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Remote sensing of tundra gross ecosystem productivity and light use efficiency under varying temperature and moisture conditions

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ABSTRACT

Satellite observations have shown greening trends in tundra in response to climate change, suggesting increases in productivity. To better understand the ability of remote sensing to detect climate impacts on tundra vegetation productivity, we applied a photosynthetic light use efficiency model to simulated climate change treatments of tundra vegetation. We examined changes in the Normalized Difference Vegetation Index (NDVI) and photosynthetic light use efficiency (ε) in experimental warming and moisture treatments designed to simulate climate change in northern Alaska. Plots were warmed either passively, using Open Top Chambers, or actively using electric heaters in the soil. In one set of plots water table depth was actively altered, while other plots were established in locations that were naturally wet or dry. Over two growing seasons, plot-level carbon flux and spectral reflectance measurements were collected, and the results were used to derive a light use efficiency model that could explore the effects of moisture and temperature treatments using remote sensing.

Warming increased values of canopy greenness (NDVI) relative to control plots, this effect being more pronounced in wet plots than in dry plots. Light use efficiency (LUE), the relationship between absorbed photosynthetically active radiation (PAR) and gross ecosystem production (GEP), was consistent across warming treatments, growing season, subsequent years, and sites. However, LUE was affected by vegetation type, which varied with moisture; plots in naturally dry locations showed reduced light use efficiency relative to moist plots. Additionally moss exhibited reduced LUE relative to vascular plants. Understory moss production, not accounted for by the usual definition of the fraction of absorbed PAR (f_{APAR}), was found to be a significant part of total GEP, particularly in areas with low vascular plant cover. These results support the use of light use efficiency models driven by spectral reflectance for estimating GEP in tundra vegetation, provided effects of vegetation functional type (e.g. mosses versus vascular plants) and microtopography are considered.

1. Introduction

High northern latitudes are undergoing dramatic changes in climate experiencing temperature increases as well as changes in precipitation patterns (ACIA, 2004). Tundra ecosystems are expected to be particularly responsive to changes in climate with a number of ways in which higher temperatures may affect ecosystem carbon balance in this biome (Oberbauer et al., 2007). Increased warming during the growing season is expected to increase plant primary

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production (Welker et al., 2000). Warming in springtime may cause earlier melting of snow cover, lengthening the growing season and increasing opportunities for plant growth (Lafleur & Humphreys, 2007; Lafleur et al., 2001; Oberbauer et al., 1998). Autumn warming may also lengthen the growing season, but with less impact on production because of lower amounts of solar radiation at that time of year (Piao et al., 2008). Increasing air temperature is also leading to increased active layer depth in permafrost altering soil microbial activity, nutrient cycles and soil moisture (Mack et al., 2004; van Wijk et al., 2004). Over large regions of the Arctic, hydrological changes are evident (Smith et al., 2005), with likely consequences for vegetation cover and carbon flux. These environmental changes not only alter existing plant growth and ecosystem carbon balance over the short term, but will affect competitive interactions between species that can result in dramatic changes in vegetation composition over the long term. For example, Sturm et al. (2001) have shown that shrub coverage has increased over the past 50 years in some areas of the tundra.

Evidence of widespread ecosystem response to climate change in northern latitudes has been inferred from multi-year trends in satellite observations of Normalized Difference Vegetation Index (NDVI) (Goetz et al., 2005; Jia et al., 2003; Myneni et al., 1997; Zhou et al., 2001), but these studies have generally lacked ground validation, leaving the exact interpretation of these NDVI changes unclear. An increase in NDVI is typically associated with an increase in the amount of green vegetation (Riedel et al., 2005) and with that an increase in gross ecosystem productivity (Boelman et al., 2003). If warming results in an increase in carbon uptake by the biosphere it could act as a negative feedback to global warming by slowing the atmospheric increase of carbon dioxide. Alternatively, increased temperature, combined with altered hydrology, could accelerate overall ecosystem carbon losses, resulting in positive feedback despite increased production (Oechel et al., 1998, 2000).

Gross ecosystem production (GEP) has been related to NDVI for arctic tundra (Boelman et al., 2003; McMichael et al., 1999; Shaver et al., 2007; Street et al., 2007). The link between NDVI and GEP is often described in 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:

$$G = \varepsilon f_{\mathrm{APARg}} Q_{\mathrm{in}} \tag{1}$$

where G is GEP, Q_{in} is the incoming photosynthetically active radiation (PAR) and f_{APARg} is the fraction of PAR absorbed by green vegetation. Absorbed PAR (APAR) is the product of Q_{in} and f_{APAR}. Efficiency (ε) is the light use efficiency, a measure of the plant's ability to convert absorbed energy into biomass (Monteith, 1977; Russell et al., 1989). Efficiency may vary over time and can be affected by many variables, including temperature, soil type, water availability, disease, nutrient availability, plant type, and plant age (Gamon et al., 2001; Prince, 1991). NDVI enters the model as a way to determine f_{APAR} (Goward & Huemmrich, 1992; Kumar & Monteith, 1981; Prince, 1991).

Total f_{APARt} is calculated as:

$$f_{\mathrm{APARt}} = \left[(Q_{\mathrm{in}} + Q_{\mathrm{rb}}) - (Q_{\mathrm{r}} + Q_{\mathrm{t}})\right] / Q_{\mathrm{in}} \tag{2}$$

where Q_{in} is again the incident PAR, Q_{t} is the PAR transmitted through the canopy, Q_{rb} is the PAR reflected from the background back into the canopy, and Q_{r} is the PAR reflected from the canopy top (Hipps et al., 1983). When there is a significant amount of non-photosynthetic material in the vegetation canopy green f_{APAR} (f_{APARg}) should be used in the LUE model. f_{APARg} is the fraction of green vegetation multiplied by f_{APARt} to give the fraction of PAR absorbed by green vegetation (Hall et al., 1992).

Light use efficiency models typically treat a vegetation stand as a single entity, ignoring separate overstory and understory layers. However, in the tundra non-vascular plants (mosses and lichens) may represent significant fractions of the landscape cover (Cornelissen et al., 2001; Olthof et al., 2009; Petzold & Goward, 1988). In particular, the moss layer often forms a “second canopy” underneath the taller vascular plant canopy. These non-vascular plants have different physiological responses as well as different spectral characteristics from vascular plants or from bare soils (Douma et al., 2007; Van Gaalen et al., 2007), which are often assumed to make up the background for vegetation canopies in many remote sensing models. The effects of the moss layer on tundra GEP can be included by expanding the LUE to a two-layer model:

$$\mathrm{Gt} = \mathrm{Go} + \mathrm{Gm} = \varepsilon_{\mathrm{o}} Q_{\mathrm{ao}} + \varepsilon_{\mathrm{m}} Q_{\mathrm{am}} \tag{3}$$

where Gt is the total GEP with Go and Gm being the fractions of GEP from the overstory and moss layers, respectively. The gross carbon uptake of each layer is the product of the light use efficiency of the plants for that layer (ε_{o}, ε_{m}) and the PAR absorbed (APAR) by the plants of that layer (Q_{ao}, Q_{am}). As light has to pass through the overstory to reach the moss layer, Q_{ao} and Q_{am} are related. Assuming a negligible fraction of incoming light is transmitted through a continuous moss layer, the only light that leaves the entire canopy is that which is reflected from the canopy. Thus, the fraction of PAR absorbed by the entire canopy is $1 - Q_{\mathrm{r}}/Q_{\mathrm{in}}$, where $Q_{\mathrm{r}}/Q_{\mathrm{in}}$ is the PAR albedo. f_{APARt} from Eq. (2) is the fraction of PAR absorbed by the overstory so the fraction of PAR absorbed by the moss layer (f_{APARm}) is:

$$f_{\mathrm{APARm}} = (1 - Q_{\mathrm{r}} / Q_{\mathrm{in}}) - f_{\mathrm{APARt}}. \tag{4}$$

The purpose of this study was to test the light use efficiency model in a tundra ecosystem examining spectral reflectance and carbon flux of plots under different warming and moisture conditions to explore their effects on the individual terms of the model as a basis for evaluating the potential significance of recent satellite observations indicating northern greening. To provide a robust test of this model, we deliberately compared these treatment effects from two different experiments (passive and active manipulation), two different tundra locations (Barrow and Atqasuk), and two different moisture regimes (wet and dry) on the Alaskan North Slope. We also examined contrasting functional types (the moss understory versus the vascular plant overstory).

2. Methods

To examine the effects of temperature and moisture on tundra NDVI and GEP, plots on the North Slope of Alaska were warmed and their spectral reflectance and carbon exchange were measured throughout the growing season in 2001 and 2002. Data from two separate manipulation experiments are analyzed in this study. Both experiments were designed to examine the effects of warming and differences in water table on tundra carbon balance, but different treatment methods were used. One experiment, performed by San Diego State University and referred to as the SDSU study in this paper, operated between 1999 and 2001 with 18 closely spaced plots located outside of Barrow, AK (Kinoshita, 2005). Water table depth and temperature were manipulated in these plots using sump pumps and electric heating units in the soil. The other experiment operated as part of the International Tundra Experiment and referred to as the ITEX study in this paper. The ITEX study had plots divided between well-drained upland sites and frequently inundated wet sites. Half of the ITEX plots were passively warmed using Open Top Chambers (OTCs). The ITEX study began in 1994 and had sites located both near Barrow and Atqasuk, AK (Hollister, 2003; Hollister et al., 2005). Spectral reflectance measurements were collected in 2001 for the SDSU plots and 2002 for the ITEX plots. A summary of the study plots