University of Alberta

Monitoring year-to-year variability in dry mixed-grass prairie yield using multi-sensor remote sensing

by

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Abstract

The Normalized Difference Vegetation Index (NDVI) and harvested biomass were compared to assess rangeland productivity (above-ground green biomass or “yield”) in southern Albertan dry mixed-grass prairie. Seasonal trends during the 2009 and 2010 growing seasons were investigated using harvested biomass and NDVI derived from ground spectrometry and the Aqua and Terra Moderate Resolution Imaging Spectroradiometers (MODIS) and Système Pour l'Observation de la Terre (SPOT) satellite platforms. Drought in 2009 and high precipitation in 2010 provided contrasting “treatments” that were captured with measurements of NDVI. NDVI showed a saturating response to green plant biomass, with the strongest correlation (R^2=0.97) arising from mid-summer measurements. NDVI from satellite remote sensing can accurately estimate interannual variation in standing green biomass, and field spectrometry can provide validation for satellite data. These methods can be used to identify the effects of yearly precipitation variability on above-ground biomass in the dry mixed-grass prairie.

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List of Abbreviations

AFSC - Agricultural Financial Services Corporation

MODIS - Moderate resolution imaging spectroradiometer

NDVI - Normalized Difference Vegetation Index

SPOT - Système Pour l'Observation de la Terre

CHAPTER 1 - INTRODUCTION: BACKGROUND, CONTEXT

Rangelands currently occupy 26 - 36% of the world's land area (Fay *et al.*, 2003; Schino *et al.*, 2003) and nearly 7 million hectares of Alberta (Bedard *et al.*, 2006; Bremer, 2008). Rangelands are composed of many ecosystems, including shrublands, savannas, tundra, deserts, alpine communities, coastal marshes, forests, meadows and grasslands (Kustas *et al.*, 1991). Historically, grasslands covered 300 million ha in the United States and 50 million ha in Canada (Sims and Risser, 2000). The dry mixed-grass natural subregion is a transitional zone between the Great Plains and the fescue grasslands contained within the foothills fescue and foothills parkland natural subregions (Adams *et al.* 2005). It is distinguished by being dominated by Brown Chernozemic and Solonetzic soils and the dominant vegetation is Blue grama (*Bouteloua gracilis*) and Needle and Thread (*Stipa comata*) grasses (Adams *et al.* 2005). Seven per cent of the area of Alberta falls within the dry mixed-grass prairie natural subregion, of which 43 per cent of the original 11.8 million acres remain (Adams *et al.* 2005). In comparison to high productivity areas that have historically been converted to crop production (Psomas *et al.*, 2011), mixed-grass prairie is comprised of less productive arid and semiarid regions characterized by variable precipitation, high evaporation potential, high albedo, high soil-heat flux and low annual runoff (Coupland, 1958; Kustas *et al.*, 1991; Hunt *et al.*, 2003), making these areas largely untenable for yield based crops.

Due to the low and highly variable biomass yields characteristic of these grassland ecosystems, companies that provide agricultural insurance coverage for ranchers have become interested in developing greater accuracy in above-ground biomass estimation over large areas. Because prairies do not produce traditional crops where productivity is easily measureable by harvested yields (Rowley *et al.*, 2007), remote sensing is increasingly used to estimate yield (within this thesis yield is equated with above-ground biomass) in these ecosystems (Tueller, 1989). While economic incentives spur the adoption of accurate monitoring and measurement of prairie biomass, growing interest in biological carbon sequestration and ecological goods and services provide additional motivation for assessing rangeland yields (Psomas *et al.*, 2011). Grasslands' ability to sequester carbon makes these ecosystems desirable for maximizing carbon sequestration and storage (Bremer, 2008). As in any carbon sequestration scheme, biospheric carbon sequestration requires accurate monitoring of productivity to be successful. These economic and ecological incentives are leading managers of mixed-grass prairie to investigate increasingly accurate biomass monitoring methods.

In the interest of reducing manpower and fieldwork, rangeland managers have historically been interested in reducing the ratio of time spent in the field to that in the office (Tueller, 1989). Remote sensing methods allow managers to acquire information from appropriate spatial and temporal scales distributed over the landscape efficiently and relatively inexpensively (Booth and Tueller, 2003). Various remote sensing methods, including aerial photography, satellite multispectral scanners, airborne hyperspectral scanners, radar, lidar and video systems have been utilized by rangeland managers for change detection, mapping soils, measuring indicators of range health (bare ground for example), analyzing ground cover, tracking individual species, evaluating grazing management and making inferences about vegetation productivity and biomass levels (Tueller, 1989; Booth and Tueller, 2003; Hunt *et al*., 2003). The agricultural insurance industry's desire for accurate estimation of rangeland yields has been one of the more recent motivations for the adoption of remote sensing for range management (Rowley *et al.*, 2007). Increased technological and scientific capabilities are critical instruments for rangeland resource management and will likely result in changes in range management (Tueller, 1989).

Accurate monitoring of above-ground biomass can lead to a better understanding of vegetation resilience due to variations in weather/climate, which is necessary for understanding the sustainability of Alberta's grasslands. Disturbance of prairie ecosystems can have various effects upon their yield and potential for carbon sequestration. Moderate grazing pressure could have a compensatory effect on plant growth, through increased nutrient availability and altered community structure, which could also maintain soil carbon stocks (Bremer, 2008). However, overgrazing has an impact on net primary productivity, litter accumulation and decomposition and can result in the replacement of C_3 grasses with C_4 grasses (Lynch *et al.*, 2005; Ingram *et al.*, 2008). Heavy grazing pressure can also result in rooting changes which can increase the vulnerability of the ecosystem to drought conditions, which may occur with altered precipitation patterns (Fay *et al.*, 2003). Enhanced monitoring methods can be utilized for intensive management of grazing regimes, in an effort to avoid excess disturbance and maintain range health.

The goal of this research is to enhance our understanding of the relationship between ground and satellite-derived NDVI products and above-ground biomass ("yield"), which can be used to assess the capabilities of existing satellite remote sensing platforms for accurate regional monitoring purposes within dry mixed-grass ecosystems. Accurate estimation of rangeland productivity is essential for large jurisdictional monitoring programs, and payment functions for drought stress are of critical importance to the insurance and ranching industries. The monitoring of rangelands involves large spatial scales, which is difficult to accomplish with point based measurements. Therefore, accurate analysis of primary productivity through remote sensing would be of interest to corporations, such as the Agricultural Financial Services Corporation (AFSC) of Alberta, in an effort to increase the confidence of both the insurer and the consumer in rangeland vegetation index based insurance programs. Accurate productivity measurements would also be of benefit to the development of carbon markets that consider biospheric carbon storage.

This project examines some of the inherent difficulties dry-mixed grass ecosystems present for estimation of primary productivity. The ability to estimate productivity is important for ranchers in planning ranching operations such as cattle rotations within paddocks. Climate change is likely to result in increased temperatures and altered summer precipitation (Christensen *et al.*, 2007). The ability to assess and through integrated resource management, maintain a positive carbon uptake in Alberta is important for reaching carbon management goals (Schuman *et al.*, 2002; Haugen-Kozyra, 2004). Additional land use management (such as altered grazing systems from continuous to rotational) (Willms and Jefferson, 1993) in conjunction with remote sensing methods of estimating yield can be important for mitigating the effect of weather variability on the capacity of managed rangelands to maintain range health (Tueller, 1989). Evaluating the reliability of currently utilized remote sensing methods is necessary for range management and range health monitoring purposes (Booth and Tueller, 2003). This study can help with this undertaking by enhancing our understanding of the relationship between satellite and ground derived NDVI and green biomass in the dry mixed-grass prairie, and by demonstrating the necessary methods of estimating biomass for enhanced monitoring.

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CHAPTER 2 –MONITORING PRAIRIE YIELD WITH MULTI-SENSOR REMOTE SENSING

Introduction

Rangelands comprise between 26 to 36% of the terrestrial land surface (Fay *et al.*, 2003; Schino *et al.*, 2003). They include many ecosystems, including shrublands, savannas, tundra, deserts, alpine communities, coastal marshes, forests, meadows and grasslands (Kustas *et al.*, 1991). The dry mixed-grass natural subregion is a transitional zone between the Great Plains and the fescue grasslands contained within the foothills fescue and foothills parkland natural subregions (Adams *et al.* 2005) and is located in southern Alberta and Saskatchewan, Canada and extends southward into northern Texas (Coupland, 1961). It is distinguished by being dominated by Brown Chernozemic and Solonetzic soils, with the dominant vegetation being Blue grama (*Bouteloua gracilis*) and Needle and Thread (*Stipa comata*) grasses (Adams *et al.* 2005). Approximately 7% of the area of Alberta is covered by the dry mixed-grass prairie natural subregion, of which 43% remains uncultivated (Adams *et al.* 2005).

Water and soil nutrients produce the greatest constraints on primary production in the dry-mixed grass prairie (Willms and Jefferson, 1993); with precipitation from April through July, being highly correlated with forage production (Smoliak, 1986). Since precipitation is highly variable, the timing of stress induced by xeric conditions relative to phenological stage is extremely important for seedling establishment (Willms and Jefferson, 1993). Climate change is expected to increase the amount and duration of growing season drought, as well as alter the frequency and intensity of growing season precipitation (Groisman *et al.*, 1999; Fay *et al.*, 2003, Christensen *et al.* 2007). Knapp and Smith (2001) demonstrated that prairie ecosystems have high production potential and substantial variability and are likely to be one of the most responsive biomes to future climate change.

Human interest in these areas is usually focused on yearly productivity (Bernhardt-Romermann *et al.*, 2011) or biomass yields for economic and ecological monitoring purposes. The greatest land use in the dry mixed-grass prairie is ranching, as much of it is too dry to accommodate crop production without irrigation. Consequently, the economy in these regions is dominated by livestock ranching and supporting businesses. An ongoing interest in prairie regions is prairie yield assessment for the agricultural insurance industry, which is limited by the inability to easily produce a measurable yield; unlike intensive agriculture, a harvested crop yield is not the end product (Rowley *et al.*, 2007). Ecologically, prairie vegetation provides the ability to minimize soil erosion and resist landscape degradation, allows groundwater recharge, sequesters large amounts of carbon dioxide, and supports plant and animal diversity (Hunt *et al.*, 2003; Svejcar *et al.*, 2008). Due to the potential for carbon sequestration with proper management and the increasingly important issue of anthropogenically induced climate change, there is also an emerging possibility of targeted carbon markets and economic incentives for proper land stewardship in these areas (Schuman *et al.*, 2002; Haugen-Kozyra, 2004). These issues drive the desire for increasingly accurate methods of monitoring rangeland response to interannual variations in precipitation and for evaluating prairie biomass yield, especially given the current climate variability and predictions for future climate change (Christensen *et al.*, 2007).

Accurate monitoring methods are essential for proper management of the mixed prairie. Traditionally range management has been accomplished through the subjective evaluation and monitoring of large areas by skilled professionals relying on accumulated judgement and experience (Booth and Tueller, 2003). This methodology has limitations for widespread application. Estimations of prairie productivity have often been conducted through biomass harvests which are expensive and time consuming (Tucker *et al.*, 1975; Tueller, 1989; West and Smith, 1997; Bork *et al.*, 1999; Booth and Tueller, 2003; Pineiro *et al.*, 2006). Furthermore, biomass harvests are destructive sampling methods, so repeated sampling of a single plot is not possible, limiting the temporal practicality of the method. The time consumed by harvesting and the expansive size of these ecosystems further limit the utility of biomass harvests for prairie management (Tucker *et al.*, 1975; Bork *et al.*, 1999; Pineiro *et al.*, 2006). Harvests require measurements be performed in a small number of places during a short time period and extrapolated to useful spatial and temporal scales. This will introduce extrapolation error which could impair successful management.

The requirement for a sampling method that limits the error introduced by inadequate sample size and distribution, as well as personal bias (Booth and Tueller, 2003), has led to the exploration of remote sensing techniques for rangeland monitoring. Spectral reflectance enables synoptic data acquisition with non-destructive sampling and the ability to sample at different spatial and temporal scales (Tueller, 1989). Remote sensing data from multiple satellite platforms have been available since the 1970s (Booth and Tueller, 2003). There are many publicly funded satellites now in orbit, including the NASA Terra and Aqua satellites which carry the MODIS (Moderate Resolution Imaging Spectroradiometer) sensor. These sensors provide 250m spatial resolution from 36 spectral bands, with 1 or 2 day coverage (Reeves *et al*., 2001; Booth and Tueller, 2003). MODIS NDVI products are created from quality controlled surface radiance and reflectance from MODIS bands 1 and 2, which are freely available through websites developed by government agencies in the United States. This wide availability of quality controlled satellite data has led to their widespread use and increased practicality for management and science.

Remote sensing data is also available for purchase from commercial satellite vendors. The Système Pour l'Observation de la Terre (SPOT) 5 satellite produces 10m spatial resolution multispectral imagery (SPOT4 can also produce 10m spatial resolution by co-registering a 10m panchromatic and 20m color image) from four bands, two in the visible wavelengths, one in the near infrared and one in the shortwave infrared (Atrium-geo.com). The increased spatial resolution limits the possible temporal resolution such that SPOT samples a position on the Earth every 26 days, although the sensor can be pointed off nadir at targets not directly below the satellite, increasing the temporal resolution (Booth and Tueller, 2003). Images from commercial systems are often prohibitively expensive for practical application for range management (Booth and Tueller, 2003). Commercial satellites also require tasking requests and data gaps can occur if there is too much cloud cover or otherwise reduced image quality during the tasking period (Kustas *et al.*, 1991). Despite these limitations, private satellites represent alternatives to government-funded programs and are also being explored for rangeland monitoring.

Various applications have been developed for utilizing remote sensing products for rangeland management (Tueller, 1989; Booth and Tueller, 2003; Hunt *et al*., 2003). Many remote sensing methods and technologies have been produced over time, including aerial photography, satellite multispectral scanners, airborne hyperspectral scanners, ground spectrometry, radar, lidar, thermal infrared sensors and video systems have been utilized by rangeland managers (Tueller, 1989; Booth and Tueller, 2003; Hunt *et al*., 2003). Rangeland specific applications of these technologies have been for land use and land cover inventory and change detection, mapping soils, measuring indicators of range health (bare ground for example), analyzing ground cover, tracking individual species (such as noxious weeds), analyzing soil moisture, watershed studies, mapping wildlife habitat, evaluating grazing management and making inferences about vegetation productivity and biomass levels (Tueller, 1989; Booth and Tueller, 2003; Hunt *et al*., 2003).

Remote sensing has also been used to accurately estimate plant biomass or yield (Tucker *et al.*, 1985; Gamon *et al.*, 1995; Bork *et al.*, 1999; Booth and Tueller, 2003; Running *et al.*, 2004) and allows repetitive sampling, i.e. the creation of time series. These methods have the ability to monitor productivity in near real time, relatively inexpensively and with multiple scales of coverage. Many vegetation indices have been created as proxy measures of vegetation biophysical properties, including the simple ratio, green vegetation index, the perpendicular vegetation index, the soil adjusted vegetation index, the enhanced vegetation index and the normalized difference vegetation index (Jackson and Huete, 1991; Ahamed *et al.* 2011). These indices are developed from remotely sensed data, and can be used to diagnose rangeland condition and trend (Huete and Tucker, 1991; Washington-Allen *et al.*, 2006). The most commonly used vegetation index is the Normalized Difference Vegetation Index (NDVI) (Guo *et al.*, 2000; Pineiro *et al.*, 2006). This index utilizes the low reflectance of photosynthetic materials in the red wavelengths and the high reflectance in the near-infrared to produce an estimation of plant biophysical parameters (Rouse et al. 1973; Tucker, 1979). The NDVI has been shown to strongly correlate with green biomass and leaf area index in numerous studies (Tucker *et al.*, 1975; Tucker *et al.*, 1985; Gamon *et al.*, 1995; Bork *et al.*, 1999; Frank and Karn, 2003).

Due to the emerging economic implications for accurate monitoring of prairie ecosystems there is renewed commercial interest in evaluating cost-effective methods of assessing mixed prairie biomass. For example, the Agricultural Financial Services Corporation (AFSC) of Alberta, Canada is currently adopting a satellite remote sensing based insurance program and is interested in increasing the accuracy of yield estimation in an effort to enhance the confidence of ranchers in the program. Consequently the purpose of this study was to evaluate how effectively the NDVI produced from different commonly used satellite sensors can estimate biomass and how they compare to biomass harvests and the NDVI from ground measurement. A common practice in analyzing the utility of remote sensing for rangeland management is to not utilize intensive ground sampling with field spectrometers and rely only on data derived from broad-band satellite sensors (Bork *et al.*, 1999), leaving issues of satellite validation unresolved. Willms and Jefferson (1993) determined that the greatest opportunity for increasing secondary productivity in the dry mixed-grass prairie is a result of increased grazing efficiency, which may be accomplished with the utilization of remote sensing based management of grazing systems.

In this study we utilized data from the SPOT, Terra and Aqua platforms, as well as ground spectrometry to calculate the NDVI and compared them with harvested biomass from two consecutive summers (2009 and 2010). The objectives of the study were to, (1) determine whether the NDVI time-series from satellite systems that are currently heavily utilized for estimating productivity are similar to those from a ground spectrometer and harvested biomass, (2) determine whether variation in productivity as a result of varying weather conditions over two consecutive summers are identifiable, which would be indicative of the utility of remote sensing for monitoring year-to-year weather variability and possibly long-term or climate variability in prairie systems and (3) determine the practical utility of the NDVI for estimating above-ground biomass ("yield") in the dry mixed-grass prairie from remote sensing. Addressing the last objective is an essential foundation for cost-effective satellite-based rangeland insurance or carbon management programs. This study is unique in that it addresses the question of the utility of remote sensing for accurately measuring dry mixed-grass prairie yield with a multi-sensor approach, with the intention of addressing agricultural industry monitoring needs in the most cost-effective manner.

Methods

Study Location & Design - This project combined field biomass harvests, field optical sampling, and satellite remote sensing. Field sites were located in the dry mixed-grass prairie ecoregion, specifically within the Sounding Creek and Pinhorn Grazing Reserves in southern Alberta, Canada (Figure 2-1). The Sounding Creek Grazing Reserve is located near the northern extent of the dry mixed-grass prairie, consequently it is dominated by the *Stipa comata –Bouteloua gracilis* range type (Adams *et al.* 2005). The Pinhorn Grazing Reserve is dominated by *Bouteloua gracilis* with some *Stipa comata* and *Agropyron* species due to slightly increased sand content and soil aridity (Adams *et al.* 2005).

Figure 2-1: Location of Sounding Creek and Pinhorn grazing reserves in Southern Alberta, Canada.

Average annual precipitation and mean April to July temperature in the Albertan dry mixed-grass prairie are around 327mm per year and 12.8°C respectively

(Smoliak, 1986). The field data were collected in the summers of 2009 and 2010 within each of the Grazing Reserves. These data were collected from ten randomly selected sites from each Grazing Reserve and all sites were located within the *Stipa comata –Bouteloua gracilis* range type; with a density of no more than one site per section (one square mile, approximately 260ha). This design created site replicates at the township (36 sections) level, which when combined through data aggregation allowed examination of the data at different spatial scales (refer to Appendix A for more information on spatial scales). The methodology utilized for this projected were adapted from the Agricultural Financial Services Corporations clipping program methodology.

Plot selection and sample design – At each of the ten sampling locations within each Grazing Reserve, three (2009) or four (2010) plots were selected for harvesting, all located within "grassland" vegetation (i.e. sites with shrubs or trees were avoided). Within a location, these plots were in close proximity (several meters) to each other, matching vegetation types and landscape positions. To eliminate possible artifacts due to grazing, sample plots selected for harvesting consisted of a 1-m diameter grazing exclosure, a modified wire mesh tree basket, secured to the ground (Figure 2-2). Each site also had a naturally grazed plot, which consisted of a similarly sized sampling plot without an exclosure located 10m from the others, in a different direction each month (Figure 2-2). A simulated heavy grazing treatment consisted of a caged plot that was repeatedly sampled (once each month) during the growing season (Figure 2-2). In these treatments, the exclosure was removed prior to sampling reflectance and biomass, and replaced following sampling. Preliminary analysis of NDVI and biomass data with a t-test, indicated no significant difference in the NDVI between the naturally grazed and ungrazed plot results, so these data were combined for the purposes of this study (Appendix C). The simulated grazing treatment altered the fundamental relationship between NDVI and green biomass, so these data were excluded from this analysis (Appendix C).

Weather Data – The average daily temperature (°C), average daily precipitation (mm) and the 1961-2008 normal monthly accumulated precipitation (mm) data (the average monthly precipitation based on the period from 1961-2008) for each month were downloaded from the Alberta Agriculture and Rural Development website (http://www.agric.gov.ab.ca/app116/stationview.jsp), utilizing data from the Onefour (approximately 25km East of the Pinhorn grazing reserve) weather station and from the Oyen (approximately 20km East of the Sounding Creek grazing reserve) weather station, which were the closest available locations to each grazing reserve. Monthly accumulated precipitation for both grazing reserves was calculated from the daily precipitation average.

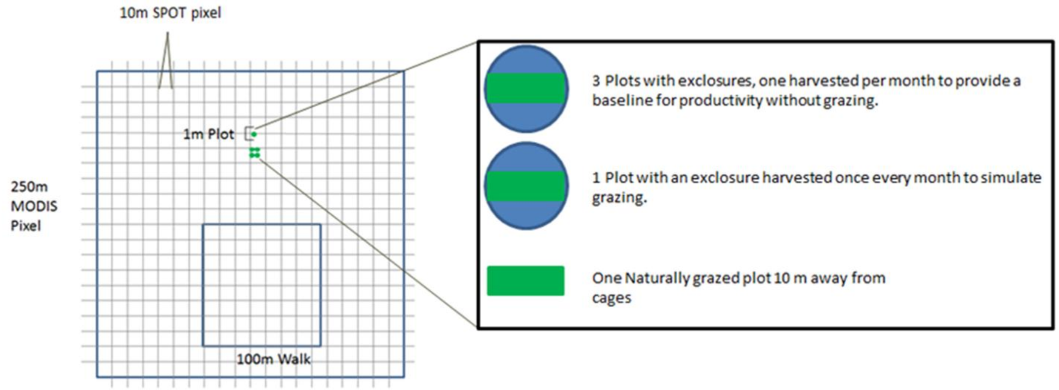

Figure 2-2: Summary of the experimental design and a comparison of the different spatial scales of the measurements conducted at each of the ten sampling location within the Sounding Creek and Pinhorn Grazing Reserves. The green rectangles represent the plot area that was harvested.

Biomass Harvests – Plots were sampled on a monthly basis during the growing season (May, June, July, and August), although the May date was not sampled in 2009. Harvesting included removing the exclosure, setting out the sampling frame, sweeping the loose litter, and clipping and separately bagging the forbs and graminoid components. To mark the material to be harvested, a 1-m x ½-m metal sampling frame, the length of which closely matched the diameter of the exclosure, was placed under the vegetation, with a North to South orientation at each sampling location.

In each harvest, the vegetation within the frame was cut close ($\leq$2 cm) to the ground and the forbs and grass components of the vegetation were bagged separately. All samples were processed in the lab, which included sorting, weighing and oven drying. The different categories of biomass are listed in Table 2-1 and explained below. Each month, at each sampling site within the Sounding Creek and Pinhorn Grazing Reserves, an ungrazed control plot, a simulated grazing treatment plot and a naturally grazed plot were harvested. The collected grass and forb components from each plot were hand sorted, with all of the visibly green material removed from the brown. These materials were then oven dried and weighed (g/m^2) as separate categories (green forbs, dead forbs, green grass & dead grass). The large time commitment required for this methodology necessitated sorting a subsample of the harvested material, calculating the percent (by dry mass) of the subsample that was green and multiplying this representative "green fraction" of the subsample by the dry weight of the total sample to produce an estimated weight of green grass and forbs (Figure 2-3). This green fraction was then used to calculate the green biomass and green standing biomass weights (Figure 2-3). Total biomass was defined as all of the above-ground material (green + dead) harvested at a plot. Standing biomass was defined as the total grasses present, including both green and dead. Green biomass included the green forbs, as well as the green grasses, while the green standing biomass only including the green grasses.

Table 2-1: The vegetation types included in each category of harvested biomass.

	Green Forbs	Dead Forbs	Green Grass	Dead Grass
Total Biomass	YES	YES	YES	YES
Green Biomass	YES	NO	YES	NO
Standing Biomass	NO	NO	YES	YES
Green Standing Biomass	NO	NO	YES	NO

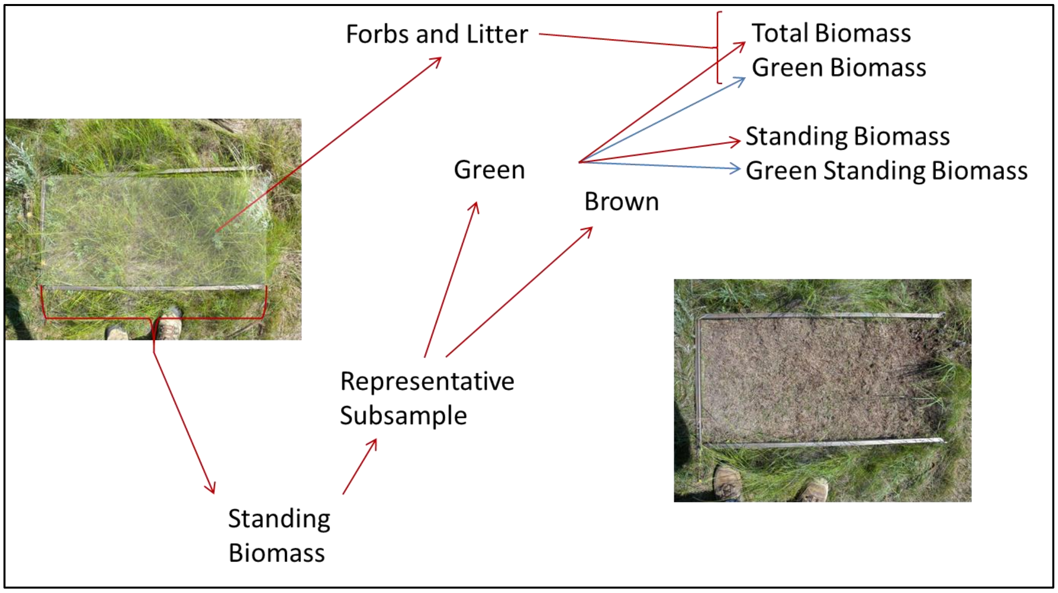

Figure 2-3: Flow chart summarizing the harvest and sorting methodology. The representative subsamples for each plot were hand sorted, separating the visibly green from the brown material. The samples were then dried and weighed (g/m2). The ratio of green to brown was then multiplied by the total biomass to estimate green biomass and the standing biomass to estimate green standing biomass. Red arrows represent harvest results determined from direct measurements. Blue arrows are representative of harvest results that were estimated through the mathematical application of the green: brown ratio.

NDVI measurements – The Normalized Difference Vegetation Index (NDVI), a measure of green vegetation derived from measurements of reflected radiation (Gamon *et al.*, 1995), was calculated several ways. Different methods are indicated by distinct subscripts, as listed in Table 2-2 and explained below. For ground NDVI ($NDVI_G$), measurements of the treatment plots were taken before harvesting using a field spectrometer (Uni-SpecDC, PP Systems, Amesbury, MA, USA) fitted with fiber optics. One fiber (UNI686, PP Systems, Amesbury MA, USA) was attached to an upward-looking cosine-corrected foreoptic (UNI435, PP Systems, Amesbury MA, USA) for downwelling irradiance. The downward-looking fiber (UNI684, PP Systems, Amesbury MA, USA) was fitted with a field-of-view restrictor ("hypotube"- UNI688, PP Systems, Amesbury MA, USA) that limited the field-of-view to approximately 20° (Gamon *et al.*, 2006). From these reflectance measurements, we calculated the NDVI for each plot, using reflectance in the red and near-infrared wavebands as follows:

$$NDVI_G = (R_{NIR} - R_{RED}) / (R_{NIR} + R_{RED})$$

where "R" indicates reflectance and the subscript "NIR" indicates the near-infrared waveband (800 nm in this case) and the subscript "RED" indicates the red waveband (680 nm in this case).

Table 2-2: Description of the versions of the NDVI derived from the different sensors used in this study.

Type	Description
$NDVI_G$	NDVI from ground spectrometry methods.
$NDVI_T$	NDVI rom the MODIS Terra platform.
$NDVI_A$	NDVI from the MODIS Aqua platform.
$NDVI_S$	NDVI calculated from the SPOT system.
ΔNDVI	NDVI calculated from the difference between NDVI calculated from spectrometer measurements from before and after the plots were harvested.

From field observations, we noted that very low-growing green vegetation (e.g. *Artemisia* sp. and *Selaginella* sp., bryophytes, and lichens) was common at many sites. This vegetation could confound our study results because it was too low to be easily harvested or grazed, yet could contribute to the green biomass signal detected by NDVI (Hall-beyer and Gwyn, 1996). To explore the possible artifacts due to low-growing green vegetation, in 2010 we also made a separate set of $NDVI_G$ measurements following each harvest in 2010. After the treatment plots were harvested a second set of spectrometer measurements were taken immediately following the harvest and were used to calculate differential $NDVI_G$ (ΔNDVI) by subtracting the $NDVI_G$ calculated from the post-harvest measurements from the pre-harvest measurements. Our expectation was that this analysis would help us determine the effect of very low green vegetation that was too small to harvest, yet would contribute to the NDVI signal.

NDVI derived from the Moderate Resolution Imaging Spectroradiometer (MODIS) were downloaded as ASCII subsets from the Oak Ridge National Laboratory Distributed Active Archive Center website (Oak Ridge National Laboratory Distributed Active Archive, 2011.) for both the Terra ($NDVI_T$) and Aqua ($NDVI_A$) satellite platforms. The Terra platform crosses the equator in the morning from North to South, while the Aqua platform crosses the equator in the afternoon and in the opposite direction (MODIS Web, n.d.). The data were derived from a single MODIS pixel ($250m^2$) located over the center of the monthly plot sampling locations for each site. These products are 16 day composites created with a combination of bidirectional reflectance distribution function (BRDF) and maximum value composite (MVC) methods, which would select for the least cloud and atmosphere contaminated values, enhancing data accuracy and quality (MODIS Web, n.d.).

NDVI was also calculated from images taken by the Système Pour l'Observation de la Terre (SPOT) satellite network and purchased from, georeferenced, and processed to reflectance by the Alberta Terrestrial Imaging Center ($NDVI_S$).

$$NDVI_S = (\text{Band 3} - \text{Band2}) / (\text{Band 3} + \text{Band 2})$$

The SPOT orbit is polar, circular, sun-synchronous and phased, so that imagery over a particular area of the Earth is produced at the same time each day, at a constant altitude every 26 days (Astrium, 2012). The SPOT imagery used in this study was obtained from the SPOT 4 (summer 2009) and SPOT 5 (summers of 2009 and 2010) platforms and have a 10m spatial resolution.

Results

The summers of 2009 and 2010 provided extreme contrasts in weather conditions, with a significant difference in the amount of accumulated precipitation between the two summers (t-test; $P<0.001$). The months of May and June were very dry in 2009, especially in the Sounding Creek and Pinhorn grazing reserves, with comparatively high early growing season temperatures (Figure 2-4). The 2010 growing season experienced very wet conditions throughout the summer, with much more temperature variability and lower temperatures in the early months (Figure 2-4).

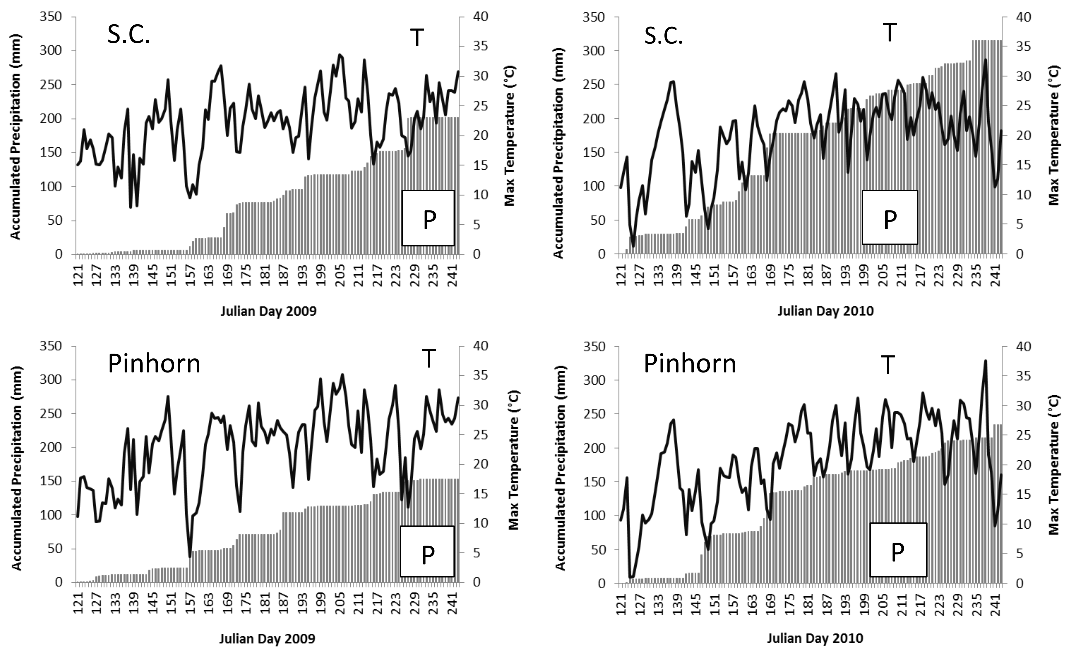

Figure 2-4: Maximum temperature and accumulated precipitation versus Julian day for the months of May, June, July and August in 2009 and 2010 for the Sounding Creek grazing reserve (top frames) and the Pinhorn grazing reserve (Bottom frames). The weather data is courtesy of Alberta Agriculture and Rural Development. T stands for temperature, P stands for precipitation.

The differences between the two growing seasons were more extreme in the Sounding Creek grazing reserve than in the Pinhorn. In 2009, the accumulated precipitation was lower than the normal for both grazing reserves, with August in

Sounding Creek being the only exception (Figure 2-5). In this year, early growing season accumulated precipitation was higher in the Pinhorn than in the Sounding Creek grazing reserve. In 2010 the accumulated precipitation was higher than normal for all months in both grazing reserves, although these differences were greater in Sounding Creek than in Pinhorn. These conditions produced a natural experiment characterized by arid conditions in 2009 and above-normal rainfall in 2010 (relative to the 1961-2008 normal).

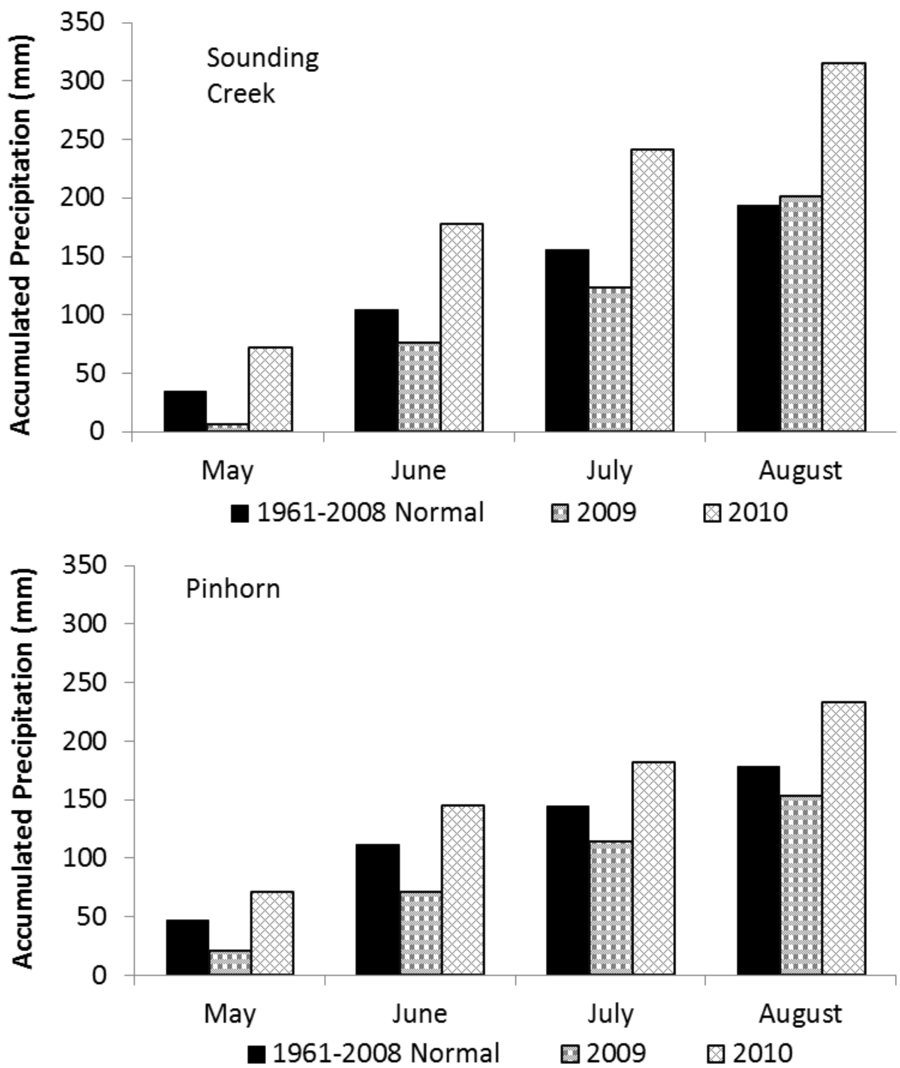

Figure 2-5: Comparison of the normal accumulated precipitation (1961 to 2008) to the accumulated precipitation measured at the Sounding Creek grazing reserve (top frame) and the Pinhorn grazing reserve (bottom frame) from the 2009 and 2010 growing seasons. The weather data is courtesy of Alberta Agriculture and Rural Development.

In both grazing reserves, there was high year-to-year variation in NDVI (Figure 2-6). In 2009 and 2010 peak $NDVI_G$ occurred in July for both locations (Figure 2-6A). Measurements of green standing biomass (largely graminoids) showed little seasonality in 2009 and greatly increased seasonality in 2010 (Figure 2-6B).

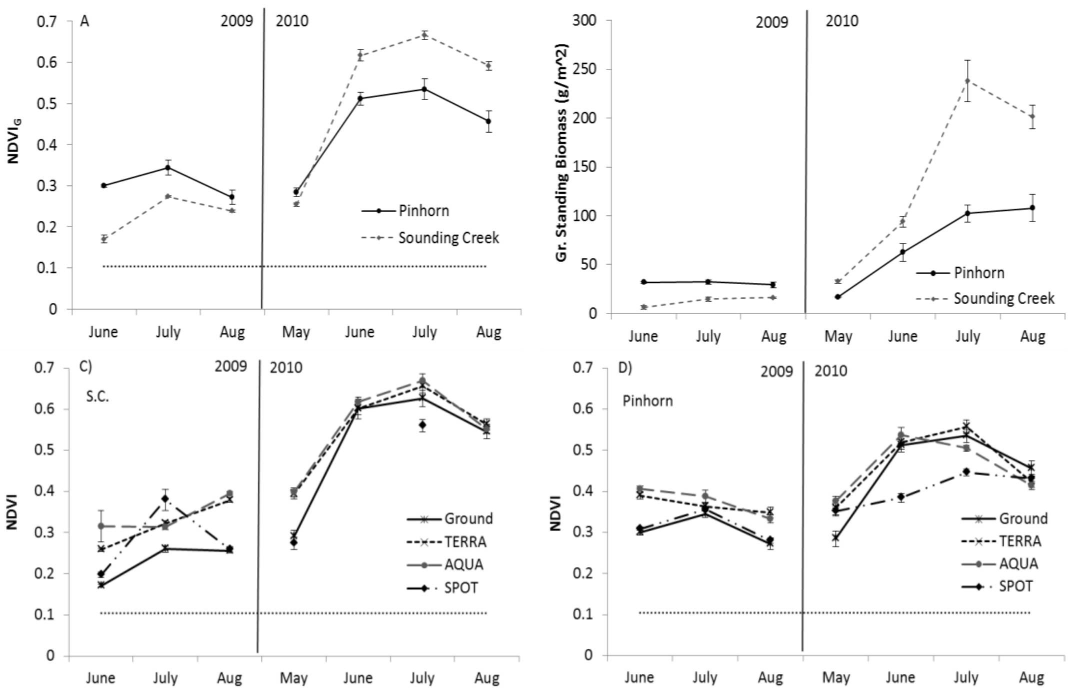

Figure 2-6: Time series of NDVI derived from ground spectrometry ($NDVI_G$) (A) and harvested green fraction of the standing biomass (B) from both grazing reserves as well as the time series of NDVI from ground spectrometer data, MODIS data from the Terra and Aqua platforms and SPOT data from the Sounding Creek grazing reserve (C) and Pinhorn grazing reserve (D) during the summers of 2009 and 2010. The dotted baselines illustrate the mean NDVI for bare soil. Error bars denote standard error of the mean.

The high peak in Sounding Creek in 2010 reflected higher production and greater standing biomass. In the Pinhorn, peak green biomass occurred in July in 2009, while in 2010 there was little difference in biomass between July and August (Figure 2-6B). The year-to-year trends in $NDVI_G$ and green standing biomass both demonstrate greater productivity in 2010 relative to 2009 (Figure 2-6). This pattern is also apparent from the satellite sampling methods (Figure 2-6). The

MODIS instruments produce NDVI values that are generally higher than the NDVI from the ground spectrometer, particularly for low NDVI values early in the season. SPOT offered the least coverage and its NDVI values deviated the most from the other satellites.

Comparison of NDVI calculated from ground measurements ($NDVI_G$) and the different metrics of biomass yielded exponential relationships (Figure 2-7). The correlations between $NDVI_G$ and the green biomass (green + dead grass) and the green standing biomass (green grass) were much stronger than the total biomass and total standing biomass. Expression of the biomass values on a logarithmic scale linearized the plots between NDVI and all biomass measurements.

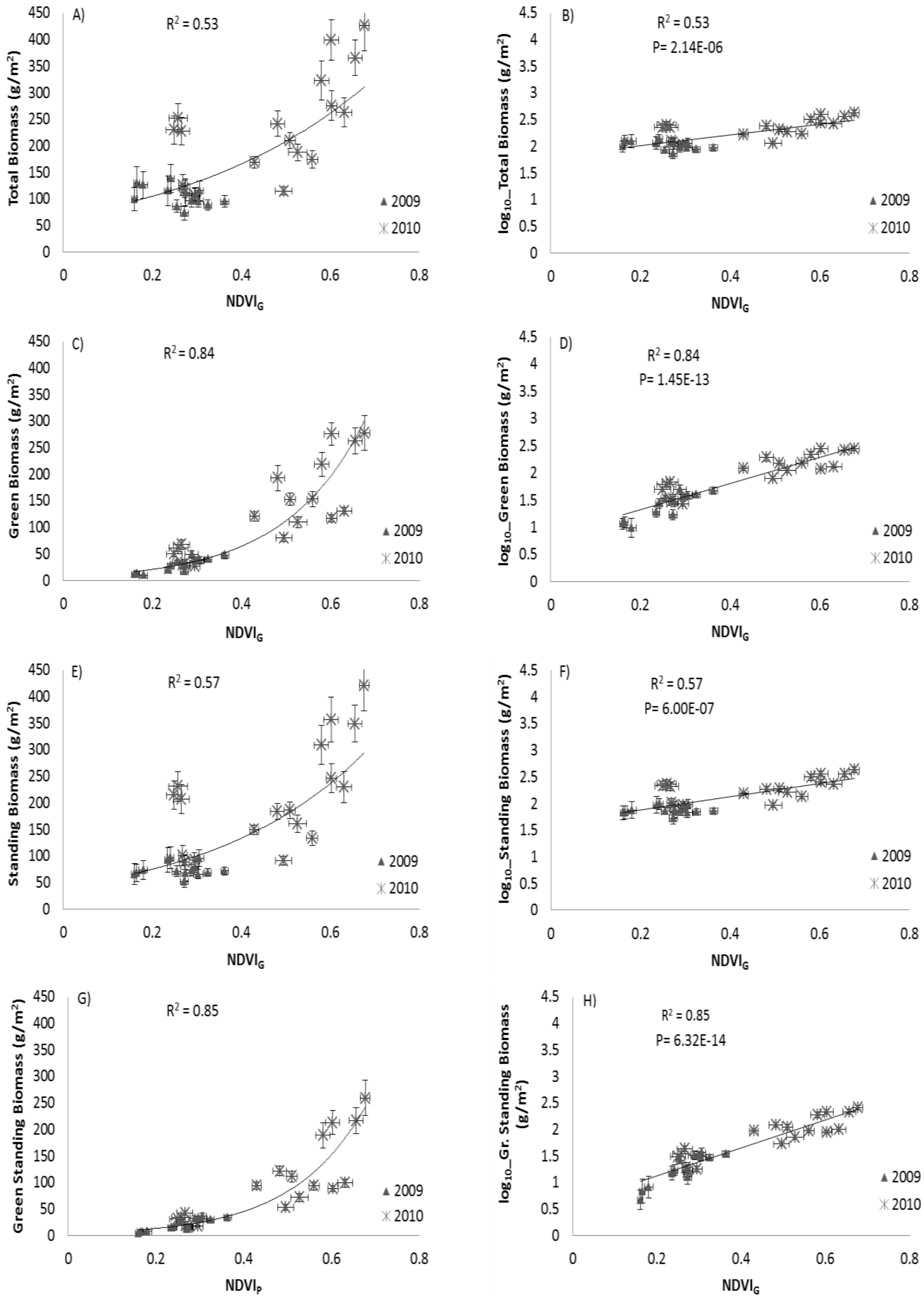

Figure 2-7: Relationship between NDVI and biomass for the Sounding Creek and Pinhorn grazing reserves in the 2009 and 2010 growing seasons. The panels on the left ground spectrometer NDVI vs. total biomass (A), the green biomass (C), the standing biomass (E), and the green standing biomass (G). The panels on the right are the relationships of NDVI vs. the log of total biomass (B), the log of green biomass (D), the log of standing biomass (F), and the log of green standing biomass (H). The solid lines represent the regressions (exponential for the left panels and linear for the right panels) for both growing seasons together. Error bars denote standard error of the mean and the number of samples comprising each point are N=56 for the 2009 data and N=40 for the 2010 data.

To evaluate the potentially confounding effects of varying canopy layers on the NDVI signal, we compared the NDVI-green biomass relationship in 2010 to that obtained by taking the difference in NDVI before and after biomass harvest. The use of the difference in NDVI (ΔNDVI) improved the correlation with green biomass slightly (Figure 2-8).

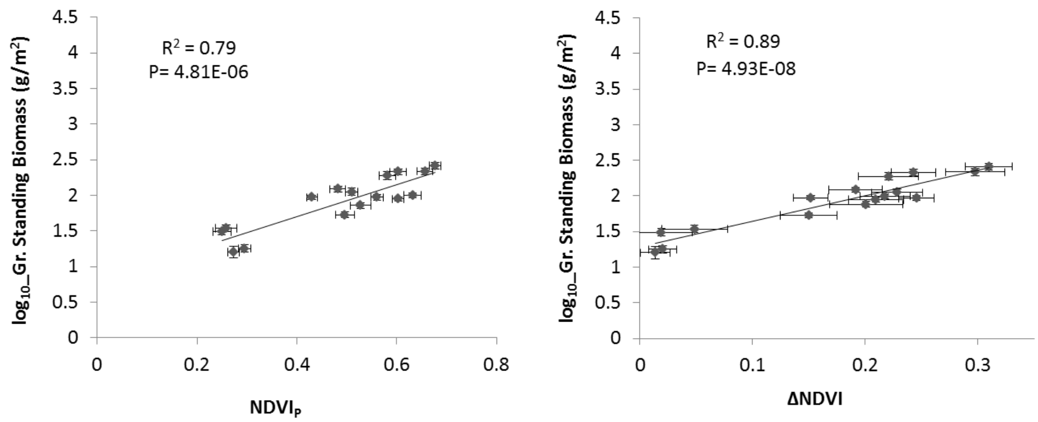

Figure 2-8: Relationships between the green standing biomass on a logarithmic scale and the ground NDVI. The left panel shows green standing biomass vs. ground NDVI ($NDVI_G$), the right panel shows green standing biomass vs. the difference between ground spectrometer measurements before and after the harvests (ΔNDVI) for the Sounding Creek and Pinhorn grazing reserves in the 2010 growing season. The solid line represents the linear regression, error bars denote standard error of the mean and the number of samples comprising each point are N=40.

To highlight year-to-year differences in productivity, we summarized seasonal peak biomass and NDVI values by showing only the July values (Figure 2-9). Slight differences were observed for NDVI values from different satellite platforms. Analysis of the seasonal trends indicates that the MODIS instruments (Aqua and Terra) produce similar interannual differences. SPOT exhibited the greatest differences in NDVI in comparison to the other platforms and sampling methods. In both growing seasons the SPOT data suggests that Sounding Creek produced more new biomass than the Pinhorn, which deviates from the observations from the MODIS and ground sensors.

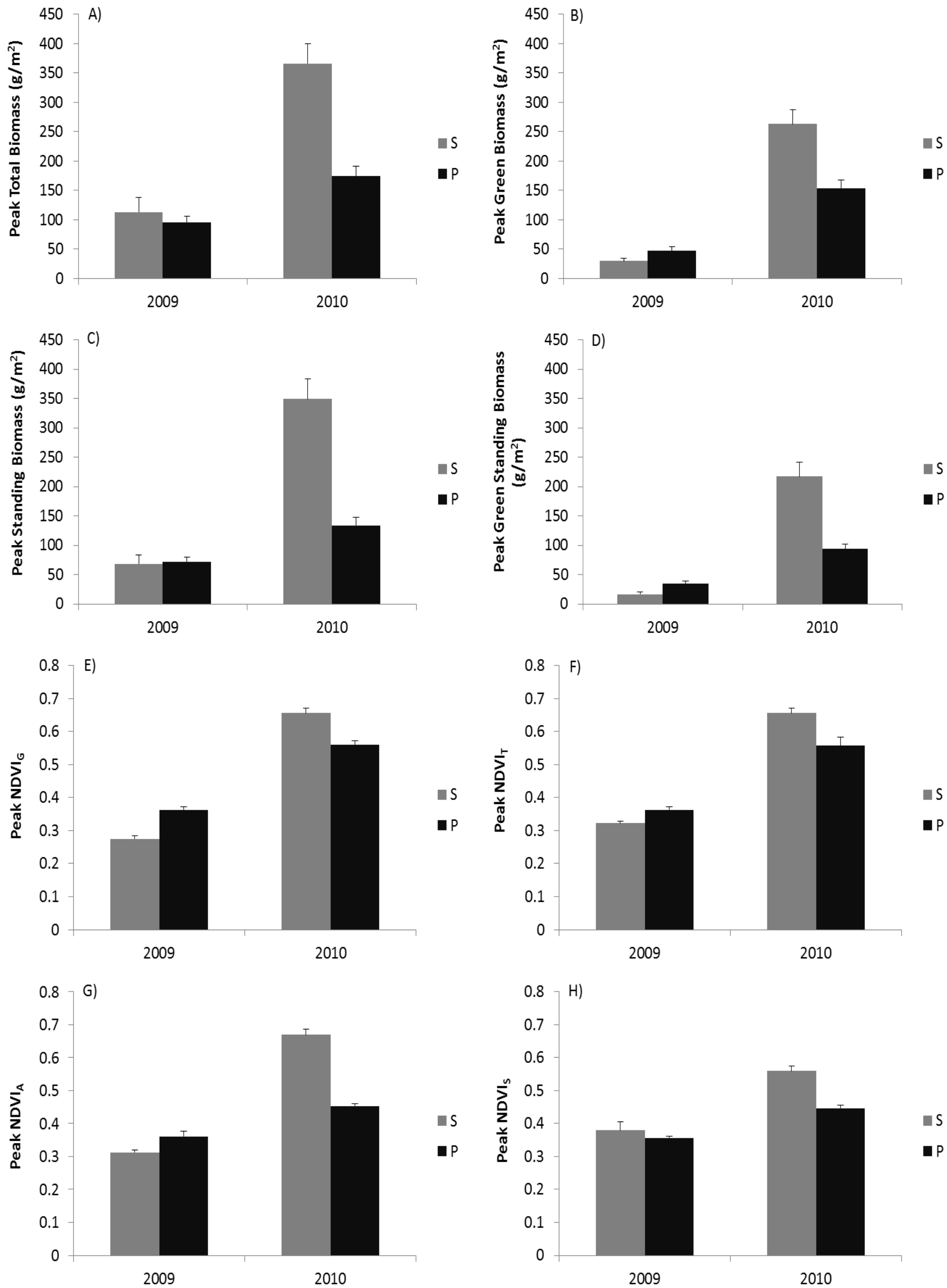

Figure 2-9: Peak values for total biomass (A), green biomass (B), standing biomass (C), green standing biomass (D), NDVI from ground spectrometry (E) and NDVI derived from the Terra (F), Aqua (G) and SPOT (H) satellites from the Sounding Creek and Pinhorn grazing reserves in the 2009 and 2010 growing seasons. Error bars denote standard error of the mean and the number of samples comprising each point are N=28 for the 2009 data and N=20 for the 2010 data.

In an attempt to mitigate the effects of a seasonally evolving NDVI-biomass relationship (Appendix B), we also examined the NDVI-biomass relationship for peak-season (July) only (Figure 2-10). These peak-season results yielded a stronger correlation (R^2=0.97, Figure 2-10) than the comparable results using data from the full growing season (R^2=0.85, Figure 2-7, panel H).

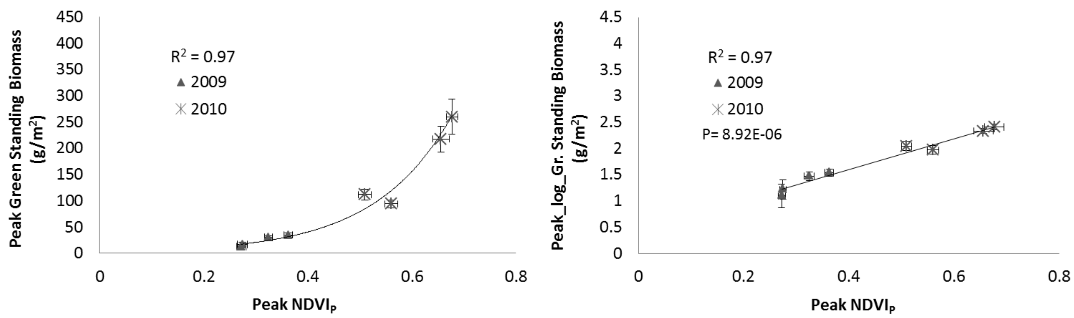

Figure 2-10: Relationships between peak NDVI and peak green standing biomass for the combined Sounding Creek and Pinhorn grazing reserves in the 2009 and 2010 growing seasons. The panel on the left shows the peak ground spectrometer NDVI vs. the peak green standing biomass. The panel on the right is the relationship between the peak NDVI and the log transformed peak green standing biomass. The solid lines represent the regressions (exponential for the left panel and linear for the right panel) for both growing seasons together. Error bars denote standard error of the mean and the number of samples comprising each point are N=28 for the 2009 data and N=20 for the 2010 data.

To examine the practical use of the different satellite platforms for monitoring rangeland yield, the NDVI from the different platforms were compared to the NDVI produced from ground spectrometry ($NDVI_G$) (Figure 2-11). For both MODIS platforms there were similar offsets from the 1:1 line, in comparison to $NDVI_G$. In comparison to the MODIS platforms the offset between the SPOT data and the ground NDVI was more variable (Figure 2-11). The difference between NDVI from the Terra and Aqua platforms was greatest at the lower values (see also Figure 2-6). The slope of the regression between $NDVI_G$ and NDVI from the SPOT ($NDVI_S$) satellites is significantly different than from the MODIS platforms, indicating clear differences between sensors (Terra vs. Aqua P=0.645, Terra vs. SPOT P=0.0004, Aqua vs. SPOT P=0.0002). The strongest correlation between $NDVI_G$ and satellite derived NDVI was from the Terra platform (R^2=0.94, Figure 2-11). The SPOT satellite provided the least coverage and the worst correlation with the ground sensor (lowest correlation coefficient, R^2=0.81, Figure 2-11).

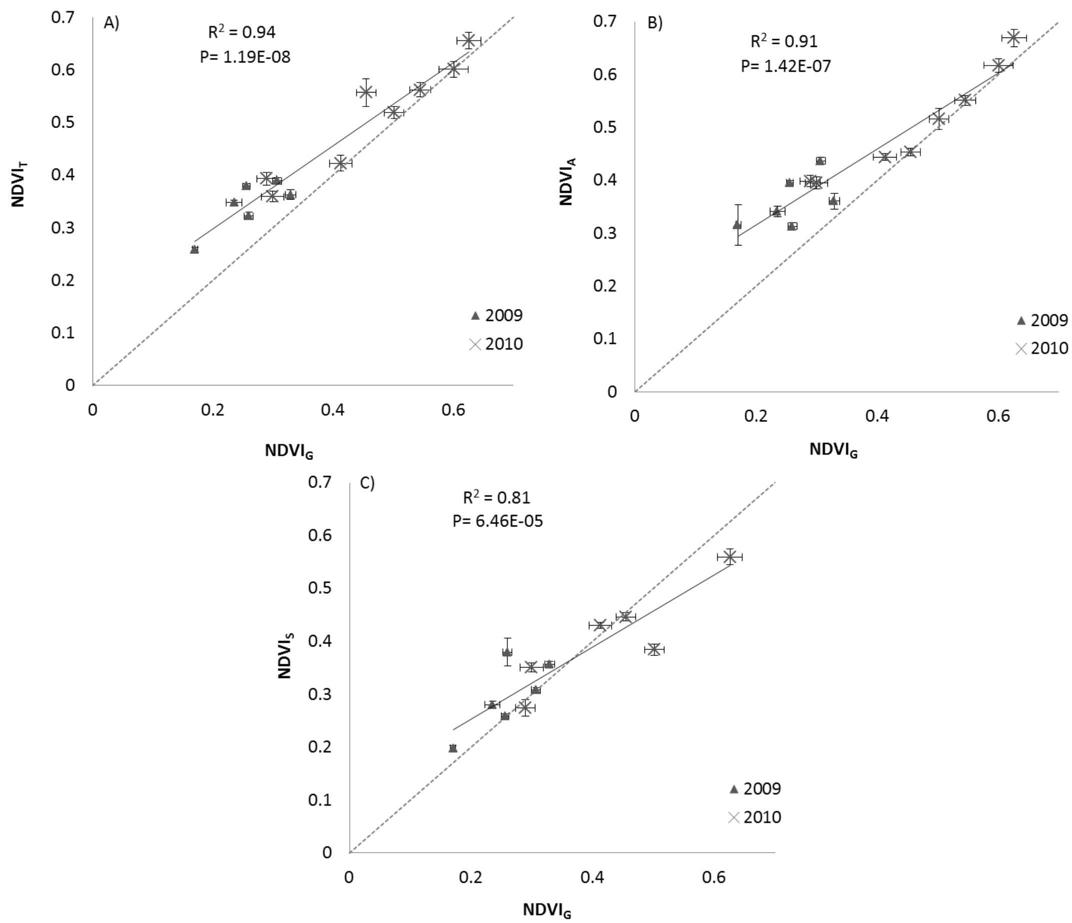

Figure 2-11: Relationships between ground NDVI and satellite derived NDVI for the combined Sounding Creek and Pinhorn grazing reserves in the 2009 and 2010 growing seasons. The $NDVI_G$ vs. the Terra MODIS platform (A), the Aqua MODIS platform (B) and the SPOT system (C). The solid lines show linear regressions and the dotted lines are the 1:1 lines. Error bars denote standard error of the mean and the number of samples comprising each point are N=94 for the 2009 data and N=80 for the 2010 data.

Discussion

Our findings of a large rainfall effect are consistent with the reports of Knapp and Smith (2001) and Camberlin *et al.* (2007) who determined that grasslands, such as the dry mixed-grass prairie, have the capacity for large production response to uncommonly high precipitation. Smoliak (1986) reported that the April to June precipitation could be reliably used to predict forage production in the dry mixed-grass prairie of Southern Alberta. The weather conditions encountered during this project produced a natural experiment which demonstrated this phenomenon and provided a good test of the utility of remote sensing for monitoring interannual variation in yield. The precipitation differences in the two summers resulted in a large amount of variability in NDVI/biomass measurements. This variability allowed a more accurate understanding of the full growth response of vegetation to varying moisture conditions and subsequently the ability of remote sensing to function across such a wide range of growth responses and detect differences in interannual productivity. Remote sensing methods provide an effective means for tracking year-to-year variation in above-ground green biomass as a result of different weather conditions in this prairie biome.

The time series of the NDVI calculated from the ground spectrometer, SPOT and the MODIS platforms all show trends that are similar to the standing biomass, indicating that there is a clear effect of seasonality and weather on NDVI and biomass, which can be monitored with different remote sensing methods. While the general NDVI trends were similar for the different sampling methods, the exact shapes were not the same. Interannual changes in NDVI and standing green biomass (yield) were similar (Figure 2-9), which indicates that NDVI can be used as a proxy measure for the standing green biomass in the dry mixed-grass prairie. The different shapes of these seasonal trends for NDVI and standing green biomass can be largely attributable to the non-linear relationship between NDVI and biomass (Figure 2-7), which has been reported before (e.g., Gamon *et al.*, 1995). The exponential relationship between green biomass and the NDVI creates a “saturation problem”, where over a certain value the NDVI becomes almost invariant to changes in vegetation amount and/or condition (Walthall and Middleton, 1992; Gamon *et al.*, 1995; Frank and Karn, 2003). This saturation is a natural result of the shape of the NDVI-biomass relationship (Gamon *et al.*, 1995) and can be readily corrected (linearized) by taking the log of biomass (Figures 2-5 and 2-8). Linearizing this relationship removes the saturation effect making the data easier to work with; furthermore, this transformation allows the statistical assumption of normality to be achieved.

Additional factors can confound these seasonal patterns and introduce errors in the NDVI-biomass relationships. Scatter in the NDVI-green biomass relationship can be a result of different canopy structure, which has an effect on NDVI (Sellers, 1985). In May the variation between NDVI and biomass is partly due to vegetation carryover from the previous year masking new growth. At the beginning of the growing season there has been little or no new green growth, with the initial growth likely to be hidden by last season’s biomass (the carryover error). The effects of dead biomass on reducing the NDVI correlations with biomass are likely to be strongest in the beginning of the season (due to “carryover" of dead standing biomass from the previous year) and towards the end of the season, when vegetation senescence has begun (Cyr *et al.*, 1995; Butterfield and Malmstrom, 2009). The shift in the NDVI-biomass relationship over the three summer months is likely due to senescence which causes a decline in chlorophyll content (which would affect NDVI); this gradually changing greenness was not fully considered by our harvesting method, that distinguished between green and brown vegetation but did not consider varying fractions of green associated with different growth stages. Also, our seasonal results could have been influenced by the different species composition in the two townships (Davison and Csillag, 2003), since the Pinhorn has greater amounts of drought resistant C_4 graminoids than the C_3 species dominant in Sounding Creek. Together, these effects led to scatter in the NDVI-green biomass relationship when all seasons are combined (Figure 2-7). Focusing on midsummer peak values (Figure 2-10), as suggested by Butterfield and Malmstrom (2009), effectively removes early-season carryover error and the late-season senescence phase, and results in accurate biomass estimation.

Another source of error in NDVI measurements is background contamination from soil, litter, snow or surface wetness (Huete and Tucker, 1991). For instance, Hall-beyer and Gwyn (1996) determined that the presence of *Selaginella densa*, a mat-forming member of the fern phylum which is present in the dry mixed-grass prairie, can also lead to error in biomass estimates from optical remote sensing. *Selaginella densa* mimics sparse grasses in NDVI measurements, yet it does not grow tall enough to be harvested with the methodology used here, so it was not included in the biomass data. This effect explains the results in Figure 2-8, where scatter in the NDVI-green biomass relationship (a result of the harvest sampling method not accounting for very low-lying green vegetation) was reduced when this “background” green vegetation was explicitly included in the analysis. Error resulting from this phenomenon would vary with rainfall and productivity. For example, drought could decrease the standing component of the vegetation and could allow more reflectance from lower canopy layers. Alternatively, early in the growing season during a drought year there can be more masking of the slowly emerging green biomass by the litter that is present from previous growing seasons (carryover effect). This would decrease the amount of green vegetation visible to the spectrometer. These results indicate that careful consideration of the seasonal factors (the method of temporal sampling and data aggregation) is warranted when developing a biomass monitoring program from satellite data. Selection of peak-season data largely removes these complications, facilitating a clear comparison of year-to-year productivity differences (Figure 2-10). In an Italian Alps grassland Vescovo and Gianelle (2006) utilized reflectance in the green wavelengths to calculate a Green-NDVI, with which they found a strong correlation with the green herbage ratio (biomass/biomass + necromass). The green herbage ratio is essentially a measure of the fraction of green herbage that is turning into brown herbage. This index could be an alternative to NDVI, as it could provide a more accurate measurement of vegetation maturity, senescence, response to drought, or phonological stages where NDVI measurements are less robust, which could aid in range management in the dry mixed-grass prairie (Vescovo and Gianelle, 2006).

The two MODIS platforms were similar, yet the data from Aqua demonstrate depressed NDVI values in July 2009 and 2010, in comparison to the Terra data. This is more clearly demonstrated by the correlations with the ground NDVI, where the offsets for the two platforms were very similar, yet the correlation was slightly stronger for Terra than Aqua. This is likely due to a variety of reasons, including specific calibration and instrument characteristics for each platform. Deering *et al.*, (1992) found that at the FIFE prairie site sensor viewing angle and solar zenith angle had a large effect on vegetation indices. Different viewing and solar zenith angles, in this case would result from directly comparing data captured at different times of day, such that shadows and effects of surface anisotropy would affect the angular dependent signal due to the geometric configuration of the sun, sensor and target (Huete *et al.*, 1994). The exact cause of the differences between these two MODIS sensors is currently unknown. The tendency of MODIS to produce values that are higher than the corresponding NDVI values calculated from ground spectrometers, has been previously reported by Cheng *et al.* (2006). These authors speculated that this could be an effect of the data processing such as the atmospheric correction, which is applied to all MODIS data, or could be a specific characteristic of the sensor itself (Cheng *et al.*, 2006); however, further studies need to be conducted to definitively explain this difference.

Based on our results, the utility of the SPOT platform for monitoring year-to-year variability is limited by inadequate temporal coverage and periodic cloud contamination. The Alberta Terrestrial Imaging Center will not sell SPOT images if there is greater than 10 per cent cloud cover within the image, so imagery was unavailable for both June and August, making direct comparisons with other methods difficult. In comparison to the MODIS time series, the SPOT time series had a less consistent offset in comparison to $NDVI_{G.}$ In July it overestimated in 2009 and underestimated in 2010, which is made clearer by comparing the regression with the 1:1 line. This greater scatter would make correcting for the offset much more difficult and reduces the reliability of SPOT for monitoring variations in rangeland yield. The SPOT satellite imagery has a spatial resolution of 10m; this greater detail on the ground results in decreased temporal resolution, as the smaller field of view requires more orbits of the Earth to cover the same position (Tueller, 1989). In comparison to the daily coverage by the MODIS platforms, the 26 day temporal resolution of SPOT is inadequate to ensure repeat coverage of an area with adequate data quality. While MODIS sensors have lower spatial resolution, the daily coverage allows creation of 8 day composites (by combining imagery from Aqua and Terra), so poor quality data and clouds are removed from the data with maximum value compositing and bidirectional reflectance distribution function correction (MODIS Web). The SPOT sensor can be directed off-nadir to increase the temporal coverage; however, this introduces error due to altered sensor angle (Tueller, 1989). From these observations, we conclude that the SPOT sensor is less useful than MODIS for dry mixed-grass prairie yield monitoring and management.

The emerging economic and ecological importance of the dry mixed-grass prairie creates a need for accurate and cost effective biomass monitoring. This study has demonstrated that remote sensing can accurately estimate biomass in these areas and that altered productivity due to interannual weather variability can be detected. These results are important for increasing the confidence of data users in the context of economic applications such as insurance payment programs and carbon markets. Rancher's perception of the accuracy of sampling methods is important for adoption and maintenance of remote sensing programs. Carbon sequestration also requires accurate monitoring in the mixed prairie, as varying climate and management regimes can undoubtedly influence sequestration. Climate change is likely to result in altered precipitation in the areas being studied (Groisman *et al.*, 1999). The ability of our methodology to differentiate between the weather differences during the two years of this study suggest that satellite methods should be able to monitor biomass changes that may occur as a result of a changing climate, if changing precipitation is involved.

Conclusions

Clearly, inter-annual vegetation and NDVI patterns were strongly affected by the moisture regime available for plant growth during the two growing seasons studied. The NDVI can be utilized as a proxy measure for green standing biomass, as the interannual trends were similar for all NDVI products, and the changes in biomass due to variable precipitation between the two years was clearly identifiable. The NDVI illustrated that the 2010 growing season had much greater biomass than was present in 2009. The NDVI trends also clearly detected the initial increase at the beginning of each growing season and the subsequent decrease in green biomass at the end of each growing season due to senescence. Our results indicate that NDVI-based estimates of biomass production are feasible with these methods and that the Terra platform provided the best satellite estimate of the NDVI of the three platforms studied. Midsummer peak values avoid the early-season carryover error and the late-season senescence phase providing accurate biomass estimation. These results indicate that careful consideration of the seasonal factors (how data are aggregated temporally) is warranted when developing a biomass monitoring program from satellite data. Alternatively, these temporal effects including seasonal and yearly variability may have to be considered in more detail.

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CHAPTER 3 – GENERAL DISCUSSION AND CONCLUSIONS

Project Conclusions

To evaluate the relationship with yield, seasonal trends during the 2009 and 2010 growing seasons were investigated from harvested biomass and NDVI from ground spectrometry and three satellite platforms: the Aqua and Terra Moderate Resolution Imaging Spectroradiometer (MODIS) platforms and the Système Pour l'Observation de la Terre (SPOT). Correlations between ground spectrometry and harvested biomass were also examined for each growing season. The field sites experienced a drought in 2009 and abnormally high precipitation in 2010, and these contrasting “treatments” were easily captured with satellite and field NDVI values and with green biomass measurements. NDVI provided a proxy measure for green plant biomass, which was exponentially related to NDVI. NDVI trends detected the initial increase at the beginning of each growing season and the subsequent decrease in green biomass at the end of each growing season due to senescence. Utilizing a regression equation from a single dry year did not provide enough variability in growth to accurately model the NDVI-biomass relationship for the area under study, but combining data over both wet and dry years provided improved regressions. NDVI-biomass regressions evolved over time due to seasonal senescence and carryover of dead biomass to the following year. Additionally, interpretation of NDVI can be confounded by low-growing green vegetation, particularly in a dry year, which leads to error in the NDVI-green biomass relationship using conventional harvest methods. Seasonal changes in the greenness of standing green biomass can also confound the NDVI-green biomass relationship. Consequently, mid-summer measurements yielded the strongest correlation (R^2=0.97) between NDVI and green biomass. These results demonstrate that, used properly, NDVI from satellite remote sensing can accurately estimate interannual variation in standing green biomass and field spectrometry can provide useful validation for satellite data in a biomass monitoring program. Together, these methods can be used to identify the effects of year-to-year precipitation variability on above-ground biomass in the dry mixed-grass prairie.

Suggestions for Future Research

There are additional factors requiring more study, which could further refine biomass monitoring in the dry mixed-grass prairie (as well as other rangelands), that were beyond the scope of this project. Our methods focused on the NDVI, but future studies might consider other vegetation indices as well. Vescovo and Gianelle (2008) demonstrated that disturbance can affect the correlation between vegetation indices and biomass in rangelands. There are indices such as the enhanced vegetation index, soil adjusted vegetation index, and the scaled difference vegetation index (Huete and Tucker, 1991), which are designed to remove the effects of soil or atmosphere on green biomass estimation. Gianelle and Vescovo (2007) produced the Green-NDVI, which was designed to estimate the green herbage ratio (the percentage of the total phytomass that is green); this index could be utilized in conjunction with NDVI to allow accurate measurement throughout the full course of the phonological cycle. These indices utilize different portions of the visible and near to mid-infrared spectrum and in the future, comparisons could be performed to see which vegetation indices (including the NDVI) provide the best estimates of above-ground biomass in the areas studied.

Future studies might consider the use of remote sensing products as input parameters in productivity models, including the light-use efficiency model (Monteith, 1972 and1977). The light-use efficiency model is widely utilized to estimate net primary productivity with remote sensing (Running *et al.,* 2004). Combining estimates of absorbed radiation and efficiency in a light-use efficiency model can provide an approximation of ecosystem carbon exchange, a key indicator of ecosystem health and carbon sequestration. For a more complete accounting of ecosystem carbon fluxes and stocks, below-ground carbon and cattle grazing should also be considered. Future research could utilize the methods outlined in this study, to produce remote sensing metrics of ecosystem productivity to determine appropriate stocking rates to enhance carbon sequestration, or to assist in monitoring rangeland health, which could shift in a period of changing climate. Finally, future research using the methodology from this study should be performed in other range types, different soil types and vegetation over a large geographic range, which could improve confidence in this approach to biomass monitoring for rangeland management.

As part of a more complete system of carbon monitoring, these methods could be used to provide accurate estimates of biomass yield and carbon dynamics in Alberta’s dry mixed-grass prairie. They could also help increase the scope and reduce the cost of conventional field monitoring programs. A program based on these results could be instituted in which rangelands are stratified by range type, such as the classification suggested by Coupland (1961), where rangelands are separated into distinct associations based on the dominant vegetation and soil type. Intensive field surveying could then be performed for each category. These surveys could include a combination of above- and below-ground monitoring and phenology which could be derived from field sensors. Remote sensing could be used to extrapolate these more local ground surveys for the whole province and models could be utilized to analyze these data to recreate the spatial and temporal patterns of carbon dynamics. Provided adequate political and/or industrial interest leading to the necessary funding, carbon measured in this manner could be used to estimate carbon sequestration and to eventually determine a baseline for evaluating future changes in carbon to determine net gain or loss over time. The improved yield estimates could be linked to payment functions to improve the efficacy of rangeland insurance programs.

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APPENDIX A – SCALE OF AGGREGATION

The importance of spatial scale becomes apparent when the relationship between green standing biomass and the Normalized Difference Vegetation Index (NDVI) is examined at the plot level (Figure A-1A) and contrasted with the relationship from the data aggregated to the township level (Figure A-1C). Combining the data from the 2009 and 2010 growing seasons for both grazing reserves produces a significant but fairly weak relationship (R^2= 0.56) between NDVI and green standing biomass (green graminoids) at the scale of individual plot treatments (Figure A-1A). Aggregating the data by averaging the natural and ungrazed treatments increases the strength of this relationship slightly (R^2=0.61, Figure A-1B). These relatively weak relationships are likely due to a variety of things, including the large heterogeneity within the landscape (fine-scale variation in vegetation cover), the effect of green vegetation being masked by the standing litter and the effect of a "green soil" or very low-lying green vegetation. Aggregating the data from the scattered sites up to the township scale removed a lot of the scatter and greatly increased the strength of the relationship (R^2= 0.85, Figure A-1C). This indicates that fine-scale heterogeneity was a large source of error at the scale of individual plots, and this error averaged out at larger spatial scales. Rangeland monitoring programs are generally interested in paddocks or full pastures; therefore, matching the scale of field validation sites to the scale of satellite measurement can minimize the heterogeneity error and ensure that the true relationship between the NDVI and biomass emerges. The remaining error may be due, in part, to the seasonally changing greenness associated with different vegetation growth stages (Appendix B). For example, plant senescence causes a decline in chlorophyll content (which would affect the NDVI), and this gradually changing greenness was not fully considered by our harvesting method, which distinguished green and brown vegetation, but not varying degrees of green associated with different growth stages. Analysis of the peak season data for the NDVI and standing green biomass, at the grazing reserve scale accounts for this error and produces a very strong relationship (R^2=0.97, Figure A-1D).

Temporal and spatial scale issues affected the results presented here, and both should be carefully considered in designing an effective satellite monitoring program for rangelands. Aggregation of fine-scale field values over a large region can reveal the true nature of the NDVI-biomass relationship. These relationships evolve over time (Appendix B), and are particularly affected by early-season carryover (which can vary from year to year). It is possible that coupling a dynamic modeling approach, utilizing a Light Use Efficiency model (Monteith, 1977; Hall *et al.* 2011), with the static harvest-based methods used here could enable a better understanding of how to accommodate the temporal sampling challenge in a satellite monitoring program. Alternatively, a sampling method based on the period of peak mid-summer growth may avoid much of this within-season complexity and still yield an effective monitoring program for capturing year-to-year variability.

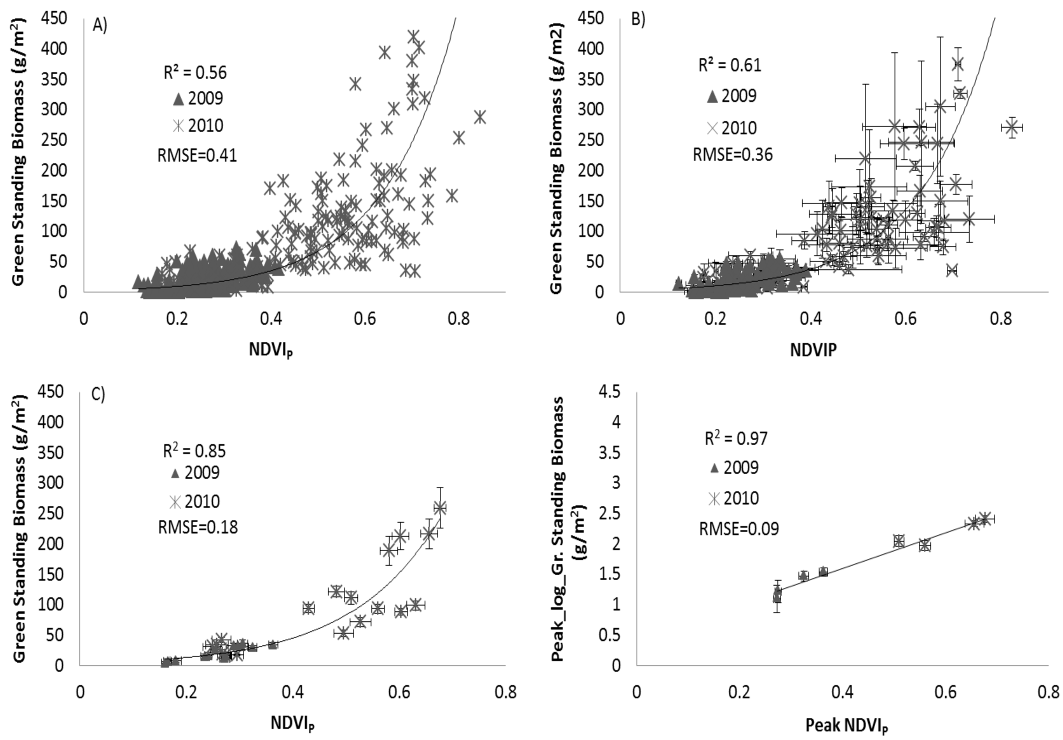

Figure A-1: Effect of spatial scale and temporal aggregation on the relationship between Green standing biomass and plot-sampled NDVI from the Sounding Creek and Pinhorn grazing reserves from the growing seasons of 2009 and 2010. A) Natural grazed and ungrazed control treatments for all sites. Per-point sample size is N=1. B) Natural grazed and ungrazed control treatments averaged for all sites. Per-point sample size is N=2. C) Natural grazed and ungrazed control treatments averaged for each month for all sites. Per-point sample size is N=56 for the 2009 data and N=40 for the 2010 data. D) Natural grazed and ungrazed control treatments for all sites for July. Per-point sample size is N=28 for the 2009 data and N=20 for the 2010 data. Error bars denote standard error of the mean, root mean square error was calculated from logarithm transformed data.

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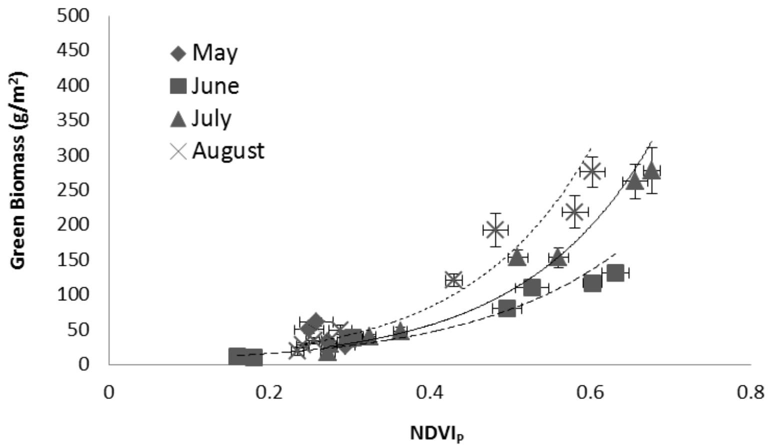
APPENDIX B - TEMPORAL EVOLUTION

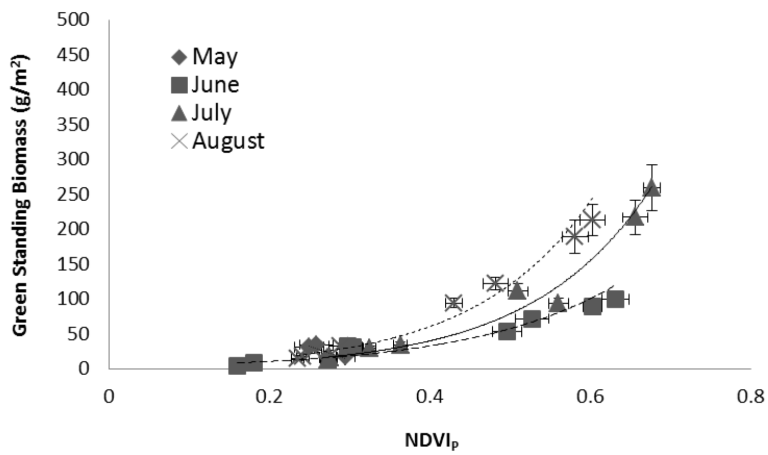
When the data from the wet growing season in 2010 and dry growing season in 2009 are compared directly, the underlying relationship between harvested biomass and the Normalized Difference Vegetation Index (NDVI) derived from optical sampling become apparent (Figure 2-7). Correlations are stronger when considering green biomass only, since this excludes senesced vegetation not clearly detected by NDVI, and this agrees with previous literature (e.g. Gamon *et al.* 1995). These effects of brown biomass on the NDVI biomass relationship are likely to be strongest in the beginning of the season (due to "carry-over" of dead standing biomass from the previous year) and towards the end of the season (when vegetation senescence has begun).

When these relationships are analyzed by month, there are strong correlations between green biomass (green forbs and graminoids) and NDVI (Figure B-1) similar correlations were determined between green standing biomass (green graminoids) and NDVI (Figure B-2). There were also strong monthly relationships between NDVI and total biomass (all forbs and graminoids) and standing biomass (all graminoids) (Figures B-3 and B-4 respectively). Carryover has a confounding effect on the NDVI - green biomass relationship as is evident by the weaker correlation between total biomass and NDVI, in comparison to the green biomass and NDVI (Figure 2-7). This is also demonstrated by the weaker correlation between standing biomass and NDVI in comparison to the green fraction of the standing biomass and NDVI (Figures 2-5). The correlation during May is weaker for all measures of biomass due to a combination of carryover effect and the lack of data for May 2009. At the beginning of the growing season there has been little or no new green growth, and the initial growth is likely to be hidden by last season's biomass (carryover error), and this leads to scatter in the NDVI-biomass relationship. The seasonally evolving relationship between green vegetation and NDVI can be problematic for modeling rangeland productivity as it increases the complexity of the data processing required. These results indicate that careful consideration of the seasonal factors (how data are aggregated temporally) is warranted when developing a biomass monitoring program from satellite data. It is possible that a focus on midsummer peak values can avoid the early-season carryover error and the late-season senescence phase, and still result in accurate biomass estimation (Figure 2-10). For this to be a viable option, year-to-year phenological variation has to be considered, as precipitation variability could lead to peak biomass occurring at different times in the growing season. Alternatively, these temporal effects including seasonal and yearly variability may have to be considered in more detail. The best choice may depend upon the degree of accuracy required.



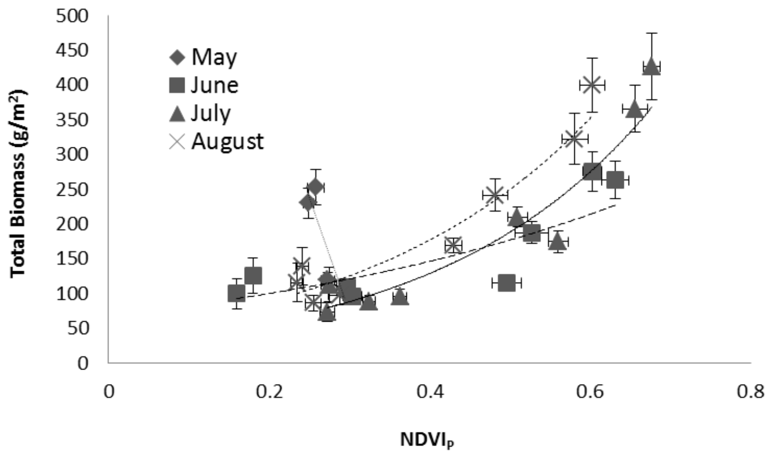
	R^2
May	0.71
June	0.94
July	0.96
August	0.95

Figure B-1: Seasonal variation in the relationships between green biomass (green forbs + green grass) and plot-sampled NDVI for each month in the Sounding Creek and Pinhorn grazing reserves. The number of samples comprising each point are N=56 for the 2009 data and N=40 for the 2010 data. Note that there is no data for May in 2009. The included table lists the R^2 for each month. May R^2 = 0.71, P=0.122; June R^2=0.94, P=0.012; July R^2=0.96, P=1.17E-03; August R^2=0.95, P=4.75E-4. Error bars denote standard error of the mean.



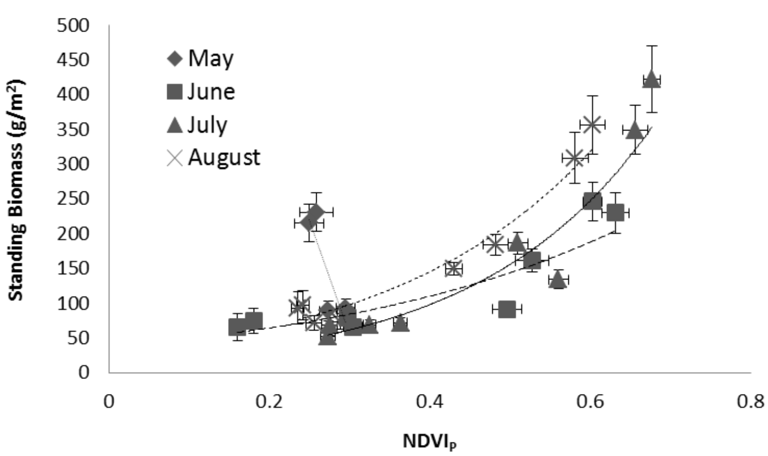
	R^2
May	0.64
June	0.88
July	0.97
August	0.97

Figure B-2: Seasonal variation in the relationships between green standing biomass (green grass) and plot-sampled NDVI for each month in the Sounding Creek and Pinhorn grazing reserves. The number of samples comprising each point are N=56 for the 2009 data and N=40 for the 2010 data. Note that there is no data for May in 2009. The included table lists the R^2 for each month. May R^2 = 0.64, P=0.155; June R^2=0.88, P=2.48E-06; July R^2=0.97, P=1.02E-05; August R^2=0.97, P=4.76E-06. Error bars denote standard error of the mean.



	R^2
May	0.77
June	0.69
July	0.91
August	0.89

Figure B-3: Seasonal variation in the relationships between total biomass (green and brown forbs and grass) and plot-sampled NDVI for each month in the Sounding Creek and Pinhorn grazing reserves. The number of samples comprising each point are N=56 for the 2009 data and N=40 for the 2010 data. Note that there is no data for May in 2009. The included table lists the R^2 for each month. May R^2 = 0.77, P=0.152; June R^2=0.69, P=4.95E-03; July R^2=0.91, P=1.67E-03; August R^2=0.89, P=3.58E-04. Error bars denote standard error of the mean.



	R^2
May	0.72
June	0.82
July	0.93
August	0.93

Figure B-4: Seasonal variation in the relationships between standing biomass (brown and green grass) and plot-sampled NDVI for each month in the Sounding Creek and Pinhorn grazing reserves. The number of samples comprising each point are N=56 for the 2009 data and N=40 for the 2010 data. Note that there is no data for May in 2009. The included table lists the R^2 for each month. May R^2 = 0.72, P=0.202; June R^2=0.82, P=7.57E-06; July R^2=0.93, P=3.52E-04; August R^2=0.93, P=1.79E-06. Error bars denote standard error of the mean.

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APPENDIX C - GRAZING EFFECTS

The grazing treatments were designed to provide a preliminary assessment of the effect of herbivory on the NDVI-biomass relationship. An additional goal was to see if grazing effects could be detected using the methods of this study.

The trends in the NDVI calculated from ungrazed and naturally grazed treatments were very similar. In both the Sounding Creek and Pinhorn grazing reserves; however, there was a peak in the NDVI from the simulated grazing treatment in July of 2009 and a depression in the NDVI in July of 2010 (Figure C-1A and C). In the Sounding Creek grazing reserve there is less variation between the three grazing treatments than there is in the Pinhorn.

The seasonal trends of harvested standing green biomass (g/m^2) from the naturally grazed treatment and the ungrazed treatment were similar (Figure C-1B and D). This suggests that the percentage of use levels in these Grazing Reserves is very low, so it is likely that on average the Grazing Reserves are underutilized. However, the trends from the simulated grazing treatment are different than the other treatments, with a strong reduction in standing green biomass through July and August, without a corresponding reduction in August in the NDVI. Presumably, this is a result of the carryover and litter being removed during the initial harvest, such that afterwards only new growth from the previous month is harvested. The repeated harvesting of this simulated grazing treatment caused the time series of the green standing biomass to decline with time. The NDVI trends for this treatment did not exhibit this strong decline and, other than a strong drop in July followed a similar pattern as the other treatments.

In the NDVI seasonal trend plots there was a stronger agreement between the naturally grazed treatment and the ungrazed treatment in Sounding Creek than in the Pinhorn (Figure C-1). This could be due to greater grazing pressure as a result of higher stocking rates in the Pinhorn, and may represent an ability of the NDVI to detect slight differences in grazing levels. However, information on stocking rates and cattle movement within the grazing reserves during the sampling period was unavailable so this hypothesis could not be tested.

If grazing had an effect on the NDVI-biomass relationships, we would expect to see different relationships between NDVI and biomass for the different grazing treatments. The NDVI-green standing biomass relationship is not significantly different (ANCOVA, P=0.73) when comparing the ungrazed and naturally grazed treatments (Figure C-2). However, there is a significant difference, when comparing the NDVI-green standing biomass relationship for the simulated grazing treatment with that of the naturally grazed and ungrazed (ANCOVA, P=0.0013 and P=0.0025 respectively). This indicates that removal of the litter and carryover, results in the pasture “looking” greener to the optical sensor than ungrazed or lightly grazed pastures for a given amount of biomass. These results suggest that heavy grazing could impact estimations of pasture productivity since severe defoliation results in a different NDVI-green biomass relationship than would otherwise be the case. It is also probable that our simulated grazing treatment did not replicate the way that cattle actually graze, so this could represent an artifact of our simulated grazing treatment. The correlation was also much weaker for the simulated grazing treatment, than for the natural grazed and ungrazed treatments, because removal of the litter and carryover exposes more of the background signal (soil and low-lying vegetation), confounding the NDVI measurements. Since simulated grazing appeared to fundamentally alter the core NDVI-standing green biomass relationship, this treatment was not incorporated in the analyses in the previous sections. These effects could be studied in more detail by managing stocking rates to produce different utilization of a paddock over time and monitoring the vegetation utilization with the NDVI. Another possible study could be conducted through piosphere analysis, where animal impact attenuates in a radiating sphere away from a concentrator (such as a water source) (Washington-Allen *et al.* 2004), so sampling along a transect would allow monitoring of decreasing grazing pressure with increased distance from the concentrator.

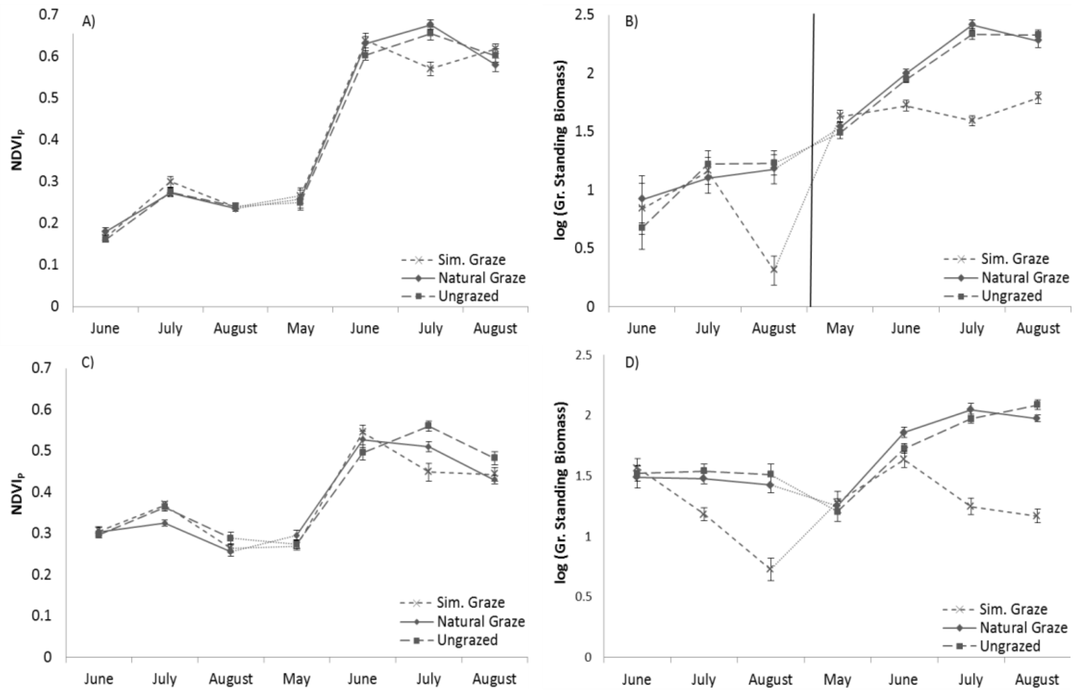
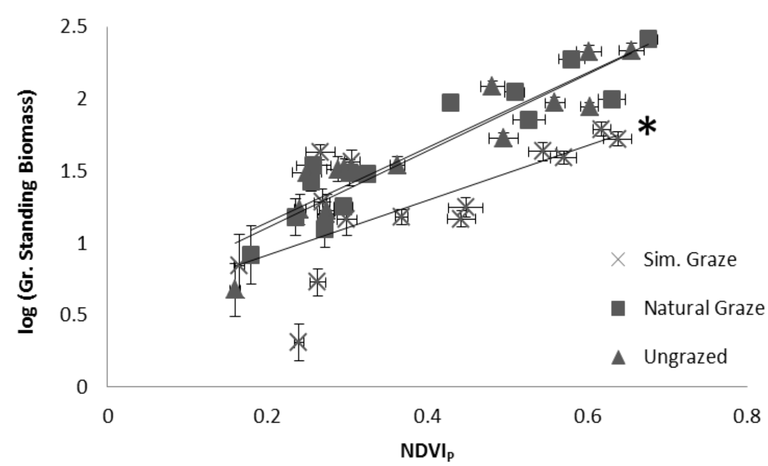


Figure C-1: Seasonal trends for plot-sampled NDVI and logarithm transformed green standing biomass (g/m^2) during the 2009 and 2010 growing seasons. The top frames are from the Sounding Creek grazing reserve and the bottom frames are from the Pinhorn grazing reserve. The error bars denote standard error of the mean and the per-point sample size is N=28 for the 2009 data and N=20 for the 2010 data.



	R^2
Sim. Graze	0.47
Natural Graze	0.87
Ungrazed	0.86

Figure C-2: Logarithm transformed green standing biomass from the Sounding Creek and Pinhorn, each point is an average of all sites in each grazing reserve for each month for the simulated grazing, natural grazing and ungrazed treatments. Per-point sample size is N=28 for the 2009 data and N=20 for the 2010 data. The asterisk (*) designates a statistically significant difference in the slope of the line (ANCOVA, Simulated graze vs. Natural P=0.0013; Simulated graze vs. Ungrazed P=0.0025). The error bars denote standard error of the mean. The included table lists the R^2 for each treatment. Simulated Graze R^2 = 0.47, P=2.42E-03; Natural graze R^2=0.87, P=3.29E-05; Ungrazed R^2=0.86, P=7.22E-05.

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