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ECOSYSTEMS

CLIMATE CHANGE IMPACTS ON TERRESTRIAL ECOSYSTEMS (CLIMOOR)

Novel Approaches to Study Climate Change Effects on Terrestrial Ecosystems in the Field: Drought and Passive Nighttime Warming

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ABSTRACT

This article describes new approaches for manipulation of temperature and water input in the field. Nighttime warming was created by reflection of infrared radiation. Automatically operated reflective curtains covered the vegetation at night to reduce heat loss to the atmosphere. This approach mimicked the way climate change, caused by increased cloudiness and increased greenhouse gas emissions, alters the heat balance of ecosystems. Drought conditions were created by automatically covering the vegetation with transparent curtains during rain events over a 2–5-month period. The experimental approach has been evaluated at four European sites across a climate gradient. All sites were dominated (more than 50%) by shrubs of the ericaceous family. Within each site, replicated 4-m × 5-m plots were established for control, warming, and drought treatments and the effect on climate variables recorded. Results over a two-year period indicate that the warming treatment was successful in achieving an increase of the minimum temperatures by 0.4–1.2°C in the air and soil. The drought treatment resulted in a soil moisture reduction of 33%–82% at the peak of the drought. The data presented demonstrate that the approach minimizes unintended artifacts with respect to water balance, moisture conditions, and light, while causing a small but significant reduction in wind speed by the curtains. Temperature measurements demonstrated that the edge effects associated with the treatments were small. Our method provides a valuable tool for investigating the effects of climate change in remote locations with minimal artifacts.

Key words: Experimental manipulation; nighttime warming; drought; shrubland ecosystem; climate change; artefacts; edge effects.

INTRODUCTION

Historical records show an increase in mean global temperature of 0.6°C over the last 100 years (Houghton and others 2001). The increase over

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land has mainly been due to an increase in the daily minimum temperatures ($T_{\min}$) which have increased twice as much as maximum temperatures ($T_{\max}$), primarily because of increased cloudiness (IPCC 1995). The increased minimum rather than average temperatures have been shown important for the effects (Alward and others 1999). This increase in global temperature has co-occurred with elevated atmospheric CO_2 (Watson and others 1991; Luxmoore and others 1998). Therefore, scenarios for anthropogenic emissions of CO_2 and other greenhouse gases predict an increased global mean surface temperature of 1.4– 5.8°C (Houghton and others 2001). Along with these changes a more vigorous hydrological cycle is expected to lead to more severe droughts and floods (Houghton and others 2001).

Temperature and water are the main drivers for many biological and chemical processes and, thus, ecosystem functioning. Therefore, CO_2 enrichment and warming, in combination with the predicted changes in rainfall pattern, will potentially influence the functioning of natural and seminatural environments both directly and through interactions with land management and pollutant loading (IPCC 1990). For example, elevated temperatures may affect the overall C storage in ecosystems (Cao and Woodward 1998; Lindroth and others 1998) and, thus, have the potential to change ecosystems from sinks to sources for carbon (Shaver and others 1992) and nitrogen (for example, Wright and others 1998). Increased frequency of summer droughts may have profound effects on soils and water quality directly through changes in soil structure (Wolters and others 2000) or indirectly through effects on soil organic matter turnover (Freeman and others 1993). Changes in soil physical parameters, temperature, and resource allocation may strongly affect plant competitiveness (Shaver and others 2000; Wolters and others 2000) and lead to changes in species richness and biodiversity (Farnsworth and others 1995; Chapin and others 1996). This may affect the resistance and resilience of the ecosystem to environmental and climatic pressures such as drought (Tilman and Downing 1994). However, the effects of global change on ecosystem structure and function, including exchange of carbon, are complex and remain uncertain.

Understanding and predicting the climate-driven changes in ecosystem functioning requires studies at the ecosystem level, involving experimental manipulation of temperature, water, and CO_2. Ecosystem manipulations with warming (in some cases in combination with CO_2) have been performed in a large number of projects during the last decade by various methods, such as heating cables on top of or in the soil (for example, Peterjohn and others 1993; Lukewille and Wright 1997; Bergh and Linder 1999), warmed mesh put on top of the soil (Ineson and others 1998b), infrared lamps (Harte and others 1995; Wan and others 2002), large whole ecosystem greenhouses (Van Breemen and others 1998), large open-top chambers (OTC) (Norby and others 1997), small OTCs (Marion and others 1997), domes/shelters (for example, Chapin and others 1995; Jonasson and others 1999; Miles and others 1997), and transplanting soils or mesocosms (Ineson and others 1998a).

All experimental manipulation methods involve a number of unintended or undesirable changes, such as disturbance to the soil by installing heating cables (McHale and Mitchell 1996) and reducing light intensity (Van Breemen and others 1998) and wind stress (Rasmussen and others 2002) by building chambers or greenhouses. Consequently most methods have restricted applicability to study ecosystem responses and some may be unrealistic as tools to study whole ecosystem responses (Schulze and others 1999). The ultimate goal in ecosystem experimentation is to find solutions that maximize the scientific outcome within economic and technological constraints without causing large and unacceptable artifacts. The potential artifacts we considered of greatest importance in this study were the *physical scale* (plot size should be sufficient to capture whole plant responses and interaction and to ensure that measurements were not affected by edge effects), the *light regime* (disturbance of the light regime should be avoided), the *wind stress* (obstruction of the wind stress should be minimized), and *water conditions* (influence on rainfall quantity and chemistry, spatial and temporal distribution, and air humidity should be minimized).

Here we present an experimental concept used within the ecosystem project, CLIMOOR (climate-driven changes in the functioning of health and moorland ecosystems), to study the effects of warming and drought on ecosystem functioning of heath and moorland ecosystems. Our aims were to:

- describe two novel manipulation approaches to conduct ecosystem warming ("passive nighttime warming") and drought in the field
- assess the applicability and artifacts associated with the methods and their suitability for studies of climate-induced ecological effects at the ecosystem scale.

Table 1. Main Characteristics for CLIMOOR Sites

Site name Country	Mols DK	Clocaenog UK	Oldebroek NL	Garraf SP
Location	56°23' N 10°57' E	53°03' N 3°28' W	52°24' N 5°55' E	41°18' N 1°49' E
Altitude (m)	58	490	25	210
Air temperature (°C)				
Year:	9.4	8.2	10.1	15.1
January:	1.6	4.3	2.0	7.4
July:	18.1	12.4	17.8	22.5
Precipitation 1998–2000 (mm)	758	1741	1042	455
Soil	Sandy podzol	Peaty podzol	Sandy podzol	Petrocalcic calcixerepts
Dominant species	*Calluna vulgaris* *Desch. flexuosaa*	*Calluna vulgaris* *Desch. flexuosaa* *Vacc. myrtillus* *Empetrum nigrum*	*Calluna vulgaris* *Desch. flexuosaa* *Mollinia caerulea*	*Erica multiflora* *Globularia alypum*
Plant cover (%)	100	100	95	57
Aboveground				
C stock (g C m^{-2})	500	1790	584	275
N stock (g N m^{-2})	9	34	10	5
C/N	55	53	58	60
Belowground (0–45 cm)				
C stock (g C m^{-2})	3760	14800	6835	3684
N stock (g C m^{-2})	275	390	283	354
C/N in organic soil layer	18.5	37.4	22.5	n.d.
N -input 1998–2000 (kg N ha^{-1})	25–30	20–25	30–40	10–15

Desch. flexuosa—Deschampsia flexuosa.
Vacc. myrtillus—Vaccinium myrtillus.

SITE DESCRIPTIONS

The manipulations within CLIMOOR were carried out at four shrubland sites in Mols, Denmark (DK); Oldebroek, The Netherlands (NL); Clocaenog, United Kingdom (UK) and Garraf, Spain (SP) (Table 1). Shrubland ecosystems were chosen because they represent an important natural resource known to be sensitive to observed changes in environmental pressures (Heil and Bobbink 1993). All sites were dominated by shrubs (more than 50%) of which a major component was from the ericaceous family. The sites in DK, UK, and NL were comparable with respect to vegetation being dominated by *Calluna vulgaris* and *Deschampsia flexuosa* to various degrees. The Spanish site was a low Mediterranean shrubland dominated by *Erica multiflora* and *Globularia alypum*. The difference in vegetation limits the comparability among sites but increases the geographical relevance of the ecosystems studied at the specific sites.

Climatically, the sites differed, with temperature being higher southward and precipitation increasing westward (Table 1). Thus, the sites spanned gradients in the same climatic factors as were experimentally manipulated, thatis, temperature and precipitation. Furthermore, the sites differed by a factor of 4 with respect to nitrogen deposition (Table 1), which is believed to be a very important factor interacting with climate variables. The combination of gradients and experimental manipulation of temperature and precipitation increases the potential for evaluating the generality of the observed responses to the changes in the climatic drivers.

MANIPULATIONS AND EXPERIMENTAL DESIGN

CLIMOOR involved experimental manipulation of temperature (3 plots per site) and precipitation (3 plots per site) in the field.

Warming Treatment

The warming treatment was applied to three study plots of 20 m^2 (5 m × 4 m) at each site. The warning treatment was designed to mimc the increased minimum temperatures (night) rather than the general diurnal temperature increase. The warming plots

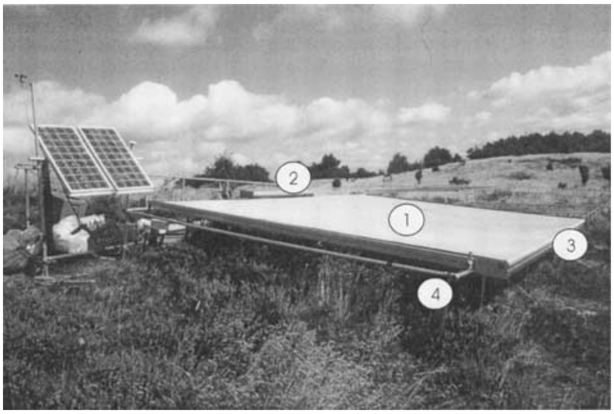

Figure 1. Curtain of aluminum for nighttime warming at Mols, DK, covering a 20-m^2 study plot. The curtains covered only the plots at night and were automatically operated according to light, rain, and wind conditions. Parallel plastic curtains serve as drought treatment. 1: curtain, 2: motor, 3: roll-bar for rolling the curtain at daylight. 4: supporting structure.

were covered by a light scaffolding carrying a curtain reflecting infrared (IR) radiation. The scaffolding was a frame of galvanized steel tubes covered by polyethylene plastic tubing to avoid leaching of contaminants from the frame into the plots. The curtain material consisted of 5-mm-wide aluminum strips knitted into a high-density polyethylene (HDPE) mesh (ILS ALU, AB Ludvig Svensson, Kinna, Sweden). The curtains reflected 97% of the direct and 96% of the diffuse radiation and allowed transfer of water vapor. The curtains were coiled on a beam and connected to a motor (Figure 1). The motor was activated automatically by an electronic controller set to the following climatic conditions throughout the year:

- *Light intensity*—at sunset (light intensity < 0.4 W m^{-2}) the curtains were automatically drawn over the vegetation to reduce the loss of IR radiation. At sunrise the curtains were retracted to leave the plots open during the day.
- *Rain*—to keep the hydrological conditions in the plots unaffected, a tipping-bucket rain sensor activated the removal of the curtains in case of rain during the night (sensitivity < 0.3 mm). When the rain stopped, the curtains were automatically drawn over the vegetation again.
- *Wind*—to avoid damage to the curtains, a wind sensor activated the removal of the curtains when wind speeds exceeded 10 m s^{-1} during the night. When the wind speed dropped below 10 m s^{-1}, the curtains were automatically drawn over the vegetation again.

The curtains were operated sequentially causing a delay time of approximately 4 min from the first to the last curtain in the sequence. The height of the curtains matched the height of the vegetation at each site and was 0.6–1.0 m above the soil surface. The study plots were open on all sides. All curtains operated on 24 V DC supplied by main power (Clocaenog, UK) or by solar panels (Mols, DK; Oldebroek, NL; Garraf, SP). At Garraf and Oldebroek the warming treatments were stopped once or twice for 2–4 weeks during the dormant season for calibration of temperature sensors.

Drought Treatment

The drought treatment was applied to three study plots of 20 m^2 at each site for extended periods in the growing season (Table 2). The drought plots were constructed similarly to the warming treatments except that the curtain material was a transparent polyethylene (PE) plastic. A rain sensor activated the curtains to cover the plots whenever it rained and to remove them when it stopped. The water collected by the curtains was removed from the area by gutters. The curtains were removed automatically if the wind speed exceeded 10 m s^{-1}. Beyond the time of the drought treatment, the drought plots were run parallel to the control plots.

Control

Parallel to the warming and drought treatments, three untreated control plots were operated for comparison. The control plots were covered by a similar light scaffolding as for the warming and drought treatments, but there was no curtain.

Measurements

To assess the functioning and effect of the curtains, various measurements were conducted.

Temperature. The temperature of the air and the soil was measured at each site by installation of temperature sensors in the air (20 cm above the soil surface) and in the soil (0, $-2/-5$, and -10 cm). The temperature sensors were thermocouple reference thermistor types (Probe 107, Campbell Scientific, Logan, UT, USA) at Mols (DK, 110 samplers) and Clocaenog (UK); PT100 thermistors (Campbell Scientific) at Oldebroek (NL) and RTD Pt100 1/3DIN (Desin Instruments, Barcelona, Spain) at Garraf (SP). At Mols (DK) 5 temperature sensors were placed in the center of each plot (1 air and 4 soil depths). An additional 20 sensors were placed in the corners and along the edges in all warming plots to assess the potential edge effects (Figure 2). At Clocaenog (UK), Oldebroek (NL), and Garraf

Table 2. Periods and Length of Drought Treatment at Each of the CLIMOOR Sites During 1999 and 2000

	Mols	Clocaenog	Oldebroek	Garraf
1999	18 May–29 Jul 72 days	18 Jun–31 Aug 74 days	26 May–4 Aug 70 days	17 Mar–19 Aug 155 days 4 Sep–2 Dec 89 days
2000	23 May–1 Aug 70 days	11 Jul–4 Sep 55 days	24 May–25 Jul 62 days	18 Apr–8 Sep 143 days 6 Oct–31 Dec 86 days

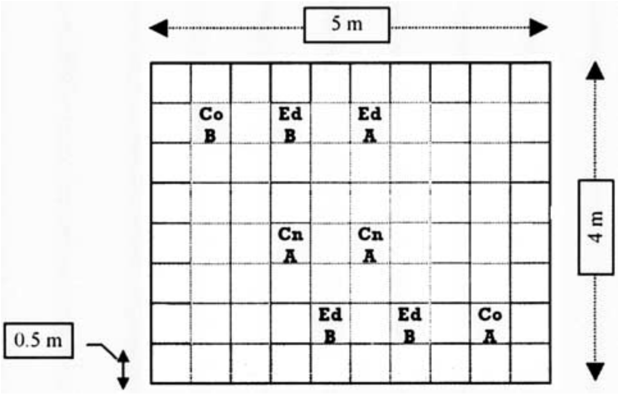

Figure 2. Position of temperature sensors at the warming plots at Mols. Grids show 0.5-m intervals. Gray area is the buffer zone not used for measurements. Positions are Co: "corner," Cn: "center," and Ed: "edge." Positions marked with letter "A" had sensors in +20, 0, −2, and −10 cm. Positions marked with letter "B" had sensors in 0 and −2 cm.

(SP), one temperature sensor per depth and plot was placed in the center of one of each of the treatment plots.

Precipitation and Water Input. Precipitation to the site was collected monthly, biweekly, or weekly by 1–2 regular rain gauges (∅ 15–25 cm) placed 1–2 m above the ground outside the study plots. Inside each study plot 1–3 rain gauges (∅ 12–20 cm) placed above the height of the vegetation recorded the water input to each plot.

Radiation. At Mols (DK) net radiometers (NR-lite, Kipp & Zonen, Delft, The Netherlands) were installed in May 2001–September 2001 to investigate the effect of the curtains on the radiation balance. Two sensors were installed at the height of the vegetation (0.5 m aboveground), one in a warming plot and one in a control plot. The net radiation in each plot was measured every 10 min and averaged at 40-min intervals.

Humidity. At Mols (DK) humidity sensors (VAISALA humitter 50, Helsinki, Finland) were installed at the center of one of the control plots and one of the warming plots, two sensors in each plot at 20 cm aboveground. The humidity was measured every 5 min and averaged at 2-h intervals.

Wind. At Mols (DK) anemometers (RIS∅ Cup anemometer P2546A, Roskilde, Denmark) were installed in the center of one control and one warming plot to test the effect of the extended curtain on wind speed. One anemometer was installed in each plot in May 2001–September 2001 at the height of the vegetation (0.5 m aboveground). The average wind speed over 20-min intervals was recorded.

Calculation of Growth Indices

The treatment effect on the potential for growth was calculated using two indices: growing degree-days (GDD) and growing season days (GSD). Growing degree-days can be calculated in various ways. We used a relatively simple averaging approach (see for example, Roltsch and others 1999). Lower- and upper-threshold temperatures were chosen (t_l and t_u, respectively) indicating the temperature range within which plant growth occurs. The growing degree-days for each single day i, GDD_i, was then calculated as

$$\mathrm{GDD}_i = (T_{\max(i)} + T_{\min(i)})/2 - t_l \qquad (1)$$

If $\mathrm{GDD}_i < 0$ or if $\mathrm{GDD}_i > (t_u - t_l)$, GDD_i was set to zero. Growing degree-days for the year (GDD) was calculated as the sum of all the daily growing degree-days:

$$\mathrm{GDD} = \Sigma \mathrm{GDD}_i \qquad \text{for } i = 1\text{–}365 \qquad (2)$$

Correspondingly, growing season-days (GSD) was calculated as the number of days in a year where the average temperature was within the temperature range set by t_u and t_l. For each day, it was decided whether the day added to the growing season by the following consideration:

$$\mathrm{GSD}_i \begin{cases} 1 & \text{if } t_l < (T_{\max(i)} + T_{\min(i)})/2 < t_u \\ 0 & \text{if } (T_{\max(i)} + T_{\min(i)})/2 < t_l \\ & \text{or } (T_{\max(i)} + T_{\min(i)})/2 > t_u \end{cases} \quad (3)$$

The yearly GSD is calculated as

$$\mathrm{GSD} = \Sigma \mathrm{GSD}_i \text{ for } i = 1\text{–}365 \quad (4)$$

The threshold temperatures t_u and t_l ideally should be chosen individually for each organism and climatic region. In this study, where the focus was on the relative change in GDD and GSD rather than the exact number of GDD and GSD, we chose the thresholds t_l = 5°C and t_u = 25°C in accordance with other studies (Bootsma 1994). A more sophisticated modification of the GDD calculations in Eqs. (1) and (2), the Single Triangulation Method (Roltsch and others 1999), was tested but little difference in the relative change in GDD between treatments and sites was observed.

Statistics

The treatment effect on the air and soil temperatures at Mols, DK, was tested by comparing the warming and the drought treatments with the control separately by using monthly averages per plot. The monthly averages were analyzed by single-factor analysis of variance, that is, the effects of control versus warming and control versus drought were analyzed separately. At Oldebroek (NL) and Garraf (SP) the temperature measurements from the calibration periods were used to calibrate the temperature sensors for the complete treatment period. The effect of warming and drought treatments on the air and soil temperatures was tested on data from all four sites by a Wilcoxon signed rank test. We tested if the monthly temperature differences (warming − control and drought − control, respectively) could be assumed to be greater than zero. The potential edge effect of the treatment at Mols was tested by a pairwise comparison of the average temperatures at the corners and edges, respectively, with average temperatures at the center of each plot (*t*-test performed on the temperature difference for each warming plot). Treatment effects on the soil moisture were tested by an analysis of covariance (GLM procedure in SAS, SAS Institute 1987) on monthly soil moisture measurements using the pretreatment soil moisture in each plot as a covariant.

RESULTS

Warming Treatment

The passive nighttime warming method involved covering the experimental plots to reduce the heat loss by IR radiation during the night. During the day there was a net radiation input to the plots with very little difference between the control and the warming plots (Figures 3 and 4). At sunset and during the night the control plots lost part of the energy conserved during the day and the radiation balance in the control plots became negative. In the warming plots the curtains reflected most of the outgoing radiation for the 5-month measurement period. The heat loss was reduced by 64% from 33 to 12 W m^{-2} compared with the control (Figure 3 and Table 3). The reduced heat loss in the warmed plots increased the temperatures in the air and soil compared with the control plots, showing a diurnal pattern with a maximum in the air at mid and late night and a minimum in the late afternoon (Figure 5 and Table 4). Although the heat loss was reduced only during the night, the warming of the soil was sustained during the day with almost consistent temperature increases in the soil over the night and

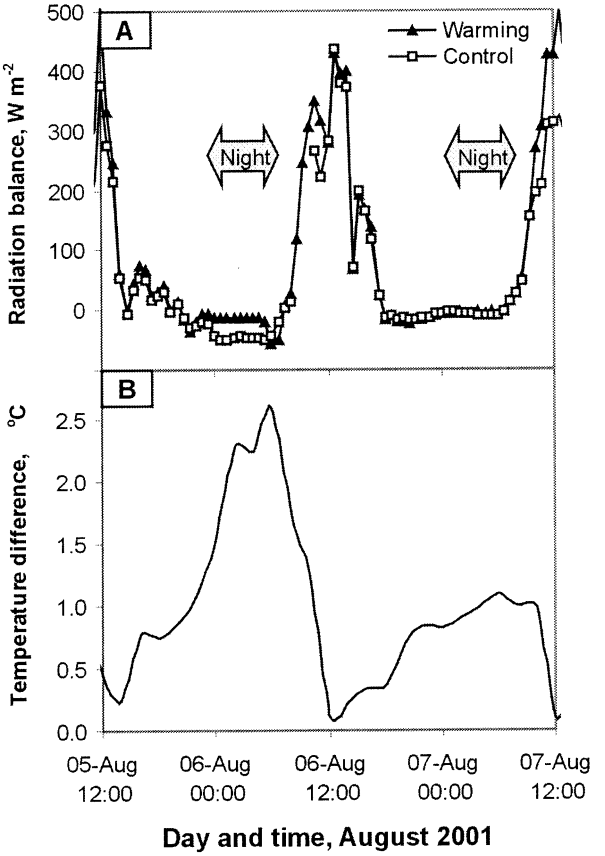

Figure 3. (**A**) Net radiation (W m^{-2}) in a warming plot and a control plot and (**B**) the corresponding difference in air temperature between the same treatments at Mols, DK, during a clear night (6 August 2001) and a cloudy night (7 August 2001). Gray arrows indicate time for curtain coverage.

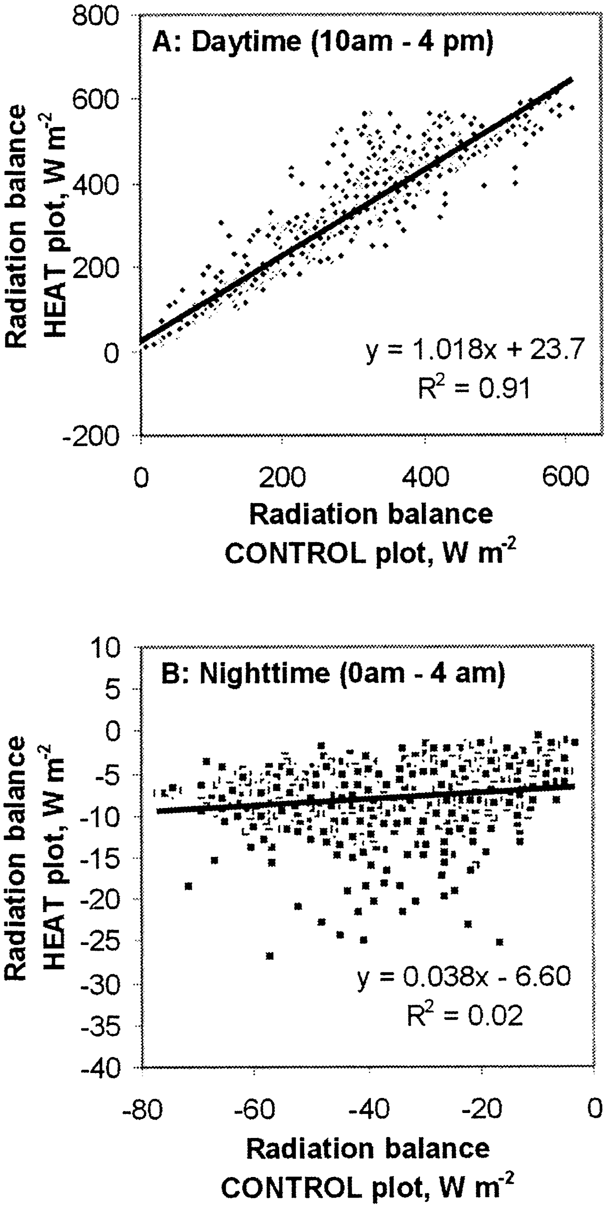

Figure 4. Radiation balance (2 h means, W m^{-2}) for the warming treatment versus the control at Mols during (**A**) daytime (10 a.m., 12 a.m., 2 p.m., and 4 p.m.) and (**B**) nighttime (0 a.m., 2 a.m., and 4 a.m.).

Table 3. Average Nighttime Radiation Balances per month [April–August 2001 (W m^{-2})] in the Warming and Control Plots at Mols and the Reduction in Energy Loss in the Warming Treatment Relative to the Control

Net radiation balance at night (W m^2)	Treatment	
	Control	Warming
April 2001	−35	−10
May 2001	−39	−11
June 2001	−37	−14
July 2001	−27	−12
August 2001	−31	−9
Average Apr–Aug 2001	−33	−12
Reduction in energy loss (% of control)		64

day, whereas in the air the warming was gradually decreased during the day.

At the low light intensities just before sunset and just after sunrise when the plots were not covered, the warming plots lost energy as did the control plots (Figure 3). This was the general pattern in the energy-related dynamics. Occasionally, cloudy weather conditions reduced the heat loss from the control plots in the same way as the curtains, resulting in little or no temperature difference between the warming and control plots as demonstrated 7 August 2001 (Figure 3). Furthermore, the day-to-day pattern in temperature increase was strongly affected by changes in the ambient temperature. When the ambient temperature decreased, the curtains tended to conserve the heat stored in the soil and thereby increase warming above the average. Likewise, when ambient temperatures increased, the curtains tended to keep the soil cold leading to occasional cooling (Figure 6).

The ambient temperature differed over the sites from the relatively cold and wet site in Wales, UK, over the intermediate Dutch and Danish sites, to the warm and dry Spanish site (Table 1 and Figure 7. The warming treatment generally increased the monthly average air and soil temperatures by 0.5–2°C across all sites ($p < 0.01$, Wilcoxon signed rank test). This was specifically tested and supported at Mols showing significantly increased mean monthly nighttime temperatures in the warming plots for all months in the air ($p < 0.05$), and for all months in the soil ($p < 0.05$), except the midsummer months June and July in both 1999 and 2000 where soil temperatures only tended to be increased ($p < 0.07$). There was no difference between the control and the drought plots (Figures 5 and 8).

The warming treatment affected the air and soil temperatures differently at the various sites presumably because of differences in site vegetation characteristics and climatic conditions. In general, the temperature difference was largest at Garraf which had the highest energy input to the soil and therefore the largest potential for energy conservation. At the three Northern sites (Mols, Clocaenog, and Oldebroek), the temperature difference in both

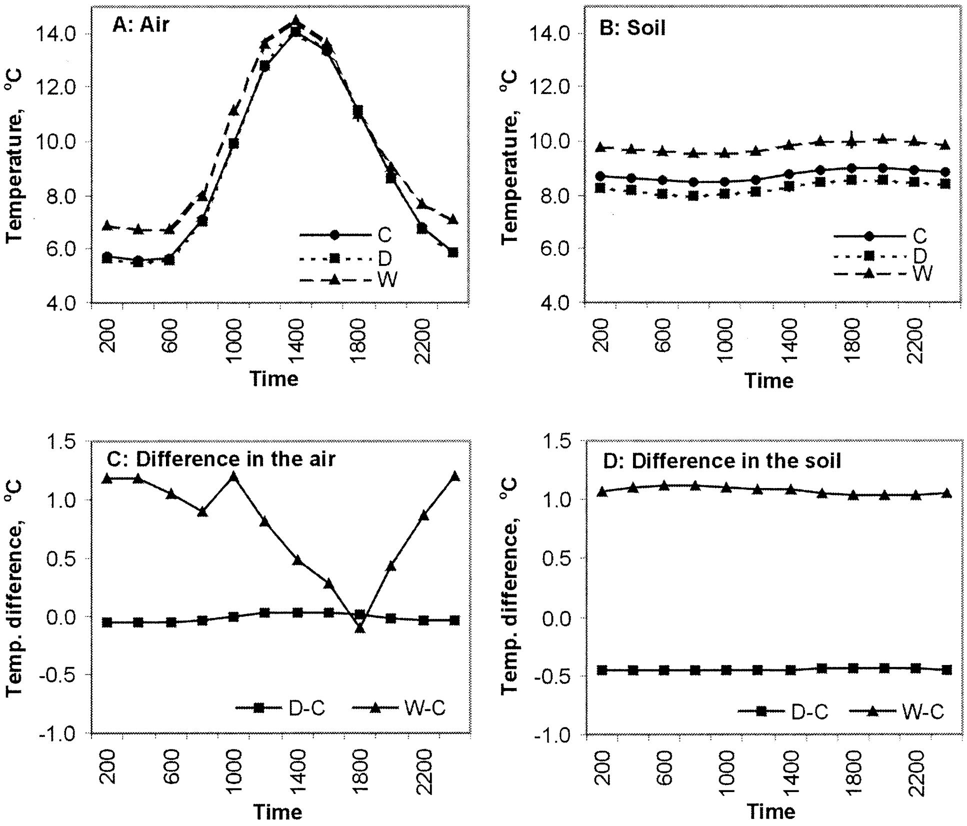

Figure 5. Average diurnal temperature in the (**A**) air (+20 cm) and (**B**) soil (−10 cm) of the control (C) warming (W) and drought (D) treatments at Mols 1999–2000 and the temperature differences (warming − control and drought − control) in the (**C**) air and (**D**) soil over the diurnal cycle.

Table 4. Mean Annual (1999–2000) Temperature (°C) in Control (C) and Warming (W) Treatments and Temperature Difference (W − C) (°C) in the Air and Soil at Night (0400) during the Day (1600) and Diurnal at the Four Sites

		Time (0400)			Time (1600)			Time − diurnal		
Level	Site	C	W	W − C	C	W	W − C	C	W	W − C
Air	Mols	5.6	6.8	1.2	13.3	13.6	0.3	9.5	10.2	0.7
	Clocaenog	5.2	6.3	1.0	9.9	10.3	0.5	7.6	8.3	0.7
	Oldebroek	5.5	6.2	0.7	15.3	15.1	−0.2	10.4	10.7	0.3
	Garraf	10.1	11.0	0.9	21.2	20.8	−0.4	15.6	15.9	0.3
Soil	Mols	8.6	9.7	1.1	8.9	10.0	1.1	8.8	9.9	1.1
	Clocaenog	5.9	6.6	0.7	7.1	8.0	0.9	6.2	6.8	0.6
	Oldebroek	9.4	9.8	0.4	9.6	10.1	0.5	9.5	9.9	0.5
	Garraf	15.5	16.3	0.8	20.6	21.6	1.0	18.0	19.0	0.9

the air and the soil showed a yearly pattern with the largest increases during the summer whereas at Garraf the largest temperature difference was in the winter (Figure 7).

Warming increased GDD and GSD by 3%–16% at the three northern sites (Table 5). At the Spanish site GDD was affected negligibly and sometimes even negatively because the temperature was already high, and temperature is unlikely to be a limiting factor for the growing season. Finally, the warming treatment reduced the number of days with frost ($t_{\min} < 0$) by 44% at Mols, 34% at Clocaenog, and 19% at Oldebroek for the two-year period 1999– 2000 and by 40% at Garraf (2000–2001). Drought had no effect on GDD, GSD, or days with frost (data not shown).

Drought Treatment

In the drought treatment 64%–95% of the water was removed during the drought period amounting

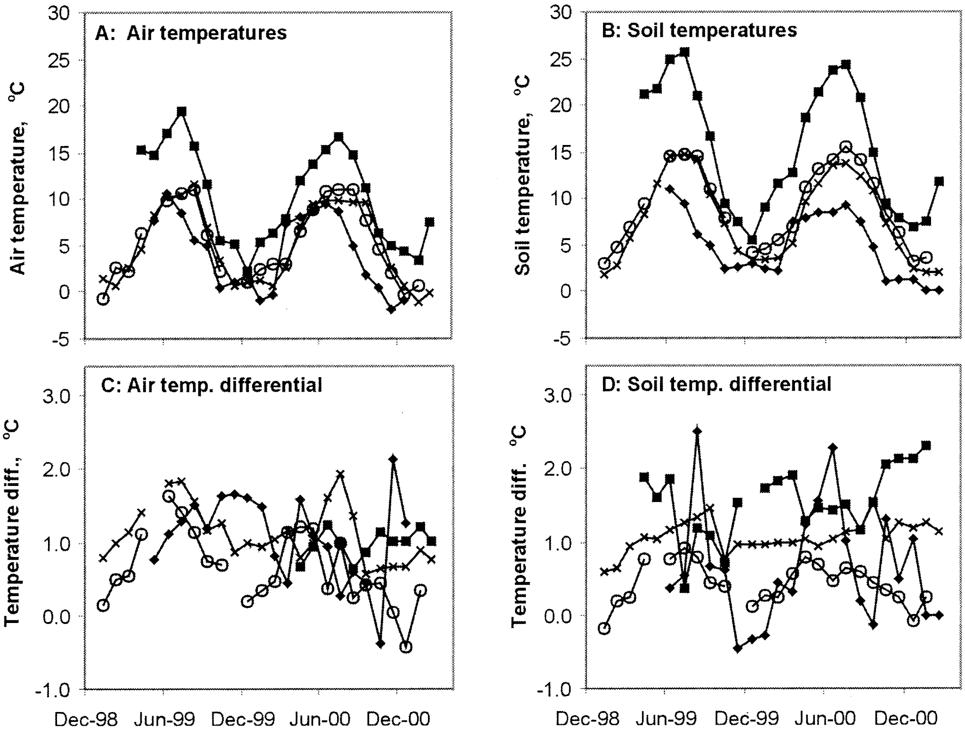

Figure 7. Monthly average (**A**) air and (**B**) soil temperatures (°C) at night (time = 0400 h) and the temperature differential between the warming and the control plots in the (**C**) air and (**D**) soil at Mols (crosses), Clocaenog (filled diamonds), Oldebroek (open circles), and Garraf (filled squares).

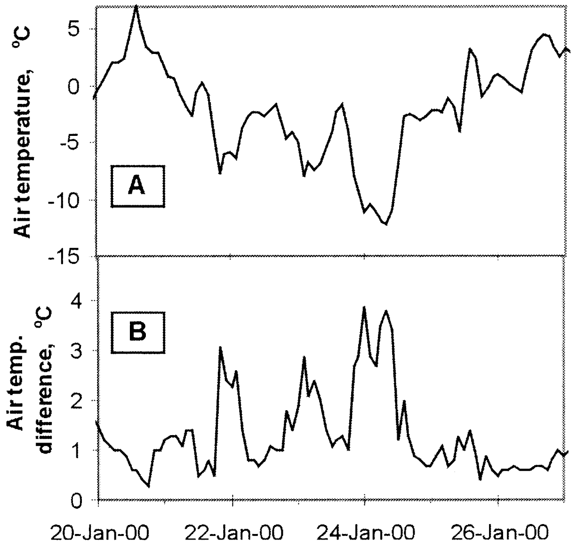

Figure 6. The change in the effect of the warming treatment during a period of large temperature changes at Mols 20–26 January 2000. (**A**) Ambient air temperature and (**B**) the temperature difference between the warming and the control plots.

to approximately 9%–72% of the total yearly water input (Table 6). At Oldebroek the yearly water budgets for the warming and the drought treatments were almost similar. However, the two treatments were very different because the water removal in the drought plots occurred during the two months of drought, while in the warmed plots a small fraction of the water was removed throughout the year and did not directly lead to drought events.

The water removal at the Garraf drought treatment was very high with a total removal of 72% of all incoming rain over the two years. This was because drought was applied in the two growing seasons, spring and autumn, where almost all precipitation occurred.

The soil water content was reduced by 33%–82% at the peak of the drought treatment (Table 6 and Figure 9). After the drought treatments stopped each year, the soil moisture content returned to its original level relatively quickly. However, at Oldebroek the soil moisture content stayed low after the drought in 2000 because of a very dry autumn. In general, the warming treatment did not affect the soil water content although tendencies were seen at Mols for increased moisture content during the summer of 2000 ($p < 0.15$). At Oldebroek a slight reduction in the soil water content caused by the warming treatment may be indicated, but in general the difference was there before the treatment started and it was not significant ($p > 0.20$). There was no evidence of any trend or a significant effect of the warming treatment on soil water content at Clocaenog from the limited data available.

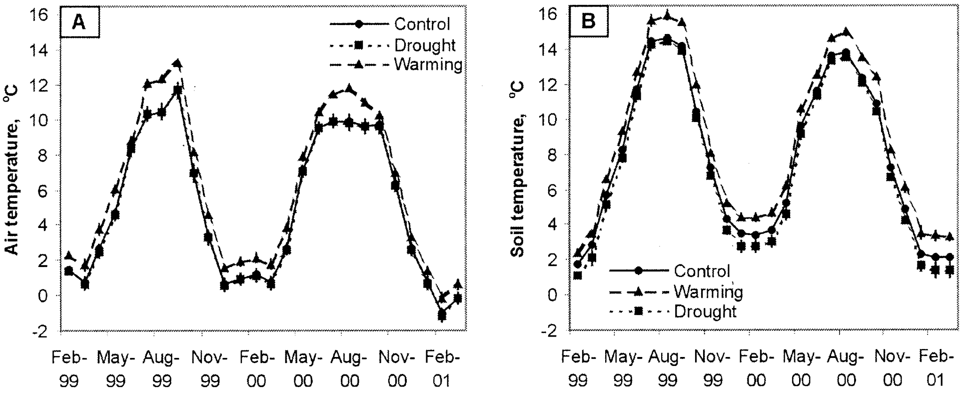

Figure 8. Monthly average nighttime (0400 h) temperature in the (**A**) air (+20 cm) and (**B**) soil (−10 cm) of the control, drought, and warming treatments at Mols, DK, during 1999 and 2000. Error bars indicate SE.

Table 5. Mean Annual (1999–2000) Number of Growing Degree-Days (GDD) and Growing Season-Days (GSD) in the Control (C) and Warming (W) Plots and the Change in Warming (% of control)

	Air			Soil		
	C	W	Change (%)	C	W	Change (%)
Growing degree-days						
Mols	1909	2146	112	1510	1795	116
Clocaenog	1312	1525	116	1368	1490	109
Oldebroek	2111	2310	109	1713	1865	109
Garraf	3607	3609	100	2684	2794	104
Growing season-days						
Mols	242	267	110	245	275	112
Clocaenog	211	234	111	220	229	104
Oldebroek	266	277	105	302	311	103
Garraf	341	334	98	279	271	97

Table 6. Effects of the Different Treatments on Water Input to the Plots and the Soil Moisture over the Annual Cycles and during the Drought Periods[a]

	Mols			Clocaenog			Oldebroek			Garraf		
	C	W	D	C	W	D	C	W	D	C	W	D
Mean annual (1999–2000)												
Water input (mm y^{-1})	806	742	536	1741	1729	1593	1042	950	924	455	432	129
−reduction (% of control)		8	33		1	9		9	13		5	72
Soil moisture content (%)	16.7	18.0	15.0	46.4	47.7	31.2	14.4	13.1	8.7	22.2	20.1	17.0
−reduction (% of control)		−8	10		−3	33		9	33		10	15
During drought (1999–2000)												
Water input (mm)	271	249	16	228	215	81	135	133	35	338	304	16
−reduction (% of control)		8	94		6	64		1	74		10	95
Minimum soil moisture (%)	16.1	16.6	6.1	57.4	63.1	34.1	11.7	11.1	2.0	25.9	22.9	15.5
−reduction (% of control)		−3	63		−10	46		5	82		11	33

[a] *C = control, W = warming, and D = drought.*

Artifacts and Edge Effects

Effects on Temperature. Slightly less warming near the edges of the warmed plots was seen in both the air and the soil. In general, this edge effect was small resulting in lower average monthly air and soil temperatures at the edges/corners of the plots compared with the center on the order of 0.0–0.4°C (Table 7). These differences were not statisti-

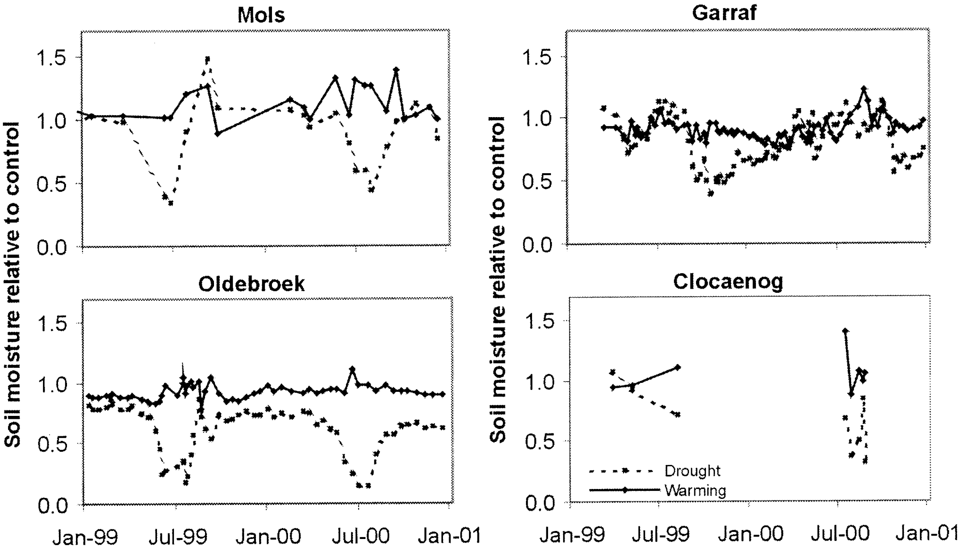

Figure 9. Soil water content in the top 15–25 cm soil layer in the warming (solid line and diamonds) and drought (dotted lines and crosses) treatments at all four CLIMOOR sites relative to the control.

Table 7. Average Temperature Differential during the Night and Day between Center (Cn) and Corner (Co) Sensors and between Center (Cn) and Edge (Ed) Sensors in the Air, Soil surface, and Soil at Mols during 1999–2000[a]

	Nighttime (0400)		Daytime (1600)	
	Cn − Co Delta T (°C)	Cn − Ed Delta T (°C)	Cn − Co Delta T (°C)	Cn − Ed Delta T (°C)
Air (+20 cm)	0.0(p=0.70)	0.0(p=0.06)	0.0(p=0.89)	0.0(p=0.20)
Soil surface (−2 cm)	0.4(p=0.03)	0.0(p=0.80)	0.4(p=0.88)	0.0(p=0.88)
Soil (−10 cm)	0.2(p=0.34)	0.1(p=0.68)	0.2(p=0.68)	0.1(p=0.68)

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[a] *p values indicate levels of significance in pairwise t-test comparison.*

cally significant ($p > 0.20$) except at the soil surface where a significantly lower temperature increase was observed at the corners ($p = 0.03$). Comparing the temperature response at the different positions during periods with stable and unstable ambient temperatures respectively gave further evidence for a small edge effect. The roofs increased the degree of warming during periods of decreasing ambient temperature. In the case of a significant edge effect, we would expect this additional warming to be smaller near the edges and corners. However, measurements showed that during stable temperature conditions the difference in temperature between the corner and the center in the warmed plots was small and relatively constant and increased only slightly during occasional large and fast changes in ambient temperature. This was illustrated at Mols 14–21 October 1999 where a drop in the soil temperature of 2°C over 3 days increased the center − corner difference from 0.1 to 0.2°C to stabilize at

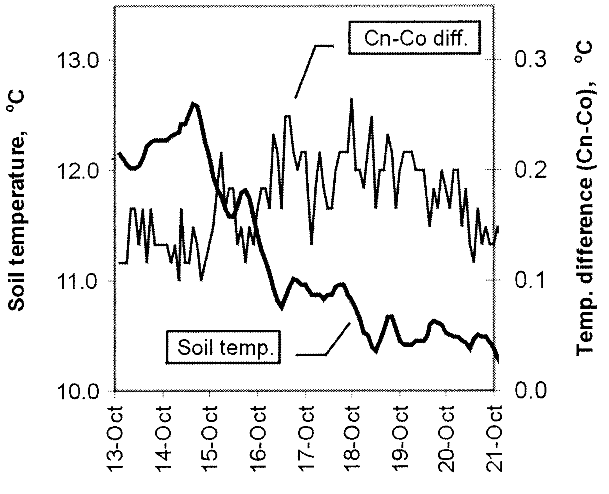

Figure 10. Hourly soil temperature in the warming plots at Mols, 13–21 October 1999, showing a 2°C drop 15–18 October and the accompanying change in the temperature difference between the center (Cn) and corner (Co) position.

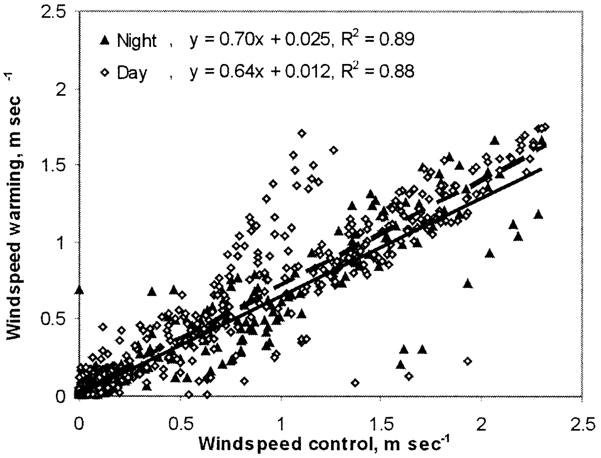

Figure 11. Relationship between wind speed at the top height of the vegetation in the control and warming treatment during the day (time = 1600 h) and at night (time = 0400 h) during May–August 2001 at Mols.

0.1°C within one day after ambient temperatures had stabilized (Figure 10).

Effect on Water Input and Humidity. The precipitation inputs to the warming plots were 1%–9% less than those to the control plots (Table 6), mainly because of the delay time associated with registration of rain events and physical coverage of the plots. At Mols, humidity in the air in the warmed plots was generally increased by 0%–5%, and occasionally by up to 15%, compared with the control plot (data not shown).

Effect on Wind. In the spring and summer of 2001 at Mols, DK, almost similar relationships between wind speeds in the warming and control plots were observed during the day and night (Figure 11). However, there was a significant reduction in the wind speed of 9%–10% in the warmed plot compared with that of the control during the night ($p = 0.04$). The difference in wind speed between the warming and the control treatments was mainly due to differences at lower wind speeds because no differences were found if wind speeds stronger than only 1 m s^{-1} were tested ($p = 0.12$). Absolute values of the average wind speed over 3 months were 21% lower in the warming plots compared with the control plots during the day when the warming plots were not covered. The difference increased to 34% at night when the curtains covered the vegetation. This difference in absolute values was assumed to be due to the specific placement of the anemometers within the canopy in the control and the warming plots.

DISCUSSION

Warming

The nighttime warming treatment increased the monthly air and soil temperature by 0.5–2°C. This was a relatively small increase not exceeding the natural year-to-year difference at the sites. On the other hand, it is realistic in relation to the temperature increase of 0.6°C observed during the last century (Houghton and others 2001) and predicted future temperature increases. It also reflects the pattern of increased minimum temperatures in the air rather than a general diurnal increase (IPCC 1995). Although this was only a modest temperature increase, perhaps more importantly the warming treatment resulted in a large increase in the number of plant growth-days (GDD and GSD) in the northern sites and reduced the number days with frost at all sites. The changes in GDD and GSD were not observed at the Spanish sites where temperature was not a limiting factor of plant growth. The large increases in GDD and GSD and reduction in days with frost will have strong effects on plant growth, particularly at the start and end of the growing season. This was demonstrated by clear treatment effects on plant growth reported by Peñuelas and others (2004) and Llorens and others (2004). The moderate temperature increase was comparable to temperature increases reported for other field-scale experimental methods such as IR heaters (Harte and others 1995; Wan and others 2002) and OTCs (for example, Norby and others 1997). There are other methods that provide even larger temperature increases, such as closed tents and cloches (for example, Kennedy 1994) and active-warming systems such as heating cables (for example, Bergh and Linder 1999) and heated greenhouses (for example, Wright 1998). However, active-heating approaches are generally expensive and often involve larger disturbance effects as a result of installation of cables or shading by greenhouses.

Drought

The drought treatment removed 65%–90% of the water during the drought period, which was less than the 100% obtained by permanent roof covers applied in other studies (Lamersdorf and others 1998). The drought approach applied in this project can be optimized to remove more than 95% of the water, but a 100% removal of water is not possible due to delays in activating the movement of the curtains.

Artifacts

The edge effects were judged by measurements of wind, light, water input, and humidity. Near the edge of the study plots, the risk of edge effects from the treatments and the influence of outside activities such as trampling is greater.

Effects on Temperature. The *a priori* expectation would be that the warming effect might be smaller near the edges than at the center because of increased heat loss and air movement near the edges. The 20-m^2 plot size was chosen as a compromise between practical/economical perspectives and the minimum requirement for the ecosystem studied in the CLIMOOR project. We assigned the outer 0.5 m of each study plot as a buffer zone with all measurements carried out in a central 12-m^2 area. The temperature measurements at Mols demonstrated that the 0.5-m buffer zone was sufficient to ensure that the central measurement area was unaffected by undesirable edge effects in the warming treatment.

Precipitation Input and Moisture. One of the problems with many warming experiments employing greenhouses or permanent covers is the accompanying change in rainfall pattern and rainfall amount (Gundersen and others 1998). By removing the curtains during the day and when it rains at night, the influence on precipitation was greatly reduced, although some unintended water exclusion was seen at all sites. In the cases of large surpluses of water, as at the three northern sites, we expect this to be a small problem as none of these sites were generally water limited, whereas at Garraf, with a yearly precipitation less than 500 mm, even small reductions of water input may affect plant growth. However, the measurements of plant performance at Garraf do not indicate negative effects of the warming (Llorens and others 2004).

The slight unintended input of water to the drought plots during the drought event because of the delay in cover activation only reduced the severity of the drought. The removal of more than 65% of the water for a 6–22-week period reduced the water availability in the soil at all sites (Figure 7). However, at the UK site, which had high rainfall, more than 1700 mm y^{-1}, the drought treatment removed approximately 100 mm y^{-1} and the soil moisture content never fell below 60%. This was shown to be a threshold for changing mineralization and nitrification processes (Emmett and others 2004), and, consequently, longer drought periods might be needed at wetter sites if significant ecological effects are to be expected.

Edge effects related to unintended water input by surface runoff flowing from the outside into the plots and plants near the edges growing roots outside the study plots might be a potential problem for the drought treatments. Lateral water flow was considered a potential problem only at Garraf (SP) because of the soil type and the sloping conditions. This was partly avoided by digging trenches on the upslope side of those drought plots where lateral flow was considered to be important. The TDR measurements showed a 50% reduction in soil moisture content at the peak of the drought events which suggests that, even though some lateral flow occurred at the Spanish site, a significant drought was obtained. At all sites the potential rooting problem was reduced by leaving the outer 0.5 m of the study plots as a buffer zone.

Snow. Snow could be a critical problem for the nighttime warming approach. In the absence of an effective snow detector, the curtains will remain over the plots during precipitation events thereby affecting the input of precipitation as well as preventing the potential insulation of the soil by the snow cover. In the present study snow was occasionally a problem for 1–7 days during the two years of operation, but none of the sites experienced permanent periods of snow cover, and the problem is therefore not expected to have had significant effects on the efficiency of the method or the artefacts. However, it may be an important consideration at other sites where snow represents a significant proportion of annual precipitation.

Humidity. We were concerned that the curtains may increase the relative humidity in the air, and thus the vapor pressure deficit (VPD), and thereby photosynthesis. The humidity increase observed in the warmed plots at Mols was moderate and we do not expect this increase to have had important effects on plant growth because it occurred at night when plants are not photosynthetically active. Although measurements of treatment effects on humidity do not exist from all sites, measurements of photosynthesis at all sites showed no difference between the warming and the control plots (Llorens and others 2004). A more important concern relates to the effect of the curtains on dewfall at sunset and sunrise, which is of particular importance at the drier sites. Dewfall was not directly measured but, to avoid the problem, a delay factor can be set to keep the curtains open until after dewfall has occurred.

Wind Speed. In general, little is known about the potential biological effects of experimentally induced changes in wind stress. However, in a recent warming and CO_2 enrichment study in a boreal forest ecosystem, the exclusion of the wind by the ecosystem enclosure strongly affected plant growth through elongation of pine needles (Rasmussen and others 2002). In our study, the warming and drought covers were therefore designed with open sides to allow free air exchange with the surroundings and thereby minimize the impact on the wind movement inside the plots. The wind velocity measurements underneath the curtains showed that the curtains reduced the wind speed by 11% relative to the untreated control at Mols. In most cases this reduction is small considering the large ambient variation, and at moderate to higher wind speeds the reduction was smaller and not significant. Finally, compared with methods based on enclosures the effect on the wind stress is small.

Light Regime. Greenhouses or permanent covers will almost inevitably lead to changes in the light regime available for the plants. Because changes in the light conditions may have a significant effect on plant growth and plant behavior, removable covers were an important design component for our experimental system. By removing the warming covers from sunrise to sunset, the only influence on the light was the shading of the plants by the scaffolding. The scaffolding covered approximately 5% of the area and was similar for treatment and control plots. Removable covers in the drought treatment limited the potential for light reduction to periods of rainfall only. In areas of high rainfall, the curtains will be on for longer times thus reducing this benefit, although it is likely rainfall events would often be associated with periods of low light intensities.

CONCLUSIONS

The use of retractable covers as a research tool to investigate the effects of increased temperature and extended drought has been investigated at four sites across a climatic gradient. The warming approach has been shown to be successful at increasing the yearly average minimum temperature by 0.4–1.2°C and the drought approach removed 64%–95% of the precipitation during the growing season. Generally, the artifacts and edge effects associated with the warming and drought approaches were relatively small. However, some practical concerns and potential artifacts have been identified, in particular for drier sites where dew input is important in the annual water budget and for sites with high snowfall. There may also be biological artefacts not identified here such as nocturnal animals seeking refuge under the curtains and associated disturbance through increased foraging activity. All of these factors have to be taken into account in any specific site application.

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