

**The use of repeat colour digital photography to monitor high Arctic
tundra vegetation**

by

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Abstract

High Arctic ecosystems are experiencing some of the earliest and most extreme changes in climate as a result of global climate change. Temperature increases twice the hemispheric average are initiating changes to terrestrial systems including shifts in timing of phenology, aboveground biomass and community composition of Arctic vegetation. Satellite imagery from the last 30 years has shown a greening across tundra ecosystems with increases in peak productivity and growing season length. A few plot scale field studies support these large-scale trends but overall validation at the plot scale is still lacking. Current manual and automated methods for monitoring vegetation at the community and plot scale is both time consuming and employs expensive, sensitive multispectral instrumentation that can be cumbersome to use in Arctic field sites. In this thesis I examine the utility of colour digital photography in monitoring tundra vegetation across four different vegetation communities, inside and outside of passive warming chambers. Colour and infrared photos were taken on one day peak season in 2010. Relationships between a greenness index derived from colour photographs and biomass data were compared to relationships with NDVI derived from infrared photographs. Results suggest that colour photographs can be used as a proxy for productivity and aboveground biomass in multiple tundra vegetation communities. These data were then used to infer phenological signals at multiple spatial scales from a set of colour photographs taken on six days during the 2012 growing season. Results show higher greenness values due to treatment at the plot scale but not at the individual scale suggesting greater green biomass in warmed plots. At the individual scale site differences emerged for two study species (*Salix arctica*, *Dryas integrifolia*) suggesting a difference in vegetation vigor due to differences in soil moisture and perhaps competition. The phenological signal was strongest at the species scale due to reduced interference from bare soil, litter and standing water. Overall, these results show the potential for this methodology for measuring vegetation in the Arctic. Its simplicity, affordability and efficiency has great potential for use in a vegetation monitoring network in the Arctic.

Preface

The experimental design used in this thesis was established by Dr. G. Henry. The overall study is part of the International Tundra Experiment (ITEX), an international collaboration monitoring tundra ecosystems in Arctic and alpine ecosystems (Henry and Molau 1997). None of the text in this thesis is taken directly from previously published or collaborative work.

Wiebe Nijland wrote the photo-processing program used in Chapter 2 and 3 and Samuel Robinson wrote the flower counting algorithm in Chapter 3. Marc Edwards took the digital and infrared images of plots in 2010 as part of his MSc thesis with Dr. Henry. All data analysis in the thesis including processing the photographs and statistical analyses are my original work.

The in-field photography methodology and data collection was of my own design. The environmental data collection was based on protocols established by Dr. Henry for the site and related to those used in ITEX, and was the result of collaborative efforts at Alexandra Fiord during the 2010 and 2012 field seasons.

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Abbreviations

AF Alexandra Fiord Lowland

ANOVA Analysis of Variance, a set of statistical techniques to identify sources of variability between groups

DOY Day of Year

ER Ecosystem Respiration

FDML First Day Mature Leaf

FDMF First Day Mature Flower

FDLS First Day Leaf Senescence

FOV Field of View

GEI Greenness Excess Index

GPP Gross Primary Productivity

GEP Gross Ecosystem Productivity

IR Infrared

ITEX International Tundra Experiment

LAI Leaf Area Index

NDVI Normalized Differential Vegetation Index

OTC Open Top Chambers

RGB Red, Green, Blue

TLH Total Live Hit biomass

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1 Introduction

Overview

Average global temperatures have risen at an unprecedented rate over the last century and are expected to continue to rise throughout the 21st century (IPCC 2007). Arctic ecosystems are experiencing some of the earliest and most extreme changes in climate with temperature increases twice the hemispheric average (IPCC 2007; Kaufman et al. 2009). These climatic shifts are cascading through terrestrial systems altering the structure and function of tundra ecosystems (Post et al. 2009). Large-scale shifts in species distribution, cover, and community composition, as well as small-scale shifts in individual plant phenology and reproduction, have already been observed from satellite imagery and field studies (Walker et al. 2006; Bhatt et al. 2010; Elmendorf et al. 2012b). However, these vegetation changes are complex with strong site and species-specific responses through space and time highlighting the heterogeneous nature of these systems (Walker et al. 2006; Elmendorf et al. 2012a).

Monitoring ecological change in the Arctic is important due to the implications of climate change on biodiversity, nutrient and carbon cycling, atmospheric warming, and associated feedbacks. Long-term ecological records in the Arctic are limited, but programs like the International Tundra Experiment (ITEX) have resulted in 20-year vegetation records in some locations. The reliability of long-term datasets is difficult to maintain even with set protocols and traditional field-based phenology observations are time consuming and expensive in remote areas. However, phenology is recognized as one of the most responsive vegetation traits to climate change in nature (IPCC 2007). Across the Arctic phenological shifts such as earlier leaf and flowering have been observed as a result of earlier snowmelt and warming temperatures (Myneni et al. 1997; Arft et al. 1999; Wolkovich et al. 2012; Oberbauer et al. 2013). Increasing the volume, accuracy and consistency of phenology data and associated vegetation characteristics will aid in teasing out the complex response of Arctic vegetation to climate change. Digital photography could be a tool to provide consistent and inexpensive phenology and

vegetation data in remote tundra systems. It has already been shown to be useful in estimating qualitative (e.g. vigor) (Adamsen et al. 1999) and quantitative (e.g. cover) changes in biomass (Ewing and Horton 1999, Richardson et al. 2001) as well as for phenological observations (Crimmins and Crimmins 2008; Ide and Oguma 2010; Migliavacca et al. 2011). Additionally, digital cameras are affordable and easy to use making them an attractive field instrument for recording environmental phenomena. Automation of vegetation monitoring at the community scale through the implementation of repeat digital photography could achieve a greater volume and consistency of data by reducing human error associated with field-based measures.

In this thesis, I examine the utility of colour and infrared photography in monitoring several key characteristics of tundra vegetation in four vegetation communities arrayed along a natural moisture gradient. I explore the use of colour photography in monitoring biomass, productivity and phenology at both the plot and species scale. I also discuss how the results and methodology have potential for implementation across the Arctic. Photography is a powerful visual tool for monitoring and communicating ecological change. Chapter 1 reviews the relevant topics in the literature, describes the study site, and outlines the objectives for the thesis. Chapter 2 compares digital photography and spectral photography in measuring key vegetation characteristics. Chapter 3 examines seasonal productivity signals derived from digital photographs at the plot and species scale. Chapter 4 summarizes and concludes the major findings.

Terrestrial Arctic climate change

The Arctic is an excellent indicator of climate change as it is dominated by the modern cryosphere (i.e. permafrost, areas of snow, freshwater ice, sea ice, glaciers, ice caps, and ice sheets), the stability of which is dependent on a consistently cold ($T < 0^{\circ}\text{C}$) thermal regime. Changes to the Arctic tundra biome are important as it plays a critical role in both the global carbon budget and the global energy balance (Bliss 1992; Chapin et al. 2005). Despite having low ecosystem productivity and species diversity, the tundra sequesters a significant amount of atmospheric carbon dioxide (CO_2) into organic soils due to low rates of decomposition. Furthermore, the predominantly short, patchy

vegetation and prolonged snow cover creates a relatively high surface albedo cooling the atmosphere (Callaghan et al. 1995; Chapin et al. 2005). Current warming trends spanning atmospheric, terrestrial, and marine systems are affecting the crucial role they play in regulating the global climate system (Serreze et al. 2000; Chapin et al. 2005).

The intimately coupled nature of Arctic cryosphere stability and atmospheric temperatures are initiating cascading changes in Arctic terrestrial ecosystems. This in turn is initiating climate feedbacks with snow, sea ice, permafrost, and vegetation cover, which can both amplify and dampen climate warming through a variety of physical processes. (Hinzman et al. 2005; McGuire et al. 2009; Bhatt et al. 2010). Increases in soil temperature, active layer depth, nutrient cycling, and precipitation and changes in soil moisture are all expected with increasing temperatures (Kattsov and Walsh 2000; Serreze et al. 2007). The direction and magnitude of feedbacks from vegetation change (Cornelissen et al. 2007) are not fully understood. From compositional shifts such as shrub expansion decreasing albedo but increasing carbon storage, to changing rates of litter accumulation and decomposition, the responses of vegetation and associated feedbacks to climate change cannot be generalized easily (Sturm et al. 2001, Chapin et al. 2005, Cornelissen et al. 2007).

Measuring biome scale vegetation changes in recent decades has been accomplished with a combination of satellite observations, field measurements and modeling. Satellite imagery up until the 1990s, showed a relatively uniform greening across the Arctic and northern boreal forest biome (Myneni et al. 1997; Zhou et al. 2001; Lucht et al. 2002). Since 1990, greening has become more apparent in Arctic tundra supporting the projected amplification of climate change at high latitudes (Myneni et al. 1997; Bhatt et al. 2010). Increases in peak productivity and growing season length derived from satellites over the last 30 years have been validated with field studies (ACIA 2004; Walker et al. 2006; Bhatt et al. 2010; Loranty 2011). These productivity changes have been accompanied by large-scale vegetation changes including woody shrub expansion in areas of the low Arctic (Myneni et al. 1997; Sturm et al. 2001; Verbyla 2008), and changes in composition and density of herbaceous species across the Arctic (Epstein et al. 2004; Hudson et al. 2011; Elmendorf et al. 2012b). However, changes in community composition, above ground biomass and the timing of phenology

vary significantly across different vegetation communities (Elmendorf et al. 2012a, b). Even the same species in different communities can respond differently to changes in temperature, moisture and nutrients. Observed short-term changes in communities may not reflect long-term trends due to evolutionary history and unique factors that limit growth and dispersal of certain species (Chapin et al. 1996).

Arctic plants and plant communities

The Arctic tundra biome is characterized as areas north of the boreal/taiga tree line covers an area of more than 7 million km² (Bliss 1992). A further subdivision between low and high Arctic has been made by Bliss (1992) based on ecological characteristics dictated by latitude and climate. The low Arctic is dominated by “tundra”, a generic definition of landscapes with 80-100% vegetation cover. The high Arctic is dominated by “polar desert” and “polar semi-desert” with only 10-30% vegetation coverage.

Heterogeneity defines Arctic landscapes creating a mosaic of vegetation communities driven by variable local climates, hydrology, topography and geology (Bliss 1992).

Tundra vegetation communities have been grouped into five broad subzones according to the Circumpolar Arctic Vegetation Map (CAVM; Walker et al. 2005) that span across the low and high Arctic: (A) cushion forb, (B) prostrate dwarf shrub, (C) hemi-prostrate dwarf shrub, (D) erect dwarf shrub, and (E) low shrub. Within these broad classifications there are approximately 900 vascular species, only 0.4% of the world’s total (Billings 1997, Bliss 1979). Species richness and diversity is greatest in the low Arctic and decreases along a latitudinal gradient from low- to high-Arctic (Matveyeva and Chernov 2000), with concurrent decreases in zenith angle, photoperiod and mean annual temperature. Vegetation also shifts from woody to herbaceous along this gradient. Despite low richness and diversity at the biome scale, at the community scale Arctic tundra boasts a diversity of species comparable to those of temperate grassland and coniferous biomes (Bliss *et al.* 1981).

Morphologically, tundra plants are generally low biomass species with up to 98% allocation to belowground structures, an adaptation to the harsh climate, limited nutrients, light and at times extensive herbivory (Callaghan et al. 1999). The low stature

of tundra vegetation allows them to take advantage of the surface boundary layer that can be between 3 and 8 °C warmer than surrounding air (Molgaard 1982). This characteristic also minimizes desiccation from wind (Oberbauer and Dawson 1992) and maximizes insulation by snow (Sturm et al. 2005). Many species in the Arctic are adapted to low soil moisture due to limited precipitation. Adaptations include low transpiration rates, high concentrations of carbohydrates, and adjustable water potential for drought resistance (Billings and Mooney 1968). Arctic plants are capable of photosynthesis at low light levels, an important adaptation given the limited growing season length (Chapin and Shaver 1985). Plant growth and reproduction occur quickly after environments become snow free. This is made possible by the stored carbohydrates in roots and rhizomes of perennial Arctic plants (Billings and Mooney 1968). Additionally, flower buds and shoots formed in the previous fall can overwinter giving the plants a head start once snow melts. Tundra species are adapted the cold harsh climate of the Arctic, they are slow growing, long lived and have low fecundity, which may limit their ability to adapt to changes in climate (Callaghan et al. 1995).

International Tundra Experiment

The International Tundra Experiment (ITEX) was established in 1990 as a collaborative network of over 20 sites in both Arctic and alpine ecosystems to study the responses of a diverse selection of tundra ecosystems to high latitude warming. The main objective was to monitor changes to growth, phenology, and reproduction of circumpolar vascular plant species to environmental manipulations (Henry and Molau 1997). These environmental manipulations included, passive warming through the use of open top chambers (OTC), extension and reduction of growing season length through snow removal and addition, and soil nutrient availability through nutrient addition. The following study examines the responses of tundra plants and plant communities to OTCs , which have been shown to increase near surface air temperatures 1 – 3°C simulating predicted climate change (Henry and Molau 1997; Marion et al. 1997). ITEX has standard protocols for study design, data collection, and measurement techniques allowing for meta-analyses of these data (Arft et al. 1999; Walker et al. 2006; Elmendorf et al. 2012a, b).

Study site – Alexandra Fiord

All research was conducted at the Alexandra Fiord Twin Glacier lowland on the east-central coast of Ellesmere Island, Nunavut (78°53'N, 75°55'W). The 8 km² lowland is considerably more vegetated than the surrounding polar desert and semi-desert ecosystems to the east and west. To the north are the waters of Alexandra Fiord and to the south are the two lobes of the Twin Glacier, which drains the Prince of Wales ice cap. The lowland has two rivers and several creeks and streams that run south to north with the gently north sloping topography. This periglacial outwash plain is characterized by glacial and permafrost features such as granite outcrops, glacial erratics, frost boils, and sorted polygons (Freedman et al. 1994). Soils are characteristic of recently deglaciated terrain; young and poorly developed however, they are relatively high in organic matter compared to the surrounding terrain (Muc et al. 1994). Approximately 100 – 200 mm of precipitation falls annually with 10 – 50 mm of that falling during the growing season (Labine 1994). Average growing season temperatures are approximately 5 – 8°C (Labine 1994; G Henry, unpublished data).

The soil moisture conditions of the lowland strongly affect the plant community structure (Muc et al. 1989). Plant communities vary significantly across small spatial scales. A total of 96 vascular plant species have been recorded across the lowland, dominated by the dwarf shrubs *Salix arctica*, *Dryas integrifolia*, *Cassiope tetragona*, graminoids such as *Arctagrostis latifolia*, *Luzula* spp., *Carex* spp., and forbs such as *Saxifraga oppositifolia*, *Draba* spp., and *Papaver radicum* (Ball and Hill 1994). Soil moisture is dictated by snowmelt and localized topography. Drainage is constrained vertically by continuous permafrost underlying the site, and topography horizontally (Freedman et al. 1994).

This study was conducted in four distinct vegetation communities arrayed along the soil moisture gradient as defined by the Circumpolar Arctic Vegetation Map (CAVM; Walker et al. 2005). The driest site was a xeric-mesic prostrate dwarf-shrub herb tundra, dominated by *Salix arctica* (Willow site) with *Dryas integrifolia*, *Saxifraga oppositifolia* and graminoids, such as *Poa arctica* and *Luzula confusa*. This site had approximately 71g m⁻² of standing crop, sandy soils, and experiences the earliest snowmelt of the four study sites (Muc et al. 1994). Two mesic to hydric-mesic prostrate dwarf-shrub herb

tundra, dominated by *Cassiope tetragona* (Cassiope site) and *Dryas integrifolia* (Dryas Site) respectively, with an estimated aboveground biomass of 190 g m^{-2} and included important contributions from the graminoids *Arctagrostis latifolia* and *C. misandra*. The wettest site was a hydric sedge-moss dwarf-shrub wetland, (Meadow site) with $250 - 370 \text{ g m}^{-2}$ of standing crop (Henry et al. 1990). Hill and Henry (2010) noted increases of 145 – 515% in standing crop in the Meadow site from 1980 to 2005. There is surface water flow in the Meadow site through much of the growing season. Sedges (*Carex aquatilis stans*, *C. membranacea*, and *Eriophorum angustifolium triste*) dominate in the wet hollows and dwarf shrubs (*S. arctica*, *D. integrifolia*) on the drier hummocks (Henry 1998). The growing season of all four communities lasts from early June to mid August. Within the four vegetation communities, ten randomly selected 1 m^2 plots have been passively warmed using open top chambers (OTCs), with ten corresponding 1 m^2 control plots. This experiment was established in 1992, resulting in 20 years of passive warming in six vegetation communities at Alexandra Fiord as the first ITEX site.

Objectives

The objective of this thesis was to examine the utility of colour digital photography to detect seasonal patterns of greenness at multiple spatial scales, across different vegetation communities, inside and outside of passive warming chambers in the Canadian high Arctic. This study aims to demonstrate the usefulness of data derived from colour photographs as a proxy for measuring phenology, productivity, and biomass. Our first objective was to compare correlations to biomass measures of greenness data derived from RGB data of colour digital photos and of NDVI derived from spectral photos. Our second objective was to use RGB data to examine differences at the plot scale in phenology between communities along a moisture gradient and responses in long-term warming experiments. A third objective was to use RGB data to examine differences in phenology and long-term warming experiments at the species scale. A final objective was to compare flower counts from digital photographs using an automated flower counting algorithm to manual flower counts in the vegetation communities.

2 Method Validation

Introduction

Seasonal patterns of productivity are an important indicator of ecological and global change. Satellite imagery has shown a greening of arctic tundra, suggesting an increase in productivity as a result of the changing climate (Myneni et al. 1997; Zhou et al. 2001; Lucht et al. 2002;). Warmer spring temperatures have the potential to lengthen the growing season through earlier snowmelt as well as increase active layer depth and related microbial activity and nutrient cycling (ACIA, 2005; IPCC, 2007). These changes are currently and will continue to alter primary productivity and potentially timing of plant phenology of these temperature-sensitive ecosystems (Marchand et al. 2004; Walker et al. 2006). There is evidence from long-term monitoring of satellite derived vegetation indices such as the Normalized Differential Vegetation Index (NDVI), that at the biome scale, tundra ecosystems are greening in response to climate change (Myneni et al. 1997; Goetz et al. 2005; Bhatt et al. 2010). However, validation of this trend at the plot scale in terms of photosynthetic, phenological, or biomass change is lacking. Large scale NDVI does not distinguish between changes in quantitative greenness (i.e. growth and infilling) and changes in qualitative greenness (i.e. vigor) (Marchand et al. 2004). These sorts of distinctions have important implications for determining the true mechanisms behind this apparent vegetation change in the arctic tundra.

Field based monitoring of vegetation can be time consuming and in the High Arctic, expensive. Recording enough measurements to capture the variability in productivity (i.e. CO₂ exchange) at the plot scale is made difficult by instrumentation and sampling constraints. Accurate phenological records and destructive biomass measurements take careful and patient work, while destructive biomass harvesting is detrimental to long-term monitoring. Due to these issues, developing a simple, all-in-one methodology to capture plot scale heterogeneity of all aspects of vegetation change in the high arctic is highly advantageous.

Current methodology for assessing the relationship between climate and plant growth varies greatly depending on scale, application of the information, and the ecosystem in question. Plot based NDVI in Arctic ecosystems has shown strong correlations to Gross Ecosystem Productivity (GEP), Ecosystem Respiration (ER), and aboveground biomass (Boelman et al. 2003; Boelman et al. 2005; Boelman et al. 2011). Conducting NDVI measurements at the plot scale involves costly and sensitive instrumentation such as spectrometers or multispectral digital cameras. While these instruments provide valuable information, in remote and meteorologically variable field locations, dealing with these sensitive instruments can be cumbersome. For these reasons, digital photography is emerging as a simple methodology to monitor productivity variables, including seasonal greenness (i.e. GPP), phenology, and changes in biomass.

The objective of this study was to examine the utility of colour digital photography compared to infrared imagery in detecting differences in seasonal patterns of greenness across different moisture-defined vegetation communities and inside and outside of passive warming chambers in the Canadian High Arctic. Digital photography has already been shown to be useful in estimating qualitative (Adamsen et al. 1999) and quantitative changes in biomass (Ewing and Horton 1999; Richardson et al. 2001) as well as for phenological observations (Crimmins and Crimmins 2008; Ide and Oguma 2010; Migiliavacca et al. 2011). This study aims to demonstrate the usefulness of RGB data derived from digital photographs as a proxy for measuring productivity, phenology, and biomass. In this study, we present a direct comparison of a set of colour and infrared photographs from three sites, representing a natural moisture gradient, on one day peak season in 2010. NDVI (Tucker 1979) and Greenness Excess Index (GEI, Richardson et al. 2007) were calculated from infrared and colour photos, respectively, and were compared with one another and two non-destructive biomass measures. Those results were then used to infer seasonal patterns of vegetation change from a set of colour photographs from the 2012 growing season.

Methods

2.1.1 Study site

The study site is located on the East coast of Ellesmere Island, Nunavut in the Alexandra Fiord (AF) coastal lowland (78°53'N, 75°55'W). The 8 km², well-vegetated lowland is classified as a polar oasis due to favorable climatic conditions as a result of surrounding topography (Freedman et al. 1994). Average growing season temperatures range between 3 and 8°C and average yearly precipitation is less than 50 mm (Labine 1994). The growing season lasts from early June to the middle of August. The moisture regime of the lowland is controlled by snowmelt and glacial melt water and soil moisture is highly variable across the lowland. Variability in soil moisture dictates the plant community types found (Muc et al. 1989, 1994).

The study was conducted in four vegetation communities that varied in soil moisture (Table 3.1). They included: a xeric-mesic prostrate dwarf-shrub herb tundra dominated by *Salix arctica* (Willow site) with sandy soils, and experiences the earliest snowmelt of the four study sites (Muc et al. 1989, 1994); a mesic prostrate dwarf-shrub herb tundra, dominated by *Dryas integrifolia* (Dryas site), and included important contributions from the evergreen dwarf shrub *Cassiope tetragona*, and the graminoids *Arctagrostis latifolia* and *C. misandra*; a mesic prostrate/hemiprostrate dwarf-shrub herb tundra, dominated by *C. tetragona* (Cassiope site) which also included contributions from the evergreen dwarf shrub *D. integrifolia*, and the graminoids *A. latifolia* and *C. misandra*; and a hydric sedge, moss, dwarf-shrub wetland, (Meadow site) with surface water flow in much of the site throughout the growing season, dominated by sedges (*Carex membranacea*, *C. aquatilis stans* and *Eriophorum angustifolium triste*) in the wet hollows and dwarf shrubs (*S. arctica*, *D. integrifolia*) on the drier hummocks (Henry et al. 1990).

In 1992, warming experiments were established in each of the communities consisting of 20 randomly selected 1 m² plots, and half the plots were warmed using open top chambers (OTCs) with ten corresponding 1m² control plots. The OTCs passively warm the surface air temperature by 1 – 3°C, similar to increases projected in climate

change models (Marion et al. 1997). Marion et al. (1997), Hollister and Webber (2000) and Bokhorst et al. (2013) provide details on the performance of OTCs. The study site is part of the International Tundra Experiment (ITEX), a collaborative network of over 20 arctic and alpine sites established in 1990 to monitor the effect of experimental and ambient warming on tundra vegetation (Henry and Molau 1997).

Table 2.1 Characteristics of the four tundra communities at Alexandra Fiord

Site	CAVM* classification	Moisture	Above ground live standing crop (g m ⁻²)**	Major Species
Willow	Prostrate dwarf-shrub herb tundra	Xeric	71	<i>S. arctica</i> , <i>Luzula confusa</i> , <i>Poa arctica</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Cassiope	Prostrate/hemiprostrate dwarf-shrub herb tundra	Mesic	190	<i>C. tetragona</i> , <i>D. integrifolia</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Dryas	Prostrate dwarf-shrub herb tundra	Mesic	190	<i>D. integrifolia</i> , <i>C. tetragona</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Meadow	Sedge, moss, dwarf-shrub wetland	Hydric	132	<i>Eriophorum angustifolium</i> , <i>E. triste</i> , <i>C. stans</i> , <i>C. membranacea</i> , <i>D. integrifolia</i>

* Circumpolar Arctic Vegetation Map (Walker et al. 2006).

** from Muc et al. (1994)

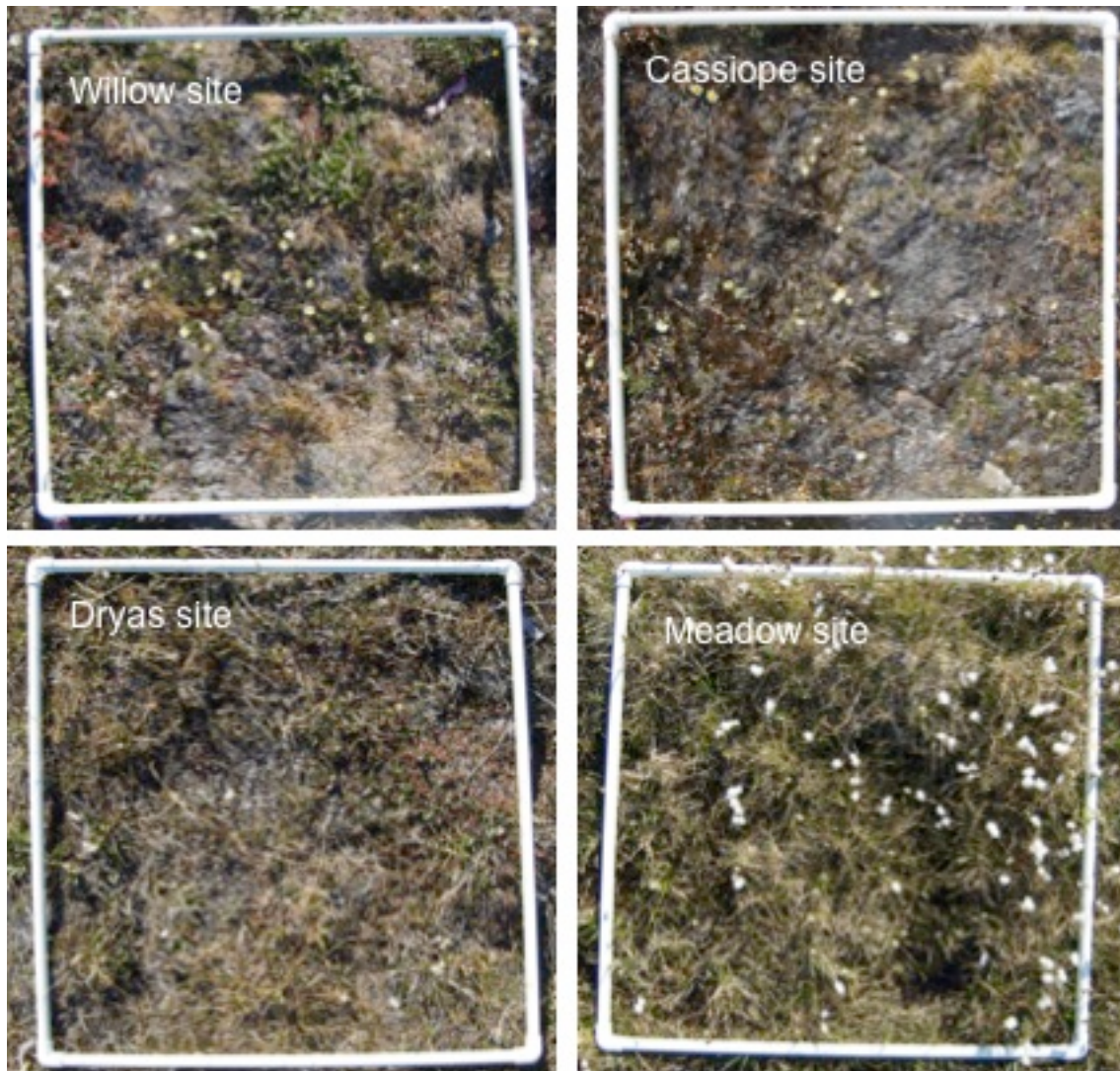


Figure 2.1 Vegetation communities photographed in 2010 and 2012. White frame represents a 1 m x 1 m quadrant.

2.1.2 Photography

To examine effectiveness of digital photography in detecting the influence of temperature and moisture on seasonal productivity over one growing season, plots were photographed with a digital camera (Nikon D40 SLR, Nikon Corporation, Japan) six times over the growing season in 2012 beginning on Day Of Year (DOY) 165 (June 15) and ending on DOY 215 (August 2). Photographs were taken 1 m off the ground at nadir from the same south facing position on each date. Photos were saved in a Nikon raw format at 3,008 x 2,000 pixels and were taken between 0900h and 1200h and in the same

cloudless climatic conditions at each plot to minimize the influence of solar angle or irradiance.

Soil Moisture was measured in three locations in each plot, three times throughout the growing season. Phenology was monitored every three days and observations of First Day of Mature Leaf (FDML), First Day of Mature Flower (FDMF), and First Day of Leaf Senescence (FDLS) were recorded.

2.1.3 Colour digital photo analysis

Colour photos from each plot were initially processed using Creative Suite 6 (Adobe Systems Incorporated, 2013) to stack and align the pixels of the six photos from each plot. This was done automatically and manual adjustments were made where there were discrepancies. Photos were then cropped to a standard 1:1 ratio size and exported as individual tiff files. Some images were excluded if the alignment processing failed. After this pre-processing, pixel values of each channel (Red, Green, and Blue) were extracted from each photo.

Extraction of pixel information was done using a function written with the `rgdal` package (0.8-4: Keitt et al. 2013) in R version 2.15.2 (R Development Core Team 2012). The photographs were transformed into a data frame and pixel values from each channel were extracted and averaged by photo. To get an estimation of greenness of each photo and to normalize variations in irradiance among photos, the green ratio (rG) was also calculated and averaged by photo (Eq. (1)):

$$rG = G / (R + G + B) \quad (1)$$

Where G = green, R = red, B = blue. A ratio was also calculated for the red (rR) and blue (rB) channels by rearranging Eq. (1). A final index, the Greenness Excess Index (GEI), was calculated using the red, green, and blue ratios (Eq. (2)); Richardson et al. 2009):

$$2*rG - (rR + rB) \quad (2)$$

Where rG = green ratio, rR = red ratio, rB = blue ratio. Although rG can be used to track phenological and productivity changes in vegetation, Eq. (2), provides a more sensitive indicator of changes in plant pigment (Ide and Oguma 2010). This is desirable in tundra ecosystems as changes in vegetation activity, i.e. photosynthesis, flowering, and senescence can be subtle.

2.1.4 Comparison with infrared images

In order to validate the GEI derived from digital photography, this methodology was compared to the more conventional productivity proxy of infrared imagery. A sample of colour and infrared (IR) images taken during the 2010 growing season from plots in three of the four sites photographed in 2012 were compared. The three sites photographed were the Willow, Meadow, and Dryas sites. Photographs were taken one after the other with a digital camera (Panasonic, DMC-LX3) and a portable multispectral vegetation camera (Tetracam ADC, Chatsworth, CA, USA) on one day mid-season in the 2010. This resulted in a total of 60 photographs from each camera, 20 (10 warmed, 10 control) in each site. Colour photos were saved in a jpeg format at 3776 x 2520 pixels and were taken at similar times and in similar climatic conditions at each plot to minimize the influence of solar angle or irradiance. Infrared images were saved in a Tetracam raw format at 2048 x 1536 pixels.

Pre-processing was done again using Creative Suite 6 to manually remove non-vegetated areas such as bare ground, rocks and standing water. For each photo identified non-vegetated areas were manually selected and removed. Finally photos were cropped to a standard (1:1) ratio size. RGB data was extracted using the same method listed above. Infrared images were processed using Tetracam's PixelWrench 2.0 software (Tetracam, Chatsworth, CA, USA), which automatically calculates NDVI. As with the colour photos, bare ground, rocks and standing water were removed from each image before the software calculated NDVI. Four images were removed from the analysis due to overexposure in the infrared image.

2.1.5 Biomass index

Above ground biomass estimated from total live-hit (TLH) point-intercept pin hit data from 2010 was used to compare the GEI and NDVI values derived from the 2010 photographs to biomass. In 2010, the same 60 permanent 1 m² plots that were photographed were sampled using a modified version of the ITEX point-intercept method (Molau and Mølgaard 1996). This non-destructive method uses a 1 m² frame with 10 cm grid spacing to record vegetation type for all layers of the canopy at the 100 intersection points within each plot. This method has shown strong correlations to harvest methods (Jonasson 1988; Shaver et al. 2001). In each plot vegetation was recorded to the species level and data were later combined by functional group. Average canopy height was also recorded from 25 points in the 1 m² frame, per plot.

2.1.6 Data analysis

Linear mixed models were constructed in R version 2.15.2 (R Development Core Team 2012), using the nlme package (nlme; Pinheiro and Bates 2000) to model the relationship between 2012 GEI and treatment. Soil moisture and average first day of mature leaf were used as covariates if they improved the model significantly. To account for the repeated measures of the data, day was used as a random effect. Models were constructed at the Site level. Important phenological dates were visually compared to the temporal trends of GEI to infer the ability of GEI to detect phenological changes. Simple linear regression was used to examine the relationship between GEI and NDVI. This method was also used to examine the relationship between the two indices and the TLH biomass data. To explore this relationship further, multiple linear regression was used to identify functional groups that were influencing the increases in NDVI and GEI. An alpha level of 0.05 was used for all statistical tests.

Results

2.1.7 Overall trends

The time series of GEI derived from 10 plots for each treatment in each site showed varying temporal patterns in greenness and treatment effects, reflecting the heterogeneous responses of the moisture-defined vegetation communities at AF (Figure 2.2). This temporal variation picked up by the RGB data follows a logical seasonal green-up pattern and corresponds well to the mean phenological dates for the major species recorded for each site (Figure 2.2). This is particularly true in the Meadow site, where an obvious mid season plateau corresponds with the FDMF of the major species, *E. triste* and *D. integrifolia*. Both species produce showy white blooms likely causing the plateau seen. While less obvious, this trend was also seen in the Willow site where the dominant species *S. arctica* produces an extensive greyish/red bloom. This trend was not seen in the Dryas or Cassiope sites likely due to the relatively fewer flowers in those sites (Table 2.2). The Dryas, Willow and Meadow sites all show an agreement with FDLS and showed downward trends in GEI near the end of the growing season. FDML had varying degrees of agreement in each site.

Table 2.2 Total flowers in all plots at each site recorded by manual counting. Counts were recorded on DOY 188 in all sites. Flower counts are the sum of the following species in a mature, senescing, or dispersal stage; *D. integrifolia*, *S. arctica*, *P. Radicatum*, *E. triste*, *E. schuezerii*. Species were chosen for their dominance in the canopy and the showiness of their blooms.

		Site			
		Willow	Cassiope	Dryas	Meadow
Number of flowers	Warmed	418	178	196	368
	Control	392	93	159	241

The Meadow site had the greatest GEI values followed by the Willow site and the Dryas site, with the lowest GEI in the Cassiope site. These results are a logical reflection of vegetation communities present in each of the four sites (Table 2.1). All sites showed greater GEI values in the warmed plots compared to the control plots though the

magnitude and significance of this difference varied by site (Table 2.3). Warming did not appear to accelerate greening across the growing season. Warmed plots started greener and stayed greener across the growing season. This is likely a result of increased biomass caused by 20 years of passive warming by OTCs.

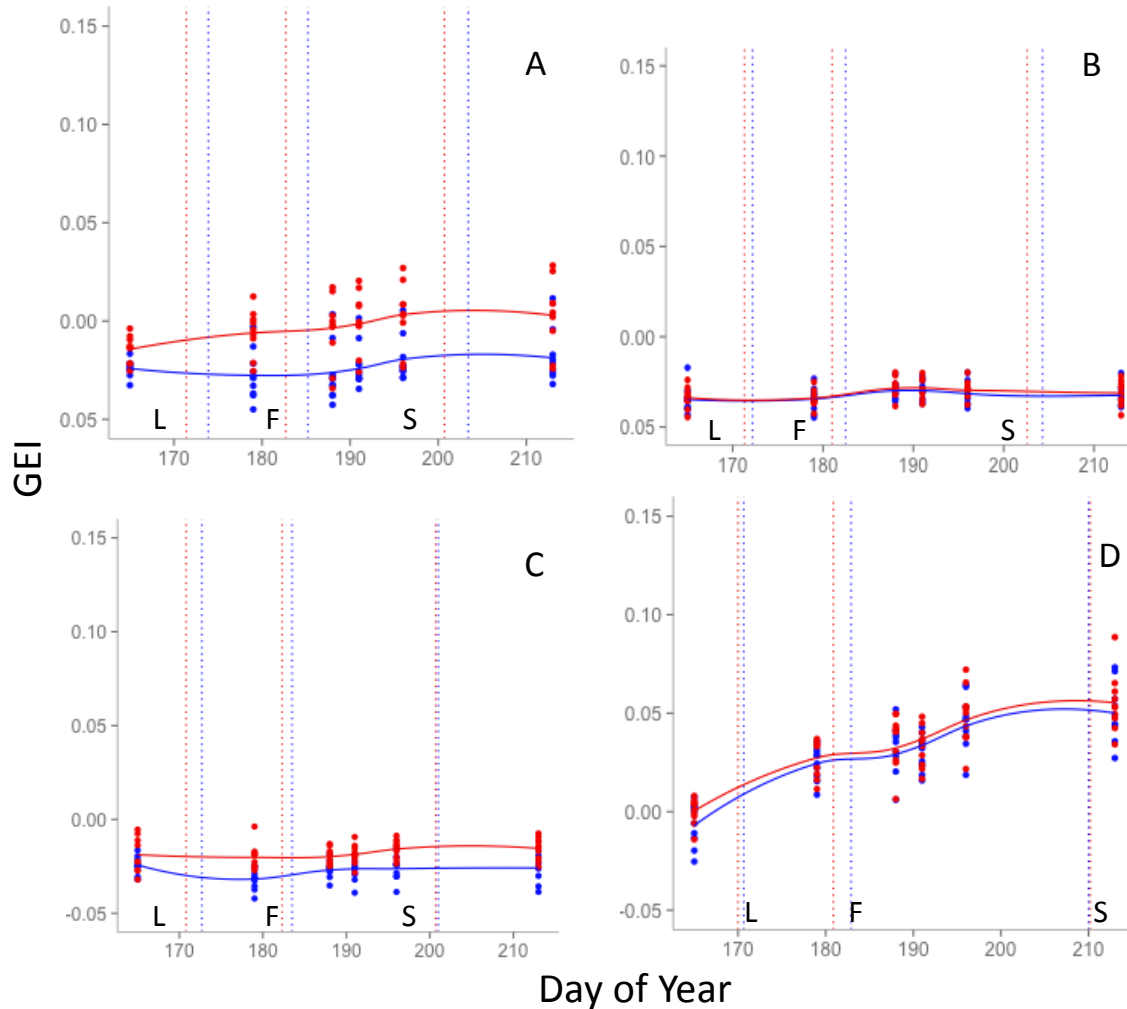


Figure 2.2 Temporal patterns of GEI across the 2012 growing season in the A) Willow site, B) Cassiope site, C) Dryas site, and D) Meadow site. Colours correspond to the warming treatment (red) and control (blue) plots. Vertical lines represent an average date of all plots in each site of major phenological events for all major species followed; L: first day mature leaf, F: first day mature flower, S: first day leaf senescence.

Results from the linear mixed models showed that when all four sites were grouped together, GEI responded significantly to treatment and was significantly

improved by the addition of soil moisture (Table 2.3). When examined by site, a treatment signal was seen in the Willow and Dryas sites (Figure 2.2A). The models for the Willow, Cassiope, and Meadow sites were not significantly improved by the addition of average day of first mature leaf or soil moisture. The addition of first day of mature leaf significantly improved the model for the mesic Dryas site. Variables and interactions that did not significantly improve the models were removed based on AIC values.

Table 2.3 Results of linear mixed models for all sites and the significance of the warming treatment.

Site	Model	AIC	LogLik	Treatment <i>p</i> -value
All	Simple	-1877	942.3	
	Soil moisture	-1873	943.7	< .0001
Willow	Simple	-624.8	316.4	< .0001
Cassiope	Simple	-855.8	431.9	0.258
Dryas	Simple	-838.7	423.4	
	Mature leaf	-822.5	416.3	< .0001
Meadow	Simple	-661.4	334.7	0.0612

2.1.8 Comparison of GEI to NDVI and biomass measurements

Simple linear regression showed a moderate positive relationship between GEI and NDVI from the 2010 photographs (Figure 2.3). The relationship moderate due to error caused by the varying performance of each method in each of the sites. The relationship between GEI and NDVI was strongest in the Willow site ($R^2 = 0.28$, $F_{54} = 6.90$, $p = 0.01$), while both the Meadow site ($R^2 = 0.16$, $F_{54} = 2.48$, $p = 0.14$), and Dryas site ($R^2 = 0.12$, $F_{54} = 2.62$, $p = 0.12$) showed weak correlations between the two methods.

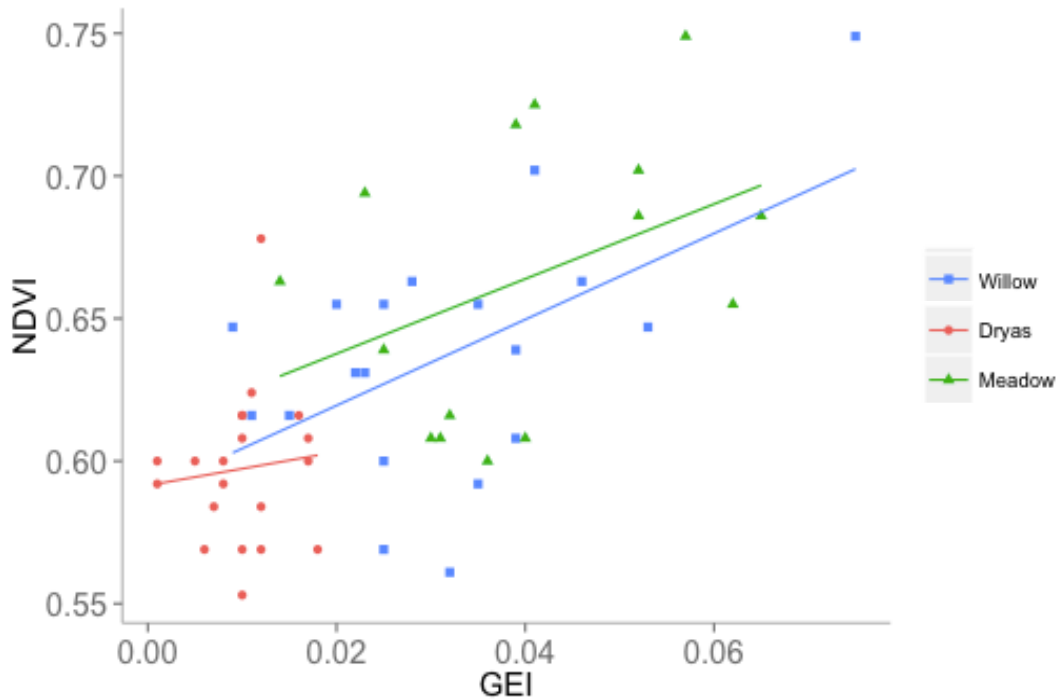


Figure 2.3 Simple linear regression by Site; Dryas site; ($R^2 = 0.12$, $F_{54} = 2.62$, $p = 0.12$) Meadow site; ($R^2 = 0.16$, $F_{54} = 2.48$, $p = 0.14$), Willow site; ($R^2 = 0.28$, $F_{54} = 6.90$, $p = 0.01$). Each point represents one photograph from each plot in each of the three sites.

TLH biomass data showed a slightly stronger relationship to NDVI than GEI when all sites were grouped together (Table 2.4). However, when sites were examined individually, results from the linear regression showed the two indices were highly comparable across sites with the exception of the Meadow site (Figure 2.3). GEI showed slightly stronger correlations in both the Willow and Dryas sites, while NDVI had a notably stronger correlation in the Meadow site.

Table 2.4 Linear regression results between sites and TLH biomass index for both GEI and NDVI.

Site	Index	R^2	F_{df}	p -value
<i>All</i>	<i>NDVI</i>	0.36	30.38	<0.001
	<i>GEI</i>	0.21	13.83	<0.001
<i>Willow</i>	<i>NDVI</i>	0.26	6.13	0.024
	<i>GEI</i>	0.27	6.58	0.020
<i>Dryas</i>	<i>NDVI</i>	0.12	2.55	0.127
	<i>GEI</i>	0.15	3.31	0.086
<i>Meadow</i>	<i>NDVI</i>	0.52	16.5	0.001
	<i>GEI</i>	0.33	6.45	0.025

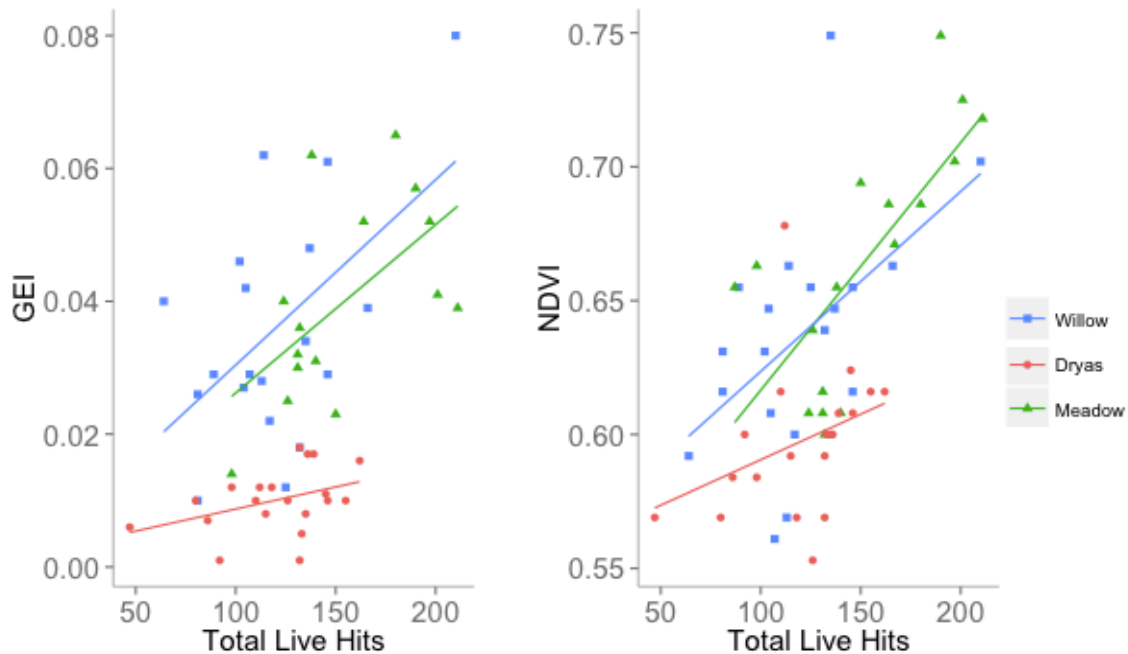


Figure 2.4 Simple linear regression of GEI and NDVI with TLH biomass by site. Each point represents the TLH for each plot in each site. See Table 2.4 for regression analysis.

Deciduous shrubs and graminoids were identified as important functional groups overall in both indices (Table 2.5). The Willow site had the same significant functional groups for both indices. The Dryas and Meadow sites however, had varying results between the indices. No significant functional groups were identified in the regression

analysis with NDVI in either the Dryas or Meadow sites. GEI however, showed a significant relationship with graminoids in the Dryas site ($p = 0.014$), and evergreen shrubs ($p = 0.002$) and graminoids ($p = 0.002$) in the Meadow site.

Table 2.5 Multiple regression results identifying functional groups that drive NDVI and GEI values in plots at three high Arctic tundra plant communities. The explanatory variables are the number of live hits of each of the functional group.

Site	Index	R^2 full model	F_{df}	p - value	Significant functional group
All	<i>NDVI</i>	0.43	51	<0.001	- <i>Deciduous shrubs</i> - <i>Graminoids</i>
	<i>GEI</i>	0.50	53	<0.001	- <i>Deciduous shrubs</i> - <i>Graminoids</i>
Willow	<i>NDVI</i>	0.49	14	0.01	- <i>Deciduous shrubs</i>
	<i>GEI</i>	0.42	15	0.01	- <i>Deciduous shrubs</i>
Dryas	<i>NDVI</i>	0.05	15	0.32	
	<i>GEI</i>	0.32	15	0.04	- <i>Graminoids</i>
Meadow	<i>NDVI</i>	0.05	12	0.35	
	<i>GEI</i>	0.68	13	<0.001	- <i>Evergreen shrubs</i> - <i>Graminoids</i>

A final comparison of the indices was made with measures of average canopy height. Both indices showed a moderate positive relationship with average canopy height, however, GEI showed a stronger correlation than NDVI (Figure 2.5).

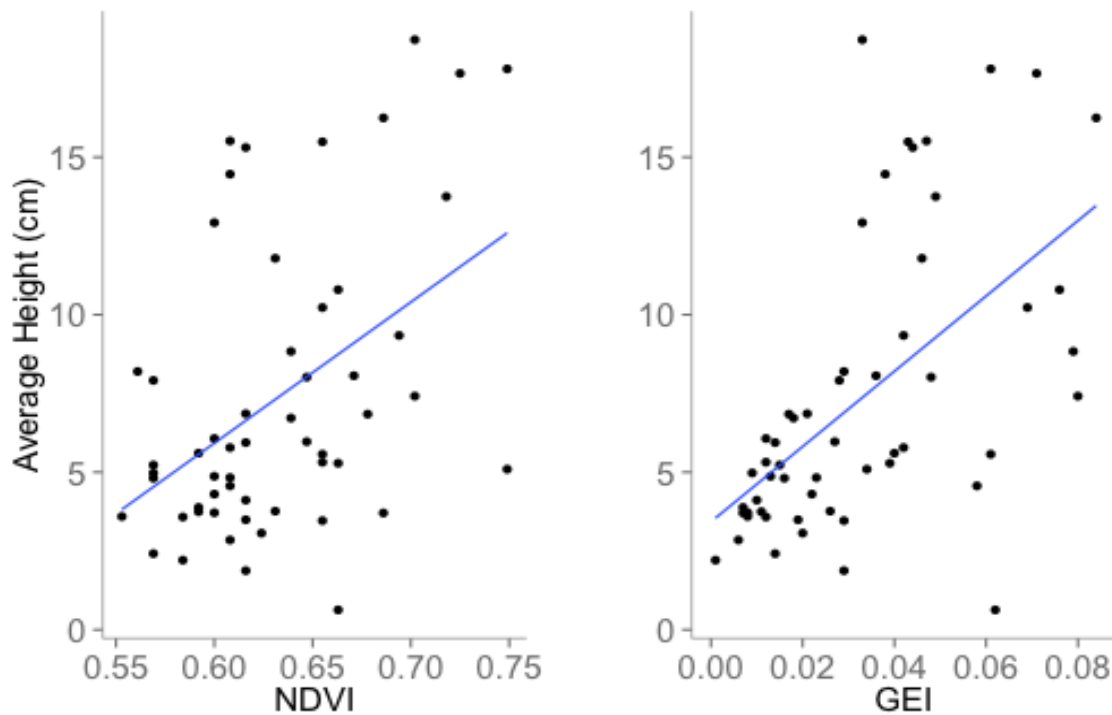


Figure 2.5 Linear regressions between average canopy height and each method; (NDVI: $R^2 = 0.21$, $F_{54} = 13.38$, $p < 0.001$, GEI: $R^2 = 0.36$, $F_{54} = 30.38$, $p < 0.001$). Each point represents an average of 25 canopy height measurements at each plot in all three sites.

Discussion

2.1.9 Evaluation of GEI and the advantages of digital photography

Comparisons between the two indices and biomass measures indicate that GEI, derived from the colour photographs, may be suitable as a method for monitoring multiple aspects of vegetation change in high Arctic tundra ecosystems and perhaps in other low stature vegetation types. Both GEI and NDVI showed very similar relationships to the biomass index data. GEI was able to identify significant functional groups in all sites suggesting it is more sensitive to green vegetation in the plots than NDVI, as the functional groups identified encompass the major species in the sites. Differing sensitivities of colour and IR images to non-photosynthetic standing litter could explain this trend. Numerous studies have shown that the presence of standing litter can lead to

disproportionate changes in canopy reflectance in the IR band, particularly in sparsely vegetated ecosystems (Huete and Jackson 1987; van Leeuwen and Huete 1996; Laidlerler and Treitz 2003; Dawelbait and Morari 2008). Disproportionate reflectance of standing litter can mask the reflectance of green vegetation potentially explaining the lack of significant functional groups for NDVI in Dryas and Meadow sites where standing litter was extensive.

The strong relationships of GEI with TLH and canopy height and the similarity to those with NDVI validate the utility of colour images as a proxy for vegetation productivity. GEI has shown strong (R^2 : 0.78 – 0.84) correlations with GEP measured by eddy covariance methods in both grassland and temperate forest ecosystems (Ahrends et al. 2009; Migliavacca et al. 2011). Although carbon fluxes at the plot scale in tundra ecosystems tend to be small and variable (Oberbauer et al. 2007), the results highlight the potential for estimating productivity indirectly with this method.

The temporal trend of GEI derived from the digital photographs in 2012 provides reliable information on vegetation status. Field-based phenological measures correspond logically with the seasonal patterns derived from photos. Similar results of greenness indices derived from colour photographs accurately identifying phenological events down to the species level, have been found in both grassland and forest ecosystems (Ide and Oguma 2010; Migliavacca et al. 2011). GEI was able to identify a warming treatment signal and show that warmed plots are significantly greener than control plots in all but the Cassiope site. This trend is reasonable given the greater aboveground biomass in the warmed plots at the AF lowland and across the tundra biome (Walker et al. 2006; Hudson and Henry 2009; Hill and Henry 2011; Hudson et al. 2011, Elmendorf et al. 2012a). The lack of treatment signal in the Cassiope site could be the result of the nature of the vegetation in that site (Hudson and Henry 2010). *Cassiope tetragona*, an evergreen dwarf shrub, is the dominant vascular plant species and only the tips of the branches are green. The majority of the branches are covered with dead leaves that remain attached for many years (Rayback and Henry 2006) and there is only a very subtle colour change throughout the season. These subtle changes may be detected using greater pixel density in the photographs.

There is great potential for this method to be utilized extensively in vegetation monitoring at both the landscape and plot scale. Digital cameras are affordable, robust, and easy to use, making them very appealing field instruments. It takes less time and effort in the field to obtain the images than to record detailed observations. The photographs can be taken by one person, while the detailed observations usually require at least two people: one to observe and one to record the data. Using digital cameras to obtain vegetation data, such as GEI, is also more cost effective than using a standard field instrument for NDVI like the ADC. The cost of implementing ten Nikon D40 (Nikon D40 SLR, Nikon Corporation, Japan; CDN \$500) digital cameras in fixed locations to continually monitor vegetation over one growing season is roughly equivalent to the cost of one ADC (Tetracam ADC, Chatsworth, CA, USA; CDN \$4800, tetracam.com). A Nikon D40 has twice the megapixels of an ADC (6.0 vs. 3.2), producing finer resolution images, increasing the amount of RGB data in each photograph. More detailed photographs increase the accuracy of estimating biomass and phenological information. Digital cameras also reduce the amount of human error in the field through automatic focus, and exposure adjustments. The ADC was far more difficult to focus and sensitive to changes in solar illumination leading to unusable images and a loss of data. This case study highlights the utility of digital cameras in field-based monitoring of vegetation. It presents a novel opportunity for the implementation, across the tundra biome, of a simple methodology for tracking seasonal productivity, phenology and biomass.

Conclusions

Colour digital photography is able to detect differences in seasonal patterns of greenness across different moisture-defined vegetation communities inside and outside of passively warmed plots using OTCs. Seasonal patterns of GEI derived from 2012 data are logical and correspond well to field-based observations of phenology. Seasonal patterns from 2012 were validated through the similarities between biomass index – GEI and biomass index – NDVI relationships from the 2010 data. The most important factor

in the utility of colour digital photography for monitoring vegetation lies with the ease, robustness, and affordability of operating and implementing this method. We conclude that colour photographs accurately describe vegetation status in high Arctic tundra ecosystems both qualitatively (i.e. phenology) and quantitatively (i.e. biomass, productivity) in a simple and cost-effective way.

3 Landscape Patterns

Introduction

Plant phenology is controlled by climatic conditions and is an important indicator of climate change impacts in terrestrial ecosystems (Schwartz et al. 2006; Cleland et al. 2007; Badeck et al. 2008; Inouye 2008; Høye et al. 2013). Both observational and experimental warming studies have shown that vegetation phenology is sensitive to climate warming (Arft et al. 1999; Wolkovich et al. 2012; Oberbauer et al. 2013). Warming has long been predicted to be earliest and most intense at high latitudes (IPCC 2007) causing changes in vegetation abundance and composition (Elmendorf et al. 2012a), as well as affecting tundra plant phenology in many sites (Høye et al. 2013; Oberbauer et al. 2013). Expanded monitoring of tundra plant phenology will provide important information about the impacts of current and future climate warming in the Arctic and globally.

Over the last 20 years, earlier leaf-out (Myneni et al. 1997; Arft et al. 1999; Oberbauer et al. 2013) and delayed senescence (Marchand et al. 2004; Høye et al. 2013) have been observed in ambient and experimental warming studies across the Arctic. However, changes in timing of phenology, community composition, and above ground biomass vary significantly across different vegetation communities (Elmendorf et al. 2012a; Oberbauer et al. 2013). Populations of the same species in different vegetation communities can respond differently to changes in temperature, moisture and nutrients (Jones et al. 1999; Kudo and Hiraio 2006). At the same study site used in this study, Hudson et al. (2011) demonstrated how the response of different vegetation communities to 16 years of experimental warming was highly variable. A hydric sedge meadow site showed no significant difference in plant size traits while a mesic prostrate dwarf-shrub herb tundra site showed significant differences in all traits (Hudson et al. 2011). These site and species-specific responses to environmental change highlight the importance of long-term measurements of vegetation at the plot and species scale.

Monitoring phenology in remote ecosystems is expensive and time consuming. Traditional field based tracking of phenology involves patient, detailed observation of individual plants every few days. Reliable, long-term phenological datasets are difficult to maintain even with common protocols such as those used in the International Tundra Experiment (ITEX, Henry and Molau 1997). The IPCC (2007) has recognized phenology as one of the most responsive traits to climate change in nature. Increasing the number of sites involved and the accuracy and consistency of phenology data is important to improve its use as an indicator of climate change and, hence, inclusion in decision-making processes. Developing efficient and cost effective methods of monitoring tundra vegetation is advantageous.

Repeat colour digital photography is emerging as a simple and effective tool for monitoring vegetation. This methodology has been employed successfully to obtain phenological dates such as first flower as well as quantitative data such as shifts in vegetation greenness in a variety of temperate and alpine ecosystems (Ide and Oguma 2013; Richardson et al. 2013). Repeat photography is simple to conduct and allows users to easily visualize changes in an ecosystem. This methodology presents a unique opportunity to implement a simple, cost effective, vegetation-monitoring network in the Arctic to accompany existing long-term vegetation and environmental data.

The objective of this study was to determine the effectiveness of digital photography in monitoring tundra vegetation at multiple scales. Using colour digital photographs and a vegetation greenness excess index (GEI) derived from the photos, we (1) assessed green-up and senescence signals, (2) compared automated and manual flower counts, and (3) determined differences in above ground biomass and vegetation vigor in response to experimental warming and site moisture status.

Methods

3.1.1 Study site

The study was conducted in the Alexandra Fiord (AF) coastal lowland (78°53'N, 75°55'W), on the eastern coast of Ellesmere Island, Nunavut. Due to the surrounding topography and resulting favorable climatic conditions, the 8 km² lowland is considered a polar oasis (Freedman et al. 1994). It is well vegetated compared to surrounding areas and average yearly precipitation is less than 50 mm. Average growing season temperatures range between 3 and 8°C and the growing season lasts from early June to mid August. The moisture regime is controlled by snowmelt and glacial melt water and soil moisture is highly variable across the lowland. Plant community types found in the lowland are dictated by the varying soil moisture regimes (Muc et al. 1989). More detailed information on the environmental setting of Alexandra Fiord is found in Svoboda and Freedman (1994).

The study was conducted in four vegetation communities that varied in soil moisture (Table 3.1). They included: a xeric-mesic prostrate dwarf-shrub herb tundra dominated by *Salix arctica* (Willow site) with sandy soils, and experiences the earliest snowmelt of the four study sites (Muc et al. 1994), a mesic prostrate dwarf-shrub herb tundra, dominated by *Dryas integrifolia* (Dryas site), and included important contributions from the evergreen dwarf shrub *Cassiope tetragona*, and the graminoids *Arctagrostis latifolia* and *C. misandra*; a mesic prostrate/hemiprostrate dwarf-shrub herb tundra, dominated by *C. tetragona* (Cassiope site) which also included contributions from the evergreen dwarf shrub *D. integrifolia*, and the graminoids *A. latifolia* and *C. misandra*; and a hydric sedge, moss, dwarf-shrub wetland, (Meadow site) with surface water flow in much of the site throughout the growing season, dominated by sedges (*Carex membranacea*, *C. aquatilis stans* and *Eriophorum angustifolium triste*) in the wet hollows and dwarf shrubs (*S. arctica*, *D. integrifolia*) on the drier hummocks (Henry et al. 1990).

In 1992, warming experiments were established in each of the communities consisting of 20 randomly selected 1 m² plots, and half the plots were warmed using open top chambers (OTCs) with ten corresponding 1m² control plots. The OTCs passively

warm the surface air temperature by 1 – 3°C, similar to increases projected in climate change models (Marion et al. 1997). Marion et al. (1997), Hollister and Webber (2000) and Bokhorst et al. (2013) provide details on the performance of OTCs in general, and Hudson and Henry (2010) and Hudson et al. (2011) describe the OTC temperature effects at Alexandra Fiord. The study site is part of the International Tundra Experiment (ITEX), a collaborative network of over 20 arctic and alpine sites established in 1990 to monitor the effect of experimental and ambient warming on tundra vegetation (Henry and Molau 1997).

Table 3.1 Characteristics of the four tundra communities at Alexandra Fiord

Site	CAVM classification*	Moisture	Above ground live standing crop (g m ⁻²)**	Major Species
Willow	Prostrate dwarf-shrub herb tundra	Xeric	71	<i>S. arctica</i> , <i>Luzula confuse</i> , <i>Poa arctica</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Cassiope	Prostrate/hemiprostrate dwarf-shrub herb tundra	Mesic	190	<i>C. tetragona</i> , <i>D. integrifolia</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Dryas	Prostrate dwarf-shrub herb tundra	Mesic	190	<i>D. integrifolia</i> , <i>C. tetragona</i> , <i>Papaver radicum</i> , <i>Oxyria dygina</i>
Meadow	Sedge, moss, dwarf-shrub wetland	Hydric	132	<i>Eriophorum angustifolium triste</i> , <i>C. stans</i> , <i>C. membranacea</i> , <i>D. integrifolia</i>

* Circumpolar Arctic Vegetation Map (Walker et al. 2006)

** from Muc et al. (1994)

3.1.2 Photography

All plots in each of the four communities were photographed with a digital camera (Nikon D40 SLR, Nikon Corporation, Japan) six times over the growing season in 2012 beginning on June 13 (Day Of Year (DOY) 165) and ending on August 2 (DOY 215). Photographs were taken approximately 2 m nadir from the ground from the same south

facing position on each date. A 1 m x 1 m white frame was positioned for each photograph in plots on permanent corner markers. They were taken between 0900h and 1200h in cloudless conditions to reduce the influence of changes in solar angle or irradiance and saved in a Nikon raw (NEF) format at 3,008 x 2,000 pixels.

Volumetric soil moisture was measured using a Hydrosense II soil-water sensor (Campbell Scientific Inc., Edmonton, Canada) inserted 12 cm into the soil at points in the south, center and north sections of each plot, three times throughout the growing season. Every three days phenological observations were made on tagged plants of the major species in each site and important dates such as first day of mature leaf, first day of mature flower, and first day of leaf senescence were recorded.

3.1.3 Biomass data

Above ground biomass was estimated from total live-hit (TLH) point-intercept pin hit data from 2010 (Edwards 2012, Henry et al. unpublished). These data were used to explore covariation with greenness data. The non-destructive TLH method uses a 1 m² frame with 10 cm grid spacing to record vegetation type for all layers of the canopy at the 100 intersection points within each plot (Molau and Molgaard 1996). This method has shown strong correlations to harvest methods (Jonasson 1988; Shaver et al. 2001). In each plot live hits of all vascular species were recorded to the species level and data were later combined by functional group. Average canopy height was also recorded from 25 points in the 1 m² frame, per plot.

3.1.4 Colour digital photo analysis

The six colour photos from each plot, representing a time series were initially processed using Creative Suite 6 (Adobe Systems Incorporated, 2013) to stack and align the images. Alignment was done automatically by matching pixels and manual adjustments were made where there were discrepancies. Photos were excluded from the time series if alignment failed. Stacked photos were cropped to a standard 1:1 ratio size and exported as individual TIFF files. After pre-processing, pixel values of each channel (Red, Green, and Blue) were extracted from each photo.

Extraction of pixel information was done using a function written with the `rgdal` package (0.8-4: Keitt et al. 2013) in R version 2.15.2 (R Development Core Team 2012). Pixels from the photos were transformed into data frames and Red, Green, and Blue (RGB) values were extracted and averaged by photo. Using a sample of photos from each site, unobstructed, well-separated individuals of *S. arctica*, *P. radicum*, and *D. integrifolia* were identified within plots and separated as subsets from the larger photograph. Pixel information was extracted for the subset area using the same function to examine species-specific responses.

To get an estimation of greenness of each photo and to normalize variations in irradiance among photos, the green ratio (rG) was also calculated and averaged by photo (Eq. (1)):

$$rG = G / (R + G + B) \quad (1)$$

Where G = green, R = red, B= blue. A ratio was also calculated for the red (rR) and blue (rB) channels by rearranging Eq. 1. A final index, the Greenness Excess Index (GEI), was calculated using the red, green, and blue ratios (Eq. (2)); Richardson et al. 2007):

$$GEI = 2*rG - (rR + rB) \quad (2)$$

Where rG = green ratio, rR = red ratio, rB = blue ratio. Although rG can be used to track phenological and productivity changes in vegetation, Eq. (2), provides a more sensitive indicator of changes in plant pigment (Ide and Oguma 2010). This is desirable in tundra ecosystems as the changes can be subtle.

3.1.5 Peak flower counting program

The number of flowers in an image was counted using an intensity thresholding algorithm (created by Samuel Robinson) implemented in the Image Processing Toolbox in MATLAB version 7.90.529 (Math Works 2013). The original image $A(x; y; c)$ was desaturated to create a flattened matrix of intensity values, $I(x; y)$. A threshold of

brightness values, p , was manually chosen to eliminate background colours, creating a binary image $B(x,y)$ such that:

$$B(x,y) = \begin{cases} 1 & \text{if } I(x,y) \geq 255 \cdot p \\ 0 & \text{if } I(x,y) < 255 \cdot p \end{cases} \quad (3)$$

Automated selection of p by Otsu's method (Otsu 1975) proved to be too liberal for the images. The binary image $B(x,y)$ was then subjected to morphological opening and closing (for examples, see Gonzalez et al 2009, and Dougherty 1992), in order to remove small, non-continuous bright areas such as leaf litter or plant tags. Finally, the number of connected components in the last binary image was counted automatically, giving the total number of bright contiguous areas in each image. Manual flower counts were conducted between DOY 187 (July 5) and 188 (July 6) in the three sites using the same 1 x 1m point frame as the photographs to get an estimation of peak flowering. Mature flowers of *D. integrifolia*, *P. radicum*, *Eriophorum triste*, and *E. scheuchzeri* were compared to numbers detected by the algorithm in photographs taken on DOY 188. These species were chosen for the comparison because they have large flowers and are the most obvious and easily identifiable.

3.1.6 Statistical analysis

Descriptive statistics, including mean, median, range, and standard deviation were calculated for GEI, soil moisture, TLH, average canopy height and first day mature leaf in each Site by treatment. One-way ANOVAs were used to examine differences between sites and treatments of TLH and canopy height. One-way repeated measures ANOVAs were used to examine differences in soil moisture and first day mature leaf between sites and treatments within sites. Linear mixed models were constructed in R version 2.15.2 (R Development Core Team 2013), using the lme4 package (lme4; Bates, Maechler and Bolker, 2011) to model the relationship between GEI, treatment and environmental variables in each of the three sites and for the two species. Species models include data from a subset of plots with the species of interest present. Warming treatment was used as a fixed effect. For the species models site was used as a random effect. For the site models, day was used as a random effect to account for repeated measures. The biomass

index (TLH), average canopy height, soil moisture, and average day of mature leaf, were added as random effects at all scales only if they improved the model AIC value. Simple two-way ANOVAs were used to test for differences among treatment for field-based phenology observations. Simple linear regression was used to examine the relationship between manual and automated flower counts. An alpha of 0.05 was used for all significance testing.

Results

3.1.7 Timing of phenology

Plant growth, flowering and senescence are identifiable in the images and correspond well to field based phenology observations (Figure 3.1). The first photos taken on day 165 were dominated by red/brown standing litter with little to no green with the exception of mosses. Photos taken on day 179 showed a greening and new growth of vegetation penetrating through standing litter. By 188, the majority of the canopy was green in all sites and the major species were flowering. In the remaining three days (191, 196 and 213) the changes in greenness were subtle and difficult to detect by human eye. There was a gradual senescence of all flowers and the very beginning of leaf senescence in some images by 213. Seasonal changes in greenness were most pronounced at the species scale and in the more vegetated Meadow and Willow sites.

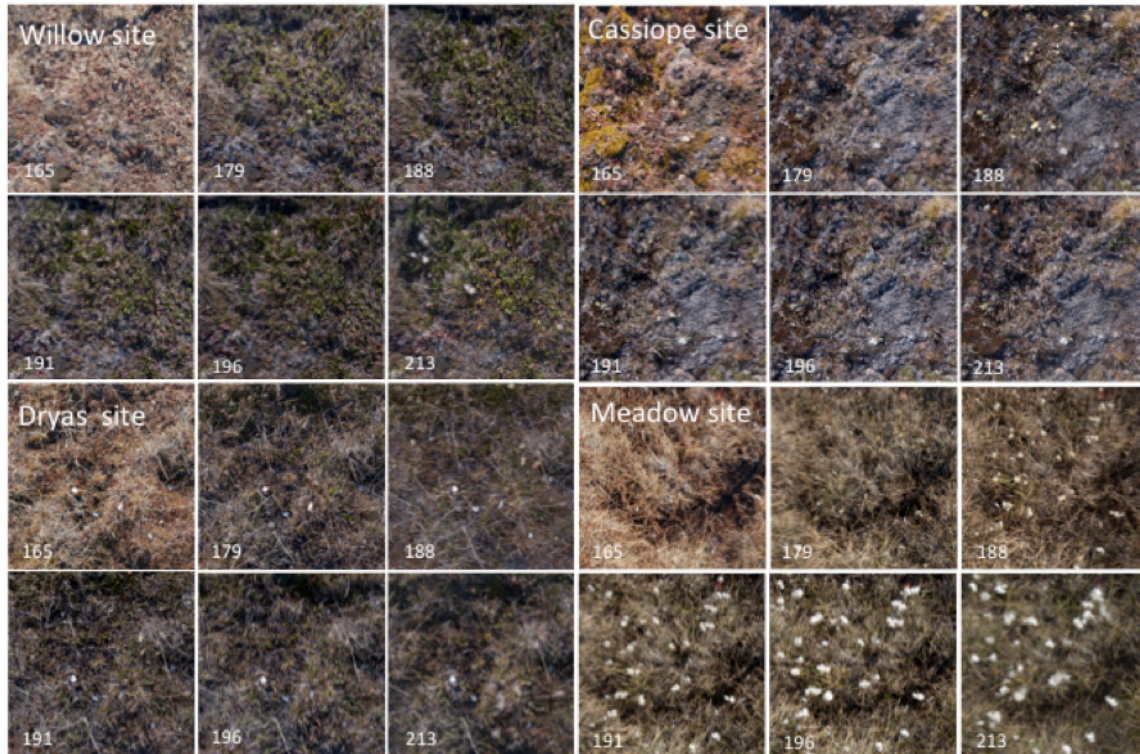


Figure 3.1 Examples of seasonal patterns of green-up from the photographs in each of the four sites.

3.1.8 Quantifying greenness

Green-up from the first to the second photos was easily detected by the human eye and was matched by the changes in GEI (Figure 3.2 and 3.3). GEI from all sites combined showed an increase from day 165 to 196 and a leveling off by 213, suggesting the beginning of senescence (Figure 3.3A). The senescence signal was weak as most of the vegetation was still green on the final day of photography. Plotting GEI data also revealed a treatment signal at the plot scale but not at the species scale. The magnitude of the difference in GEI between warmed and control plots were greatest in the Willow site. Density plots, i.e. the distribution of GEI values, (Figure 3.3 insets) show that the Dryas and Willow sites have more green pixels in the warmed plots compared to control plots.

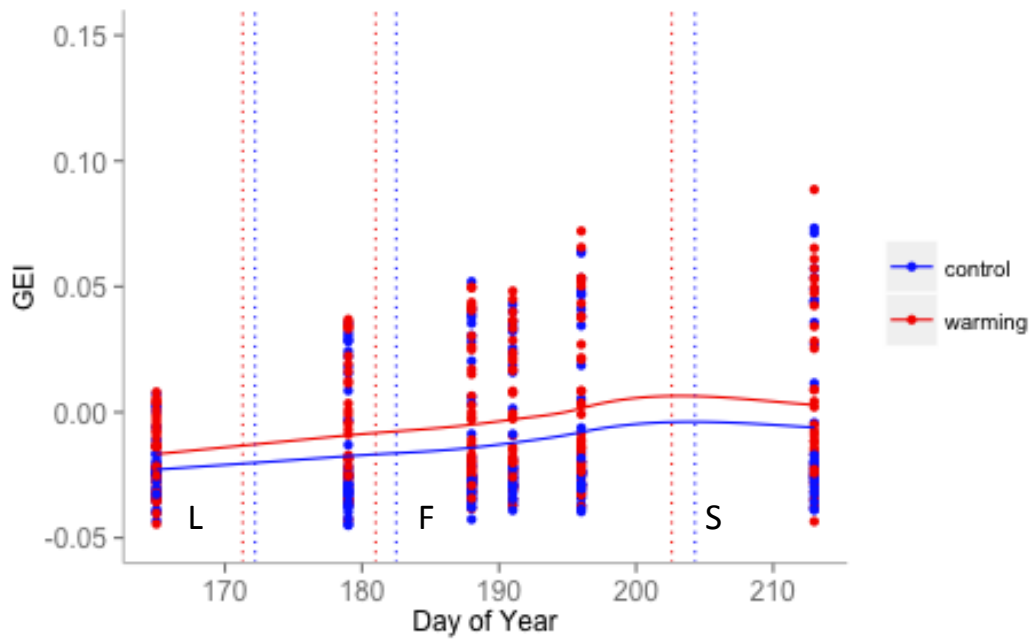


Figure 3.2 Seasonal patterns of GEI in all sites combined. Data are fit with a loess curve. Insets represent density plots of GEI values. Vertical lines represent important phenological observations collected in the field.

When all sites were grouped together the green-up and senescence signal was well defined (Figure 3.2). There was a pronounced green-up and senescence signal in the Willow and Meadow sites (Figure 3.3A, D). The pattern is less straightforward in the Cassiope and Dryas site as there was very little change in GEI over the growing season, likely a result of the vegetation cover and plant species present (Figure 3.3B, C).

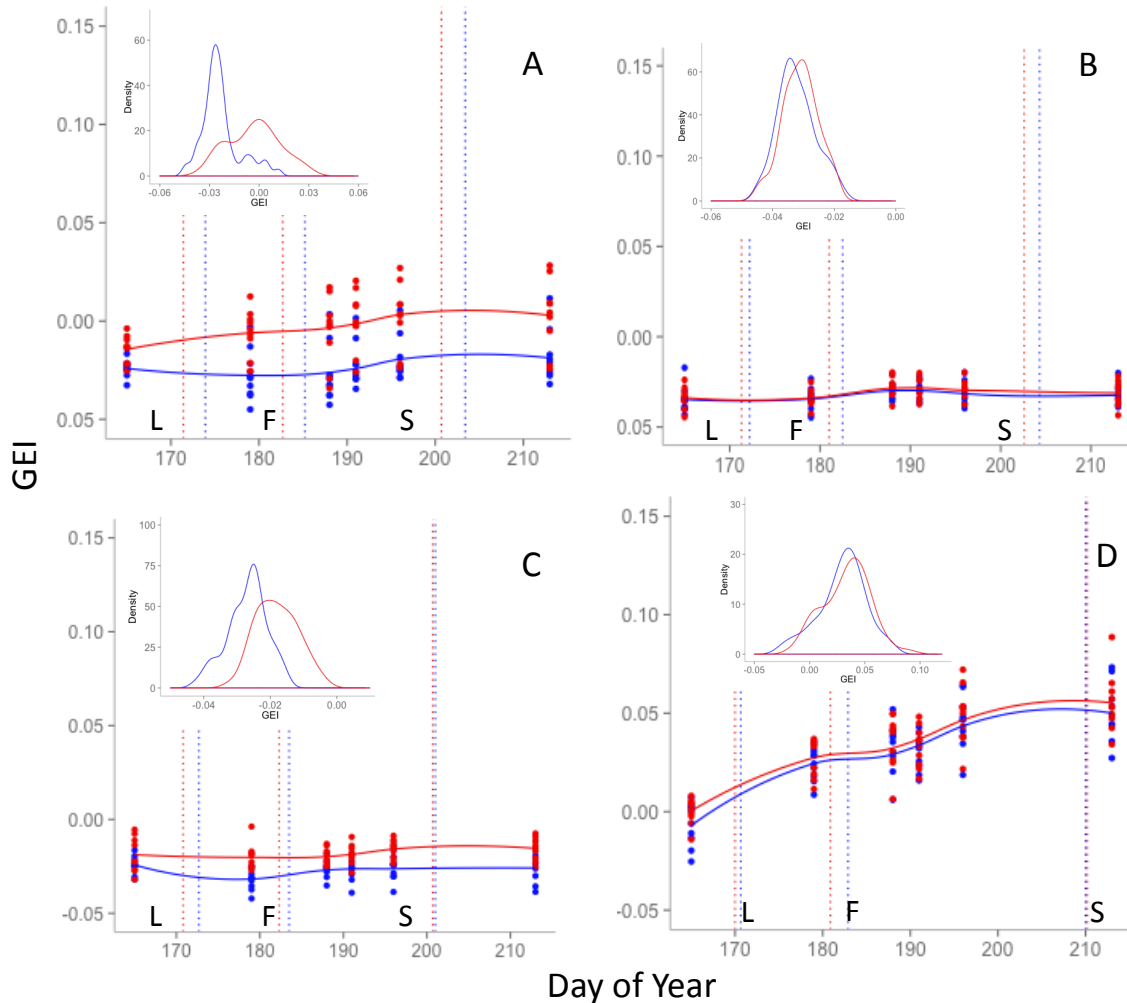


Figure 3.3 Seasonal patterns of GEI at the plot scale (A: Willow site, B: Cassiope site; C: Dryas site; D: Meadow site). Data are fit with a loess curve. Insets represent density plots of GEI values. (L: first day mature leaf, F: first day mature flower, S: first day leaf senescence). Vertical lines represent important phenological observations collected in the field and averaged across plots for each site.

At the individual scale, there was a strong green-up and senescence signal for both species. The deciduous shrub *S. arctica* had a stronger signal than the evergreen shrub *D. integrifolia* (Figure 3.4). There was a strong site-specific response of both species across the three sites (Figure 3.5). For *S. arctica* GEI was greatest in the Willow site where it is the most dominant species, followed by the Meadow site and finally the Dryas site. For *D. integrifolia* GEI was greatest in the Meadow site with no difference between the Dryas and Willow sites. The seasonal patterns of GEI at all scales are

validated by their correspondence to field based measures of phenology and by examination of density plots of GEI by day (Figure 3.6, 3.7 and 3.8).

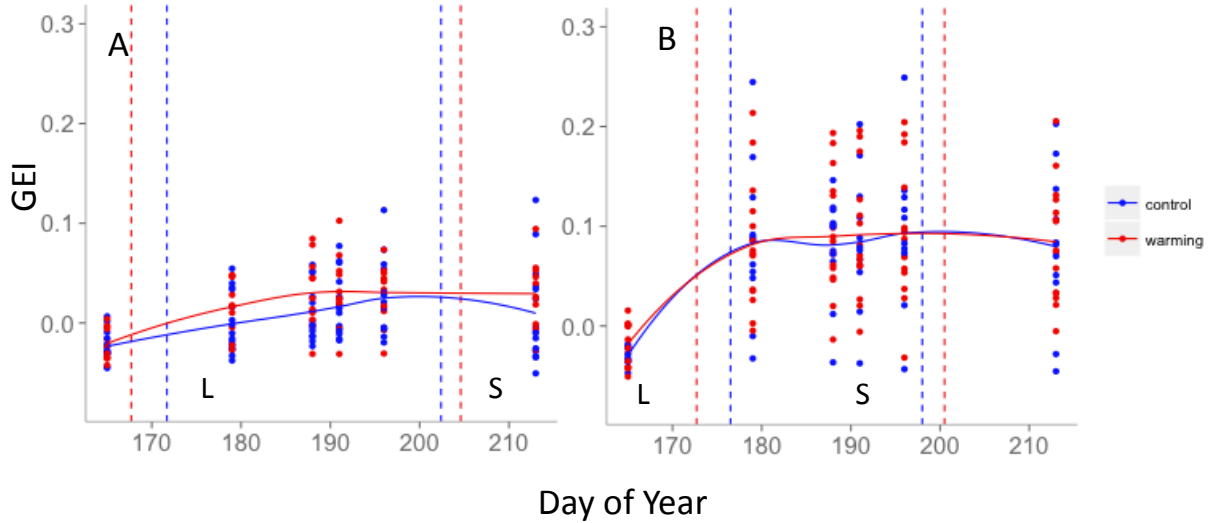


Figure 3.4 Seasonal patterns of GEI at the species scale (A: *S. arctica*; B: *D. integrifolia*). Data are fit with a loess curve. (L: first day mature leaf, S: first day leaf senescence). Vertical lines represent important phenological observations collected in the field and averaged for each species across plots in all sites.

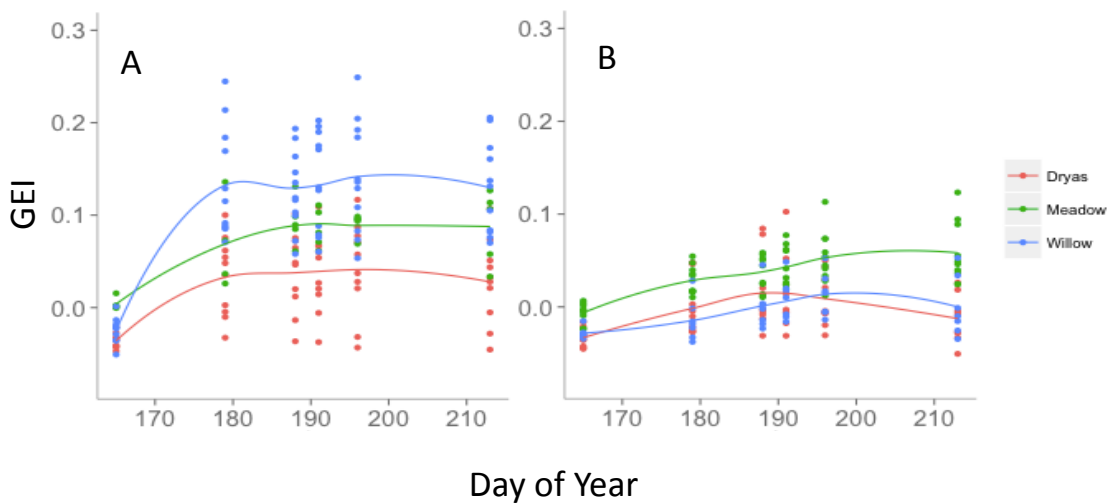


Figure 3.5 Seasonal patterns of GEI of *S. arctica* (A) and *D. integrifolia* (B) in the three study sites. Data are fit with a loess curve.

When three sites representing the moisture gradient were grouped together a double Gaussian type distribution of GEI values emerged with the first peak representing bare ground and standing litter and the second peak representing green vegetation, somewhat confounding the vegetation signal (Figure 3.6). However, when the second peak was examined more closely a logical seasonal shift in GEI density emerges. There was a high density of GEI values close to zero (i.e. not green) past day 165 in the Cassiope, Dryas and Willow sites due to the species present, extensive standing litter and bare soil that exist in these sites (Figure 3.7B, C). After day 165, in the Willow site a double Gaussian type distribution emerged (Figure 3.7A). In the hydric sedge Meadow site there was little to no bare ground present and GEI density shifted obviously by day (Figure 3.7D). An interesting pattern emerged in the Meadow site where day 188 was greener than 191, likely the result of peak flowering masking the green vegetation. Bare soil and standing litter were less of an issue at the species scale and this was reflected in the density plots (Figure 8). Both species demonstrated increasing GEI as the season advances and clearer senescence signals on day 213 than at the plot scale. There was no flower-masking signal at the species scale as areas with flowers were excluded from the analysis.

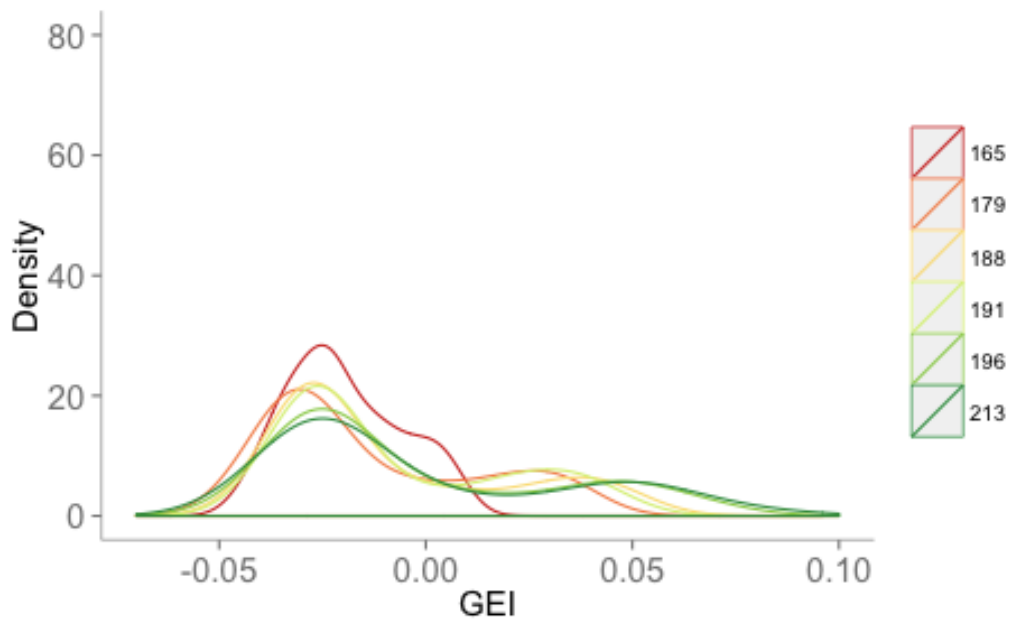


Figure 3.6 Density plot of GEI values by sample day at the plot scale in all sites combined.

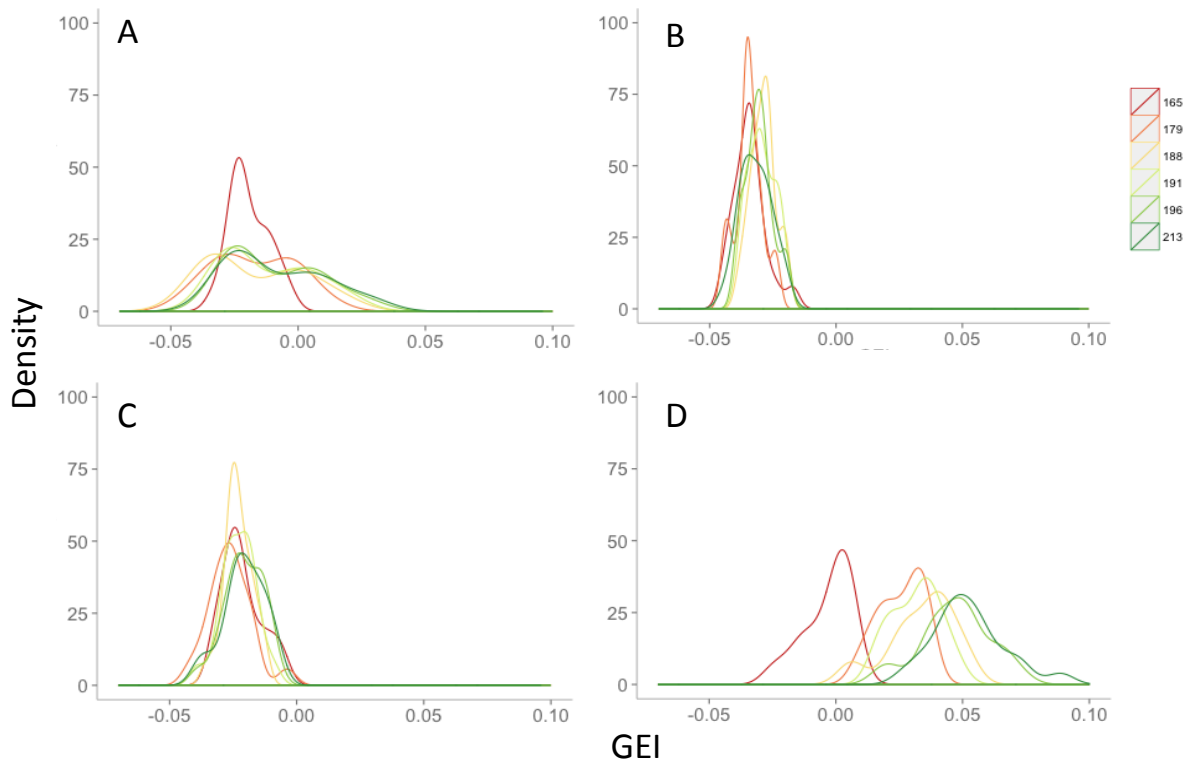


Figure 3.7 Density plots of GEI values by sample day at the plot scale. (A: Willow; B: Cassiope; C: Dryas Site; D: Meadow Site).

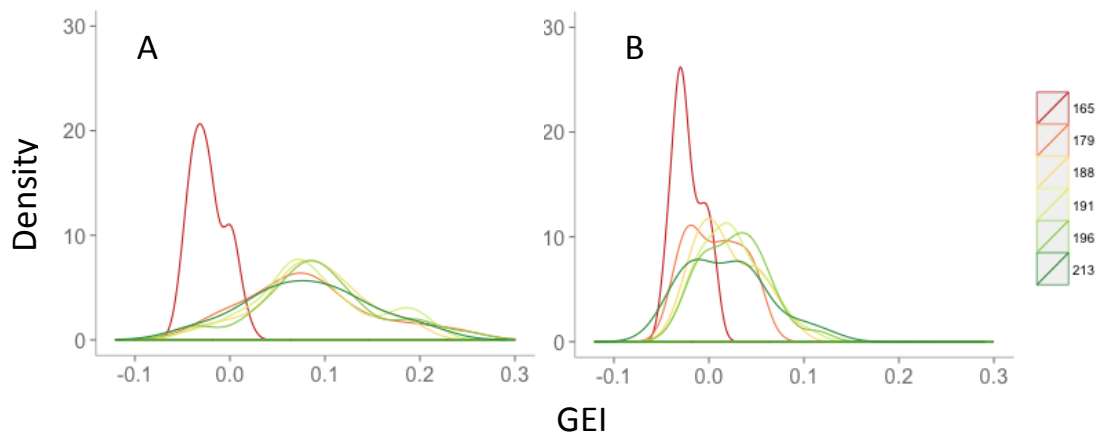


Figure 3.8 Density plots of GEI values by day (A: *S. arctica*; B: *D. integrifolia*).

3.1.9 Modeling GEI

Linear mixed models (Table 3.2) confirm that the warming treatment had significantly greater GEI values at the plot scale in all sites combined ($p < .0001$), the Dryas ($p < .0001$)

and Willow sites ($p < .0001$). The treatment was not significant at the individual scale (*S. arctica*: $p = 0.533$, *D. integrifolia*: $p = 0.128$) suggesting vegetation showed no difference in greenness. The addition of soil moisture as a random effect improved the model AIC at the plot scale for all sites combined, and for both species. Mature leaf was improved the model AIC at the community scale in the Dryas site.

Table 3.2 Analysis of GEI by linear mixed models. Simple models include treatment as a fixed effect and site as a random effect. Soil moisture and mature leaf models include those variables as random effect because they improve upon the simple model.

Site / species	Model	AIC	logLik	Treatment <i>p</i> -value
All	Simple	-1877	942.3	
	Soil moisture	-1873	943.7	< 0.001
Willow	Simple	-624.8	316.4	< 0.001
Cassiope	Simple	-855.8	431.8	0.258
Dryas	Simple	-838.7	423.4	
	Mature leaf	-822.5	416.3	< 0.001
Meadow	Simple	-661.4	334.7	0.0612
<i>Salix arctica</i>	Simple	-397.8	202.9	
	Soil moisture	-392.8	203.3	0.5328
<i>Dryas integrifolia</i>	Simple	-607.3	307.7	
	Soil moisture	-604.0	309.0	0.1282

3.1.10 Peak flower bloom detection

The program was able to detect mature flowers of *D. integrifolia*, *Papaver radicum*, *Eriophorum triste*, and *E. scheuchzeri* from digital photographs with high accuracy (Figure 3.9). There was a strong correlation between manual and program counts for all sites. There was no significant difference in performance by site or treatment (Figure 3.10). The meadow site, dominated by *Eriophorum* spp. had the greatest number of flowers and greatest range in flower numbers (0 – 83).

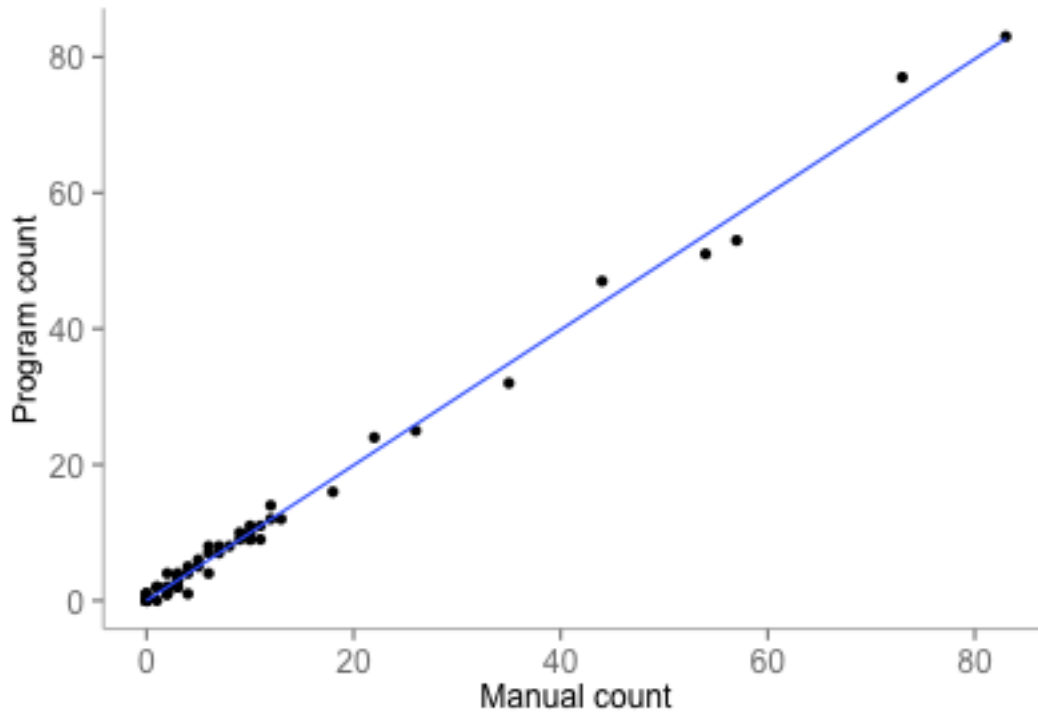


Figure 3.9 Linear regression between manual and program flower counts of *D. integrifolia*, *Papaver radicatum*, *E. triste*, and *E. scheuchzeri* in all sites ($R^2 = 0.99$, $p < 0.0001$).

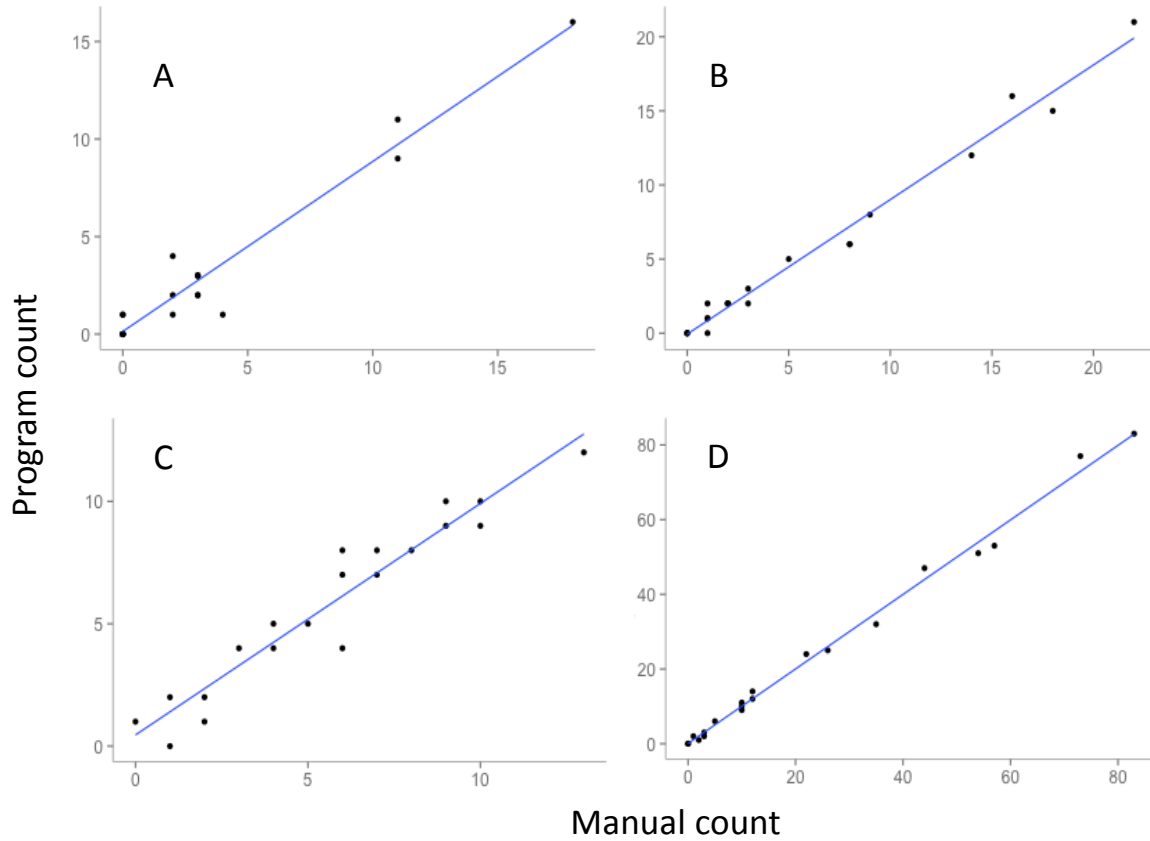


Figure 3.10 Linear regression between manual and program flower counts for each of the study sites. A: Willow site, $R^2 = 0.94$, $p < 0.0001$, flowers of *D. integrifolia* and *P. radicatum*, B: Cassiope, $R^2 = 0.98$, $p < 0.0001$, flowers of *D. integrifolia* and *P. radicatum*; C: Dryas site, $R^2 = 0.91$, $p < 0.0001$, flowers of *D. integrifolia*, *P. radicatum*, and *E. triste*; D: Meadow site, $R^2 = 0.99$, $p < 0.0001$, flowers of *Eriophorum* spp.).

3.1.11 Descriptive statistics of GEI and environmental data

The Meadow site had the greatest mean, standard deviation (0.03 ± 0.02), and range (0.1) in GEI values and the Cassiope site had the lowest (-0.32 ± 0.006 , 0.02) (Figure 3.11). Treatment plots had higher GEI in all sites but as the linear mixed models showed, only Dryas and Willow were significant (Table 3.2). In all sites but Cassiope, the treatment plots have greater variance in GEI values than control plots. At the individual species scale, *S. arctica* had greater mean, standard deviation (0.070 ± 0.070), and range (0.30) when compared to *D. integrifolia* (0.012 ± 0.035) (Figure 3.12). There was no significant difference between treatments for either species at any site (Table 3.2).

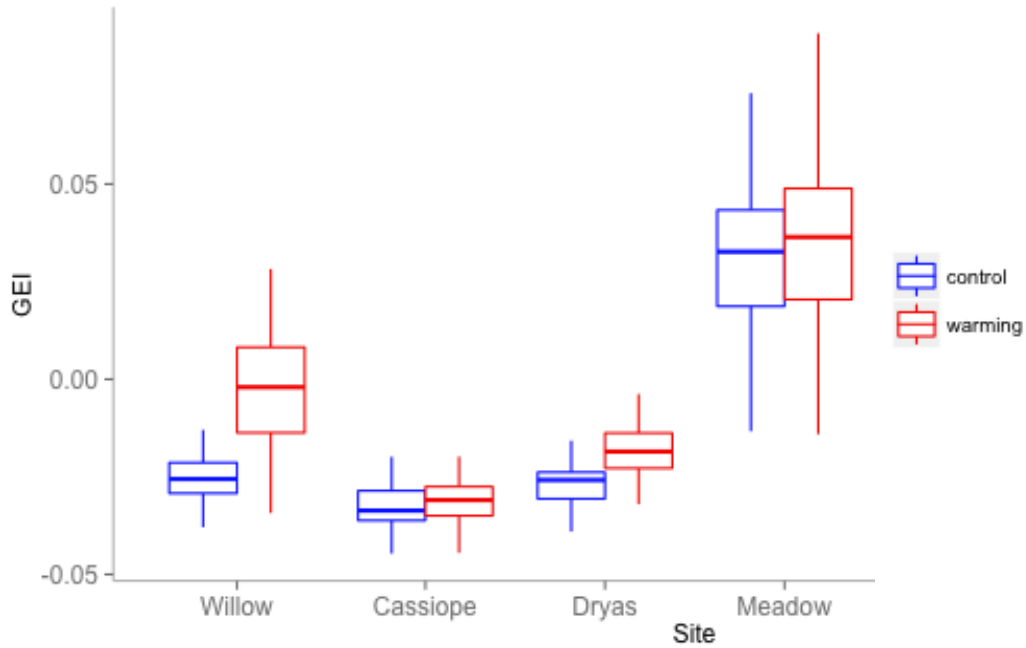


Figure 3.11 Boxplot of GEI values by site. Error bars represent the highest/lowest value within 1.5 of the interquartile range.

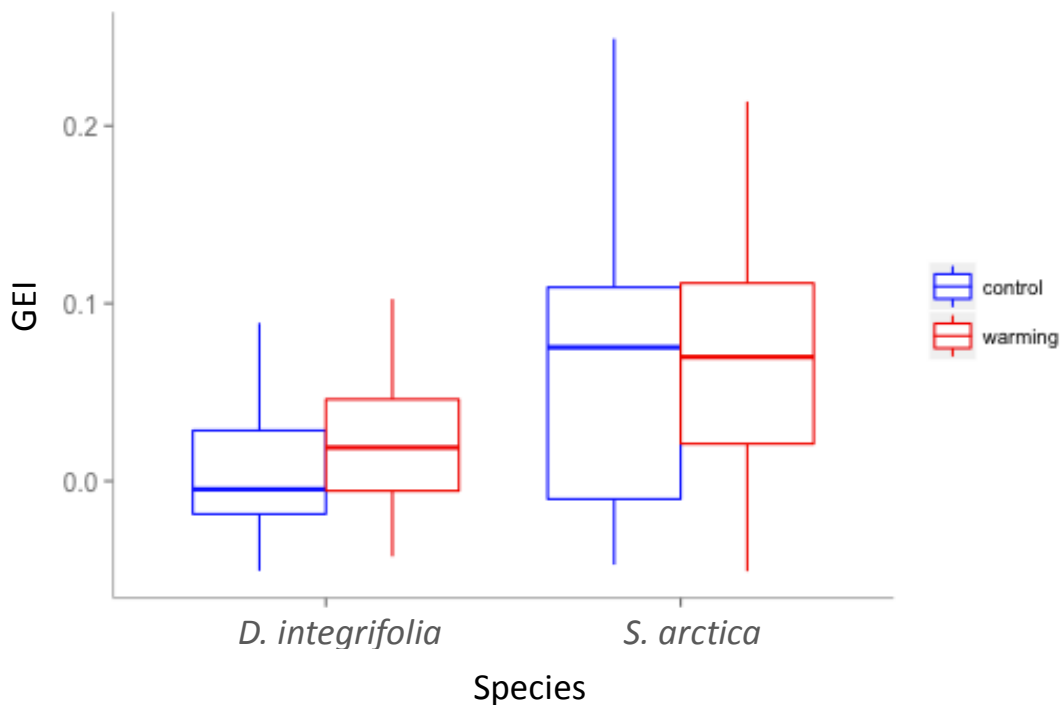


Figure 3.12 Boxplot of GEI values by species. Error bars represent the highest/lowest value within 1.5 of the interquartile range.

Corresponding to the highest mean GEI, the Meadow site had the greatest TLH (153 ± 34.0) and canopy height (12.2 ± 4.22) (Figure 3.13B, C). The Meadow site had significantly greater TLH ($p < 0.0001$) and canopy height ($p < 0.0001$) than the Cassiope, Dryas, and Willow sites. There was no difference in TLH or canopy height between the Dryas and Willow sites. TLH was significantly greater in the warmed plots of the Dryas ($p = 0.04$) and Willow site ($p < 0.0001$). The Willow site had a significantly taller canopy than the Dryas site ($p < 0.001$). Canopy height was significantly greater in the control plots of the Meadow site ($p < 0.0001$) but there was no difference between treatments in the Dryas or Willow sites (Figure 3.13C).

As expected, the Meadow site had the highest soil moisture ($76.7\% \pm 10.2$) and was significantly greater than all other sites ($p < 0.0001$). Unexpectedly, the Cassiope site had the lowest soil moisture ($21.9\% \pm 5.52$) (Figure 3.13A). The Dryas site had significantly greater soil moisture compared to both the Willow ($p = 0.02$) and the Cassiope site ($p < 0.0001$) and the Willow site had significantly greater soil moisture compared to the Cassiope site ($p < 0.0001$). There was no significant difference in soil moisture due to treatment in any of the sites.

First day of mature leaf was earliest in the Meadow site (170 ± 1.99) and the Dryas site had the greatest range in first leaf date (12 days) (Figure 13D). There was no significant difference in first day of mature leaf in warmed plots between sites. In the control plots, Willow was significantly later than Dryas ($p = 0.02$) and Cassiope ($p < 0.0001$) and Meadow was significantly earlier than Dryas ($p = 0.002$). First day of mature leaf was significantly earlier in warmed plots of all sites ($p < 0.001$) except the Cassiope site.

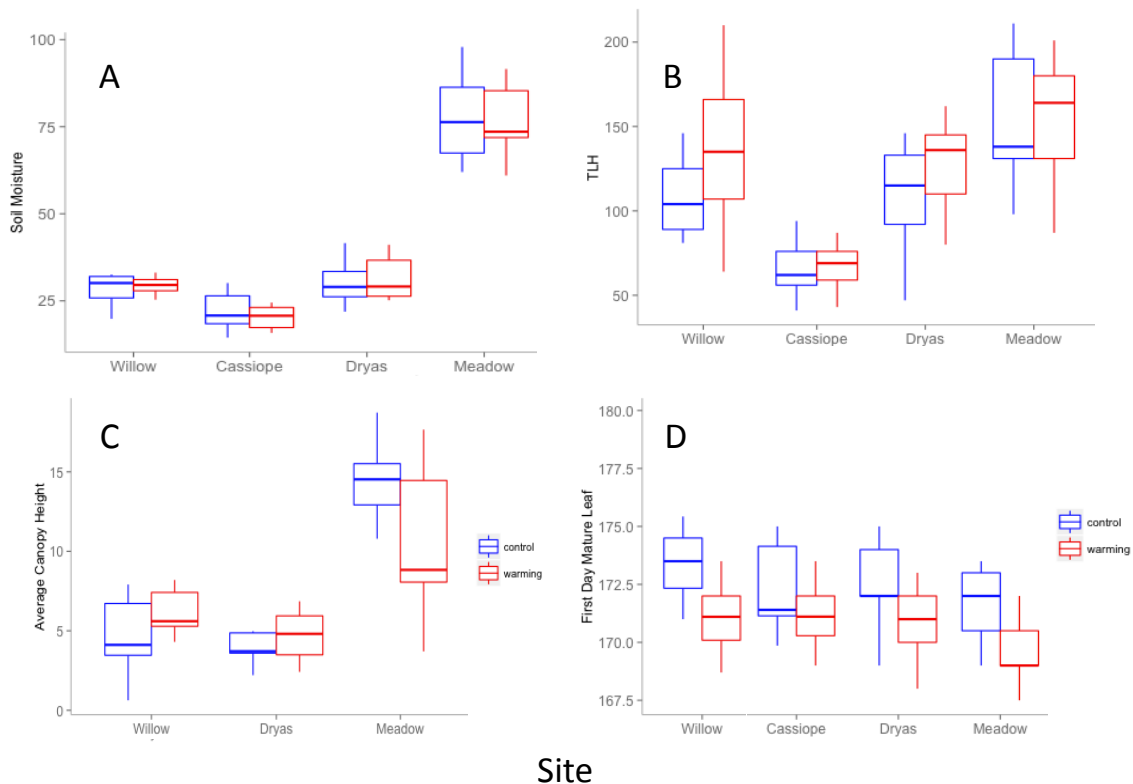


Figure 3.13 Boxplot of **A: Soil Moisture, B: Total live hit biomass, C: Average canopy height, D: First day mature leaf.** Error bars represent the highest/lowest value within 1.5 of the interquartile range.

Discussion

3.1.12 Evaluation of photographs in detecting phenological changes

Phenological observations have been conducted at AF for 20 years using modified ITEX protocols (Molau and Mølgaard 1996). Tagged plants of mainly dominant species have been monitored nearly annually in all vegetation communities inside and outside of warmed plots (Oberbauer et al. 2013). This long-term dataset contains highly valuable ecological information, but changing species of interest, evolving methodology, missing data and observer error has affected the dataset. Similarly, other ITEX data sets have been affected by these issues, and some have abandoned the detailed phenological measurements (Oberbauer et al. 2013). The analysis in this chapter demonstrates the

potential of photo analysis to reduce error of field-based phenological observations at the plot scale through automation of the method.

Phenological signals of tundra vegetation were detectable at multiple scales using GEI extracted from a small sample of colour digital photographs. As with previous studies in alpine and temperate forest ecosystems, there was an overall agreement between GEI and field-based phenological data supporting the validity of inferring phenological stage from GEI (Richardson et al. 2007; Ahrends et al. 2008; Graham et al. 2010; Ide and Oguma, 2010). The peak flower counts of major species are another example of phenological data extractable from colour photographs. The difference in number of flowers by site and treatment can provide information about reproductive effort under warming treatment and different hydrological regimes. The program performed well in all sites and was in agreement with manual counts, but will need to be improved to identify individual species.

Phenological signal strength varied with spatial scale, vegetation community and species. This photographic methodology has largely been applied in well-vegetated temperate forests and alpine meadows using a large landscape field of view (FOV) (Richardson et al. 2007; Crimmins and Crimmins 2008, Ide and Oguma, 2010). AF is well vegetated for the High Arctic but areas of bare soil, rock, standing litter and standing water, interfere with the phenological signal at the plot scale at which the photos were taken. This is well demonstrated in the analysis as the weakest signal was in the Dryas site where litter and bare soil are extensive. Individual species had the strongest phenological signal because the influence of non-vegetated areas was minimized as individual plants encompass the entire FOV.

Early season temporal patterns of GEI in the Dryas and Willow sites show a different rate of green-up in the treatment plots of these sites. Field-based observations suggest significantly earlier mature leaves in warmed plots of both sites. This was reflected in the time series though greenness appears to decrease slightly from day 165 to day 179 in control plots of both sites. This decrease could be the result of green mosses in the canopy on day 165 taking advantage of moisture following snowmelt. Mosses rely on ample surface water so once the snow and early season saturation dissipates they become susceptible to desiccation potentially explaining the apparent decrease in GEI

(Oechel and Sveinbjörnsson 1978). The lack of a clear temporal signal in green-up could also be the result of the low frequency of photographs early in the season. After day 188 temporal patterns were similar in the Dryas and Willow sites suggesting no difference in the timing of senescence due to treatment. A temporal change was observed at the Meadow site after day 188 but there was no significant ($P > 0.05$) difference in timing of senescence due to treatment in field-based observations. Greater frequency of photos would likely strengthen all phenological signals. Future application of this method at AF will endeavor to achieve this to gain a clearer understanding of the site and species differences.

3.1.13 Evaluation of GEI in detecting vegetative differences

In addition to phenological patterns, results demonstrate that GEI is able to detect differences in vegetation cover and vigor at the plot and individual scale, respectively. Warmed plots of the Dryas and Willow sites had significantly greater GEI values and a higher density of green pixels suggesting greater coverage of green vegetation in the photographs due to warming. Previous research in these sites by Hudson et al. (2011) found experimental warming resulted in larger leaf size and height of the dominant plant species. Migilavacca et al. (2011) found strong correlations between GEI, green biomass ($r = 0.67$) and LAI ($r = 0.74$) in an alpine ecosystem and at AF, moderate correlations between GEI and TLH and average canopy height have been found (Table 2.4; Figure 2.5; Beamish *et al. unpublished data*). This highlights the ability of GEI to detect differences in vegetation cover at the plot scale.

The strong site-specific response of *S. arctica* represents a difference in the greenness of the individual species in each site not the amount of greenness (i.e. cover) as seen at the plot scale. Previous research showed greenness ratios derived from colour digital photographs are highly correlated ($r^2 = 0.91$) to physiological traits such as chlorophyll content (Adamsen et al. 1999). Differences in growth form of *S. arctica* driven by soil moisture and the resulting community composition have been documented at AF (Jones et al. 1999; Hudson et al. 2011). The well-drained mesic conditions of the Willow site allows *S. arctica* to thrive and grow taller and larger (Walker et al. 2006). This may explain the differences seen between the Willow and hydric Meadow site

where conditions are not ideal for *S. arctica*. The Dryas site has similar site conditions to the Willow site but it melts out later than Willow and recent flooding of that community has caused a shift towards a sedge and grass dominated ecosystem (Henry et al. unpublished). This changing moisture regime and shifting vegetation composition could explain the lower GEI of *S. arctica* in this site. A recent meta-analysis of experimental warming data highlights the importance of these site and species-specific response of vegetation to understanding tundra vegetation change (Elmendorf et al. 2012b). This photo analysis method provides the opportunity to easily monitor specific species responses to environmental changes in multiple vegetation communities.

Conclusions

We analyzed the phenological signal derived from a small set of repeat colour digital photographs at the plot and individual species scale in a High Arctic ITEX site. GEI derived from the photographs was able to detect a seasonal phenological signal at all spatial scales. The clarity of the signal decreased with increasing spatial scale. GEI was also able to detect differences in vigor of individual species and above ground biomass at the plot scale. Density plots of GEI by day indicated that flowering was detected at the plot scale and the senescence signal was strongest at the individual species scale. We also developed an algorithm that was able to accurately predict peak total flower numbers automatically. Soil moisture emerged as the most important environmental factor in modeling GEI. This methodology is simple, affordable and efficient and has great potential for use in a vegetation monitoring network in the Arctic.

4 Summary and Synthesis

Introduction

The goal of this project was to determine the utility of colour digital photography in detecting differences in vegetation and vegetation phenology over one growing season across a moisture gradient, and in response to experimental warming. The magnitude and direction of vegetation change due to warming is highly variable (Elmendorf et al. 2012a). Increasing the volume and consistency of vegetation data through automation of data collection will aid in understanding this heterogeneity that defines tundra ecosystems. Photographs were taken in four moisture defined vegetation communities in plots that have been passively warmed for the last 20 years and corresponding control plots. These data were used to answer the following questions:

- (1) How does greenness data (GEI) from colour digital photographs relate to biomass measures?
- (2) How do greenness-biomass relationships compare to NDVI-biomass relationships?
- (3) Can greenness data detect seasonal patterns of green-up and senescence at the plot and species scale?
- (4) Can greenness data detect differences due to treatment?
- (5) Can greenness data detect differences due to differences in hydrological regimes?
- (6) Can we automate flower counting with an algorithm?

Summary of results

GEI derived from digital photography demonstrated moderate positive correlations to TLH and canopy height data. These relationships were very similar to correlations between NDVI and the biomass measures suggesting that GEI is a suitable proxy for aboveground biomass and productivity. This is supported by previous research, which

has found strong to moderate positive correlations between GEI, live biomass and GPP in both grassland and temperate forests (Ahrends et al. 2009; Migliavacca et al. 2011).

When GEI values were plotted in a time series, logical phenological signals of green-up and senescence emerged which corresponded well to field based phenological observations. Agreement between phenological stage inferred from GEI and observed phenological stage has been found in a number of ecosystems including a high alpine meadow (Richardson et al. 2007; Ahrends et al. 2008; Graham et al. 2010; Ide and Oguma, 2010). The strength of the phenological signal was dependent on site and scale. The signal was strongest at the individual species scale because green vegetation encompassed the entire field of view (FOV). The deciduous shrub *S. arctica* had the strongest green-up and senescence signal. The Cassiope site had the weakest signal due to the dominance of non-green biomass.

Differences due to treatment were detectable at the plot scale. The GEI values in warmed plots at the Dryas and Willow sites were significantly higher than control plots. This was supported by significantly greater TLH in these plots. These results show that GEI is able to detect differences in the amount of green vegetation cover at the plot scale. There was no difference between treatments at the species scale (for *S. arctica* and *D. integrifolia*) further supporting the ability of GEI to detect quantitative differences in vegetation cover. Though there was a lack of treatment signal at the species scale, there were significant differences in GEI values by site. This is likely the result of differences in vigor of the species due to different moisture regimes as well as other soil characteristics and the resulting community composition and competition. Adamsen et al. (2009) found strong correlations of greenness ratios derived from digital photographs to physiological traits such as chlorophyll content. Different growth forms of some species have been recorded in the different vegetation communities at AF (Jones et al. 1999; Hudson et al. 2011).

The Meadow site had the greatest GEI values, which corresponded to the greatest TLH and canopy height values. The Meadow site also had the greatest range in GEI values, which is reflected in the time series showing change in greenness over the season at the plot scale. Overall, GEI values were more variable in the warmed plots suggesting a variable response even from plot to plot within sites. A recent study of tundra

vegetation change found strong site and species-specific responses of tundra vegetation to experimental warming highlighting the importance of understanding this within site heterogeneity (Elmendorf et al. 2012a).

Peak flower production was accurately estimated from the digital photos using an algorithm. Strong correlations between estimated and manual counts were found in all sites. This additional quantitative vegetation data can provide important information about reproductive effort and differences due to soil moisture and warming.

Limitations

The major limitation for this study was the limited temporal scale of the photo dataset. The six photographs gave a snapshot of changes in seasonal vegetation status but did not provide detailed information regarding early season green-up patterns when changes are the most rapid. Increasing the frequency of photographs would greatly improve our ability to infer phenological patterns more accurately from RGB data. An additional limitation was the biomass estimations. More detailed biomass information including belowground biomass, LAI, and percent cover could help increase the accuracy of GEI in estimating biomass and productivity.

Future research

Future work to expand upon the results presented in this thesis is first and foremost a photo dataset with a higher temporal frequency. Ideally, time-lapse cameras would take multiple photos of each plot each day (ore even more frequently) through the growing season from pre-snow melt to full leaf senescence. This would provide a better understanding of snowmelt timing and the resulting green-up and senescence inside and outside of OTCs as well as differences by site. The addition of a larger spatial data set, i.e. the landscape scale would also add valuable information about how the lowland changes as a mosaic rather than just community by community. This would require the use of cameras at varying elevations, and could be accomplished through the use of balloons or drone aircraft.

Conclusions

The results of this thesis demonstrate the utility of repeat colour digital photography in monitoring tundra vegetation in the high Arctic. The RGB data derived from photographs was able to detect seasonal phenological patterns of green-up and senescence at the plot and individual species scale. It was also able to detect differences in greenness of vegetation due to differences in cover and differences in vigor. These results coupled with the ease and accessibility of digital photography highlights the potential for implementation of a semi-automated monitoring network at Alexandra Fiord and across the Arctic.

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Appendix

A.1 RGB data extraction program

```
get_photo <- function(directory, ...){
  # get the files in the directory and their creation dates and load them into a dataframe
  files <- list.files(directory, pattern="(?.i)tif$", full.names=TRUE)
  photos <- data.frame(file=I(files), Av_R=NA, Av_G=NA, Av_B=NA, Index=NA,
Index2=NA, Index3=NA)

  for (i in 1:nrow(photos) ){
    f <- GDAL.open(photos[i, 'file'])
    r <- getRasterData(f, band=1) #extracts band 1 = Red
    av_r <- mean(r)
    photos[i, 'Av_R'] <- av_r

    g <- getRasterData(f, band=2) #extracts band 2 = Green
    av_g <- mean(g)
```

```

photos[i, 'Av_G'] <- av_g

b <- getRasterData(f, band=3) #extracts band 3 = Blue
av_b <- mean(b)
photos[i, 'Av_B'] <- av_b

index <- ((av_g)/(av_r + av_g + av_b)) #calculates a normalized green value = rG
av_index <- mean(index)
photos[i, 'Index'] <- av_index

index2 <- ((av_r)/(av_r + av_g + av_b)) #calculates a normalized red value = rR
av_index2 <- mean(index2)
photos[i, 'Index2'] <- av_index2

index3 <- ((av_b)/(av_r + av_g + av_b)) #calculates a normalized blue value = rB
av_index3 <- mean(index3)
photos[i, 'Index3'] <- av_index3

GDAL.close(f)
}

return (photos)
}

```

A.2 Flower counting algorithm

```

function flowers(~)
%FLOWERS Counts number of light objects (flowers) in digital photos

%Written by Samuel Robinson, May 2013. Adapted from SEEDS program to work
%with image opening and image closing functions.

%% GUI Constructor
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
close all;
clc

window_size=[100 100 1000 600];
default_colour=get(0,'defaultUicontrolBackgroundColor');
colourmap=[0.2 0.2 0.2; 1.0 1.0 1.0]; % Colour map for displaying difference objects

%Variables
current_dir='F:\AB_NDVI2012_ALL\flowers\Dryas_control'; %Directory containing
photos
filelist=cell(0); %Cell array to store filenames

```

```

reviewed=[]; %Logical vector for storing which photos have been reviewed
crop_params=[]; %Matrix for storing cropping parameters. Column order: [Photolist
number, x,y,w,h]
objectnum=[]; %Array for storing numbers of objects in each photo
strelsize=5; %Variable for structuring element size
threshold=0.9;

```

```

%The main figure box (and parent to all other functions in the GUI)

```

```

window=figure('Visible','off',...
    'Name','Flower Counter',...
    'NumberTitle','off',...
    'Position',window_size,...
    'MenuBar','none',...
    'Color',default_colour);

```

```

%Title text over current_dir box

```

```

current_dir_title = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3 44.5 17 1],...
    'String','Current Directory',...
    'Style','text'); %#ok<*NASGU>

```

```

%Current directory box

```

```

current_dir=uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[3 40 35 4],...
    'String',current_dir,...
    'Style','text');

```

```

%Button to change directories

```

```

chdir_button = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3 37 34.5 2],...
    'String','Load Directory',...
    'Tag','Changes working directory',...
    'Callback',@chdir_button_push);

```

```

%Title text over photolist box

```

```

photolist_title = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[4 34.8 25.8 1],...
    'String','Photos in current directory',...

```

```

'Style','text');

%Box for list of photos
photolist_listbox = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[3 20 35.2 14],...
    'String','',...
    'Style','listbox',...
    'Value',1,... %First thing selected
    'Max',1,'Min',1,... %Max #things selected
    'Callback',@photolist_listbox_click);

%Buttons to advance photos
next_button = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3 17.5 17 2],...
    'String','Next',...
    'Tag','Next Photo',...
    'Callback',@next_button_push);

%Buttons to change photos
prev_button = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[21.5 17.5 16.5 2],...
    'String','Prev',...
    'Tag','Previous Photo',...
    'Callback',@prev_button_push);

%Label for brightness threshold box
threshold_label = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3 15.5 23 1],...
    'ToolTipString','Brightness threshold for subtracted images',...
    'String','Brightness Threshold',...
    'Style','text');

%Textbox for setting threshold values
threshold_textbox = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[29 15.5 8 1],...
    'ToolTipString','Must be between 0 and 1. Default = 0.9',...

```

```

'String',num2str(threshold),...
'Style','edit',...
'Callback',@threshold_check);

%Label for structuring element size box
strelsize_label = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3.8 14 23 1],...
    'ToolTipString','Size of structuring element used to join areas of difference',...
    'String','Stucturing Element Size',...
    'Style','text');

%Textbox for setting size of structuring element used to join areas
%brightness
strelsize_textbox = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[29 14 8 1],...
    'ToolTipString','Must be a positive integer. Default = 5',...
    'String','5',...
    'Style','edit',...
    'Callback',@strelsize_check);

%Title text for objects box
objectbox_title = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[4 12.5 17 1],...
    'String','OBJECTS FOUND ->',...
    'Style','text'); %#ok< *NASGU>

%Objects found box
objectbox=uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[23 12.5 16 1],...
    'String','0',...
    'Style','text');

%Button to crop photos
crop_button = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[3 10 16 2],...
    'String','Crop Photo',...

```

```

'Callback',@crop_button_push);

%Button to save photos
save_button = uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',default_colour,...
    'Position',[23 10 16 2],...
    'String','Save object list',...
    'Tag','Save list to ',...
    'Callback',@save_button_push);

%Current directory box
console=uicontrol(window,...
    'Units','characters',...
    'BackgroundColor',[1 1 1],...
    'Position',[4 1.3 37 8],...
    'String','Select a directory to begin',...
    'Style','text');

%Picture
pic_axes=axes('Parent',window,...
    'Units','characters',...
    'Position',[44.5 1.5 152 44],...
    'TickLength',[0 0],...
    'XTickLabel',{},'YTickLabel',{},...
    'Box','on');

% Makes the entire GUI visible at the end of initialization
set(window,'Visible','on');
%Turns off warnings, so they don't clutter the console window. Errors will
%still be reported.
warning('off','all')

%% Callbacks
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Called to change directory and populate filelist
function chdir_button_push(~,~)
    set(console,'String','Loading photos...');
    drawnow update;
    newdir=uigetdir(get(current_dir,'String'));
    if newdir~=0
        set(current_dir,'String',newdir); %Changes current_dir to a directory specified in
uigetdir (pop-up window)
        files=dir(newdir); %Gets a structure of the files contained in current_dir
        formats={' .jpg';'.tif';'.png';'.bmp'}; %Accepted file formats

```

```

        choose=[]; %Files to be chosen
        for i = 3:length(files) %Iterates through files, choosing ones that have the correct
        extentions (defined in 'formats')
            [~,~,a,~]=fileparts(files(i).name);
            if sum(strcmp(a,formats))>0
                choose=[choose i]; %#ok<AGROW>
            end
        end
        [filelist{1:length(choose)}] = deal(files(choose).name); %Puts file names into cell
        array "filelist"

```

```

        crop_params=[]; %Removes previous cropping parameters
        reviewed=false(length(filelist),1); %Sets entire photo list to "unreviewed"
        objectnum=NaN(length(filelist),1); %Sets number of objects found in each photo
        to NaN
        set(photolist_listbox,'String',filelist,'Value',1); %Sets the strings in
        photolist_listbox to the filelist cell array
        refresh_photos; %Refreshes the photo seen in the main axis of the GUI
        set(console,'String',['Set directory to ' get(current_dir,'String') '. '
        num2str(length(filelist)) ' photos found.']);
        else
            set(console,'String','No photos found');
            return
        end
    end
end

```

```

%Advances photos by 1
function next_button_push(~,~)
    current=get(photolist_listbox,'Value');
    if current<length(reviewed)
        set(photolist_listbox,'Value',current+1)
        refresh_photos;
    else
        beep
    end
end
end

```

```

%Decrements photos by 1
function prev_button_push(~,~)
    current=get(photolist_listbox,'Value');
    if current>1
        set(photolist_listbox,'Value',current-1)
        refresh_photos;
    else
        beep
    end
end

```

```

end

%When photolist_listbox is clicked
function photolist_listbox_click(~,~)
    set(console,'String','Working...');
    refresh_photos;
    set(console,'String',['Photo ' num2str(get(photolist_listbox,'Value')) ' of '
num2str(length(filelist))]);
    drawnow update;
end

%Checks and changes threshold values in threshold_textbox
function threshold_check(~,~)
    temp=get(threshold_textbox,'String');
    temp=str2double(temp);
    if (temp<=0)||(temp>=1)||(isnan(temp))
        msgbox('Enter a number between 0 and 1','Error','error')
        set(threshold_textbox,'String',num2str(threshold));
        return
    end
    threshold=temp;
    refresh_photos;
    set(console,'String','Changed brightness threshold');
end

%Saves the results to a CSV file
function save_button_push(~,~)
    if range(isnan(objectnum))
        set(console,'String','Some photos have not been reviewed');
        beep
        return
    end
    [filename,pathname]=uiputfile(get(current_dir,'String'));
    if filename==0
        return
    else
        csv=NaN(length(filelist),2);
        csv(:,1)=1:length(filelist);
        csv(:,2)=objectnum;
        csvwrite(fullfile(pathname,[filename '.csv']),csv);
    end
    set(console,'String','Saved object list');
end

%Triggered when a new value is entered for strelsize. Parses new inputs
%and rejects incorrectly formatted entries.

```



```

function strelsize_check(~,~)
    temp=get(strelsize_textbox,'String');
    temp=round(str2num(temp)); %#ok<*ST2NM>
    if (isempty(temp))||(temp<0)
        set(console,'String','Enter an integer greater than 1')
        set(strelsize_textbox,'String',num2str(strelsize));
        return
    end
    strelsize=temp;
    set(strelsize_textbox,'String',num2str(strelsize));
    refresh_photos;
    set(console,'String','Changed size of structuring element');
end

%Collects parameters for cropping,
function crop_button_push(~,~)
    done=false;
    while done==false
        set(console,'String','Select area to crop');
        params=getrect();
        if
            isempty(crop_params)||(sum(crop_params(:,1))==get(photolist_listbox,'Value'))~=1) %If
            cropping parameters don't exist
                crop_params(size(crop_params,1)+1,:)=get(photolist_listbox,'Value'),params];
            %Tags a new set of parameters onto the bottom of crop_params
        else %If cropping parameters do exist
            row=crop_params(:,1)==get(photolist_listbox,'Value'); %Row containing
            cropping parameters specific to selected photo

            new_params=[get(photolist_listbox,'Value'),crop_params(row,2:3)+params(1:2),params(
            3:4)]; %New cropping parameters
            crop_params(row,:)=new_params; %Replaces old cropping parameters with
            new ones
        end
        refresh_photos;
        button = questdlg('Use current cropping
selection?','Selection','Yes','No','Redo','Yes');
        switch button
            case 'Yes'
                done=true;
            case 'Redo'
                crop_params(crop_params(:,1)==get(photolist_listbox,'Value'),:)=[];
                refresh_photos;
            case {'No',''}
                crop_params(crop_params(:,1)==get(photolist_listbox,'Value'),:)=[];
                refresh_photos;
        end
    end
end

```

```

        done=true;
    end
end
end
end

%% Convenience functions
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%Used to refresh and process sets of photos(uses SEEDCOUNT.M)
function refresh_photos(~,~)
    if isempty(filelist) %If no photos are found
        return %Exits the function
    end
    selected_photo=get(photolist_listbox,'Value'); %Gets position of the selected photo
    from photolist_listbox
    path=fullfile(get(current_dir,'String'),filelist{selected_photo}); %Creates the full
    path of the selected photo
    photo=imread(path); %Reads selected photo
    if ~isempty(crop_params)&&sum(crop_params(:,1)==selected_photo)==1 %If
    matching cropping parameters are found
        photo=imcrop(photo,crop_params(crop_params(:,1)==selected_photo,2:5));
    %Crops photo
    end
    thresh=str2double(get(threshold_textbox,'String')); %Threshold of pixels
    num=flowercount(photo,thresh); %Counts number of objects in photo, using
    threshold provided
    set(objectbox,'String',num); %Displays the number of objects in the objectbox
    objectnum(selected_photo)=num; %Saves the number of objects found
    imshow(photo,'Parent',pic_axes); %Displays photo
    reviewed(selected_photo)=true; %Sets photo as 'reviewed'
    set(console,'String',[num2str(num) ' objects found.']);
end

function count=flowercount(photo,thresh)
% SEEDCOUNT Number of light objects (flowers) in an image
%
% COUNT=SEEDCOUNT(PHOTO,THRESH) Uses uint8 image PHOTO,
thresholds
% and groups objects using THRESH. Returns the number of dark objects
% found within the image as integer COUNT.
%
% PATH String
% THRESH Proportion of darkest pixels to use (0.1 works well)
%
% Written by Samuel Robinson, Spring 2013

```

```
A=im2bw(photo,thresh); %Thresholds THRESH brightest part of image
A=imopen(A,strel('disk',strelsize));
A=imclose(A,strel('disk',strelsize));
objects=bwconncomp(A,4);
count=objects.NumObjects;
end

end
```