Erratum

Tundra vegetation effects on pan-Arctic albedo
Michael M Loranty, Scott J Goetz and Pieter S A Beck
2011 Environ. Res. Lett. 6 024014

Received 2 June 2011
Published 7 June 2011

The Environmental Research Letters publishing team would like to apologise to the authors of the above paper. Due to an inadvertent omission, the paper was published without the correct acknowledgments. This section should read:

‘Funding for this research was provided by the National Science Foundation Office of Polar Programs-IPY (Grant 0732954), the NASA Carbon Cycle & Ecosystems Program (Grant NNX08AG13G), and the NOAA Global Carbon Cycle Program (Grant NA08OAR4310526). We wish to thank Yufang Jin, Jim Randerson, and two anonymous reviewers whose comments helped to improve the manuscript. We also acknowledge the MODIS Land Science Team for continued maintenance and development of the BRDF/Albedo products.’
Tundra vegetation effects on pan-Arctic albedo

Michael M Loranty, Scott J Goetz and Pieter S A Beck

The Woods Hole Research Center, 149 Woods Hole Road, Falmouth, MA 02540, USA

E-mail: mloranty@whrc.org

Received 3 February 2011
Accepted for publication 17 May 2011
Published 31 May 2011
Online at stacks.iop.org/ERL/6/024014

Abstract

Recent field experiments in tundra ecosystems describe how increased shrub cover reduces winter albedo, and how subsequent changes in surface net radiation lead to altered rates of snowmelt. These findings imply that tundra vegetation change will alter regional energy budgets, but to date the effects have not been documented at regional or greater scales. Using satellite observations and a pan-Arctic vegetation map, we examined the effects of shrub vegetation on albedo across the terrestrial Arctic. We included vegetation classes dominated by low shrubs, dwarf shrubs, tussock-dominated graminoid tundra, and non-tussock graminoid tundra. Each class was further stratified by bioclimate subzones. Low-shrub tundra had higher normalized difference vegetation index values and earlier albedo decline in spring than dwarf-shrub tundra, but for tussock tundra, spring albedo declined earlier than for low-shrub tundra. Our results illustrate how relatively small changes in vegetation properties result in differences in albedo dynamics, regardless of shrub growth, that may lead to differences in net radiation upwards of 50 W m$^{-2}$ at weekly time scales. Further, our findings imply that changes to the terrestrial Arctic energy budget during this important seasonal transition are under way regardless of whether recent satellite observed productivity trends are the result of shrub expansion. We conclude that a better understanding of changes in vegetation productivity and distribution in Arctic tundra is essential for accurately quantifying and predicting carbon and energy fluxes and associated climate feedbacks.

Keywords: tundra, greening, climate change, shrubs, forcing, feedback, Arctic

1. Introduction

Terrestrial ecosystems across the Arctic are experiencing amplified climate warming and undergoing myriad changes as a result (ACIA 2004). Concurrent increases in vegetation productivity have been observed in satellite data at the pan-Arctic scale (Bunn and Goetz 2006, Goetz et al 2007, Jia et al 2003). One particularly noteworthy change is an increase in the extent and abundance of shrubs, which has been observed at local and regional scales (Sturm et al 2001b, Forbes et al 2009, Tape et al 2006, Hallinger and Wilmking 2011, Blok et al 2011). More generally, experimental warming significantly increases the shrub cover and vegetation height, for a variety of growth forms, in as little as four years, and the effects are particularly pronounced in the low-Arctic (Walker et al 2006, Wahren et al 2005). These findings offer evidence of ongoing changes in ecosystem structure with consequences for a range of biogeochemical and biophysical processes that regulate exchanges of mass and energy between the biosphere and the atmosphere. A comprehensive understanding of these processes is necessary to quantify the net impacts of ecosystem change on climate (Anderson et al 2011).

Tundra ecosystems are generally dominated by low-stature vegetation comprised of both woody and non-woody growth forms. Therefore, increases in shrub height and abundance, similar to that observed in Alaska (Sturm et al 2001b, Tape et al 2006), represent a structural change with potentially significant consequences for albedo dynamics and surface radiation budgets in these snow-dominated landscapes. The effects of increased shrub cover on tundra ecosystem
energetic budgets via changes in albedo during the growing season have been addressed in considerable detail (Chapin III et al 2005), however, taller shrubs that protrude above the snowpack can greatly reduce albedo outside of the snow-free season (Sturm et al 2001a). Due to the long polar night, changes in albedo during the period of continuous snow cover are most important during the spring. Differences in springtime albedo associated with vegetation stature can lead to differences in the timing and rate of snowmelt and altered surface radiation budgets (Sturm et al 2005; Marsh et al 2010). In the context of recent observations of tundra vegetation change, these findings imply ongoing alteration of regional energy budgets and associated climate feedbacks, with indirect consequences for ecosystem biogeochemical processes (Sturm et al 2001a). A pan-Arctic understanding of the relationship between tundra vegetation and albedo is necessary to improve our understanding of current and future climate change.

The effects of vegetation change on springtime albedo dynamics remain undocumented at the pan-Arctic scale, yet it is imperative to understand these effects given the evidence for shrub expansion (Tape et al 2006), the relationship between vegetation stature and springtime albedo at local scales (Sturm et al 2005; Marsh et al 2010), and the associated implications for energy budgets (Chapin III et al 2005). Here we examine differences in pan-Arctic patterns of albedo associated with differences in shrub cover between dominant Arctic vegetation types, and interpret the results in the context of the energy balance of terrestrial Arctic ecosystems. We also examine differences in the normalized difference vegetation index (NDVI) between vegetation mapping units in order to understand the consequences of recent tundra greening trends (Bunn and Goetz 2006, Goetz et al 2007; Jia et al 2003) for surface energy budgets.

2. Methods
2.1. Study area and data sets

The Circumpolar Arctic Vegetation Map (CAVM) (Walker et al 2005) was used to define the extent of our study region. The CAVM represents the culmination of an international collaborative effort to define and map the dominant vegetation assemblages of the Arctic tundra biome. Information describing soils, topography, geology, hydrology and remote sensing imagery, as well as bioclimate subzones, were used to derive the CAVM. The five bioclimate subzones outlined in the CAVM represent approximately 2 °C isopleths of mean July temperature, with the three northernmost zones (A–C; mean July temperature ranges of 1–3 °C, 4–5 °C, and 6–7 °C, respectively) representative of high-Arctic tundra, and the two southernmost zones (D–E; mean July temperature ranges of 8–9 °C and 10–12 °C, respectively; figure 1), representing the low-Arctic (Walker et al 2005). Given that much of the vegetation change relevant to our study has been described in the low-Arctic (Tape et al 2006) and that high-Arctic plant communities are less responsive to temperature increases, particularly with respect to canopy height (Walker et al 2006), our analysis was focused on the low-Arctic as defined by bioclimate subzones D and E (figure 1(b)).

Bioclimate subzones D and E represent the areas with mean July temperature ranges of 8–9 °C and 10–12 °C respectively; an area that constitutes 66% of the non-glaciated terrestrial Arctic (Walker et al 2005). Our analyses focused on four vegetation classes: non-tussock sedge, dwarf-shrub, moss tundra (G3, hereafter; non-tussock tundra), tussock-sedge, dwarf-shrub, moss tundra (G4, hereafter; tussock tundra), erect dwarf-shrub tundra (S1, hereafter; dwarf-shrub tundra), erect dwarf-shrub tundra (S1, hereafter; dwarf-shrub tundra),

Figure 1. (a) Map of vegetation classes used for analysis. Mosaic refers to a forest–shrub mosaic, comprised of several GLC-2000 classes dominated by deciduous and evergreen species, just below latitudinal tree line. Tussock, non-tussock, low-shrub, and dwarf-shrub tundra classes are from the Circumpolar Arctic Vegetation Maps (CAVM) (Walker et al 2005)). Low-shrub tundra is described as being dominated by low shrubs (>40 cm) and existing primarily in bioclimate zone E (mean July temp 10–12 °C). Erect dwarf-shrub tundra is dominated by erect dwarf shrubs (<40 cm) and exists primarily in subzone D (mean July temp 8–9 °C). Tussock-sedge, dwarf-shrub, moss tundra is dominated by tussock grass and dwarf shrubs in zones D and E. C Non-tussock sedge, dwarf-shrub, moss tundra is dominated by sedges and dwarf shrubs, occurring in subzones C, D and E. (b) Map of bioclimate zones as specified by the CAVM mapping team. Latitudinal tree line delineated the southern extent, and the borders between successive zones (E and D) represent ~2 °C isopleths in mean summer temperature.
and low-shrub tundra (S2, hereafter; low-shrub) (figure 1(a)). These classes were selected because recent work suggests that increased productivity in the Arctic is coinciding with shrub expansion, and shrub expansion, particularly increases in stature, has been shown to strongly influence seasonal albedo dynamics at local scales. Comparing low-shrub and dwarf-shrub tundra allowed us to understand how shrub growth impacts albedo. Moreover, the tussock and non-tussock tundra classes served as a benchmark that helped characterize the albedo consequences of shrub expansion into new areas. These four vegetation classes are among the most prevalent in the Arctic, with dwarf-shrub tundra, low-shrub tundra, non-tussock tundra and tussock tundra representing 13.7, 12.1, 11.3 and 6.7%, respectively, of the non-glaciated terrestrial Arctic. Furthermore, non-tussock tundra, dwarf-shrub tundra and low-shrub tundra are the three largest and most widely distributed of all the Arctic vegetation classes. The total area of these four CAVM classes contained within subzones D and E was 2.2 × 10^6 km^2, or 42% of the non-glaciated Arctic. Subzone E contains 88, 70, 61 and 24%, of low-shrub, tussock, dwarf-shrub and non-tussock tundra vegetation classes respectively (Walker et al 2005).

Differences in albedo between vegetation classes were examined within bioclimate subzones in order to isolate the effects of vegetation cover as opposed to climate gradients. The broad geographic coverage of these classes provided the additional benefit of minimizing the influence of local and regional variations in weather. As a reference we also incorporated a 100 km buffer below latitudinal tree line that includes forested and shrub-mosaic classes derived from the Global Land Cover 2000 (GLC-2000) map (Bartholomé and Belward 2005).

We used data products from NASA’s Moderate Resolution Imaging Spectroradiometer (MODIS) to characterize albedo, and the normalized difference vegetation index (NDVI) throughout the study region. The MODIS albedo product, derived using bidirectional reflectance distribution functions (BRDF) (Schaaf et al 2002, Liu et al 2009) (MCD43A3) was used to map albedo at 500 m resolution for the 2001–2009 period. Prior to mapping the data were screened using the quality control flags provided with the MODIS albedo products (MCD43A2). Land-only pixels of the highest quality (full BRDF inversion) were retained for analysis. Additionally we excluded data collected with a solar zenith angle greater than 70° as the product is not recommended for use under these conditions. We examined both diffuse and direct broadband albedo (0.3–5.0 μm) but because differences between the two were small (slope of linear regression = 0.98, intercept = 0.01, r^2 = 1.0, for the study period), particularly during the growing season when solar zenith angles were lowest and the proportion of direct radiation highest, we used diffuse albedo as a proxy for total albedo. Utilizing diffuse albedo also obviates the need to correct for solar zenith angle as it is integrated over the entire hemisphere (Schaaf et al 2002, Liu et al 2009). Information on the presence of snow cover is included in the MODIS albedo processing, and the albedo products have been validated for snow-covered surfaces (Stroeve et al 2005). NDVI was derived from the MODIS 1 km monthly global vegetation indices product (MOD13A3) (Huete et al 2002). The embedded quality products were used to select only high quality data over land areas for analysis. Retained pixels were used to calculate mean summer (July–August) NDVI for the 2001–2009 period.

In order to understand variability in incident temperature and shortwave radiation across the study domain, and to quantify the potential effects of albedo differences on surface shortwave radiation, we used the newly released NCEP Climate Forecast System Reanalysis (CFSR) (Saha et al 2010). The CFSR is comprised of a suite of climate variables, including incident surface shortwave radiation and surface air temperature (2 m), at roughly 38 km spatial resolution and 6 h temporal resolution. This data set represents the state of the art and was chosen because of its relatively high spatial resolution and the fact that it contains data for the 2001–2009 period. For this study we first calculated mean daily incident shortwave radiation and maximum daily air temperature for the 2001–2009 period, and aggregated those data to correspond with the 16 day MODIS compositing periods.

2.2. Analytical approach

We restricted our analyses to the April–July period in order to focus on the spring snowmelt period that captures the transition from maximum to minimum albedo. Preliminary analyses revealed that the fall transition from snow-free to snow-covered state was strongly dependent on weather, with high variability due to snow events followed by rapid melting, so we excluded this period from our analyses. For each MODIS compositing period collected from 2001–2009, we calculated albedo for each vegetation class by taking the mean and variance of all grid cells located within the class. These calculations were performed for each of the vegetation classes, and both bioclimate subzones. In addition, we calculated albedo for each vegetation class within each bioclimate subzone, in order to minimize the effects of spatial variability in climate. As a result we obtained nine albedo trajectories for each areal unit to use for analyses, and we further aggregated these into a single trajectory to minimize the effects of interannual variability. Identical calculations were made for MODIS summer NDVI, CSFR air temperature, and CSFR surface shortwave radiation. Within each bioclimate subzone, we calculated net surface shortwave radiation for each vegetation class. This was done using mean incident radiation for each bioclimate zone, so that calculated differences in net radiation could be attributed to differences in vegetation and not differences in incident radiation. We note that these values represent broad spatial and temporal averages, and should be interpreted as approximate potential differences in surface net radiation rather than absolute radiative forcing factors.

3. Results

Table 1 summarizes the patterns of summer NDVI and maximum albedo (early April, snow-covered) observed within and between vegetation classes. Over the entire study domain the two tree line classes had the highest NDVI, followed by
Figure 2. (a) Mean 2001–2009 spring–summer albedo trajectory by vegetation class. (b) Mean 2001–2009 spring–summer albedo trajectory by CAVM bioclimate subzone. For both plots, points indicate MODIS observations and lines are linear interpolations. Data for the entire CAVM domain are signified by squares ■, bioclimate subzone D and E are represented by circles ● and triangles ▲, respectively.

Figure 3. NDVI plotted against maximum albedo (a) and maximum albedo standard deviation (b). Data for the entire CAVM domain are signified by squares ■, bioclimate subzone D and E are represented by circles ● and triangles ▲, respectively.

Table 1. Mean maximum (April) diffuse albedo and July–August NDVI for the 2001–2009 period by vegetation class for the pan-Arctic region, and within bioclimate subzone D and E. Values in parentheses are standard deviations.

| Vegetation Class | Albedo | NDVI |
|------------------|--------|------|
|                  | pan-Arctic | Subzone D | Subzone E | pan-Arctic | Subzone D | Subzone E |
| Forest           | 0.403 (0.134) | 0.714 (0.081) |
| Tree–shrub mosaic| 0.501 (0.143) | 0.662 (0.072) |
| Sedge            | 0.757 (0.048) | 0.763 (0.039) |
| Tussock          | 0.723 (0.088) | 0.739 (0.062) |
| Dwarf shrub      | 0.738 (0.080) | 0.744 (0.077) |
| Low shrub        | 0.721 (0.089) | 0.742 (0.054) |

Note: a Includes areas outside of bioclimate subzones D and E.
   b Derived from GLC-2000 classification.

low-shrub tundra, tussock tundra, dwarf-shrub tundra, and sedge tundra. This pattern was retained when tundra vegetation classes were partitioned by bioclimate subzone. Within these subdivisions the differences between low-shrub and tussock tundra NDVI were very small. An inverse pattern was observed for albedo, with sedge tundra having the highest albedo, followed by dwarf shrub, tussock, low shrub, and finally the tree line classes (table 1). This pattern was also retained when vegetation classes were partitioned by bioclimate subzones.

Within tundra vegetation classes, the greater mean July temperatures in bioclimate subzone E, in comparison to subzone D, corresponded to higher NDVI for all vegetation classes (table 1). Alternatively, early April albedo was lower for all classes in bioclimate subzone E. For the dwarf-shrub tundra class, the difference between April albedo in subzones D and E was notably smaller than those observed for the remaining classes. The overall relationship between NDVI and maximum albedo for tundra vegetation classes, regardless of which area is considered, were summarized by a significant linear relationship between NDVI and maximum albedo ($r^2 = 0.88$, $p < 0.01$; figure 2(a)), and a significant positive linear relationship between NDVI and standard deviation of maximum albedo ($r^2 = 0.52$, $p < 0.01$; figure 2(b)).

Lower April albedo corresponded to an earlier decline in springtime albedo for the two bioclimate subzones considered here (figure 3). Across each of the six classes, a lower
maximum albedo value (table 1) corresponded to an earlier and generally slower spring albedo decline (figure 3(a)) during snowmelt. A similar relationship was observed between bioclimate subzones D and E without differentiating by vegetation type (figure 3(b)). In comparison to subzone D, subzone E exhibited earlier albedo decline, lower maximum albedo (0.726 and 0.751) and higher NDVI (0.607 and 0.528) during the spring snowmelt period, as expected given its warmer, more southerly, location.

Within bioclimate subzone D there were only small differences in maximum albedo between tussock, low-shrub and dwarf-shrub tundra classes (0.739, 0.742, and 0.744 respectively), with sedge tundra having a notably higher maximum albedo value (0.763), presumably owing to a lack of vegetation protruding above the snowpack. Differences in albedo decline during the snowmelt period are apparent despite these small differences in maximum albedo (figure 4(a)), and classes with lower maximum albedo exhibit generally earlier albedo decline. However, examination of temperature observations illustrate that the albedo trajectories diverge when mean daily maximum temperature for the compositing period exceeded freezing (0°C), indicating that differences in albedo were the result of temperature (figure 4(b)). Additionally once maximum temperatures exceeded freezing, differences in albedo between vegetation classes were proportional to temperature differences (figure 4(b)). Further, differences in reflected shortwave radiation did not become large until temperatures exceeded freezing (figure 4(c)).

In bioclimate subzone E more pronounced differences in maximum albedo were apparent. Low-shrub and tussock tundra had similar low albedo values (0.719 and 0.716 respectively), in comparison to dwarf-shrub and sedge tundra, which had values of 0.736, and 0.742 respectively. These differences in maximum albedo were maintained throughout the snowmelt period, notably more so than in bioclimate subzone D, with areas of lower maximum albedo exhibiting earlier albedo decline (figure 4(d)). Temperature differences between the different vegetation zones were small, particularly relative to subzone D, and albedo differences were established well before mean daily maximum temperatures were above freezing (figure 4(e)). Variability in albedo between vegetation classes led to differences in net surface shortwave radiation upwards of 50 W m⁻² during the snowmelt period (figure 4(f)).

4. Discussion

These results reveal that variation in springtime albedo is influenced by vegetation type across the tundra biome. Observed differences in albedo trajectories between low-shrub and dwarf-shrub vegetation classes within bioclimate subzone E (figure 4(d)) were consistent with the effects of increased shrub cover at documented local scales by field observation and photo records (Racine et al 2003, Sturm et al 2005, Tape et al 2006, Marsh et al 2010). That is, decreased winter albedo is associated with increased shrub cover leading to earlier albedo decline, resulting in a net increase of absorbed radiation during the spring. The local-scale experiment conducted by Sturm et al (2005) was preceded by several regional studies documenting shrub expansion over the past half-century in central Alaska (Sturm et al 2001a, 2001b, Tape et al 2006).
Since the height distinction between low-shrub (>40 cm) and dwarf-shrub (<40 cm) tundra classes (Walker et al. 2005) is less pronounced than the shrub expansion described by Sturm et al. over a 50 year period, our results indicate that even small increases in shrub height occurring over shorter time scales may impact tundra energy budgets.

Considering tussock and non-tussock tundra vegetation classes suggests that vertical stature associated with the tussock growth form influenced albedo as well. Tussock tundra exhibited earlier albedo decline than low-shrub tundra (figure 4(a)) despite having higher maximum albedo and lower NDVI (table 1). Areas of tussock tundra can be highly heterogeneous (Lantz et al. 2010), with tussocks acting structurally similar to shrubs, and can also include shrub components that impact NDVI (Boelman et al. 2003). Moreover, a previous study utilizing the CAVM and a different data set reported similar NDVI patterns (Raynolds et al. 2006). Additionally, a recently developed map of shrub cover in Alaska (Beck et al. 2011 at press) shows the highest cover of tall shrubs (>1 m) in areas classified as tussock tundra. This is not to say the CAVM classification is incorrect, but rather to highlight the range of variability within vegetation classes and point out the possibility that areas classified as tussock tundra contain microsites that support tall shrubs. Alternatively, our result may also be influenced by regional differences in snow depth, a factor that could not be directly considered in our analyses. Overall our results demonstrate a clear link between vegetation stature and springtime albedo dynamics for a variety of growth forms across the pan-Arctic region.

In bioclimate subzone D, differences in maximum albedo between vegetation classes were small (table 1, figure 3(a)) and subsequent differences in albedo decline (figure 4(a)) were a result of temperature variability (figure 4(b)). However, in subzone E, differences in maximum albedo were more pronounced (table 1, figure 3(a)) and temperature differences were small (figure 4(c)), resulting in rates of albedo decline (figure 4(d)) that could be attributed to differences in vegetation structure. These findings, in conjunction with the inverse relationship observed between NDVI and maximum albedo, indicate that information on dominant vegetation will become increasingly important to understanding the energy balance of tundra ecosystems as warming progresses. This assertion is supported by our observation that the variability in maximum albedo increases with NDVI (figure 3(b)), which could be the result of vegetation protruding above the snowpack, vegetation altering the distribution or physical properties of snow, or more likely a combination of the three, as all have been observed more locally (Pomeroy et al. 2006, Marsh et al. 2010, Liston et al. 2002). Given pan-Arctic increases in tundra NDVI over the past 30 years (Goetz et al. 2010) in conjunction with rising temperature (ACIA 2004), and observational evidence that tundra plants exhibit height increases in response to warming (Walker et al. 2006), our results indicate that changes in springtime albedo are under way. Further, these changes may be occurring irrespective of whether positive NDVI trends are the result of shrub expansion specifically or increased tundra vegetation productivity more generally.

The implication that increases in tundra productivity will lead to changes in springtime albedo across the tundra biome has potentially wide-ranging effects. Our analyses indicate that changes in net radiation associated with differences in vegetation type at weekly time scales may be upwards of 50 W m⁻². This value should be interpreted as an approximation of the magnitude of potential changes in net surface radiation in tundra ecosystems associated with differences, and potential changes, in vegetation height. An obvious effect of reduced albedo that we can infer from our analyses is earlier snowmelt (e.g. figure 4(d)). This may lead to an earlier start of the growing season, although the temporal resolution of the MODIS albedo data used here does not lend itself well to determining the snow-free date (owing to the need to temporally composite reflectance to derive BRDF and albedo). An earlier local-scale analysis revealed no differences in snow-free date despite albedo dynamics altered by vegetation stature, but the analysis included only one graminoid class (Sturm et al. 2005). If differences in the start of the growing season are related to albedo dynamics, a lengthening of the growing season would result in increased annual vegetation productivity (Lafleur and Humphreys 2008). Additionally, greater soil heat fluxes resulting in increased soil temperature may lead to increased respiration and permafrost thaw. Given the large amount of soil carbon in permafrost vulnerable to mobilization with warming (Schuur et al. 2009) such changes to the soil thermal regime may have large effects on regional carbon cycling and act as a positive feedback to climate warming. Lastly, changes in snow distribution and physical properties in conjunction with altered radiation budgets may impact the timing and magnitude of key hydrologic events such as surface runoff from snowmelt and active layer evolution (Marsh et al. 2010, Pomeroy et al. 2006).

5. Conclusions

The results presented here suggest that distinguishing between tundra vegetation communities and the associated differences in albedo dynamics is necessary to increase the accuracy of modelled energy budgets for Arctic tundra. Such differentiation would help to refine our understanding of how tundra ecosystems contribute to global climate dynamics, and how vegetation changes will feedback to climate. Due to the relatively large areas and short (i.e. decadal) time scales of change, understanding the nature and extent of vegetation change in the Arctic, and associated changes in carbon and energy budgets, is relevant to accurately quantify current and future terrestrial Arctic feedbacks to climate (Wookey et al. 2009).

Specifically, we demonstrate that tundra vegetation types exert significant influence on albedo dynamics, particularly during the rapid spring transition, with consequences for surface energy budgets and related ecosystem processes at the pan-Arctic scale. Further, we find that observed increases in tundra productivity are changing albedo irrespective of whether shrub expansion is occurring. The MODIS albedo data series reveals spatio-temporal patterns that are consistent with field observations of shrub–snow-albedo dynamics, and thus provide a valuable record of these interactions across the
Arctic. We conclude that it is important to understand current vegetation distribution as well as the processes governing vegetation change in order to accurately predict current and future energy budgets, as well as other key ecosystem processes, such as active layer depth and surface hydrology, associated with terrestrial carbon and water fluxes.

Acknowledgments

Funding for this research was provided by the National Science Foundation (grant OPP-0732954 to SG.) We wish to thank two anonymous reviewers whose comments helped to improve the manuscript. We also acknowledge the MODIS Land Science Team for continued maintenance and development of the BRDF/Albedo products.

References

ACIA 2004 Arctic Climate Change Impact Assessment (Cambridge: Cambridge University Press)
Anderson R G et al 2011 Biophysical considerations in forestry for climate protection Front. Ecol. Environ. 9 174–82
Bartholomé E and Belward A S 2005 Glc2000: a new approach to global landcover mapping from earth observation data Int. J. Remote Sens. 235 1959–77
Beck P S A, Horning N, Goetz S J, Loranty M M and Tape K D 2011 Shrub cover on the north slope of Alaska: a circa 2000 baseline map Arctic, Antarctic, and Alpine Research at press
Blok D, Sass-Klaassen U, Schaepman-Strub G, Heijmans M M P D, Daamen P and Berendse F 2011 What are the main climate drivers for shrub growth in northeastern Siberian tundra? Biogeosci. Discuss. 8 771–99
Boelman N, Stiglitz M, Ruehl H, Sommerkorn M, Griffin K L, Shaver G and Gamon J 2003 Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra Oecologia 135 414–21
Bunn A G and Goetz S J 2006 Trends in satellite-observed circumpolar photosynthetic activity from 1982 to 2003: the influence of seasonality, cover type, and vegetation density Earth Interact. 10 12
Chapin F S III et al 2005 Role of land-surface changes in arctic summer warming Science 310 657–60
Forbes B C, Fauria M M and Zetterberg P 2009 Russian arctic warming and ‘greening’ are closely tracked by tundra shrub willows Global Change Biol. 16 1542–54
Goetz S J, Mack M, Gurney K, Randerson J and Houghton R 2007 Ecosystem responses to recent climate change and fire disturbance at northern high latitudes: observations and model results contrasting northern Eurasia and North America Environ. Res. Lett. 2 045031
Goetz S J et al 2010 Recent changes in arctic vegetation: satellite observations and simulation model predictions Arctic Land Cover and Land Use in a Changing Climate ed G Gutman (Amsterdam: Springer)
Hallinger M and Wilmking M 2011 No change without a cause—why climate change remains the most plausible reason for shrub growth dynamics in Scandinavia New Phytol. 189 902–8
Huete A, Didan K, Miura T, Rodriguez E P, Gao X and Ferreira L G 2002 Overview of the radiometric and biophysical performance of the modis vegetation indices Remote Sens. Environ. 83 195–213
Jia G, Epstein H and Walker D 2003 Greening of arctic Alaska, 1981–2001 Geophys. Res. Lett. 30 2067
Laffleur P and Humphreys E 2008 Spring warming and carbon dioxide exchange over low arctic tundra in central Canada Glob. Change Biol. 14 740–56
Lantz T C, Gergel S E and Kokelj S V 2010 Spatial heterogeneity in the shrub tundra ecotone in the Mackenzie Delta region, northwest territories: implications for arctic environmental change Ecosystems 13 194–204
Liston G E, Mcfadden J P, Sturm M and Pielke R A 2002 Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs Glob. Change Biol. 8 17–32
Liu J, Schaaf C, Strahler A, Jiao Z, Shuai Y, Zhang Q, Roman M, Augustine J A and Dutton E G 2009 Validation of Moderate Resolution Imaging Spectroradiometer (MODIS) albedo retrieval algorithm: dependence of albedo on solar zenith angle J. Geophys. Res. 114 D01106
Marsh P, Bartlett P, MacKay M, Pohl S and Lantz T 2010 Snowmelt energetics at a shrub tundra site in the western Canadian arctic Hydrol. Process. 24 3603–20
Pomeroy J W, Burslem D F R, Essery R L H, Hedstrom N R, Link T, Granger R J, Sicart J E, Ellis C R and Janowicz J R 2006 Shrub tundra snowmelt Hydrol. Process. 20 923–41
Racine C, Sturm M and Tape K 2005 Repeat photography to detect arctic tundra vegetation change during the past half-century Remote Sens. Environ. 89 281–308
Raynolds M, Walker D and Maier H 2006 NDVI patterns and phytomass distribution in the circumpolar arctic Remote Sens. Environ. 102 271–81
Saha S et al 2010 The NCEP climate forecast system reanalysis Bull. Am. Meteorol. Soc. 91 1015–57
Schaaf C B et al 2002 First operational BRDF, albedo and nadir reflectance products from MODIS Remote Sens. Environ. 83 135–48
Schuur E A G, Vogel J G, Crummer K G, Lee H, Sickman J O and Osterkamp T E 2009 The effect of permafrost thaw on old carbon release and net carbon exchange from tundra Nature 459 556–9
Stroeve J, Box J, Gao F, Liang S, Nolin A and Schaaf C 2005 Accuracy assessment of the MODIS 16 day albedo product for snow: comparisons with Greenland in situ measurements Remote Sens. Environ. 94 46–60
Sturm M, Douglass T, Racine C and Liston G 2005 Changing snow and shrub conditions affect albedo with global implications J. Geophys. Res. 110 G01004
Sturm M, McFadden J P, Liston G E and Chapin F S III 2001a Snow–shrub interactions in arctic tundra: a hypothesis with climatic implications J. Clim. 14 336–44
Sturm M, Racine C and Tape K 2001b Increasing shrub abundance in the arctic Nature 411 546–7
Tape K, Sturm M and Racine C 2006 The evidence for shrub expansion in northern alaska and the pan-arctic Global Change Biol. 12 686–702
Walker D A et al 2005 The Circumpolar Arctic vegetation map J. Vegetation Sci. 16 267–82
Walker M et al 2006 Plant community responses to experimental warming across the tundra biome Proc. Natl Acad. Sci. 103 1342–6
Woodyer P A et al 2009 Ecosystem feedbacks and cascade processes: understanding their role in the responses of arctic and alpine ecosystems to environmental change Global Change Biol. 15 1153–72