Relationships between NDVI and climatological variability in the Prairie ecozone of Canada

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Abstract: Seasonal characteristics of plants are closely related to characteristics of the annual cycle of weather patterns, therefore changes in plant phenological events may signal important year-to-year climatic variations or even global environmental changes. Monitoring ecosystems that are sensitive to climate change can improve our understanding of the relationships between climate and ecosystem dynamics. This improved understanding is critical for future land-use planning purposes. The objective of this paper was to examine relationships between Normalized Difference Vegetation Index (NDVI) and climatic data. Results showed that temperature and precipitation were correlated to NDVI, which was derived from the NOAA's Advanced Very High Resolution Radiometer (AVHRR). The Pearson correlation (r) was about 0.65 between NDVI and temperature, and the number is much lower for NDVI and precipitation (r=0.26). However, the relationships were increased when previous time periods were considered. The highest correlations occurred when mean of 20-day temperature and sum of 60-day precipitation were used (r=0.69 and 0.56 respectively). Comparing among ecoregions and land cover types, higher correlation between NDVI and climate variables occurred in the regions with higher NDVI values, such as the cropland woodland (r=0.86 with temperature and 0.50 with precipitation) and the Aspen Parkland (r=0.83 with temperature and 0.58 with precipitation). In addition, vegetation was strongly affected by climate variability in spring (April and May).

Introduction

Ecosystem processes include the exchange of water, energy, and greenhouse gases between the soil, vegetation, and the atmosphere. The ability to detect changes in ecosystem processes such as carbon fixation, nutrient cycling, net primary production, and litter decomposition is an important part of defining global biogeochemical cycles. Seasonal characteristics of plants are closely related to characteristics of the annual cycle of weather patterns, therefore, changes in plant phenological events may signal important year-to-year climatic variations or even global environmental change. Researchers have been focusing on large-scale changes in terrestrial ecosystems (*e.g.*, Dixon *et al*. 1994; Ojima *et al*. 1994; Lambin and Ehrlich 1997). It is accepted that at the global scale rapid environmental changes are mainly a result of climatic variations and anthropogenic activities. Environmental degradation is also associated with declines in primary productivity that alter biogeochemical exchanges between the earth and atmosphere (Running *et al*. 1994). Monitoring ecosystems that are sensitive to climate change can improve our understanding of the relationships between climate and ecosystem dynamics. This improved understanding is critical for future land-use planning purposes.

Recent advances in remote sensing technology and theory have expanded opportunities to characterize the seasonal and inter-annual dynamics of vegetation communities. Time series analysis of the National Oceanic and Atmospheric Administration's (NOAA) Advanced Very High Resolution Radiometer (AVHRR) 1-km multispectral imagery has allowed scientists to examine larger-scale phenological phenomena such as greenup, duration of green period, and onset of senescence (Reed *et al*. 1994), as well as change in seasonally-dependent biophysical variables such as leaf area index (LAI), biomass, and net primary productivity (Roller and Colwell 1986; Gallo and Eidenshink 1988; Achard and Brisco 1990; Teng 1990). Using time-integrated normalized difference vegetation index (NDVI) data, Yang *et al*. (1998) revealed that spatial and temporal variability in growing season precipitation, potential evapotranspiration, and growing degree days are the most important controls on grassland performance and productivity in the central and northern Great Plains. Wang *et al*. (2001) concluded that NDVI was more strongly related to precipitation than to temperature in the Great Plains of the USA.

Temperature increases over the last century within the Mixed Prairie ecosystem have been among the most dramatic in the world and have resulted in the droughts of the 1930s, 1961, the 1980s, and several others (Wheaton 2000). In southern Saskatchewan, 2001 and 2002 were two of the driest years in decades, causing severe crop damage (Hayward 2002). Anderson *et al*. (2001) concluded that the temperature in the prairie ecozone of Saskatchewan is expected to increase 3.5^{0}C to 4.0^{0}C in the next 50 years. Water availability will decrease because of increasing potential evapotranspiration even with increasing precipitation. Climate change will markedly alter the vegetation regime. Global warming may result in an advance of the northern boundary of C^4 species (Davidson and Csillag 2001) in the mixed prairie ecosystem. C^4 species have been defined as “Plants that use PEP carboxylase during initial carbon fixation to make a four-carbon compound that is subsequently transferred to specialized cells where carbon dioxide is internally released and refixed using rubisco” (Ziska and Bunce 1999). Southern Saskatchewan is the approximate northern boundary of C^4 species, and the boundary shifting will be a signal of climate change. From a study conducted by Mitchell and Csillag (2001), precipitation is the primary control factor for vegetation annual productivity in the mixed prairie ecosystem.

However, research into the relationship between vegetation phenology and climate variability has not been fully investigated. The objective of this paper is to examine relationships between NDVI and climate data, specifically for temperature and precipitation.

Study Area

The study area is southern Saskatchewan. This is bounded by 49^0 N latitude in the south, the Boreal forest ecozone in the north, and extends between longitudes 101.5^0 and 110^0 W (Fung 1999). The area falls within the prairie ecozone according to the ecological land classification developed in 1991 by the Ecological Stratification Working Group of the federal, provincial and territorial governments. This framework, primarily based on soil, climate and vegetation, comprises three levels of stratification, namely ecozone, ecoregion, and ecodistrict. Ecozone “lies at the top of the ecological hierarchy, and as such, it defines, on a subcontinental scale, the major physiographic features of the country”, while ecoregion is defined as “subdivisions of the ecozone, characterized by distinctive climatic zones or regional landforms, and constitute the major bridge between the subcontinental scale ecozones and the more localized ecodistricts” (Acton *et al.* 1998, 3).

The prairie ecozone encompasses four ecoregions extending from the southwest corner of Cypress Upland northward to Mixed Grassland, Moist Mixed Grassland, and Aspen Parkland. The Cypress Upland was eliminated from this study because it has only three weather stations, which are not large enough to develop correlation or regression models. The prairie ecozone is dominated by a temperate climate with 1,800 growing degree-days and annual precipitation of 310 mm (Sauchyn and Beaudoin 1998). These dry conditions subside moving northward and eastward to the Aspen Parkland. Prior to European settlement, southern Saskatchewan was covered with natural vegetation, mixed prairie ecosystem. The natural grasslands are fragmented by settlement and agriculture. However, even in the most altered areas, there are pockets of native vegetation, which allow us to visualize the landscape as it was. Recently, human settlement and, in particular, agricultural development have been the predominant forces in the evolution of the Saskatchewan landscape (Fung 1999).

Methods

Canada-wide 1-km AVHRR 10-day composite maps were derived from NOAA AVHRR data by the Canadian Centre of Remote Sensing (CCRS) for the CCRS Northern Biosphere Observation and Modelling Experiment (NBIOME) project. NDVI, as a vegetation index, is a ratio of the difference between channels 2 (near-infrared wavelength region) and 1 (red wavelength region) to the sum of these two channels. It has the advantages of enhancing vegetation signals, reducing the effects of soil and other non-vegetation features, and standardizing the values. NDVI has been used as a greenness index for vegetation because the green vegetation has high near-infrared reflectance and low red reflectance. Bare soil or areas with low vegetation cover have low or negative NDVI values. During the vegetation growing cycle the NDVI value acts as an indicator of the density of chlorophyll on the ground and increases as the vegetation starts to green up. It reaches a maximum at the highest productivity level and starts to decrease as vegetation senesces. According to Acton *et al*. (1998), ecoregions were classified based on vegetation, climate, and soil. Therefore, the NDVI has the potential ability to signal the vegetation features of different ecoregions and provides valuable information as a remote sensing tool in studying vegetation phenology cycles at a regional scale. Multitemporal 10-day composite AVHRR data were obtained covering growing seasons (April 11 to October 21) of six years from 1993 to 1998 (data were obtained from Geogratis, *http://www.geogratis.gc.ca/* , Natural Resources Canada). NDVI values were derived for all weather stations (See Guo 2002 for details).

To reflect the land cover types, the digital Land Cover of Canada map (Cihlar *et al*. 1998) was clipped to the boundary of the Prairie Ecozone in southern Saskatchewan. Land cover type for each weather station was determined by laying the weather station layer over the land cover map. The five land cover types in the prairie region include: 1) grassland, land with herbaceous (non-woody) vegetation cover; the ground cover area of trees or shrubs is less than 10%; 2) medium biomass cropland, cropland dominated by crops with medium biomass, due to cover type or climate (subhumid); 3) low biomass cropland, cropland dominated by crops with lower biomass, due to cover type (e.g., grain) or climate (semiarid region); 4) cropland-woodland, mosaic land in which cropland is more prevalent

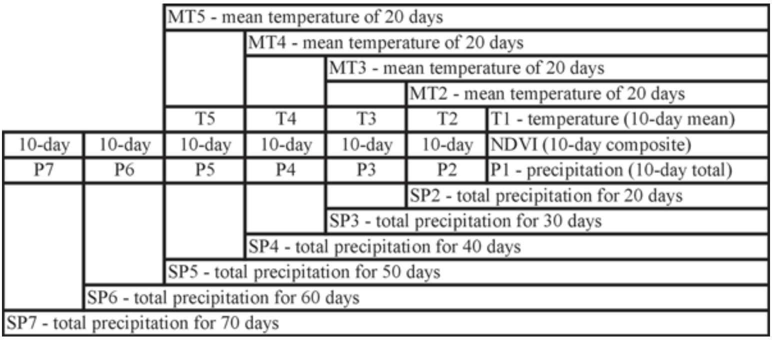

Figure 1: *Variables used in analyses include NDVI, temperature (T), and precipitation (P) from 10-day period when NDVI was derived to previous six 10-day periods.*

than forest cover (mostly broadleaf deciduous forest); and 5) woodland-cropland, mosaic land in which tree cover (mostly broadleaf deciduous species) and shrubs are more prevalent than cropland.

Historical climate data including daily temperature and precipitation were obtained from Environment Canada. Among 2,225 weather stations in Saskatchewan, 141 active weather stations in the prairie ecozone during the 1993 to 1998 period were selected for analysis. Climate data were processed to a 10-day period of total precipitation and mean temperature to match 10-day NDVI values for each weather station. There were 36 10-day periods each year, and this resulted in 216 10-day periods over the six years. Temperatures were averaged with values from previous 10-day, 30-day, and 40-day temperatures. Similarly, precipitation was also summed with values from previous 10-day, 20-day, 30-day, 40-day, 50-day, 60-day periods. These variables are illustrated in Figure 1.

Statistical analyses were performed on the dataset described above; including climate and NDVI data, on different ecoregions and land cover types. Pearson Bivariate Correlation analysis was conducted to test the relationship between NDVI and climate variables. Since the correlation analysis can't provide the magnitude of the relationship, a stepwise multiple regression analysis was further performed to test how well the NDVI variance can be explained by climate variables as well as the most significant climate variables contributed to NDVI's variability (Clark and Hosking 1985). To validate models derived by the linear regression analysis, adjusted R^2 was used because it "estimates how much variance on y [NDVI] would be accounted for if we had derived the prediction equation in the population from which the sample was drawn" (Stevens 1996:96). Among these analyses, the relationships between NDVI and climate variables were also tested for temperature and precipitation considering previous periods up to 60 days earlier. Based on the knowledge that spring is a critical time for the prairie region and the climate change has occurred significantly in spring, a further regression analysis was tested on monthly basis for different ecoregions.

Results

NDVI, Temperature, and Precipitation Variations:

The mean NDVI, temperature, and precipitation for the study area were plotted along a six-year time series (Figure 2). The graph was able to visually show that the maximum NDVI values changed from one year to another. From Figure 2, the general pattern of NDVI responds to the pattern of temperature well and is also related with previous year's precipitation. The highest maximum NDVI occurred in 1996 following a wet year of 1995, and the lowest maximum NDVI was in 1995 with a dry year of 1994 in advance. However, with the large study area, the climate influences on vegetation may differ on different ecoregions or land covers. Therefore, a simple mean for the whole area is not representative, and further evaluation is necessary.

Correlation Between NDVI and Climate Variables:

Pearson's product-moment correlation analysis results revealed that temperature was more strongly correlated with NDVI than precipitation (Table 1). When the correlation analysis was performed for all weather stations, the correlation coefficient (r) was 0.26 between NDVI and precipitation and 0.65 between NDVI and temperature; however, for precipitation, the correlation coefficient was increased when previous 10-day periods were used in the analysis. For example, the r value was 0.31 for the relationship between NDVI and the first previous 10-day precipitation, and it was 0.33 when the second previous 10-day period precipitation was used in the analysis. When the analysis was performed for multiple time periods, the highest correlation for temperature was the mean temperature from the first two 10-day periods (r=0.69), while the highest correlation for precipitation occurred when two-month's total precipitation was used in the analysis (r=0.56).

When the dataset was stratified into ecoregions or land cover types, the r values were increased for most categories. The correlation between NDVI and temperature was 0.82 and the number was 0.32 for precipitation for Cropland Woodland land cover type, and 0.76 and 0.29 for temperature and precipitation respectively for Medium Biomass Cropland land cover

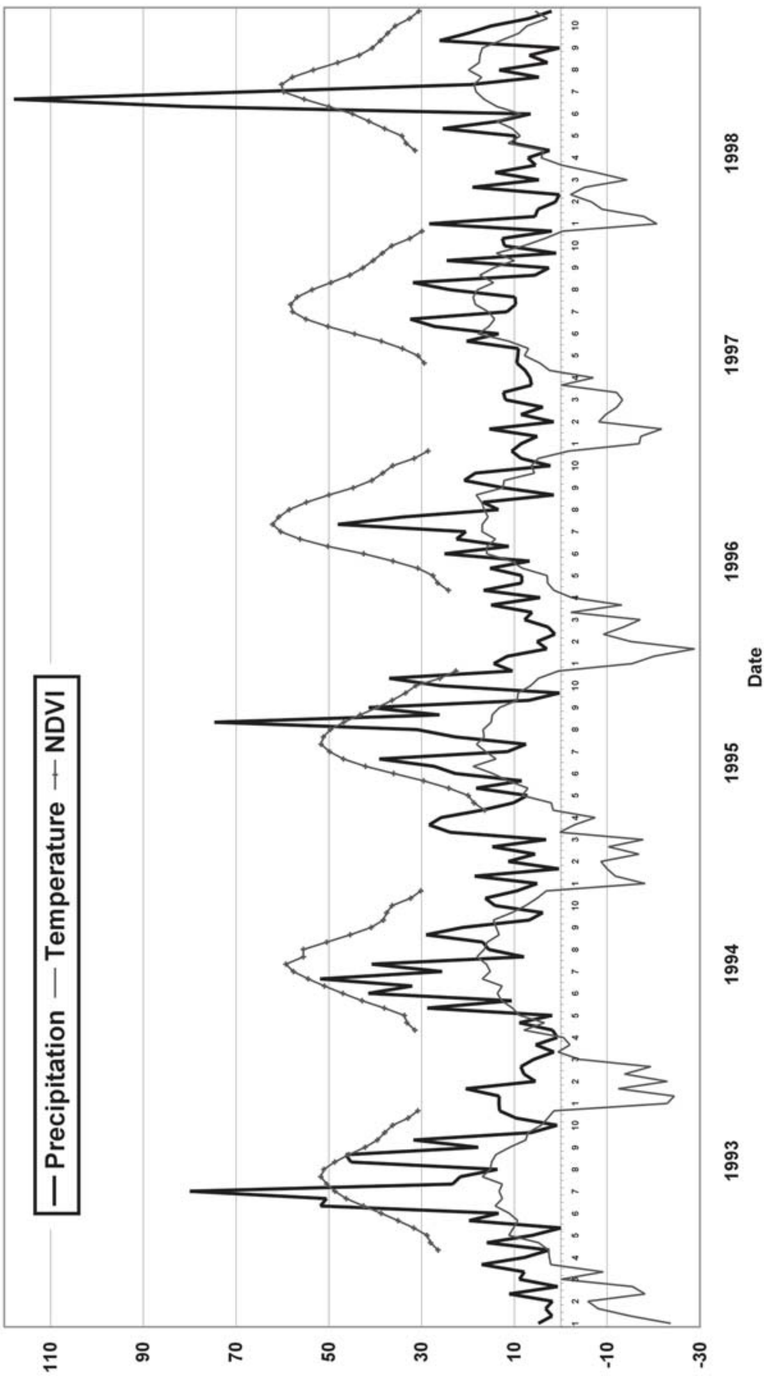

Figure 2: *Overall patterns of NDVI (after multiple 100), temperature (degree Celsius), and precipitation (mm) over six years (1993-1998).*

Table 1: *Correlation coefficient (r) values between NDVI and climate variables.*

Climate Variables		All Sites		Land Cover										Ecoregions					
				Grassland		Low Biomass Cropland		Medium Biomass Cropland		Woodland Cropland		Cropland Woodland		Mixed Grassland		Moist Mixed Grassland		Aspen Parkland	
		n	r	n	r	n	r	n	r	n	r	n	r	n	r	n	r	n	r
10-day precipitation	P1	9174	.263**	767	.220**	3716	.196**	3023	.291**	1320	.293**	348	.317**	3129	.181**	1708	.209**	3986	.300**
	P2	9163	.312**	766	.242**	3711	.273**	3021	.335**	1318	.340**	347	**.321****	3125	.246**	1705	.289**	3983	.342**
	P3	9146	**.330****	764	.237**	3706	.309**	3018	**.349****	1312	**.366****	346	.313**	3119	.270**	1702	.328**	3976	**.361****
	P4	9128	.323**	762	**.258****	3701	**.330****	3015	.322**	1305	.331**	345	.266**	3113	**.299****	1699	**.342****	3968	.326**
	P5	9110	.263**	760	.212**	3696	.276**	3012	.253**	1298	.255**	344	.195**	3107	.249**	1696	.289**	3960	.252**
	P6	9090	.193**	758	.212**	3689	.209**	3009	.168**	1291	.158**	343	.120*	3101	.201**	1692	.220**	3951	.156**
	P7	9070	.115**	756	.138**	3682	.139**	3006	.077**	1284	.066*	342	0.063	3095	.135**	1688	.133**	3942	.065**
Precipitation of longer periods	SP1	9163	.374**	766	.299**	3711	.311**	3021	.406**	1318	.412**	347	.393**	3125	.280**	1705	.336**	3983	.416**
	SP2	9146	.455**	764	.350**	3706	.399**	3018	.489**	1312	.502**	346	.451**	3119	.354**	1702	.435**	3976	.500**
	SP3	9128	.519**	762	.402**	3701	.478**	3015	.548**	1305	.564**	345	.486**	3113	.425**	1699	.520**	3968	.558**
	SP4	9110	.550**	760	.431**	3696	.518**	3012	**.577****	1298	**.589****	344	**.495****	3107	.462**	1696	.565**	3960	**.582****
	SP5	9090	**.556****	758	**.454****	3689	**.532****	3009	.574**	1291	.583**	343	.485**	3101	**.480****	1692	**.580****	3951	.574**
	SP6	9070	.539**	756	.454**	3682	.524**	3006	.545**	1284	.550**	342	.464**	3095	.477**	1688	.567**	3942	.540**
10-day temperature	T1	7431	**.651****	767	**.526****	3002	.684**	2351	.761**	963	.718**	348	**.820****	2534	**.632****	1470	**.717****	3076	.780**
	T2	7420	.650**	766	.495**	2997	.678**	2349	**.769****	961	**.726****	347	.809**	2530	.608**	1467	**.717****	3073	**.792****
	T3	7403	.575**	764	.407**	2992	.595**	2346	.690**	955	.652**	346	.714**	2524	.517**	1464	.635**	3066	.714**
	T4	7385	.482**	762	.309**	2987	.494**	2343	.594**	948	.554**	345	.598**	2518	.412**	1461	.534**	3058	.618**
	T5	7367	.411**	760	.245**	2982	.424**	2340	.509**	941	.469**	344	.513**	2512	.346**	1458	.457**	3050	.531**
Temperature of longer periods	MT1	7420	**.685****	766	**.537****	2997	**.716****	2349	**.808****	961	**.760****	347	**.857****	2530	**.652****	1467	**.754****	3073	**.829****
	MT2	7403	.678**	764	.515**	2992	.708**	2346	.804**	955	.758**	346	.844**	2524	.635**	1464	.748**	3066	.828**
	MT3	7385	.651**	762	.477**	2987	.678**	2343	.778**	948	.732**	345	.809**	2518	.601**	1461	.719**	3058	.803**
	MT4	7367	.611**	760	.432**	2982	.637**	2340	.734**	941	.690**	344	.757**	2512	.557**	1458	.675**	3050	.759**

Note: Numbers with ** are significant at 0.01 level; numbers with * are significant at 0.05 level.
Please refer to figure 1 for definitions of climate variables.
Numbers in bold showing the highest r value in each climate variable group.

type. For ecoregions, Aspen Parkland had the numbers of 0.78 and 0.30 for temperature and precipitation respectively. When the analysis was performed using individual 10-day period back to two months before the NDVI data, the highest correlation between NDVI and temperature was either for the same time period or 10 days earlier. The highest correlation coefficient between NDVI and the first previous 10-day mean temperature was 0.79 for Aspen Parkland, and the highest number was 0.53 for grassland when the same time period was used. For precipitation variables, there was at least a 10-day lag for the highest relationship. NDVI was most highly correlated with the third previous 10-day precipitation with r of 0.34, and it was 0.32 between the NDVI and the first previous 10-day precipitation for Cropland Woodland land cover. The highest correlation (r=0.86) between NDVI and temperature was for the Cropland Woodland land cover when the mean temperature of the first two 10-day periods was used, and the highest correlation (r=0.59) for precipitation occurred when the 40-day total precipitation was included for the Woodland Cropland land cover.

Nevertheless, Table 1 shows a confusing result regarding the significance level and r values. Even though nearly all results were significant at the 0.01-level, r values were relatively low, ranging from 0.15 to 0.83. This is caused by a large sample size (Table 1). Significance and r value are two aspects of the correlation analysis. The significance shows a confidence level, while r value is a magnitude of the relationship. If two variables show a correlation significant at the 0.01 level, it means that the probability of the result by chance is lower than 1%. A stronger relationship between two variables will be indicated by a higher r value, however, both are influenced by sample size. As the number of samples increases, the significance of a result increases and the probability of the result being by chance decreases (Rummel 1976). Practically, the results of this study have high confidence, and the relationship revealed above caused by chance is very low.

Regression results:

Table 2 shows the regression analysis results between NDVI and climate variables when the stepwise multivariate regression method was used and only the first two entered variables were selected to develop the models. When all weather stations were used to build the model, the mean temperature (MT2) calculated from the same time period of NDVI and the first previous 10-day period temperature gave the highest ability to predict the NDVI variable (that is, it entered the model first). The next climate variable that showed a high ability to predict NDVI was the total precipitation, from the previous two months. These two variables explained

Table 2: *Regression analysis results between NDVI and climate variables.*

Land Cover category		Adjusted R^2	F	Predictors
All sites		0.55	4473.1	MT2, SP5
Land Cover	Grassland	0.33	189.6	MT2, SP6
	Low Biomass	0.58	2028.3	MT2, SP5
	Medium Biomass	0.7	2682	MT2, SP4
	Woodland Cropland	0.65	848.4	MT2, SP5
	Cropland Woodland	0.77	571.6	MT2, SP4
Ecoregion	Mixed Grassland	0.48	1160.8	MT2, SP5
	Moist Mixed Grassland	0.63	1215.7	MT2, SP5
	Aspen Parkland	0.73	4055.8	MT2, SP4

Note: Please refer to figure 1 for definitions of climate variables.

55% of the NDVI variance. When comparing the ecoregions, NDVI for the Aspen Parkland could be explained by the mean temperature combined with the first previous 10-day period value (MT2) and the total precipitation for 40 days (SP4) with R^2 of 73%, and the Mixed Grassland could only be explained by 20-day mean temperature (MT2) and 50-day total precipitation (SP5) with R^2 of 48%. For different land cover types, the adjusted R^2 values were not as high as for the ecoregions, but the trends were the same; the higher the NDVI number, the higher the adjusted R^2 value. The highest adjusted R^2 value was 0.77 for cropland woodland with 20-day mean temperature and 40-day total precipitation as independent variables, and the lowest 0.33 for grassland with 20-day mean temperature and 50-day total precipitation as predictors.

NDVI is affected by climate variability differently at different stages of the growing season (Table 3). Climate variability could explain about half of the NDVI variance in early spring (April). The adjusted R^2 are 0.57, 0.50, and 0.69 for the Mixed Grassland, Moist Mixed Grassland, and Aspen Parkland ecoregions respectively. For Aspen Parkland, climate variables were key factors of NDVI changes until June, while the climate influence was decreasing as the location moved south and the season changed to summer. Temperature was always the key factor, especially a 20-day mean temperature. Longer periods of precipitation could affect vegetation through soil moisture availability, especially in spring. With the fact that temperature has increased in spring, global warming may benefit vegetation on the prairies since temperature is a key factor for vegetation in this region. However, this conclusion should be treated with caution, as further study needs to be developed to investigate how precipitation will be changed as temperature increases and what the threshold will be for vegetation response to precipitation.

Table 3: *Regression analysis results showing monthly influence of climate variables on NDVI of three ecoregions of the prairie ecozone.*

Month	Model	Mixed Grassland Adjusted R^2	Moist Mixed Grassland Adjusted R^2	Aspen Parkland Adjusted R^2
April	1	0.51	0.42	0.54
	2	0.57	0.47	0.67
	3	0.57	0.50	0.68
	4			0.69
	5			0.69
	Variables entered	MT1,MT4,P6	MT1,MT4,P1	MT1,SP4,SP2,SP5,MT3
May	1	0.25	0.31	0.47
	2	0.29	0.34	0.57
	3	0.30	0.35	0.60
	4	0.31	0.37	0.61
	Variables entered	MT3,P5,P2,P6	MT3,P5,P2,P6	MT3,SP6,SP3,P3
June	1	0.11	0.33	0.44
	2	0.16	0.46	0.48
	3		0.48	0.53
	4			0.54
	5			0.55
	6			0.56
	Variables entered	MT4,SP5	SP4,MT4,MT1	MT4,SP1,P6,T3,SP6,T4
July	1	0.03	0.13	0.19
	2	0.05	0.21	0.20
	3		0.25	0.21
	4		0.28	0.22
	5		0.29	
	Variables entered	MT1,SP6	MT1,SP6,SP2,P6,MT3	T2,MT2,P5,P7
August	1	0.11	0.09	0.08
	2	0.14	0.25	0.12
	3	0.17	0.28	0.17
	4	0.18	0.30	0.19
	5	0.19	0.31	0.20
	6			0.20
	7			0.21
	Variables entered	T5,P4,MT1,T3,P5	SP1,SP5,T5,T1,T3	P7,T3,P3,MT1,P2
September	1	0.04	0.07	0.17
	2	0.05	0.12	0.23
	3	0.06	0.13	0.24
	4	0.07		0.25
	5	0.08		
	6	0.09		
	Variables entered	P7,P6,T1,T4,T5,T3	P7,SP2,SP6	T2,SP6,T5,T3
October	1	0.13	0.16	0.33
	2	0.14	0.19	0.39
	3		0.22	0.47
	4			0.49
	Variables entered	T1,T4	MT4,SP1,P3	MT4,SP1,SP3,MT2

Discussion and Conclusion

The study has shown that the NDVI values of vegetation varied over years. The NDVI was correlated with temperature and precipitation; however, temperature showed higher correlation with NDVI compared to precipitation. This results conflict with those obtained by Wang *et al*. (2001) for the central Great Plains, which showed NDVI had higher correlation with precipitation. The reason for this may be that the present study area is further north then that used by Wang *et al*. and is more influenced by temperature. The results seem to conflict with another study by Mitchell and Csillag (2001). In their study, they concluded that precipitation was the critical variable for vegetation in the mixed prairie ecosystem. In this study, only the general correlation and regression between NDVI and climate variables were compared, and a more detailed study should be conducted to reveal how precipitation is critical, what time of year is more important for precipitation, as well as which vegetation type is more sensitive to precipitation.

This study's results also showed that the relationship between NDVI and precipitation became stronger when previous time periods were included in the model. The fact that there was a lag for the highest relationship between NDVI and precipitation means that current precipitation could influence vegetation two months later or that the influence only 'kicks in' after extended accumulation of precipitation. Two factors may contribute to this phenomenon, 1) there is a lag time from vegetation absorbing water to photosynthesis taking place, and 2) soil acts as a reservoir that regulates soil moisture content in a certain period.

Comparing ecoregions, climate variables were highly related with NDVI of the Aspen Parkland (r=0.83 and 0.58 for temperature and precipitation respectively), and NDVI from the Mixed Grassland showed the weakest relationships with climate variables (r=0.75 and 0.58 for temperature and precipitation respectively). Among land cover types, Cropland Woodland had the highest correlation coefficients between NDVI and climate variables (r=0.86 and 0.50 for temperature and precipitation respectively) and grassland had the lowest correlations between NDVI and climate variables (r=0.54 and 0.45 for temperature and precipitation respectively). This is because for land cover types with lower vegetation, especially grassland, other factors such as bare soil and dead grasses contribute to the signal intercepted by the satellite sensor, while the NDVI is an indicator of greenness.

Comparing two land cover classification systems, ecoregions showed better relationships between NDVI and climate variables compared to the relationships for land cover types. The weaker relationships with land cover types are probably caused by the fact that this is a nation-wide classification map and it was focused more on the boreal forest region, while the ecoregion classification was for Saskatchewan only, which promised a more accurate result regarding the consideration of vegetation, climate, and soil. Moreover, the ecoregion map does not account for current land use (e.g., grassland vs. cropland). The land classification derived by the Saskatchewan Research Council using Landsat in the late 90's should show better results because of its higher spatial resolution and more classes.

However, the more land cover types there are, the fewer weather stations there are in each category. Therefore, it may be less accurate.

Several limitations of this study restricted further explanation of the analysis results. First, only mean temperature and precipitation were considered in the data analysis. The maximum temperature, minimum temperature, and growing degree days may be more closely related with vegetation. Additionally, the Palmer Drought Severity Index and the ratio of precipitation to potential evapotranspiration, which combine temperature and precipitation, should be investigated, especially for the prairie region. Indeed, these variables are being processed and will be used in a study associated with the Moderate Resolution Imaging Spectroradiometer (MODIS) data. Second, the influence of climate variability on vegetation green-up and senescent stages couldn't be investigated because of the dataset downloaded is only from April 11 to October 21. Instead, with the monthly regression analysis, the impact of climate data on different vegetation stages was investigated even though it is not specific on how climate affect the time of vegetation onset of greenness. Finally, the dataset is only for a six-year period, which is not long enough to detect climate change. In addition, the yearly climate variability is also influenced by El Niño events, which was not discussed in this paper while 1998 was an El Niño year. This paper revealed that vegetation is positively responsible with climate variability, and satellite, through vegetation indices (e.g., NDVI), could be used for climate change study.

Acknowledgements

This study was supported by the President's NSERC grant from the University of Saskatchewan. AVHRR data were downloaded from the Natural Resources Canada Geogratis website. I would like to thank my husband Yunpei Lu for his voluntary effort in climate data processing. Special thanks go to the two anonymous reviewers for their valuable comments and suggestions.

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