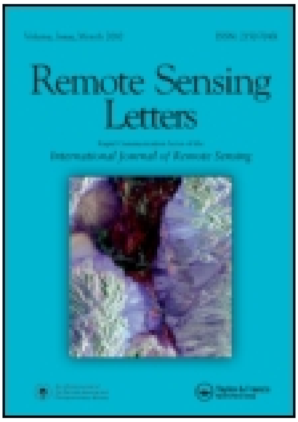

Remote Sensing Letters
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/trsl20

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Martha K. Raynolds [a] , Donald A. Walker [a] , Howard E. Epstein [b] , Jorge E. Pinzon [c] & Compton J. Tucker [c]

[a] Institute of Arctic Biology, University of Alaska, Fairbanks, AK, 99775, USA

[b] Department of Environmental Sciences, University of Virginia, Charlottesville, VA, 22904, USA

[c] Biospheric Science Branch, NASA Goddard Space Flight Center, Greenbelt, MD, 20771, USA

Available online: 07 Sep 2011

Remote Sensing Letters
Vol. 3, No. 5, September 2012, 403–411

A new estimate of tundra-biome phytomass from trans-Arctic field data and AVHRR NDVI

MARTHA K. RAYNOLDS*†, DONALD A. WALKER†, HOWARD E. EPSTEIN‡, JORGE E. PINZON§ and COMPTON J. TUCKER§
†Institute of Arctic Biology, University of Alaska, Fairbanks, AK 99775, USA
‡Department of Environmental Sciences, University of Virginia, Charlottesville, VA 22904, USA
§Biospheric Science Branch, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA

(*Received 29 April 2011; in final form 26 July 2011*)

It is often assumed that the Normalized Difference Vegetation Index (NDVI) can be equated to aboveground plant biomass, but such a relationship has never been quantified at a global biome scale. We sampled aboveground plant biomass (phytomass) at representative zonal sites along two trans-Arctic transects, one in North America and one in Eurasia, and compared these data to satellite-derived NDVI. The results showed a remarkably strong correlation between total aboveground phytomass sampled at the peak of summer and the maximum annual NDVI ($R^2 = 0.94$, $p < 0.001$). The relationship was almost identical for the North America and Eurasia transects. The NDVI–phytomass relationship was used to make an aboveground phytomass map of the tundra biome. The approach uses a new and more accurate NDVI data set for the Arctic (GIMMS3g) and a sampling protocol that employs consistent methods for site selection, clip harvest and sorting and weighing of plant material. Extrapolation of the results to zonal landscape-level phytomass estimates provides valuable data for monitoring and modelling tundra vegetation.

1. Introduction

Data from Earth-orbiting satellites indicate that Arctic tundra vegetation is changing and that the changes are occurring more rapidly in some parts of the Arctic than in others (Myneni *et al.* 1997, Bhatt *et al.* 2010). A recent study shows that during the period of global observations by the Advanced Very High Resolution Radiometer (AVHRR) sensors aboard the National Oceanic and Atmospheric Administration (NOAA) weather satellites (1982–2008), the average maximum greenness in the North America Arctic increased by 9% (as measured by the Normalized Difference Vegetation Index (NDVI)), whereas the Eurasia Arctic tundra NDVI increased by only 2%. Some areas such as those near the Beaufort Sea and Baffin Bay increased by as much as 15% (Bhatt *et al.* 2010). These changes correspond to a general warming of the Arctic and large losses of summer sea ice during the same period. If the

*Corresponding author. Email: mkraynolds@alaska.edu

Remote Sensing Letters
ISSN 2150-704X print/ISSN 2150-7058 online © 2012 Taylor & Francis
http://www.tandf.co.uk/journals
DOI: 10.1080/01431161.2011.609188

downward trend in sea-ice and the upward trends in Arctic land temperatures continue as predicted by most climate models, the rate of tundra vegetation change could accelerate with large effects to permafrost, wildlife and human use of the Arctic.

The NDVI is the most common satellite index used to measure global-scale vegetation productivity. The index is derived from the difference in reflectivity of the land surface in the near-infrared (NIR) band where vegetation reflects strongly, and the red (R) band where vegetation absorbs strongly. The difference is divided by the sum of reflectances in the same two bands to normalize for differing illumination conditions (NDVI = (NIR − R)/(NIR + R)). The NDVI was interpreted as the photosynthetic capacity of the vegetation (Tucker and Sellers 1986) and has been shown to be correlated with ground measurements of biomass, leaf-area index (LAI), intercepted photosynthetically active radiation (IPAR), carbon dioxide flux and other measures of tundra photosynthetic activity (Stow *et al.* 1993, Walker *et al.* 2003, Hope *et al.* 2005, Riedel *et al.* 2005). However, researchers have had difficulty refining the relationship between NDVI values and ground-measured tundra phytomass. This is mostly due to difficulties in matching the scale of ground data with the NDVI data, which vary between instruments depending on, among other things, the red and infrared spectral band widths and the spatial resolution of the sampling (pixel size). Previous studies have found that NDVI from different sources can be linearly adjusted and compared, but the relationship of the NDVI values to biophysical characteristics of Arctic vegetation vary widely (Morisette *et al.* 2004, Gallo *et al.* 2005, Laidler *et al.* 2008). Attempts to combine phytomass data sets collected from throughout the Arctic (e.g. Bazilevich *et al.* 1997, Gilmanov 1997) have resulted in rather poor correlations because various methods of harvest and sorting were used, and information was often missing regarding the sampling protocols, the exact location of the sample, the vegetation type and the timing of the sampling.

Another problem for circumpolar NDVI analyses is that until recently there has not been a consistent NDVI data set for the whole Arctic. The Global Inventory Modelling and Mapping Studies (GIMMS) data set, the most widely used global NDVI data set, was not optimized for high latitudes. The GIMMS NDVI is derived from imagery obtained from the AVHRR onboard the NOAA satellite series 7, 9, 11, 14, 16, 17 and 18. This NDVI data set has been corrected for sensor and orbital calibration, view geometry, volcanic aerosols, and other effects not related to vegetation change. The data are temporal composites of the maximum NDVI value for two halves of each month, which minimizes cloud cover. The data set has been used for monitoring trends in vegetation change and biophysical properties of the vegetation in many biomes (Tucker and Sellers 1986, Paruelo *et al.* 1997, Li *et al.* 2002, Fensholt *et al.* 2009) including the tundra biome (Jia *et al.* 2003, Goetz *et al.* 2005, Verbyla 2008). Previous versions of the GIMMS global NDVI data, however, contained a discontinuity of NDVI values caused by calibration of the AVHRR data with other satellite sources that had northern limits at 72°N. The GIMMS data were also missing for parts of the Arctic due to the non-polar projection. A corrected version of the GIMMS data (GIMMS3g), with a polar projection and revised calibration optimized for high latitudes was created for this study. To extend the continuation of a long term data set for climate related research, the GIMMS3g NDVI was processed to have similar dynamic range to a newer generation of satellite instruments having narrower channels and improved spatial resolution (e.g. Moderate Resolution Imaging Spectroradiometer (MODIS)). Thus, the NDVI values for the GIMMS3g data set are higher than for the same time and location in the GIMMS data set, allowing greater resolution in the low NDVI areas common in the Arctic (detailed methods for this data set to be published elsewhere).

2. Methods

Aboveground phytomass was sampled on transects along the Arctic bioclimate gradient in North America (1750 km long, 8 locations sampled 2003–2006) and Eurasia (1500 km, 5 locations sampled 2007–2010) (figure 1). The study locations were chosen to represent each of the five Arctic bioclimate subzones as displayed on the Circumpolar Arctic Vegetation Map (CAVM) – from Subzone A in the north where shrubs are absent, mosses and lichens are dominant, and bare ground is common, to Subzone E in the south which is characterized by complete ground cover and abundant dwarf shrubs (figure 1) (Circumpolar Arctic Vegetation Map (CAVM) Team 2003). Possible locations were restricted to areas accessible by fixed-wing aircraft, boat or road.

The sampling site at each location was chosen to represent 'zonal' vegetation. This concept developed by Russian vegetation scientists denotes a place where the vegetation is characteristic of the climate of an area, where vegetation has had a long time to develop on fine-grained soils under the prevailing climate, with no extremes of moisture, slope, soil chemistry or large-scale disturbances (Razzhivin 1999). Satellite

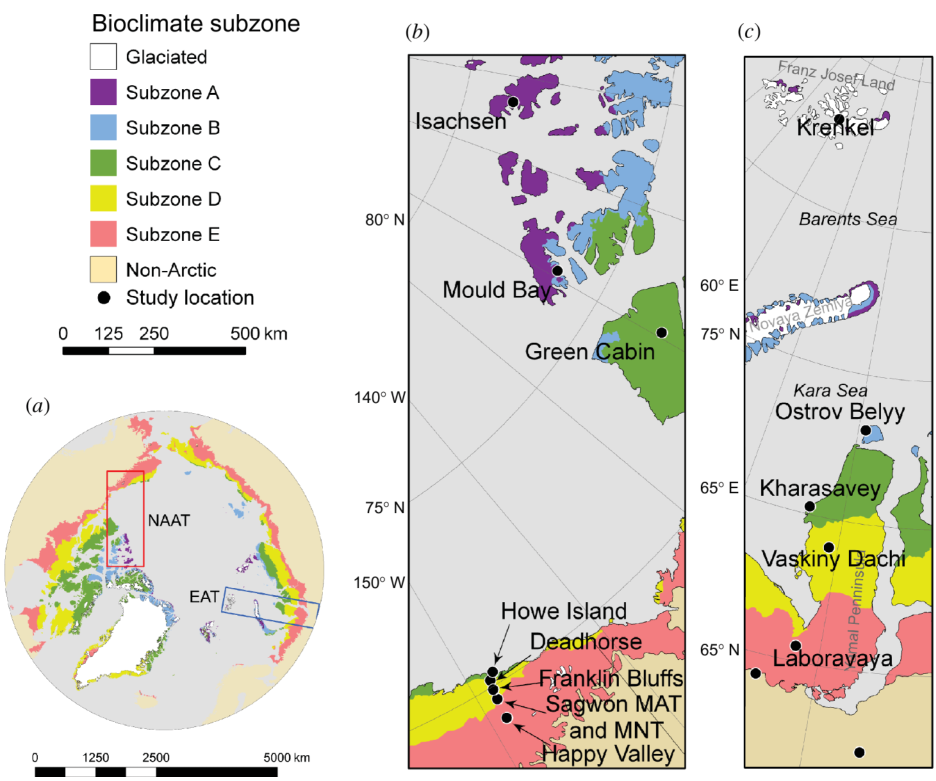

Figure 1. Arctic bioclimate subzones and relationship to study locations: (*a*) circumpolar view of transects, (*b*) North America Arctic Transect study locations and (*c*) Eurasia Arctic Transect study locations.

imagery, aerial photos, vegetation and geology maps were consulted to find large areas of representative, homogeneous zonal vegetation at each study location. Many person-days were spent on ground reconnaissance, to better understand the relationship between the landscape and the vegetation. Selected sites were at least 50 m^2 and were contained within and characteristic of much larger homogenous tundra landscapes.

On the North America Arctic Transect (NAAT) 10 m × 10 m patterned-ground landscapes were mapped at each site (Raynolds *et al.* 2008). Phytomass was clipped from five nearby 20 cm × 50 cm quadrats representative of each microhabitat occurring within the mapped area. Landscape-level phytomass was then calculated using area-weighted averages of constituent plant communities in each map. On the Eurasia Arctic Transect (EAT) vegetation was more homogeneous, so phytomass was sampled from five randomly placed 20 cm × 50 cm quadrats along evenly spaced transects within 50 × 50 m^2 areas (Walker *et al.* 2008).

Tundra phytomass clipping methods were refined based on sampling carried out over the last 30 years in all types of Arctic vegetation (Walker *et al.* 1995, 2011). Phytomass sampling was done at the time of year with peak vegetation biomass, the timing of which varies depending on the location, being somewhat earlier in North America (last week of July to first week of August) than Eurasia (middle of August). The first step was to photograph the 20 cm × 50 cm quadrat to document the undisturbed vegetation. Any shrubs that extended outside the quadrat were first trimmed so that the sample included just the portion within the quadrat. A bread knife was used to cut around the margin of the quadrat through the litter, moss and organic soil horizons into the top mineral soil horizon. The intact 20 cm × 50 cm slice of tundra was removed, often in two pieces, and placed into labelled plastic bags. No sorting was done in the field, as Arctic field conditions are not conducive to careful sorting. The samples were kept cool or frozen until sorting. All vegetation above the dead moss or soil layer was removed and sorted by plant growth-form, woody and foliar components and live versus dead. Dead mosses were separated from peat and organic soil. All samples were oven-dried and weighed. Samples contaminated with wind-blown soil and biotic soil crusts were ashed to determine the mineral fraction, which was subtracted from the original weight. Live aboveground phytomass for all plant growth forms was summed for each plot and averaged for each site. The methods have been fully described in an online report (Walker *et al.* 2008, Appendix D).

NDVI values for each phytomass sampling site were extracted from two different NDVI data sets with different spatial resolutions. The maximum NDVI for the specific year during which the phytomass data were collected for each sampling site was extracted from the 8 km GIMMS3g AVHRR data. The northernmost sites of both transects were on small Arctic islands and could not be resolved in the GIMMS3g data set due to the larger pixel size. The amount of ocean included in the pixels made the NDVI values meaningless. A finer resolution NDVI data set was sampled to include these sites, the 1 km AVHRR-derived base image from the CAVM. This data set was created by selecting pixels with maximum NDVI from biweekly AVHRR images from 11 July to 31 August in 1993 and 1995 (CAVM Team 2003).

The relationship between landscape-level zonal phytomass sampled along the Arctic transects and satellite NDVI values were compared using logarithmic regression. A logarithmic equation has been shown to best correlate with phytomass, since NDVI is asymptotically non-linear as it approaches its maximum value of 1 for areas with dense plant cover (Tucker and Sellers 1986, Walker *et al.* 2003). The regression equation relating aboveground phytomass to the GIMMS3g data for the years sampled was applied to all pixels within that image to create a map showing the distribution of Arctic phytomass and to calculate an estimate of total Arctic aboveground phytomass.

3. Results

Aboveground phytomass collected at sites varied from less than 0.10 to more than 1.20 kg m^{-2}. Bryophytes (mosses and liverworts) accounted for most of the phytomass at many sites. Shrubs, though important at sites in the southern Arctic (Subzones D and E), decreased in importance with latitude and were absent in Subzone A.

The GIMMS3g NDVI data showed a highly significant relationship with phytomass (figure 2(*a*), coefficient of determination $R^2 = 0.94$, $p < 0.001$). The CAVM NDVI had a slightly weaker correlation (figure 2(*b*), $R^2 = 0.91$, $p < 0.001$). Although the exact years of the CAVM NDVI data did not match the years of the phytomass sampling, the range of NDVI values along the climate gradient is much larger than year-to-year variation (on the order of 10%). The analysis of these data showed that the NDVI–phytomass relationship was consistent even at very low values and that the relationship was almost identical for the Eurasia and North America transects.

To produce a spatially explicit picture of phytomass distribution in the Arctic, we used the relationship between phytomass from both Arctic transects and the new GIMMS3g NDVI to create a phytomass map of the Arctic for 2010 (figure 3). The total Arctic aboveground phytomass calculated from this map was 2.024×10^{12} kg, over three-quarters of which was in Russia and Canada (table 1). Over half of Arctic phytomass was found in bioclimate Subzone E.

4. Discussion and conclusions

The very tight regression relationship between Arctic phytomass and NDVI shows that the methods described here for sampling phytomass and extrapolating using NDVI are quite robust. The relationship shown in figure 2(*b*) for North America is almost identical to the relationship for Eurasia, though the transects cover areas with very

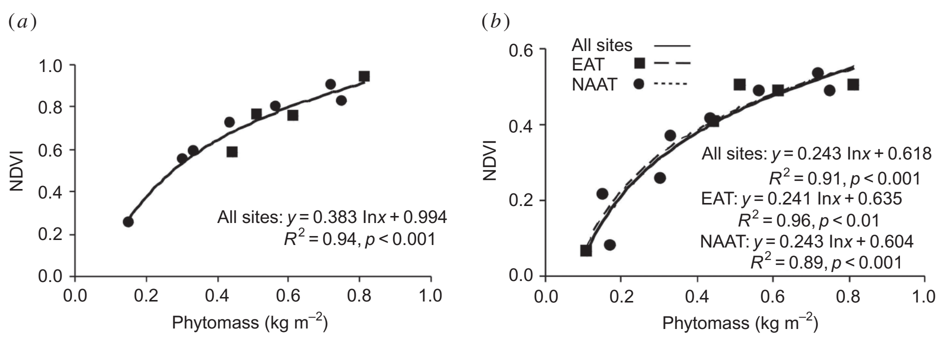

Figure 2. Relationship between the aboveground phytomass sampled at zonal sites throughout the Arctic and NDVI on the EAT and NAAT. (*a*) GIMMS3g AVHRR maximum NDVI 8 km data for year during which the phytomass was collected (2003–2010). (*b*) AVHRR maximum NDVI 1 km data from 1993 and 1995 (CAVM Team 2003) (parts of the EAT and NAAT regression lines cannot be distinguished because they are so similar to the combined regression line).
Note: EAT, Eurasia Arctic Transect; NAAT, North America Arctic Transect; NDVI, normalized difference vegetation index.

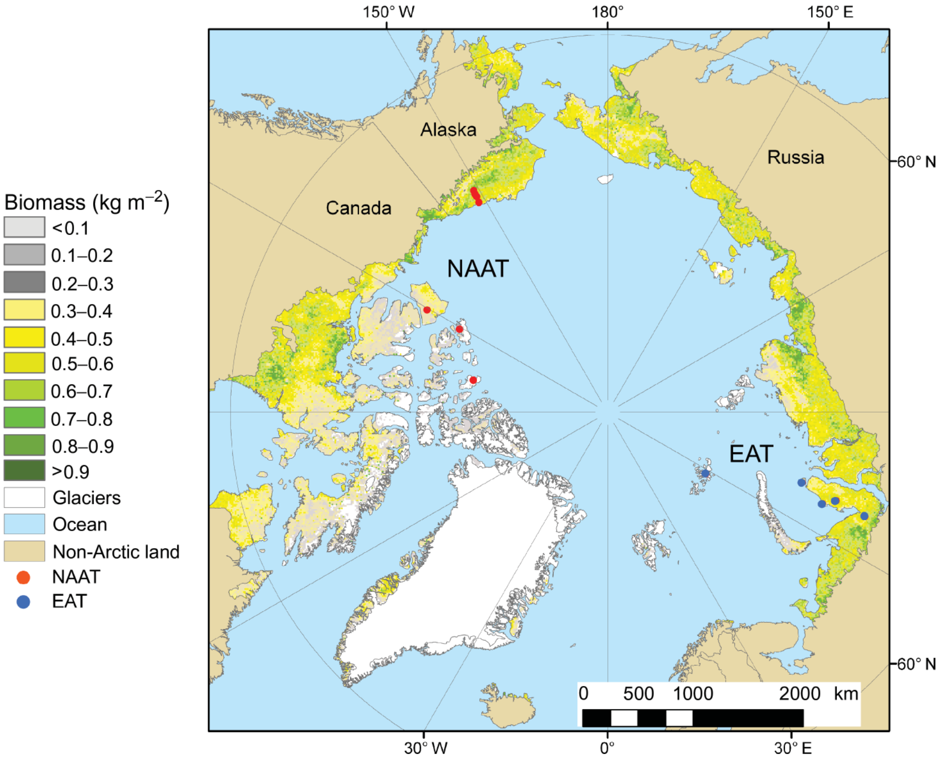

Figure 3. Aboveground phytomass in the Arctic in 2010, mapped using the relationship between phytomass and NDVI developed through field sampling of zonal sites in North America and Eurasia.

Table 1. Phytomass of different parts of the Arctic in 2010, based on GIMMS3g data and biomass sampling on North America and Eurasia Arctic.

Country	Arctic tundra area[a] ($\times 10^3$ km^2)	Average phytomass (kg m^{-2})	Total phytomass ($\times 10^9$ kg)	Total phytomass (%)
Russia	1796	0.518	931	46.0
Canada	2337	0.327	764	37.7
United States	480	0.559	269	13.3
Greenland	333	0.160	53	2.6
Norway	26	0.169	4	0.2
Iceland	6	0.445	3	0.1
Total	4979		2024	100.0
Bioclimate subzone				
A	100	0.106	11	0.5
B	446	0.157	70	3.5
C	1159	0.257	298	14.7
D	1470	0.417	613	30.3
E	1804	0.564	1017	50.2

Note: [a]excluding permanent ice and large water bodies.

different geological and glacial histories, with different vegetation communities, and were sampled as parts of different projects. Researchers have often assumed that NDVI is a proxy for phytomass throughout the Arctic (e.g. Goetz *et al.* 2005). This is the first study to quantify a highly significant and consistent NDVI–biomass relationship that can be applied to the entire Arctic.

Tundra is notoriously heterogeneous at many scales, so it is important that the sampling protocols account for this variability and that the extrapolation methods correspond to the scale of the satellite data. The sampling approach described here used carefully selected representative zonal sites, making maximum use of a relatively small data set collected over a large, inaccessible region. Extremely heterogeneous patterned ground areas were subsampled by plant community type. The Arctic lends itself to this type of zonal analysis because it has not been extensively affected by large-scale disturbances such as agriculture, erosion from overgrazing, urbanization or fire. Characterizing the zonal sites for each bioclimate subzone allowed direct extrapolation to the rest of the zonal areas throughout the bioclimate subzone. Azonal areas (such as ridges or wetlands) within a subzone may have atypical NDVI values. In the future, it would be desirable to sample additional zonal areas in other parts of the Arctic as well as azonal areas, to get phytomass values for the full range of NDVI values that occur in each bioclimate subzone of the Arctic. We describe the phytomass sampling in detail to encourage additional sampling and validation of the relationship reported.

The success of this study rests on the consistent phytomass sampling methods developed over years. Two important methods that were the same for both transects were (1) the selection of representative zonal vegetation for plot locations and (2) the careful sampling of the phytomass. Consistent methods for collecting, sorting and weighing non-vascular phytomass are critical, including the determination of live moss versus dead moss versus peat, correcting for windblown sand and silt by ashing and sampling of biotic crusts (algae and lichen).

The results of this research demonstrate that a relatively simple sampling method could be used by many researchers to monitor Arctic phytomass. A network of sampling locations could be set up, with either additional locations or repeat sampling over time at the locations used for this research, to monitor and interpret changes in satellite signals over large regions of tundra vegetation. The application of a consistent phytomass sampling protocol would allow comparison of data from one site to another. The data collected for the Arctic would provide much needed baseline data for this rapidly changing region and would also provide a data set for continued calibration of satellite data to ground measurements.

Acknowledgements
Uma S. Bhatt (UAF-GI) has been instrumental in validating the GIMMS3g NDVI data. Many people made the work possible along these remote transects, in particular the Earth Cryosphere Institute in Russia, the Aurora Institute in Canada and the field teams. This work is part of the Greening of the Arctic initiative of the International Polar Year, with funding from the US National Science Foundation (grants OPP-0120736, ARC-0531180, ARC-0425517, ARC-0902175) and the National Aeronautics and Space Administration (grants NNG6GE00A, NNX09AK56G).

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