniques to separate the efflux of various stable CO_2 isotopes ($^{12}CO_2$ and $^{13}CO_2$), determined that the inhibition of leaf respiration under light conditions was only apparent due to CO_2 uptake during photosynthesis and that respiration under light and dark conditions was the same under most conditions (PINELLI & LORETO 2003).

A primary driving factor of plant respiration is the short and long-term changes in ambient air temperature, with an increase in temperature leading to an increase in plant respiration (LAMBERS & RIBAS-CARBO 2005). The variation in this regression between biomes and plant species is typically represented by Q_{10} , the proportional change in respiration with an increase in $10^\circ C$, for example $15-25^\circ C$.

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1.2.2 SOIL MICROBE ACTIVITY: HETEROTROPHIC RESPIRATION (GOBAT ET AL. 2004)

The microorganisms of the soil that contribute to heterotrophic respiration are bacteria, fungi, algae and small animals. Microbial activity is estimated to constitute two-thirds of soil respiration, adding up to approximately $10 \text{ t ha}^{-1} \text{ y}^{-1}$. The microorganisms in the aerated zone of the soil assimilate about half of the carbon absorbed through the decomposition of litter and soil organic material (SOM) and the other 50% is oxidized (CO_2). Under constant anaerobic conditions, the microorganisms assimilate only 10% of the carbon and the rest goes into the production of methane and carbon dioxide. In fluctuating water level situations resulting in aerobic and anaerobic conditions, the catabolism (metabolic reactions that lead to energy production in the cell) of organic substrate involves fermentation followed by the production of metabolites including alcohols, hydrogen and CO_2 .

The presence of living plant roots in the soil provides a steady source of organic carbon to the soil microbes through the root exudates (~20-50% of photosynthetically assimilated matter) and dead root material. Roots can provide increased aeration in the soil due to water uptake, but as a result of root respiration, the oxygen in the rhizosphere is typically low. However, microaerophilic microorganisms are adapted to such conditions, as they find high concentrations of oxygen toxic. Due the relationship between plants and soil microorganisms, the respiration from the soil is up to five times greater in conditions with roots than without (BAATH & WALLANDER 2003; BOONE et al. 1998)

Soil moisture and heterotrophic respiration are positively correlated, i.e. when soil moisture is relatively low soil respiration is also reduced (ORCHARD & COOK 1983; REICHSTEIN et al. 2005b). In a comparison between bare soil and planted soil, it can be assumed that planted soil will have a higher level of soil moisture as plants provide insulation from the sun and excess heat and in doing so reduce evaporation from the soil. Furthermore, the rhizosphere creates an environment in which water is constantly being drawn in, but remains moist.

The classic single environmental factor correlation with soil respiration is soil temperature (LLOYD & TAYLOR 1994). A variety of factors that contribute to heterotrophic respiration

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are influenced by temperature including biological metabolism (BEGON et al. 1996). The proportional change in respiration with an increase in 10°C , Q_{10} , is also commonly used to compare soil respiration rates across ecosystems and soil types. Recently it has been shown that the presence of roots in soil does not significantly change the Q_{10} value of soil respiration (BAATH & WALLANDER 2003) and that the previously published study showing a significantly higher Q_{10} in soils with roots was due to plant interactions (BOONE et al. 1998).

1.3

Research systematic

Seasonal changes in plant phenology, soil moisture, decomposition rates, and/or soil microbe growth dynamics influence ecosystem respiration rates, and the seasonal separation of R_{eco} results in a more accurate model (REICHSTEIN et al. 2005a). Accordingly, this study arranged field campaigns to accurately capture seasonal variation including plant phenology, water table fluctuation and management events. To cope with this phenological development, the overall goal was to parameterize the R_{eco} model individually for each campaign with the temperature of best fit: air or soil temperature. In the event that the significance of the temperature regression was objectionable or the temperature range too narrow (e.g. in the winter) campaign data were combined. As a final check of the accuracy of the model, a modeled versus measured table was created and the linearity assessed.

2 MATERIALS AND METHODS

2.1 Study Site – Donauried (Baden-Württemberg, Germany)

The geographical unit “Donauried” refers to the lowlands of the Danube River valley between Ulm and Donauwörth in southwestern Germany (Figure 2-1). The investigated area of the Donauried represented in this paper lies within the German state of Baden – Württemberg.

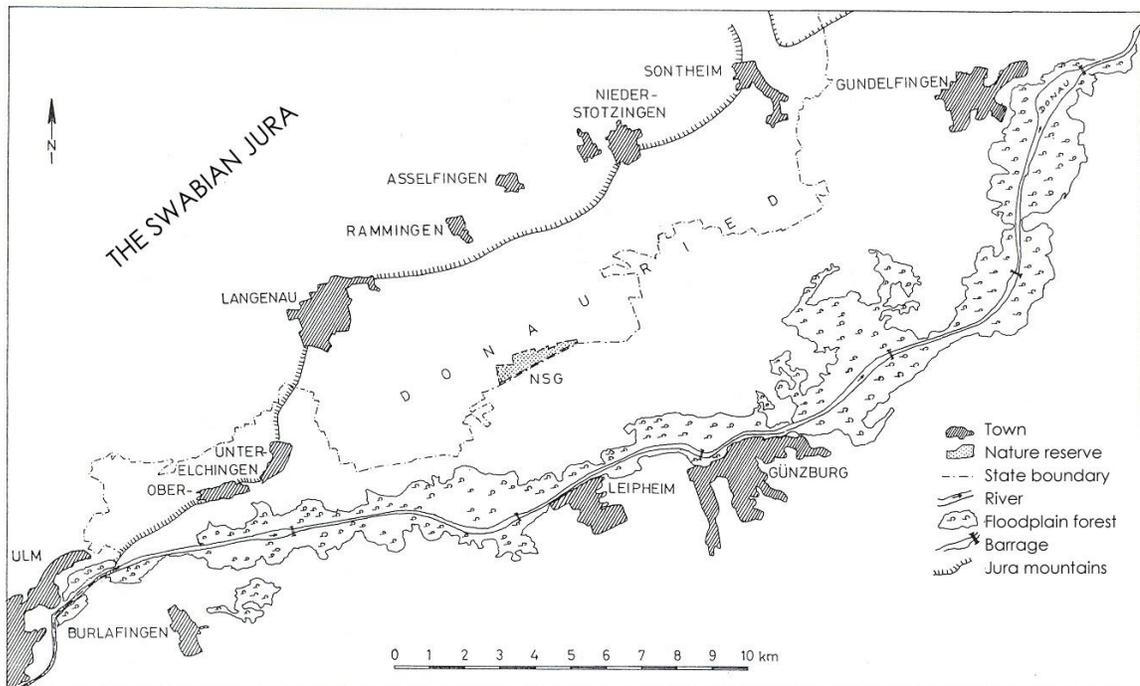


Figure 2-1. The extent of the natural fen unit Donauried situated between the Swabian Jura mountain range and the Danube River, modified from DOBLER et al. (1977).

The Donauried is currently under various levels of protection including areas of landscape protection, nature reserves, flora and fauna habitat protection, and aquifer protection. The researched area outside of the Langenauer Ried nature serve is included in the landscape protection area and the aquifer, and flora and fauna habitat protection area covers all of the sites (Figure 2-2) (LUBW 2006).

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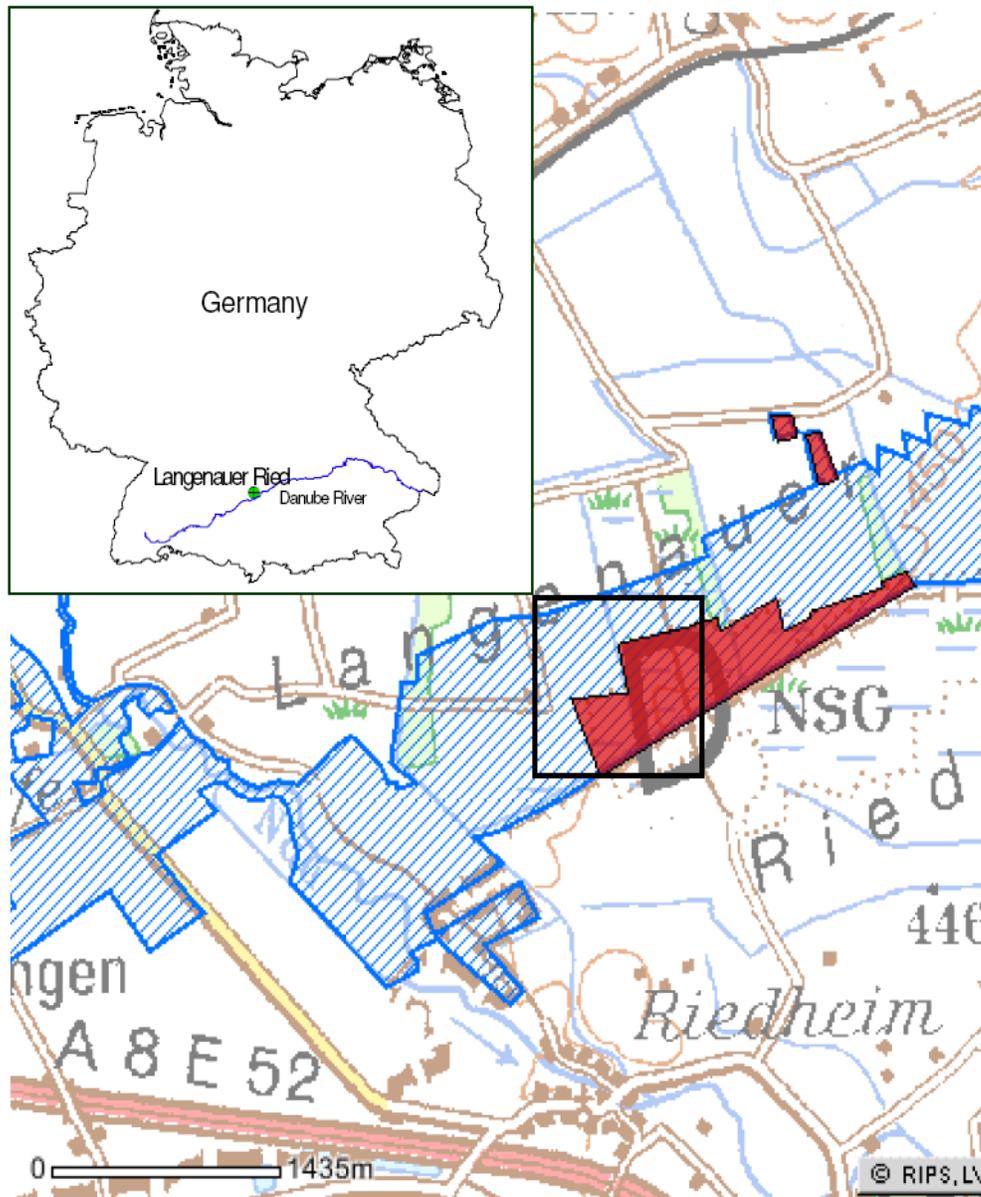


Figure 2-2. Donauried study site –The entire area shown is within the aquifer protection zone, red designates nature reserve areas and blue, flora and fauna habitat (FFH) area (LUBW 2006). The general area of the study site is marked with a black square. The inset shows the relative location of the study site in Germany on the Danube River.

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2.1.1 DONAURIED GEOLOGICAL DEVELOPMENT AND LAND USE HISTORY

2.1.1.1 The geological development of the Donauried

The conditions for peatland formation were created by the retreat of the Danube River following the last ice age. The inflow of karst water originating in the Schwabian Jura mountain range and the high groundwater backflow of the Danube resulted in the development of an extensive fen on top of the impermeable alluvial clay. By 5000 - 2000 B.C., the area was accumulating sedge and reed peat (DOBLER et al. 1977). The classification of the Langenauer Ried peatland is the transition between a paludification and percolation fen (SUCCOW 1988).

2.1.1.2 The land use history of the Donauried (DOBLER et al. 1977)

The earliest anthropogenic use of the fen (pre-1800) was as pasture for cattle. Due to the periodical flooding of the lowlands from the Danube, cultivation for agriculture was limited. In 1822-23, the fen was divided up into municipalities (Langenau, Rammingen and Asselfingen) followed by the construction of drainage trenches in order to increase the agricultural use of the extensive fen. This drainage network along municipality boundaries is still in evidence today (Figure 2-3). In a time span of around thirty years, the (at most) extensively used fen was successfully altered into intensively utilized agricultural land.

From 1873 to 1874 a more extensive drainage and road system was built in the Donauried area to enable peat harvesting for industrial use. The yearly harvest in 1897 from the three local municipalities was recorded as 7.8 million peat bricks. Commercial peat harvesting in the area was given up in 1925. Since the start of the 1900s, one major use of the Donauried has been as a drinking water supply and is presently an aquifer protection zone.

Following almost a century of intensive drainage, the sinking and mineralization of the peat layer leading to large cracks in the surface of the ground had reached catastrophic dimensions. In response, the Water and Soil Alliance Donauried was founded in 1951 to resolve the resulting environmental costs. From 1951-1971 rehabilitation measures were carried out including planting trees as wind protection and tilling the mineralized peat layer.

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In 1966 the first 10 hectares of the current 70-hectare Langenauer Ried nature reserve were designated as a protected area. A further 60 hectares were added to the nature reserve in 1977 along with a restoration plan to enhance and promote fen ecosystems. This restoration plan from DOBLER et al. (1977) (Figure 2-3) includes the installation of weirs designed to be closed or open according to the water supply needs to the fen in addition to irrigation trenches. In 1981 a pipeline from the Nau spring was installed to supply water to the nature reserve in the summer months (MÄCK 2003). The water source for the restored fen sites is consequently superficial, flooding across the surface of the fen instead of upwelling from the peat column.

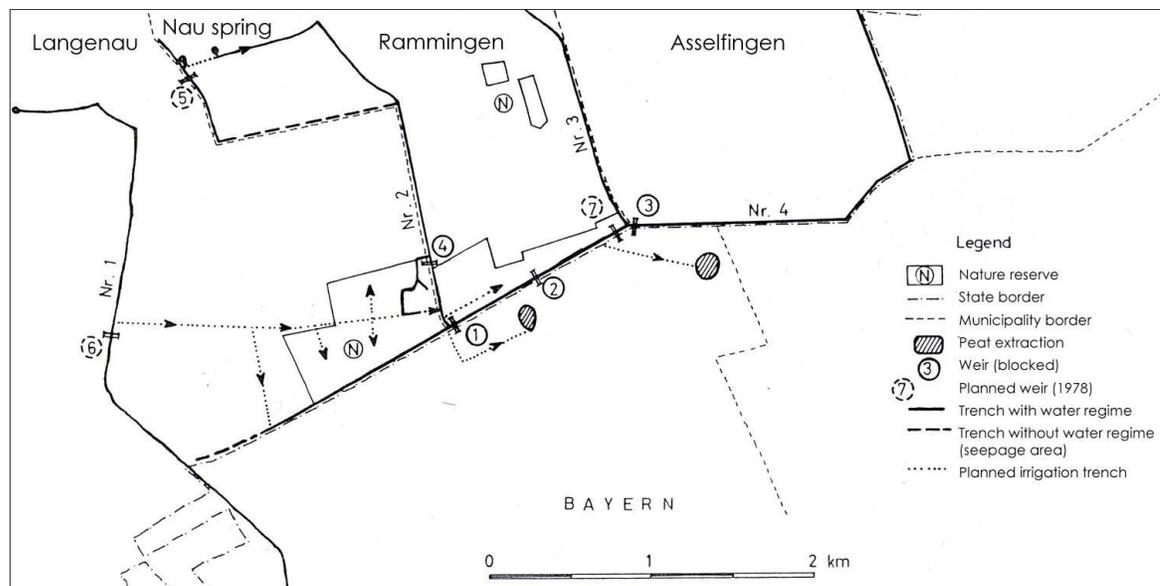


Figure 2-3. Restoration plan for Donauried and the Langenauer Ried nature reserve, modified from DOBLER et al. (1977).

Nature reserve maintenance started in 1977, including mowing in the area dominated by large tussock-forming sedges (e.g. *Carex paniculata* L.). Using sickle/scythe mowers and weed whips, this practice is being carried out every two years to the end of promoting protected species (e.g. *Dactylorhiza incarnata* (L.) Soó and various meadow breeding birds) as well as enriching plant diversity by reducing competition from the large sedges, therefore encouraging weaker competitors (JEBBERGER 2006). Current management coordination is provided by the Regierungspräsidium Tübingen, Referat 56 - Naturschutz und Landschaftspflege. In 2005, the result of 28 years of management is clear; smaller sedges (e.g. *Carex disticha* Huds. and *Carex*

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acuta L.) dominate the mowed section of the nature reserve with the endangered *Dactylorhiza incarnata* dispersed throughout.

2.1.2 STUDY SITE DESCRIPTION

Five research sites were chosen to represent the various land uses and vegetation types in the Donauried peatland area (Table 2-1). Within the restored fen in the Langenauer Ried nature reserve, three sites were selected to characterize the small-scale vegetation diversity and management: two sites mowed every other year (*Carex disticha* and *Carex acuta* as the respective dominant species) and one site without management dominated by the large, tussock-forming *Carex paniculata*. The two mowed sites had a complete moss layer, *Calliergon cordifolium* (Hedw.) Kindb., whereas the *Carex paniculata* site only had partial moss cover. A boardwalk was installed in the restored fen area to minimize disturbance during the field measurements. In the drained peatland outside of the nature reserve, one site was founded in the managed grassland and one site in the adjacent crop field, which rotates yearly between corn, wheat, legumes and carrots (Figure 2-4).

Table 2-1. Study site descriptions.

Site name	Orig. site #	Plots	Type	Description
<i>Carex disticha</i> fen	Site 1	1, 2, 3	Restored	Shorter sedge lawn with <i>Typha latifolia</i> L. Management: mowed once in early October every other year, vegetation removed from site late October.
<i>Carex paniculata</i> fen	Site 2	4, 5, 6	Restored	Large sedge tussocks, not mowed
<i>Carex acuta</i> fen	Site 3	7, 8, 9	Restored	Small lawn-forming sedges. Management: mowed once in early October every other year, vegetation removed from site late October.
Carrot field	Site 4	10, 11, 12	Drained/ cultivated	Management: herbicide in spring, mound formation and carrot planting in June, harvest mid-October for carrot crop. Yearly crop-rotation system with corn, wheat, legumes and carrots.
Grassland	Site 5	13, 14, 15	Drained/ cultivated	Management: mowed in June and August, cut vegetation removed.

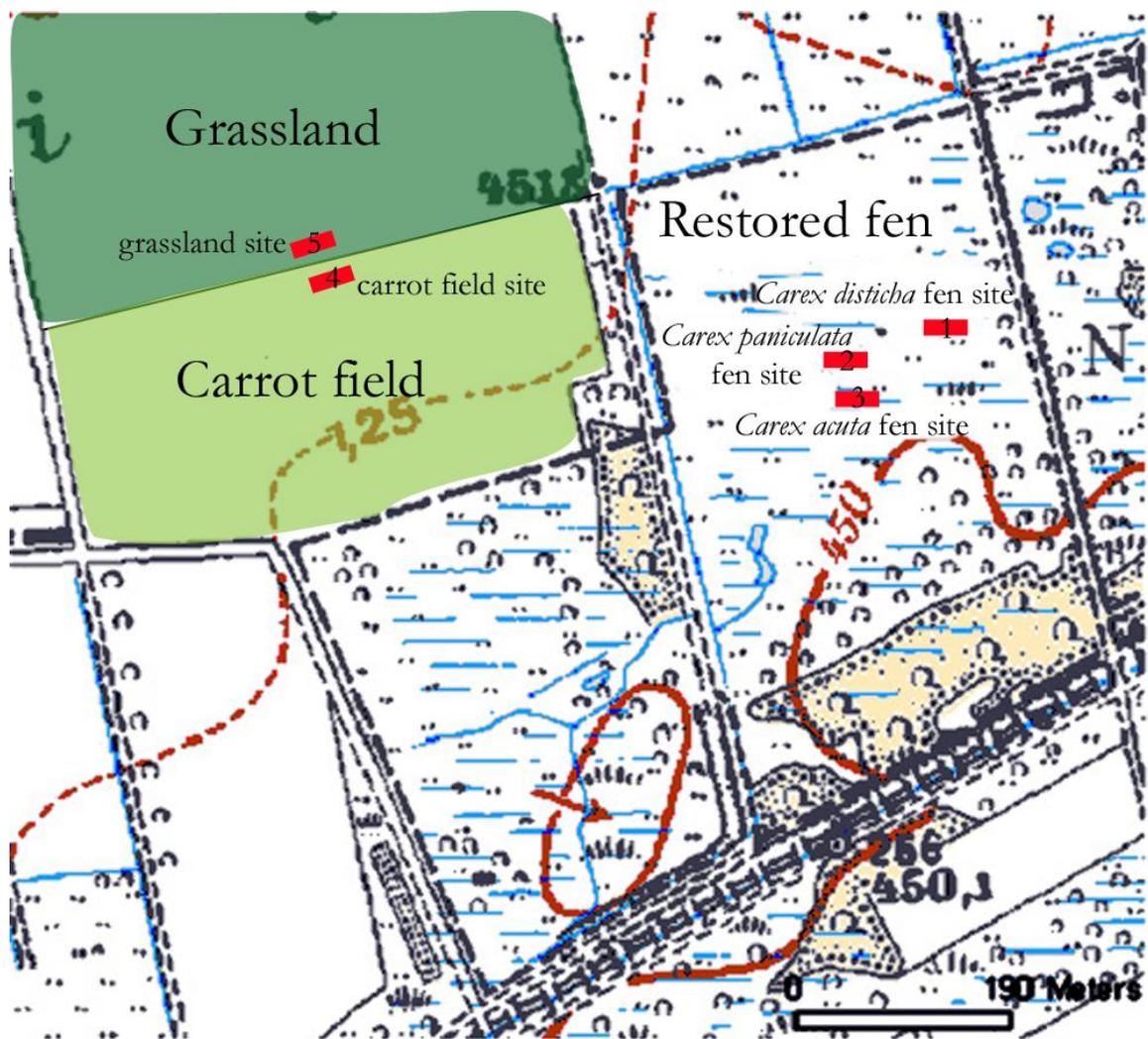


Figure 2-4. The five Donauried study sites. The grassland and carrot field are outside of the Langenauer Ried nature reserve (marked by the black dashed line), but are within the Donauried landscape protection area. The red rectangles represent the three plots assigned to the specific labeled site with the number referring to the original site number (LUBW 2006).

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a) *Carex disticha* fen site



d) Carrot field site



b) *Carex paniculata* fen site



e) Grassland site



c) *Carex acuta* fen site

Figure 2-5. Individual plot pictures from July, 2005: a) *Carex disticha* fen site, plot 2, b) *Carex paniculata* fen site, plot 5, c) *Carex acuta* fen site, plot 7, d) carrot field site, plot 11 and e) grassland site, plot 13.

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2.2 Vegetation sampling (LONDO 1976)

Vegetation was sampled once in 2005 at the height of the growing season. Due to the sites' characteristics, a one-time assessment was sufficient to accurately compare the sites with one another. Each of the 15 plots was assessed by placing a 100-cell grid on top, and the vegetation cover recorded in 1% steps and/or grouped on the 10% Londo scale (LONDO 1976). Using the grid is also a method of reducing error in plots with variable microtopography.

2.3 Net primary productivity: biomass and leaf area index (LAI)

2.3.1 BIOMASS

Aboveground biomass was collected approximately every three weeks for the grassland site, and biomass from the three restored fen sites was taken intermittently, about every two months, due to nature reserve restrictions. The carrot field was treated with herbicide before the carrots were planted; consequently the aboveground biomass for this time is estimated as zero. Aboveground biomass was cut from three samples (25cm x 25cm, 19cm x 19cm) per site, which were representative of the treatments and outside of the actual flux measurement plots. These samples were then sorted into four categories (green leaves, brown leaves, green moss and brown moss) then dried in an oven for 48 hours at 60°C and weighed. Belowground biomass production was only measured for the carrots, which were taken from the same sample area as the aboveground biomass, dried and weighed as above.

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2.3.2 LEAF AREA INDEX (LAI)

A leaf area meter (Li-3000; Licor) was used to measure the leaf area index (LAI) of green leaves, brown leaves, green moss and brown moss. The LAI was measured once in early September for the five sites in order to establish a biomass LAI regression to model the LAI curve for the rest of the year. For each site, three samples were taken as described for biomass collection and then further divided into five subsamples. Each subsample was measured separately by the leaf area meter, dried and subsequently weighed to analyze the correlation between dry weight biomass and LAI.

2.4 Environmental data collection

Climate data was recorded for all of the sites including management, precipitation, water table fluctuation, air temperature at 1 meter and soil temperatures at 5, 10, and 20 cm depth at varying time scales. The management of each site was recorded and the export of plant biomass [g m⁻²] calculated. The Langenau weather station and a rain gauge at the restored site provided daily precipitation data. The water table was gauged weekly using simple meter measurements, which were installed at each restored fen plot and a singular meter representing the drained sites. Temperature data loggers were installed at the restored and drained sites, as well as a reference moderately drained site, which hourly recorded the air temperature at 1 meter and soil temperature at 5, 10, and 20 cm for the restored sites and additionally at 40 and 60 cm depth for the reference and drained sites.

2.5 CO₂ flux measurement using the dark chamber technique

R_{eco} was measured using a dynamic closed chamber system with an infrared gas analyzer (IRGA; Li-800, Licor, Lincoln, NE, USA) for online CO₂ analysis. A closed circuit was created through two flexible inflow and outflow tubes with a constant flow of 3 l/min per minute

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(membrane pump, KNF, Germany). The total cycling time to the analyzer was estimated to be 5 seconds, and the measurements were conducted accordingly. In order to measure leaf dark respiration and soil respiration (ecosystem respiration) during daytime conditions, aluminum-covered isolation material was fitted on transparent acrylic (Plexiglas) chambers ($78 \times 78 \times 40\text{cm}^3$ and $78 \times 78 \times 50\text{cm}^3$), which blocked all incoming light. We assumed that the measured leaf dark respiration was the same as the leaf respiration under light conditions (PINELLI & LORETO 2003) and did not use a correction. At each plot a white, 3mm thick $75\text{cm} \times 75\text{cm}$ PVC soil collar was installed to maintain gas-tightness and provide a shock resistant surface for the chamber (Figure 2-6).

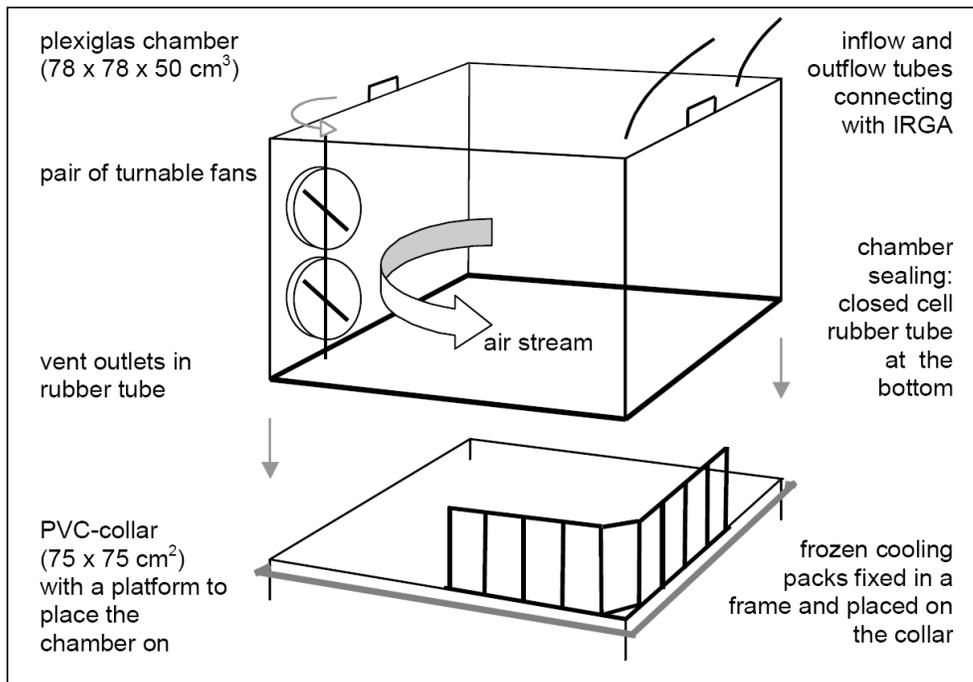


Figure 2-6. Schematic representation of the transportable chamber system with soil collar (DRÖSLER 2005).

The soil collar height was dependant on the microtopography of each plot in order to exclude any influence from the outside atmosphere during the measurement. According to the height of vegetation and water level, Plexiglas extensions ($78 \times 78 \times 11\text{cm}^3$ and $78 \times 78 \times 31\text{cm}^3$),

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covered as described above, were placed on the soil collar below the chamber. For a complete description and analysis of the chamber methodology used in this study see Drösler (2005).

Each R_{eco} measurement included the record of four temperature readings: air temperature at 20 cm height, internal chamber ambient air temperature, and soil temperature at 2 and 5 cm depth. The chamber's internal temperature was monitored throughout the 2-5 minute measurement to control that the fluctuation remained within 1.0 °C, which has been determined to influence the fluxes by a maximum of 3% (DRÖSLER 2005). In order to maintain this temperature range, a set of two fans with the option of adding ice packs along the edge of the soil collar were utilized (Figure 2-6). For ease of temperature determination during the measurement, a digital thermometer was installed inside of the chamber, with the display visible from the outside. During flooded conditions, only water temperature could be measured at 5cm depth and was recorded accordingly.

Once the dark chamber was positioned on the soil collar and secured with two bungee cords to maintain constant pressure without boundary layer disturbance, a countdown of 5 seconds preceded the first CO₂ concentration [ppm] record. Thereafter, the CO₂ concentration from the analyzer display was recorded in intervals from 10-30 seconds (depending on the overall concentration change) for a period of 2-5 minutes for a minimum of 7 concentration records. A quality check on site followed the measurement to confirm that the temperature remained within 1.0°C and that the enrichment of CO₂ was approximately linear. When these requirements were not fulfilled, the system was inspected and the measurement repeated.

Early in the year an assessment of the microtopography of each site was completed (three times for the carrot field due to management changes). Using the soil frame as the 0 reference, an extension was placed on the soil frame and the distance to the ground was measured every 7.5cm on a grid (100 points in all). This data was used to correct for the volume in the flux calculation by either subtracting volume of the plot with an average ground level above the soil frame or adding the volume of the space below the soil frame to the volume of the chamber

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space. Furthermore, for each campaign, the water above the soil frame was measured at the four corners of every plot in order to subtract water volume.

2.6 CO₂ flux calculation / respiration modeling

The data collected in the field was then entered into a spreadsheet using a selection of five concentration values per measurement to determine the linear enrichment of CO₂ within the chamber over time; $dc*dt^{-1}$ [ppm]. The linear regression was accepted if $r^2 > 0.95$ and at least three concentration values were used. The CO₂ flux [$\mu\text{mol m}^{-2} \text{s}^{-1}$] rate was calculated using Equation 2-1 (Drösler 2005).

$$F_{\text{CO}_2} = k_{\text{CO}_2} (273 * T^{-1}) (V * A^{-1}) (dc * dt^{-1}) * C \quad \text{Equation 2-1}$$

F_{CO_2} = flux rate of CO₂ [$\mu\text{mol m}^{-2} \text{s}^{-1}$]

k_{CO_2} = gas-constant at 273.15 K ($0.536 \mu\text{g C } \mu\text{l}^{-1}$)

T = instant air temperature during the measurement (K)

V = volume of the chamber with individual plot microtopography correction (l)

A = surface area within the chamber collar (m^2)

$dc * dt^{-1}$ = CO₂ concentration change within the chamber over time ($\text{ml l}^{-1} \text{h}^{-1}$)

C = conversion factor; $\text{mg C} / \mu\text{mol}$ and h/s , 0.02335859

Respiration was modeled with the LLOYD & TAYLOR (1994) exponential regression model (Equation 2-2). The activation energy, E_0 [K] and the respiration at 10°C, R_{ref} were fit individually to each dataset whereas T_{ref} and T_0 were held constant (LLOYD & TAYLOR 1994). Air temperature at 20cm and soil temperature at 2 and 5 cm depth were all entered separately into the regression model, and the temperature of best fit was chosen for the final model.

$$R_{\text{eco}} = R_{\text{ref}} e^{E_0(1/(T_{\text{ref}} - T_0) - 1/(T - T_0))} \quad \text{Equation 2-2}$$

R_{ref} = respiration at the reference temperature; CO₂ [$\mu\text{mol m}^{-2} \text{s}^{-1}$]

E_0 = activation energy; K (determinant of temperature sensitivity)

T_{ref} = reference temperature; 283.15 K, 10°C T_0 = temperature constant for the start of biological processes; 227.13 K

T = air (20cm) or soil temperature (2 and 5cm) of best fit with the dataset; K

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2.7 Modeling of CO₂ flux over the year

Temperature and respiration flux data for each campaign and site were entered into the LLOYD & TAYLOR (1994) exponential regression model (Equation 2-2) using the statistical program TABLE CURVE 2D in order to find regressions at the $p < 0.05$ significance level for both the R_{ref} and E_0 parameters. In the case that the regression was not significant, bordering campaigns of similar environmental, management, and plant phenological conditions were combined and the pooled R_{eco} values were reanalyzed. The temperature relationship of best fit was then chosen to represent the two parameters for the respective time period in the model.

The temperatures used in the individual regressions were recorded on site separately from an hourly datalogger (air temperature at 1m above ground and soil temperature at 5, 10, 20, 40 and 60 cm depth), therefore it was necessary to check for consistency and model the temperatures correlating with the campaign records. This was accomplished through averaging the temperatures (air temperature at 20cm and soil temperature at 2 and 5 cm depth) recorded in the campaign data to represent an hour and fitting a correlation with the corresponding hourly logger temperatures. Due to the lacking 2cm depth soil temperature logger, this temperature model needed to be derived from the 5cm depth model. In order to establish a feasible correlation, the 2cm depth soil temperatures for the campaigns were first forwarded two hours ahead relative to the time lag in temperature change with increasing soil depth, and then a correlation was created with the 5cm depth soil temperatures for the campaign data. This correlation was then used to fit the 2cm depth temperature model from the 5cm soil depth model followed by subtracting two hours to bring the temperature model back into proper alignment. The temperatures were then modeled at half hour resolution for the entire year by taking the average of two hours and inserting the average as the half hour step.

As each temperature regression (air temperature at 20cm, soil temperature 2cm and 5cm) could be used to calculate and model the R_{eco} values independently, a linear progression could not be established in a transition from one temperature regression to another when there was a

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switch in the temperature source. In this case the parameters R_{ref} and E_0 were held constant. However, when consecutive temperature regressions used the same temperature source, a linear progression of the parameters was introduced, creating smooth transitions. In the case where a management event (e.g. mowing or harvest) occurred before a campaign and hence, before the empirically derived temperature regression, values for the parameters were extrapolated backwards to the management event whereas the previous temperature regression was extrapolated forwards up until the management event. This same process was completed for the parameters plus and minus standard error in order to statistically evaluate the results.

Once the modeled R_{eco} values were calculated, the measured values were compared to the modeled values in TABLE CURVE 2D to assess the accuracy of the model using a 1:1 linear regression.

2.8 Statistical analysis

The TABLE CURVE 2D statistical program was used to perform non-linear regression analysis with the Lloyd & Taylor (1994) equation programmed as a user-defined equation. A detrended correspondence analysis (DCA) was carried out using PCORD for the vegetation data recorded by Drösler (2006, unpublished data) and environmental factors. The data was tested for distribution normality and correlation significance, as well as variance between means and homogenous subgroups using ANOVA and the Duncan post-hoc test with the statistical software package SPSS.

3 RESULTS

3.1 Vegetation analysis

For all plots and sites, 22 vegetative species were recorded, including a moss species. Vegetation data collected by DRÖSLER (2006) along with the ordination species codes are given in Appendix 1. Ordination was used to describe the variance between the individual plots and sites in terms of the vegetative species and cover estimates. Due to the complete turnover in vegetation species from grassland to carrot field to fen sites (i.e. non-linear vegetation distribution) a detrended correspondence analysis (DCA) was selected as the analysis method (Figure 3-1).

The first two axes together have strong explanatory power with a cumulative r^2 of 0.55 ($r^2=0.38$ and 0.17 respectively for the first two axes). The third axis, however, explains relatively little of the total variance in the data, and therefore is not discussed further (Table 3-1).

Table 3-1 The variance explained by the DCA ordination in r^2 determined using the Euclidean distance measure for the first three axes individually and cumulatively.

Axis	Increment r^2	Cumulative r^2
1	0.38	0.38
2	0.17	0.55
3	0.03	0.58

Whether the site was subject to management by mowing was correlated with the first and second axes ($r^2=0.5$ and 0.38 respectively) whereas the average water table for the sites was strongly correlated with the second axis ($r^2=0.76$) (Table 3-2). The average water table measurements were only taken for the restored wetland sites where the water table was close to the surface and small differences in micro-topography made large differences in relative wetness/flooding of each plot.

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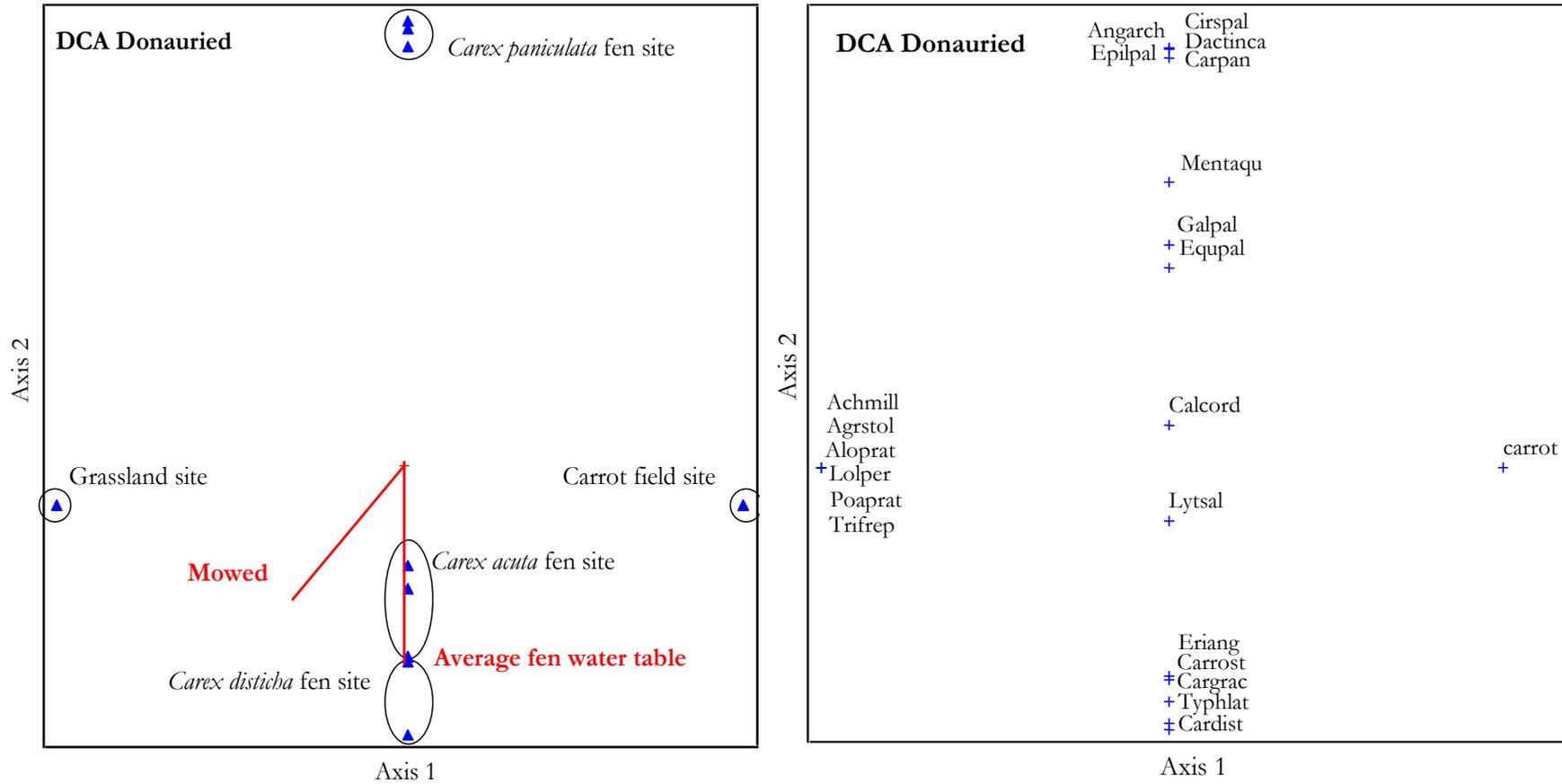


Figure 3-1. Detrended correspondence analysis (DCA) of for the three plots assigned to the five sites included in the study (min to max representation). Vegetation data collected by Drösler (2006)

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Table 3-2 Significant correlations of the DCA first two axes with quantitative environmental variables in the secondary matrix.

Axis:	1		2	
	r_s	r^2	r_s	r^2
Mowed	-0.70**	0.50**	-0.62*	0.38*
Ave. well measurements	-0.18	0.03	-0.87***	0.76***

r_s = Spearman's correlation coefficient

Order of correlation significance: *= $p < 0.05$, **= $p < 0.01$ and ***= $p < 0.001$

3.2 Net primary productivity: biomass and LAI

3.2.1 BIOMASS

The dry weight biomass for the five sites was measured five times for the wetland sites throughout the year with an additional sample taken for the mowed fen sites (*Carex disticha* and *Carex acuta* fen sites) to quantify the export of the management event. Fourteen samples were measured from the grassland site including pre-cut and post-cut samples and 1x1m export samples. As the carrot field was devoid of vegetation until the carrots were planted in June, five samples were taken during the carrot-growing season (August through mid-October), including root biomass with an additional biomass sample taken after harvest to quantify weed biomass.

The two mowed fen sites had generally similar biomass patterns, beginning the growing season in April with less than 100g m⁻² dry weight (dw) of green leaf biomass and relatively high green moss dry weight (189 and 338 g m⁻² dw respectively for the *Carex disticha* and *Carex acuta* fen sites) (Figure 3-2). Brown leaf biomass remained between 500 and 1000 g m⁻² dw for the two sites until fall, when the brown leaf biomass hit its peak at an average of 1683 and 1562 g m⁻² dw respectively. Over the growing season the moss biomass in both sites was reduced to around 50 g m⁻² dw. The mowing event removed approximately 90% of the biomass of the *Carex disticha* fen site and 80% of the *Carex acuta* fen site. Following the cut, moss biomass (brown and green g m⁻² dw) increased more than 3-fold in the *Carex disticha* fen site and more than 2-fold in the

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Carex acuta fen site for December totals of green moss 172.5 and 207.1 and brown moss 117.8 and 58.3 g m⁻² dw respectively.

The uncut large-tussock *Carex paniculata* fen site started in April with a green leaf biomass average of 483 g m⁻² dw reaching a peak in green biomass of 2076 g m⁻² dw in August. After August the green biomass quickly turned over to brown biomass ending the year in December at 463 g m⁻² dw. In April, the maximum amount of brown leaf biomass was measured at the site averaging 1740 g m⁻² dw decreasing to a low of 624 g m⁻² dw in August. In September the brown biomass was already averaging 1600 g m⁻² dw and in December averaged 1443 g m⁻² dw. Moss biomass remained steady through the year consistently below 50 g m⁻² dw.

Before the carrots were planted in late June, there was no biomass on the carrot field site. Starting in July and peaking in September, the green biomass increased from 0 g m⁻² dw to 627 g m⁻² dw in 42 days. The turnover from green to brown leaves was evident in October as brown biomass increased from 0 to an average of 247 g m⁻² dw preceding harvest. After the harvest, some weeds grew and had December averages of 16 g m⁻² dw green leaf biomass and 75 g m⁻² dw brown biomass. The root growth of the carrots was first measured in the last week of July at an average of 16 g m⁻² dw and hit their peak at harvest with 886 g m⁻² dw.

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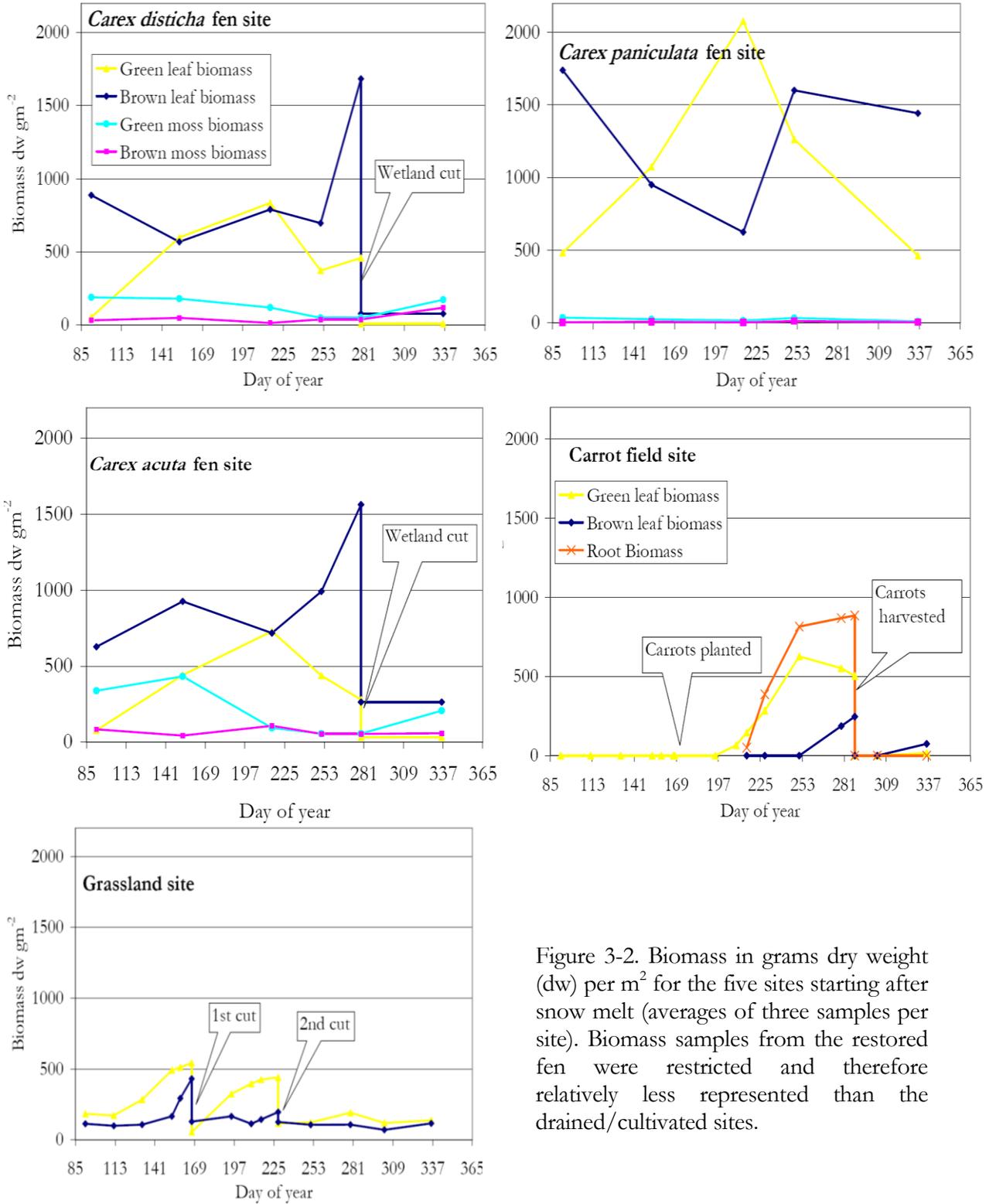


Figure 3-2. Biomass in grams dry weight (dw) per m² for the five sites starting after snow melt (averages of three samples per site). Biomass samples from the restored fen were restricted and therefore relatively less represented than the drained/cultivated sites.

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The grassland site started in April with similar amounts of green and brown leaf biomass (185 and 114 g m⁻² dw). The green leaf biomass increased steadily until the 1st cut in June and the brown biomass increased sharply in June preceding the cut. The cut removed an average of 80% of the biomass from the site; green leaf biomass from 543 to 56 g m⁻² dw and brown leaf biomass from 431 to 129 g m⁻² dw. Following the cut, the green biomass increased consistently to reach a 2nd average peak of 441 g m⁻² dw and brown biomass remained under 200 g m⁻² dw, peaking at 197 g m⁻² dw. Then on the 16th of August approximately 60% of the biomass was cut and removed leaving 116 and 126 g m⁻² dw green and brown leaf biomass respectively. Into the end of the year the biomass remained under 300 g m⁻² dw total with a maximum green leaf biomass of 192 g m⁻² dw in October and gradually turning over to brown biomass until the end of the year.

An estimate of net primary productivity (NPP) was made by calculating the difference between starting green biomass at each site and the peak(s) of green leaf biomass, depending on the management events, for example the re-growth after the grassland cuts are included. The mowed fen sites achieved 781.8 ± 266.8 and 651.3 ± 99.9 g m⁻² dw for the *Carex disticha* and the *Carex acuta* fen sites respectively. The *Carex paniculata* fen site achieved the highest NPP estimate, $p < 0.01$ ANOVA, at 1593.9 ± 326.6 g m⁻² dw. The two drained sites had no significant statistical difference with the mowed fen sites with 627.2 ± 56.5 and 758.7 ± 176.6 g m⁻² dw for the carrot field and grassland sites respectively.

3.2.2 LEAF AREA INDEX (LAI)

Leaf area index (LAI) was determined from the correlation established with September biomass leaf area for each site. Since the same correlation was used throughout the year, the year course is the same as shown in Figure 3-2. An one-way ANOVA on green leaf area index (mid-April, late May, beginning of August, beginning of September and the beginning of December) determined significant differences between the sites, Duncan post-hoc test, $p < 0.05$, $N=3$ (Figure 3-3). Each

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date was tested separately to determine variance and homogenous subgroups, represented by the same letter. Since the carrot field had no biomass on the site until mid-summer, the site is first considered in ANOVA for August.

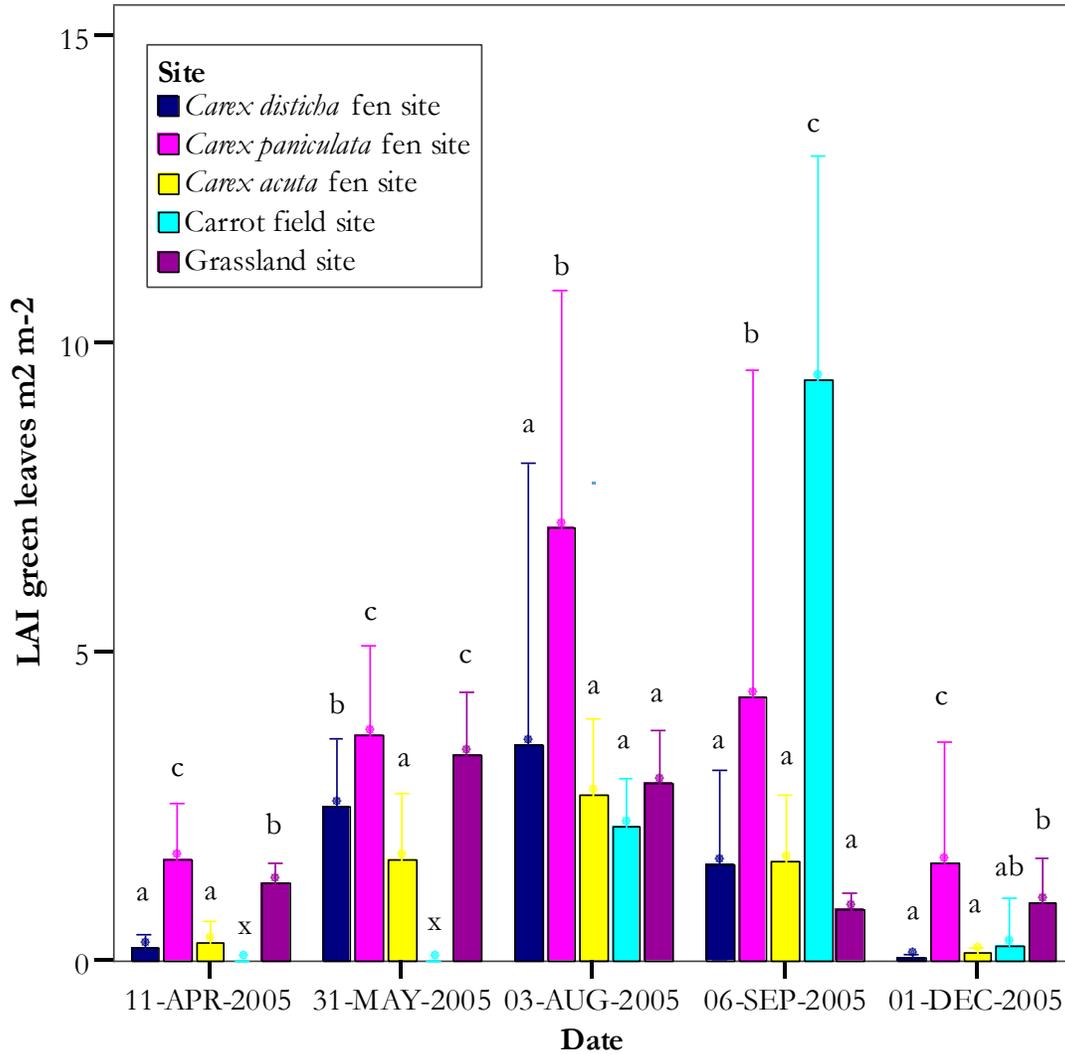


Figure 3-3 Green leaf area index (LAI) in m² leaf area to m² ground surface for the five sites during the growing season, three samples per site per date shown. Statistically homogenous groups for each date (separately analyzed) have the same letter (ANOVA, Duncan test, $p > 0.05$). The LAI for the carrot field site pre-carrot planting is represented by x, all values = 0.

The *Carex paniculata* fen site consistently had a higher green leaf LAI than the other fen sites and in general had a greater LAI than the grassland (except in May, no significant difference, $p > 0.05$)

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and the carrot field (except in September when carrots had a higher LAI, $p < 0.05$). The green leaf LAI for the *Carex disticha* fen site was only significantly different from the *Carex acuta* fen site in May, with a mean green leaf LAI of 2.5 compared with 1.5 for the *Carex acuta* fen site. The restored fen sites all consistently increased in green leaf LAI until their peak in August and decreased to reach their minimum in December. The grassland and carrot field sites reacted differently due to their management events with the grassland reaching its maximum green leaf LAI in May preceding the first cut and the carrot field reached its maximum in September, a month before harvest, being planted first in July. The carrots reached the maximum recorded LAI of the five sites at a mean LAI of $9.41 \text{ m}^2 \text{ m}^{-2}$ in September, which is comparable to published carrot LAI values (i.e. REID & ENGLISH 2000).

3.3 Environmental factors

3.3.1 PRECIPITATION AND WATER TABLE FLUCTUATION

The total precipitation over the year for the researched area was 824.3 mm, which is 18.1% higher than the 15-year average of 672.5 mm (Table 3-3). Large rain events in August contributed to the higher precipitation, including three consecutive days of 3.35 cm average rainfall per day. This rain event is also evident in the changes in the water table for all sites, however directly afterwards, the water table for the wetland sites lowers to the deepest level of the summer months (Figure 3-4). This quick change in the water table of the fen sites could be the result of the weirs being closed in order to prevent harmful flooding in the nature reserve.

Table 3-3 Climate data from the local weather station in Weißingen, the monthly average precipitation values from 2005 and the average monthly values from 1990 to 2005.

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total/ mean
precip 2005	34.2	46.4	56.5	90.5	86.6	50.3	103.8	137.5	94.7	60.5	26.9	36.4	824.3
precip 15yr ave	36.6	37.8	42.5	54.1	59.8	69.2	76.6	75.5	65.3	59.8	46.9	48.4	672.5

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Figure 3-4. Weekly precipitation data from the local weather station and the weekly water table fluctuation collected on site for the fen sites individually and the drained sites together.

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Due to different management, the restored sites have a significantly higher average water table than the drained/cultivated sites, $p < 0.001$ (Table 3-4). The drained sites did not have a depth to water table less than 22cm whereas the restored fen sites were often flooded during the summer months (Figure 3-4). Furthermore the range of the water table level was much higher in the drained sites with a fluctuation range of 93 cm in comparison to 21-25cm in the restored sites.

Table 3-4 Water table fluctuation data, positive values are aboveground. Statistically differentiated homogenous groups determined by Mann-Whitney U-Test, $p < 0.001$. Note: Carrot field and grassland sites are represented with the same measuring station data.

Water table [cm]				
Site	Mean \pm SE	Min	Max	Range
<i>Carex disticha</i> fen site	0.51 \pm 5.659a	-9	14	23
<i>Carex paniculata</i> fen site	-1.63 \pm 5.74a	-11	10	21
<i>Carex acuta</i> fen site	0.436 \pm 6.06a	-10	15	25
Carrot field site	-75.82 \pm 22.39b	-115	-22	93
Grassland site	-75.82 \pm 22.39b	-115	-22	93

3.3.2 AIR AND SOIL TEMPERATURE

The average temperature for 2005, 7.8 °C, was slightly below the 15-yr average of 8.2°C, which was apparently the result of colder winter periods (Table 3-5). The following graphs are based on the temperature models established from the correlation between the campaign-measured temperatures and the temperature readings of the hourly datalogger for the restored fen sites. However, due to technical difficulties with the drained sites' datalogger, air and soil temperatures from the Weißingen weather station were substituted in creating the correlations and the final temperature models for the carrot field and grassland sites.

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Table 3-5. Climate data from the local weather station in Weißingen. Air temperatures were recorded at 2m height for the monthly 2005 and 15-yr average.

month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total/ mean
temp 2005	-0.3	-3.8	3.6	9.5	12.2	16.5	17.5	15.3	13.7	9.0	2.1	-1.1	7.8
temp 15yr ave	-0.6	0.4	4.6	8.0	12.8	15.6	17.2	17.3	12.5	8.2	3.0	0.0	8.2

The modeled air temperature at 20cm height differed little between the five sites (Figure 3-5). However, soil temperatures at 2 and 5cm diverged at higher temperatures, with the carrot field displaying markedly higher temperatures than the other sites – even higher than the site’s air temperatures. Apparently the exposed black peat soil (only covered at the height of the carrots) exhibited a higher albedo and increased soil temperatures to that higher than the other sites, which were plant-covered for the entire season. The weekly averages in air temperature for all sites are relatively lower than soil temperatures due to the lower temperatures achieved during nighttime.

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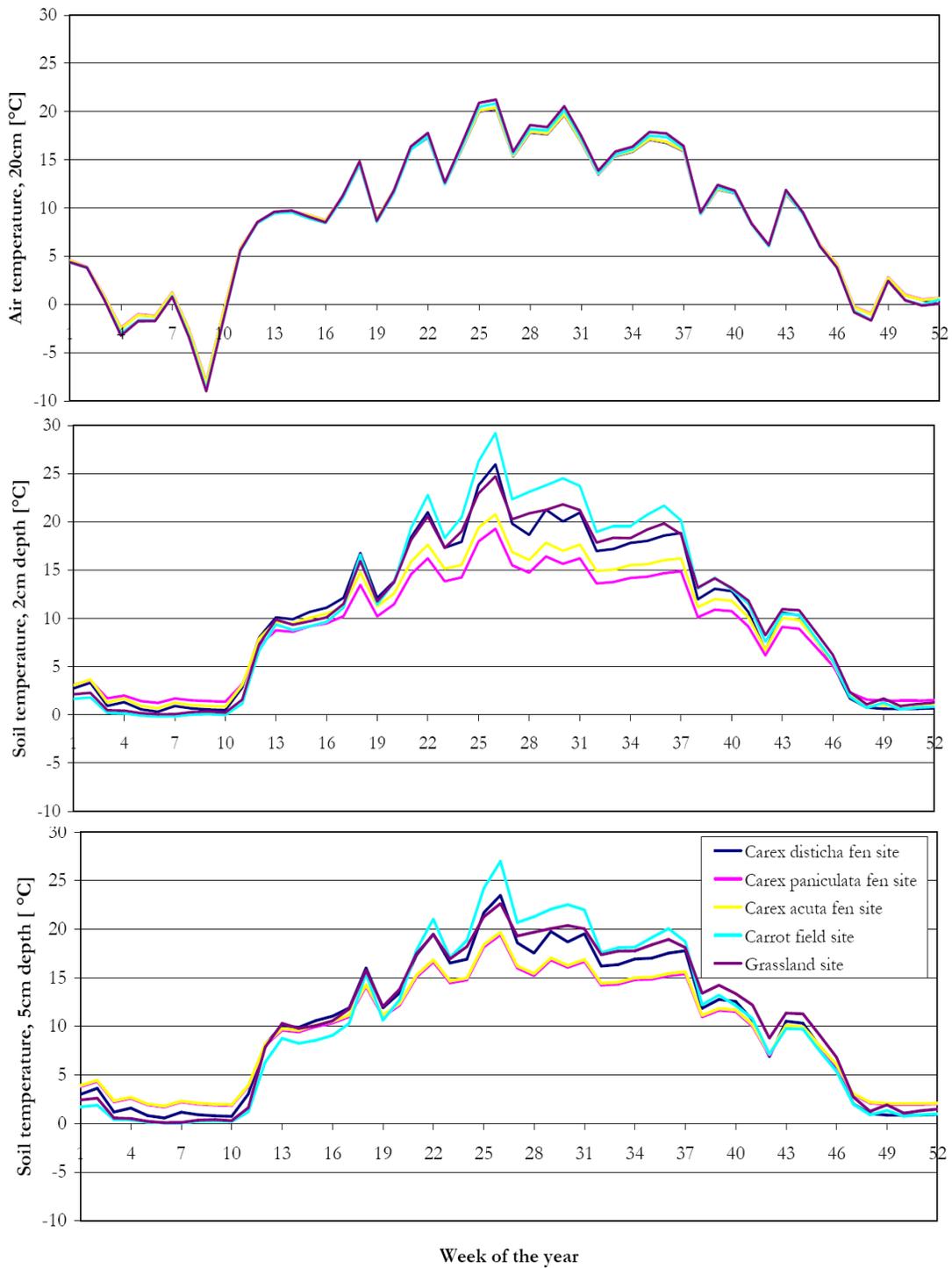


Figure 3-5. Air temperature at 20 cm height and soil temperatures at 2 and 5 cm depth for the five sites as modeled from the correlation between the campaign observed temperatures and the hourly datalogger data.

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3.4 Daytime respiration

The CO₂ flux values over the course of the day were correlated with the temperature pattern, either air temperature at 20 cm or soil temperature at 2 or 5cm depth. In the summer, all sites responded to the air temperature pattern with the lowest fluxes before sunrise (lowest soil and air temperatures) and rising until the peak of air temperature around noon and falling until sunset (Figure 3-6, mid August). Accordingly, the R_{eco} model for each site used air temperature in the Lloyd & Taylor exponential regression (Equation 2-2) during the summer months (Table 3-6), with the exception of the grassland site subsequent to the 1st cut in mid-June, in which case soil temperature at 2cm depth provided the best regression. In contrast the snow-covered season was correlated with soil temperature at either 2 or 5cm depth, as the respiration was primarily from the soil and therefore not influenced by the air temperature pattern (Figure 3-6, December).

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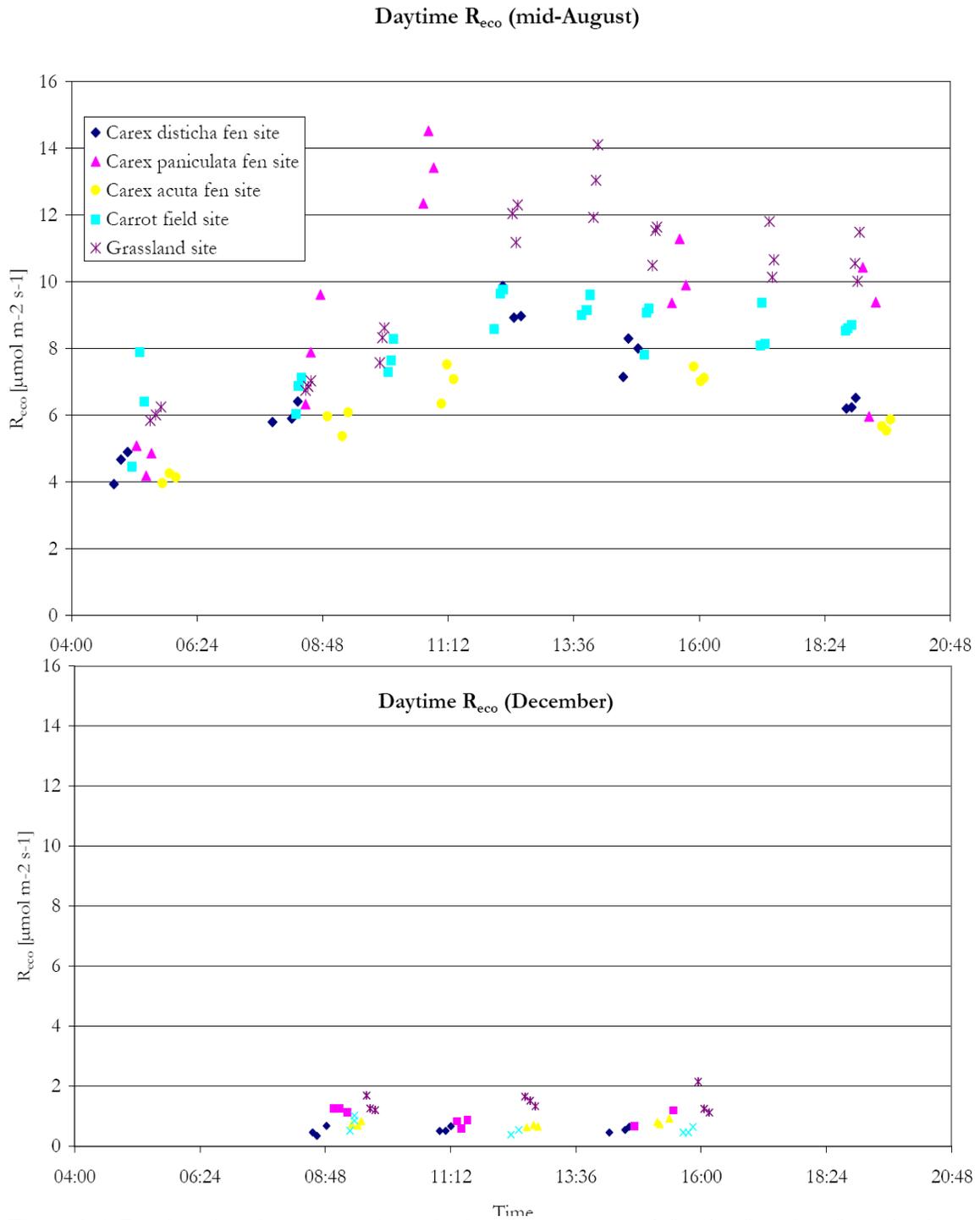


Figure 3-6. Daytime (sunrise to sunset) respiration fluxes measured for the five sites for a day in mid-August and beginning December. According to the campaign schedule the three restored fen sites were sampled the day before the carrot field and grassland sites. Note: the grassland site for the August graph had been cut two days earlier.

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3.5 Modeled annual CO₂ respiration

The parameterization of the LLOYD & TAYLOR (1994) exponential regression respiration model was separated into individual campaign regression results or a combination of campaign data sets depending on the significance of the temperature vs. CO₂ flux regression (Table 3-6). The range of the significant regression coefficients (r^2) is between 0.28, $p < 0.01$ and 0.91, $p < 0.001$. Variability over the year is evident by the changing parameter values for E_0 , the activation energy, and R_{ref} , the reference respiration rate at 10°C. The *Carex disticha* and *Carex paniculata* fen sites were modeled with eight separate regressions, the *Carex acuta* site with seven and the drained sites (carrot field and grassland) both with nine separate regressions.

During the snow-covered period, only soil temperature regressions were selected, however the majority of the regressions over the year had the best fit with air temperature. The selected seasonally determined regressions are given in Appendix 2.

The highest R_{ref} rate was measured in the grassland site with 9.10 ± 0.96 [$\mu\text{mol m}^{-2} \text{s}^{-1}$], air temperature at 20cm, for the 2nd of June until the 16th of June at which point the area was mowed. The *Carex paniculata* fen site had the lowest R_{ref} rate, 0.62 ± 0.05 [$\mu\text{mol m}^{-2} \text{s}^{-1}$], soil temperature at 2cm depth, for the winter period of the 1st of January through the 11th of April. The highest activation energy (E_0) was obtained in the *Carex acuta* fen site at 669.20 ± 121.18 K, soil temperature at 5cm depth, for the 6th of October (when the site was mown) to the 15th of November. The carrot field site exhibited the lowest activation energy at 62.92 ± 18.45 K for peak of the carrot growth period, the 7th of September to the 7th of October.

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Table 3-6. Respiration parameters for the Lloyd and Taylor exponential regression model (Equation 2-2); temperature versus CO₂-flux. Significance tested with TABLECURVE 2D. The Q₁₀ value, the proportional change in respiration flux with an increase of 10 °C, was derived for 15 –25 °C.

Site	Dates	Days	Temp	r2	Sig	R ref ±SE	E ₀ ±SE	N	Q ₁₀ (15-25)
CD	1.01.-11.04.2005; 15.11.-31.12.2005	147	ST2	0.50 ***		1.03 ±0.10	240.43 ±40.61	29	1.74
CD	11.04.-16.06.2005	66	Tair-20	0.67 ***		2.73 ±0.23	279.83 ±37.65	33	1.91
CD	16.06.-13.07.2005	27	Tair-20	0.53 **		4.12 ±0.57	155.21 ±42.21	16	1.43
CD	13.07.-27.07.2005	14	Tair-20	0.87 ***		4.88 ±0.43	175.65 ±23.44	14	1.50
CD	27.07.-17.08.2005	21	Tair-20	0.90 ***		3.44 ±0.35	179.93 ±23.11	11	1.51
CD	17.08.-06.09.2005	20	Tair-20	0.79 ***		4.94 ±0.35	156.18 ±25.66	15	1.43
CD	06.09.-06.10.2005	30	Tair-20	0.83 ***		7.60 ±0.30	84.58 ±11.67	15	1.22
CD	06.10.-15.11.2005	40	ST5	0.55 ***		2.29 ±0.21	542.78 ±109.25	22	3.50
CP	1.01.-11.04.2005	101	ST2	0.90 ***		0.62 ±0.05	262.49 ±46.44	9	1.83
CP	11.04.-16.06.2005	66	Tair-20	0.91 ***		2.98 ±0.32	452.58 ±39.50	26	2.84
CP	16.06.-13.07.2005	27	Tair-20	0.79 ***		6.01 ±0.56	179.6 ±28.05	13	1.51
CP	13.07.-27.07.2005	14	Tair-20	0.89 ***		7.67 ±0.29	106.03 ±14.87	8	1.28
CP	27.07.-17.08.2005	21	Tair-20	0.75 ***		4.07 ±0.80	208.17 ±43.06	12	1.62
CP	17.08.-06.09.2005	20	Tair-20	0.66 **		5.71 ±0.88	217.60 ±56.66	15	1.65
CP	06.09.-29.10.2005	53	Tair-20	0.62 ***		4.70 ±0.46	171.14 ±29.32	25	1.48
CP	29.10.-31.12.2005	63	ST2	0.91 ***		4.17 ±0.18	499.21 ±51.27	26	3.16
CA	1.01.-11.04.2005; 15.11.-31.12.2005	147	ST2	0.41 ***		1.10 ±0.11	174.54 ±37.82	26	1.50
CA	11.04.-16.06.2005	66	Tair-20	0.75 ***		2.51 ±0.22	280.52 ±34.57	28	1.91
CA	16.06.-13.07.2005	27	Tair-20	0.68 ***		4.46 ±0.59	177.95 ±37.25	15	1.51
CA	13.07.-27.07.2005	14	Tair-20	0.79 ***		5.35 ±0.46	141.57 ±24.56	12	1.39
CA	27.07.-17.08.2005	21	Tair-20	0.91 ***		3.21 ±0.28	186.48 ±19.97	12	1.54
CA	17.08.-06.10.2005	50	Tair-20	0.74 ***		4.84 ±0.23	108.63 ±14	27	1.28
CA	06.10.-15.11.2005	40	ST5	0.61 ***		2.43 ±0.21	669.20 ±121.18	24	4.68
CRF	1.01.-11.04.2005; 1.12.-31.12.2005	131	ST2	0.28 **		0.78 ±0.09	172.48 ±49.90	27	1.49
CRF	11.04.-17.06.2005	67	Tair-20	0.76 ***		2.31 ±0.27	336.03 ±36.58	37	2.17
CRF	17.06.-14.07.2005	27	Tair-20	0.42 **		2.52 ±0.66	242.45 ±79.85	21	1.75
CRF	14.07.-28.07.2005	14	Tair-20	0.61 **		4.10 ±0.39	95.14 ±23.15	16	1.25
CRF	28.07.-18.08.2005	21	Tair-20	0.53 ***		6.45 ±0.73	117.51 ±28.57	18	1.31
CRF	18.08.-07.09.2005	20	Tair-20	0.65 ***		5.51 ±0.39	136.27 ±22.73	24	1.37
CRF	07.09.-07.10.2005	30	Tair-20	0.61 **		7.51 ±0.42	62.92 ±18.45	10	1.16
CRF	07.10.-15.10.2005	8	Tair-20	0.47 **		3.80 ±0.13	99.99 ±26.57	17	1.26
CRF	15.10.-1.12.2005	47	ST2 bot	0.49 **		1.51 ±0.11	611.96 ±163.75	15	4.10

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Site	Dates	Days	Temp	r2	Sig	R ref ±SE	E0 ±SE	N	Q ₁₀ (15-25)
GL	1.01.-11.04.2005; 1.12.-31.12.2005	131	ST2	0.40	***	2.24 ±0.16	132.98 ±30.23	28	1.36
GL	11.04.-02.06.2005	52	Tair-20	0.63	***	7.58 ±0.35	183.17 ±32.51	21	1.53
GL	02.06.-16.06.2005	14	Tair-20	0.71	***	9.10 ±0.96	179.18 ±33.38	17	1.51
GL	16.06.-14.07.2005	28	ST2	0.34	**	4.76 ±0.75	158.43 ±53.41	21	1.44
GL	14.07.-28.07.2005	14	Tair-20	0.77	***	8.23 ±0.84	132.99 ±24.70	15	1.36
GL	28.07.-16.08.2005	19	Tair-20	0.64	***	7.82 ±0.88	149.64 ±27.70	21	1.41
GL	16.08.-07.09.2005	22	Tair-20	0.72	***	5.25 ±0.54	204.52 ±29.58	24	1.60
GL	07.09.-23.09.2005	16	Tair-20	0.76	***	8.01 ±0.44	101.47 ±17.16	15	1.26
GL	23.09.-1.12.2005	69	ST2	0.51	***	2.98 ±0.16	419.40 ±74.37	33	2.63

Site codes as follows: CD= *Carex disticha* fen site, CP= *Carex paniculata* fen site, CA= *Carex acuta* fen site, CRF= Carrot field site, GL= Grassland site. Temperature codes: ST2= soil temperature at 2cm depth (bot= bottom of trough for carrot field), ST5= soil temperature at 5cm depth, and Tair-20= air temperature at 20cm height.

3.5.1 SEASONAL VARIANCE IN RESPIRATION AND MANAGEMENT EFFECTS

As ecosystem respiration is highly correlated with temperature and was modeled accordingly, it is apparent that the winter months with correspondingly colder temperatures will have a similarly low respiration rate (Figure 3-7). As soon as the temperature increases, the snow melts, the plants begin to grow and the ecosystem respiration rate climbs. Already in the last week of May, the grassland site had reached the year's highest average weekly respiration rate (579.22 mg CO₂-C m⁻² h⁻¹). The other sites continually increased respiration with the *Carex paniculata* and *Carex acuta* fen sites peaking in the last week of June with 436.56 and 327.81 mg CO₂-C m⁻² h⁻¹ respectively. At the height of the carrot season and during a low water period in the *Carex disticha* fen site, the second week in September has the highest respiration for the two sites: 359.19 and 377.06 mg CO₂-C m⁻² h⁻¹ respectively. With the falling temperatures of fall, all sites showed decreasing respiration rates starting in late September and early October through the end of the year.

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R_{eco} weekly average

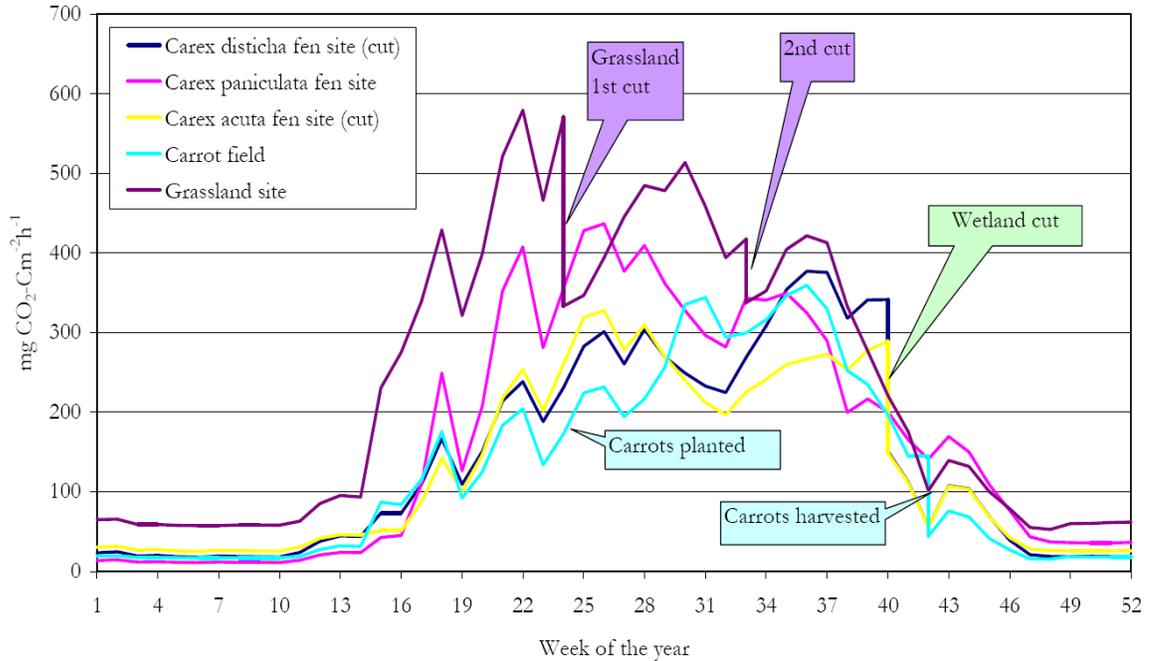
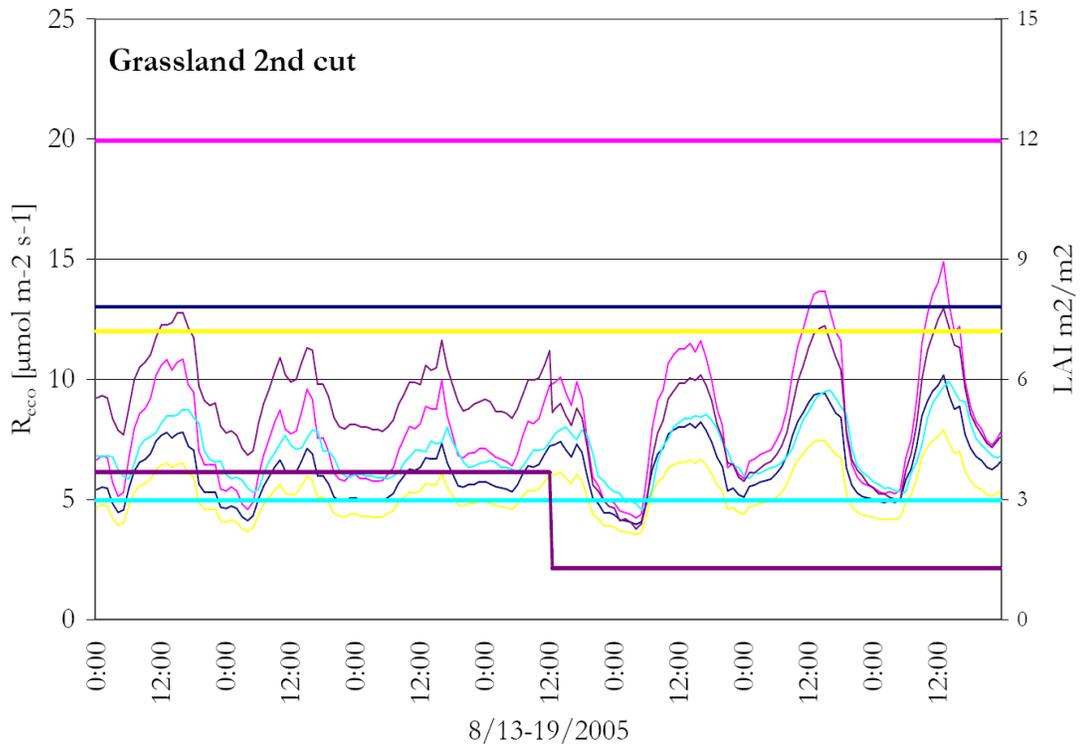
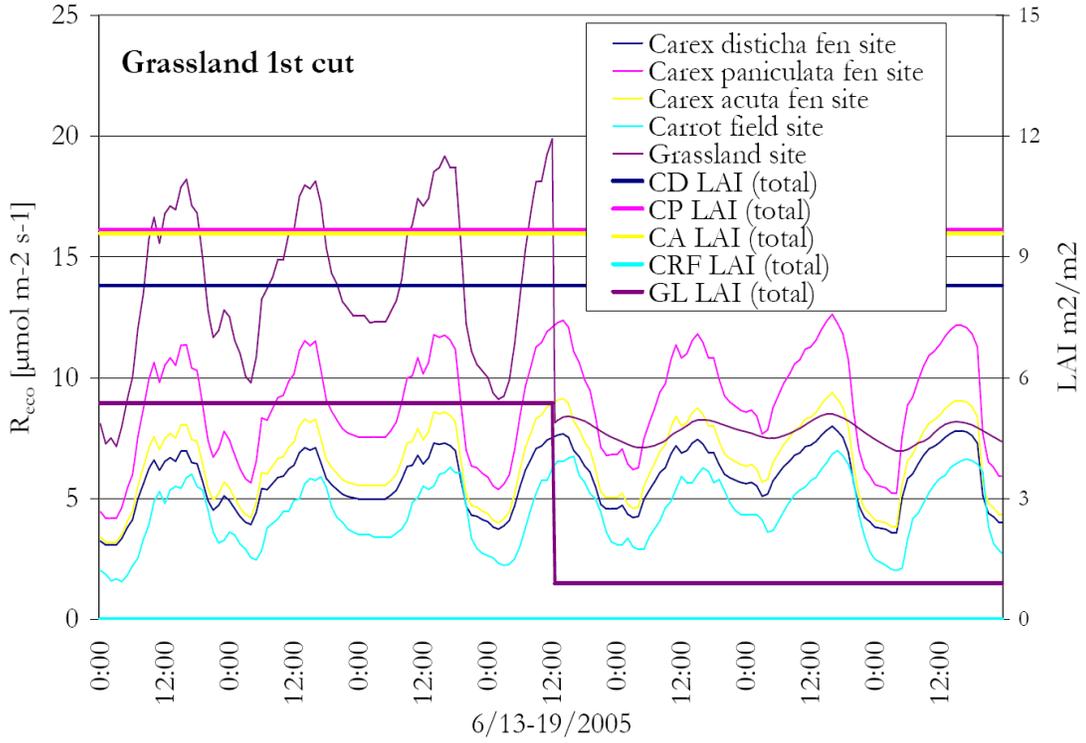


Figure 3-7. Variation of R_{eco} over the course of a year and management events (average weekly modeled CO₂ flux [mg CO₂-C m⁻² h⁻¹]).

Management events in the grassland, carrot field and mowed fen sites drastically reduced weekly respiration rates. The first cut in the grassland was the most extreme, when the respiration rate fell from 571.09 to 333.29 mg CO₂-C m⁻² h⁻¹; a 41.6% decrease in respiration. The second cut in the grassland produced a decrease from 417.41 to 337.4 mg CO₂-C m⁻² h⁻¹; a decrease of 19.2%. Even though the wetland cut was later in the year, the 6th of October, the effects on respiration were substantial, the *Carex disticha* and *Carex acuta* fen sites' respiration were reduced from 341.42 and 289.05 to 150.62 and 148.29 mg CO₂-C m⁻² h⁻¹, a decrease of 55.9 and 48.6%, respectively. The *Carex paniculata* fen site was not mowed. The harvest of the carrots in mid-October reduced the site's respiration rate from 144.72 to 44.67 mg CO₂-C m⁻² h⁻¹; a reduction of 69.1%.

The instantaneous results of management on R_{eco} aligned with the reduction in total leaf area index (LAI), green leaf and moss plus brown leaf and moss area [m²] per m² of ground surface and is clear in the R_{eco} model at half hour resolution (Figure 3-8).

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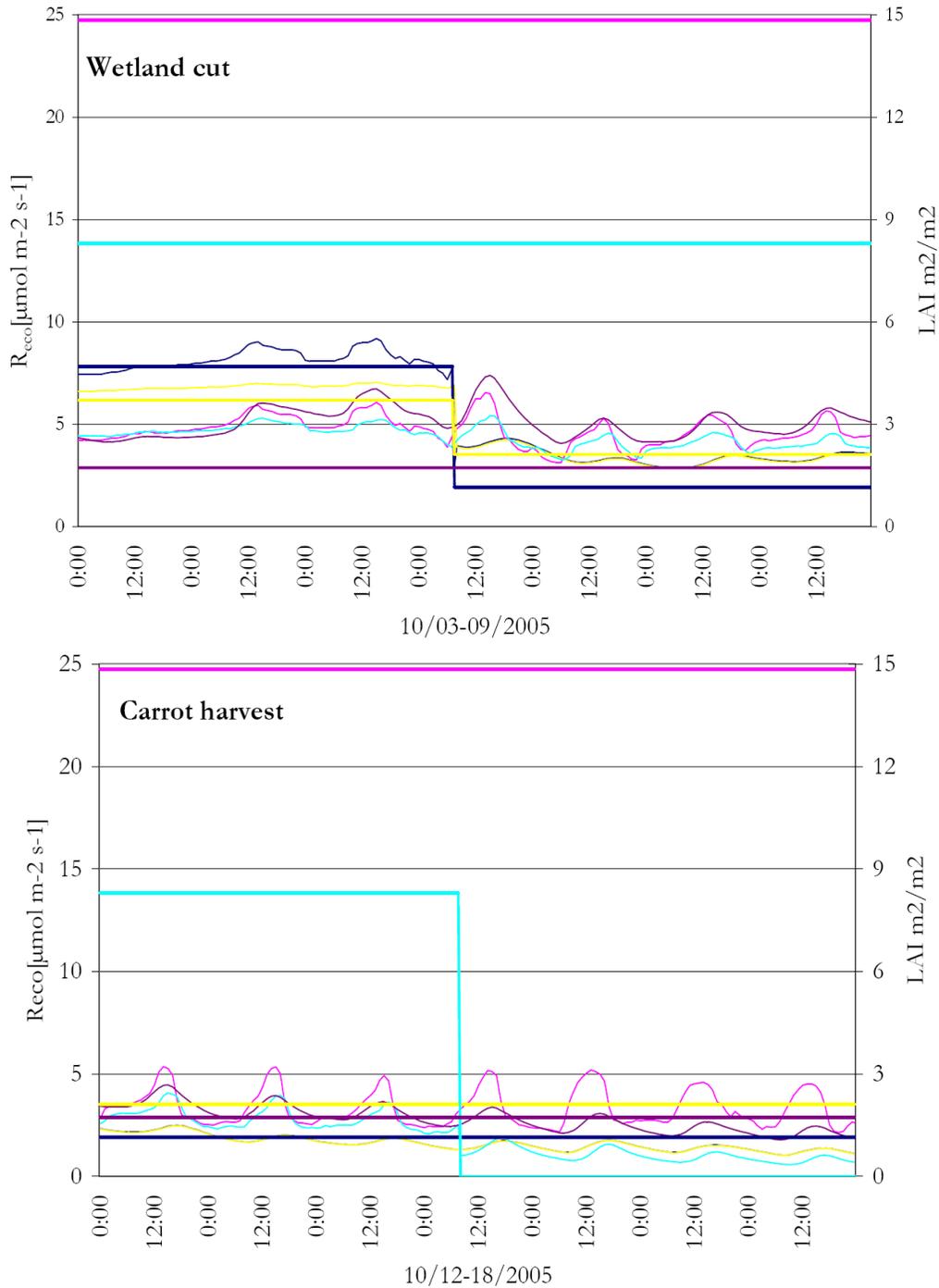


Figure 3-8. Management week sections from the Reco model (at half-hour resolution) including the two cuts of the grassland (the 16th of June and the 16th of August), the wetland cut on the 6th of October for the *Carex disticha* and *Carex acuta* fen sites and the carrot harvest on the 15th of October. The total leaf area index (LAI, m^2 leaf area per m^2 surface area) and changes due to management are indicated for each site.

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3.5.2 CUMULATIVE R_{eco} FOR 2005

The total R_{eco} for the year was calculated by summing the individual fluxes at half hour resolution from the R_{eco} model. The pattern of the cumulative increase of the R_{eco} values [$g\ CO_2-C\ m^{-2}$] followed a similar pattern for all the sites (Figure 3-9). The beginning winter months have a slow increase in total CO_2-C in $g\ m^{-2}$. Then during the growing season up until approximately mid-October the slope increases considerably, with minor changes due to management events. Finally, into the end of the year the slope decreases, as the sites are respiring less carbon dioxide.

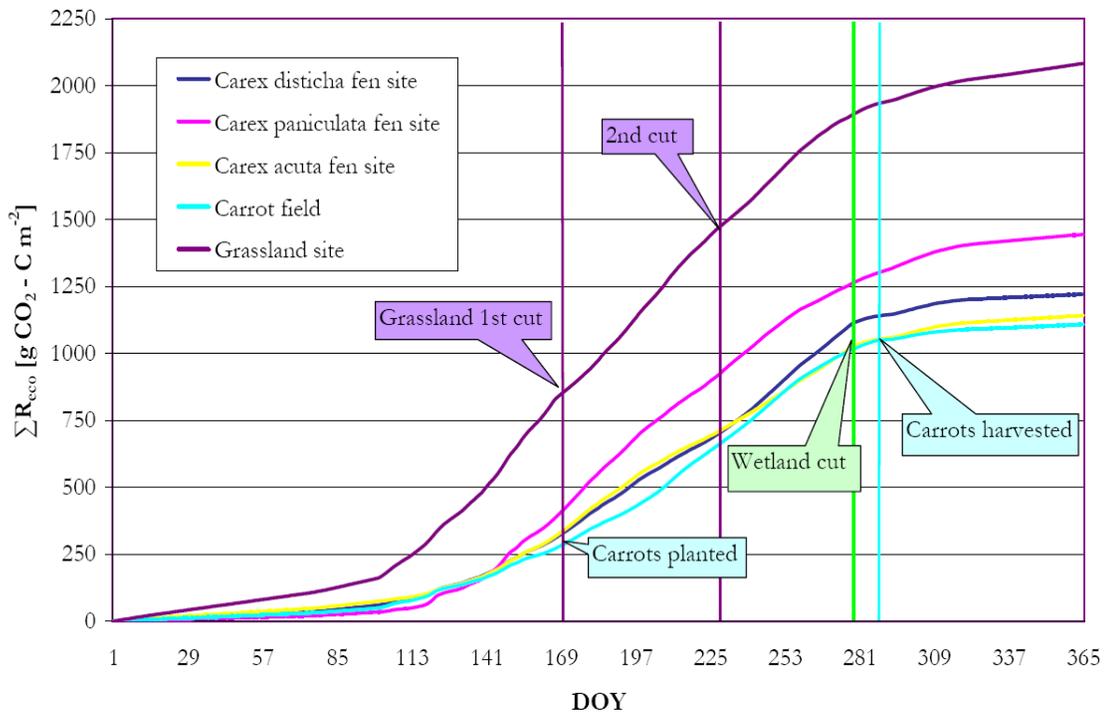


Figure 3-9. The cumulative ecosystem respiration [CO_2-C in $g\ m^{-2}$] in 2005 for the five sites.

The grassland site has a significantly higher annual R_{eco} total than the other sites at 1823.55-2339.78 $g\ CO_2-C\ m^{-2}\ y^{-1}$ (including the model's standard error) compared with the *Carex disticha* fen site at 1084.87-1361.26, *Carex paniculata* fen site at 1244.22-1676.93, *Carex acuta* fen site at 1025.74-1270.39 and the carrot field at 958.82-1282.73 $g\ CO_2-C\ m^{-2}\ y^{-1}$, one-way ANOVA,

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$p < 0.001$, $N = 3$ (Figure 3-10). The other sites did not differ significantly, one-way ANOVA, Duncan post-hoc test, $p > 0.05$ $N = 3$.

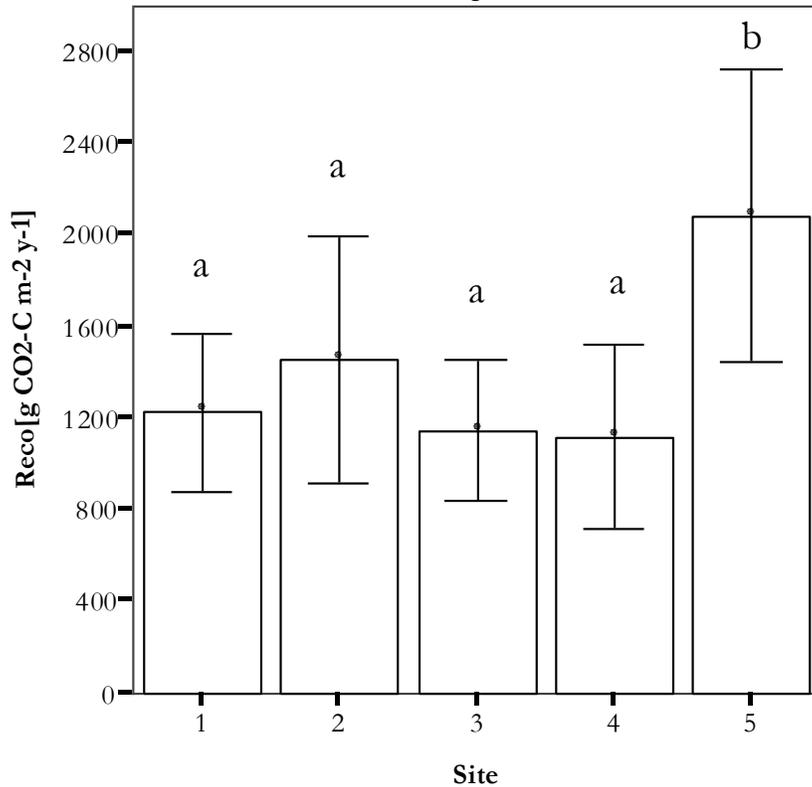


Figure 3-10 The R_{eco} total values [g CO₂-C m⁻² y⁻¹] for the five sites as calculated by the seasonal model, error bars signify model standard error. Groups with the same letter are not statistically different (ANOVA, Duncan post-hoc test, $p < 0.05$, $n = 3$). Site codes: 1 = *Carex disticha* fen site, 2 = *Carex paniculata* fen site, 3 = *Carex acuta* fen site, 4 = carrot field site and 5 = grassland site.

3.5.3 R_{ECO} CORRELATION WITH GREEN LEAF LAI AND WATER LEVEL

Besides the correlation with soil and air temperature included in the ecosystem respiration model, the environmental factors of water level and green leaf area index (LAI) change over the season and are reflected in the seasonally-determined model parameters. A positive correlation between green leaf LAI estimates for campaign weeks (including management events) and

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weekly R_{eco} flux [$\text{mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$] was significant for all sites except for the carrot field, in which case $p=0.06$; Pearson or Spearman's correlation coefficient as noted, $p<0.05$ (Table 3-7).

Table 3-7. Correlation coefficients for the relationship between the weekly averages of green leaf area index (LAI) [$\text{m}^2 \text{ m}^{-2}$] and weekly R_{eco} flux [$\text{mg CO}_2\text{-C m}^{-2} \text{ h}^{-1}$] averages.

Site	Green leaf area index (LAI) with R_{eco} weekly averages				
	r	rs	r2	Sig	N
<i>Carex disticha</i> fen site		0.65	0.42	*	14
<i>Carex paniculata</i> fen site	0.77		0.59	**	13
<i>Carex acuta</i> fen site		0.55	0.3	*	14
Carrot field site		0.54	0.29	$p=0.06$	14
Grassland site	0.73		0.53	**	15

r=Pearson's correlation coefficient and r_s =Spearman's correlation coefficient

Weekly water level for campaign weeks during the growing season (mid-April, July for the carrot field, to mid-October) or up until the first management period was negatively correlated with the corresponding R_{ref} at 10°C parameter of the model for the *Carex disticha* and *Carex acuta* fen sites; Pearson's correlation coefficient, $p<0.05$, $N=9$ (Table 3-8).

Table 3-8 Correlation coefficients for the relationship between water level [cm] for campaign weeks during the growing season (mid-April to mid-October, July for the carrot field) or until the first management event with the corresponding fitted reference respiration flux [$\mu\text{mol m}^{-2} \text{ s}^{-1}$] parameter, R_{ref} , for the five sites.

Site	Weekly water level with fitted campaign R_{ref} parameter			
	r	r2	Sig	N
<i>Carex disticha</i> fen site	-0.76	0.57	*	9
<i>Carex paniculata</i> fen site	-0.47	0.22		11
<i>Carex acuta</i> fen site	-0.84	0.70	**	9
Carrot field site	-0.19	0.04		5
Grassland site	-0.20	0.04		4

In fact the *Carex disticha* fen site reaches its maximum weekly flux averages during a period of low water in the wetland, as determined from campaign measurements (Figure 3-11). No

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significant correlation was found between the campaign weekly water level and the green leaf LAI, $p > 0.05$.

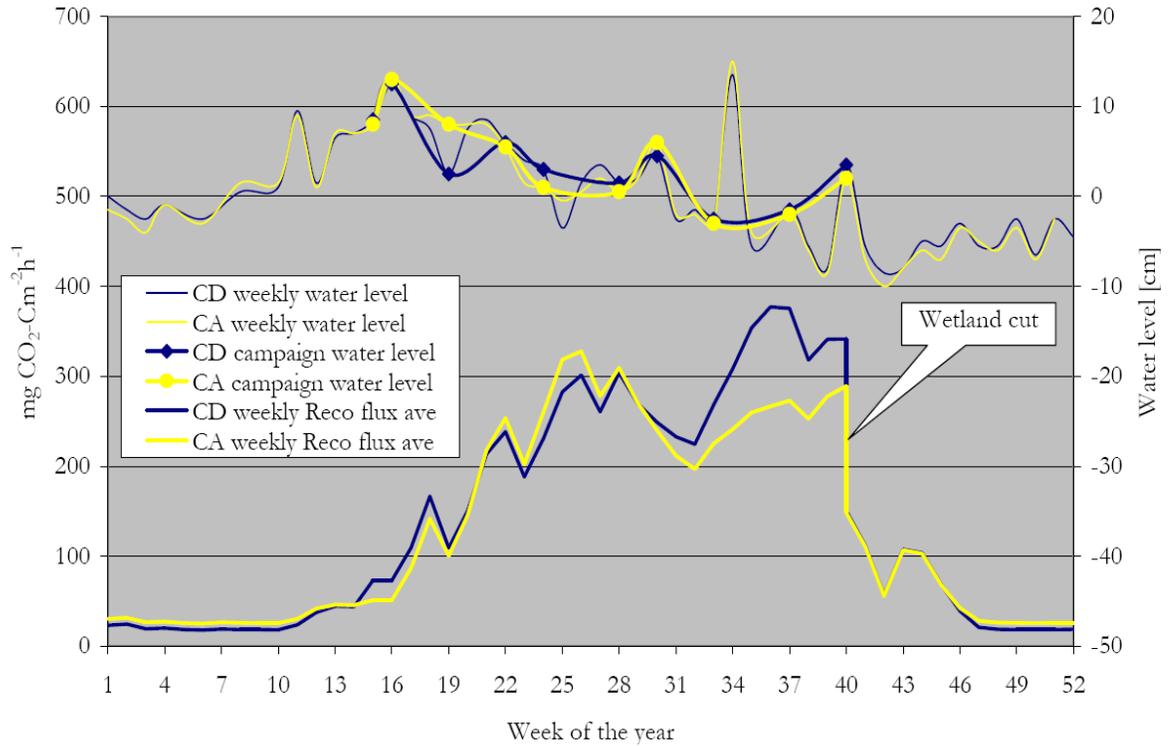


Figure 3-11. R_{eco} weekly flux average [$\text{mg CO}_2\text{-C m}^{-2} \text{h}^{-1}$] for the mowed fen sites (CD= *Carex disticha* fen site and CA=*Carex acuta* fen site) along with water table fluctuation data on a weekly and campaign basis during the growing season. The correlation between the campaign water level and the reference respiration at 10°C parameter for the R_{eco} model was significant for the two sites; $r^2=0.57$, $p<0.05$ for the *Carex disticha* fen site and $r^2=0.70$, $p<0.01$ for the *Carex acuta* fen site.

3.5.4 MODELED RESPIRATION VERSUS MEASURED RESPIRATION

As a final check of the R_{eco} model, the linearity of the relationship between the measured and the modeled CO_2 fluxes was tested (Table 3-9). The regression coefficients (r^2) ranged from 0.882 at the carrot field site to 0.947 for the *Carex disticha* fen site. Overall, the linearity of the relationship is convincing with minor over-estimation in the carrot field (Figure 3-12).

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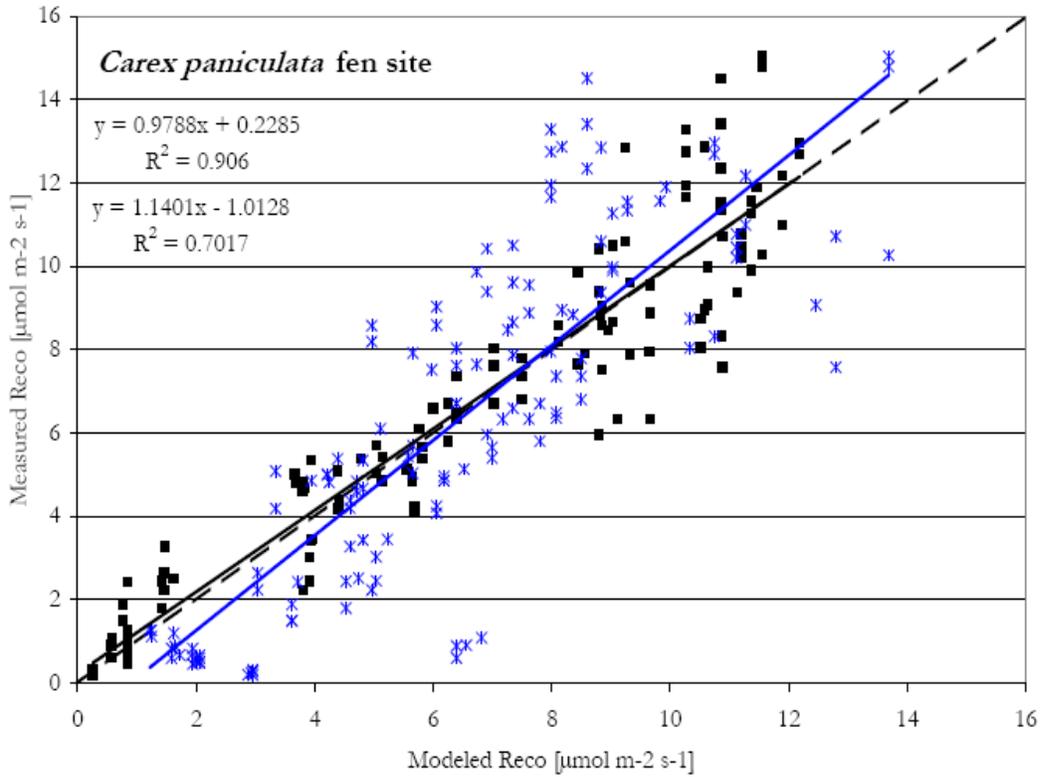
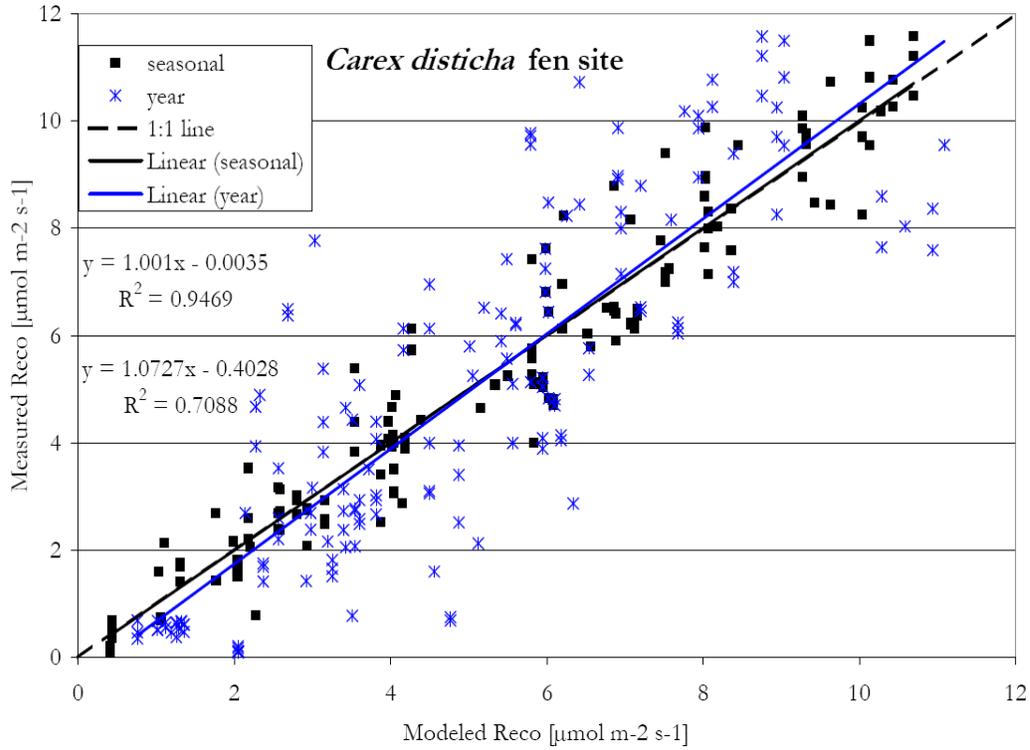
Table 3-9. Assessment of the R_{eco} modeled values as compared to the measured values.

Site	Modeled vs. measured linear regression	r ² value	N
<i>Carex disticha</i> fen site	$y = 1.001x - 0.004$	0.947	155
<i>Carex paniculata</i> fen site	$y = 0.979x + 0.229$	0.906	134
<i>Carex acuta</i> fen site	$y = 0.997x + 0.071$	0.939	145
Carrot field site	$y = 0.995x + 0.264$	0.882	185
Grassland site	$y = 0.988x - 0.002$	0.912	195

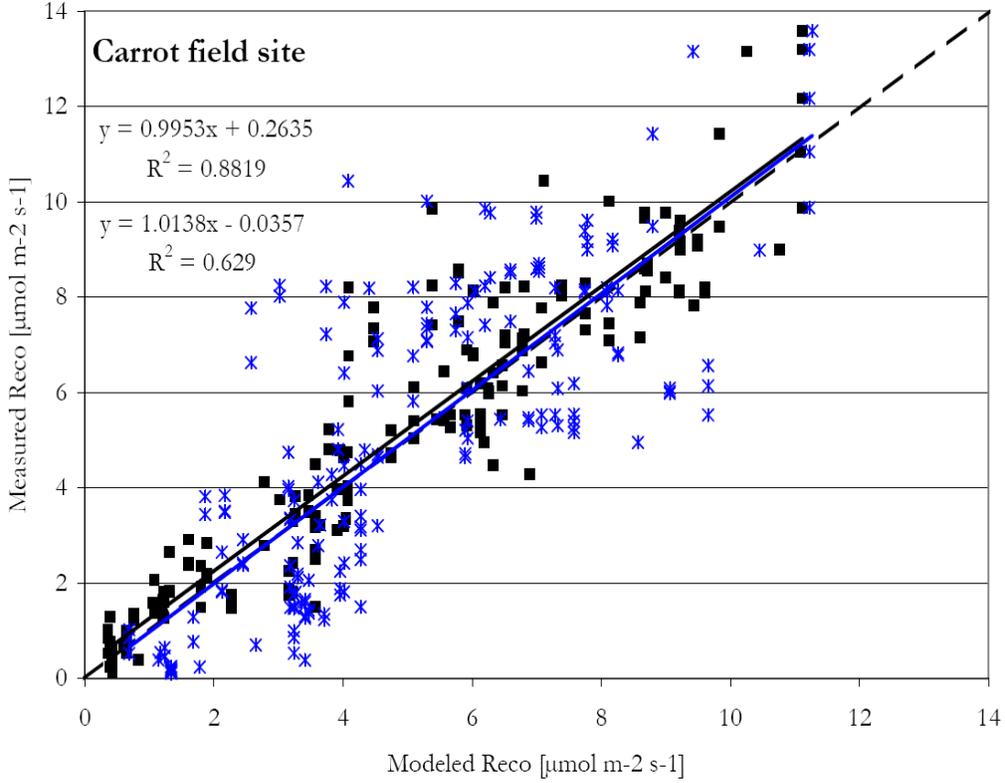
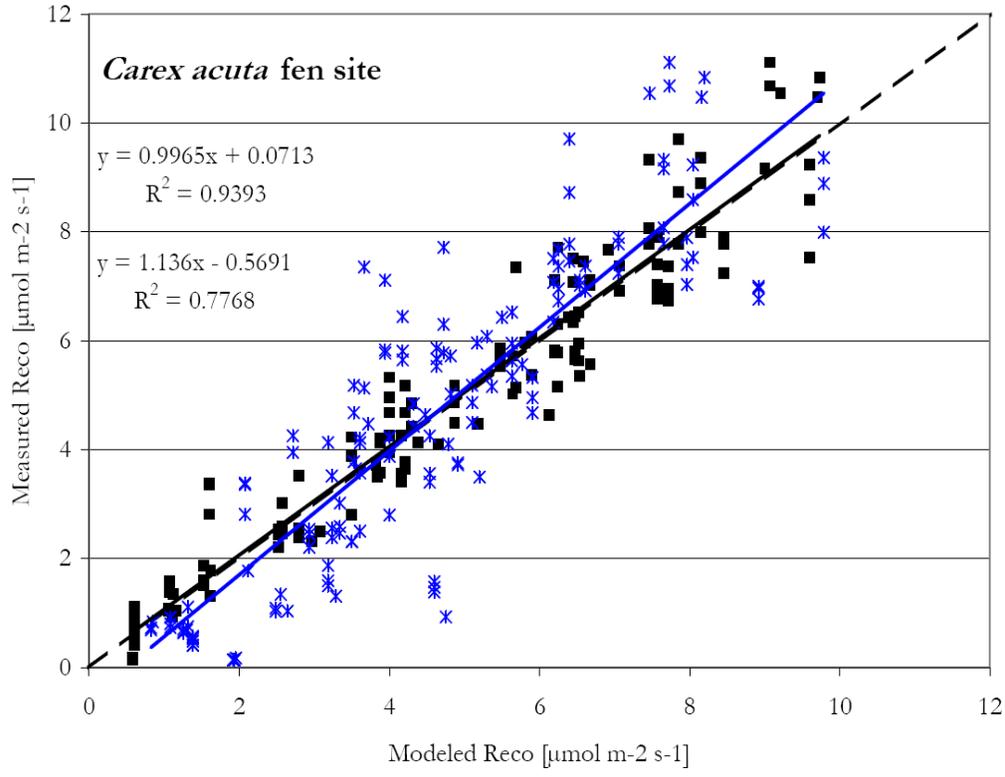
3.6 Seasonal model versus year model

As a further assessment into the validity and accuracy of the seasonally parameterized model hereafter named ‘seasonal model’, a comparison was made with a singularly parameterized model, hereafter named ‘year model’. The year model was created by finding the best-fit temperature regression with all of the year’s R_{eco} measurements and using the corresponding parameters to model the year’s respiration at half-hour resolution. The modeled versus measured R_{eco} values were then plotted and compared to the linear regression as with the seasonal model (Figure 3-12). Almost all of the sites show the same pattern, the lower R_{eco} measurements from winter are over-estimated and the summer higher R_{eco} values are underestimated with the exception of the carrot field, which maintained close to a 1:1 ratio. Moreover the overall fit of the model is much less accurate - evident from the increased scatter in the diagram - than the seasonal model with r² values ranging from 0.63 to 0.78.

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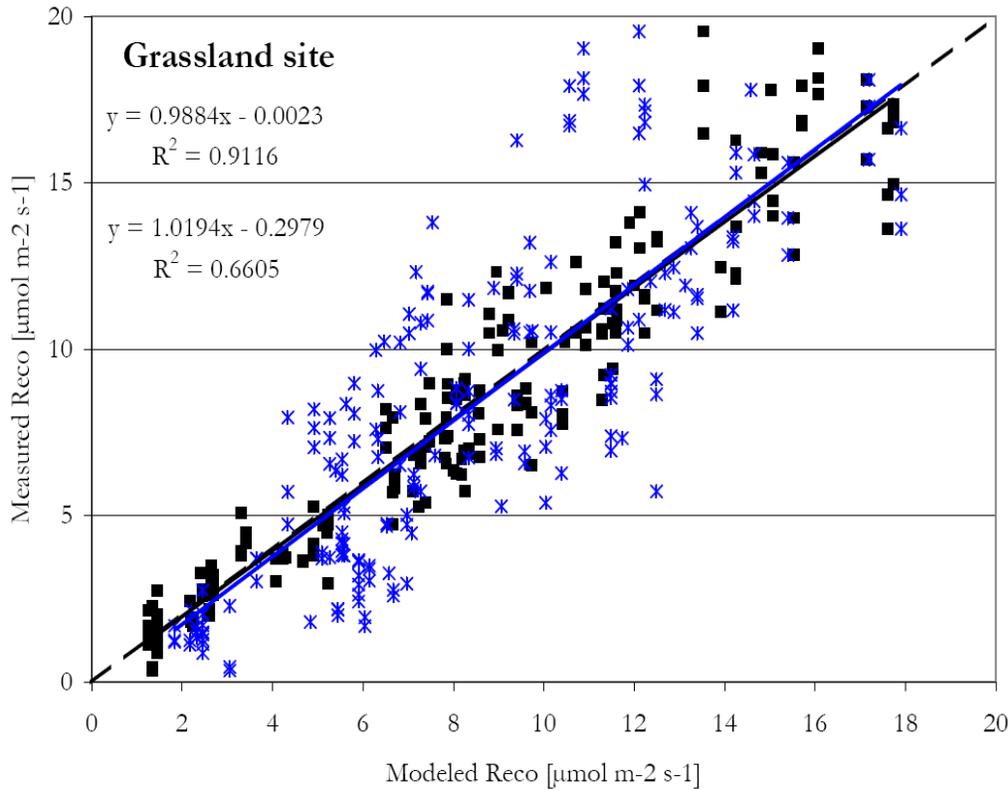


Figure 3-12. Modeled versus measured R_{eco} values fitted with a linear regression for the seasonally parameterized (seasonal) ■ and singularly parameterized (year) * models.

Considering that the seasonal model more accurately represented, the year model apparently overestimates respiration values in the yearly balance (Table 3-10). The overestimation of the *Carex paniculata* fen site is on the order of 13% [223 g $\text{CO}_2\text{-Cm}^{-2}\text{y}^{-1}$]. To a lesser extent the *Carex acuta* fen site and the carrot field were overestimated by 12% and 8% [146 and 103 g $\text{CO}_2\text{-Cm}^{-2}\text{y}^{-1}$] respectively. However the end carbon respiration ($\text{CO}_2\text{-C}$) balance estimation for the *Carex disticha* and grassland sites by the year model were slightly under the seasonal model only differing by 1-8 g $\text{CO}_2\text{-Cm}^{-2}\text{y}^{-1}$ respectively. These differences are however not statistically significant, ANOVA, $p > 0.05$, $N = 3$ (Figure 3-13).

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Table 3-10 R_{eco} total values for 2005 as estimated by seasonal and year models.

Site	seasonal [g CO ₂ -Cm ⁻² y ⁻¹]	Year [g CO ₂ -Cm ⁻² y ⁻¹]
<i>Carex disticha</i> fen site	1221.61	1220.32
<i>Carex paniculata</i> fen site	1445.30	1668.44
<i>Carex acuta</i> fen site	1142.63	1289.04
Carrot field site	1108.64	1212.04
Grassland site	2083.86	2075.72

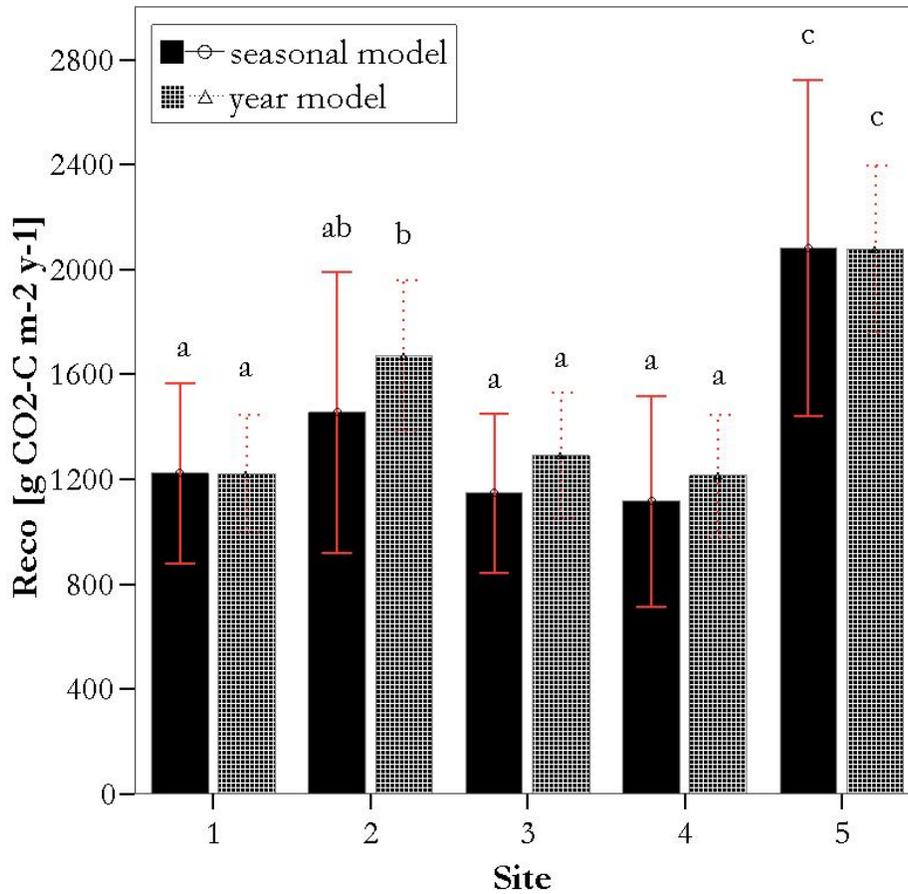


Figure 3-13. Comparison of the Reco total values [g CO₂-C m⁻² y⁻¹] for the seasonal and year models (error bars signify standard error), groups with the same letter are not statistically different (ANOVA, Duncan post-hoc test, p<0.05, n=3). Site codes: 1 = *Carex disticha* fen site, 2 = *Carex paniculata* fen site, 3 = *Carex acuta* fen site, 4 = carrot field site and 5 = grassland site.

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The apparent overestimation by the singularly parameterized model (year) originates partially from the use of air temperature as the best fit for the exponential temperature regression (Equation 2-2) in the less variable and partially snow-covered winter months. Furthermore, the year model lacks the ability to adjust to differences in growing season respiration changes due to plant growth, water level fluctuation and the effects of management (Figure 3-14).

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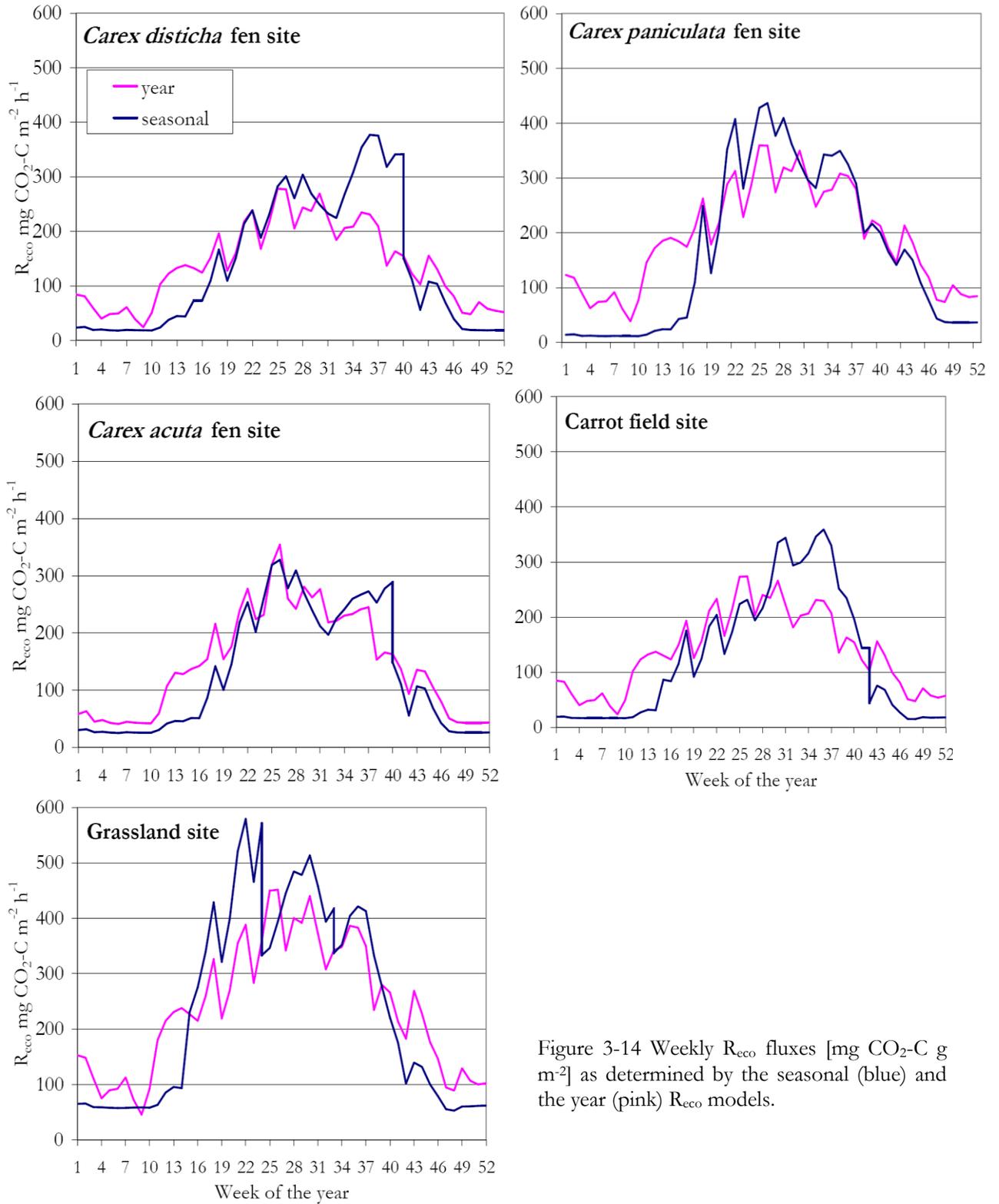


Figure 3-14 Weekly R_{eco} fluxes [mg CO₂-C g m⁻²] as determined by the seasonal (blue) and the year (pink) R_{eco} models.

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3.7 Sources of error

Environmental factors that could be sources of error during the field measurement included the effects of early morning CO₂ settling within the sites, sudden windy conditions and the record of water temperature instead of soil temperature at 2 and 5cm. The settling of a layer of CO₂-rich air after windless nights, caused measurement readings to reach the maximum limit of the analyzer and therefore accurate readings could not be taken. A gust of wind blowing through the sites had caused certain measurements taken directly afterward to be abnormally high. The cause could be the stirring up of the boundary layer of CO₂ that is typically protected and not part of the ecosystem exchange of carbon dioxide under normal conditions. During flooding in the restored fen, the water table was above 5cm and 2cm soil depth and therefore the measurements for soil temperature followed a daily water temperature pattern instead of the slower reacting soil temperature. However, because flooding was mainly segregated to the summer months, air temperature tended to be the best temperature fit for the data.

Technical sources of error also were evident in the field including low analyzer battery effects (typically resulting in abnormally low concentration change readings), lack of air tightness in the chamber due to cracks and water inside of the connection tubes between the analyzer and the chamber.

4 DISCUSSION

4.1 Seasonal determination of R_{eco} parameters for annual model

4.1.1 SEASONAL VERSUS ANNUAL TEMPERATURE SENSITIVITY AND ACCURACY IN CARBON BALANCE DETERMINATION

Determining the R_{eco} component of the carbon balance according to seasonal parameters improved the overall respiration temperature exponential regression accuracy compared to the measured R_{eco} values. In this way the model is more realistic, because it inherently includes confounding factors including water level and plant activity, which change over the season, without having to input them into the model separately. The overestimation of R_{eco} by the singularly parameterized model (year) reported by REICHSTEIN et al. (2005a), however, was not significantly supported by this study. The year model consistently overestimated ecosystem respiration in the winter months, but underestimated the effects of plant phenology and management during the growing season resulting in statistically insignificant differences in the total annual respiration rate.

4.1.2 AIR TEMPERATURE VERSUS SOIL TEMPERATURE

The parameterization of the model into campaign blocks allowed for soil temperature to be used to represent primarily soil-driven respiration in the winter months, and then switch to ambient air temperature when the driving factor was plant activity. The transitions between the temperatures in the model were typically smooth, even when subject to temperature source changes.

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4.2 Effects of seasonal variation in water level and LAI on R_{eco}

4.2.1 WATER LEVEL FLUCTUATION

Water levels during the campaign measurements were negatively correlated with the reference respiration parameter of the R_{eco} regression for the two mowed fen sites. Due to the time resolution of water level fluctuation, the model fails to respond quickly to water level changes and is still sensitive to this factor. However, this was only the case in the sites most prone to flooded conditions and did not have a significant effect on the *Carex paniculata* fen site or the drained sites. This indicates that different respiration processes affected by water level may be more pronounced for various sites due to vegetation type and the ratio of autotrophic to heterotrophic respiration.

BLODAU et al. (2004) determined that plant respiration in peatland mesocosms was reduced by about 40% under low water table conditions whereas the carbon mineralization increased by one third. One of the differences evident between the restored fen sites was the tussock formation of the *Carex paniculata* fen site in contrast to the lawn-forming *Carex disticha* and *Carex acuta* fen sites. The tussock itself is able to host other vegetation including moss and other vascular species above the normal water table within its stable structure, increasing the amount of biomass buffered from water level fluctuation (TUITTILA et al. 1999). In contrast, the lawn fen sites had lower plant biomass over the year than the *Carex paniculata* site and had a higher percentage of total plant biomass subject to the immediate changes in water level.

Although soil water content is a significant factor regulating ecosystem respiration in drained peatland sites as well (GLATZEL et al. 2004; PETRONE et al. 2003), the water table over the year was apparently too low in the grassland and carrot field site to indicate the fluctuation in soil moisture (compare with MALJANEN et al. 2001).

4.2.2 GREEN LEAF LAI

The seasonal change in green leaf area index (LAI) was correlated to ecosystem respiration weekly average fluxes, except for the carrots, which had a later growing season ending in October. As the temperature of best fit for the R_{eco} model for spring to late fall is air temperature for every site, it is apparent that plant interaction acts as the overriding factor for R_{eco} during the growing season. This finding is in agreement with other studies in fens (PETRONE et al. 2003; TUUTTILA et al. 1999). KOMULAINEN et al. (1999) compared the CO_2 efflux of vegetated and non-vegetated peatland sites and found that 50–70% of R_{eco} could be attributed to the respiration of recent allocation of carbon through photosynthesis. In grassland sites, FLANAGAN & JOHNSON (2005) reported that 94% of the variation in the reference respiration, R_{ref} at 10°C , of a temperate grassland could be attributed to the factors of plant biomass and soil moisture.

Due to the efficiency of carrot plants in allocating carbon to tubers, i.e. a low plant respiration to gross photosynthesis ratio (AMTHOR & BALDOCCHI 2001; KYEI-BOAHEN et al. 2003), combined with the cooler temperatures at the height of the carrots in mid-October, the LAI had no significant relationship with weekly ecosystem respiration rate averages in the carrot field site. Nevertheless, the year model underestimates the carrot field site respiration during the carrot-growing season, indicating an effect outside of temperature tied to plant interaction, which is not consistent throughout the growing season.

Peak LAI was not correlated with R_{eco} annual CO_2 respiration rates between the sites. Although the grassland site had a statistically lower LAI than the *Carex paniculata* fen site throughout the year, it has a higher total annual respiration rate, indicating a larger role for other environmental factors.

4.3 Effects of management on R_{eco}

Besides more accurately representing important seasonal differences in R_{eco} due to plant phenological and biological metabolism variation than the singularly parameterized R_{eco} model, the seasonally parameterized R_{eco} model can immediately respond to the effects of management

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not characterized by temperature alone (compare with BREMER & HAM 2002; BYRNE et al. 2005; CRAINE & WEDIN 2002). This study furthermore gives evidence for the effects of mowing management on fen ecosystems in addition to grasslands.

4.3.1 HYDROLOGY

The primary management difference grouping the peatland sites was drainage. The restored sites were statistically homogenous with water levels fluctuating between flooded and slightly below the surface (approximately –10cm to 15cm) whereas the drained sites had a depth to water table no lower than 22cm. As the CO₂ respiration in peat under aerobic conditions is higher than anaerobic conditions, all other factors being equal, drained peatland sites have a higher potential for CO₂ respiration (GLATZEL et al. 2004). However, the grassland site had a significantly higher total CO₂ respiration emission than the carrot field site, indicating that the difference in management between the two drained sites, particularly the length of the vegetation period, influenced ecosystem respiration. Moreover, the carrot field site did not differ significantly from the restored fen sites in total respiration of CO₂, indicating that factors outside of water level determined the respiration rate of the sites, similar to UPDEGRAFF et al. (2001).

4.3.2 SOIL CONDITIONS

Although the peat profile of the various sites was comparable (DRÖSLER 2006), the soil moisture and soil carbon between the sites due to different management regimes probably provided a significant difference in total annual respiration of CO₂. In peat-mined soils, readily decomposable carbon from the exposed peat has already been utilized by heterotrophs (HOGG et al. 1992), therefore the respiration rate of CO₂ is relatively reduced in soils without new carbon entering the system from vegetation (TUITILA et al. 1999). Hence the higher respiration rate in the grassland can be partially attributed to the constant source of new photosynthates to the soil, in addition to the higher potential for carbon dioxide respiration due to constant aerobic

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respiration conditions, whereas the carrot field site was devoid of new carbon sources (i.e. without vegetation) for two-thirds of the year.

The carrot field had higher soil temperatures at 2cm depth (max. 36°C) than air temperature at 20cm (max. 34°C) during the summer months and had bare dark brown-black soil for 8 of 12 months. Although soil moisture was not measured, it can be inferred that the soil moisture content of the plowed, bare, heated soil was less than that of the neighboring vegetated grassland site. Soil moisture has been found in grasslands to be an important factor in ecosystem respiration, with middle values (~25% soil moisture) having the highest soil respiration, and values lower than 10% at significantly lower levels of total respiration (BYRNE et al. 2005).

4.3.3 VEGETATION AND CROP MANAGEMENT

Every site, with the exception of the *Carex paniculata* fen site, is subject to vegetation management at least every other year. The obvious impact of mowing events is the immediate decrease in the ecosystem respiration of CO₂ in part due to the removal of respiring plant material. Additionally, cutting aboveground plant material decreases root metabolism and consequentially the amount of root exudates, leading to less new carbon sources available to heterotrophs (CRAINE & WEDIN 2002). The soil respiration is therefore reduced even at increased soil temperatures after mowing (BREMER & HAM 2002). As a result, the total annual respiration rates are ultimately lower than would be without management.

After every mowing event, except for the second grassland cut, the best-fit temperature switched from air temperature to soil temperature for the exponential temperature regression (Equation 2.2) indicating that the plant respiration had been the driving respiratory source previous to cutting and, afterwards, soil respiration. Since the second cut in the grassland left on average twice as much green leaf biomass standing as the first cut, perhaps the plant respiration remained the primary respiration source, which resulted in the air temperature having a better fit. The first cut in the grassland could serve as an approximation of the ratio between soil and total

Section 4: Discussion

respiration of the grassland, approximately 0.59, which is comparable to other ratios found in agricultural grasslands on peat soils, i.e. 0.62 (LOHILA et al. 2003).

The development of the carrots from July to October exhibited lower respiration rates than the grassland, even at the height of the carrots and after the second cut in the grassland. Since the soil conditions are presumed to be similar between the two sites during the full cover of carrots, the vegetative difference between the sites seems to be the principal factor determining their respiration rates. And indeed, managed grasslands have been shown to autotrophically respire up to 65% of the carbon allocated by photosynthesis, whereas tuber crops including carrots are much more efficient in storing carbohydrates in their root systems and only respire about 35-50% of allocated carbon through plant respiration (AMTHOR & BALDOCCHI 2001). In fact, in a study on the photosynthetic response of carrots to varying irradiance, the ratio of the dark respiration of carrot leaves at 20°C (photosynthetically active radiation, PAR=0) to the leaf net photosynthetic rate at 1000 [$\mu\text{mol m}^{-2} \text{s}^{-1}$] PAR was approximately 0.16 (KYEI-BOAHEN et al. 2003).

Additionally, since a portion of the new sources of easily decomposable carbon for heterotrophic respiration comes from root exudates, the surface area of grass roots in comparison carrot roots could provide a significantly greater amount of new carbon into the system, fueling higher soil respiration. LOHILA et al. (2003) exhibited similar results between cultivation of grass and potatoes on peat soils, the peak R_{eco} rate of grass cultivation being 25% higher than the tuber crop.

The harvest of the carrots immediately reduced the ecosystem respiration rate by over two-thirds as the site was returned to bare soil conditions, devoid of plant respiration and new carbon input for heterotrophic respiration. The grassland, on the other hand, retains green leaf biomass throughout the winter with the potential to photosynthesize. This factor combined with an aerated soil above 0°C, could explain the higher respiration rate of the grassland during the winter months in comparison to the restored fen sites and the carrot field.

The variance in the respiration rate between sites and years has been shown to explain significant differences in net ecosystem exchange (NEE) in peatlands (BUBIER et al. 2003). Through the seasonal parameterization of the R_{eco} model over the year, variation due to the often-confounding factors of plant phenology, soil microbe activity and gas diffusion was inherently included in the model, resulting in a more accurate representation of the ecosystem respiration variation over the year and between restored and drained peatland sites in the Donauried.

In order to improve this model, a water-level parameter could be included as to create a more accurate representation of ecosystem respiration on a higher resolution than every three weeks. Measurement of the soil moisture in the drained sites could provide further insight into respiration rate variability between grassland and cropland R_{eco} . Moreover, due to crop rotation on arable land in the Donauried, it is important to evaluate each crop type to characterize the variation in respiration rates due to vegetation period, plant production and carbon allocation efficiency.

Peat soils drained and used for agricultural purposes have been shown to respire 2 to 3 times as much CO_2 than mineral or sandy soils with the highest efflux coming from grassland sites (LOHILA et al. 2003). As approximately 83% of Germany's total fen area is utilized for agriculture, 6,396 km^2 in managed grasslands and 3,937 km^2 of 12,434 km^2 as arable land (FREIBAUER et al. in prep. cited in BYRNE et al. 2004), the potential for mitigating greenhouse gas emissions through changes in land management is substantial. This study shows that vegetation management in combination with drainage influences ecosystem respiration rates as the grassland on drained peat soils had a significantly higher CO_2 efflux than the restored fen microsites and the plowed carrot field. In the upcoming calculation of the carbon balance of these sites, the variation in respiration rates could determine whether a site is a sink or a source of carbon.

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**ECOSYSTEM RESPIRATION OF RESTORED
AND DEGRADED FENS SITES IN THE
DONAURIED, SOUTHERN GERMANY**

Master's Thesis by Rachel Schultz

Appendix 1:

Vegetation data

(DRÖSLER 2006)

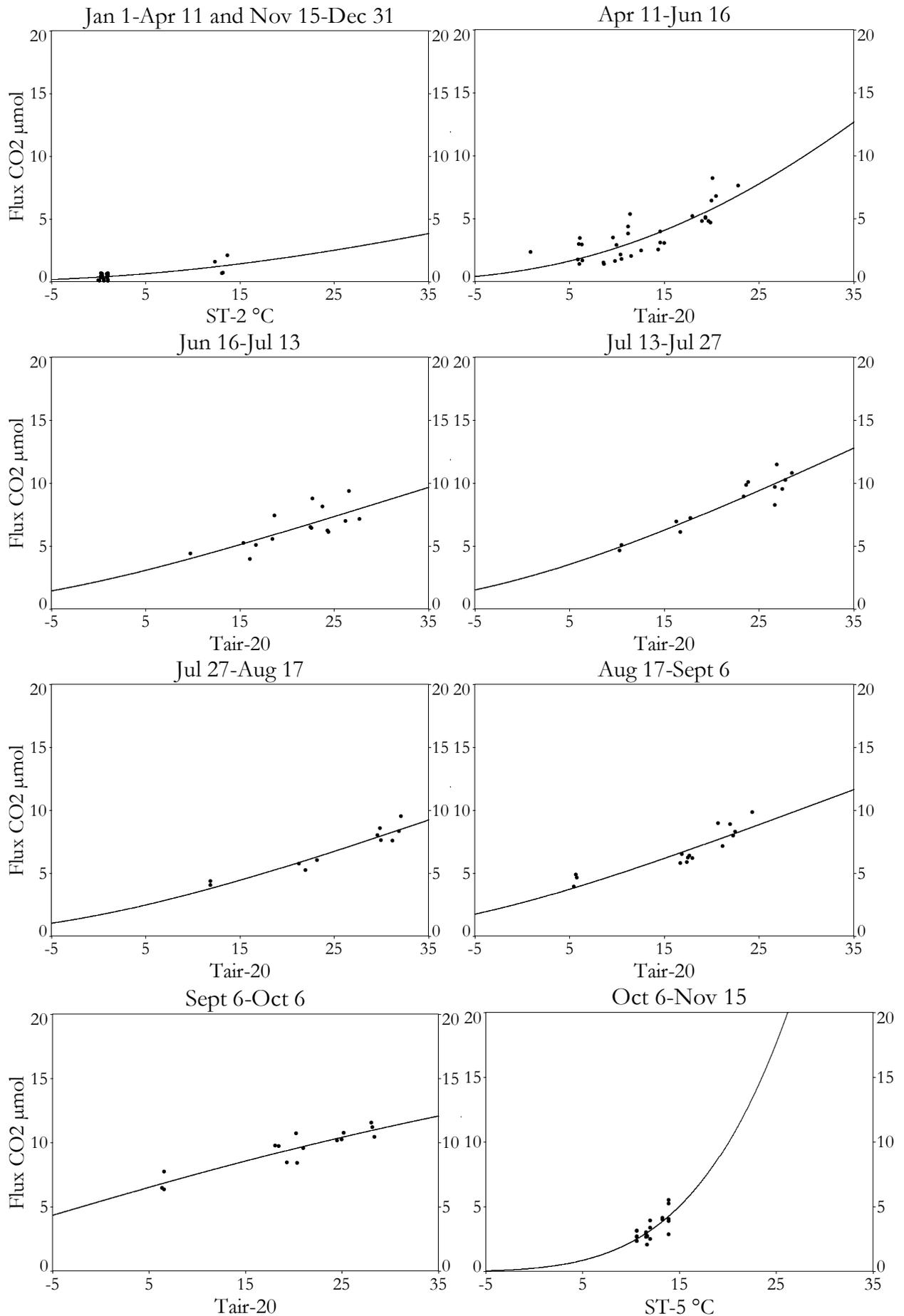
PCORD	Scientific name	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12	P13	P14	P15
Achmill	<i>Achillea millefolium</i> L.													20	20	25
Agrstol	<i>Agrostis stolonifera</i> L.													25	20	15
Aloprat	<i>Alopecurus pratensis</i> L.													35	33	30
Angarch	<i>Angelica archangelica</i> L.						3									
Calcord	<i>Calliargon cordifolium</i> (Hedw.)Kindb.	100	100	100	80	80	80	100	100	100						
Cardist	<i>Carex disticha</i> Huds.	65	30	20												
Cargrac	<i>Carex acuta</i> L.	20	50	60				50	45	40						
Carpan	<i>Carex paniculata</i> L.				85	85	85									
Carrost	<i>Carex rostrata</i> Stokes							30	30	30						
Cirspal	<i>Cirsium palustre</i> (L.) Scop.					2										
Dactincar	<i>Dactylorhiza incarnata</i> (L.) Soó					2										
Eriang	<i>Eriophorum angustifolium</i> Honck.							5	10	10						
Epilpal	<i>Epilobium palustre</i> L.					2	5									
Equpal	<i>Equisetum palustre</i> L.		3	3	5	5	2	10	10	10						
Galpal	<i>Galium palustre</i> L. s. l.	2	2	2	5	2	2	2	5	5						
Lolper	<i>Lolium perenne</i> L.													10	15	15
Lytsal	<i>Lythrum salicaria</i> L.	3	3	2		2	3		2	5						
Mentaqu	<i>Mentha aquatica</i> L.		2	2	5	2	2		3	8						
Poaprat	<i>Poa pratensis</i> L. s. str.													5	10	10
Trifrep	<i>Trifolium repens</i> L.													5	2	5
Typhlat	<i>Typha latifolia</i> L.	10	10	10				3								
carrot	<i>Daucus carota</i> subsp. <i>sativus</i> (Hoffm.) Arcang.										100	100	100			
	Total # of species	6	8	8	5	9	8	7	8	8	1	1	1	6	6	6

Appendix 2:

Ecosystem respiration relationship to temperature:

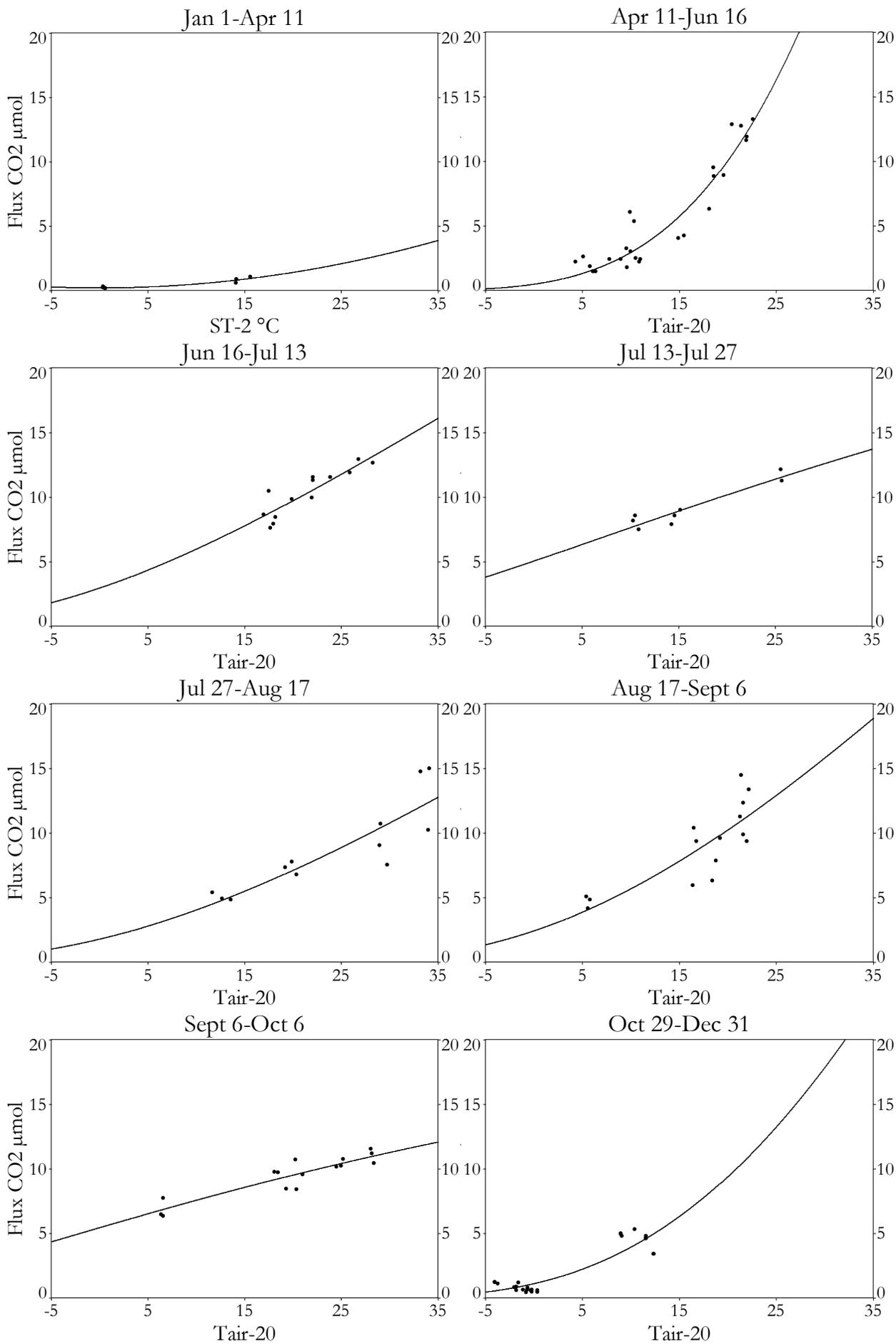
LLOYD & TAYLOR (1994) exponential regression model graphs fit to individual campaign periods for either air temperature at 20cm (T_{air-20}) or soil temperature at 2 or 5cm depth (ST2, ST5).

Carex disticha fen site 2005

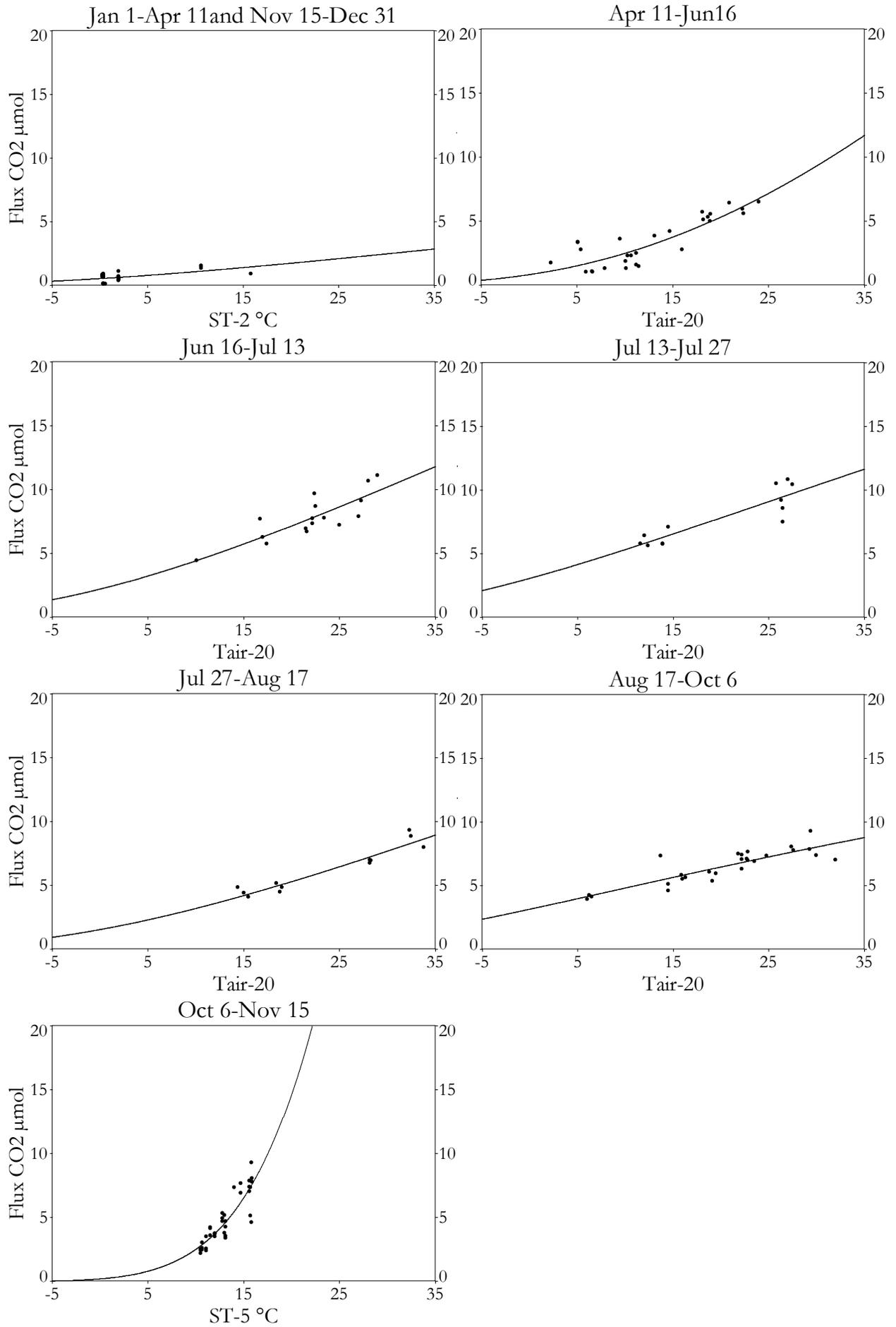


Note: CO₂ fluxes are in $\mu\text{mol m}^{-2} \text{s}^{-1}$, see Table 3-6 for specifics on the Lloyd & Taylor (1994) regression parameters.

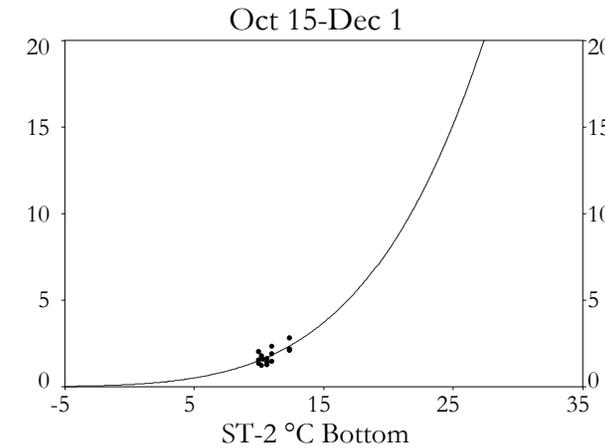
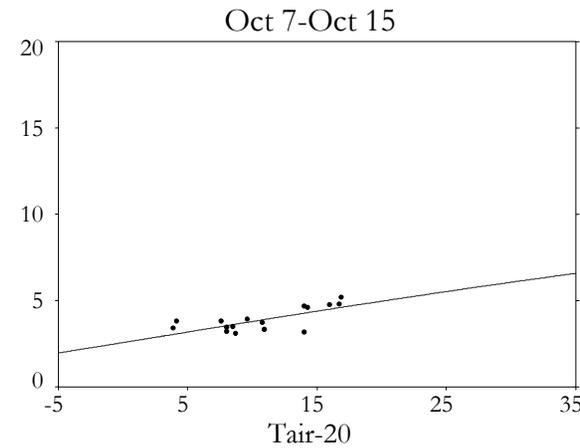
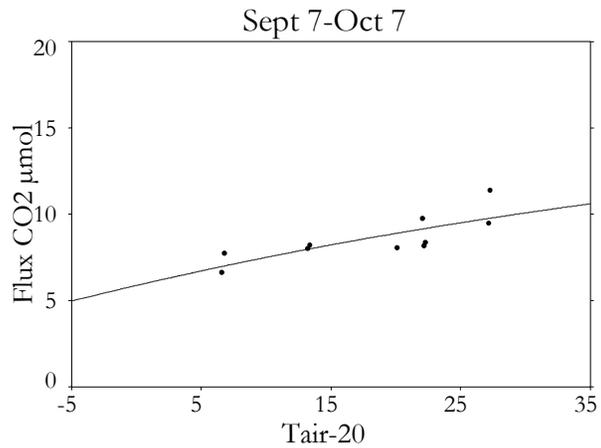
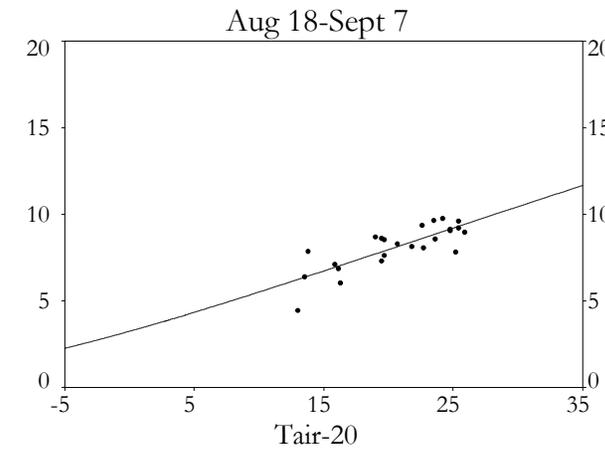
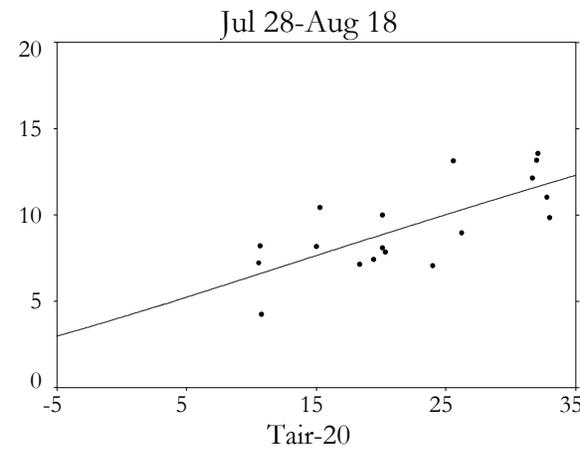
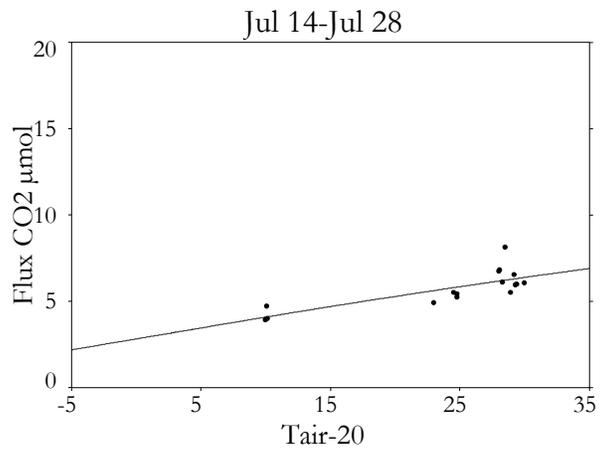
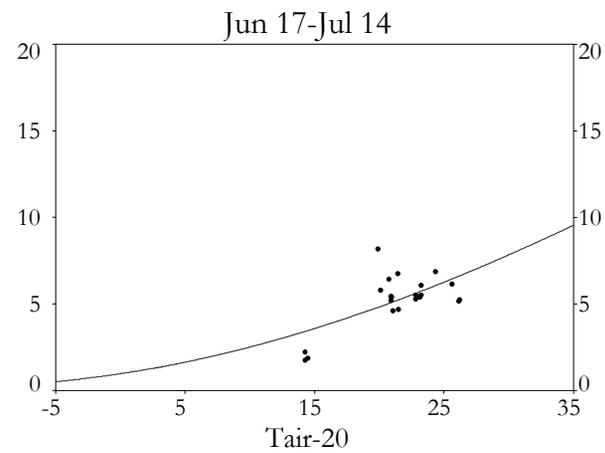
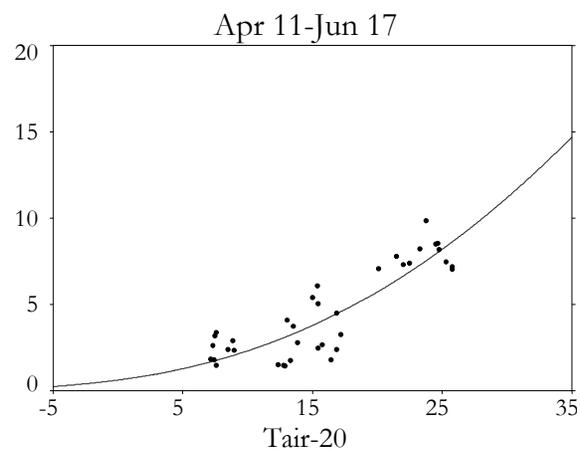
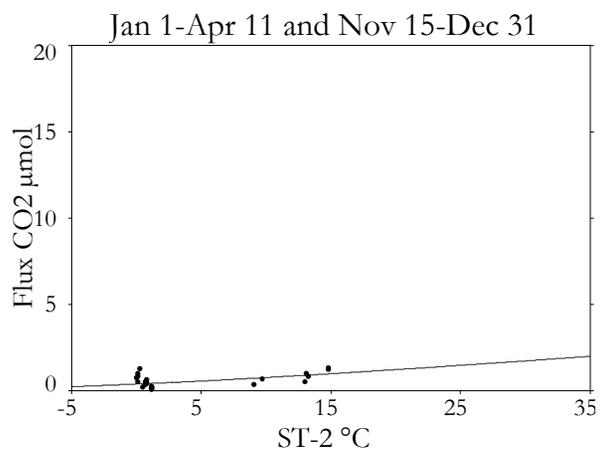
Carex paniculata fen site 2005



Carex acuta fen site 2005



Carrot field site 2005



Grassland site 2005

