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Tundra carbon balance under varying temperature and moisture regimes

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[1] To understand the effects of environmental change on tundra carbon balance, a manipulation experiment was performed in wet sedge tundra near Barrow, Alaska. Three replicates of six environmental treatments were made: control, heating, raising or lowering water table, and heating along with raising or lowering water table. Carbon fluxes were measured using a portable chamber for six days during the 2001 growing season. Spectral reflectance and meteorological measurements were also collected. Empirical models derived from flux measurements were developed for daily gross ecosystem production (GEP) and ecosystem respiration (Re). The amount of photosynthetically active radiation absorbed by the plants was strongly correlated with GEP. This relationship was not affected by treatment or time during the growing season. Re was related to soil temperature with a different relationship for each water level treatment. Re in the lowered water table treatment had a strong response to temperature changes, while the raised water table treatment showed little temperature response. These models calculated daily net ecosystem exchange for all of the treatments over the growing season. Warming increased both the seasonal carbon gain and carbon loss. By the end of summer the lowered water table treatments, both heated and unheated, were net carbon sources while all other treatments were sinks. Warming and/or raising the water table increased the strength of the net sink. Over the timescale of this experiment, water table primarily determined whether the ecosystem was a source or sink, with temperature modifying the strength of the source or sink.

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1. Introduction

[2] High northern latitudes are experiencing climate change in the form of temperature increases as well as changes in precipitation patterns [*Arctic Climate Impact Assessment* (*ACIA*), 2004]. Changes in tundra vegetation characteristics that may be related to climate change have been observed both on the ground and from satellite data [*Sturm et al.*, 2001; *Myneni et al.*, 1997; *Goetz et al.*, 2005]. There are a number of ways that tundra ecosystems may respond to these climate changes that have an effect on ecosystem carbon balance [*Oberbauer et al.*, 2007]. Springtime warming can result in earlier snowmelt, lengthening the growing season, while increased warming during the growing season may increase plant primary production [*Welker et al.*, 2000; *Lafleur et al.*, 2001; *Lafleur and Humphreys*, 2007]. Autumn warming could also lengthen the growing season, but may have less effect on production because incident solar radiation rapidly drops off in that season [*Chapin and Shaver*, 1985; *ACIA*, 2004; *Piao et al.*, 2008]. Increasing air temperature will further affect productivity due to increased soil microbial activity, greater active layer depth in permafrost, and alteration of nutrient cycles in soils [*Mack et al.*, 2004; *van Wijk et al.*, 2004; *Schuur et al.*, 2008]. While changes in precipitation patterns [*New et al.*, 2001] coupled with changes in soil drainage due to melting of permafrost [*Smith et al.*, 2005] will affect soil moisture. These environmental changes, along with increased amounts of biomass from increased productivity, will affect ecosystem respiration [*Vourlitis et al.*, 2000a, 2000b; *Oechel et al.*, 2000; *Shaver et al.*, 2007].

[3] We hypothesize that both soil moisture as well as warming affect tundra carbon balance. To examine these effects, plots on the North Slope of Alaska were manipulated

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by actively warming and altering water table depth [*Kinoshita*, 2005; G. Y. Kinoshita et al., Effects of elevated soil temperature and water table manipulation on ecosystem carbon fluxes of an arctic coastal tundra ecosystem near Barrow, Alaska, submitted to *Journal of Geophysical Research*, 2010]. Carbon fluxes of the plots were measured using a portable chamber for six days in the growing season of 2001. However, the goal was to study the seasonal carbon exchange, and there can be significant day-to-day variation in net ecosystem exchange (NEE) for this site [*Kwon et al.*, 2006] making it difficult to extrapolate from the limited set of carbon flux measurements. To account for daily variability in NEE while filling in the gaps between flux measurements, models were developed using the flux measurements to describe gross ecosystem production (GEP) and ecosystem respiration (Re). These models were driven by non-invasive, easily collected measurements, spectral reflectance, incident photosynthetically active radiation (PAR), and soil temperature, which were measured throughout the growing season in 2001.

2. Methods

2.1. Site Description

[4] The study site was located near the city of Barrow, Alaska at 71.322°N, 156.602°W on wet sedge tundra approximately 4.7 m above sea level. Wet sedge tundra is a dominant land cover type in the northern part of the Alaskan North Slope [*Mullier et al.*, 1999], and at a more local scale it is a significant cover type within the region around Barrow [*Stow et al.*, 2004]. The site was dominated by *Carex aquatilis*, *Eriophorum angustifolium*, and *Dupontia fischeri* growing over a moss layer consisting mostly of *Dicranum elongatum* and *Dicranum undulatum* [*Houston*, 2004; *Kinoshita*, 2005; Kinoshita et al., submitted manuscript, 2010].

2.2. Experimental Manipulations

[5] The experimental procedures are summarized in this section with a full description of the experiment design and data provided by Kinoshita et al. (submitted manuscript, 2010). Study plots consisted of eighteen 60 cm diameter polycarbonate cylinders embedded in the ground within a single homogeneous region, with each plot beginning with the same soil composition and vegetation coverage. Plots were divided into three blocks of six plots, with treatments randomly assigned within each block: control (C), heating (H), raising of the water table (W+), lowering of the water table (W−), heating and raising of the water table (H + W), and heating and lowering of the water table (H − W) [*Kinoshita*, 2005; Kinoshita et al., submitted manuscript, 2010]. The treatments were applied through the growing seasons of 1999 through 2001.

[6] Plots were warmed using silicon heaters (Omegalux, Inc., 15.6 W m^{-2}) attached to the cylinder interiors. The heated treatments maintained soil temperatures 5°C warmer than ambient soil temperatures in the 1999 growing season and 2°C in the growing seasons of 2000 and 2001. The temperature gradient was lowered for the second and third seasons because of soil subsidence from melting subsurface permafrost. Soil temperatures were measured with type-t thermocouples along with T-107 thermistors connected to a data logger (Campbell Scientific, Inc.), recording temperatures at half-hour intervals. Daily average soil temperature was calculated using data from all of the available soil temperature sensors for each plot at a depth of 5 cm [*Huemmrich et al.*, 2010; Kinoshita et al., submitted manuscript, 2010]. Water wells were drilled into all plots and lined with perforated PVC pipes. The water table was lowered using automatic electronic water pumps (Rule, Inc.) placed within the wells, and distilled water was pumped into the wells to raise water tables (Kinoshita et al., submitted manuscript, 2010).

2.3. Measurements

[7] Net CO_2 flux and ecosystem respiration measurements were made on each plot using a portable infrared gas analyzer (a Li-6200 portable photosynthesis system, LI-COR, Inc, Lincoln, Nebraska) and clear cuvette [*Bartlett et al.*, 1989; *Whiting et al.*, 1991; *Vourlitis et al.*, 1993]. The cuvette was made of clear polycarbonate with an internal volume of 239 L with a square base that attached to permanent collars in the soil [*Vourlitis et al.*, 1993; Kinoshita et al., submitted manuscript, 2010]. The cuvette had a measured PAR transmittance of 0.81, which was applied in the development of the light use efficiency models [*Huemmrich et al.*, 2010]. Both net CO_2 flux and dark respiration were measured every time (Kinoshita et al., submitted manuscript, 2010). Each measurement consisted of three 30-s sampling periods. If the values of the sequential readings differed substantially, the process was repeated until a steady value was obtained. After each measurement of net CO_2 flux the cuvette was removed and aired out then replaced for a second set of three measurements made with the cuvette covered to block out light and measure respiration (Kinoshita et al., submitted manuscript, 2010). Six sets of measurements were made over the course of 24 h at 4-h intervals. These measurements were used to determine diurnal NEE and Re, by integrating them using the trapezoidal rule. The differences between the daily NEE and Re were used to calculate daily GEP. Six diurnal CO_2 flux measurements were collected at intervals through the growing season on June 18, July 2, 18, 23, 30, and August 10, 2001.

[8] Spectral reflectance of the plots was measured at approximately weekly intervals throughout the 2001 growing season using a portable spectrometer (UniSpec SC, PP Systems, Amesbury MA, USA). Measurements were made near midday from a height of approximately 60 cm, resulting in a field of view on the ground of approximately 15 cm. Within each flux collar five reflectance measurements were made, taking care that the instrument viewing area was at least 10 cm from the collar as well as avoiding shadowing from the collar to minimize contamination of the ground reflectance by the collar. These measurements were averaged together. Reflectance spectra were interpolated to 1 nm bands with NDVI calculated using reflectances at 670 and 800 nm. Daily NDVI values were determined by a linear interpolation between the days with reflectance measurements [*Huemmrich et al.*, 2010].

[9] NDVI was used to derive the fraction of incident photosynthetically active radiation absorbed by green vegetation (f_{APAR}) from the relationship

$$f_{APAR} = 1.43\ \mathrm{NDVI} - 0.41 \quad (1)$$

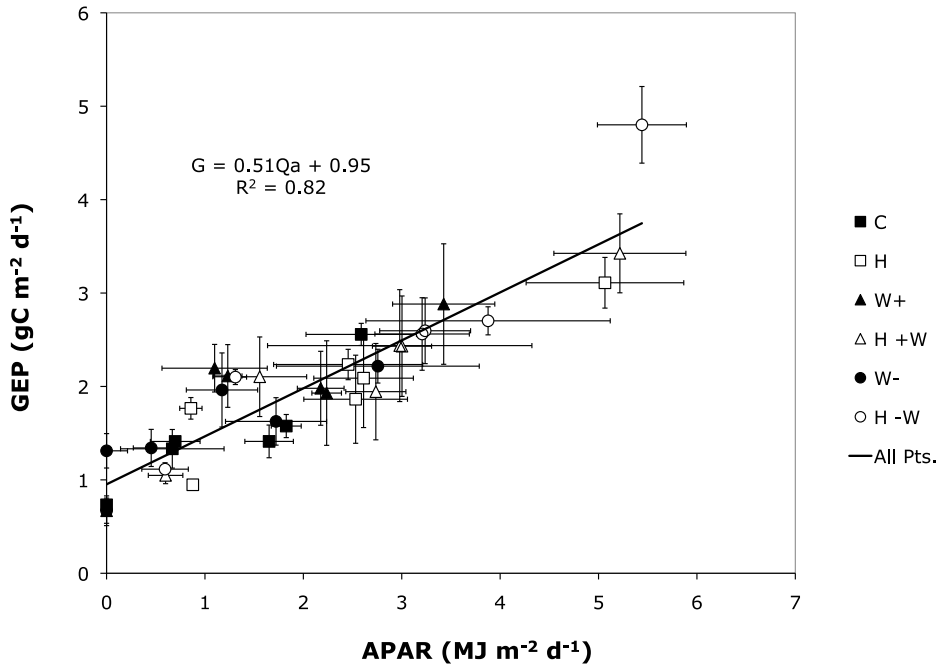

Figure 1. Daily GEP versus daily APAR from 2001 with the linear regression line applied to all manipulations. The manipulations are as follows: control (C), heating (H), raised water table (W+), lowered water table (W−), heating and raised water table (H + W), and heating and lowered water table (H − W). Error bars are ±1 SEM. From *Huemmrich et al.* [2010].

developed at the site [*Huemmrich et al.*, 2010]. If the NDVI value resulted in a f_{APAR} that was less than zero, f_{APAR} was set to zero.

[10] Automated meteorological instruments mounted on a flux tower located less than 0.3 km away collected data including: incident photosynthetic photon flux density, air temperature, soil temperature, wind speed and direction, relative humidity, and precipitation, at half-hourly intervals [*Kwon et al.*, 2006]. Daily incident PAR values were calculated by summing the half-hourly values of photosynthetic photon flux density from the tower instruments.

3. Results

3.1. Model Development

[11] To estimate NEE models were used to simulate its components: GEP and Re.

[12] The observed relationship between NDVI and GEP for arctic tundra [*McMichael et al.*, 1999; *Boelman et al.*, 2003; *Shaver et al.*, 2007; *Street et al.*, 2007] makes it a useful tool, as reflectance measurements do not disturb the site, allow repeatable observations, and are easy to collect. The link between NDVI and GEP can be described through a light use efficiency (LUE) model, where GEP is a linear function of absorbed photosynthetically active radiation (APAR). The basic form for a LUE model is given by:

$$GEP = \varepsilon\, f_{APAR}\, Q_{in} \tag{2}$$

where Q_{in} is the incoming PAR, with APAR being the product of Q_{in} and f_{APAR}, and ε is the light-use efficiency [*Monteith*, 1977; *Russell et al.*, 1989].

[13] Using the data from the diurnal flux measurements from all of the plots, a single relationship between APAR and daily GEP was derived (Figure 1):

$$GEP = 0.51\, Qa + 0.95 \tag{3}$$

where Qa is APAR (n = 36, r^2 = 0.82, P < 0.0001, and standard error of regression 0.35 gC m^{-2} d^{-1}). In the development of this model an adjustment was made for the PAR transmittance of the cuvette. The offset term in equation (3), not shown in equation (2), is due to the presence of mosses in plots that are not accounted for in the standard LUE model due to the difference in light use efficiency between the overstory vascular plants and the understory mosses as well as the PAR absorbed by the background not being included in the standard definition of f_{APAR} [*Huemmrich et al.*, 2010]. This offset term would introduce errors in GEP when incident PAR equals 0, however during the study period this never occurred.

[14] Re is described as an exponential function of soil temperature [*Vourlitis et al.*, 2000a, 2000b; *Shaver et al.*, 2007; *Street et al.*, 2007], with daily Re given by

$$Re = a\, \exp(b\, T) \tag{4}$$

where T is the daily average soil temperature at 5 cm depth, a is Re when T = 0°C, and b describes the temperature sensitivity of respiration (b is related to Q10). Soil temperature is a better indicator of microbial activity in the soil than air temperature, although air temperature has been successfully used in this type of model for tundra ecosystems [*Vourlitis et al.*, 2000a, 2000b]. Since the soil in the plots was directly heated in the manipulations, soil temperature also provides

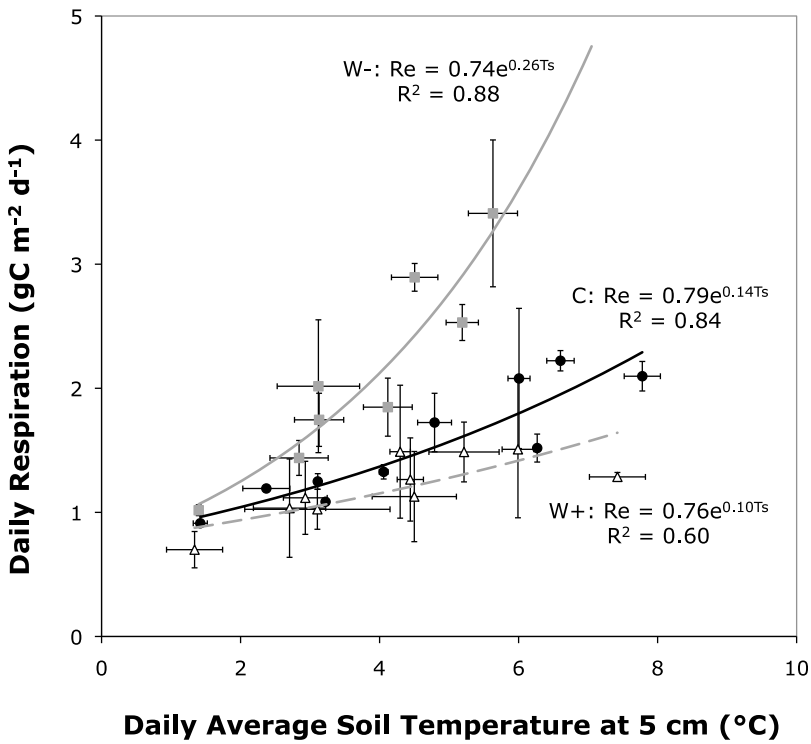

Figure 2. Daily Re and daily average soil temperature at 5 cm from the 2001 growing season for the three water table treatments: black circles are control plots, gray squares are lowered water table plots, and open triangles are raised water table plots. Lines are exponential functions fit to each water table treatment with equations and R^2 values shown on plot. Error bars are ±1 SEM.

the best measurement for distinguishing the effects of warming in this experiment.

[15] Soil moisture and water table depth affect the temperature response of Re [*Vourlitis et al.*, 2000a, 2000b]. Separate parameterizations of equation (4) were developed for each water table manipulation (control, raised, and lowered water table). For the respiration models plot values were grouped by treatment with heated and unheated treatments combined. Some outlier points were removed, in particular points from the July 2 and 18 measurements. For the raised water table treatments the July 2 data were removed because a dry period affected the measurements with points from the raised water table treatments grouped with lowered water table treatment points. While the July 18 lowered water table treatment points were removed because there was heavy rain on that day that caused these points to fall in with the raised water table points. This results in n = 10 for the control and raised water table and n = 8 for lowered water table cases. The resulting relationships were (Figure 2):

$$\begin{aligned} &\text{Lowered water table}: \mathrm{Re} = 0.74\exp(0.26\,\mathrm{Ts}) \\ &\text{Control}: \mathrm{Re} = 0.79\exp(0.14\,\mathrm{Ts}) \\ &\text{Raised water table}: \mathrm{Re} = 0.76\exp(0.10\,\mathrm{Ts}), \end{aligned} \tag{5}$$

with $r^2 = 0.84$ ($P < 0.001$) for control, $r^2 = 0.88$ ($P < 0.001$) for lowered water table, and $r^2 = 0.60$ ($P < 0.01$) for the raised water table, and the standard error of regression 1.14, 1.15, and 1.17 gC m^{-1} d^{-1} respectively. Although the exponential coefficient (b in equation (4)) differs among the manipulations, the 95% confidence intervals for this coefficient overlap (W− ± 0.10, C ± 0.05, W+ ± 0.07).

[16] Daily NEE was calculated as the difference between daily values of Re and GEP, resulting in negative values of NEE representing a carbon sink and positive values representing a carbon source. Re and GEP were calculated every day using input variables (temperature, incident PAR, and NDVI) that were far easier and less intrusive to measure than direct measurements of gas exchange. Because a single relationship defined GEP for all manipulations, a single model formulation was used to determine GEP (equation (3)), while Re was sensitive to moisture state so Re was modeled using different parameters for each water table manipulation (equations (5)).

3.2. Calculation of Fluxes

[17] Daily values of NEE, GEP, and Re were calculated from the models (Figure 3). These model results show how values of NEE may change dramatically from day to day. For example a warm spell that started on day 196 caused many of the treatments to flip from being carbon sinks to sources in a single day. This volatility points out the need for the empirical models to account for daily variability in NEE when determining seasonal carbon balances from intermittent measurements of carbon fluxes.

[18] To examine the effects of the manipulations on seasonal carbon balance the modeled daily fluxes were accumulated over the time period from June 15 to August 20, 2001 (Figure 4 and Table 1). In the seasonal sums, heated treatments had higher seasonal GEP than the corresponding

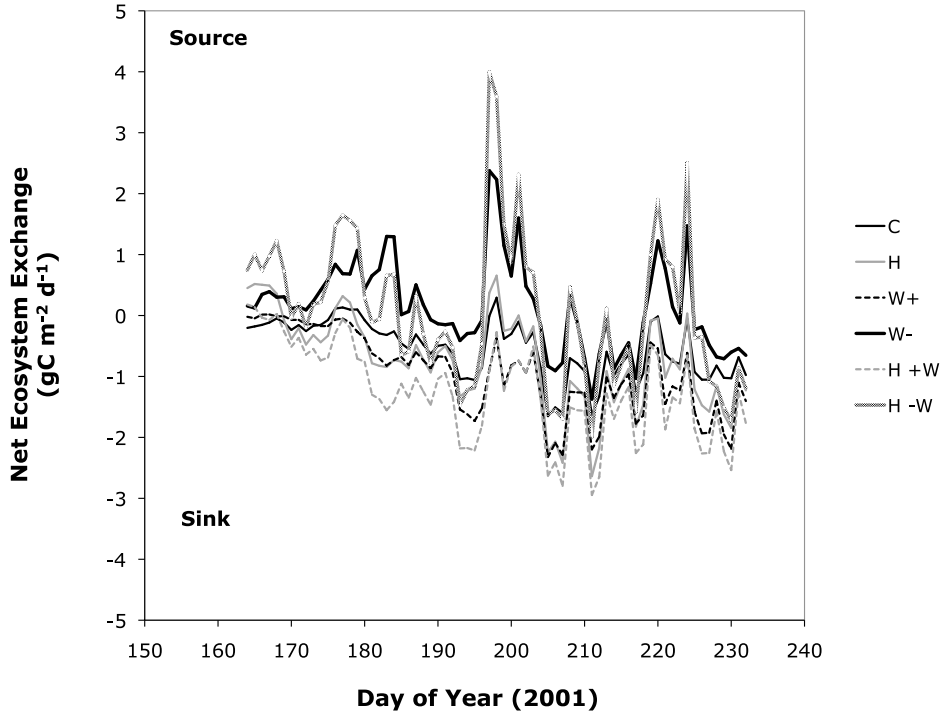

Figure 3. Modeled daily net ecosystem carbon exchange for Barrow treatments in 2001. Positive values represent carbon loss to the atmosphere (source), and negative values are carbon sinks. See Figure 1 for description of treatment codes.

unheated treatments. The heated treatment (H) seasonal accumulated GEP was 29% greater than the control (C). Moisture status may have an effect on seasonal GEP, with the lowered water table treatment (W−), the treatment with the lowest seasonal GEP, having 10% less seasonal GEP than the control, while the raised water table treatment (W+) seasonal GEP was 13% greater than the control. The heated with lowered water table treatment (H − W) had the highest sea-

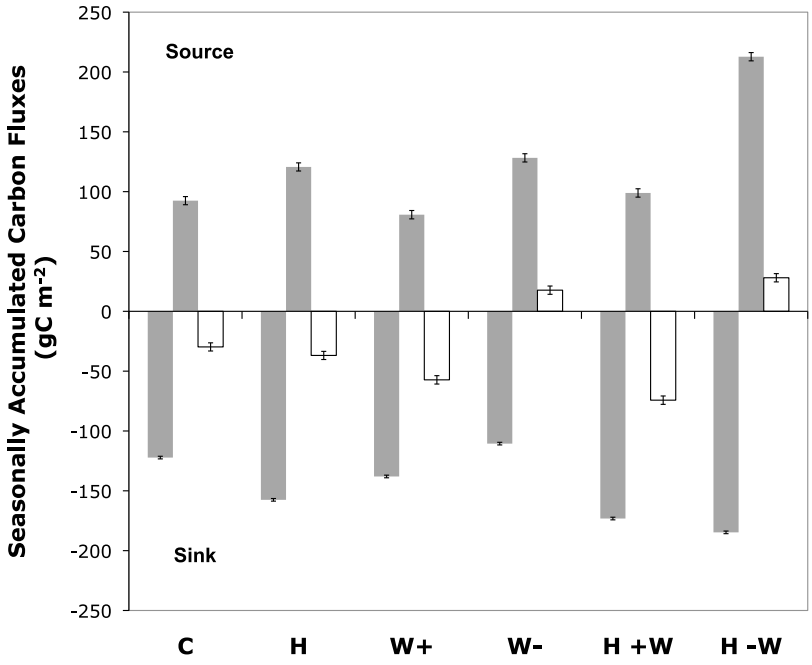

Figure 4. Seasonal accumulated carbon flux calculated from daily modeled fluxes for the different treatments. See Figure 1 for description of treatment codes. The net ecosystem exchange values are shown as white bars. NEE is partitioned into respiration (positive values) and gross carbon uptake (negative values) shown as gray bars. Error bars are the standard deviation based on the standard error of the regressions.

Table 1. Seasonal Sums of Carbon Fluxes for Manipulation Plots[a]

Treatment	GEP (gC m^{-2})	Standard Deviation (gC m^{-2})	Percent Difference From C
C	−122.2	1.1	
H	−157.5	1.1	29
W+	−138.0	1.1	13
W−	−110.6	1.1	−10
H + W	−173.2	1.1	42
H − W	−184.7	1.1	51
Treatment	**Re (gC m^{-2})**	**Standard Deviation (gC m^{-2})**	**Percent Difference From C**
C	92.5	3.4	
H	120.7	3.4	30
W+	80.8	3.5	−13
W−	128.2	3.5	39
H + W	98.9	3.5	7
H − W	212.8	3.5	130
Treatment	**NEE (gC m^{-2})**	**Standard Deviation (gC m^{-2})**	**Percent Difference From C**
C	−29.7	3.4	
H	−36.9	3.4	24
W+	−57.3	3.5	93
W−	17.7	3.5	−159
H + W	−74.2	3.5	150
H − W	28.0	3.5	−194

[a]Each value is the total sum of the daily values between days 153 and 232 of 2001 in gC m^{-2} with positive values indicating carbon source, i.e., leaving the ecosystem and entering the atmosphere, and negative values indicating a carbon sink. Standard deviation is based on the standard error of the regressions. The manipulations are as follows: control (C), heating (H), raised water table (W+), lowered water table (W−), heating and raised water table (H + W), and heating and lowered water table (H − W).

sonal cumulative GEP (67% greater than the lowered water table treatment (W−) and 51% greater than the control).

[19] Lowering the water table had the greatest effect on seasonal Re, with H − W and W− treatments having the highest seasonal carbon loss. The cooler and wetter treatments had lower seasonal carbon losses with the W+ and C treatments having the smallest values. The H − W treatment lost 163% more carbon over the season than the W+ treatment, and 130% more than the control.

[20] At the beginning of the growing season all treatments lost carbon with Re exceeding GEP (Figure 5). For most treatments as the tundra greens, GEP increased until it reached a point where carbon gain was greater than carbon loss. The seasonal pattern of accumulated NEE from the simulation for the control plots (Figure 5) was similar to the temporal pattern of accumulated NEE from the nearby flux tower for 2001 [*Kwon et al.*, 2006], showing initial carbon loss early in the growing season, followed by eventual carbon gain by the end of the season. For the lowered water table treatments (W− and H − W) accumulated Re remained greater than GEP through the entire growing season. Lowering the water table alone (W−) increased seasonal Re slightly more than warming alone, however lowering the water table also decreased GEP, with a net effect of the plot becoming a carbon source throughout the season. Warming and lowering the water table (H − W) strongly increased Re as well as GEP, and this treatment was also a net carbon source for the entire study period.

[21] Over the study period, the control had both low GEP and Re and overall was a small net carbon sink. Warming (H) alone increased both seasonal GEP and Re resulting in a slightly larger net carbon sink (24% increase, Figure 5). Both of the raised water table treatments (W+ and H + W) had the greatest seasonal net gain. Raising the water table alone (W+) increased GEP over the control and decreased seasonal Re

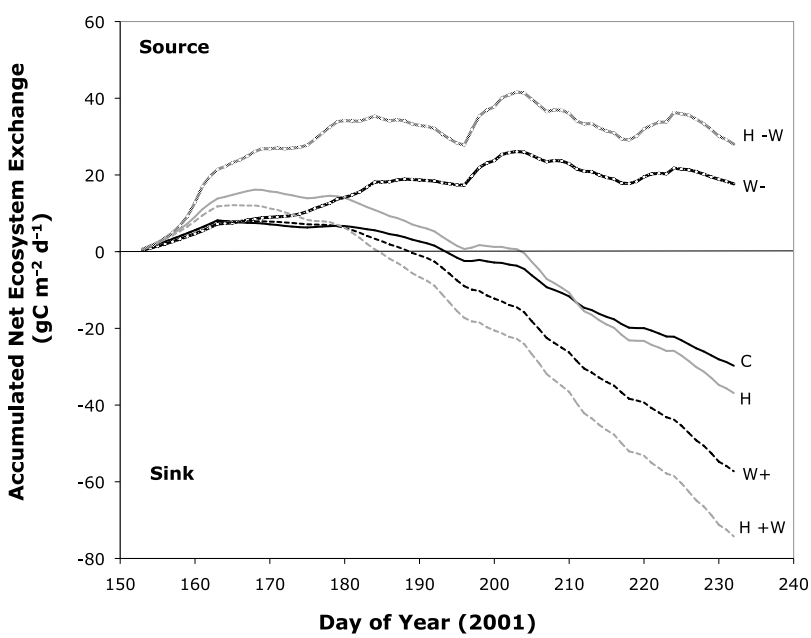

Figure 5. Modeled accumulated daily net ecosystem carbon exchange for Barrow treatments in 2001. See Table 1 for description of treatment codes. Positive values represent carbon loss to the atmosphere (source), and negative values are carbon sinks.

with a net carbon gain almost twice the control net gain (93% increase). Warming and raising the water table (H + W) resulted in much higher GEP, but with Re nearly the same as the control. This produced a strong net sink, with a 150% increase of the control net gain.

4. Discussion

[22] Day-to-day variation in NEE complicates the evaluation of seasonal carbon balance based on a sampling of daily carbon fluxes from chamber measurements, so models become important tools in the analysis of field data, as a method of interpolating between direct measurements of the fluxes, for developing approaches that extend the results to other regions, and providing insights into how the environmental factors affect carbon balance. The LUE model allowed the calculation of seasonal GEP for each of the manipulation plots by accounting for both plant growth and day-to-day variations in incident PAR. GEP increased with warming through increased plant growth as observed in the NDVI measurements. However, a single relationship was found to determine GEP from APAR (equation (3)) indicating that within the time frame of this experiment ecosystem light use efficiency was not changed due to the manipulations [*Huemmrich et al.*, 2010]. Re was related to soil temperature and water table status, with increasing soil temperature increasing Re and lowering the water table also increasing Re (equation (5) and Figure 2). The raised water table treatment had small responses in Re to changes in temperature, while the lowered water table treatment responded strongly to temperature. As expected, the control treatment relationship fell between the two others, but much closer the raised water table treatment relationship. Under lower temperature conditions differences between water table treatments were small but with increasing temperatures the differences in Re due to water table depth were enhanced. Further, the flux measurements indicated that short-term changes in water table due to rain or drought could affect Re. The model results clearly show that soil moisture status is a key variable determining tundra carbon balance. Variations in water table depth, independent of enhanced warming, may act as a switch, flipping a region between carbon sink and source, pointing out the need for information on both soil wetness and temperature in determining Re [*Vourlitis et al.*, 2000a, 2000b].

[23] Seasonal NEE for this area has also been measured using eddy covariance measurements from a flux tower [*Kwon et al.*, 2006]. The total accumulated NEE for the 2001 growing season from the tower was −46 g C m^{-2}, reasonably close to the model result of −30 g C m^{-2} for the control treatment. Differences between the model results and the tower may be partly due to the heterogeneity of the landscape. The footprints of the tower flux measurements were large, compared to the scale of the landscape heterogeneity, observing varying mixtures of wet and dry tundra. This heterogeneity, combined with the range of modeled accumulated NEE for the unheated treatments (−57 g C m^{-2} for the W+ treatment to 18 for the W− treatment), can reasonably account for much of the differences in accumulated NEE between these two methods. A further difference between the model results and the tower measurements relates to the contrasting integration times with a 10-day difference between the tower and model accumulation period. Also, the model determines carbon fluxes for idealized manipulations, with brief occurrences of heavy rain or dry periods being removed, whereas the eddy covariance measurements will capture these effects on the carbon exchange. These events may be short-lived but they can have noticeable effects on the cumulative seasonal carbon balance. Finally, there are errors associated with both the chambers and the eddy covariance methods with several sources and types of error, both systematic and random affecting seasonal sums [*Goulden et al.*, 1996]. The flux tower data for 2001 contained large data gaps, with approximately 25% of the data missing; consequently the seasonal course values calculated from eddy covariance includes a combination of measured and modeled ("gap filled") data [*Kwon et al.*, 2006]. Different gap filling methods can have different effects on the modeled carbon flux [*Moffat et al.*, 2007], so missing flux data is presumably another source of error in this comparison.

[24] The seasonal NEE of the arctic tundra is highly variable. *Kwon et al.* [2006] report seasonal NEE values based on flux tower data for this site over a five-year period ranged from −46 to −70 g C m^{-2}. Our model produced a seasonal NEE for the control sites similar to, but lower than, the flux tower value. Out of the five years reported by *Kwon et al.* [2006] (from 1999 to 2003) 2001 was the year with the lowest seasonal NEE, so this study may not be fully representative of the larger period. More research is required to examine the effects of the temperature and moisture treatments in the context of year-to-year variability in climatic conditions (see Kinoshita et al., submitted manuscript, 2010).

[25] The period over which the system was modeled was not the entire growing season. The end of the modeling period was August 20, with about a month left before snow covered the plants. During the tundra autumn we expect a drop off in green f_{APAR} along with the seasonal decrease in incident PAR, resulting in a rapid decrease in daily GEP. Soil temperatures would slowly fall resulting in a slow decrease in daily Re through the autumn, along with continuing Re through the long winter [*Fahnestock et al.*, 1998]. The lack of data over this period makes it difficult to determine the exact effect on the annual NEE, but it may result in treatments that were shown to be small net carbon sinks, such as the Control, to be annual carbon sources. We can speculate that environmental warming during the fall, when GEP is constrained by the seasonal decrease in incident PAR, will result in more carbon loss [*Piao et al.*, 2008]. In contrast with autumn, an earlier start to the growing season would most likely increase both annual GEP and Re. The spring has seasonally high levels of incident PAR for increased GEP, while earlier soil warming would increase Re. Thus the effect the lengthening of the Arctic growing season has on annual carbon balance depends on how much change in temperature or moisture occurs in the spring or fall seasons.

5. Conclusions

[26] Overall, warming the tundra increases metabolic activity in both plants and soil microorganisms, resulting in increases of both GEP and Re [*Oechel et al.*, 1993; *Smith and Shugart*, 1993]. The results of this study indicate warming a tundra system will generally cause it to become a stronger carbon sink, while drying out the tundra can cause it to become a net carbon source even without warming. Thus, a

key question for future arctic studies is whether the tundra ecosystem is drying out or not. The findings of this study, along with observations of large-scale precipitation increases [*New et al.*, 2001; *Serreze et al.*, 2000] coupled with hydrological changes [*Smith et al.*, 2005] have important implications for the carbon budget of arctic regions.

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