CCIAD Project A733
The vulnerability of land management in the grassland - forest transition to climate
change impacts on ecosystems and soil landscapes

Final Report – April, 2007

The Saskatchewan River valley below the confluence of the North and South
Saskatchewan Rivers

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The vulnerability of land management in the grassland - forest transition to climate
change impacts on ecosystems and soil landscapes

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Executive Summary

The ecological gradient from grassland to forest in Canada's western interior is a large region of national significance. It is a climatically sensitive ecotone that supports forestry and agriculture, includes various parks and protected areas, and is the location of a number of First Nations reserves. By mid-century the climate of this region is expected to have shifted from subhumid to dry subhumid with a longer and warmer growing season, possibly causing dieback of the forest, and soil moisture limitations on plant growth and productivity. These impacts have major implications for the use and management of soil, water, forest and pasture, including the capacity of current management structures and practices to sustain soil and ecosystem health. The goal of this project was to contribute to science-based decision making about adaptation to climate change in this region by providing new scientific information on the ecological response to climate variability and change at monthly to decadal time scales. This new information improves the capacity to anticipate impacts of global warming and address vulnerabilities to climate identified by stakeholders who manage the natural resources of this region.

The project objectives were to

1. determine the climate sensitivity of ecosystems and soil landscapes in a major part of the Prairie Province grassland – forest transition zone
2. assess the vulnerability of soil and vegetation use and management to climate-induced ecosystem and landscape change,
3. contribute to science-based decision making concerning adaptation to climate change with a focus on the forest industry and the management of parks and protected areas
4. assign a quantitative degree of certainty (confidence) to our climate change and impact scenarios

The principal objective of determining the climate sensitivity of a major part of the Prairie Province grassland – forest transition zone was met and possibly exceeded in terms of the amount of new information on the historical response of vegetation to climate variables. The time series of correlated indicators of vegetation and climate inform the assessment of climate change impacts on the ecosystems of the grassland-forest transition zone. These data also can be used to calibrate models that project change in plant productivity and species distribution under climate change.

We examined the ecological response to past climate variability at various temporal scales from correlations among indicators of monthly climate and plant productivity to the variation in relative abundance of plant taxa at 5-25 year intervals for the past millennium. At the shorter time scales, temporal and spatial variations in plant productivity can be related to specific climate variables. Plant productivity depends on temperature in May but, in the rest of growing season, responds mostly to precipitation with about a one month lag. An increasing trend in July to October productivity over most of the grassland to forest transition zone suggests a lengthening of the growing season. At longer time scales, time series of pollen records from four lakes show significant fluctuations in the relative abundances of plant taxa. Much of this variability can be related to departures from mean climate conditions as inferred from tree-ring records and from the geographic distribution of modern pollen relative to climate gradients. The impact of dry years is especially apparent with substantial reductions in pollen concentrations for coniferous tree taxa, reflecting suppressed productivity. Decreased pollen outputs from these tree species is correlated with decreased lake productivity as indicated by algal pigment concentrations in the lake sediment record.

With regards to the vulnerability of vegetation use and management to climate-induced ecosystem and landscape change, we were able to satisfactorily address this objective by consulting with resource managers in the sectors of agriculture, forestry and parks and protected areas. This consultation was achieved with two workshops staged by the project and during other meetings attended by project researchers where local resource managers were in attendance. At the project workshops, stakeholders identified barriers to adaptation and adaptive management related to the uncertainty associated with conventional climate change and impact scenarios. Current projections of the ecological impacts of climate change are based on associations between current climate and the boundaries between natural regions, and on the present ranges of individual species. Shifts in the distribution of ecosystems will be driven by encroachment of species into previously unsuitable areas, for example, at the interface of grassland with parkland and forest. Resource managers need information on the trajectory that ecosystems follow in response to fluctuating and directionally-changing climate.

We were able to contribute to science-based decision making concerning adaptation to climate change to the extent that project researchers presented the results of our research at the two stakeholder workshops and at other conference and workshops on the topic of climate change impacts and adaptation in western Canada. The degree to which this knowledge transfer influenced decision making is difficult to assess. We expect that more knowledge translation and interaction with stakeholders will be required to have a

meaningful influence on the planning of adaptation to climate change. But a general indication of the perceived value of this research is shown in the development of new funding applications in collaboration with stakeholders and First Nations groups.

The final objective of assigning a degree of certainty (confidence) to our climate change and impact scenarios was achieved in terms of having a better understanding of the climate sensitivity of the ecosystems of the forest – grassland transition zone. We have yet to meet this objective, however, in terms of producing a more robust assessment of climate impacts, because the components of the project have not yet been fully integrated. We intend to pursue this full integration of the project components and deliver improved assessments of the ecological impacts of climate change to project partners and stakeholders.

Introduction

The grassland to forest transition zone of western Canada is a large region of national significance. It is a major ecotone, that is, both forest and grassland species are at the limits of their geographic range. The ecosystems support the northern limit of arable agriculture in North America, commercial forestry, and traditional land uses by First Nations. There are various parks and protected areas providing recreation and protecting representative ecosystems.

Climate change scenarios derived from global climate models (*e.g.*, CGCM3, HadCM3, CSIROMk2b) suggest that the climate of this region will warm significantly in this century, supporting increased agricultural and forest productivity initially but reduced productivity ultimately as the availability of moisture in most soils becomes a limiting factor (Johnston *et al.*, 2003). By mid-century the climate is expected to have shifted from subhumid to dry subhumid (Sauchyn *et al.*, 2003), suggesting dieback of the forest, soil moisture limitations, and increased soil erosion risk; dry subhumid landscapes are by definition at risk of desertification (Middelton and Thomas, 1992). These impacts have major implications for the use and management of soil, water, forest and pasture, including the capacity of current management structures/practices to sustain soil and ecosystem health (Henderson *et al.*, 2002). This project examined the climate sensitivity of the terrestrial ecosystems in a major part of the grassland – forest transition zone in central Saskatchewan.

Objectives

The goal of this project was to contribute to science-based decision making about adaptation to climate change in the grassland-forest transition zone by improving impact scenarios of vegetation change and by addressing vulnerabilities to climate identified by stakeholders.

The specific objectives were to

1. determine the climate sensitivity of ecosystems and soil landscapes in a major part of the Prairie Province grassland – forest transition zone
2. assess the vulnerability of soil and vegetation use and management to climate-induced ecosystem and landscape change
3. contribute to science-based decision making concerning adaptation to climate change with a focus on the forest industry and the management of parks and protected areas
4. assign a quantitative degree of certainty (confidence) to our climate change and impact scenarios

The transition from grassland to forest in the Prairie Provinces follows the climate gradient from dry subhumid to humid (Hogg, 1994; Hogg and Hurdle, 1995). Thus the position and composition of this large ecotonal bioclimatic region is largely climatically controlled. This project examined critical thresholds in climate variability, and in particular drought severity, that have caused ecological change in this region. Subhumid ecosystems and soil landscapes are sensitive to fluctuations in the surface and soil water balances (Lemmen and Vance, 1999). Sustained periods of low precipitation and soil moisture lower resistance to disturbance such that climatic variability may exceed thresholds for land degradation (Campbell, 1998; Wheaton, 1990; Wolfe and Nickling, 1997). In general, biophysical systems react to short-term climate variability and to extreme events before they respond to gradual changes in mean conditions (Hulme *et al.*, 1999; Knox, 1984). Less protective cover of the soil surface is generally given or implied as the cause of higher rates of erosion in semiarid landscapes; however, plants also reduce runoff erosion through the transpiration of soil water and the positive influence of stems, roots and organic matter on the infiltration of rain and snowmelt water (Thornes, 1985). Global climate model (GCM) scenarios of increased aridity, in both average conditions and extremes (drought), imply increased disturbance of ecosystems and soil landscapes.

Climate change presents new challenges for the management of parks and protected areas as "current ecological communities will begin to disassemble and 'resort' into new assemblages" (Scott and Suffling 2000). These changes, in combination with expected increases in forest fire frequency and intensity and forest disease outbreaks and insect infestations will likely result in loss of boreal forest to grassland and temperate forest (de Groot *et al.*,2002). Prince Albert National Park, for example, is mandated to protect fescue grassland, aspen parkland and southern boreal forest within the national system. However, "In a world of climate change, selection of protected areas may need to focus on site heterogeneity and habitat diversity (as these provide some buffer against climate change) rather than on representativeness." (Henderson *et al.*,2002). As the southern boreal forest is impacted by a warmer climate, it may be reduced to remnants of forest at more favourable (wetter, cooler) sites persisting as islands in the advancing grasslands. Highly intrusive management likely would be necessary to preserve some type of forest cover at these sites, given the greater vulnerability to catastrophic disturbances such as wildfire, pathogen attack or severe drought (Henderson *et al.*,2002).

Adaptation to the impacts of climate change, including adaptive resource management, will depend on 1) recognition and understanding of the climate forcing of ecological and landscape change and 2) improving the certainty of climate change impact scenarios. We addressed these knowledge gaps by applying statistical methods and time series analyses to establish current and historical relationships between climatic and ecological parameters. Impact scenarios are commonly derived from mechanistic models that simulate ecological processes operating at finer spatial and temporal scales than the scales relevant to forest and land management practices (Sauchyn, 2001).

The Grassland to Forest Transition Zone

The grassland to forest transition zone is defined by the Boreal Transition and Aspen Parkland ecoregions (Figure 1) that occupy 135,600 km^2 or about 21% of Saskatchewan's total area. The climate of this region is characterized by relatively low mean annual (420 – 450 mm) and growing season precipitation and high summer temperatures (mean July temperatures of 17-18 ^{0}C), and therefore a moderate annual moisture deficit (Figure 2). Cropland occupies 62% of the area, with grassland and pasture, trees and shrubs, and lakes and wetlands comprising the rest of the landcover (Figure 3).

The Boreal Transition ecoregion is a mix of forest and farmland. Trembling aspen and white spruce are the dominant trees; secondary tree species include balsam poplar, black spruce, tamarack and jack pine. Wetlands and fescue prairie (Vetter, 1999) form openings in the forest. The Aspen Parkland ecoregion has lost most of its native vegetation to cultivation. Among the cropland and pasture, groves of aspen remain on stony or hilly land and willows ring wetlands (sloughs).
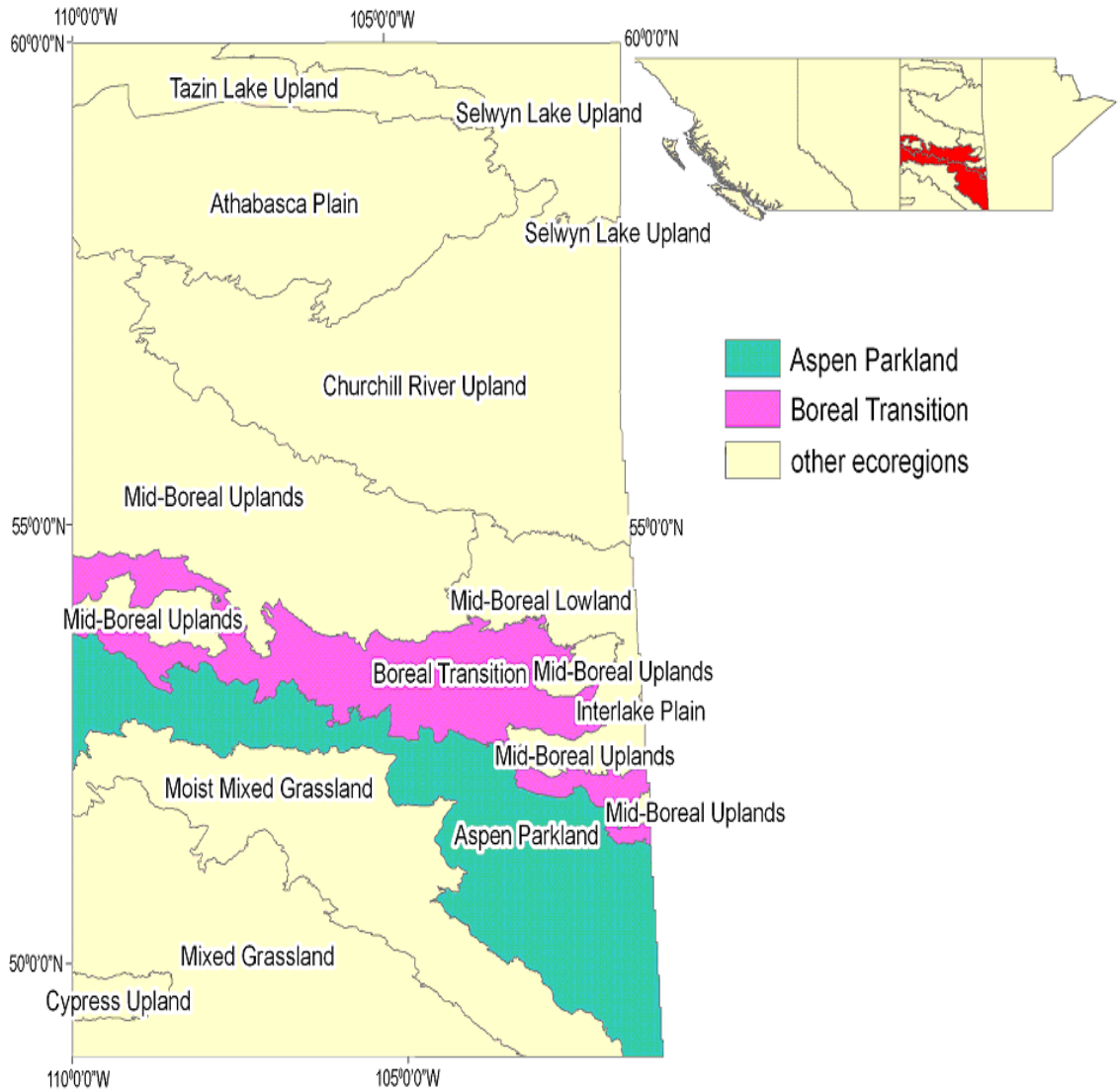
Figure 1. The grassland-forest transition zone in central Saskatchewan. It can be defined as the Aspen Parkland and Boreal Transition ecoregions.
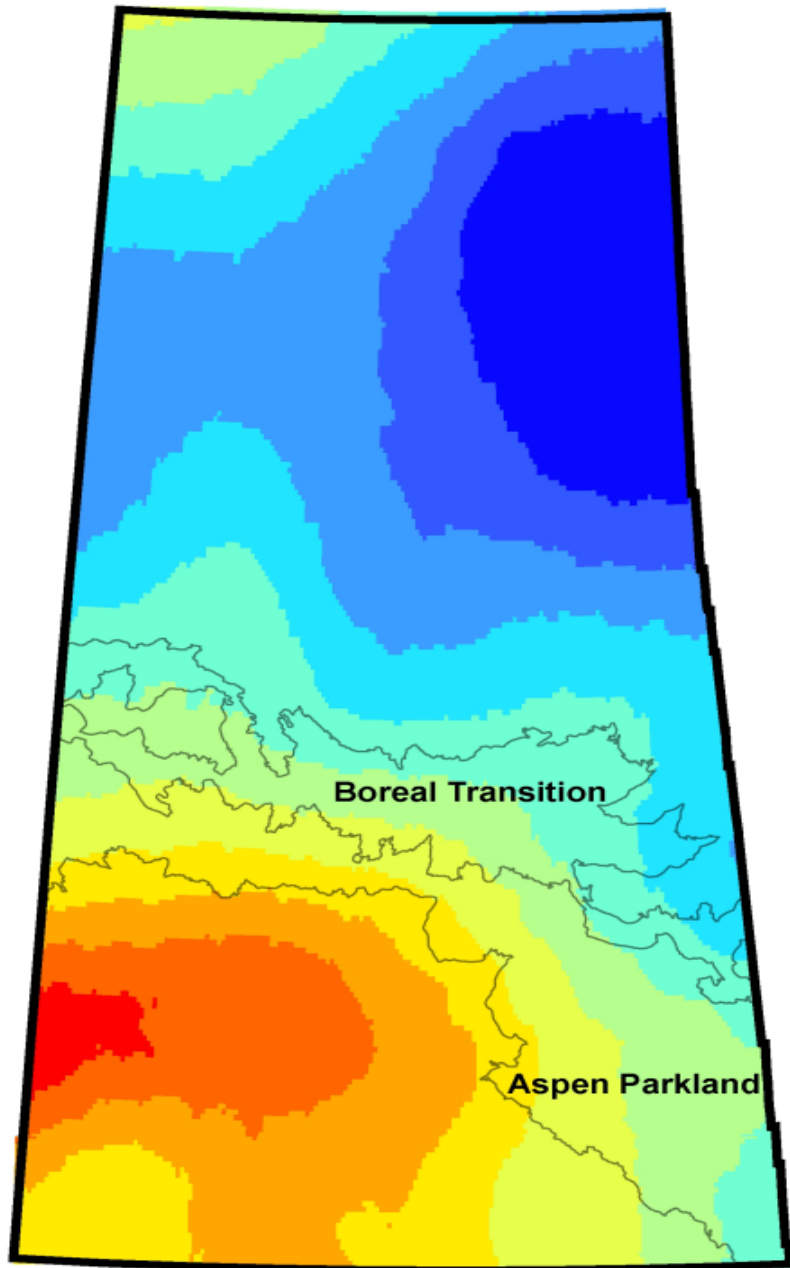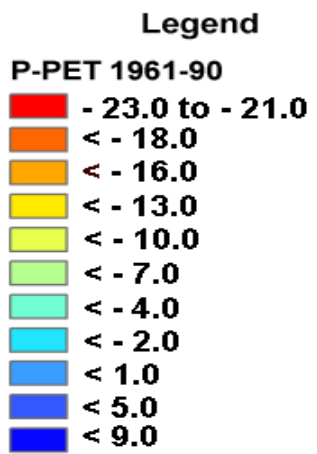
Figure 2. A map of Saskatchewan showing the 1961-90 distribution of the Climate Moisture Index (P-PET) and the Aspen Parkland and Boreal Transition ecoregions.

landcover types
- <all other values>
- Wetlands
- Water bodies
- Trees
- Shrubs
- Grassland
- Forage
- Cropland
- Sask. transition zone
- province_boundary

0   75   150   300 Kilometers
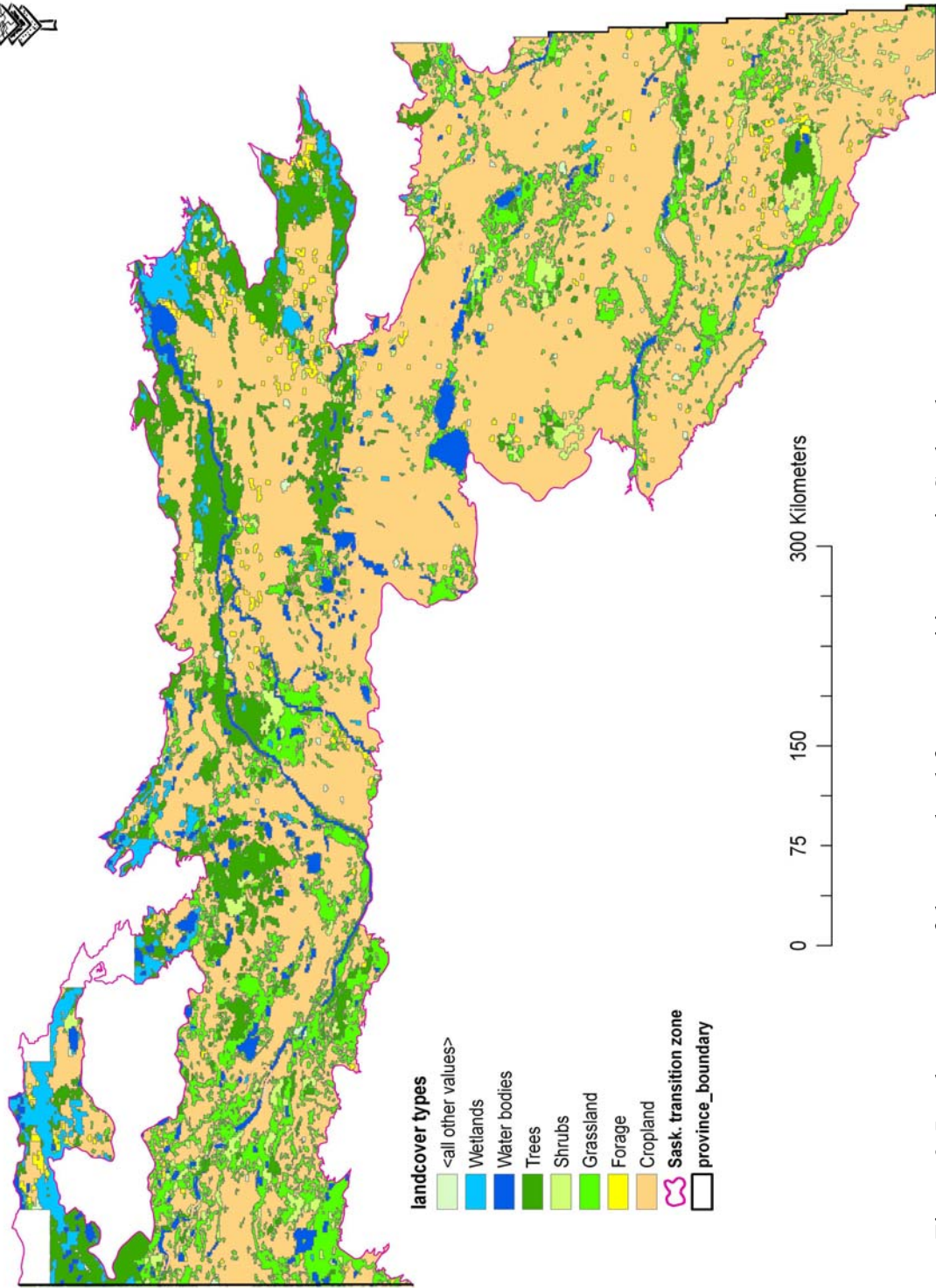
Figure 3. Landcover map of the grassland-forest transition zone in Saskatchewan. Source: PFRA Generalized Landcover of the Canadian Prairies.

Stakeholder Workshops

This project was launched in March 2004. Within three weeks, a stakeholder workshop was held on March 22 at the Saskatchewan Forest Center in Prince Albert, Saskatchewan. Appendix A outlines the workshop purpose and agenda. Following the workshop, the presentations and summary of the discussion were distributed to the participants and to stakeholders who were invited but not able to attend. An outcome of this workshop was an agreement to meet again within one year to discuss the project in greater detail and further engage stakeholders in the research. This subsequent workshop was held on April 18, 2005, again at the Saskatchewan Forest Center in Prince Albert (see Appendix B). During an afternoon discussion session, project personnel posed the following questions to the stakeholders in attendance:

- Is the research useful? If so, how?
- Are there direct applications of the results to your management responsibilities?
- What is missing or should be added, *e.g.* other impacts, adaptations, and vulnerabilities?
- How can this work be expanded to make it more relevant?
- What additional questions should be addressed?
- Is there interest in supporting or participating in this work (in-kind, logistics, internal funding, etc.)?

Key stakeholder comments from 18 April 2005

- Prince Albert National Park (PANP) is supposed to represent the boreal plains region; in 50 years will it be representative? How will Parks Canada protect and maintain the areas representative of our heritage, given that individual parks are supposed to maintain and preserve examples of specific natural regions. So will the forest in PANP turn into aspen, and will PANP be able to maintain boreal forest somewhere in the park? Another issue is the risk of losing fescue grasslands in PANP; this is one of few areas of protected fescue; from what we've heard today (i.e. forecasts of spread of grasslands at expense of forest) this shouldn't be much of an issue provided remaining grassland pockets are big enough to include species diversity.
- What's going to happen in the area around PANP and how this will impact on local strategies, for example, to manage bison; we need to build on regional forecasted changes and future conditions.
- Lag times and timing of change: when will we actually see the projected changes on the landscape and in the vegetation? What will be the trajectory; rather than an equilibrium analysis (as if started from 'zero'); lags are crucial. The time lag for responses of ecosystems to climate is an important question for regeneration. How successful is regeneration under different climatic scenarios?
- Do we want to leapfrog and try to achieve targets ahead of time based on future climate scenarios, or do we want to try to maintain the vegetation types best for

present conditions in anticipation of possible changes back to present conditions sometime after climate change is ameliorated?

- We need to know how much of a priority this is and how quickly things will change; *e.g.* if we burn an area will trees not be able to successfully re-establish?
- Parks Canada's concern is representivity of forest ecosystems, rather than productivity; your productive species might be our weed. What is going to be 'native' down the line? Do we allow equilibrium to re-establish with new species range changes? Parks Canada would have concerns about bringing in foreign ecotypes, or even trees like ponderosa pine; these are 'weeds' by Parks Canada standards.
- We need landscape level models of vegetation mosaics: shifts in relative proportions of different stand types, and modeling of how stands (assuming they are made up of certain species) will perform under different climate scenarios.
- What are the mechanisms behind the decline of white spruce during the drought of the past three years?
- There is too much variability and uncertainty. Risk management: how do we prepare for risk without knowing what that risk will be; what the actual scenario will be?
- Are there suites of options that we should be incorporating into our sensitivity analyses, *e.g.* fewer frost days so fewer winter haul days; fewer ice bridge options?
- An individual park may not be able to maintain current ecosystems, but the whole system might accommodate them somewhere else. Parks Canada's ultimate goal is biodiversity; maybe we need to consider keeping all the pieces somewhere even though they might get moved around in the system.
- We made need to choose new parks and protected areas to accommodate our preservation goals based on a future scenario of species distributions … management issues are identified at local levels and then policies have to be developed at a higher level to address these. We need a body of evidence that is overwhelming before these questions are addressed at the program level.
- The national parks system is based on spatial scenarios to preserve representivity of pieces of geography/landscape that have been in place over the last little while; this goal is not temporally based over longer time scales. This is the real issue—you put a park in place at a certain time to represent what's there now, but things are changing, and have to think system-wide about priorities.

We have maintained contact with stakeholders through the project web site <http://parc.ca/cciap/CCIAP.htm> where information is available about the stakeholder workshops, including the power point presentations given by project personnel and collaborators. An "Other Documents" section of the web site includes the project proposal, progress reports, an image gallery and videos showing annual change in the Normalized Difference Vegetation Index for Saskatchewan, and modeled global temperature change for 1990-2100.

Climate and Impact Scenarios for the Grassland to Forest Transition Zone

Global climate change is expected to cause dramatic shifts in biogeograhic patterns and vegetation dynamics within the next 50-100 years, including major disruptions to both the northern and southern boundaries of the boreal forest (Hogg and Hurdle, 1995; Price and Apps, 1995; Hogg, 1997). Projected changes include increased forest fire frequency and outbreaks of insect and disease (Hogg *et al.*, 2001; Johnston *et al*, 2001). Anthropogenic impacts - logging, mining and agriculture practices, road creation, and urban development - will undoubtedly continue, and interact with climate change to modify ecosystems. The southern boreal forest may be most severely affected by this suite of disturbances given the proximity to human populations (Johnston *et al*, 2001). Therefore, change in the distribution and composition of grassland and forest ecosystems will be driven by the impacts and interaction of human and natural disturbances, climate variability and climate change.

Vegetation Zone Response to Climate Change

Models that link vegetation zones to climate change suggest a northward shift in the forest/grassland boundary in the Prairie Provinces (Hogg 1994; Vandall *et al.,*2006). Most of the boreal forest up to 54° latitude is replaced by aspen parkland and the present aspen parkland is replaced by mixed grass and fescue prairie. As species relocate at different rates, the composition of these vegetation communities will change. Vandall *et al. (*2006) suggested the following future trends:
- Reduction in tree growth in the forest regions to the slower growth and lower maximum size typical of the aspen parkland
- Regeneration failure in dry years in the forest region
- Gradual reduction in tree cover and expansion of grassland patches in the forest region
- Shrinking of aspen groves in the aspen parkland
- Reduced invasion of grassland patches by shrubs and poplar sprouts in the aspen parkland
- Decreasing shrub cover in aspen parkland and mixed prairie
- Decreases in animal species dependent on woody cover, and increases in species dependent on open grassland
- Shifts in structure of grasslands: decrease of midgrasses, increase of shortgrasses
- Decrease in cool-season (C_3) grasses, increase in warm-season (C_4) grasses
- Gradual introduction of plant and animal species currently found only in the U.S.

Models that simulate future vegetation are based largely on existing distributions of plant species and the current (static) positions of ecoregions (*e.g*., Davis and Zabinski, 1992). The boundaries between natural regions could shift abruptly with droughts and associated large-scale disturbance events (fire, insects and disease). Plants will encroach on previously unsuitable sites that have become more tolerable, but may also retain some unsuitable conditions, such as soil related to the previous climatic regime: "Many plants

have an astonishing ability to persist in unfavourable environments." (Pielou, 1991). Persistence in the face of major environmental change may only be a prelude to sudden and rapid change. Ecosystems can absorb stresses before crossing a critical threshold beyond which there is an abrupt response to climate change (Anderson *et al.,* 1998; Saporta *et al.,* 1998). Paleoecological studies have shown that the range of boreal tree species has shifted by 200 to 300 m per year during postglacial times (Davis, 1983), however, tree populations may become extirpated if migration rates cannot accommodate future disturbances and rates of climate change (Solomon and Kirilenko, 1997). Therefore, it is critical to determine whether and how vegetation is currently responding to climate changes.

Future Climate Scenarios

The pattern of global warming forecast by most climate models shows the largest increases in mean annual temperature occurring in the high latitudes of the Northern Hemisphere (IPCC, 2001: Figure 4). This zone of maximum heating dips to lower latitudes in the continental interiors, including the Canadian Prairie Provinces. A projected outcome of this warming of the earth's mid-continental regions is summertime drying as elevated potential evapotranspiration from higher temperatures is not offset by increased precipitation (Gregory *et al.,* 1997: Wetherald and Manabe, 1999: IPCC, 2001, WG I: 572-73). Consistent with these projections, temperature records from climate stations in the Prairie Provinces have had significant positive trends especially since the 1970s. Figure 5 is a plot of mean annual temperature for Prince Albert, Saskatchewan since 1895. The increase is more than 1.0 º C.
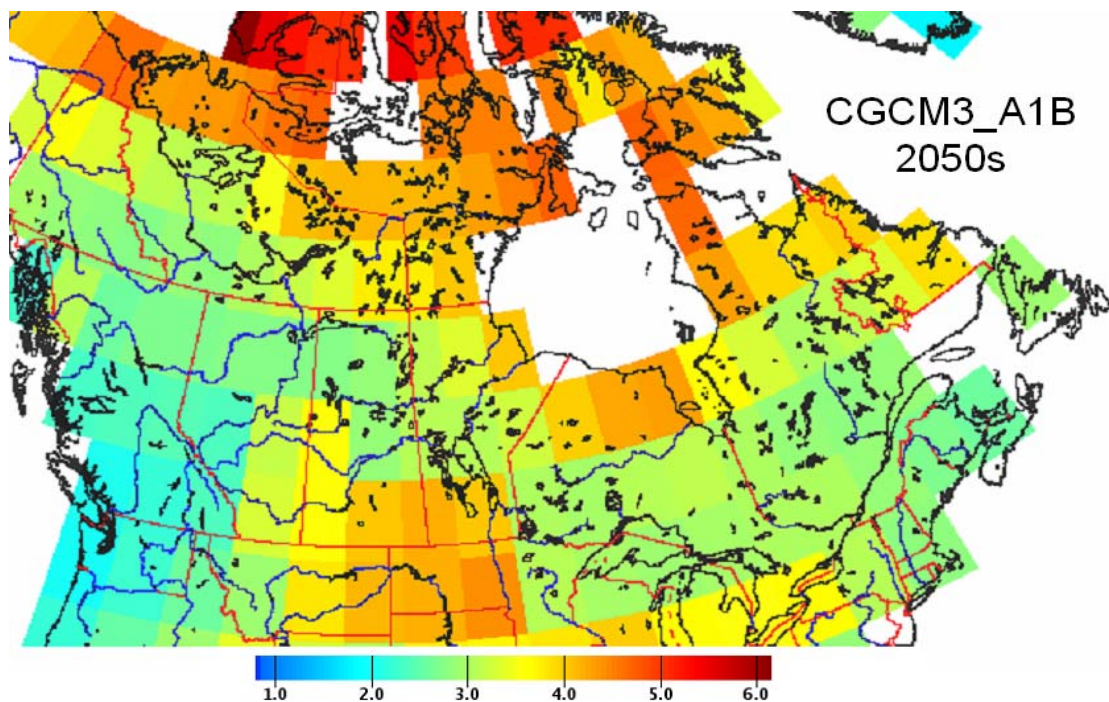
Figure 4. Change in mean annual temperature from 1961-90 to 2040-69 as projected for Canada by Canadian GCM ver 3, GHG emission scenario A1B.
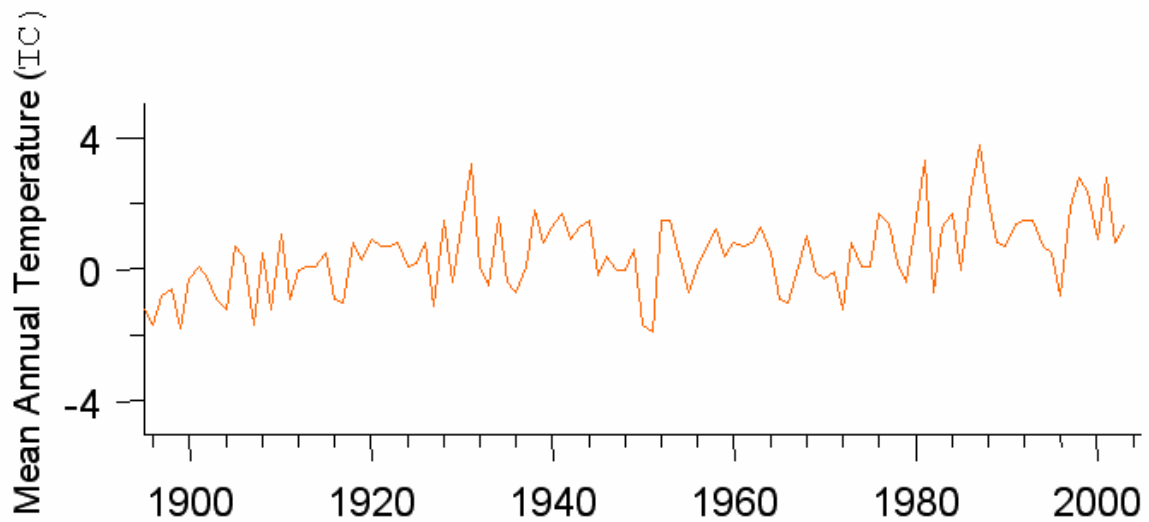
Figure 5. Mean annual temperature, Prince Albert, Saskatchewan, 1895-2005.

The major impact of global warming in the Prairie Provinces will be a shift in the distribution of water resources among basins, seasons and years (Sauchyn *et al.,* forthcoming). Therefore the key climate parameters for assessing climate risks are those that depict the hydrology and hydroclimate. The climate moisture index (CMI) is a measure of water deficit (surplus) in terms of the difference between total monthly precipitation and monthly potential evapotranspiration (P-PET). Hogg (1994) was able to reproduce the present distribution of the vegetation of the Prairie Provinces using the CMI for the period 1951-1980. Hogg and Bernier (2005) mapped the present and future extent of drought-stressed forest in western Canada using CMI data from weather stations (1961-90) and a GCM scenario (2041-70). Figure 6, from Hogg and Bernier (2005), illustrates that the Aspen Parkland is presently drought stressed and that a large part of the boreal forest will be drought stressed by 2041-70.
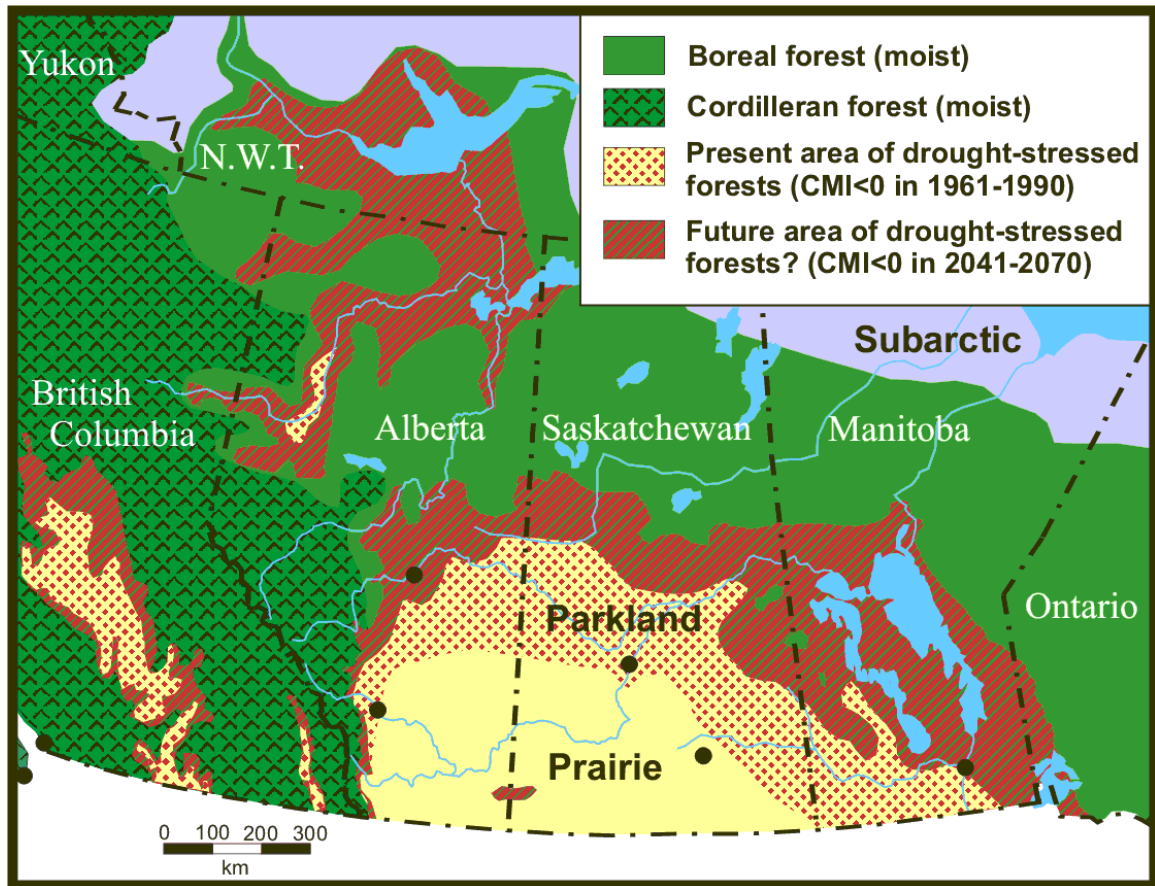
Figure 6. Present and future drought-stressed areas in western Canada (from Hogg and Bernier, 2005).

Hogg (1994) and Hogg and Bernier (2005) used the Jenson-Haise and simplified Penman-Monteith methods for calculating PET. For our analysis of the historical and future moisture status of grassland and forest ecosystems in central Saskatchewan, we used the Thornthwaite (1948) method of estimating annual PET based on the relationship between PET, temperature and shortwave radiation (number of sunlight hours per month). Little input data are required, only monthly mean temperature, total precipitation and latitude. The Thornthwaite formula is

$$PET = 1.6(T/I)^a$$

where,

PET is potential evapotranspiration (cm/month)
T is monthly mean air temp (º C)
$a = 0.49 + 0.0179\ I - 7.71 \times 10^{-5}\ I^2 + 6.75 \times 10^{-7}\ I^3$
I (annual heat index) $= \Sigma\ (T_i/5)^{1.5}$, i: month

Monthly historical precipitation and temperature data, interpolated to a 50 km grid, were obtained from the Canadian Climate Archive (www.cics.uvic.ca/climate/data.htm). Climate data are sparse in the Prairie Provinces, particularly in northern unpopulated locations. An extensive record exists only since 1950. Therefore this project focused on 1950-1999 for complete spatial coverage. CMI was calculated at each grid point for August to July which is a more meaningful 12-month period for vegetation than the calendar year. Figure 7 shows average 1961-1990 P-PET (cm) for the Prairie Provinces. For mapping purposes, the gridded 50 km data were interpolated to 10 km resolution using a regularized spline. A CMI of -15 cm corresponds closely to the semiarid mixed grassland ecoregion and -6 cm defines the boundary of the dry subhumid, aspen parkland ecoregion.

Future CMI was derived from the third generation of the Canadian Global Climate Model (CGCM3.1; www.cccma.ec.gc.ca). We chose the SRES (Special Report on Emission Scenarios) A1b, A2 and B1 experiments driven by world growth in population, economies and technology and thus with different effects on future climate. CMI was computed for all 33 CGCM3.1 grid cells that comprise the Prairie Provinces. This approach provides results that are more reliable and consistent than if we processed GCM data for just the few cells that represent the grassland to forest transition zone in central Saskatchewan, because GCMs simulate global not local climate processes.

Scenarios of future CMI were generated by applying differences in temperature and precipitation, between baseline and future periods, to observed data for the same baseline period. The observed 1950-1999 CMI 50 km grid was interpolated to match the CGCM3.1 resolution of 2.8 degrees. Precipitation scenarios were derived by computing the ratio of the mean value (*e.g.* monthly or annual) for a future time period (*e.g.* 2020s) to the baseline (*e.g.* 1961-99) and then applying this ratio to the instrumental data from 1961-90. Temperature scenarios were derived by adjusting the observed record according to the difference between modeled mean values for the future and baseline time slice or 1961-90. The CMI for the 2020s (2010-3029), 2050s (2040-2069) and 2080s (2070-2099) is mapped in Figures 8-10 for the SRES experiments A1b, A2 and B1, respectively. All scenarios show the semiarid and dry subhumid grassland region expanding to the north and east. Much of shift in vegetation zones is projected to occur within the next 30 years. The least change in moisture conditions is projected with the A1b emission scenario; the B1 scenario simulates the most expanded aridity.

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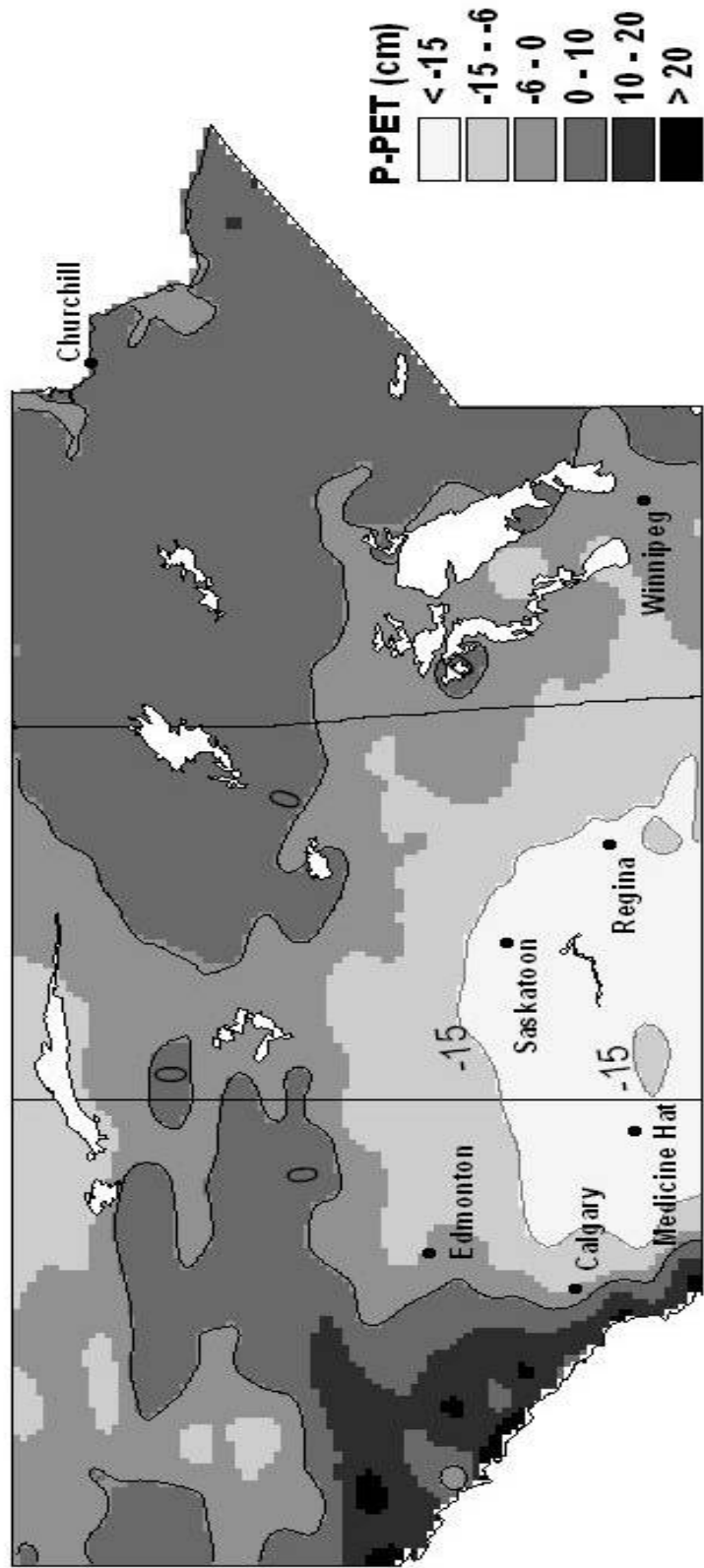
Figure 7. Average annual P-PET for 1961-90; the -15 cm isoline describes the semiarid mixed grasslands ecoregion and the -6 cm isoline defines the boundary of the dry subhumid aspen parkland ecoregion.
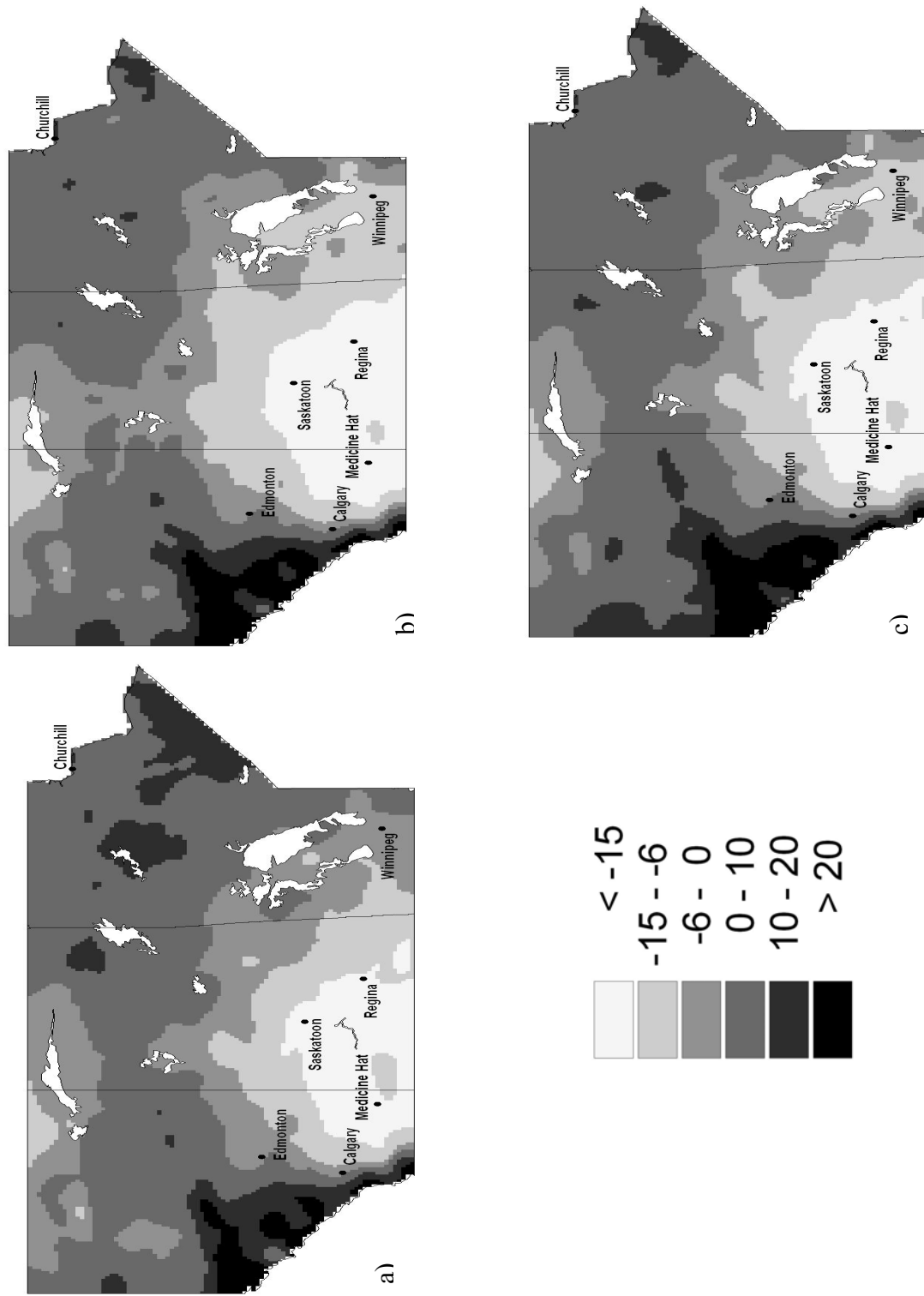
Figure 8. CMI (P-PET in cm) scenarios from the GCM3.1, SRES experiment A1b, for the a) 2020s, b: 2050s and c) 2080s.
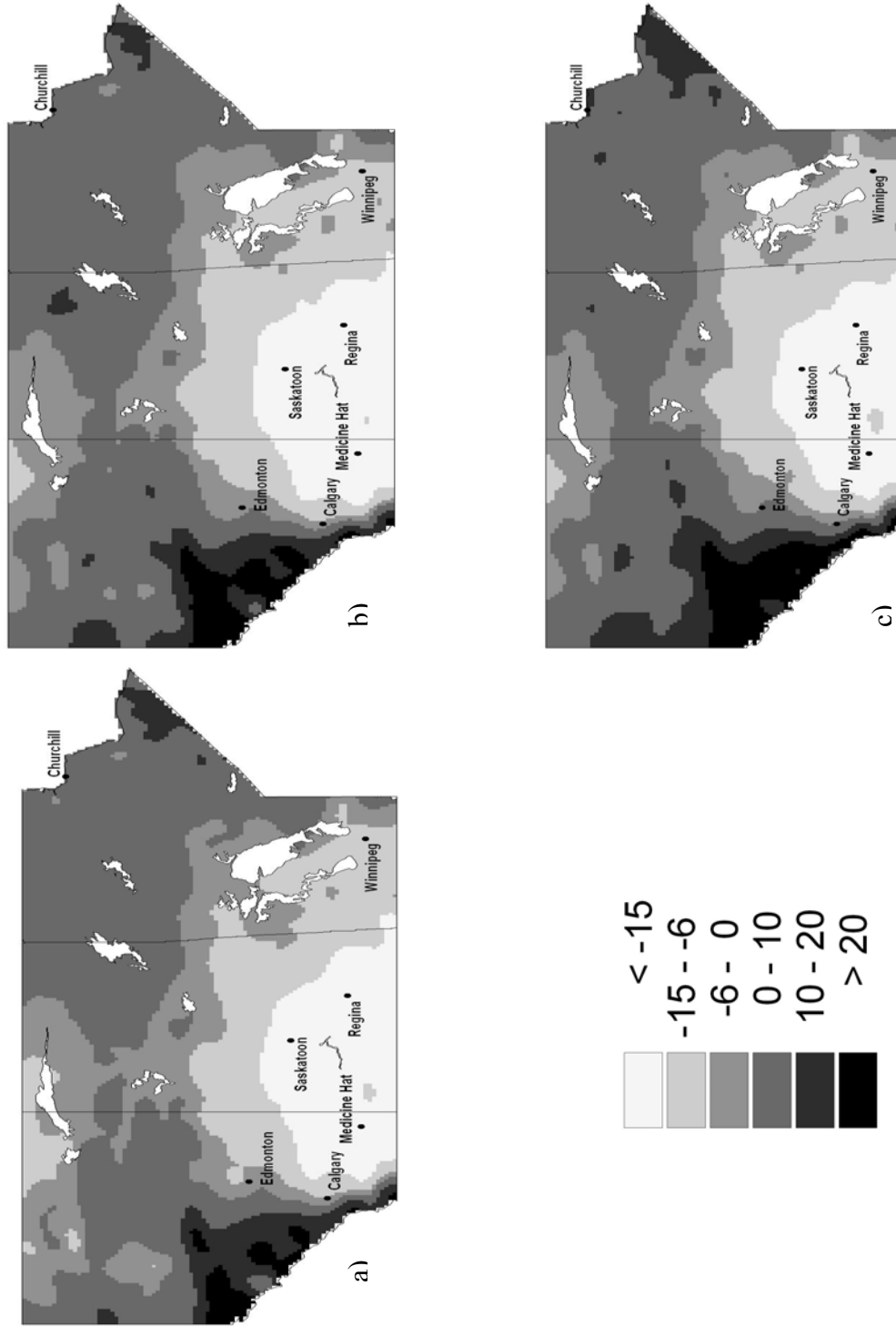
Figure 9. CMI (P-PET in cm) scenarios from the GCM3.1, SRES experiment A2, for the a) 2020s, b: 2050s and c) 2080s.
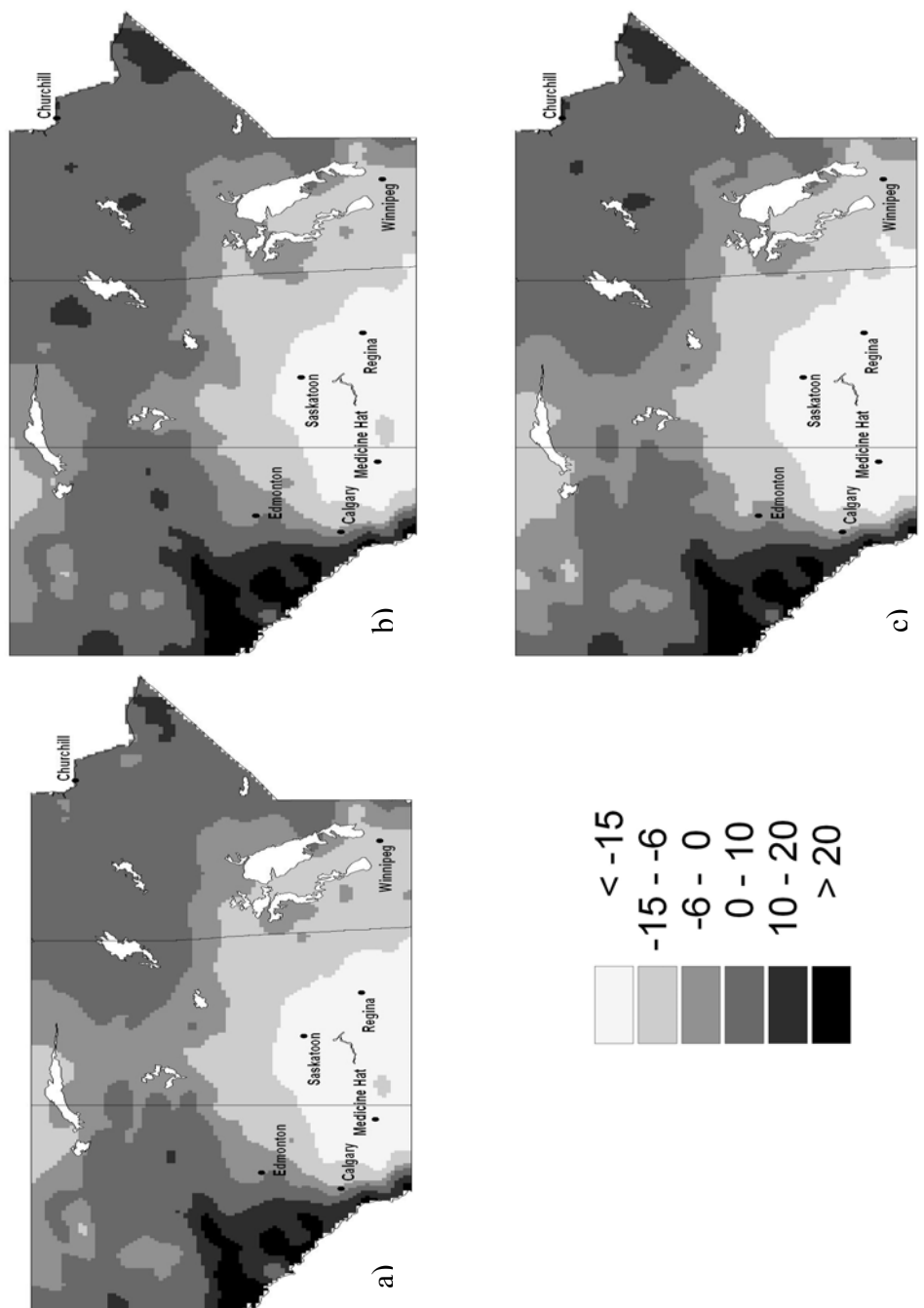
Figure 10. CMI (P-PET in cm) scenarios from the GCM3.1, SRES experiment B1, for the a) 2020s, b: 2050s and c) 2080s.

Investigations of Climatic and Ecological Variability

Primary Productivity: Spatial and Temporal Analysis of Productivity (NDVI) in relation to Climate
Luo (2007)

Introduction

The spatial and temporal responses of terrestrial ecosystems to climate are important indicators of potential impacts of future climate. This is especially true for the grassland-forest transition zone in central Saskatchewan, Canada, where the terrestrial ecosystems are sensitive to climate and have environmental, social, and economic importance (Johnston *et al.*, 2003). Recent studies suggest that the climate of this region will continue to warm and precipitation will increase in this century (Wheaton, 2001). These changes have conflicting implications for vegetation productivity since higher temperatures could increase productivity, yet conversely, productivity may be decreased by reduced soil moisture arising from enhanced evapotranspiration rates (Johnston *et al.*, 2003). Meanwhile, the spatial interactions between grasslands and forests in the transition zone further complicate our understanding of such responses. The responses of the transition ecoregions to climatic conditions are also profoundly affected by the use and management of soil, water, forest and pasture. Understanding how the grassland-forest ecosystems in the transition regions responded to historic climatic conditions will be critical to project their future changes to climate change (Sun *et al.*, 2003; Chen *et al.,* 2004). Particularly, investigating spatial and temporal relationships between terrestrial vegetation productivity and climate factors (*e.g.*, temperature and precipitation) contributes to predicting short-term vegetation productivity (Dalezios *et al.*, 2002; Hunting *et al.*, 2003) and estimating the long-term trend of ecosystem changes (Malmstrom *et al.*, 1997; Ichii *et al.*, 2001).

High temporal resolution Earth observation satellite data, available since the 1980s, provides new input to simplify the estimation of vegetation productivity and identify major trends in vegetation growth at a regional scale. The Normalized Difference Vegetation Index (NDVI), derived from multispectral remote sensing imagery (Figure 11), is generally recognized as a good indicator of terrestrial vegetation productivity (Tucker and Sellers, 1986; Goward and Dye, 1987; Prince 1991). During the past two decades, many studies have used NDVI to monitor the response of vegetation to climatic fluctuations for terrestrial forest and grassland ecosystems (Townshend *et al.*, 1986; Sarkar and Kafatos, 2004). For example, average growing season NDVI values were highly correlated with precipitation received during the current growing season and seven preceding months in the central Great Plains of the USA (Wang *et al.*, 2001). The NDVI values for forest and grassland ecosystems are related not only to climate factors but are also influenced by other environmental controls such as geomorphology, soil type, and soil moisture (Farrar *et al.*,1994).

Drought indices are good surrogate measures of soil moisture content. The Palmer Drought Severity Index (PDSI) is a combined representation of both temperature and precipitation and is widely-used in North America (Palmer, 1965). The PDSI operates on a monthly time series to produce a single numerical value between +4 and -4, representing the severity of wetness or aridity (respectively) for each month.
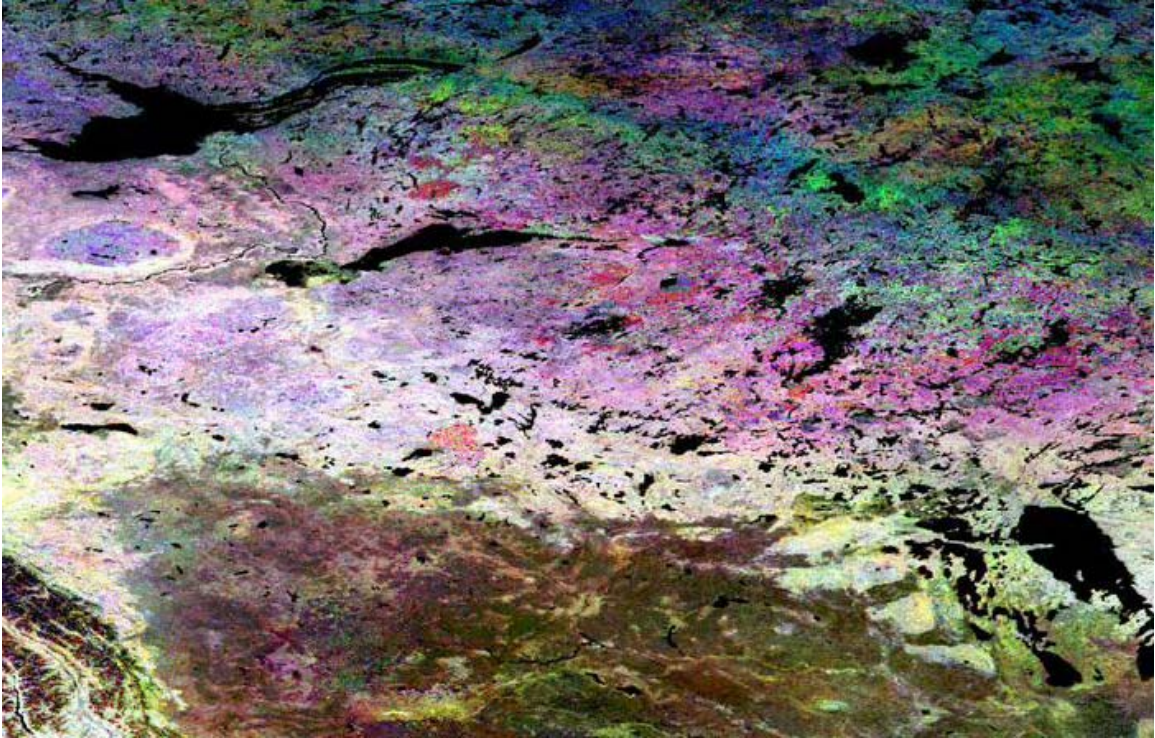
Figure 11. A NOAA AVHRR NDVI image of the western interior of Canada. The Cordillera is in the lower left (southwest), the plains are across the south (bottom) and left (west) and the Canadian shield is in the upper two-thirds of the image. The brown tones in bottom third of the image reflect the higher productivity of the forest and grassland vegetation of the Boreal Transition ecoregion versus the Boreal Shield.

Methods

This study investigated the major trends of NDVI from 1982 through 2001 and identified correlations between the NDVI and temperature, precipitation and PDSI for the grassland-forest transition zone in central Saskatchewan. Both climate and PDSI data were interpolated at a spatial resolution of 8 km resolution, which is consistent with the spatial resolution of the NDVI data. The results provide early detection of climate change impacts in this climatically sensitive region. The temporal and spatial response of NDVI to climate and drought indices illustrates which climate parameters most impact vegetation growth and where the vegetation is most sensitive to climatic conditions and soil moisture levels.

Datasets

NOAA satellites from NOAA-6 to NOAA-17 contain the Advanced Very High Resolution Radiometer (AVHRR) sensor. The swath width of AVHRR is 2400 km and the ground resolution is 1.1 km at nadir. The AVHRR has five spectral bands which include one visible band (band 1, 0.58-0.68μm), one near-infrared band (band 2, 0.72-1.10μm), and three thermal bands (band 3, 3.55-3.93μm; band 4, 10.3-11.3μm; band 5, 11.5-12.4μm).

Satellite data from the NOAA AVHRR sensor are available since 1982 and provide high temporal resolution (every 10 days) and medium spatial resolution (8 km) for monitoring land cover and vegetation changes. AVHRR data can be decomposed into NDVI images (Figure 11), which allow researchers to study global or regional vegetation characteristics and estimate vegetation productivity. The NDVI is calculated as the difference between near-infrared (NIR) and visible (VIS) reflectance values normalized over the sum of the two variables (Eidenshink and Faundeen, 1994):

$$NDVI = \frac{NIR - VIS}{NIR + VIS}$$

The NDVI has been shown to be strongly related to photosynthetic activity because the internal mesophyll structure of healthy green leaves reflects near-infrared radiation, while leaf chlorophyll and other pigments absorb a large proportion of the red visible radiation (Gausman, 1974; Sellers, 1985, 1987; Tucker and Sellers, 1986). It has been widely used to estimate landscape patterns of primary production and biomass (Gausman, 1974; Sellers, 1985, 1987; Wang *et al*., 2001, 2003). NDVI values range from -1.0 to $+1.0$, where increasing positive values indicate increasing green vegetation (and primary productivity and biomass) and negative values indicate non-vegetated features (such as water, bare ground, ice, snow or clouds). If vegetation is under stress due to unfavourable climatic conditions (*e.g.* drought) or other factors, corresponding reductions in NDVI values will be observed.

This project is based on NOAA AVHRR monthly NDVI images for the1982-2001 growing seasons (May-October). The monthly NDVI images were generated from the Global Inventory Modeling and Mapping Studies (GIMMS) AVHRR 8 km bimonthly NDVI data sets (Prinzon, 2002, Tucker *et al*., 2005). Tests of the GIMMS data with measures of vegetation and climate have shown that the GIMMS data are able to capture general patterns of vegetation, inter-annual variations of vegetation, and climate signals (Nemani *et al*., 2002; Jia *et al*., 2003; Lotsch *et al*., 2003; Poveda and Salazar, 2004). Each image includes 110×100 pixels with a resolution of 8 km. 140 NDVI images were generated.

Monthly average precipitation and temperature data (1982-2001) were obtained for 95 stations from the Meteorological Service of Environment Canada. Monthly PDSI data (May-October) for 117 stations were obtained from the National Agroclimate Information Service (AIS) of Agriculture and Agri-Food Canada (NAIS, 2005). The

PDSI was computed by the AIS by coupling the Versatile Soil Moisture Budget (VSMB) (Baier *et al.,*2000) and the original PDSI (Palmer 1965) to improve the simulation of soil moisture on the Canadian Prairies (Chipanski *et al.*, 2006). The monthly climate data (temperature, precipitation, and PDSI) were further interpolated (Inversed Distance Weighted method) into 8×8 km grids consistent with the resolution of the NDVI dataset. Figure 12 illustrates the west to east increase in multi-year growing season average precipitation. Figure 13, the spatial variation of multi-year monthly average PDSI for May to October, shows the areas that were consistently dry (PDSI < 1) and that June tends to be the most drought prone month.
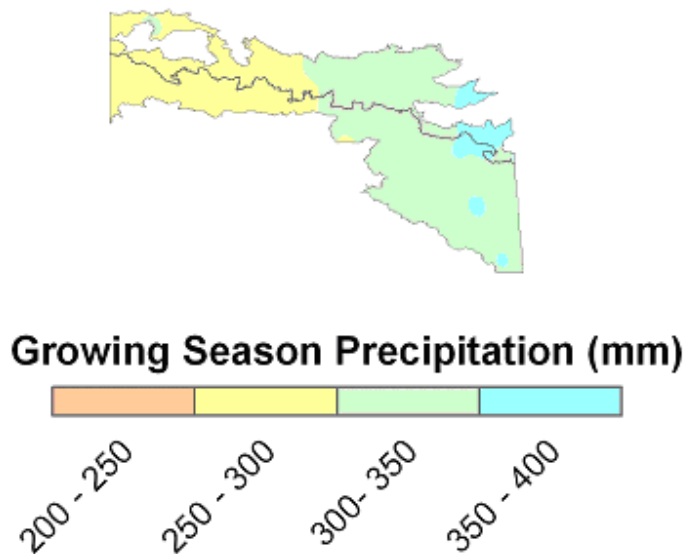
.
Figure 12. Multi-year growing season average precipitation.

Trend Analysis

A linear least squares method is often used to assess the trend in time series (Fuller, 1998). For example, Hicke *et al. (*2002) used this method to study trends in North American net primary productivity with NDVI data for the period of 1982-1998. They found that regional trends in a 17-year record varied substantially across the continent. For our study ecoregions, three sample locations (pixels) were arbitrarily selected representing forest, grassland and cropland. Figure 14 presents time series of NVDI values at each location. It illustrates the annual cyclic patterns. It also shows that the grassland has the lowest multi-year average NDVI value while the forest has the highest. For any year the NDVI value at each location increases rapidly in May and June, reaches a peak during July and August, and drop off quickly in September and October. The grassland NDVI in August 1988 is the lowest for the whole study period (1982 – 2001). This minimum is associated with the serious drought in that year. Figure 14 further shows that the NDVI values for all three land covers have an increasing trend from 1982 to 2001. Thus, it is reasonable to extend the trend analysis for the three locations to the whole study ecoregion.
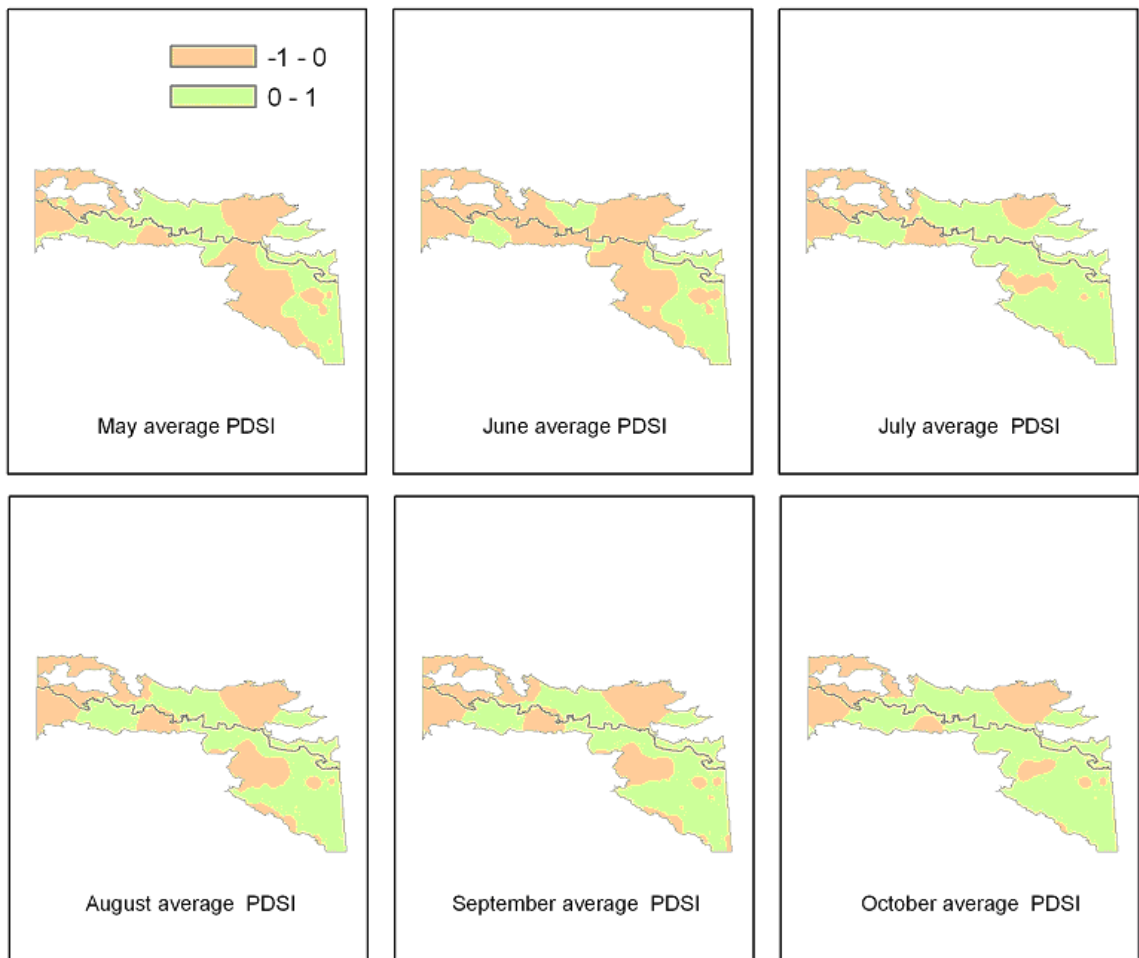
Figure 13. Multi-year monthly average PDSI.
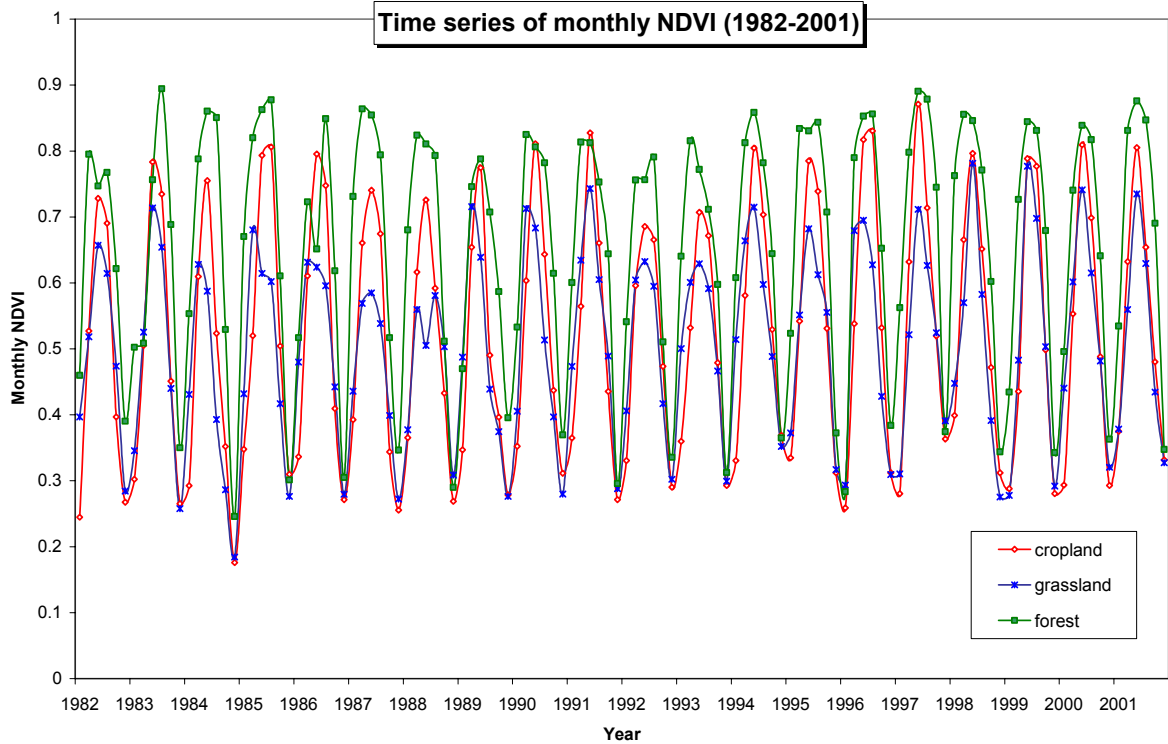
Figure 14. Time series of NDVI for the three sample pixels

Rather than plot time series for all 110 × 100 pixels, the NDVI trend can be expressed using a linear regression model:

$$Trend = \frac{N\sum(Time \cdot NDVI) - (\sum Time) \cdot (\sum NDVI)}{N\sum Time^2 - (\sum Time)^2}$$

Figure 15 illustrates the spatial distribution of NDVI trend from May to October and the growing season. Red/yellow represent high/low positive trend, green represents negative trend, and water bodies are blue. For the growing season, a visual interpretation indicates that most of the transition zone has positive trends in NDVI, that is, a consistent increase in vegetation productivity for the entire study period (1982-2001) regardless of the type of vegetation cover. A negative trend in NDVI is found only in the Prince Albert Plain and the La Corne Plain along the North Saskatchewan River and in the St. Cyr Plain in Boreal Transition Ecoregion. For May and June, the area with negative trend dominates, except for the cropland of the south-eastern Aspen Parkland Ecoregion, where positive trend dominates as crops emerge. From July to October, the majority of the area has a positive NDVI trend, indicating an increase in vegetation productivity from 1982 to 2001. In July, the largest positive trends occurred in the central and southwest Aspen Parkland (close to the boundary with the Moist Mixed Grassland) where grassland is the dominant vegetation cover. On the other hand, NDVI decreased in the Meadow Lake Plain, the St. Cyr Plain, and the Witchekan Plain in the northwest Boreal Transition Ecoregion. In

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August, the northwest Boreal Transition Ecoregion has negative NDVI trends. The largest positive NDVI trends are found in the Aspen Parkland Ecoregion where cropland and grassland dominate. In September, negative trends are limited to the Nipawin Plain; the largest positive trends occur in the west Boreal Transition and in the Mistatim Upland and Hudson Bay Plain in the east Boreal Transition Ecoregion. In October, the whole transition zone displays positive trends in NDVI except a small area in La Corne Plain along the north side of Saskatchewan River. The monthly NDVI trend images show generally positive NDVI trends in early and mid growing season, i.e. increasing quickly from May to a peak in July/August. The increasing trend over most of the transition zone in September and October suggests a lengthening of the growing season.

Previous studies found that it is not possible to say with certainty if climate has driven NDVI increases (Hicke *et al*., 2002), but climate must be considered when explaining increases observed in our study region, where terrestrial ecosystems are sensitive to climate factors. Growing season NDVI increased for the whole study region from 1982-2001. This is an important finding since this trend occurs in all three types of vegetation cover (forest, grassland, and cropland). Differences among vegetation types, before and after July, may relate to various factors such as seasonal climate conditions (temperature and precipitation), soil, pests, and human activities (farming). Monthly variation can be analyzed through correlation analyses between NDVI and climatic variables as well as the drought index (PDSI).
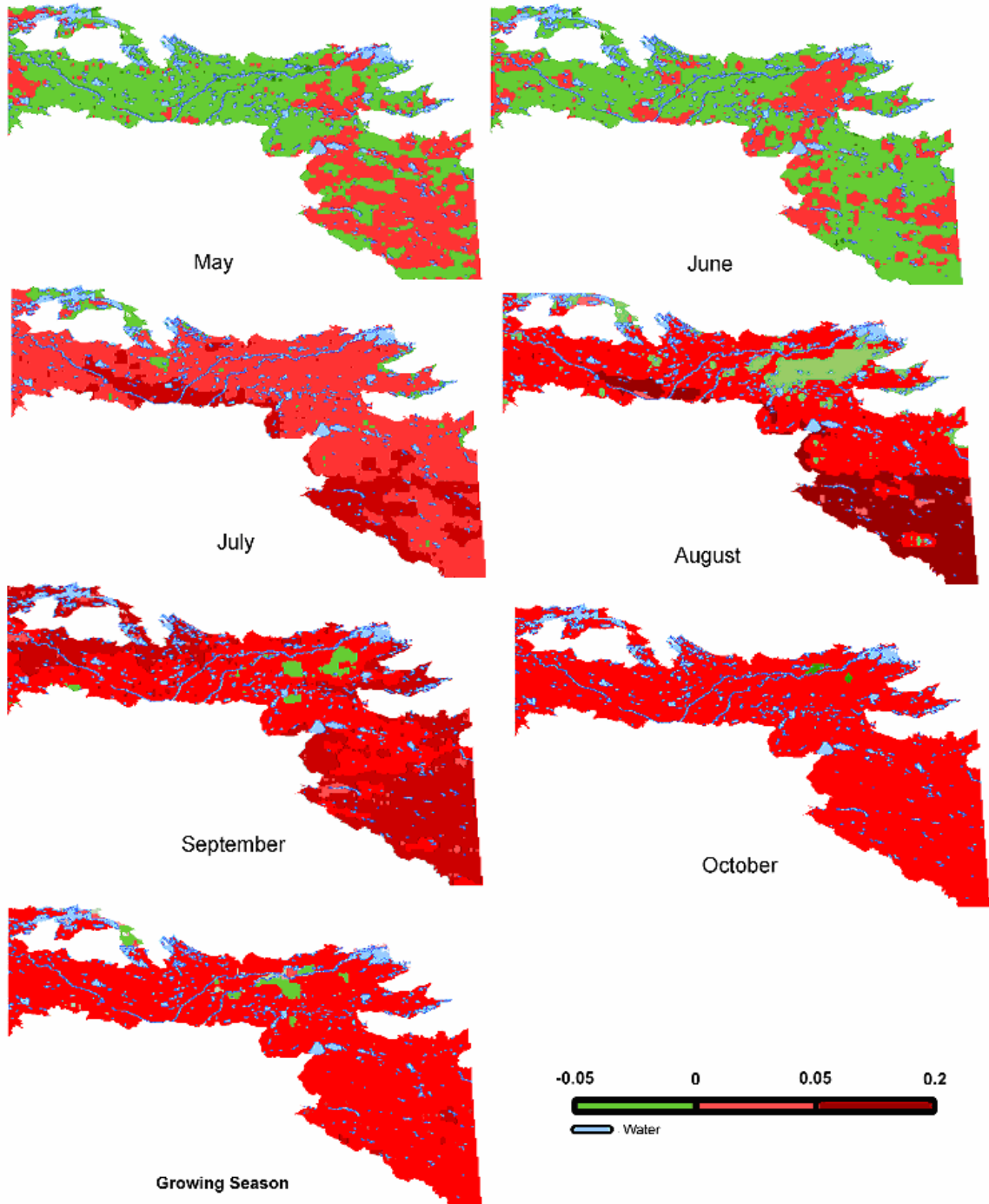
Figure 15. Spatial variations in temporal trend of NDVI (1982-2001)

Correlation Analysis

Correlation analysis is a well-established method to study the relationship between NDVI and climate variables in a wide range of environments and at different scales (Yang *et al*., 1997; Ichii *et al*., 2001; Wang *et al*., 2001). For example, using correlation analysis, Yang *et al. (*1997) found that NDVI-precipitation and NDVI-potential evapotranspiration relationships exhibited time lags, although the length of lag varied with land cover type, precipitation, and soil properties. Ichii *et al. (*2001) conducted a global correlation analysis for NDVI and climatic variables. Their study identified a significant correlation between interannual NDVI and temperature variation in the northern mid- to high latitudes between spring and autumn. For the central US Great Plains, Wang *et al. (*2001) found that temperature was positively correlated with NDVI early and late in the growing season, and biweekly NDVI was correlated with precipitation received during 2-4 preceding biweekly periods.

A preliminary analysis of the relationships between NDVI and climate factors (temperature, precipitation, and PDSI) was conducted for the three sample locations used previously. Figures 16-18 are time series of NDVI with temperature, precipitation, and PDSI, respectively, for the three vegetation cover types. The response of NDVI to precipitation exhibits a lag in that NDVI values were highly correlated with precipitation received in mid growing season.
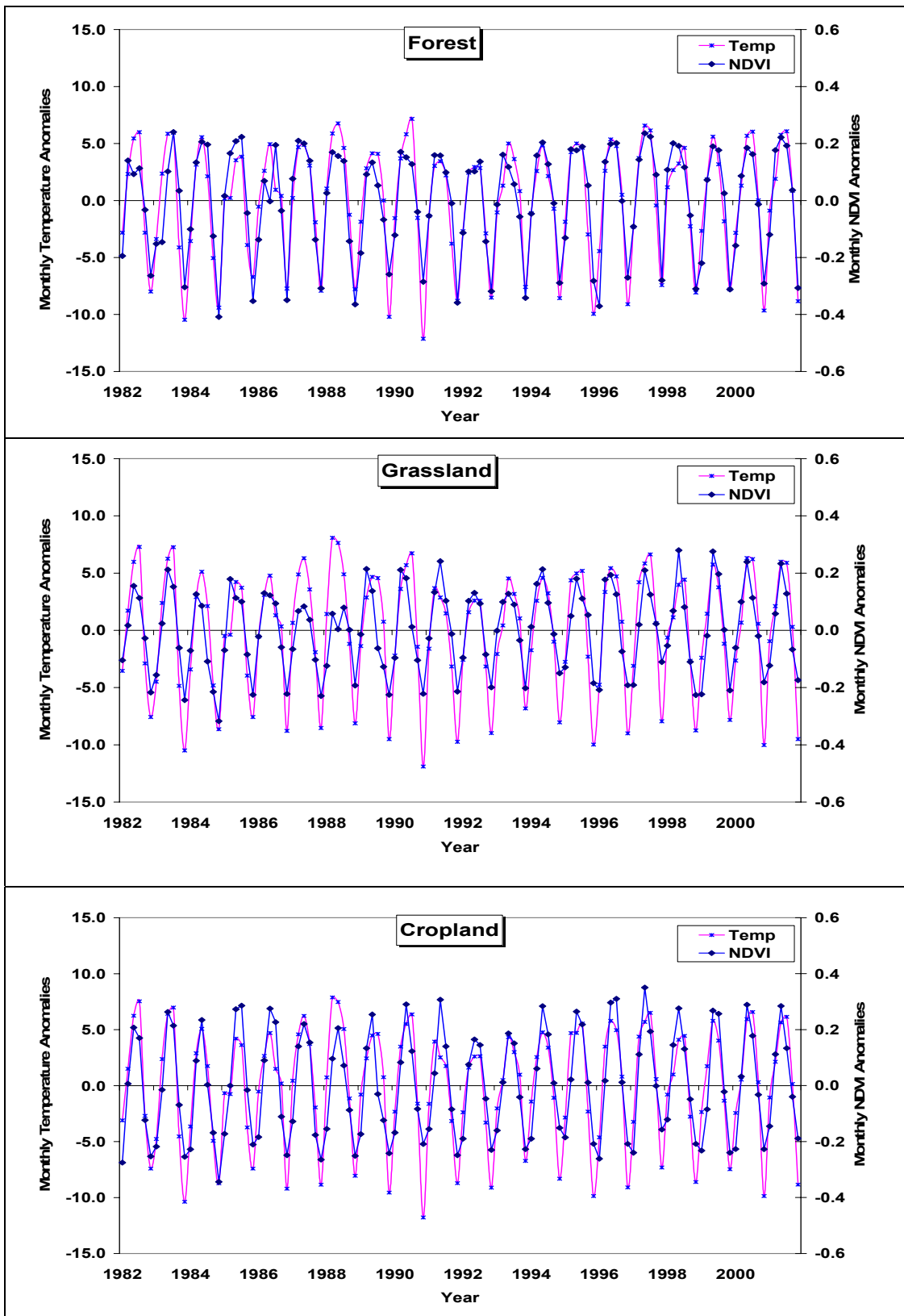
Figure 16. Time series of temperature and NDVI anomaly for three sample locations
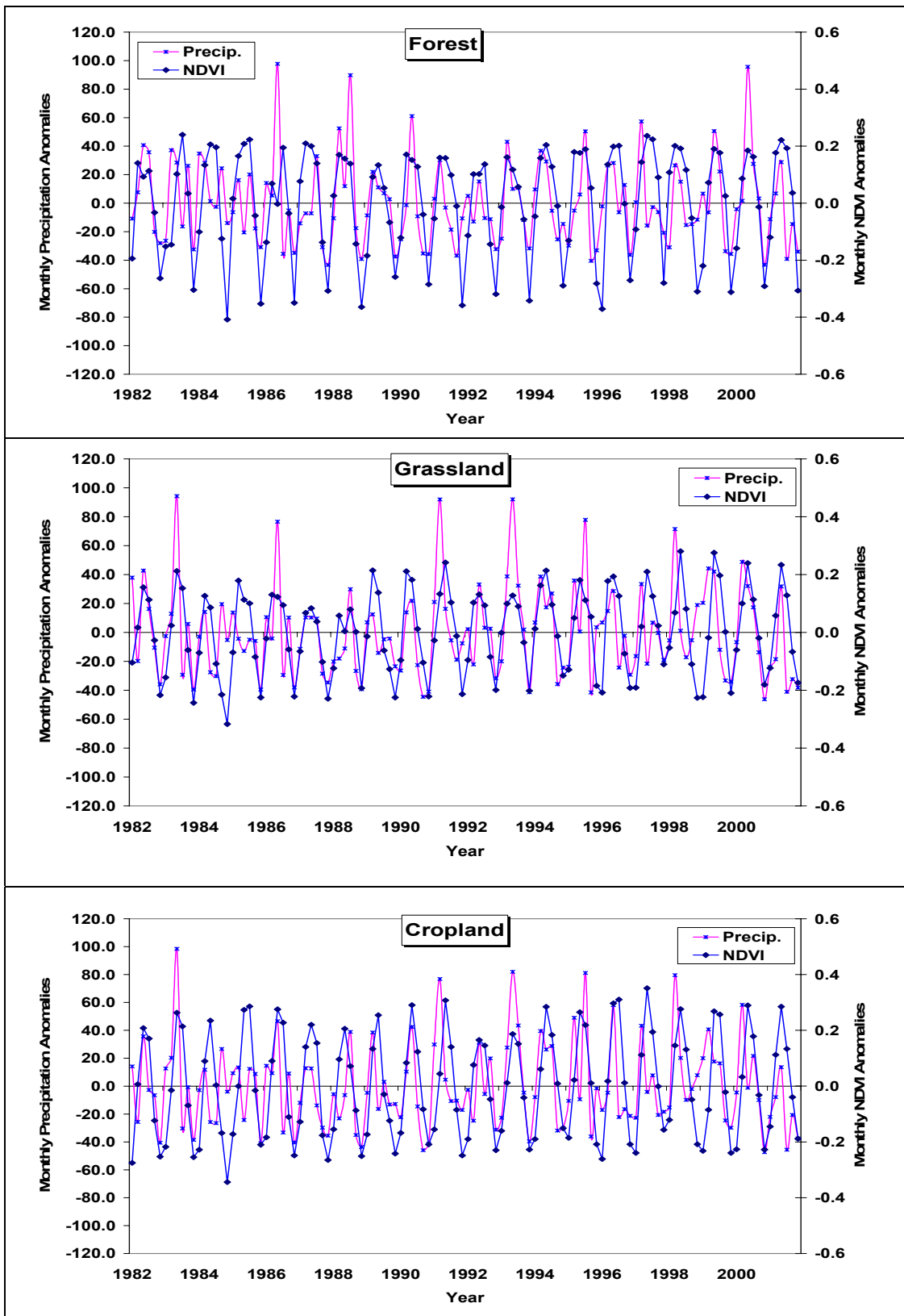
Figure 17. Time series of precipitation and NDVI anomaly for three sample locations
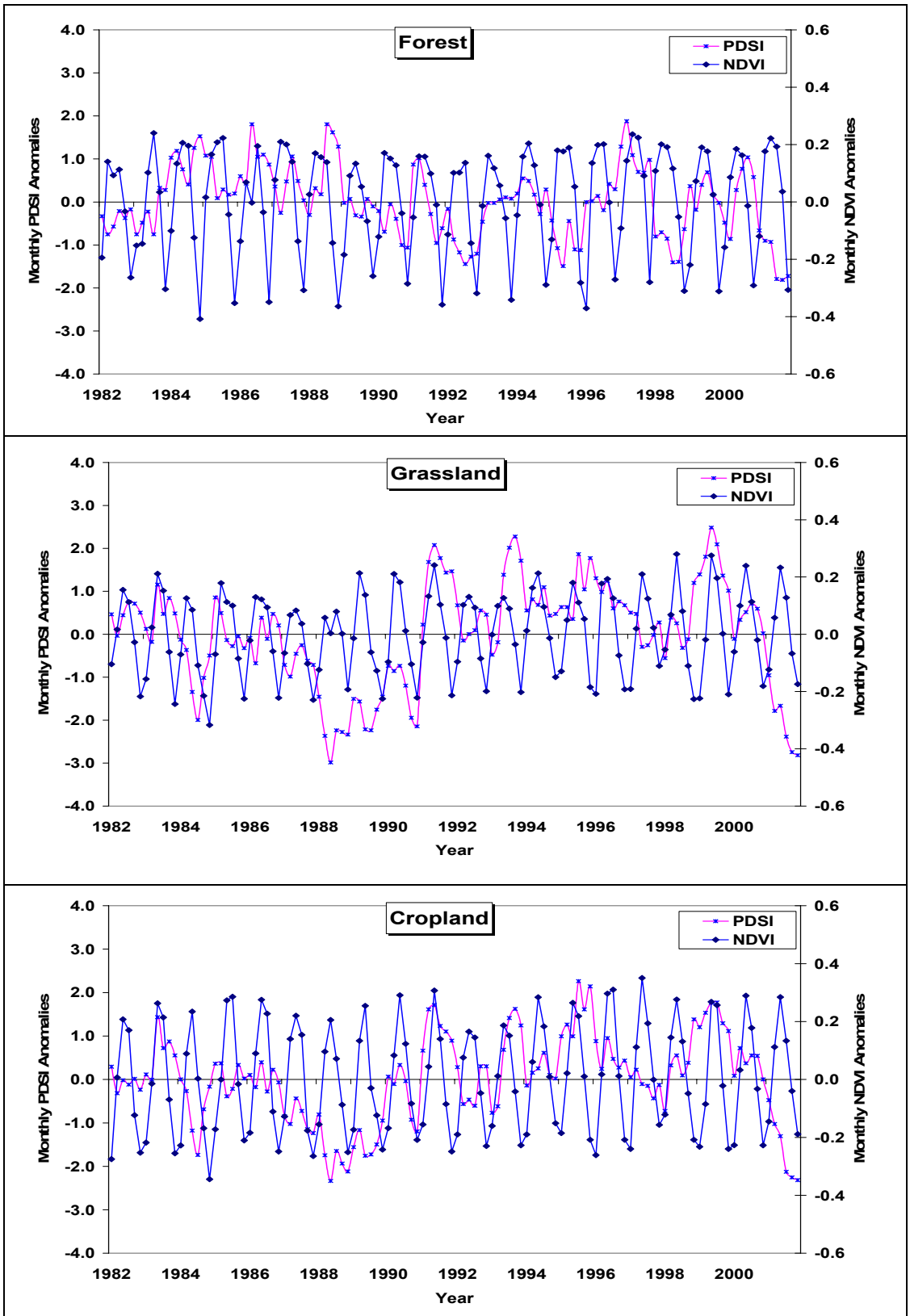
Figure 18. Time series of PDSI and NDVI anomaly for three sample locations

For the whole study region, the correlation of NDVI with temperature, precipitation and PDSI was calculated by pixel for each month from May to October and the entire growing season, for the current month and one and two month lags. New images were then created based on correlation coefficients for each pixel in the whole study region. In each image, two levels of green represent negative correlations and yellow and red display positive correlations. Figure 19 displays the geographic distribution of the correlations between NDVI and temperature. In May, NDVI is highly positively correlated with temperature over the whole study region, indicating that all vegetation greens up quickly in response to temperature increase. These positive correlations become weak during June and July for forest and cropland, while grassland in the western Aspen Parkland still shows a highly positive correlation. From August to October, the correlations between NDVI and temperature were not significant. August NDVI decreased over the 20 years in the Nipawin Plain in the Boreal Transition ecoregion. Cropland dominates this area suggesting that factors other than temperature caused the NDVI change. For the growing season, NDVI is strongly correlated with temperature in the forested area. The NDVI-temperature relationship was not lagged by a month or more. The mean correlation values are highest for forest, and lowest for cropland (Figure 20).

NDVI-precipitation relationships are characterized by a one month lag (Figure 21); during July to September, across the entire study area, the NDVI is positively correlated with precipitation of the preceding month. In August, the area with strong correlations of August NDVI with July precipitation shifts to grassland and cropland. The highest average correlation coefficients are for cropland, and forest has the lowest (Figure 22).

There is no apparent lag time effect on correlations between NDVI and PDSI (Figure 23), but the calculation of the PDSI includes lagged precipitation. The correlations are weak in late spring (May) and early summer (June), with the exception of grassland at Onion Lake Plain in the southwest Boreal Transition. In July, most regions display positive NDVI-PDSI correlations and especially the grassland and cropland. In August, the strong correlations extend over almost all of the southeastern part of Aspen Parkland and cropland area in central Boreal Transition ecoregion. The dominance of the NDVI-PDSI correlation begins to weaken in September, retreating first in the northern areas of the transition zone. For different landcover categories, cropland shows the strongest correlation in NDVI-PDSI; there are intermediate correlations for grassland; and forest shows a weak correlation during the growing season (Figure 24).

May NDVI - Temp

Growing season NDVI - Temp

June NDVI - Temp

August NDVI - Temp

July NDVI - Temp

September NDVI - Temp

■ -1- -0.5
■ -0.5 - 0
■ 0 - 0.5
■ 0.5 - 1
▭ **Sask. transition zone**

October NDVI - Temp
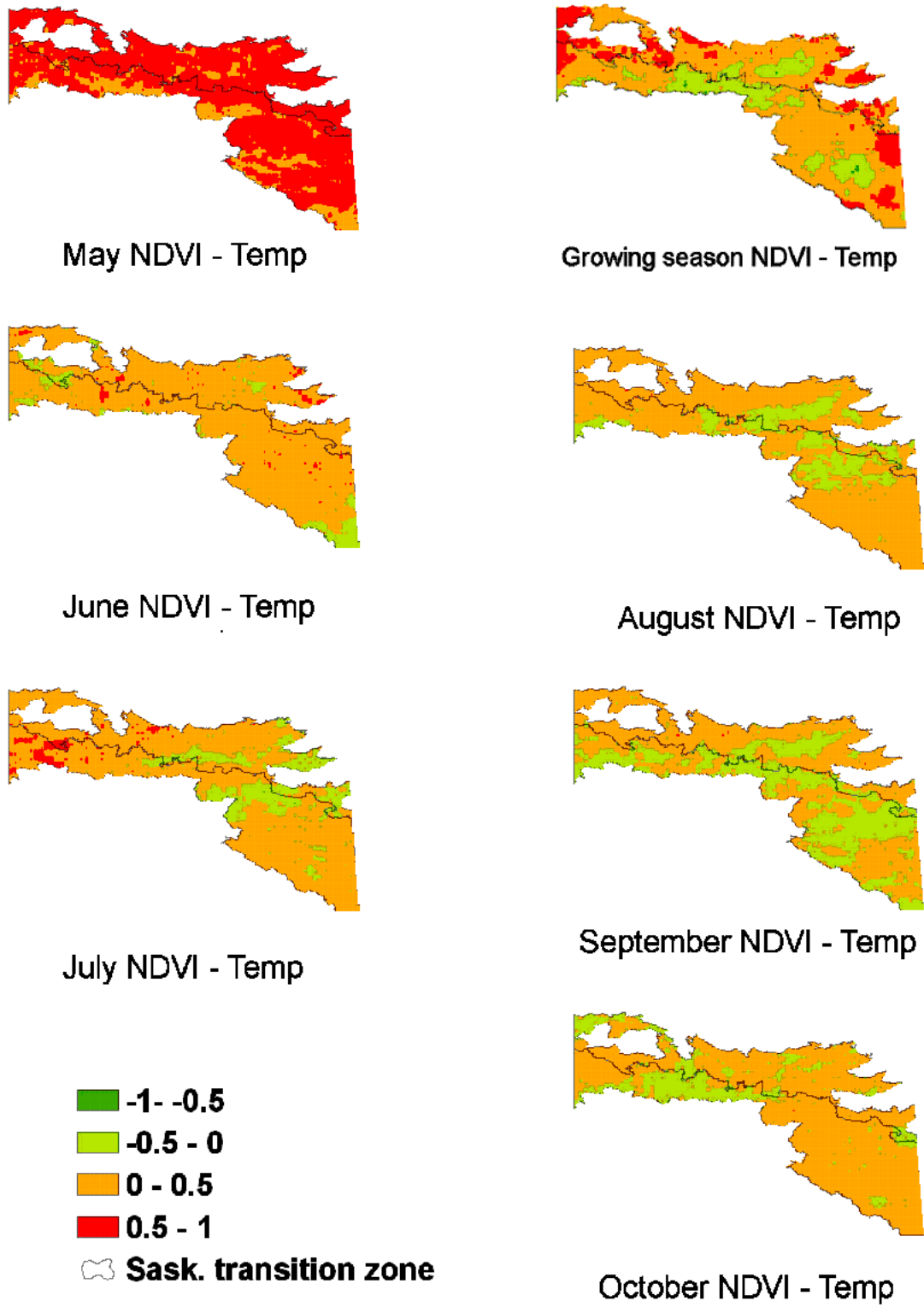
Figure 19. Correlations between NDVI and temperature
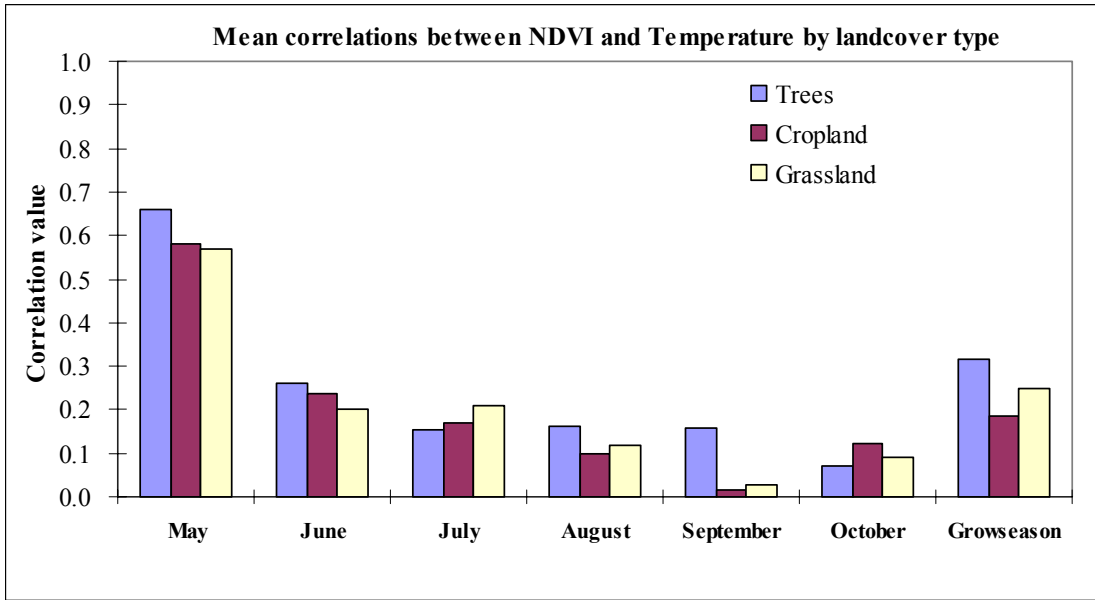
Figure 20. Mean correlation values between NDVI and temperature

May NDVI - Precip.

Growing season NDVI - Precip.
One month Lag

June NDVI - Precip.

June NDVI - Precip.

July NDVI - Precip.

July NDVI - Precip.

August NDVI - Precip.

August NDVI - Precip.

September NDVI - Precip.

September NDVI - Precip.

October NDVI - Precip.

October NDVI - Precip.

- -1- -0.5
- -0.5 - 0
- 0 - 0.5
- 0.5 - 1
- Sask. transition zone
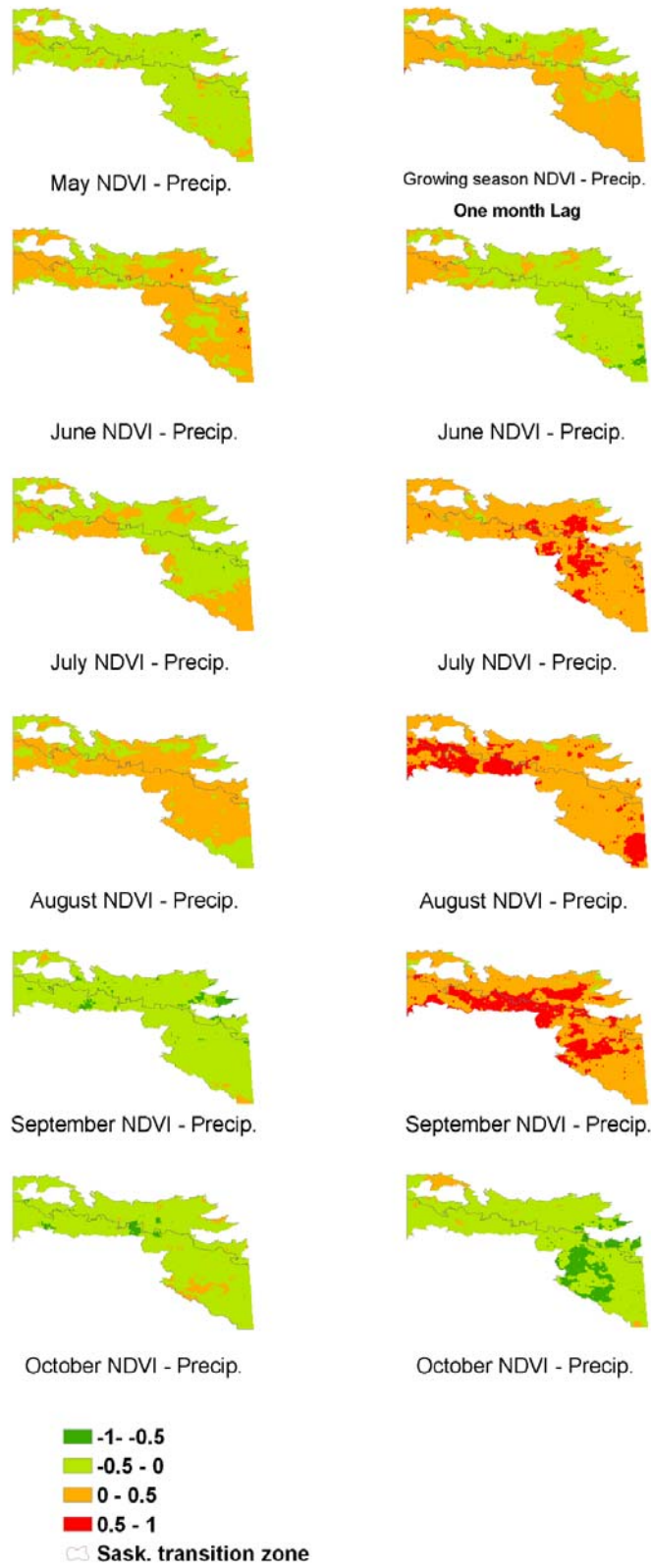
Figure 21. Correlations between NDVI and precipitation
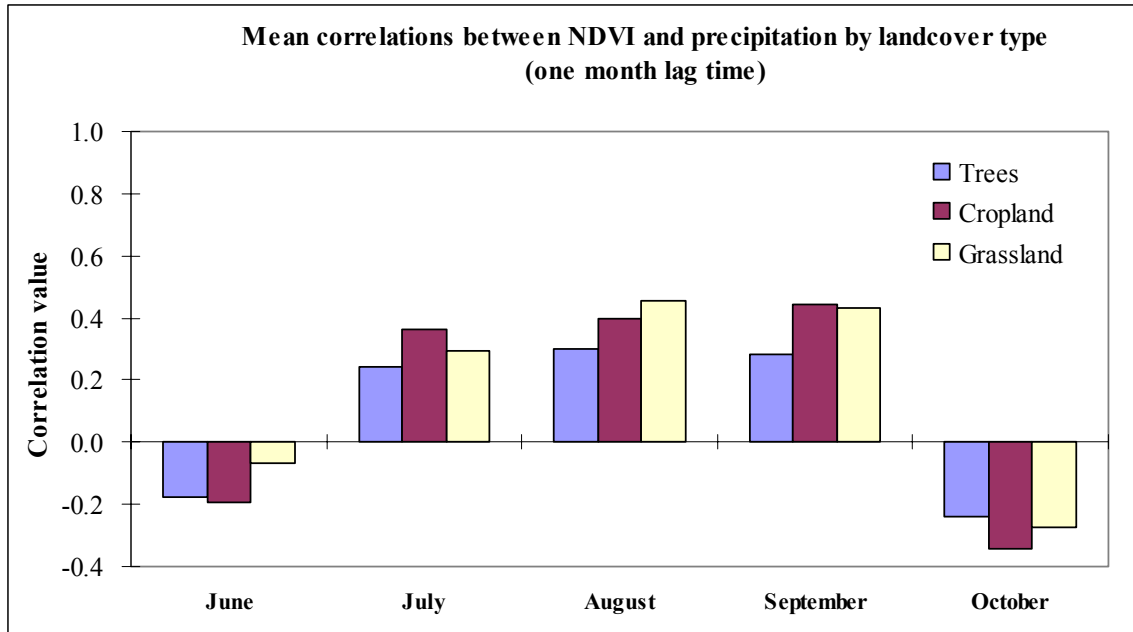
Figure 22. Mean correlation values between NDVI and precipitation

May NDVI - PDSI

Growing season NDVI - PDSI

June NDVI - PDSI

September NDVI - PDSI

July NDVI - PDSI

October NDVI - PDSI

August NDVI - PDSI

- -1- -0.5
- -0.5 - 0
- 0 - 0.5
- 0.5 - 1
- Sask. transition zone
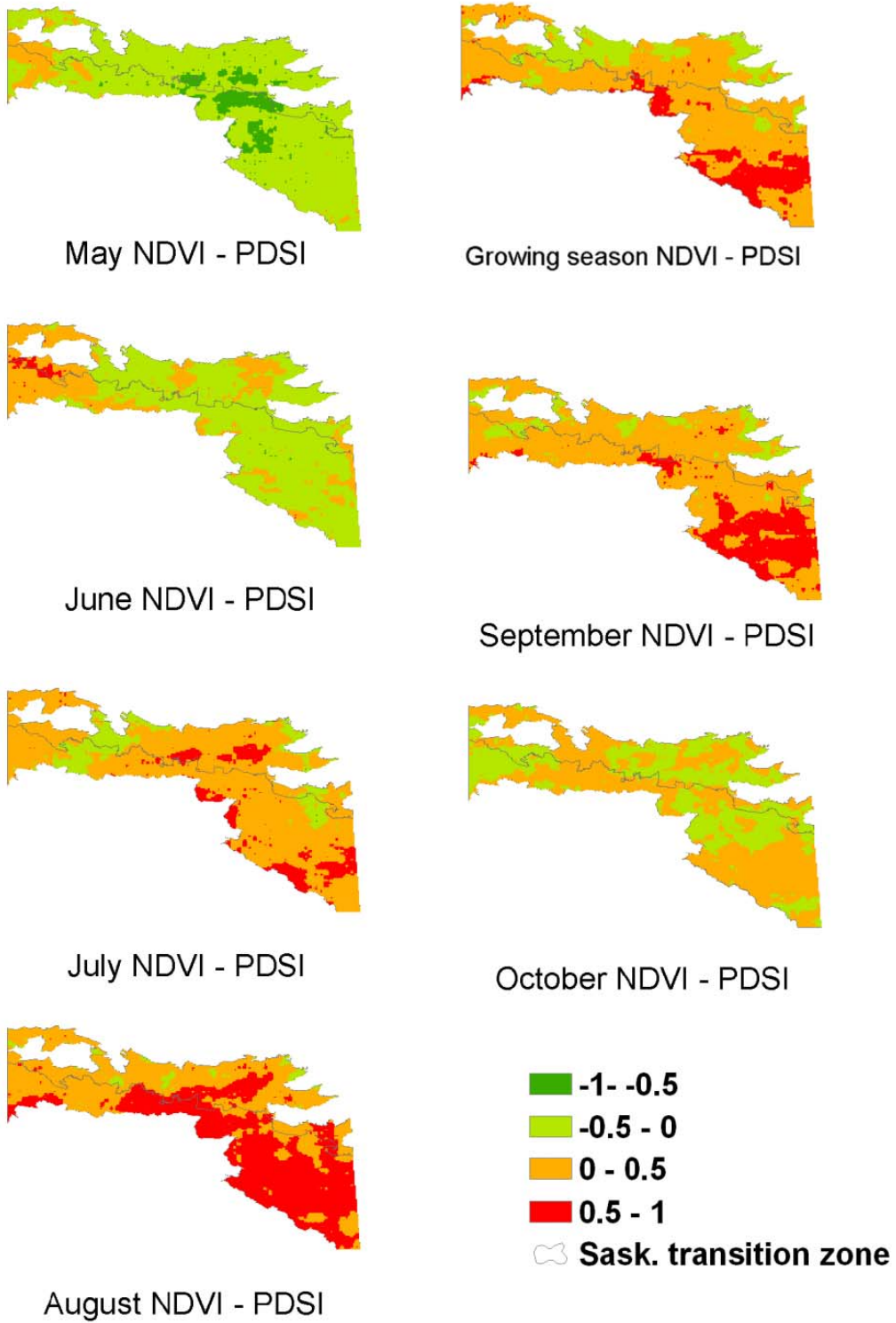
Figure 23. Correlations between NDVI and PDSI
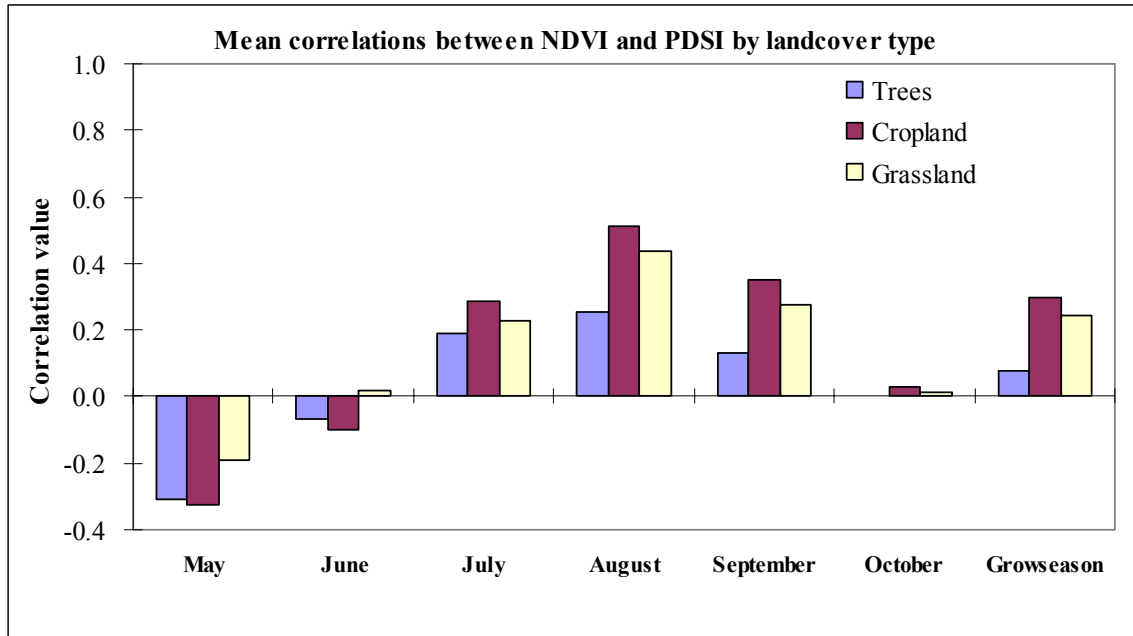
Figure 24. Mean correlation values between NDVI and PDSI

Figure 25 illustrates that in May, NDVI in the forested northern and eastern parts of the Boreal Transition and Aspen Parkland is strongly correlated with temperature, while in the cropland and pasture NDVI is most highly correlated with precipitation. In contrast, maximum correlation in July is between NDVI and PDSI throughout most of the region, with the exception of the NDVI-precipitation correlation in the forested areas of the Boreal Transition ecoregion (Figure 25). For the growing season as a whole (Figure 26), NDVI and PDSI are correlated in the cropland and grassland in the southern Aspen Parkland ecoregion and cropland in the central transition zone. Most of the western and eastern Boreal Transition ecoregion shows the highest NDVI-precipitation correlation.

legend for (a) May:
- temp (yellow)
- prep (green)
- pdsi (red)
- Sask. transition zone

(a) May

legend for (a) July (one month lag):
- Temp (yellow)
- Prep (green)
- Pdsi (red)
- Sask. transition zone

(a) July (one month lag)
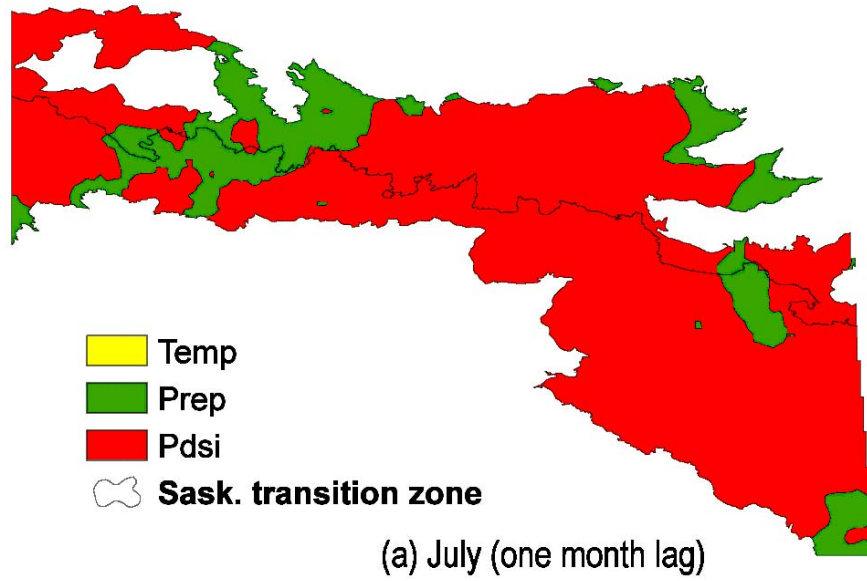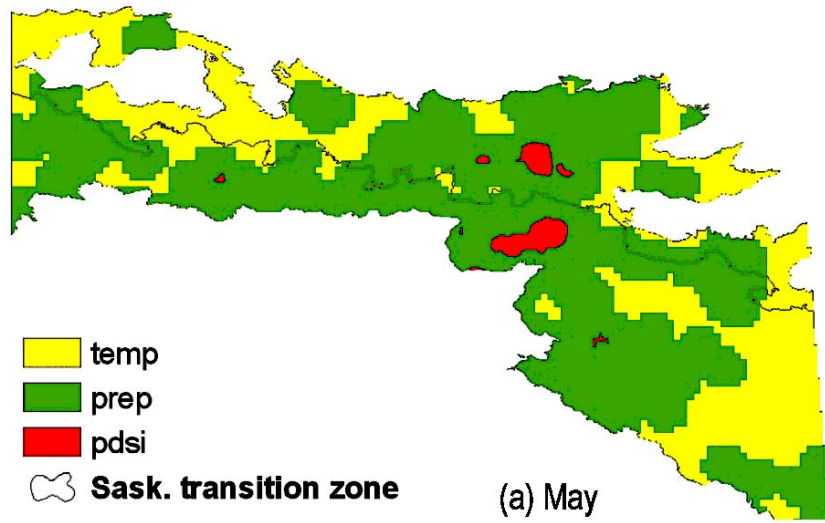
Figure 25. Maximum correlations between NDVI and the climate and PDSI variables in May and July.
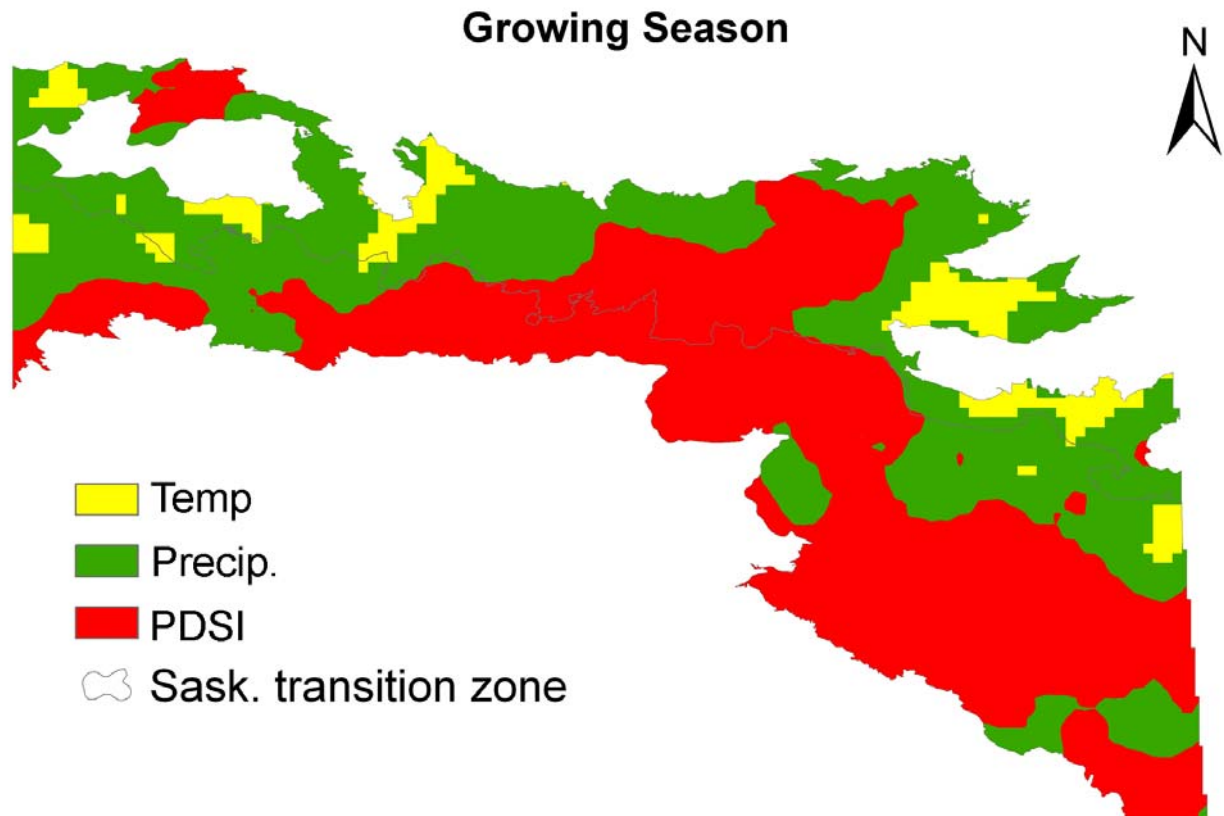
Figure 26. Maximum correlations for the whole growing season.

Discussion

The results of this study show that correlations between NDVI and three climate variables (temperature, precipitation, and PDSI) have large spatial and temporal variations across the grassland-forest transition zone in central Saskatchewan. In terms of temporal response of NDVI to climate variables, there are several findings:

a) temperature is highly correlated with NDVI positively early in the growing season (May) and there is a weak correlation between temperature and NDVI from June to October;

b) NDVI-precipitation correlations exhibited time lags; monthly NDVI values were highly correlated with precipitation received during the preceding month in mid growing season; and

c) monthly NDVI values had strong correlations with concurrent monthly PDSI from mid summer (July-August) to early autumn (September). There was a weak correlation between NDVI and PDSI early and late in the growing season.

There is substantial heterogeneity in the spatial distribution of correlations between NDVI and the climate variables:

a) NDVI is highly correlated with temperature only in forest area of the Boreal Transition ecoregion throughout the growing season and in May in the grassland and cropland in the southeastern Aspen Parkland ecoregion;
b) July NDVI is highly positively correlated with June precipitation in the central transition zone while highest NDVI-PDSI correlation occurred in the Moose Mountain Upland and Kipling Plain in the southern Aspen Parkland Ecoregion;
c) In August, strong positive NDVI-PDSI correlations dominated the cropland and grassland from the central to southern Aspen Parkland ecoregion and cropland in the central Boreal Transition ecoregion. The grassland in the western Aspen Parkland ecoregion and forest area in the western Boreal Transition ecoregion exhibited a large positive August NDVI-July precipitation correlation;
d) The strong NDVI-PDSI correlation begins to weaken in September, retreating first in the northern areas of the transition zone;
e) In October, the NDVI-PDSI correlation is dramatically reduced and gradually replaced by a strong precipitation relationship;
f) When all six months are considered together, as a growing season composite, all of the southern part of the Aspen Parkland ecoregion exhibits a high correlation between NDVI and PDSI.

Cropland occupies the largest area of the study region, and the results show that crop productivity is highly correlated with PDSI through the growing season. Most of the Boreal Transition ecoregion shows high correlation between NDVI and precipitation for the growing season. Growing season NDVI is correlated with temperature for only isolated pockets of forested area. The growing season correlations suggest that PDSI is a good estimator of NDVI and thus seasonal vegetation productivity in the Aspen Parkland ecoregion, while precipitation is a good indicator in the Boreal Transition ecoregion. Temperature does not appear to be a good indicator for establishing a regression model to estimate vegetation productivity.

Among different landcover categories, the correlation between temperature and NDVI is best for forest, grassland second, and cropland lowest. NDVI-precipitation correlation is best for forest, while relatively weak for both cropland and grassland. The correlation of NDVI with PDSI is highest for cropland, intermediate for grassland and lowest for forest. Comparing all the correlation maps between NDVI and the three climate variables, the cropland and grassland in the southern Aspen Parkland Ecoregion and grassland in the western transition zone are more stable through the growing season. The cropland in the central transition zone and forested area in the eastern Boreal Transition ecoregion exhibited more variation in the correlation of NDVI and climatic variables, suggesting climate sensitivity.

Causal relationships cannot be directly determined from correlation analyses. Other factors, such as fire and forest deforestation, and natural and human-induced change in vegetations, cannot be detected from correlation analysis. However, findings from this study are important for climate change impact analyses on vegetation productivity. They form the basis upon which regression models can be established to project vegetation productivity under future climate scenarios. The trend analysis indicated a positive trend

in NDVI from 1982 to 2001 for most of the months of May to October and thus for the entire growing season. This increasing trend was exhibited over most of transition zone from July to October, suggesting a lengthening of the growing season.

These results can provide early detection of climate change impacts in the climatically sensitive grassland to forest transition. The large sets of NDVI and climate variables dataset created for this study can be repeatedly used for further studies in this region. Further research could include building regression models between NDVI and climatic factors (temperature, precipitation and PDSI) for projecting the future NDVI values from climate change scenarios.

Assessing Vegetation Change from Aerial Photographs
Swarbrick (2004)

Introduction

Aerial photographs record vegetation at different periods in time and at large scales, making them valuable tools for vegetation studies (Miller, 1999; Herwitz *et al*., 2000). They have proved to be useful measures in assessing species associations (Howard, 1970; Lindenas, 1985), vegetation cover (Fensham and Fairfax, 2002; Fensham *et al*., 2002) and vegetation change (Bahre and Shelton, 1993; Tian *et al*., 1995; Miller, 1999). The resolution provided by aerial photographs is particularly well suited for the identification of tree species (Tian *et al*., 1995), and is advantageous over other types of remotely sensed information (*e.g*. satellite imagery) that do not provide the same amount of detail (Fensham *et al.,*2002; Fensham and Fairfax, 2002). Aerial photographs pre-date other popular forms of remotely sensed information, enabling studies over longer periods of time. Further, through the use of stereoscopic analysis, the user can view landscapes in three dimensions, permitting not only analysis of vegetation types, but also ages and sizes of stands (Fensham *et al*., 2002; Fensham and Fairfax, 2002).

Methods

A better understanding of how climate variation has affected the vegetation of the boreal forest transition zone was developed by examining and comparing aerial photographs from the late 1940s and late 1990s. In order to study the effects of climate on the vegetation, areas affected by forest fires (J. Cook, Saskatchewan Environment, personal communication; Nicleson and Gruszka, 2000), forest insect and disease outbreaks (Annual Report of the Canadian Plant Disease Survey, 1946 – 1958; Annual Report of the Forest Insect and Disease Survey, 1959-79; Forest Insect and Disease Conditions in Canada, 1980-1997) and anthropogenic disturbances (*e.g*. logging, agricultural practices, road construction) were identified and excluded as possible sites. Twenty sites (Figure 27) were chosen at random from the resulting list. Plots of 500m x 500m were delineated, and compared in photos from 1946-1949 at a scale of 1:16,000 to 1:20,000 as recommended by Howard (1970), to photos from 1995-1997 at a scale of 1:60 000.
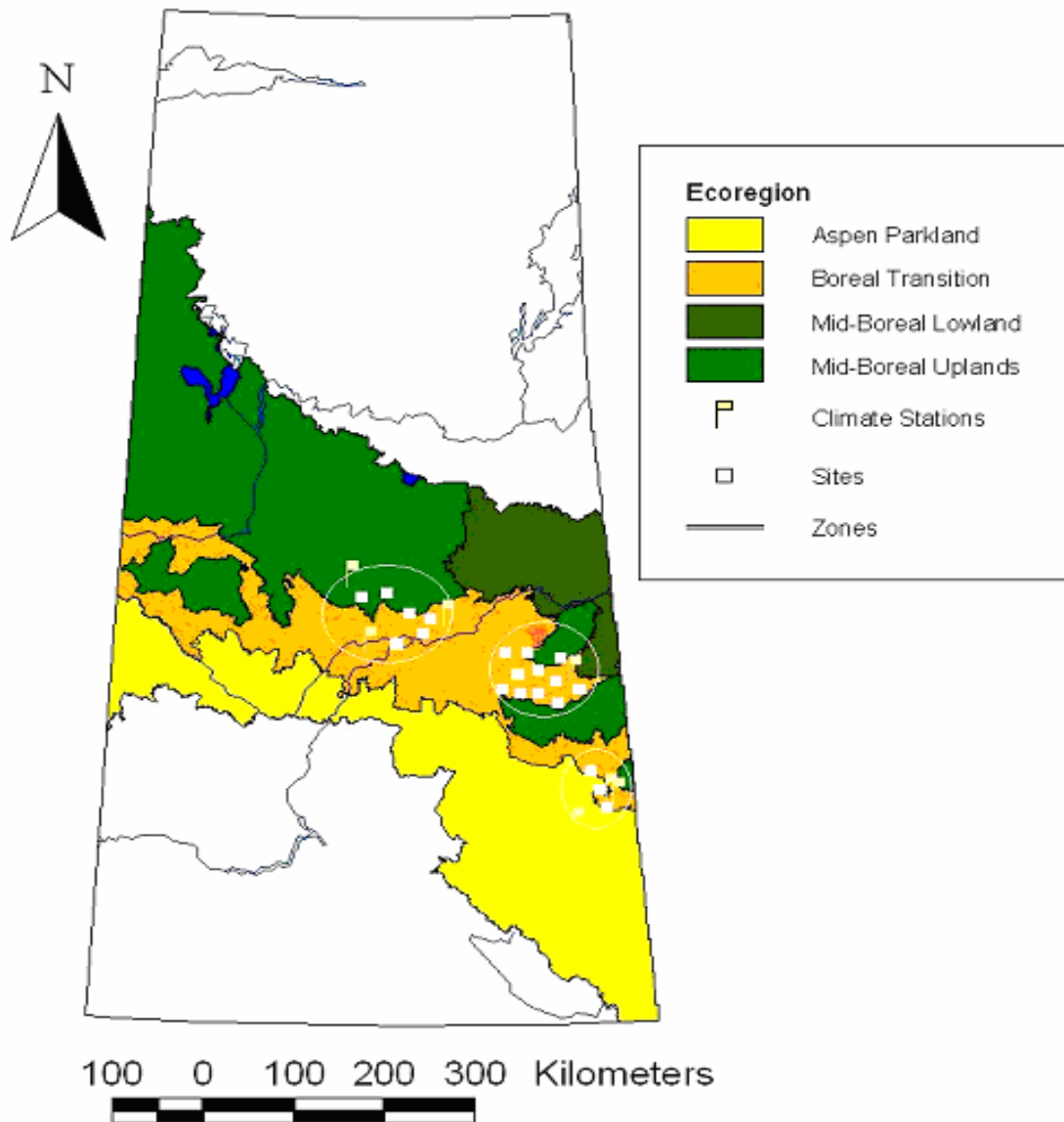
Figure 27. Study sites in the Boreal Transition and Mid-Boreal ecoregions.

Photos were scanned at 600 dots per inch (dpi), and saved as Tagged Image File Format (TIFF) files. Photos from the 1990s were georeferenced in a GIS to digital data, provided by Natural Resources Canada (Natural Resources Canada, 2004). Photos from the 1940s were then georeferenced to the defined photos from the 1990s. Stands were identified based upon keys published by Sayn-Wittgenstein (1960) and Zsilinszky (1963), and classified according to the classification system from the Saskatchewan forest inventory maintenance maps (Beckingham, 1999). Plots were outlined as polygons, and clipped from the photos. Stands within the plots were then outlined as polygons in the GIS. Area cover in hectares (ha) for each stand type was measured through the GIS, and change in

the area of individual stands from the 1940s to the 1990s was calculated. The error associated with digitizing was assessed by outlining a stand ten times, and calculating the standard deviation.

Climate data were gathered from seven stations (Table 1; Environment Canada, 2002) chosen based upon the completeness of the climate record from 1946 and 1997, and the shortest distances from the study sites. Annual mean, minimum and maximum temperatures (^{o}C), extreme annual minimum temperature (^{o}C), extreme annual maximum temperature (^{o}C), total annual rain (mm), total annual snow (mm) and total annual precipitation (mm) were calculated from monthly data. Annual summer temperature (^{o}C), which has been found to be correlated with drought and decrease in recruitment of boreal species (Hogg, 1994; Chinn and Wang, 2002), was calculated from July and August mean temperatures (^{o}C). Fall rain, snow and precipitation (mm), variables correlated with tree growth (McKenzie *et al*., 2003), were calculated from September, October and November monthly data.

Table 1. Climate Station reference information.

Name	Years:	Latitude	Longitude	Elevation (m)	ClimateID
Wascasiu Lake	1946-1995	53° 55' N	106° 4' W	532.2	4068560
	1996-1997	53° 55' N	106° 4' W	569.4	4068559
Prince Albert A	1946-1997	53° 13' N	105° 40'W	428.2	4056240
Choiceland	1948-1994	53° 30' N	104° 28'W	442	4071560
Hudson Bay	1946-1978	52° 52' N	102° 24'W	371.9	4083320
	1979-1997	52° 49' N	102° 19'W	358.1	4083321
Yorkton	1946-1997	51° 16' N	102° 28'W	498.3	4019080
Kamsack	1946-1969	51° 34' N	101° 54'W	440.4	4013640
Cote	1970-1997	51° 31' N	101° 46'W	449.6	4011846

Analysis

Multivariate ordination methods were used to assess changes in vegetation. Data were log(x+1) transformed to meet the assumptions of normality. Detrended Correspondence Analysis (DCA) was performed to assess the length of the environmental gradient and whether unimodal or linear species responses were expected. An axis 1 gradient length of 2.0 indicated that Principal Component Analysis (PCA) (linear), rather than Component Analysis (CA) (unimodal) would best suit analysis of the data (Leps and Šmilauer, 2003). PCA was then performed using CANOCO 4.5 (ter Braak and Šmilauer, 2002) on the total study area, based on the previous analysis and recommendations of its use for data sets dominated by a few species (Miranda, 2002). Species occurring only one or two times in

all of the sites were removed from the data set to avoid skewness. Ordination is a useful tool in exploratory analysis of ecological data; it is able to show patterns of community structure and variation (ter Braak, 1995). PCA spreads out the data points so that the maximum variability is visible, identifying the most important or influential gradients. Axis 1 is constructed to go through the centroid of data points, while minimizing the square distance of each point from the line, and thus creates a line as close to all the data points as possible; axis 2 does the same, but is perpendicular to axis 1 (Gauch, 1982; ter Braak, 1995). Therefore axis 1 and axis 2 scores were used as a metric of vegetation community change.

The degree of vegetation change at all sites was evaluated using a paired t-test on the Axis1 and Axis 2 sample scores from each PCA analysis, and on individual stand types. The change in stand size for each stand type was analyzed using a paired t-test on the log(x+1) transformed data. Sites were grouped into three zones based on location (Figure 27). PCA was used to assess directions and magnitudes of vegetation change in each zone. All sites were plotted in a common PCA ordination space so that changes among sites were directly comparable. A paired T-test was performed separately on log(x+1) transformed data of each stand type, in each of the three zones, to assess if significant change had occurred within any one zone. A non-parametric Kruskall-Wallis ANOVA was applied to the stand data, axis 1 and axis 2 site scores, and the distance between sites on the PCA, to assess whether vegetation change was significantly different between the three zones. A linear regression analysis was performed using climate data as the dependant variable and year as the independent variable to determine if significant changes in climate had occurred.

Results

For the 20 sites, 12 different stand types were identified. Two occurred only once (Jack Pine and Tamarack), and two occurred only twice (meadow and brush). PCA indicated vegetation change throughout the study area; however, no clear trends were discerned because direction of change varied between sites (Figure 28). Eigenvalues for Axis 1 and Axis 2 accounted for 57.4% of the variation (32.4% and 24.9% respectively). The direction of a species vector in comparison to others describes correlations between species. Species vectors at small angles in relation to each other indicate a positive correlation, and those pointing in opposite directions show a negative correlation (Gauch, 1982; ter Braak, 1995; ter Braak and Šmilauer, 2002). PCA showed that hardwood stands were negatively correlated with softwood dominated mixedwood (SH mixedwood) stands and slightly positively correlated with black spruce stands. Black spruce was shown to be slightly negatively correlated with SH mixedwood as well. Treed muskeg was negatively correlated with white spruce and hardwood dominated mixedwood (HS mixedwood), and positively correlated with bog. Bog was also negatively correlated with white spruce and HS mixedwood. White spruce and HS mixedwood were positively correlated.
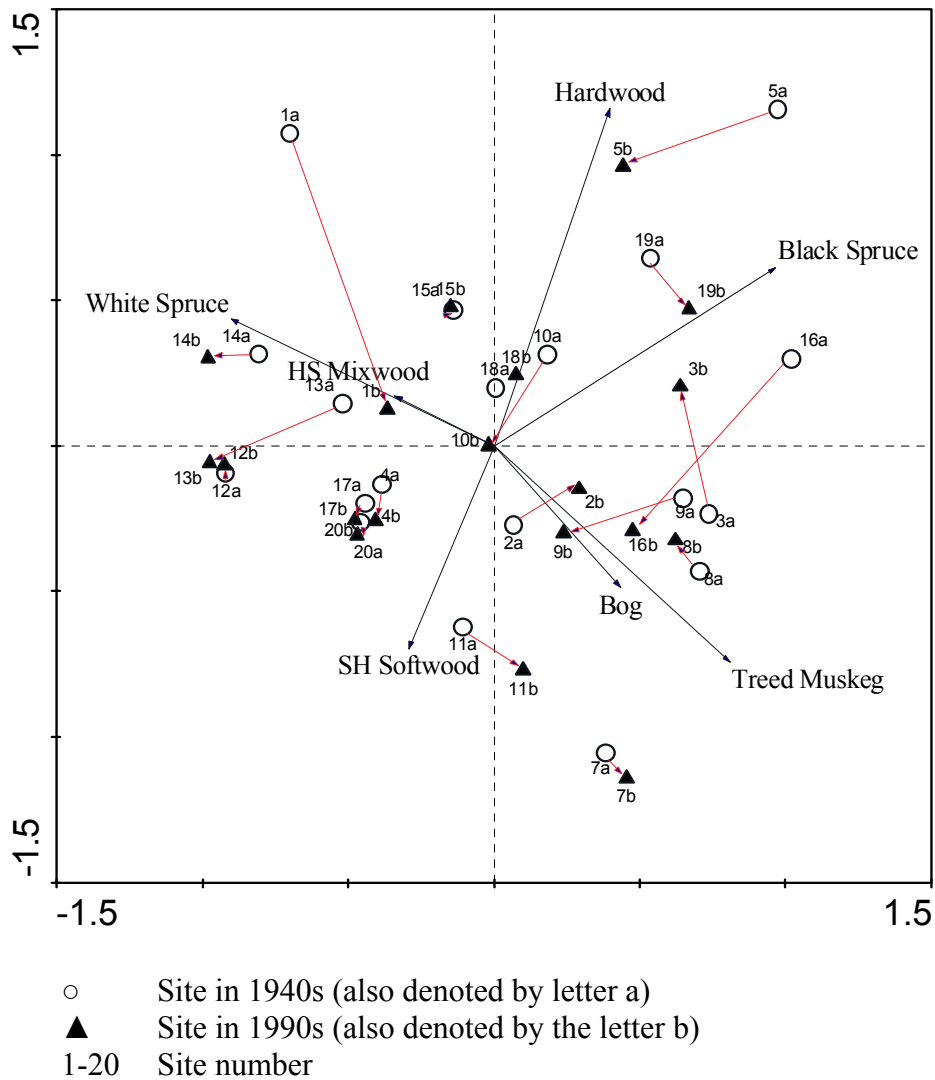
Figure 28. Principle Component Analysis of all sites in the study area.

Species loadings (Table 2) show that axis 1 is highly correlated with black spruce and treed muskeg, but is negatively correlated with white spruce. Axis 2 is also correlated with hardwood stands, and negatively correlated with treed muskeg and SH mixedwood. These axes represent theoretical environmental variables, perhaps climate variables, that differentially impact individual species (i.e. Axis 1 may represent a variable that strongly benefits hardwood stands, but favours against treed muskeg or SH mixedwood) (Gauch, 1982; ter Braak, 1995; ter Braak and Šmilauer, 2002). Despite indications of change from the PCA results, findings from the paired t-tests (Table 3) on the log (x+1) transformed data showed no significant change over time for any stand type (p>0.05). Axis 1 and Axis 2 sample scores also showed no significant change (p>0.05) between the 1940s and 1990s.

Table 2. Species loadings for axis 1 and axis 2 in Principle Component Analysis.

NAME	AX1	AX2
Eigenvalue	0.3244	0.2491
Deciduous	0.5583	1.6182
HS Mixedwood	-0.4762	0.2393
SH Mixedwood	-0.4088	-0.9737
White Spruce	-1.2616	0.6069
Black Spruce	1.3528	0.8553
Treed Muskeg	1.131	-1.041
Bog	0.6049	-0.6806

Table 3. Paired t-test results ($\alpha=0.05$).

Area	Variable	p-value
Total Study Area	Hardwood	0.25
	HS Mixedwood	0.77
	SH Mixedwood	0.13
	White Spruce	0.26
	Black Spruce	0.33
	Treed Muskeg	0.31
	Bog	0.66
	Axis 1 Site scores	0.19
	Axis 2 Site scores	0.09
Zone 1	Hardwood	0.28
	HS Mixedwood	0.24
	SH Mixedwood	0.19
	Black Spruce	0.71
	Treed Muskeg	0.18
	Bog	0.002
	Axis 1 Site Scores	0.91
	Axis 2 Site Scores	0.56
Zone 2	Hardwood	0.03
	HS Mixedwood	0.07
	SH Mixedwood	0.24
	Black Spruce	0.13
	Treed Muskeg	0.46
	Bog	0.20
	Axis 1 Site Scores	0.06
	Axis 2 Site Scores	0.06

Zone 3	Hardwood	0.38
	HS Mixedwood	0.59
	SH Mixedwood	0.01
	Black Spruce	0.03
	Axis 1 Site Scores	0.18
	Axis 2 Site Scores	0.73

Analysis of the three geographic zones separately revealed that the PCA of sites in zone 1 (Figure 29) show substantial variability in vegetation composition, but little in the way of discernable trends in magnitude or direction. However, in zone 2 there was a dominant trend of decreasing deciduous dominated stands (Figure 30). PCA of zone 3 alone (Figure 31) again indicated decreases in deciduous stands, and a shift towards black spruce stands. The magnitude of change in Zone 3 was smaller than in the other zones. Paired t-test results showed few consistent patterns among zones. Bog decreased significantly in zone 1 ($p = 0.002$). Hardwood stands decreased significantly ($p = 0.03$) in zone 2. In contrast, softwood dominated mixedwood showed a significant decrease ($p = 0.01$) while black spruce showed a significant increase ($p = 0.03$) in zone 3. Despite these trends, the Kruskall-Wallis ANOVA showed that changes in stand type, PCA axis 1 and 2 scores, and vector length did not differ significantly ($p < 0.05$) between zones.

Regression analysis of climate data from all seven climate stations showed significant increases in mean annual temperature (MAT), mean annual minimum temperature (MAMT, $^{\circ}$C), extreme minimum temperatures (EMT), and total annual rainfall (TAR). When the three latitudinal zones were analysed separately, significant ($p < 0.05$) changes in climate were also noted. In zone 1, there was increased MAT, MAMT , EMT, and TAR, while extreme maximum temperature decreased. Zone 2 had a significant increase in MAT and EMT. Zone 3 showed a significant increase in TAR, but unlike the other zones, showed a significant decrease in minimum temperature.

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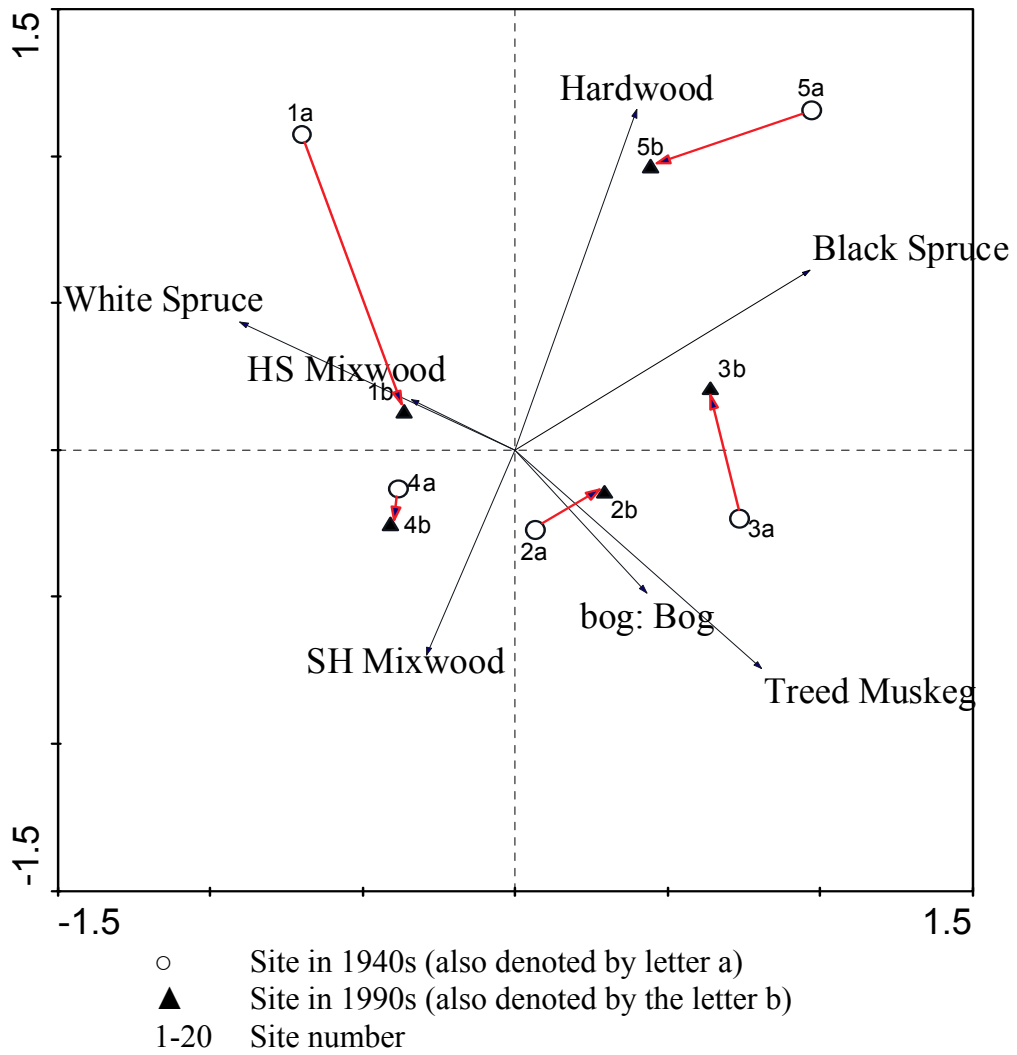
Figure 29. Principle Component Analysis of sites in Zone 1
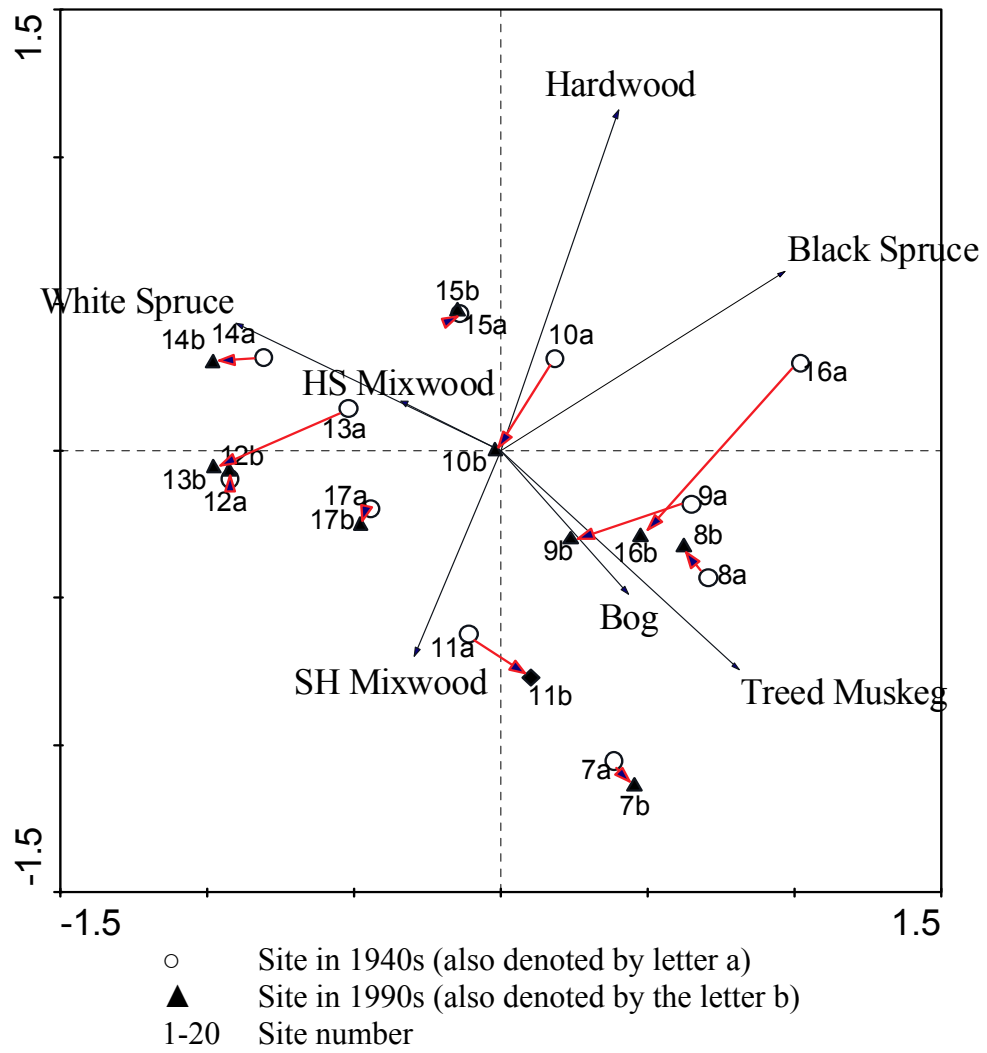
Figure 30. Principle Component Analysis of sites in Zone 2.
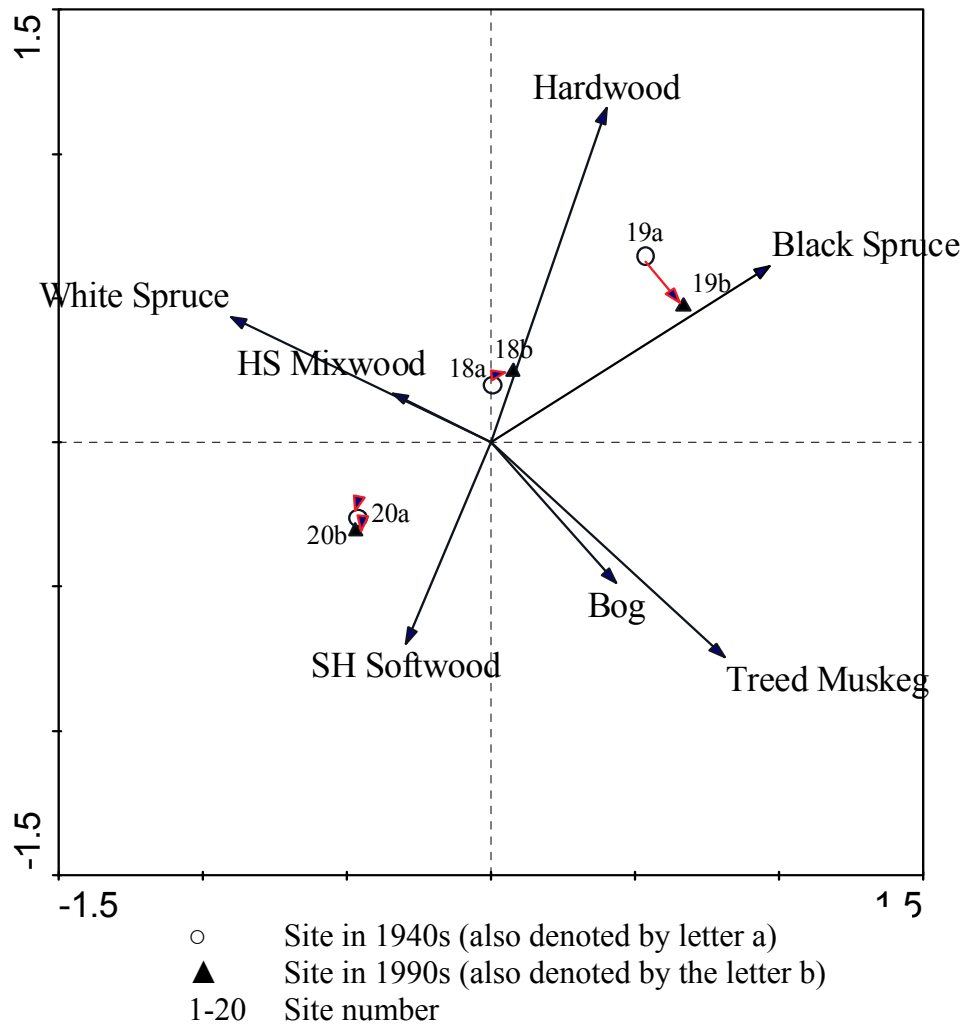
Figure 31. Principle Component Analysis of sites in Zone 3.

Discussion

While changes in climate were recorded, no statistically significant changes in vegetation were detected in the aerial photography comparisons. This may be an indication that the southern boreal forest is resistant to variability in climate (Brang, 2001). Many boreal species are able to grow in a wide variety of climates, often outside of their natural range (Bonan and Sirois, 1992). Furthermore, the dominant species of the boreal forest (black spruce, white spruce, aspen) (Rowe, 1977) are found naturally not only in boreal regions, but also across an impressively large range throughout North America (Preston, 1970; Scoggan, 1978). Since there were no significant changes overall, this study appears to support many other field and remote sensing studies on treeline shifts, which have demonstrated inconclusive results (Dullinger *et al.*, 2004).

Non-significant results may also be a result of the temporal scale. It has been suggested that arboreal ecosystems react very slowly to climate change (Solomon and Kirilenko, 1997). Indeed, boreal forest species may take from 70 to 120 years to reach maturity (Kabzems, 1984). This suggests that the temporal scale of this study may have been too short to detect changes in vegetation. However, other similar studies of the boreal forest, and elsewhere, have detected vegetation changes over comparable periods of time (Bahre and Shelton, 1993; Tian *et al*., 1995; Miller, 1999; Herwitz *et al*., 2000; Fensham *et al*., 2002; Fensham and Fairfax, 2002).

Another possibility is that the sample size was too small. Power analysis indicates that, at a power of 0.8 (β=0.2), 128 sites are needed to detect an average change in stand size of 0.5 ha. Only 34 sites are needed to detect a change of 1 ha. Unfortunately, a larger sample size was not possible in the context of this study. While no significant changes in vegetation were found for the total study area, the paired t-test suggests that significant changes occurred within individual stands along the latitudinal gradient. In zone 2, significant decreases in the size of hardwood stands, coincided with a significant increase in annual mean temperature (^{o}C), and an increase in annual mean minimum temperature (^{o}C). Studies have shown that drought is a major cause of aspen dieback, and that a warmer, drier climates is resulting in stressed stands (Auclair *et al*., 1995; Hogg *et al*., 2002). An increase in mean temperature in the absence of increased precipitation has occurred in the study area over the past 50 years, which may be determining the decrease in deciduous stand size. With succession, aspen stands in the boreal forest naturally become dominated by coniferous species (Whittaker, 1972; Aber and Melillo, 2001). However, the decrease in hardwood stand size was not matched by a significant increase in HS mixedwood, SH mixedwood or coniferous species as would be expected. Perhaps only slight increases in a few or all of the aforementioned stands occurred, but were not significant in t-tests. In the future, analysis of larger sample sizes may enable the analysis of rates of change in relation to climatic trends. Nonetheless, this study shows that hardwood stands decreased in size over the past 50 years under increased mean annual temperature (^{o}C), and mean annual minimum temperature (^{o}C).

In zone 3, there was a significant decrease in SH mixedwood, and a significant increase in black spruce, coinciding with significant increases in total annual rainfall (mm) and a decrease in mean annual temperature (^{o}C). Black spruce is commonly found on wet poorly drained sites, and on peaty sites such as treed muskeg and bog, as well as on drier sites. The distribution of black spruce has been purportedly determined by soil moisture, and not thermal regimes (Zoltai, 1975). Increases in total annual rainfall and decreases in annual mean temperature therefore benefit black spruce stands, as they prefer wetter sites.

In zone 1, there was a significant decrease in that area classified as bog. Except for a decrease in extreme annual maximum temperature, there was a significant positive trend in all the temperature variables and total annual rainfall. Bogs are an intermediary stage in hydrarch succession, wherein lakes succeed into wetlands before developing into dry terrestrial habitats (Winkler, 1988). Higher temperatures may accelerate this process by offsetting elevated rainfall, leading to higher rates of evaporation and lower soil moisture.

According to Kruskall-Wallis ANOVA, there were no significant differences in vegetation change among the zones. This may be further indication that the southern boreal forest is resistant to change, although various studies have shown the sensitivity and productivity and occurrence of boreal species (Jozsa, 1984; Zoltai *et al*., 1991; Hogg and Schwarz, 1997; Chinn and Wang, 2002). While sites were screened for disturbances to maximize the effects of climate, other environmental factors, such soil type or nutrient availability were not controlled for. Significant vegetation change was identified at individual sites. At one site, for example, land classified as meadow in 1946, had become dominated by aspen in 1995. These data coincide with studies documenting the expansion of aspen stands into grasslands during the 20th century (Archibold and Wilson, 1980; Köchy and Wilson, 2001).

In summary, there were no significant changes in vegetation in the total study area, although hardwood stands decreased in zone 3, SH mixedwood stands declined and black spruce increased in zone 2, and bog increased in zone 1. PCA also showed interesting trends in the magnitude of vegetation changes along a latitudinal gradient, with more southern sites showing a smaller degree of vegetation change than observed at northern sites. Incorporation of additional sample dates could show changes in vegetation in response to immediate climate variations. Further, a broader range of climate variables needs to be analyzed. A moisture index, such as the Climate Moisture Index (CMI) described in Hogg (1994, 1997), growing degree days, length of growing season, proportion of growing season below "wilting point" (Solomon and Bartlein, 1992), and thaw-freeze events (Braathe, 1995; Hogg *et al*., 2002) have all been shown to have notable effects on the vegetation of this area.

The Tree-Ring Record: Annual to Decadal Climate Variability

Introduction

As described above, the terrestrial ecosystems of the grassland to forest transition are sensitive to climate variation because both grassland and forest are at the margins of their range in central North America. Our approach to establishing the long-term response of these ecosystems to climate variation over the past several centuries was to develop high resolution records of climate and vegetation from tree rings (dendrochronology) and the pollen accumulated in lake sediments. Figure 32 is a map of the sites in the aspen parkland and southern boreal forest, where we collected tree rings and lake sediments. Also shown are the locations of Environment Canada weather stations with homogenized climate records.
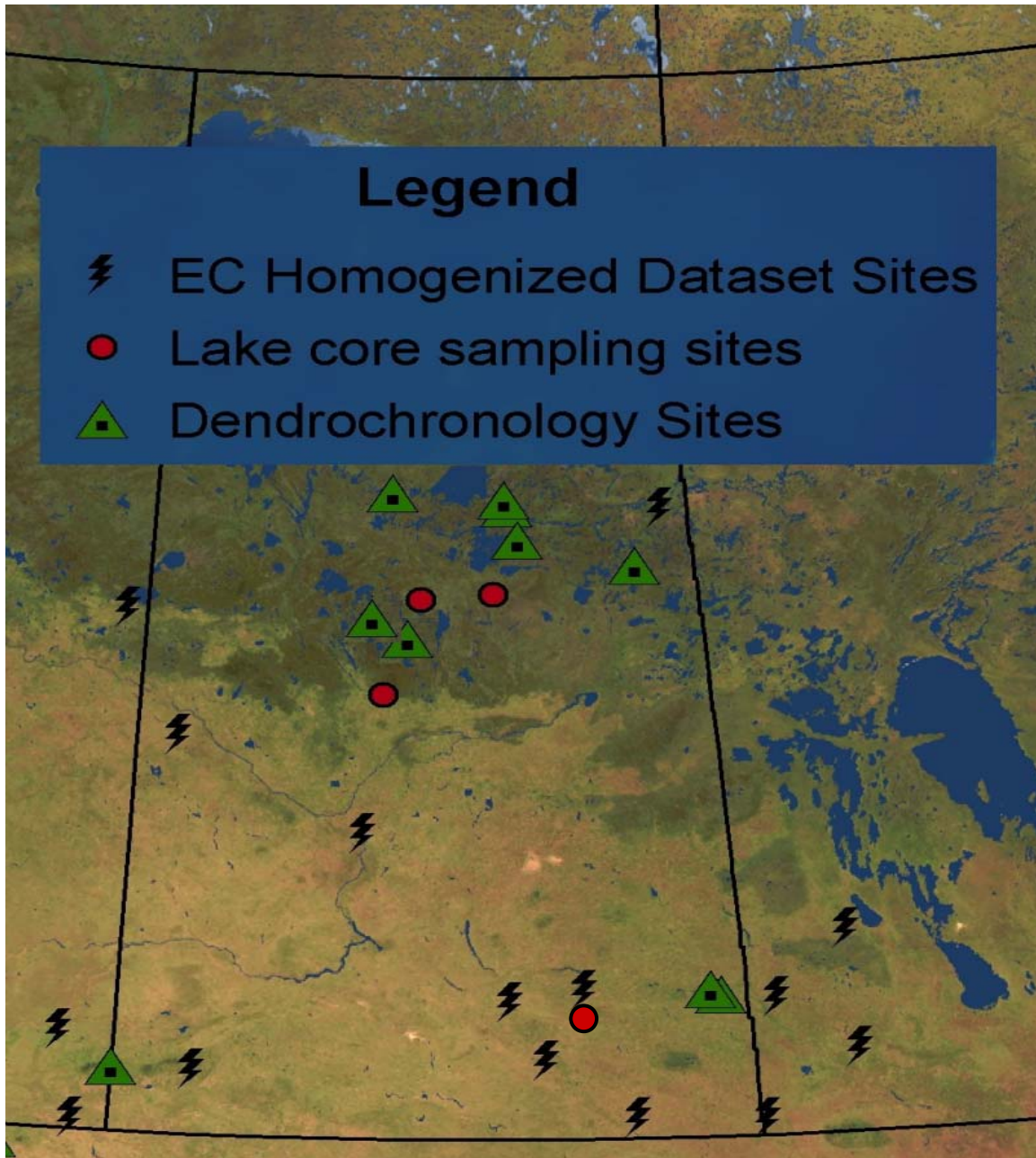
Figure 32. Location of lake coring sampling sites, tree-ring collections, and Environment Canada (EC) weather stations with homogenized records.

The relatively short length of instrumental records limits our understanding of the historical variability of climate in Canada. These records seldom exceed 100 years and most are considerably shorter, especially in remote areas. Records of this length are unlikely to capture the full range of regional climatic variability, especially in terms of the frequency of prolonged wet and dry intervals. The study of tree rings in relation to climate enables the reconstruction of climatic and hydrologic time series that pre-date instrumental data (Stahle, 1996). Annual variations in tree-ring width reflect daily and

seasonal growth limiting processes. Where soil moisture is limiting, standardized tree-ring widths tend to correlate with hydroclimatic variables such as precipitation and stream discharge (Loaiciga *et al*., 1993).

By its nature as an ecotone, the boreal transition consist of tree species that are at the limits of their ranges and thus are sensitive to, and record, climate variability. Unfortunately these trees are not long-lived and this has been a major obstacle to dendroclimatology in this ecoregion. In the southern boreal forest of central Saskatchewan, the interval between stand replacement fires is about 130 years (M. Johnson, Saskatchewan Research Council, personal communication, 2002), restricting old living trees and sub-fossil wood to a very small proportion of the area. We maximized the chances of finding older trees by avoiding areas of known recent fires and selecting sites in close proximity to large water bodies, which provide fire protection. Site characteristics that enhance moisture-sensitivity in trees include bedrock outcrops with thin soil cover, rapidly drained soil (*e.g.*, glaciofluvial deposits), and moderate to steep slopes, high local relief, and a southern aspect.

Methods

For the purpose of this project we collected tree-ring samples from four sites in the grassland to forest transition zone of central Saskatchewan (Figure 32; Table 4). Two are in the Boreal Transition ecoregion: Heart Lakes (Figure 33) in Prince Albert National Park and White Gull Lake in the Narrow Hills. Two sites are in the Aspen Parkland ecoregion: Devon Farm and Hillside in the lower reaches of the Qu'Appelle valley in eastern Saskatchewan. In addition two other tree-ring records were available for the southern boreal forest (Table 4): Patterson Peninsula on Lac La Ronge (Beriault and Sauchyn, 2006) and Boundary Bog (Case and Macdonald, 2003; Figure 34) in Prince Albert National Park.

Table 4. Tree-ring sites in the grassland to forest transition.

Site	Species	Latitude	Longitude
Heart Lakes	*Picea glauca* [1]	53.9	-106.2
Patterson Peninsula	*Picea glauca* [1]	55.2	-104.5
White Gull Creek	*Picea mariana* [2]	53.9	-104.8
Devon Farm	*Quercus macrocarpa* [3]	50.5	-102.0
Hillside	*Quercus macrocarpa* [3]	50.6	-102.1
Boundary Bog	*Picea mariana* [2]	54.9	-106.3

[1] white spruce; [2] bur oak; [3] black spruce

Figure 33. White spruce at the Heart Lakes site.

Figure 34. Boundary Bog.

Two cores, at least 90° radially apart from one another, were sampled from each tree leaving the tree unharmed. At each site, cores were extracted from two opposing radii near the base of at least 20 living trees using a 5.1mm Haglof increment borer (Grissino-Mayer, 2003). Cross sections were collected from deadfall to increase sample depth and to identify growth anomalies that may not be apparent in cores. The tree rings were processed in the University of Regina Tree-Ring Lab following standard procedures (Cook and Kairiukstis, 1989; Stokes and Smiley, 1968; Fritts, 1976). Ring width was measured with a precision of 10^{-3} mm. Common patterns of annual growth were visually matched among the ring-width series from each site and this crossdating was checked using the program COFECHA (Grissino-Mayer, 2001). A common signal was enhanced by removing series that had low correlation with the site chronology and by truncating or removing series with growth trend anomalies. The program ARSTAN was used to standardize the tree-ring data and compute dimensionless ring-width indices. The series comprising a dated chronology were averaged, using an algorithm that minimizes the effect of outliers, to generate the mean standard (STD) index chronology. A negative or modified negative exponential curve that is asymptotic with the horizontal axis was chosen to remove the age/size related trend for most series. A 100-year cubic smoothing spline with 50% variance cutoff was used for series with growth trends other than negative exponential. These detrending options are considered to be conservative and are likely to retain most of the low-frequency climatic information (Cook *et al*., 1990). Autoregressive modeling was applied to the standard chronology to produce a stationary residual (RES) index chronology.

Climate data for various stations (Figure 32), within a 100 km radius of sampling sites, were obtained from the 2001 Canadian Daily Climate Data on CD-ROM for Western Canada, provided by Environment Canada. Data in these archives have been corrected for inhomogeneities related to any change in location and/or equipment (Mekis and Hogg, 1999; Case, 2000). Streamflow data were obtained from Environment Canada's National HYDAT CD-ROM water data archive. The direction and magnitude of tree growth response to monthly and annual values of temperature and precipitation at various climate stations and streamflow gauges, were calculated over the period of overlap between the instrumental data and the individual standardized chronologies. The procedure involved the calculation of simple correlation coefficients between annual ring-width and mean annual and monthly temperature and total monthly and annual precipitation for climate stations with at least twenty years of instrumental data. Correlation coefficients were also calculated between annual ring-width and mean monthly, annual and water year (October – September) streamflow discharge from the streamflow gauges.

Statistical models that predict hydroclimate from tree-ring data are built by linear regression were tree-ring variables (lagged and current-year ring width) are the predictors and a hydroclimatic variables is the predictand. The model is calibrated and validated using instrumental climatic and hydrometric data. Models that satisfy the assumptions for parametric statistical methods, and have some predictive skill, are then used to reconstruct pre-instrumental climate and hydrology from the tree-ring records.

Previous studies have reconstructed climate and hydrology from tree rings collected in the southern boreal forest (Beriault and Sauchyn, 2006; Case and Macdonald, 2003). However, our collecting of tree-rings from bur oak (*Quercus macrocarpa)* in the Aspen Parkland ecoregion of southeastern Saskatchewan represents the first study of dendroclimatology in this region (Vanstone, 2007). These records can be paired with the high-resolution pollen records from Deep Lake in the same region, just as we sampled both trees and lake sediments in central Saskatchewan to achieve our objective of determining the past ecological response to climate variability.

Quercus macrocarpa is widely distributed throughout the eastern United States and the Great Plains. It is a drought-tolerant and slow-growing species and among the longest lived deciduous trees of the northern Plains region (Drunasky and Struve, 2005; Johnson, 1990; Nixon, 2006). In general, *Quercus* species have the ability to sustain stomatal conductance at low soil and leaf water potentials and have an inherently low capacity for water loss that contributes to their success in dry locations (Drunasky and Struve, 2005). Although most trees used for dendrochronological analysis have false or missing annual growth-rings, these types of anomalies are "unknown in oak" (Baillie, 1982: 53), thus cross-dating to produce accurate chronologies is relatively straightforward.

In Canada, the extreme edge of the western ecological range of *Quercus marcrocarpa* is located within the Qu'Appelle Valley of southeastern Saskatchewan. Tree cores were collected from the 'Devon Farm' (Figure 35) and the adjacent Bear Creek Wildlife Lands, approximately 10 km southwest of Tantallon, SK (Figure 32, Table 4). At the 'Hillside' sampling site (Figure 32, Table 4), approximately 10 km west of Tantallon, cross-sectional discs were collected from dead *Q. macrocarpa* trees, felled by the landowner in 2006.

Figure 35. Devon Farm Site.

Results

Figure 36 gives the results of an analysis of growth response to the climate for the white spruce sampled at the Heart Lakes site. This plot shows the correlation by month, from June of the previous year to August of the current year, of the standard tree-ring index chronology with temperature and precipitation. The coloured bars, representing significant ($p < 0.05$, $p < 0.01$) correlations, indicate that the white spruce responds positively to higher precipitation and negatively to higher temperatures in both the current and preceding year. That is, this stand of trees exhibits typical moisture sensitivity; their moisture stress is enhanced by high temperatures and alleviated by precipitation.
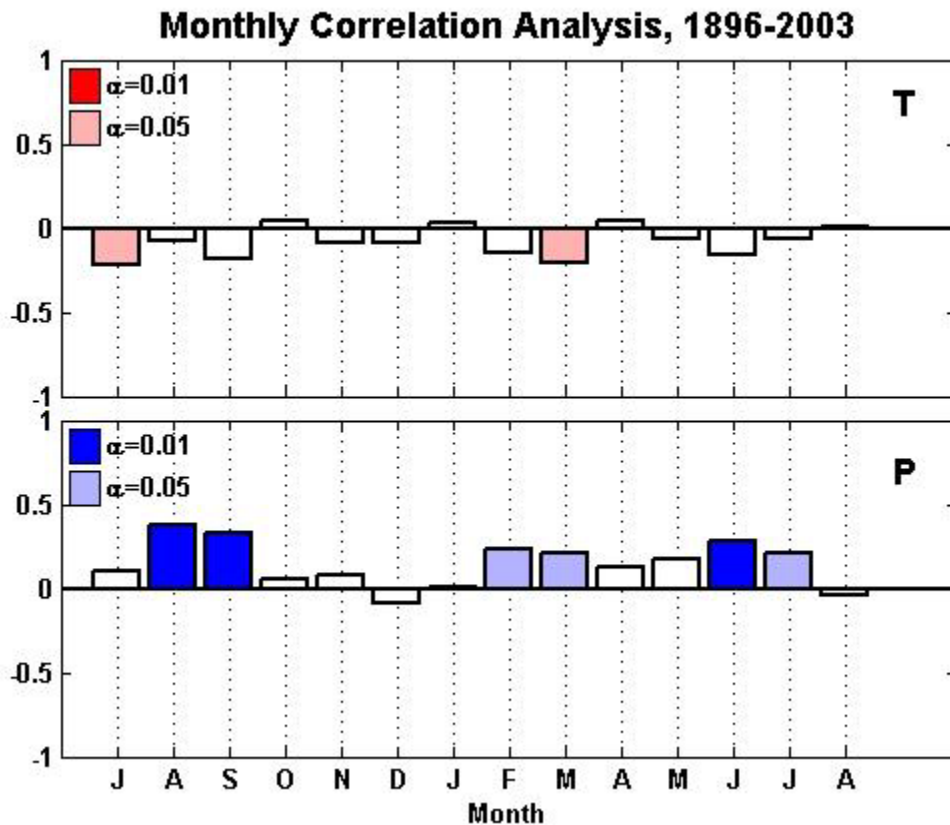
Figure 36. Growth response of white spruce at Heart Lakes to monthly temperature and precipitation measured at Prince Albert.

The white spruce from Patterson Peninsula and black spruce from Boundary Bog display the same moisture sensitivity (results from White Gull Creek are not yet available). Thus the tree-ring chronologies from Heart Lakes, and these other two sites in the Boreal Transition ecoregion, can be interpreted as records of precipitation and soil moisture. These three tree-ring index chronologies are plotted together in Figure 37. Beige highlights near synchronous dry periods (narrow tree rings) and blue highlights near synchronous wet periods (wide tree rings). Drought in the 1930s is apparent in all three records, but also apparent are pre-instrumental droughts of similar or greater severity and duration; particularly from the mid 1880s to the mid 1890s.

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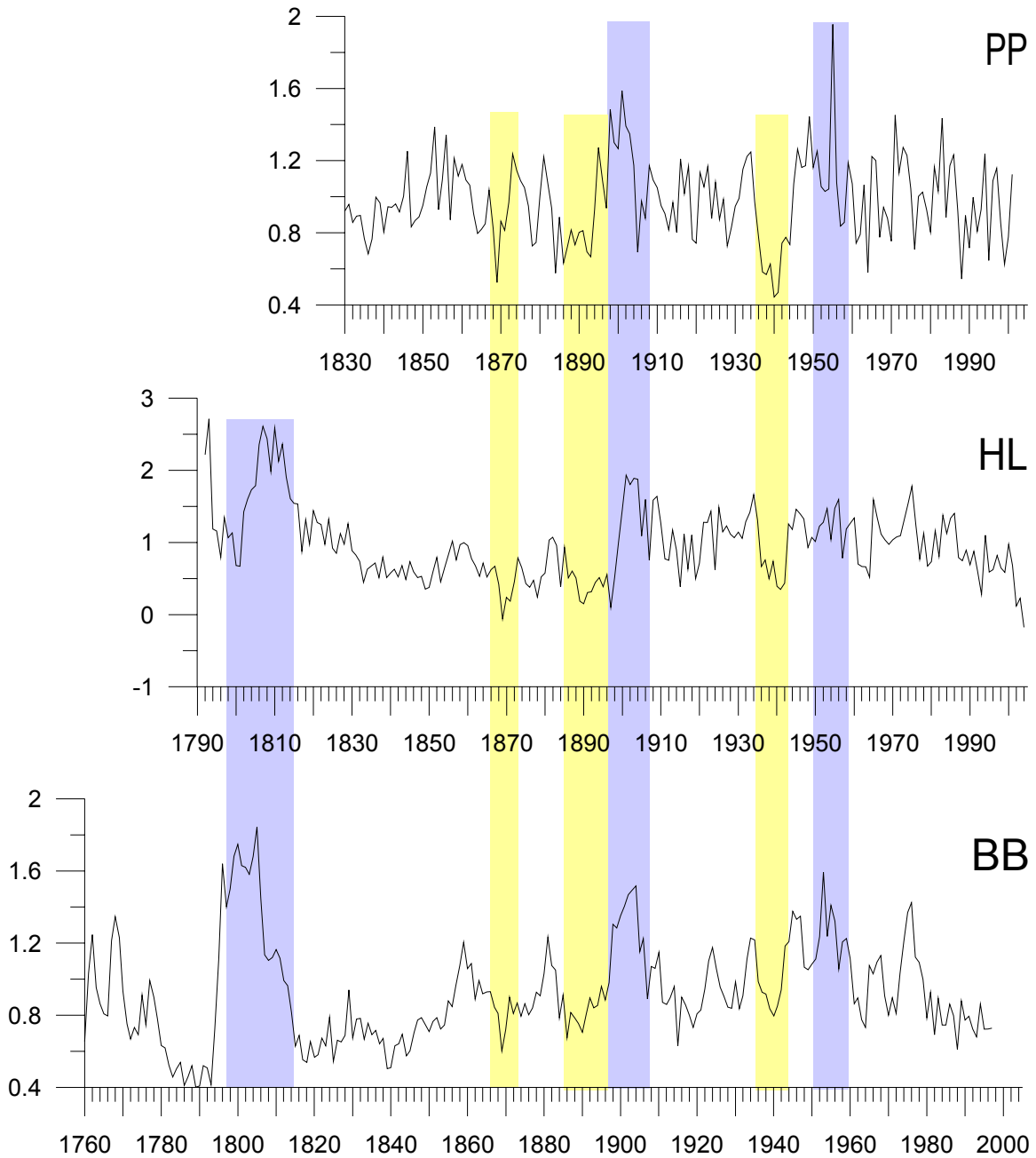
Figure 37. Standardized moisture-sensitive tree-ring chronologies from Patterson Peninsula (PP), Heart Lakes (HL) and Boundary Bog (BB). Beige highlight near synchronous dry periods and blue highlights near synchronous wet periods.

In Figure 38, the Devon Farm (DF) and Hillside (HS) bur oak chronologies are plotted together to show the coherence of ring-width variability over the period of overlap between the two sites (1909-2005). Over this interval, the chronologies are significantly

(p < 0.01) correlated and display the same pattern of sustained positive departures from average growth (index = 1) in the mid 1940s to late 1950s and suppressed growth in the early 1900s, late 1920s, and early 1930s. The correlation between the overlap of the two chronologies indicates that (1) the ring-width series of spatially distributed *Quercus macrocarpa* in southeastern Saskatchewan capture a common, coherent signal, most likely related to regional climate; and (2) *Q. macrocarpa* trees represent a valuable and as yet underutilized archive of dendroclimatological data (Case, 2000).
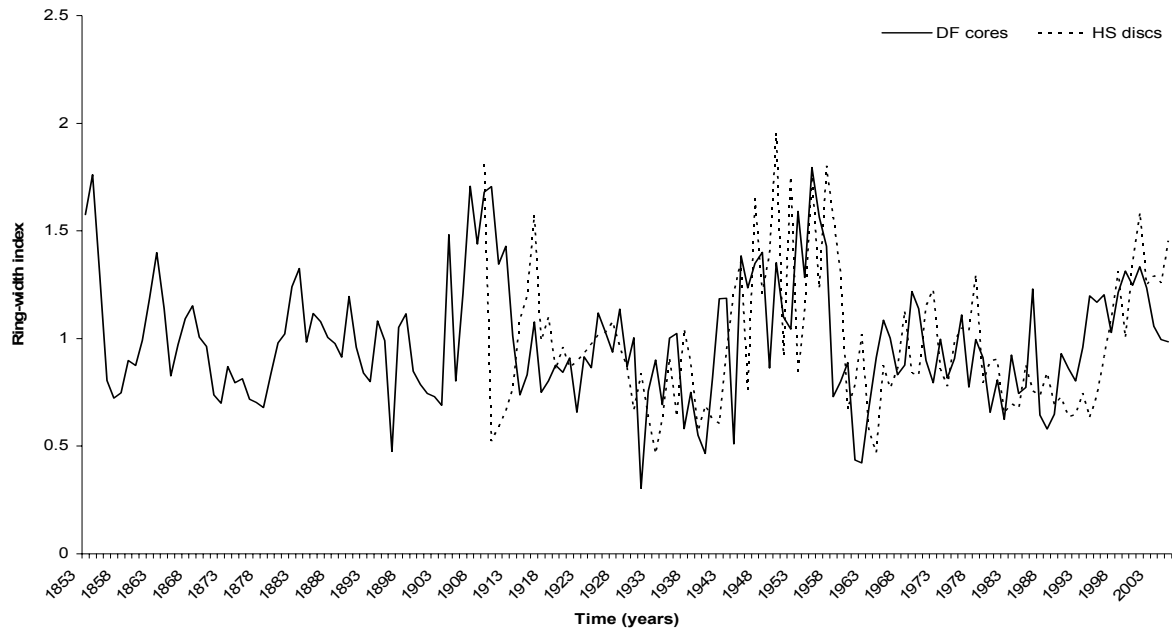
Figure 38. Standard ring-width chronologies developed from cores and cross-sectional discs of *Quercus macrocarpa*.

Correlations between trees composing standardized chronologies for DF and HS are 0.45 and 0.56, respectively. These values are in the same range as those derived for seven *Quercus macrocarpa* chronologies in Manitoba (r = 0.27-0.64; Case, 2000), and thirteen chronologies in the Dakotas (r = 0.33-0.57; Sieg *et al.,* 1996). Mean sensitivity values, measures of the interannual responsiveness of growth to environmental variables, are slightly higher than those derived from other northern Plains chronologies, most likely due to the fact that *Q. macrocarpa* sampled in the Qu'Appelle Valley were at the outermost edge of their ecological range, thereby increasing their sensitivity to climatic variables such as temperature and precipitation. Mean sensitivity values were 0.28 for the Devon Farm chronology and 0.30 for the Hillside chronology.

Table 5 lists significant (p < 0.05) correlations between the standard ring-width indices for the Devon Farm site and hydroclimatic variables: precipitation, temperature and streamflow. In almost all cases, growth is positively correlated with precipitation and negatively correlated with temperature, indicating that moisture stress in an important

limitation to growth of the species at its western ecological range (Case, 2000; St. George *et al.,* 2001). The negative growth response to temperature suggests that high temperatures in the summer months impose high evapotranspiration demand, resulting in reduced annual growth. Ring width is most strongly correlated with precipitation in summer, as well as with total annual precipitation, which includes the fall and winter precipitation that restores soil moisture for the subsequent growing season. Positive associations with precipitation in the winter months, January to April, indicate the importance of winter snowfall to soil moisture recharge and growth resumption in the spring (Robertson, 1992; Case, 2000). The strongest associations are between the ring-width index and instrumental streamflow, which tends to reflect precipitation across the watershed and not just those events recorded by a rain gauge.

Table 5. Significant ($p < 0.05$) correlations between the standard ring-width indices for the DF site and hydroclimatic variables: precipitation, temperature and streamflow.

		Instrumental Weather Stations and Streamflow gauges								
		Broadview	Fleming	Grenfell	Kipling	Langenburg	Rocanville	Tantallon*	Wapella	Welby*
January	P						0.398	0.556		0.295
	T									
February	P							0.583		0.266
	T									
March	P		0.631	0.325				0.522		0.261
	T									
April	P	0.400						0.564		0.398
	T								-0.427	
May	P							0.482		0.416
	T	-0.357		-0.332						
June	P	0.329	0.507		0.420	0.408		0.444	0.428	0.366
	T				-0.290	-0.300				
July	P							0.436		0.432
	T									
August	P							0.412		0.405
	T			-0.289						
September	P							0.356		0.321
	T						0.341			
October	P							0.321		
	T									
November	P							0.413		
	T									
December	P							0.392		
	T									
Ann. totals	P			0.493	0.441	0.452		0.673	0.436	0.436
	T									
WY								0.697		0.593

Figure 39 shows the reconstructed annual precipitation record plotted against actual values over the period of instrumental data. The model captures the direction of

interannual variation in the instrumental data; however, in a number of years, it underestimates the peaks and overestimates the lows (Case, 2000). The magnitude of precipitation in 1903, 1942-1955, 1970, 1975 and 1998, in particular, is not captured by the estimated values. The underestimation of peaks is a common characteristic of tree-ring models and reflects the fact that there are biological limits to the growth response (Loaiciga *et al.,* 1993). The overestimation of precipitation in dry years may be a result of the interacting effect of spring temperatures on growth (Case, 2000). The years 1908, 1933-1940, 1958 and 1962, for example, were very dry, but springs were cool, likely resulting in reduced evapotranspiration demand during the early growing season. In contrast, during the late 1970s to late 1980s, the reconstructions capture well the magnitude of lows, which likely are the result of warm springs and high summer temperatures and, as a result, increasing evapotranspiration causing decreased soil moisture and inhibiting the tree growth.
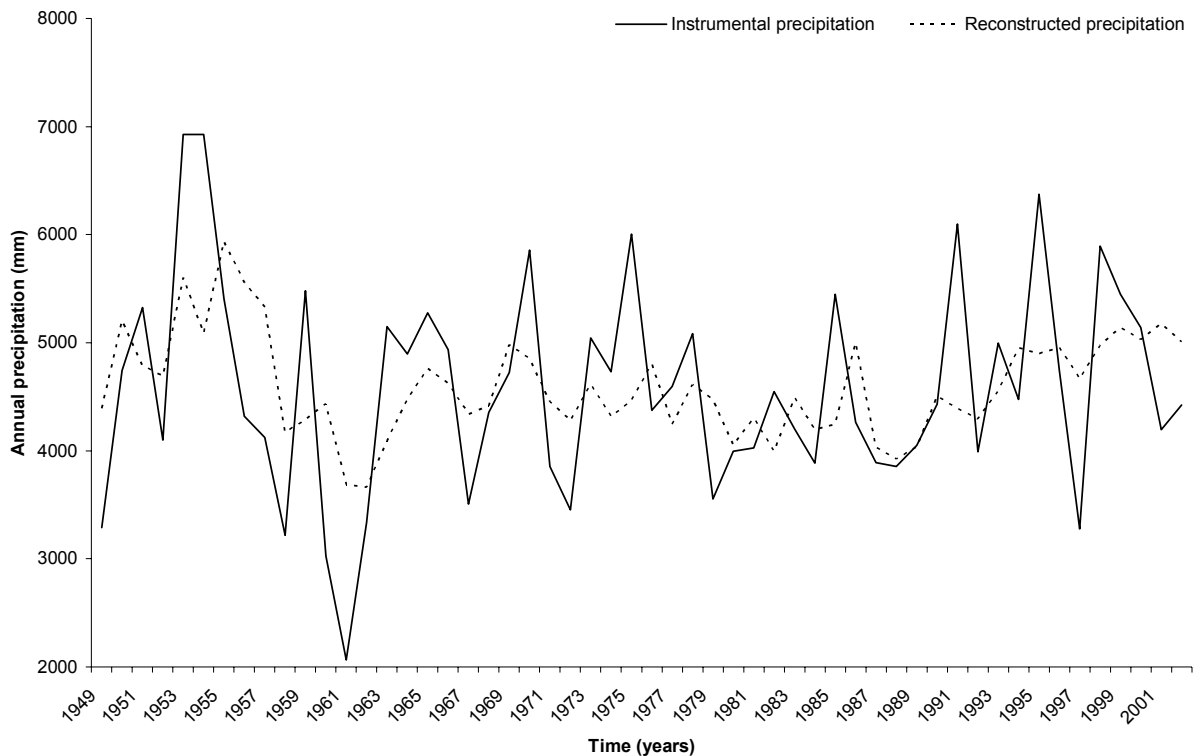
Figure 39: Actual versus reconstructed total annual precipitation at Kipling over the period of instrumental data, 1949-2003.

The streamflow reconstruction captures the direction of inter-annual variations in the instrumental data. In Figure 40, reconstructed streamflow shows similar patterns for Hillside and Devon Farm chronologies. As with the precipitation reconstruction, the peaks (wet years) are underestimated, however the lows (dry years) are much closer to the values recorded in the instrumental streamflow data (Figure 41).
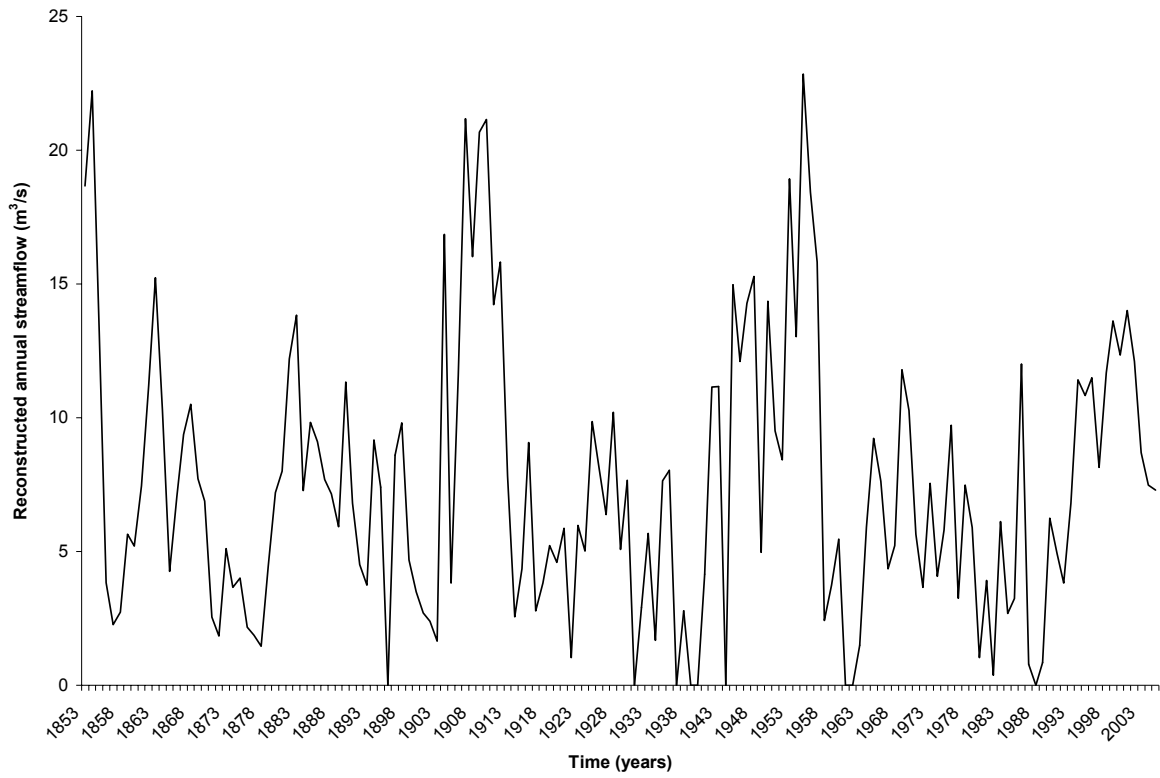
Figure 40. Reconstructed mean annual streamflow, generated from Devon Farm ring-width indices, at Tantallon over the entire tree-ring chronology, 1853-2005.
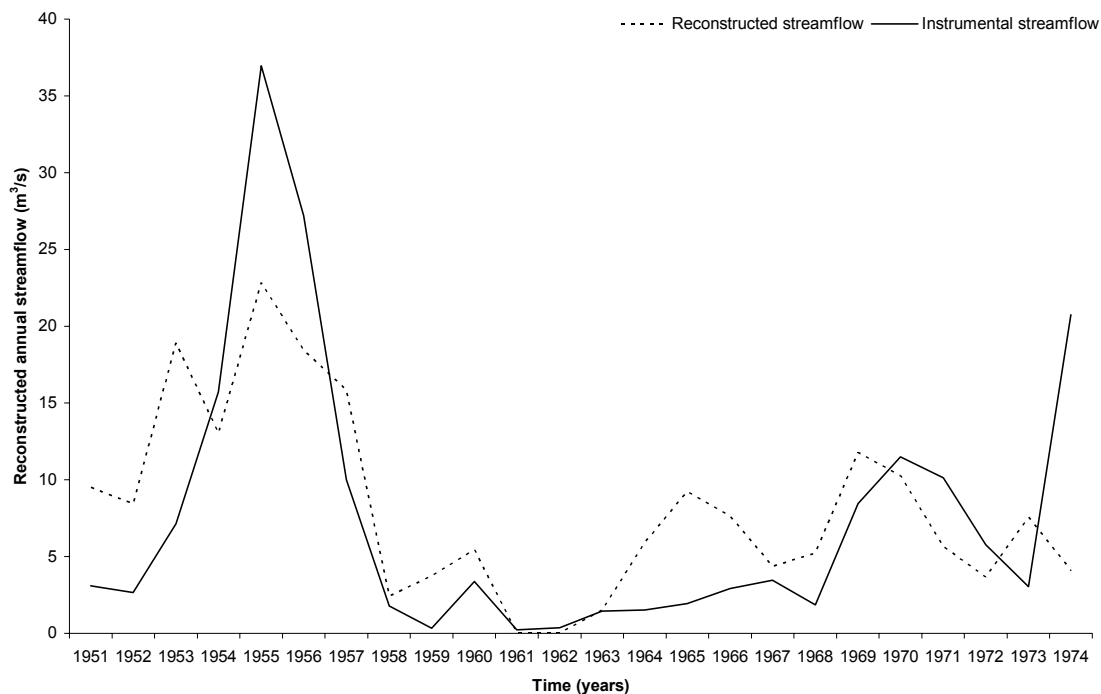
Figure 41. Actual versus reconstructed mean annual streamflow at Tantallon over the period of instrumental data, 1951-1974.

From the streamflow and precipitation reconstructions, extended dry periods occurred in the late 19th century, early to mid-20th century, and very late 20th century. The Devon Farm and Hillside records show some important similarities with other tree ring reconstructions from the northern Great Plains (Stockton and Meko, 1983; Woodhouse and Overpeck, 1998) and the Canadian Prairie Provinces (Bonsal *et al.,* 1999; Sauchyn and Skinner, 2001; Sauchyn *et al.,* 2002, 2003; Wheaton *et al.,* 1992). Most records, like the present one, show short intense droughts throughout the 20th century.

The 153-year reconstruction of total water year streamflow over this 12-month period represents the first tree-ring chronology and reconstruction of streamflow in southeastern Saskatchewan. The record shows excellent agreement with other independent dendrochronological records of drought from Alberta to Manitoba and parts of the US Great Plains, thus filling the void in the tree-ring network across the Canadian Prairies. As this is the first study to investigate the potential of dendrochronological studies for southeastern Saskatchewan, there is potential for developing a longer *Quercus macrocarpa* ring-width chronology in this area through more extensive sampling of both living and archaeological wood. This chronology would present a unique opportunity for investigating the recurrence and potential magnitude of drought events in southern Saskatchewan over a long interval.

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The Pollen Record: A High-Resolution Record of the Paleoecology

Introduction

Vegetation will respond to the climate changes projected for the western interior, with shifting ecoregion distributions and boundaries (Seppä and Birks, 2001 and 2002; Seppä *et al.,* 2004). These ecoregion changes will be accompanied by changes in individual species distributions. Predicted effects of the changes in a number of climate variables include a northward shift of the grassland-aspen parkland-southern boreal forest transition zone (MacDonald *et al.,*1998). To fully understand how the vegetation will change in response to future climate change it is essential to examine how vegetation has responded to changes in climate in the past. Using pollen grains and spores preserved in lake sediments over time, it is possible to determine the distributions of plant species and vegetation types that existed in a particular area at different times in the past (*e.g.* Bartlein & Webb 1985; Huntley & Prentice 1988; Guiot *et al.,*1989; Bartlein & Whitlock 1993; Guiot *et al.,*1993; Seppä & Birks 2001 and 2002). The shapes and surface features of pollen grains and spores are unique for different types of plants, and therefore the types and abundances of fossil pollen grains and spores indicate the vegetation present when the fossils were deposited in the lake sediments. When these vegetation records are compared to climate information, it is possible to understand the past relationship between plant distributions and climatic variables. The purpose of this component of the project was to examine how the vegetation in the study area has varied in response to changes in climate in the past, in order to better understand how the vegetation will change in response to predicted future climate changes.

Methods

Core Collection

Four lakes were sampled for high-resolution pollen analysis (Table 6). Three of the lakes are in the aspen parkland-southern boreal forest transition zone in central Saskatchewan, while one is in the mixed grass prairie-aspen parkland transition region in southern Saskatchewan. Given their locations in ecotone areas, the pollen records of these lakes will reflect changing ecoregion boundaries due to climate variations over the period of record. Careful consideration was given when selecting the three northern lakes to ensure the lake watershed was not directly impacted by agriculture or recent forest fires. All lakes possess the characteristics which make them optimal for the preservation of a good pollen record. The three northern lakes are situated in shallow depressions surrounded by forest. The southern lake is in a deep valley, with forest on the east-facing side and grassland on the hilltops and west-facing side of the valley.

Table 6. Lake locations and sampling data.

Lake	L02	L03	NFL	Deep Lake
Latitude	54° 39' 32" N	54° 35' 49" N	53° 36' 45" N	50° 24' 25" N
Longitude	104° 54' 07" W	105° 57' 65" W	106° 29' 35" W	103° 39' 50" W
Core Length (cm)	72	78	100	144
Sampling interval (mm)	5	5	10	5
Dating method	^{210}Pb and ^{14}C	^{210}Pb and ^{14}C	^{14}C	Introduced species; ^{14}C pending
Effective sampling resolution (years/cm)	~ 2.5	~ 6	~ 24	~ 14

The sediment cores were collected from the deepest part of each lake using a square rod Livingstone piston corer, a Glew gravity corer, or an acrylic tube with movable piston. In all cases the core tube was lowered through the lake to the sediments at the bottom and then pushed straight down into the sediments so that the layers of sediment and organic material (including pollen) that have accumulated over the years are preserved in layers inside the tubing. The core was held in place with a piston while the tube was pulled to the surface. The sediments were then extruded (Figure 42) from the core tube in either 1 cm or 5 mm sections, which were collected and labeled.

A 0.5 cc sample was removed from each section and processed to isolate pollen and spores using standard techniques (Faegri & Iverson, 1989). The pollen and spores sample was stained and mounted on microscope slides in silicon oil. In the preparation, a known quantity of exotic *Lycopodium* spores was added to each sample to allow the determination of pollen/spore concentrations in the sample.

Figure 42. Extruding and sampling lake sediments.

Dating

An age-depth relationship for each of the cores was developed using two types of radioisotope dating (^{210}Lead and ^{14}Carbon) and the appearance of introduced agriculture-related plants (cereal grains and Russian thistle, *Salsola kali)*. The time period in which each sediment sample was produced and deposited was thus determined. Radiocarbon dates were determined by measuring the ^{14}Carbon activity in organic material taken from the cores using AMS (accelerated mass spectrometry) dating at the National Ocean Sciences Accelerator Mass Spectrometry Facility (NOSAMS) at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. The ^{14}Carbon dates were calibrated using the computer program CALIB (Stuiver and Reimer 2003) and graphed to determine the period of time represented by the sediment core. ^{210}Lead dating was done by Flett Research Ltd., Winnipeg, MB.

Pollen counts

Morphological features of pollen and spores are taxonomically diagnostic. By counting the abundances of pollen and spore types in each sediment sample, the vegetation growing at that time around the lake can be reconstructed. Wherever possible a minimum of 500 pollen grains/spores was counted for each sample. The resulting assemblage data

are expressed both as percentages (i.e. relative abundances) and as accumulation rates (grains/cm^2 sediment surface/year) Accumulation rates have an advantage in that they express differences in pollen productivity over time, but are also very sensitive to dating uncertainties. Relative abundances can be swamped by common pollen types (*e.g.* pine, spruce) but are not affected by dating ambiguities. Relative abundances can help to elucidate changes in the relative importance of taxa in the vegetation assemblage.

Standard pollen diagrams were produced for each record. In each diagram calibrated calendar years are indicated along the vertical axis. Each pollen taxon or ecosystem group is indicated as a column, with the abundance scale indicated along the horizontal axis. Latin names of the taxa are used in the diagrams; common names are given in Table 7.

Table 7. Taxon names.

Trees		Shrubs		Herbs		Introduced	
Latin	**Common**	**Latin**	**Common**	**Latin**	**Common**	**Latin**	**Common**
Abies	Fir	*Alnus*	Alder	*Artemisia*	Sage	*Cereale*	Cereal grains
Betula	Birch	*Corylus*	Beaked hazelnut	Chenopo-diaceae	Goosefoot & amaranth families	*Salsola*	Russian thistle
Picea	Spruce	*Salix*	Willow	Cyperaceae	Sedge family		
Pinus	Pine	*Cornus*	Dogwood	Liguliflorae	Sunflower family [1]		
Populus	Poplar, aspen	Ericaceae	Blueberry family	*Plantago*	Plantain		
		Juniperus	Juniper	Tubuliflorae	Sunflower family [1]		
		Sarcobatus	Grease-wood				
		Shepherdia	Buffalo berry				

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Response surfaces

In order to determine the relationship among the pollen/spores that accumulate in lake sediments, the vegetation around the lake, and the climate, a dataset of surface pollen/spore samples, current vegetation, and current climate conditions was compiled to serve as a calibration set (*e.g.* Bartlein & Webb 1985; Whitmore *et al.,*2005). The surface sample contains the pollen that was released by the plants around the lake in recent years. A window was framed between 65-40° N and 115-95° W to include all of the vegetation types that might be represented in the fossil pollen samples. Pollen surface sample data for 174 sites in Alberta, Manitoba, Saskatchewan, Minnesota, Montana, North Dakota and South Dakota were retrieved from the North American Pollen Database (Figure 1). Climate data were acquired for the climate station closest to the lake from which each surface sample was taken. Information on the vegetation growing around the lake was compiled from ecoregion maps and vegetation descriptions. The pollen taxa were divided into the ten ecosystem groups listed in Table 8.

Table 8. Pollen ecosystem groups.

No	Ecosystem Group
1	closed conifer forest
2	bogs
3	open conifer forest
4	open successional forest
5	deciduous forest (long-distance)
6	grasslands
7	aquatics
8	disturbed
9	western montane forest/tundra
10	agricultural plant
0	taxa excluded
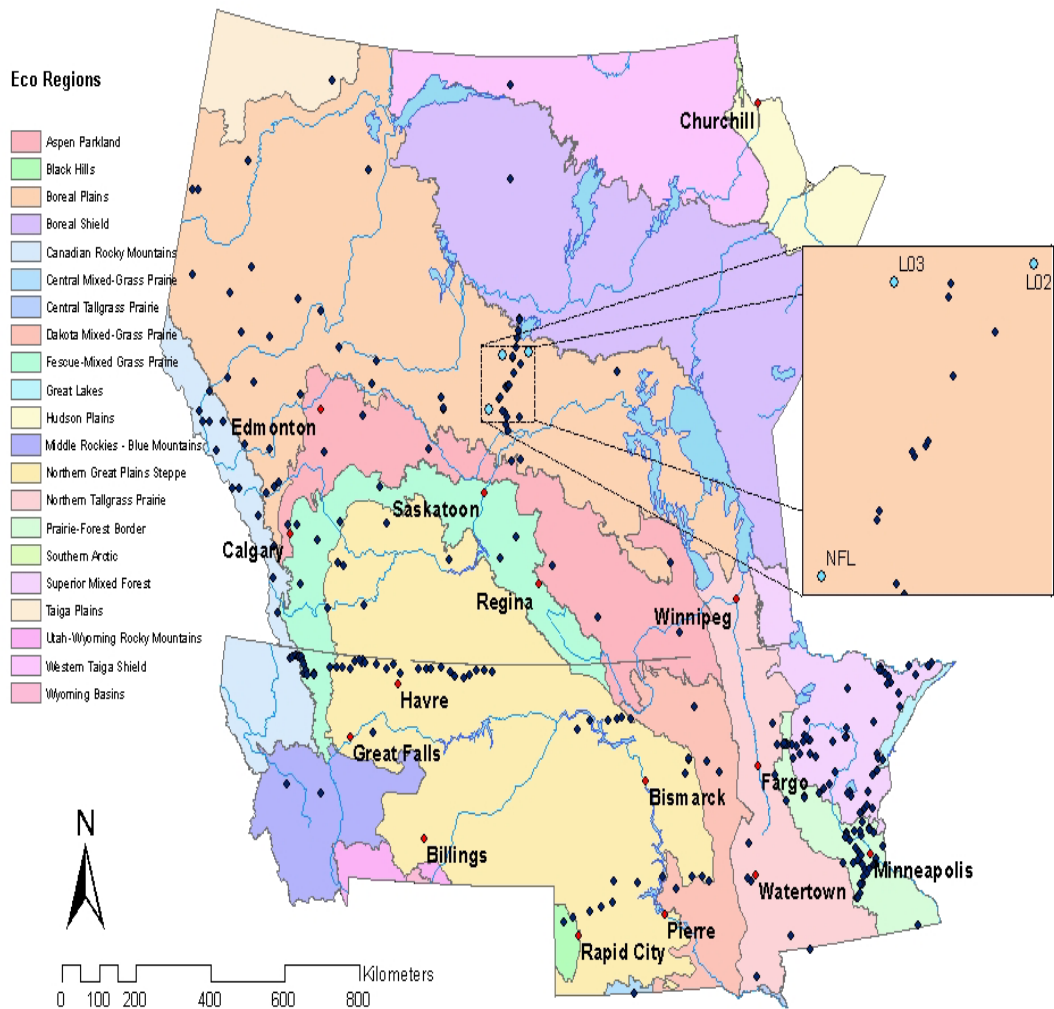
Figure 43. Pollen Surface Sample Sites.

In Figure 43, the black dots show the locations of the pollen surface samples in the context of the associated vegetation types across Alberta, Saskatchewan and Manitoba in Canada as well as in Montana, North and South Dakota and Minnesota in the United States. The key on the left hand side of the map identifies the vegetation types shown on the map. The red dots show the locations of major cities in the provinces and states. In the magnified portion of the map (smaller square) the light blue dots show the location of the lakes where the three northern sediment cores were taken. The southern core was taken from Deep Lake about 100 km directly east of Regina. Surface pollen sites were chosen to represent the range of fossil pollen groups that might be found at various depths in the lake sediment cores.

Climate reconstructions

The transfer functions for climate reconstruction were developed using the C2 software for ecological and palaeoecological data anlaysis and visualization (version 1.4, Steven Juggins, University of Newcastle, Newcastle upon Tyne; http://www.staff.ncl.ac.uk/stephen.juggins). The calibration set included modern pollen data (expressed as percentages) from 173 sites as shown in Figure 1, and climate data averaged for the most recent 30 years. The modern pollen data set was reconciled with the proxy (fossil) pollen data sets by including only the taxa that were found in both modern and proxy data sets and combining taxa were necessary (for example, white spruce and black spruce were combined and similarly tree and shrub birch). Climate data for the three stations closest to each modern pollen site were interpolated using weighted distance averaging. On the basis of the sensitivity of the taxa to climate variables as shown in the response surfaces, average annual precipitation, summer precipitation, and annual temperature were used. The transfer functions were generating using the Weighted Averaging method and bootstrap cross-validation in C2.

Results and Discussion

Climate-Pollen Response Surfaces

Response surfaces present surface pollen data in relation to climate factors, in order to estimate the response functions of the pollen taxa. The climate variables are plotted along the X- and Y-axes, and thus pollen abundances are plotted in climate space in a fashion analogous to plotting plant distributions in geographic space (Bartlein *et al*., 1986). The contour intervals on the response surfaces are read in the same way that contour intervals are read on a topographic map, showing the relative effects of the two climate variables on the predicted distribution of the plant taxon as represented by each pollen type.

Response surfaces showing pollen abundances relative to annual temperature and summer precipitation are discussed here. Six ecosystems groups (Table 8) are included: 1, 3, 4, 5, 6, and 8; the other groups included pollen that was represented in very small quantities in the sediment records. Response surfaces have been calculated for a number of other pairs of climate variables, but the conclusions drawn here are similar to those.
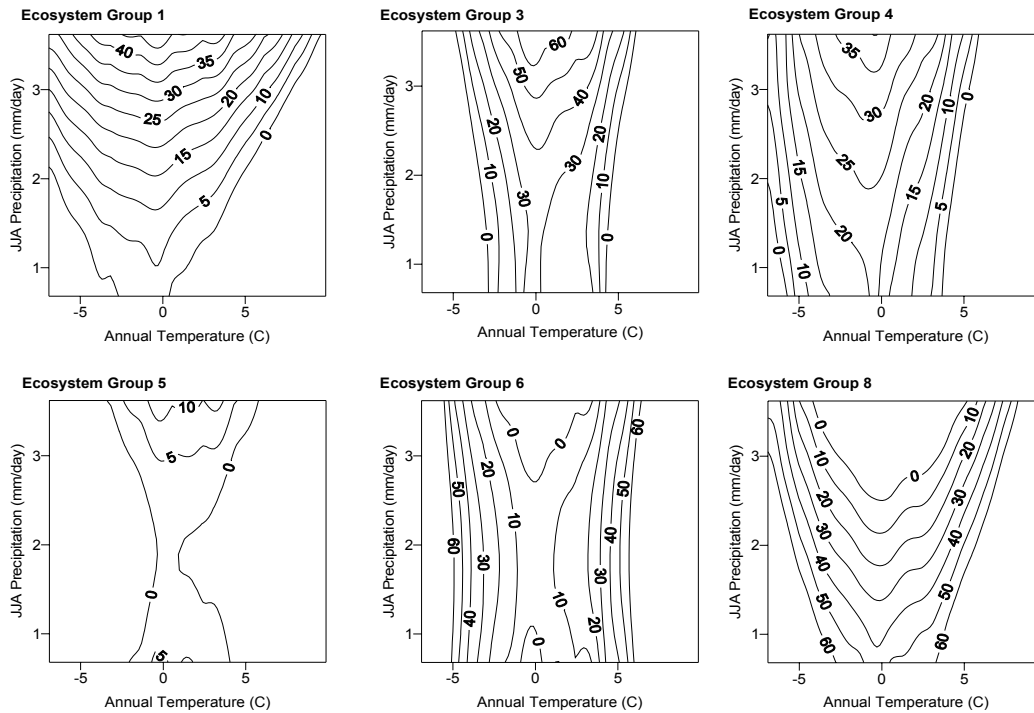
Figure 44. Response surfaces for summer (June-July-August) precipitation and annual temperature.

Closed coniferous forest (Ecosystem Group 1)

Figure 44 shows the response surfaces for the closed coniferous forest pollen taxa characteristic of climax spruce-fir boreal forest in relation to summer precipitation and annual temperature. Clearly these taxa are sensitive to both climate variables, somewhat more so to summer precipitation. Maximum pollen abundance is expected at summer precipitation values above 3 mm/day and annual temperatures around 0°C. The interaction between the two variables suggests that available moisture is an important determinant of the pollen abundance of these species. The spruce-fir forest is expected to decline with the increasing temperatures and moisture constraints resulting from global warming.

Open coniferous forest (Ecosystem Group 3)

Open coniferous forest includes pine, aspen and balsam poplar. A comparison of the response surfaces of this ecosystem group to those of closed coniferous forest (Figure 44) indicates that these taxa have similar overall response patterns but are less sensitive to low levels of summer precipitation than the spruce-fir forest. Therefore it is expected that pine-aspen forest will replace spruce-fir forest on suitable sites in a warmer and drier future scenario.

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Open successional forest (Ecosystem Group 4)

This pollen assemblage is characterized by alder, birch, beaked hazelnut, and associated shrubs and herbs. The response surfaces (Figure 44) are similar to those of the open coniferous forest, and again, this vegetation type should become more widely distributed under warmer and drier conditions, at the expense of spruce-fir forest.

Deciduous forest (Ecosystem Group 5)

This pollen assemblage represents the hardwood forests of the upper midwestern United States and Canada. Two taxa, Manitoba maple and green ash, in this group are found in moister coulees in the grassland area of southern Saskatchewan, and along with aspen form the forest component of the grassland-forest ecotone in this region. Group 5 shows a pattern of response (Figure 44) generally similar to the other forest types, but has higher optimal annual temperature and summer precipitation. Any scenario of lower precipitation will have a negative impact on this group.

Grassland (Ecosystem Group 6)

The response surfaces (Figure 44) indicate a bimodal distribution of this group with respect to annual temperature, suggesting that this is a composite group including grassland/meadow species found in both warm and cooler regions. The pollen taxa in this group represent families with broad environmental tolerances represented among the species, for example, grasses and legumes, and the somewhat separate groups may be a result. Over the annual temperature ranges, there is little sensitivity to summer precipitation.

Disturbed (Ecosystem Group 7)

This group includes taxa, some of which are introduced, characteristic of disturbed areas; the goosefoot/amaranth families are the main constitutents. This is the only group that shows higher abundances at lower levels of summer precipitation (Figure 44), suggesting increases under future warming and drying scenarios. Relatively high abundances of pollen of this type have been associated with warm, dry conditions on the prairies in the past, especially during extended droughts and the early Holocene.

Vegetation Change

Recent vegetation changes over the past 50 years

At each of the sites there is a decline in the forest taxa and an increase in either the aspen parkland and grassland taxa (at the northern sites) or the grassland taxa (at the southern site) over approximately the past 50 years and especially over the past 25 years or so. This decline is very clear in both the relative abundances (Appendix C, Figures C1, C5,

C9 and C13) the accumulation rates (Appendix C, Figures C2, C6, C10 and C14) for individual taxa and for the Ecosystem Groups (Appendix C, Figures C3, C4, C7, C8, C11, C12, C15, and C16). In the L03 record a substantial decline of most tree and shrub pollen taxa (accumulation rates) is seen over the most recent 60-70 years. This is not an agricultural area, so climatically-driven vegetation change is suggested. This is further supported by the modest increases in poplar pollen over this same time period, suggesting the expansion of aspen parkland (at least in terms of pollen productivity) at the expense of coniferous forest and cool, moist shrublands. In the L02 record there may be an indication of the effects of the 1930s drought, with a substantial decrease in all pollen accumulation rates, but this could be an artifact if there were increased sedimentation rates 'diluting' the pollen concentrations at this time. Generally, the relative abundances of birch and pine are lower, but spruce is higher; further analysis of this record is needed. Since this is the smallest of the three lakes, the pollen record may be very local in origin.

In contrast to the northern lakes, Deep Lake is in the ecotone between grassland and aspen parkland. Substantial declines in pollen accumulation rates of the tree species are seen over the past 50 years and in particular over the past 25 years. A similar change to warmer and drier vegetation types and taxa at the expense of forest is clear. The percentage (relative abundance) data show that the proportion of the pollen in the total assemblage that is spruce and pine has been increasing over this time period. Neither of these two taxa are native to the area, and this would reflect decreases in the native tree species (aspen, Manitoba maple and green ash) relative to the coniferous trees. In other words, although the trees overall are decreasing, an increasing proportion of the tree pollen comes from planted spruce and pine.

These observed changes fit very well with predictions based on the response surfaces of the ecosystem groups and with observed climate changes over the past few decades, with warmer annual temperatures and decreased moisture availability. Comparisons of the larger North Flat Lake with the smaller lakes indicates that these changes are occurring on both the regional landscape scale and the more local scale. In high resolution pollen analysis it will be challenging to separate short-term climate influences on pollen productivity vs. somewhat longer-term climate influences on vegetation community structure. Undoubtedly both effects are seen in the highest resolution record from L02, while the lower resolution records from L03 and North Flat Lake suggest that changes in vegetation community structure are underway, perhaps first manifested as lower pollen productivity and decreased tree vigour rather than actual species' replacements.

Longer-term vegetation changes

North Flat Lake (Appendix C, Figures C1, C2, C3, C4)

This lake is the largest of the three northern lakes and as a result the pollen record reflects the regional vegetation composition. There appear to be fairly large cycles from maximum to minimum pollen amounts (both relative abundances and accumulation rates) over 3-4 sample lengths (that is approximately 75-100 years). Accumulation rates are very sensitive to sedimentation rates (that is, high sedimentation rates will dilute pollen

abundances), but in general the values for spruce and pine are high when poplar values are low and vice versa. This is preliminary support for the possibility that accumulation rate 'cycles' are real manifestations of climate and/or vegetation cycles and not an artifact of sedimentation rate changes. More analysis is required, however. The accumulation rates of grass pollen, and other taxa characteristic of more open areas (*e.g. Artemisia,* Chenopodiaceae), were relatively high from the beginning of the pollen record through until about 1200 AD, but have been lower over approximately the past 600 years. The opposite is true for spruce, pine (to a lesser extent), alder, birch, and willows. These implied vegetation changes over the past 600 years, to greater forest extent at the expense of grassland, may represent the general cooling and/or moister conditions associated with the Little Ice Age in other regions of the northern hemisphere, while the more open vegetation before 1200 AD may represent the Medieval Warm Period. In general, the pollen results suggest that the present forest-aspen parkland-grassland mosaic in this region was present over the past nearly 2000 years, with changes in the relative amounts of these that may correspond to broad climate trends.

L03 and L02 (Appendix C, Figures C5-C12)

The smaller sizes of these two lakes means that the pollen record is derived from a smaller area, thus representing more local vegetation changes. In the L03 record, generally high amounts of coniferous tree and shrub pollen from about 1650 to the late 1800s suggest that Little Ice Age climatic conditions favoured forest and moist shrublands during these times, similar to the results seen in the North Flat Lake record. Similarly, a substantial decrease in coniferous forest and moist shrubland taxa is seen from about 1850 to the present in the L02 record. As with the North Flat Lake record, a vegetation mosaic of southern boreal forest-aspen parkland-grassland that is a sensitive indicator of climate conditions was found in the area over the period of record.

Deep Lake (Appendix C, Figures C13-C16)

The clearing of native grassland with the onset of agriculture in this region is clearly seen in both the pollen relative abundance and accumulation rates with the sharp decline in sage (*Artemisia*) pollen at the same time that cereal grain pollen and Russian thistle appear in the records. Over the same timeframe there is a sharp increase in Chenopodiaceae pollen, which includes taxa that are related to disturbance and/or increased soil salinity. As well, there are substantial increases in Aceraceae and *Fraxinus* pollen (in this area these would represent Manitoba maple and green ash, respectively), showing the increase in open woodlands associated with European settlement and presumably the suppression of prairie fires. This pollen record is still being counted, and will eventually extend back approximately 1000 years.

Summary

The pollen records from the three northern lakes show that a mosaic of boreal forest, aspen parkland, and grassland vegetation has been characteristic of the southern boreal forest region throughout the periods of time represented, but that changes in relative extents of these may be related to broad climate trends. The Medieval Warm Period and the Little Ice Age may be represented by less and greater extent of forest vegetation, respectively. The Deep Lake pollen record is still under development, but clearly shows the effects of agricultural settlement, presumably accompanied by forest suppression, in southern Saskatchewan. All records show that the 1930s drought had significant impacts on the vegetation, and comparison with climate records (for example from tree rings) may show impacts of other drought periods as well.

Climate Reconstruction

Three climate variables (average annual temperature, annual precipitation, and summer precipitation) were reconstructed for one lake, L03. Although all possible taxa (following reconciliation with the modern pollen data set) were used to construct the transfer functions, the results include only those taxa that were consistently found throughout the core and in at least half of the samples. Taxa eliminated were those that occurred only in very small quantities and/or sporadically throughout the length of the core.

The average annual temperature reconstruction (Figure 45) shows a slight, gradual cooling trend with coolest temperatures between about 1630 and 1730, the coolest part of the Little Ice Age. This is also a time of relatively lower summer precipitation values. A definite warming trend is seen from about 1925 through to the present time, especially over the past 15-20 years. The annual precipitation reconstruction (Figure 46) clearly shows the deep but rather short-lived drought of the 1930s. A less intense but more prolonged drought occurred from approximately 1730 to 1765. Short but intense droughts occurred in the early 1500s. It was wetter from about 1815-1850, followed by a period when the trend was to gradually drier overall but quite variable conditions, culminating in the 1930's drought. The annual precipitation shows a decreasing trend through the last half of the 20th century, especially during the last 15-20 years. Reconstructed summer precipitation (Figure 47) shows similar trends, with summer dry times in the 1930s, the mid 1700s, and the late 1600s. The recent trend over the last two decades to warmer and drier conditions corresponds to a substantial increase in *Populus* pollen, suggesting again a recent expansion of aspen parkland at the expense of coniferous forest in the southern boreal forest region.
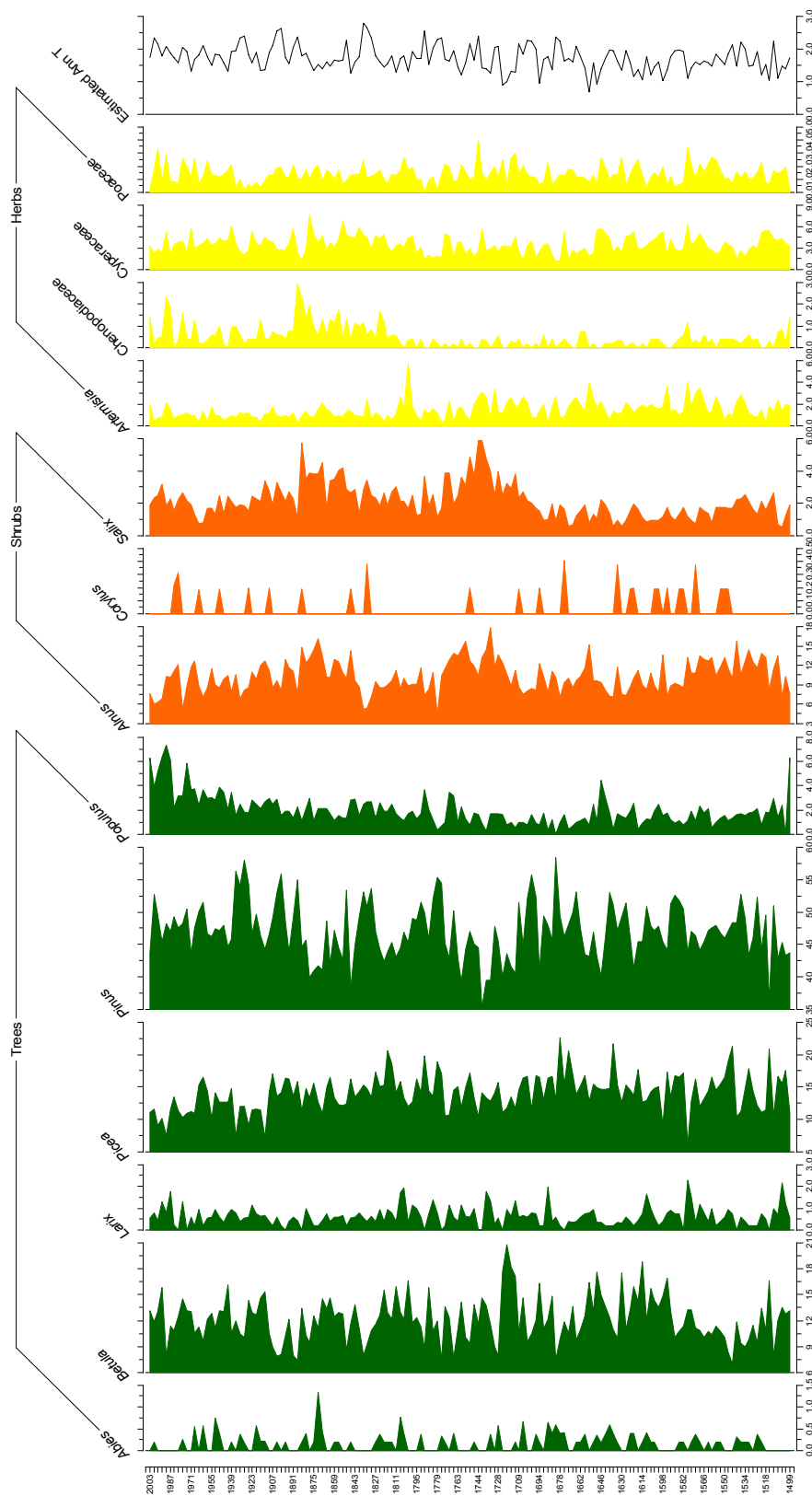
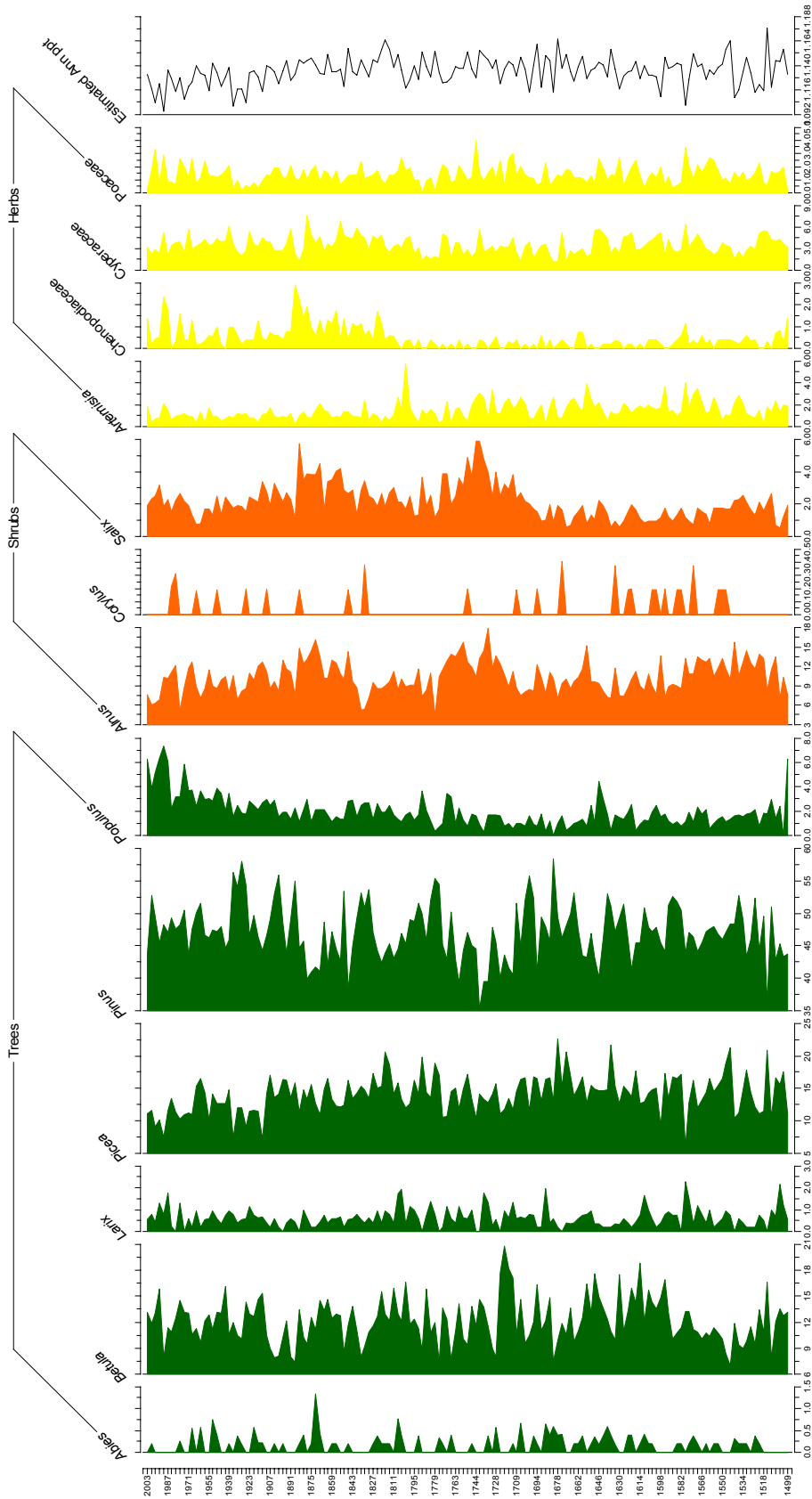Figure 45. Average annual temperature reconstruction for L03.

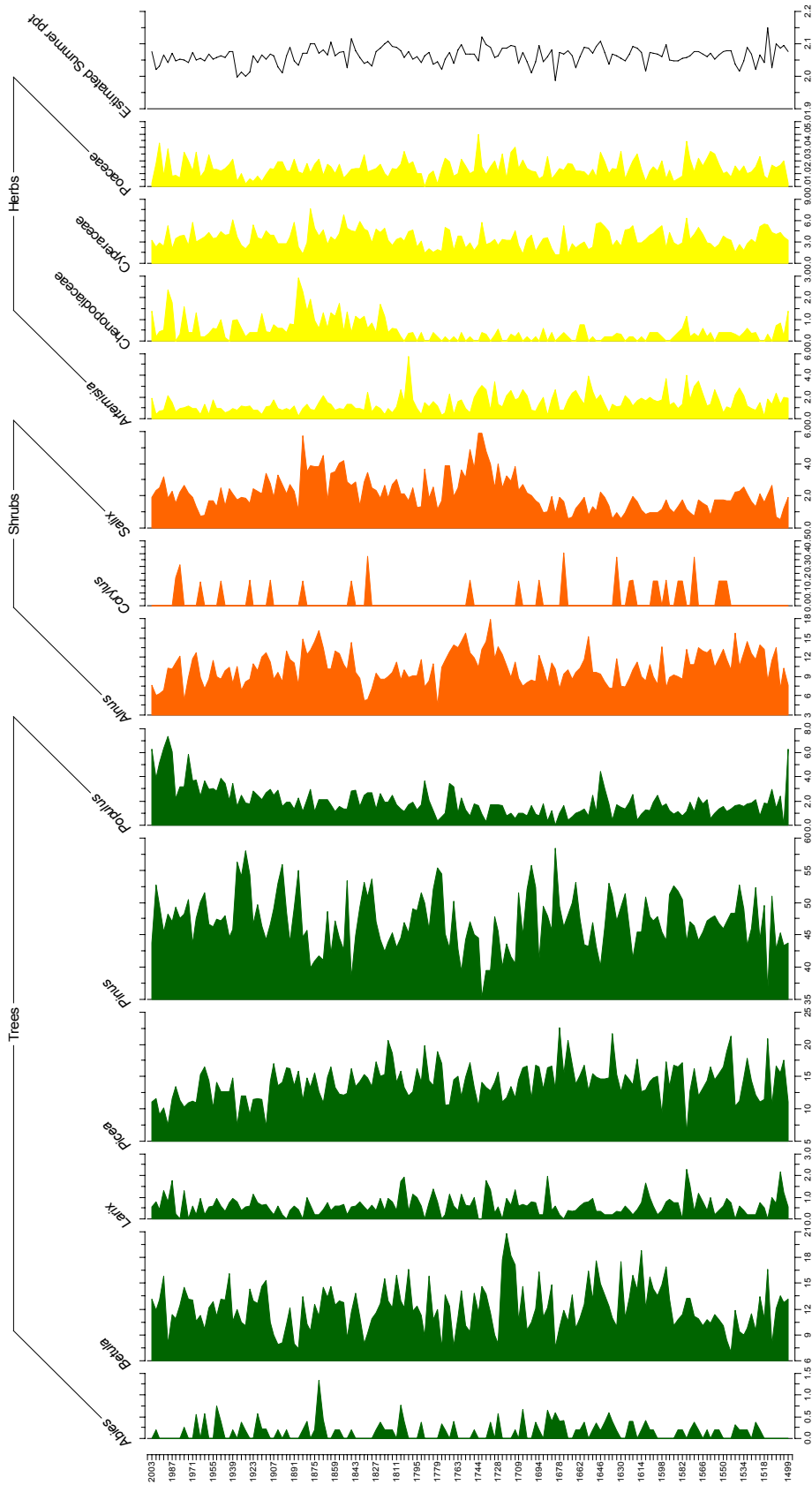Figure 46. Annual precipitation reconstruction for L03.

Figure 47. Summer precipitation reconstruction for L03.

Lake productivity: Whole-lake algal responses to pollen flux
Ranalli (2004)

Introduction

The positive relationship between nutrient loading and algal productivity in lakes has been well-established (Schindler *et al*., 1978; Planas *et al*., 2000). In small, unproductive boreal lakes, allochthonous inputs (*e.g.*, insects and plant fragments) from the surrounding forest have been found to act as nutrient subsidies (Richey and Wissmar, 1979). For example, Cole *et al. (*1990) claimed that particulate material from the surrounding forest represented a phosphorus (P) input 50-70 times greater than from summer streamflow or precipitation. Since lake productivity is most often limited by P in temperate lakes (Smith, 1982), it is not surprising that the most accurate predictor of phytoplankton biomass is total P concentration (Schindler *et al*., 1978). Oligotrophic lakes in temperate regions support only minimal levels of phytoplankton biomass and algal species diversity tends to be low (Watson *et al*., 1997). These systems are generally composed predominately of nanoflagellates of chrysophyceae (golden-brown algae), cryptophytes, small chlorophytes (green algae) or cyanophytes (Watson *et al*., 1997). In these systems, moderate nutrient enrichment can result in higher levels of phytoplankton biomass, as well as changes in the taxonomic composition of algae (Watson *et al*., 1997; Vinebrooke and Leavitt, 1998).

Despite its high nutrient content, pollen has generally been overlooked in studies of nutrient cycling in both boreal forests and lakes (Lee *et al.,*1996a). Doskey and Ugoagwu (1989) measured the content of total nitrogen (N), sulfur (S), organic carbon (C) and P, as well as water-extractable nitrate (NO_3^-), sulfate (SO_4^-), phosphate (PO_4^-) and potassium ions (K^+), in the pollen of *Pinus strobus* and *Pinus resinosa*. While the ratio of total macronutrient concentration (mg·g^{-1}pollen) between N and P was ~7: 1, the ratio of water-extractable NO_3^- and PO_4^{3-} was 1: 30 (Doskey and Ugoagwu, 1989). Similarly, Lee *et al. (*1996a) found a nearly identical ratio for total N and P in *Pinus banksiana* (jack pine) but suggested that the amount of PO_4^{3-} was three times the size of that in *P. strobus* and *P. resinosa*. Macronutrient fluxes from pine pollen in a northern Wisconsin lake were determined by multiplying the estimated pollen flux and the macronutrient content of pine pollen (Doskey and Ugoagwu, 1989). The authors concluded that the pulse of P input from pine pollen represented 45% of the external input but that it may not significantly affect the annual nutrient budget. In contrast, such pollen-derived nutrients may play an important role in phytoplankton dynamics in instances where the principal external source of nutrients is atmospheric deposition.

Because P is one of the major nutrients limiting primary production in boreal lakes, there has been a lot of interest in measuring its sources, sinks and fluxes in lakes (Richerson *et al.,*1970; Schindler *et al.,*1978; Lewis *et al.,*1985; Doskey and Ugoagwu, 1989; Cole *et al.,*1990). A P deposition pulse in early summer has been found to coincide with phytoplankton blooms in temperate-region lakes (Doskey and Ugoagwu, 1989; Cole *et al.,*1990; Campbell, 1994). While atmospheric fallout has been accredited for a considerable portion of this P pulse (Lewis *et al.,*1985; Doskey and Ugoagwu, 1989; Cole

*et al.,*1990), only one study (Doskey and Ugoagwu, 1989) concluded that the episodic deposition of pollen represented an important input of nutrients. Cole *et al. (*1990) reported that pollen was not an important component of the P flux to a New Hampshire lake, however, they noted that by late July (the time at which they deployed atmospheric deposition collectors on the lake), few trees were still releasing pollen, likely resulting in an underestimation of the importance of pollen. Richerson *et al. (*1970) concluded the N and P of pollen deposited in Lake Tahoe represented a negligible amount in terms of the annual nutrient budget for this lake. However, in smaller lakes with limited nutrient inflow and smaller volume: catchment area ratios, pollen may represent a significant nutrient source (Richerson *et al.,*1970). Lewis *et al. (*1985) used large collectors to sample P deposition at weekly intervals over the course of several years and estimated the amount of P that could be liberated from pollen of (lodge pole) pine (*Pinus contorta*). A limitation common to all of these studies is that they represent relatively short sampling periods and may miss large scale variations in pollen production associated with climatic variability or changes in forest management practices.

Due to their mode of reproduction, anemophilous (wind-pollinated) species (dominant in boreal forests) produce significantly greater amounts of pollen than do entomophilous (insect-pollinated) or hydrophilous (pollinated via water) species (Stanley and Linskens, 1974). Pine trees have been found to produce 150 cm^3 of pollen per 100 strobili (Stanley and Linskens, 1974). Lee *et al. (*1996b) reported total pollen deposition values of 4604 grains/cm^2 for *Pinus banksiana* and, 1673 grains/cm^2 for *Picea* species in a mixed boreal forest stand in Manitoba. The quantity of pollen produced by a given individual plant varies between successive years, depending on environmental factors such as light exposure, temperature, precipitation, the age of the tree and nutrient uptake by the plant (Stanley and Linskens, 1974; Lee *et al.,*1996b; Lee and Booth 2003). In addition to their influence on quantities of pollen produced, environmental conditions can also influence the time of pollen shedding between years (Stanley and Linskens, 1974; Lee *et al.,*1996b). For example, in a single pine stand, the timing of maximum pollen release can vary by up to two weeks in a period of only three to five years (Stanley and Linskens, 1974; Lee *et al.,*1996b). Therefore, unless modern experiments estimating pollen output and accumulation (and subsequent nutrient fluxes) in boreal lakes are conducted in late spring to early summer, the total nutrient input from pollen grains may be underestimated.

Individual anemophilous plant taxa produce morphologically unique pollen grains that are distributed considerable distances from their sources and are resistant to decay in sediments (Bradley, 1999). Therefore, by examining the sedimentary pollen record in lakes, long-term changes in sediment pollen concentration can be calculated and compared to long-term changes in algal abundance. These techniques provide a means of determining the significance of pollen as a nutrient source to boreal aquatic systems by examining centuries of data.

Despite degradative pigment losses during deposition, sedimentary pigment concentration and algal abundance are correlated through time (Leavitt ,1993). Long-term phytoplankton records have shown that sedimentary pigment concentrations are

significantly related to phytoplankton biomass (Leavitt *et al.,*1994; Leavitt and Findlay 1994). Because major algal groups produce taxonomically diagnostic pigments (Table 9) that are preserved in the sediments of lakes, historical changes in whole-lake algal abundance and community composition can be determined from concentrations of undegraded chlorophylls and xanthophylls (Gorham *et al.,*1974; Swain 1985; Vinebrooke *et al.,*2002). Thus, in the absence of long-term records, pigment stratigraphies provide a means of examining the response of primary producers to chemical changes in the aquatic environment.

Table 9. Taxonomically diagnostic chlorophylls and carotenoids identified in a lake sediment core taken from Northern Saskatchewan, Canada.

Pigment	Algal group
Chlorophyll a	All algae
β-carotene	All algae
Alloxanthin	Cryptophytes
Diatoxanthin	Chrysophytes and Diatoms
Fucoxanthin	Chrysophytes and Diatoms
Lutein	Chlorophytes
Zeaxanthin	Cyanobacteria

If conifer pollen represents an important nutrient source for phytoplankton growth, total algal biomass (as sedimentary β-carotene, total chlorophyll, total xanthophylls) should increase as a function of pollen flux to lakes. If, on the other hand, there is no relationship between pollen concentration and sedimentary pigments, this may indicate that nutrients derived from pollen have an insignificant role in the overall dynamics of primary production or that paleo techniques may be too coarse to quantify pollen's influence on phytoplankton abundance.

Methods

The study lake, L02 (54°39'N, 104°54'W) is located ~12 km from Cobb Lake, Saskatchewan. Lake selection was based on surface area (10-20 ha), depth (> 5 m) and accessibility to the road (< 200 m). The catchment is undisturbed, mixed forest in Narrow Hills Provincial Park. The lake had a maximum depth of 8.6 m, a surface area of 14 ha and a single inlet stream on the northwest side of the lake. Surrounding the lake, there is an approximate even mix of white spruce (*Picea glauca*) and jack pine with poplars (*Populus* species) dominating the higher elevations and birch (*Betula* species) near the shore in low-lying areas. Balsam fir (*Abies balsamea*) was also present, randomly interspersed in the lower areas.

A sediment core was taken from the deepest central area of the lake in May of 2003 with a Glew Maxi gravity corer and sampled as described in the pollen section of this report. Individual core sections were freeze-dried then kept frozen and stored in the dark until pigment extraction and subsampling for pollen analysis were performed.

Sedimentary pigment concentrations were measured with standard reversed-phase, high-pressure liquid chromatography (HPLC) procedure (Vinebrooke and Leavitt 1998). Pigments were extracted by soaking freeze-dried sediments in acetone and methanol (80: 20 v/v) at 10 ^{o}C for 24 hours. In the dark, extracts were filtered through 0.2-µm pore nylon filters, dried under nitrogen gas and then stored at -20 ^{o}C until reconstitution. Dried pigments were reconstituted with injection solution (70% HPLC-grade acetone: 25% ion pairing reagent: 5% HPLC-grade methanol) containing 3.2 mg/L of Sudan II as an internal reference. Ion-pairing reagent (IPR) contains 0.75 g of tetrabutylammonium acetate and 7.7 g of "Sigma ®" grade ammonium acetate in 100 mL of deionized water. Pigments were separated on a Hewlett-Packard (Hewlett-Packard Canada Ltd., Mississauga, ON) model 1100 system with a Rainin Model 200 C-18 column (10-cm length, 5-µm particle size). Pigments were detected using an inline HP Series 1100 diode array detector (435-nm detection wavelength) and a fluorescence detector (435-nm excitation wavelength, 667-nm detection wavelength). Separation involved isocratic delivery (1.0 mL·min^{-1}) of a mobile phase A (10% IPR in HPLC-grade methanol) for 1.5 minutes, followed by a linear succession to 100% solution B (27% HPLC-grade acetone: 73% HPLC-grade methanol) over 7 minutes and isocratic hold for 12.5 minutes. The column was then re-equilibrated by isocratic delivery for 3 minutes, a linear return to 100% solution A over 3 minutes and isocratic delivery for the last 4 minutes. Due to difficulties with the HPLC, the pigments in 64 of the 149 samples were not properly separated during chromatographic analyses. Therefore, all statistical analyses were performed on the remaining 85 samples. The 64 core sections not included were randomly dispersed throughout the depth of the core.

Pigments were identified by comparing profiles of spectral absorbance and chromatographic mobility with standards and extracts from the United States Environmental Protection Agency (USEPA, National Exposure Research Laboratory, Cincinnati, Ohio). Pigment concentrations were calculated using equations derived from dilution series of authentic standards from USEPA or from commercial standards (Sigma Chemicals, St Louis, Mo.). Pigment concentrations are expressed per gram of organic matter, determined from the mass-lost-on-ignition at 500 ^{o}C for 45 minutes. Whole-lake algal abundance and community composition were inferred from concentrations of undegraded chlorophylls (total chl a), β-carotene and taxonomically diagnostic xanthophylls (Leavitt, 1993; Jeffrey and Vesk, 1997; Vinebrooke and Leavitt, 1998). Major algal groups identified included chlorophyceae (lutein), cyanophytes (zeaxanthin), cryptophytes (alloxanthin) and chrysophyceae and bacillariophytes (diatoxanthin and fucoxanthin). Since lutein could not be separated from zeaxanthin, chlorophytes and cyanophytes were examined as a single group. Pollen was counted as described in the pollen section of this report.

Correlation analyses were performed between sedimentary pollen, β-carotene, total chlorophyll and total xanthophyll concentrations in order to determine the degree of relatedness between whole-lake algal abundance and pollen flux in anemophilous taxa. Plant taxa were included in analyses if they accounted for at least 3% of total pollen deposition and 0 grains were counted in, at most, 8 core sections ($\leq 10\%$ of the data). *Alnus*, *Betula*, *Picea* and *Pinus* species were identified as major pollen contributors according to the preceding guidelines. The statistical significance of calculated correlation coefficients was tested using critical values for correlation coefficients at the 5% significance level. Both pigment and pollen data were inspected for normality prior to statistical analyses and $\log(x + 1)$ transformations were performed when necessary. Autocorrelation analyses were also performed for pigment and pollen stratigraphies to test for sample independence. To avoid violating the statistical assumption of sample independence, pigment and pollen concentrations in a given 0.5-cm core section were subtracted from those of the adjacent section, representing the subsequent time period. In this way, pigment and pollen concentrations for any given time period (a single section) are not dependent on preceding values. However, this was not done for regression analyses since resultant models would be meaningless and reverse transformations would be impossible.

Ordinary least squares (OLS) simple linear regression analyses was used to quantify the predictive relationship between individual pigments (taxonomic groups) and pollen concentrations. While my pollen concentration values have associated residual variation, which violates one of the assumptions of model I regression analysis, presumably this amount of variance is relatively small compared to the error variances for pigment concentrations. Further, if there is error involved in estimating independent variable data (pollen concentrations), LaBarbera (1989) deemed OLS regression appropriate so long as its purpose is descriptive or predictive in nature.

Stepwise multiple regression was attempted to identify the best predictors; however, because predictor variables (individual pollen species) showed collinearity, only the single predictor that explained the most variance in pigment concentrations was used in subsequent regression models. I statistically tested my intercept and slope values with *t* tests and overall regression models with ANOVA *F*-ratios. Residual plots were inspected for normality and homogeneity of variance. Cook's distance and leverage values were used to identify sample observations that had a disproportionate influence on coefficient estimates. If outliers were identified, these values were removed and regression analyses were performed a second time. If removal of outliers increased the adjusted R^2 by at least 0.1 or changed the slope by 0.5 units or more, outliers were excluded from the model. No more than four samples (5% of the data) were excluded from each model.

The surface-sediment sample (the upper-most 0.5-cm section) was excluded from all statistical analyses to minimize the confounding effect of pigment diagenesis (Gorham *et al.,*1974; Vinebrooke, *et al.,* 2002). All statistical analyses were performed on SYSTAT Version 10.

Results

The total xanthophyll concentration varied markedly throughout the core, yet there appeared to be no obvious change in the relative proportions of individual pigment concentrations, with the exception of alloxanthin (Figure 48). Alloxanthin represents approximately one third of total xanthophyll concentration in the upper 20 cm of the core and one quarter of xanthophylls deeper in the core (Figure 48). Similarly, total chlorophyll and its chlorophyll derivative, pheophytin a, showed proportional variation throughout most of the core (with the exception of the first few centimeters), confirming that significant correlations between total chlorophyll and pollen concentrations were not a result of pigment diagenesis (Figure 49).
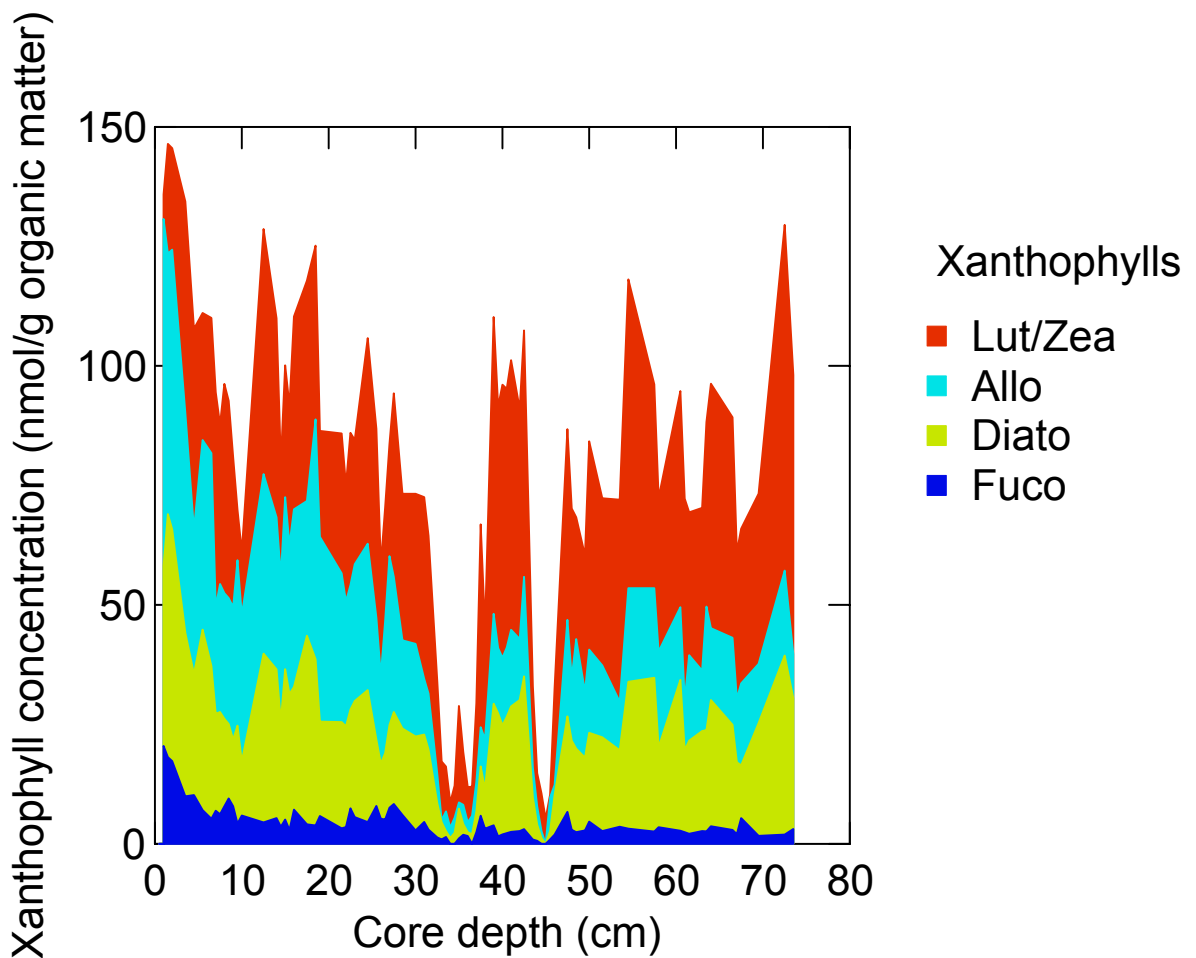

Figure 48. Sediment concentration patterns of taxonomically diagnostic xanthophylls. Lut/Zea = lutein/zeaxanthin (chlorophytes/cyanobacteria), Allo = alloxanthin (cryptophytes), Diato = diatoxanthin (chrysophytes and diatoms) and Fuco = fucoxanthin (chrysophytes and diatoms).
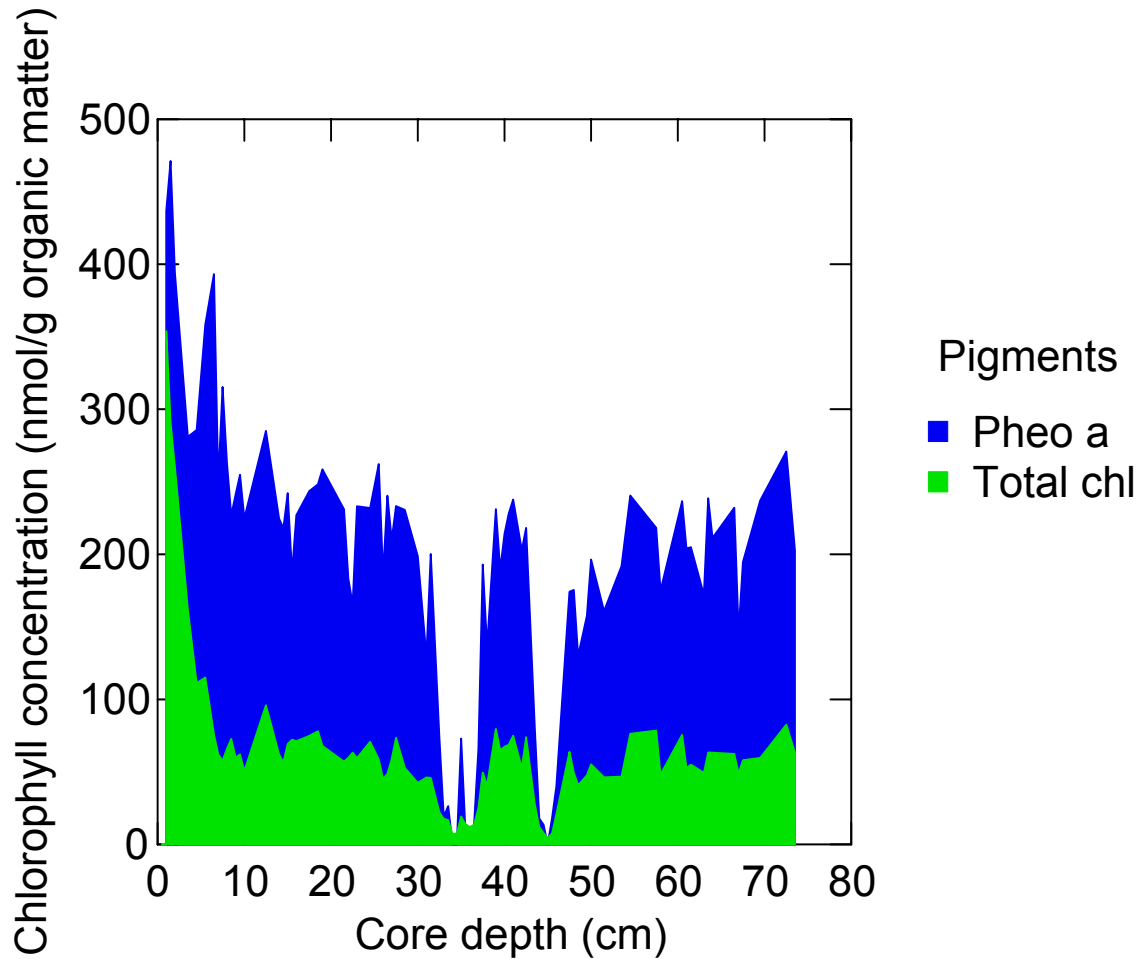
Figure 49. Sediment concentration patterns of total chlorophyll a and its derivative pheophytin a.

Following removal of temporal autocorrelation from all time series, only *Pinus*, *Betula* and *Alnus* pollen concentrations showed significant correlations with sedimentary β-carotene, total chlorophyll or total xanthophyll concentrations (Table 10). Of the 51 plant taxa identified in the core, these 3 pollen species accounted for 77% of total pollen deposition (Table 11), with pine pollen representing the largest component of the sedimentary pollen assemblage (Table 11). This result was expected since jack pine pollen is over-represented in the pollen rain of boreal forests relative to species abundance in the community (Lee *et al.,*1996b).

Table 10. Correlation coefficients (r values) for major pollen contributors and sedimentary pigment indicators of algal abundance. All correlation coefficients are based on n = 84 and were calculated using detrended time series. β-car = β-carotene, Tot chl = total chlorophyll and Tot xan = total xanthophyll.

	Alnus	*Betula*	*Picea*	*Pinus*	β-car	Tot chl	Tot xan
Alnus	1.00						
Betula	0.69***	1.00					
Picea	0.58***	0.58***	1.00				
Pinus	0.72***	0.76***	0.81***	1.00			
β-car	0.14	0.41***	0.09	0.10	1.00		
Tot chl	0.34**	0.49***	0.09	0.22*	0.67***	1.00	
Tot xan	0.40***	0.49***	0.11	0.30**	0.64***	0.89***	1.00

Note: Significance of r values was determined using critical values for correlation coefficients. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.

Table 11. Select plant taxa and the percentages of total pollen concentration. Percentages are based on species concentration sums for the entire core (n = 85).

Genera	% of pollen total
Alnus	10
Betula	15
Picea	11
Pinus	52
Other	12

The concentration of *Pinus* pollen was the best predictor of individual pigment concentrations, explaining between 33-57 % of the historical variation in past algal abundance (Figure 53). Excluding fucoxanthin, regression models were very similar among pigments. Regression coefficients were between 0.809-1.095 and adjusted R^2 values were between 0.435-0.572 ($p < 0.001$; Figure 53). The weaker relationship between fucoxanthin and pine pollen concentrations is likely a function of fucoxanthin's relatively labile nature, compared to those of lutein, zeaxanthin and alloxanthin (Leavitt, 1993). Since there were no marked changes in relative pigment abundances (Figure 48 and Figure 49) and regression models were similar among individual xanthophyll pigments (Figure 50), only those models predicting β-carotene, total chlorophyll and total xanthophyll concentrations will be discussed further.
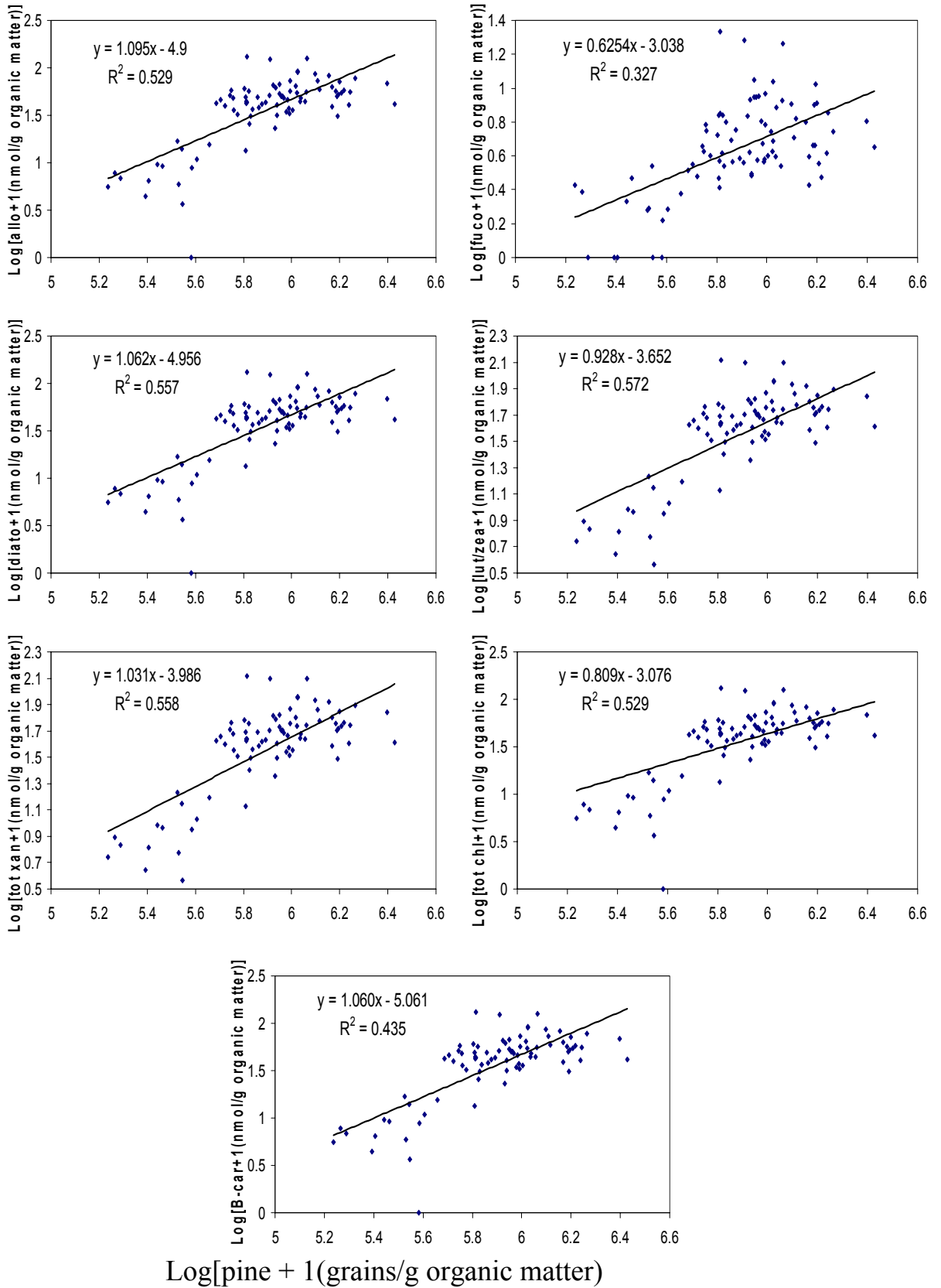
Log[pine + 1(grains/g organic matter)

96

Figure 50. OLS linear regression models for (*a*) alloxanthin (n = 84), (*b*) fucoxanthin (n = 84), (*c*) diatoxanthin (n = 84), (*d*) lutein/zeaxanthin (n = 84), (*e*) total xanthophylls (n = 84), (*f*) total chlorophyll (n = 81), (*g*) β-carotene (n = 84) and *Pinus* pollen. All R^2 values reported are adjusted R^2 values. All *t* values and *F*-ratios were highly significant (*P* < 0.001).

While *Pinus* and pigment concentration profiles do not show identical variation patterns throughout the depth of the core, some concomitant large-scale variations in pollen and pigment concentrations (*e.g.* at 45-cm and 37-cm depths) have occurred in the past (Figure 51). However, at other points in the past (*e.g.* at a core depth of 60 cm), extremely large fluctuations in pine pollen concentration (on the order of 1.2-1.6 x 10^6 grains·g^{-1} organic matter) are not associated with comparable fluctuations in pigment concentrations (Figure 51). Similarly, peaks in pigment concentrations observed in the upper 5 cm of the core were likely a function of rapid post-depositional pigment degradation (Leavitt, 1993).
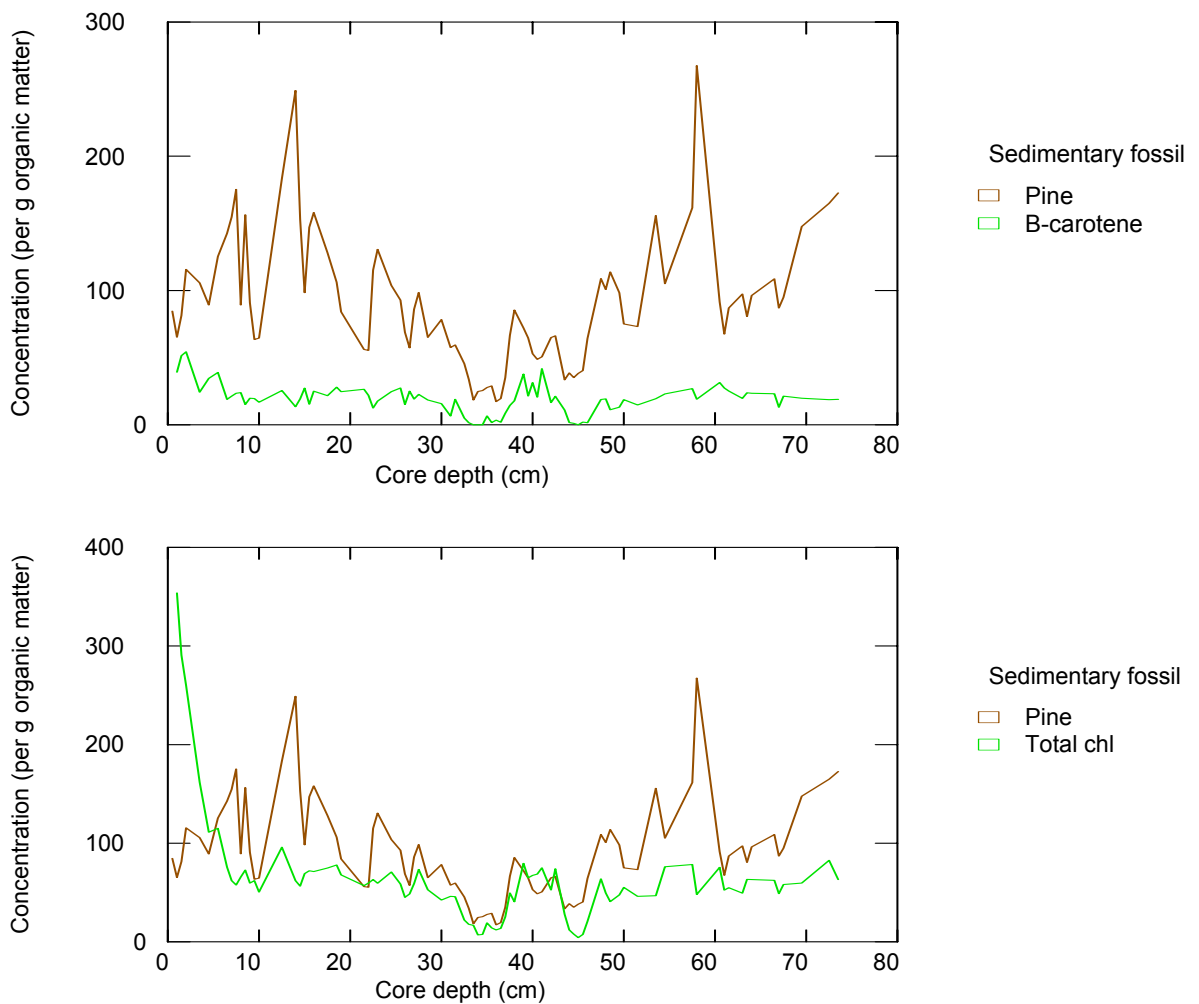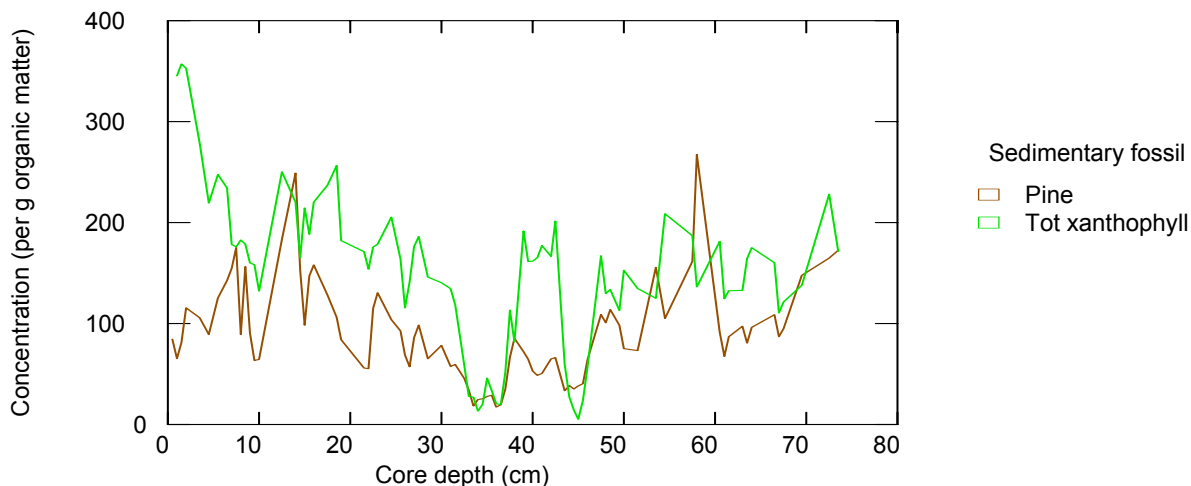
Figure 51. Variations in sedimentary Pinus pollen and (top) β-carotene, (middle) total chlorophyll and (bottom) total xanthophyll concentrations throughout the lake core (n = 84). *Pinus* pollen concentration is expressed as grains x $10^4 \cdot g^{-1}$ organic matter and pigment concentrations as nmol pigment $\cdot g^{-1}$ organic matter.

Discussion

This study provided paleolimnological evidence that algal abundance and lake pollen receipt are related in small boreal lakes. Specifically, increases in sedimentary pigment concentrations were significantly correlated with increased pollen input over the last 1150 years. This result supports the hypothesis that deposition of pollen represents an important available nutrient source for algae since sedimentary *Pinus* pollen concentration, representing the largest fraction of total pollen flux, was the best predictor of total algal abundance. Further, it is unlikely that the sedimentary pigment profiles reflect temporal changes in organic matter deposition from terrestrial vegetation or macrophytes since pigments in higher plants mostly degrade prior to deposition in the sediments (Swain, 1985; Leavitt, 1993) and because macrophytes were sparse in the study area (M. Ranalli, personal observation). Furthermore, the regression coefficients and R^2 values were similar in magnitude among β-carotene, total chlorophyll and total xanthophyll predictive models, despite the restriction of xanthophylls (excluding lutein) to algal species. Taken together, these observations suggest that changes in sedimentary pigment concentrations in Lake L02 reflected shifts in algal abundance.

The relationship between sedimentary pigment-inferred algal abundance and pine pollen deposition is likely not a reflection of littoral algal responses alone, since conifer pollen deposition does not significantly decrease with increasing distance from the shoreline (Graham, M.D. Freshwater Biodiversity Laboratory, Department of Biological Sciences, University of Alberta, personal communication). Instead, because nutrients in pine pollen are solubilized in water within 24 h (Lee *et al.,*1996b), they represent a potential source for pelagic communities as well.

While phytoplankton biomass could be predicted from pine pollen influx, there was no obvious change in algal taxonomic diversity accompanying elevated pine pollen concentrations. This finding is in discord with the claim by Watson *et al. (*1997) that moderate nutrient enrichments increases the taxonomic diversity as well as biomass of algae in oligotrophic systems. However, in those lakes, representatives of most major algal groups (Bacillariophyta, Chlorophyceae, Cryptophyta, Chrysophyceae and Cyanophyta) are found over the entire growing season (Watson *et al.,*1997). Thus, any pollen-induced change in community composition during the spring is not detectable with paleoecological techniques since taxonomic resolution of pigments is generally limited to algal families. Although the sedimentary pigment and pollen record for Lake L02 is in agreement with the hypothesis that conifer pollen represents an available nutrient source for phytoplankton growth, it is also possible that pigment and pollen concentrations are correlated because both algal abundance and pollen output are responding to unmeasured variables in a similar fashion.

Boreal aquatic and terrestrial systems are sensitive to environmental variation (Stanley and Linskens 1974; Lee *et al.,*1996b; Findlay *et al.,*2001; Lee and Booth, 2003). During periods of below normal precipitation and above average temperature, phytoplankton biomass is significantly higher than during wetter periods (Findlay *et al.,*2001). Generally nutrient levels, and not temperature, are of greatest importance in determining algal abundance (Findlay *et al.,*2001). However, with nutrient levels held relatively constant, elevated temperatures can cause increased depth of the epilimnion and the euphotic zone, increasing phytoplankton biomass (Findlay *et al.,*2001). Realistically, lake nutrient levels do not always remain constant with increases in temperature (Moser *et al.,*2002). Coincident with long-term elevated summer temperatures, total P has been shown to increase in a northern boreal lake (Moser *et al.,*2002). Moser *et al. (*2002) report that rising P levels are predominantly a result of stronger stratification and enhanced internal cycling of P. With an increase in water temperature and nutrients, in particular P, lake production increases due to increases in cyanobacterial and chlorophyte abundance (McQueen and Lean 1987; Moser *et al.,*2002). Similarly, diurnal *Pinus* pollen deposition is positively correlated with air temperature and negatively correlated with cool, wet weather (Lee *et al.,*1996b). Above average spring temperatures also result in early deposition while lower temperatures during development not only delay pollen release but, can also lower the quantity of pollen produced by *Pinus* species (Stanley and Linskens 1974; Lee *et al.,*1996b). Since algal abundance and pollen output show similar directional responses to climatic variation, the predictive relationships developed from the pigment and pollen profiles should be used with caution.

The quantitative sampling techniques used in this study provide only indirect evidence for the importance of conifer pollen as a nutrient source in boreal lakes. A third, and very likely possibility, is that conifer pollen flux does represent a small but significant available nutrient source for algae, explaining some of the variation in sedimentary pigment-inferred algal biomass while climatic variation alters algal abundance and conifer pollen flux in a directionally similar but, mechanistically independent fashion. This might explain why some fluctuations in the pollen and pigment profiles are proportionate and occur concomitantly (illustrating conifer pollen's fertilization effect as

well as similar responses to possible climatic variation) and why other, relatively large peaks in pine pollen concentration are not matched (in proportional magnitude or direction) with similar changes in the fossil pigment record (illustrating pollen's relatively limited role in phytoplankton dynamics).

The drastic drop in both pine pollen and algal pigment concentrations at core depths of 37 cm and 45 cm might signal a period of extreme drought, during which L02 could have effectively dried up. In fact, during core sectioning, I recorded how these sections were lighter in colour and more clay-like compared to others. This is a possible explanation for the near absence of both fossil pigments and pollen grains since there would have been no lake or a reduced lake, thereby, limiting algal abundance and lake pollen receipt. It might be suggested then, that these synchronous reductions in both fossil records are responsible for the observed correlations between sedimentary *Pinus* pollen and fossil pigment concentrations. However, while these two periods represent the most obviously similar fluctuations in fossil concentrations, similarity in the pattern of variation can be observed throughout the depth of the core for each pigment type (Figure 5), substantiating the use of correlation and regression analyses and the relationships and models described here.

In summary, the results suggest that the sedimentary concentration of pollen, specifically pine pollen, is an effective predictor of phytoplankton abundance in small, boreal lakes. Although it is difficult to separate the relative importance of pollen's role as a nutrient source for algal growth from the known role of climatic variables, pine pollen appears to enhance total phytoplankton abundance in small boreal lakes. Data from additional lakes and pollen addition experiments are needed to further test this hypothesis. However, the results presented here are consistent with the growing body of evidence that suggests lakes are intimately tied to their much larger terrestrial surroundings. As a result, the episodic deposition of conifer pollen should be considered an important allochthonous source of nutrients and should be included in lake nutrient budgets.

Conclusions

The funding of this project by the Climate Change Impacts and Adaptation Directorate, with matching funds from other sources, has enabled the research team to generate a large amount of new data on vegetation change and climate variability in the grassland-forest transition zone of central Saskatchewan. This information provides a wider view of ecological change than the more conventional study of vegetation plots for a series of year. Our data and interpretation are at the landscape scale and over a time span of centuries. The climate sensitivity of the terrestrial ecosystems was determined by relating high resolution (5-10 year intervals) records of fossil pollen in three lakes to climate variability and change reconstructed from tree rings for the past 250 years. More recent responses of vegetation to climate were studied by compiling data from aerial photographs, and by detecting inter-annual variation in forest and grassland productivity over the past 30 years from satellite imagery.

The Normalized Difference Vegetation Index (NDVI) was used as an indicator of vegetation productivity for the three primary vegetation types in the study area: forest, grassland and cropland. Results showed that significant temporal and spatial variations exist in both trend in NDVI and correlations between NDVI and climate factors. NDVI has a positive trend for most of the months from May to October and growing season as whole. This increasing trend was exhibited over most of the transition zone from July to October which suggested lengthening of the growing season. Temperature is highly correlated with NDVI in parts of the study area in May. NDVI-Precipitation correlations exhibit a one month lag. From July to September, NDVI is highly correlated with PDSI in most parts of the study area, especially in cropland and grassland areas. For the entire growing season, results show that NDVI is highly correlated with precipitation in the northern area and with PDSI in southern parts of the study region, while only small areas show a high correlation between NDVI and temperature.

Aerial photographs from the late 1940s and late 1990s were examined in order to develop a better understanding of how climate variation has affected the vegetation of the boreal forest transition zone. Twenty 500m x 500m plots from the southern boreal forest were analyzed. Climate data from seven climate stations in the study in the area were collected and used to assess changes in climate. Twelve stand types were identified within the forest assemblage. T-tests indicated that changes in the vegetation between the 1940s and 1990s were not statistically significant in the total study area. Kruskall-Wallis ANOVA indicated that there was no significant difference in vegetation change between the individual zones. However, Principle Component Analysis indicated that there might be subtle variations in forest composition between the zones. A significant decrease in hardwood (in zone 3) and softwood dominated mixedwood (zone 2) stand sizes, and a significant increase in bog (zone 1), and black spruce (zone 2) stand sizes were found within certain zones. Together, these analyses indicate that variations in microclimate might be having larger influences on forest composition than do larger scale changes in climate. However; in order to make more definitive conclusions about the response of boreal vegetation to climate, a larger sample size is recommended. Nonetheless, this study revealed interesting trends, and has provided a base for a more intensive study.

Recent vegetation changes observed in the record of high-resolution lake pollen include a decline in the forest taxa and an increase in either the aspen parkland and grassland taxa (at the northern sites) or the grassland taxa (at the southern site) over approximately the past 50 years and especially over the past approximately 25 years. These observed changes fit very well with observed climate changes over the past few decades: higher annual temperatures and decreased moisture availability. Changes in vegetation community structure are underway, perhaps first manifested as lower pollen productivity and decreased tree vigour rather than actual species' replacements.

The pollen record, and climate response analysis, suggests a definite warming trend from about 1925 through to the present, and especially over the past 15-20 years. The reconstruction of annual precipitation clearly shows drought such as the 1930s but also a decreasing trend through the last half of the 20th century, especially during the last 15-20 years. The recent trend over the last two decades to warmer and drier conditions

corresponds to a substantial increase in *Populus* pollen, suggesting again a recent expansion of aspen parkland at the expense of coniferous forest in the southern boreal forest region.

Pollen is hypothesized to be a nutrient source for primary producers in boreal aquatic systems because algal blooms often coincide with the time of maximum pollen dispersal early in the summer. The results of studies that have examined the deposition of macronutrients by pollen are inconsistent, possibly due to differences in methods used and time of experiment. Therefore, high-pressure liquid chromatographic analysis (HPLC) of sedimentary pigments and analysis of fossil pollen was used to measure whole-lake algal responses to fluctuations in lake pollen receipt over the last 1150 years in a small boreal lake in northern Saskatchewan, Canada. Sedimentary pigment-inferred algal abundance was significantly correlated ($P < 0.05$) with sediment pollen concentrations of *Alnus*, *Betula* and *Pinus* species (r = 0.22-0.49). Among the 51 plant taxa identified in the pollen record, these 3 genera were the main pollen contributors, accounting for 77% of total pollen deposition. *Pinus* (pine) pollen represented 52% of total grain deposition, and was the species that best predicted historical changes in algal abundance. The results presented here suggest that pine pollen influx represents an available nutrient source for phytoplankton growth. My findings also suggest that conifer pollen is an important allochthonous source of nutrients in small boreal lakes and warrants inclusion in lake nutrient budgets.

Our investigation of climate and vegetation change at various scales have revealed a great deal about past and anticipated ecological responses to climate change and variability in the grassland to forest transition zone. Much more will be revealed, however, as we more fully integrate the various components of this project and data generated for monthly to decadal time scales. Figures 52 and 53 illustrate two cases of preliminary work on integrating results. Figure 52 compares the reconstruction of summer precipitation from the pollen from lake LO3 to the moisture sensitive tree-ring records from b) Boundary Bog and c) Heart Lakes. The pollen and tree-ring records are not directly comparable given 1) differences in resolution, and 2) the timing of response of vegetation to precipitation as measured using pollen productions versus tree growth. There is some general agreement however. The grey shading indicates where the records agree in terms of the timing of wet (*e.g.* 1810s) and dry (*e.g.* 1830s, 1930s) intervals. Discrepancies among the tree-ring and pollen records, at other time, likely reflect the various ecological and climatic influences on tree growth and pollen production besides precipitation. Further analysis of other factors and, use of statistical processing of the data, should enable us to uncover responses of the vegetation to climatic variability.
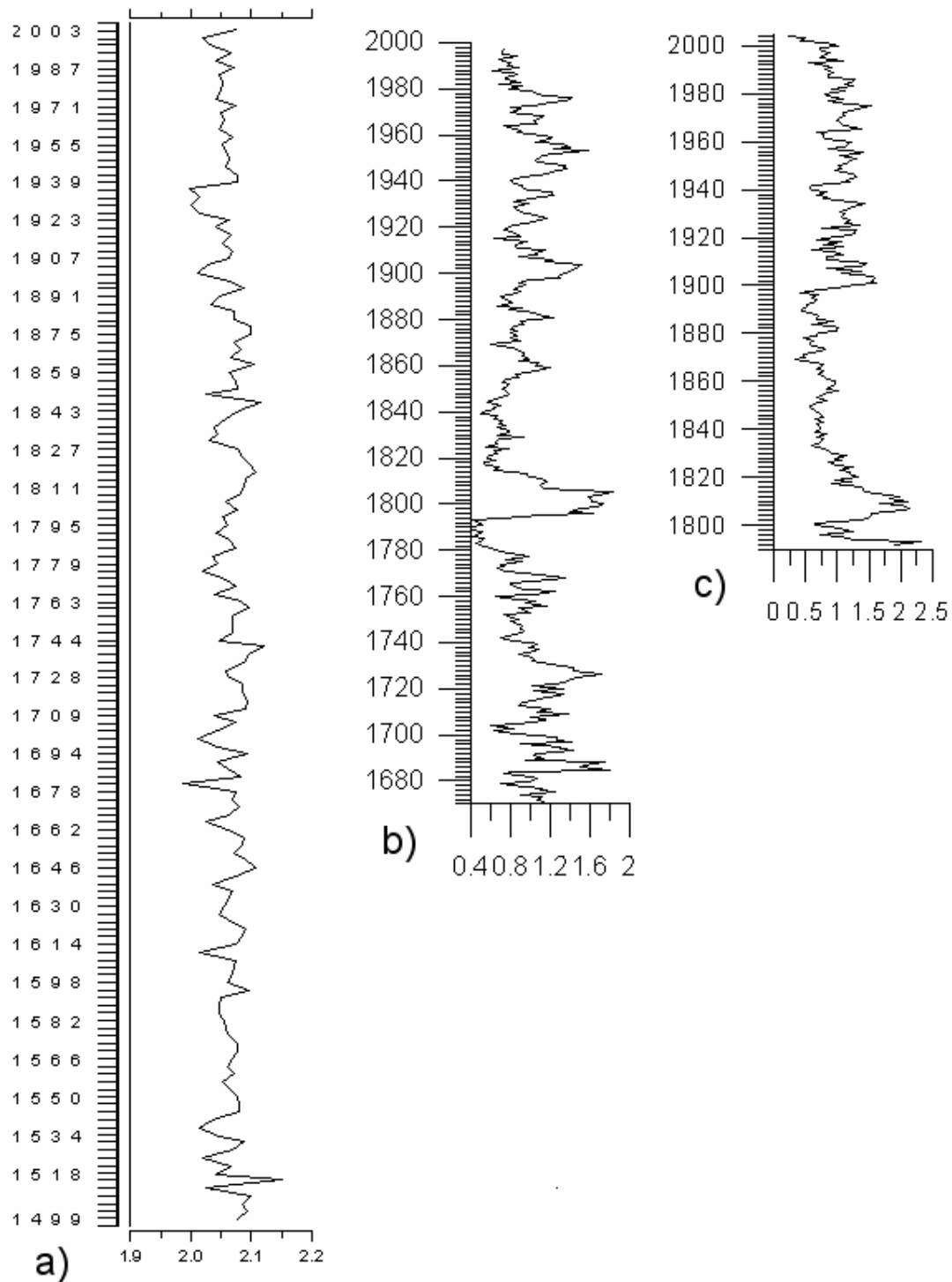
Figure 52. The a) reconstruction of summer precipitation from the pollen from lake LO3, and the moisture sensitive tree-ring records from b) Boundary Bog and c) Heart Lakes. The grey shading indicates where the records agree in terms of the timing of wet (*e.g.* 1810s) and dry (*e.g.* 1830s, 1930s) intervals.

Figure 53 illustrates our preliminary attempt to couple the tree-ring record and a model of forest productivity, by simulating white spruce productivity using the long-term record (1827-1996) summer precipitation inferred from the tree-ring records. The ratio of reconstructed June to August (JJA) precipitation for Prince Albert to the 1961-90 monthly normals was applied in the model to each day in JJA for the 1961-90 period. Under these conditions, white spruce productivity is less than predicted from normal conditions because instrumental records, and especially, for the period 1961-90, do not capture prolonged droughts that occurred before the measurement of precipitation. This analysis is simply a demonstration of the value of a longer climate record given that scenarios of future also include conditions that exceed the variability of the climate of the 20th century. Further analysis will include the effects of inter-annual climate variability on forest productivity (although trees tend to respond fairly slowly to the environment once they get established), and the impacts of an extended drought scenario, such as the drought of the mid-1880s to mid 1890s evident in the tree-ring record (Figure 37).
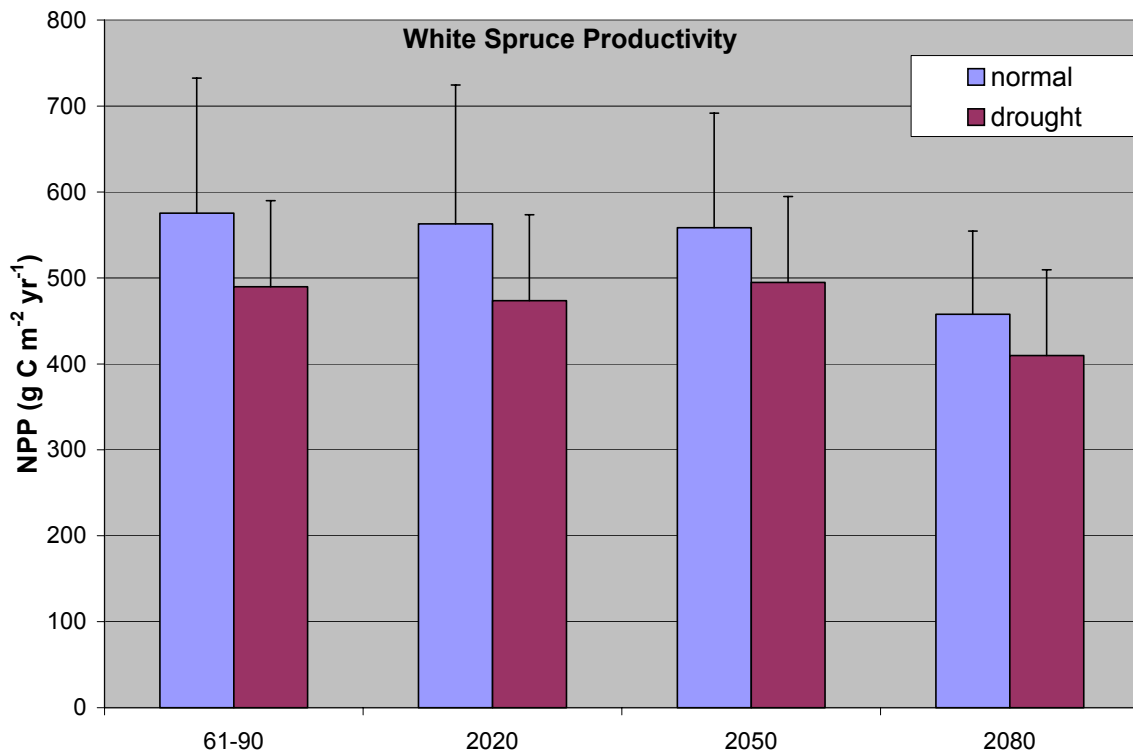

Figure 53. Scenarios of white spruce productivity under normal (1961-90) conditions versus a longer record of summer precipitation from the tree-ring record.

We examined the ecological response to past climate variability at various temporal scales from correlations among indicators of monthly climate and plant productivity to the variation in relative abundance of plant taxa at 5-25 year intervals for the past millennium. At the shorter time scales, temporal and spatial variations in plant productivity can be related to specific climate variables. Plant productivity depends on temperature in May but, in the rest of growing season, responds mostly to precipitation

with about a one month lag. An increasing trend in July to October productivity over most of the transition zone suggests a lengthening of the growing season. At longer time scales, time series of pollen records from four lakes show significant fluctuations in the relative abundances of plant taxa. Much of this variability can be related to departures from mean climate conditions as inferred from tree-ring records and from the geographic distribution of modern pollen relative to climate gradients. The impact of dry years is especially apparent with substantial reductions in pollen concentrations for coniferous tree taxa, reflecting suppressed productivity. Decreased pollen outputs from these tree species is correlated with decreased lake productivity as indicated by algal pigment concentrations in the lake sediment record.

The principal objective of determining the climate sensitivity of a major part of the Prairie Province grassland – forest transition zone was met and possibly exceeded in terms of the amount of new information on the historical response of vegetation to climate variables. The time series of correlated indicators of vegetation and climate inform the assessment of climate change impacts on the ecosystems of the grassland-forest transition zone. These data also can be used to calibrate models that project change in plant productivity and species distribution under climate change.

With regards to the vulnerability of vegetation use and management to climate-induced ecosystem and landscape change, we were able to satisfactorily address this objective by consulting with resource managers in the sectors of agriculture, forestry and parks and protected areas. This consultation was achieved with the two workshops staged by the project and during other meetings attended by project researchers where local resource managers were in attendance. At the project workshops, stakeholders identified barriers to adaptation and adaptive management related to the uncertainty associated with conventional climate change and impact scenarios. Current projections of the ecological impacts of climate change are based on associations between current climate and the boundaries between natural regions, and on the present ranges of individual species. Shifts in the distribution of ecosystems will be driven by encroachment of species into previously unsuitable areas, for example, at the interface of grassland with parkland and forest. Resource managers need information on the trajectory that ecosystems follow in response to fluctuating and directionally-changing climate.

We were able to contribute to science-based decision making concerning adaptation to climate change to the extent that project researchers presented the results of our research at the two stakeholder workshops and at other conference and workshops on the topic of climate change impacts and adaptation in western Canada. The degree to which this knowledge transfer influenced decision making is difficult to assess. We expect that more knowledge translation and interaction with stakeholders will be required to have a meaningful influence on the planning of adaptation to climate change. But a general indication of the perceived value of this research is shown in the development of new funding applications in collaboration with stakeholders and First Nations groups.

The final objective of assigning a degree of certainty (confidence) to our climate change and impact scenarios was achieved in terms of having a better understanding of the

climate sensitivity of the ecosystems of the forest – grassland transition zone. We have yet to meet this objective, however, in terms of producing a more robust assessment of climate impacts, because the components of the project have not yet been fully integrated. We intend to pursue this full integration of the project components and deliver improved assessments of the ecological impacts of climate change to project partners and stakeholders. There are various opportunities and applications that we did not anticipate until the research described in this report was completed. The integration and application of the component investigations should result a significant improved understanding of ecological responses to climate variability in the grassland to forest transition zone. This new knowledge and data will inform decisions about adaptation of resources management practices and policies to accommodate the consequences of climate change.

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Appendix A: March, 2004 Stakeholder Workshop

Land Management Vulnerability and Climate Change: A Stakeholder's Workshop

Main Boardroom, Saskatchewan Forest Centre
Saskatchewan Forest Center
Prince Albert, Saskatchewan
March 22, 2004

To register contact: Leanne Crone (306-933-7432 or crone@src.sk.ca)
Please register by March 17, 2004

Purpose of the Workshop: This workshop is an opportunity for user groups to participate in this research project by identifying vulnerabilities to current and future climate, and by applying the results of the project to planning and management decisions. It will introduce user groups to the project and to get their feedback on the concepts and design of the project.

Agenda:

8:00   Registration

8:15   Welcome, Introductions, Purpose of the Workshop (D. Sauchyn)
8:30   Exploring Climate Change and the Sensitivities of the Grassland-Forest Transition Zone
        (M. Johnston, D. Sauchyn, E. Wheaton and V. Wittrock)
9:30   Project Overview (D. Sauchyn, N. Henderson, M. Johnston, J. Piwowar, M.
        Vetter and   E. Wheaton)

10:30   Refreshment Break

11:00   Possible Adaptive Responses to Address Vulnerabilities of the Transition Zone to Current and Future Possible Climates (M. Johnston, D. Sauchyn, E. Wheaton and V. Wittrock)

12:00   Lunch (Provided)

13:00   Group Discussion Sessions, Vulnerability Assessment: Introduction (M. Johnston)
13:15   Breakout Groups: Discussions about Current and Future Vulnerabilities

15:30   Refreshment Break

16:00 Reporters report back to the main group
16:45 Wrap-Up and Next Steps (D. Sauchyn)

This research project is funded by the Climate Change Impacts and Adaptation Directorate (formerly Climate Change Action Fund) and involves scientists from the Prairie Adaptation Research Collaborative, University of Regina, and Saskatchewan Research Council.

Appendix B: April, 2005 Stakeholder Workshop

Land Management Vulnerability and Climate Change: A Stakeholder's Workshop

Main Boardroom, Saskatchewan Forest Centre
1061 Central Ave., Prince Albert SK
10 am to 3 pm, April 18, 2005

1000-1010	Introduction and Welcome	Dave Sauchyn
1010-1030	The CCIAP Project / The tree-ring record of climate variability in the southern boreal forest /	Dave Sauchyn
1030-1050	The evaluation of the sensitivity of the southern Boreal Forest to past climate change from the pollen/charcoal record of lake sediments	Mary Vetter
1050-1110	The impact of climate variability on vegetation productivity measured by remote sensing	Mei Luo
1110-1130	Impacts of the 2001-2003 drought on the aspen forests of Saskatchewan and Alberta	Ted Hogg, CFS, Edmonton
1130-1150	Climate Change, Forest Productivity and Soil Expectation Values	Mark Johnston
1150-1300	Lunch	
1300-1500	General discussion and feedback to researchers	

Appendix C: Pollen Diagrams

Figure C1. North Flat Lake relative pollen abundances (%).
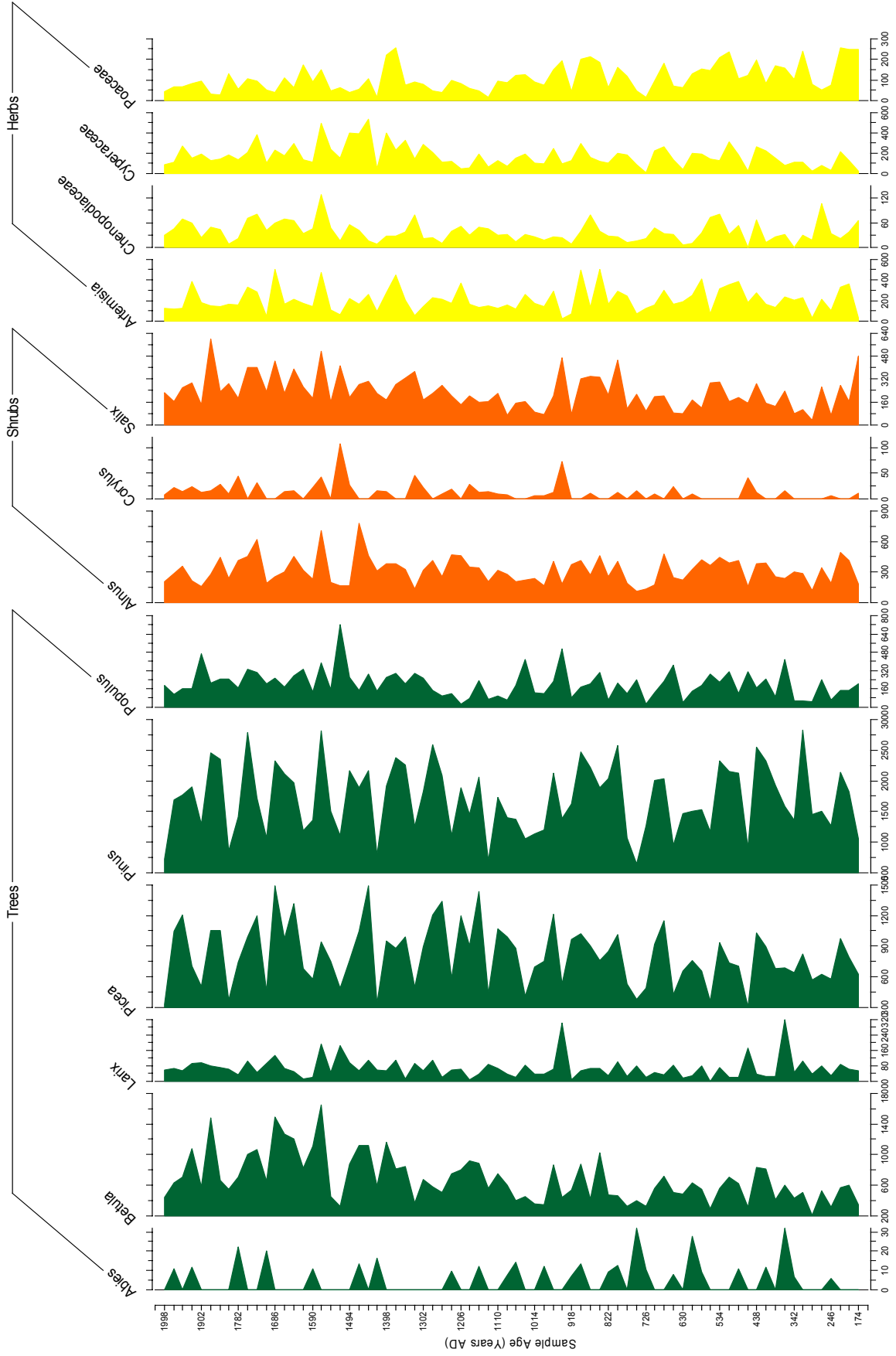
Figure C2. North Flat Lake pollen accumulation rates.
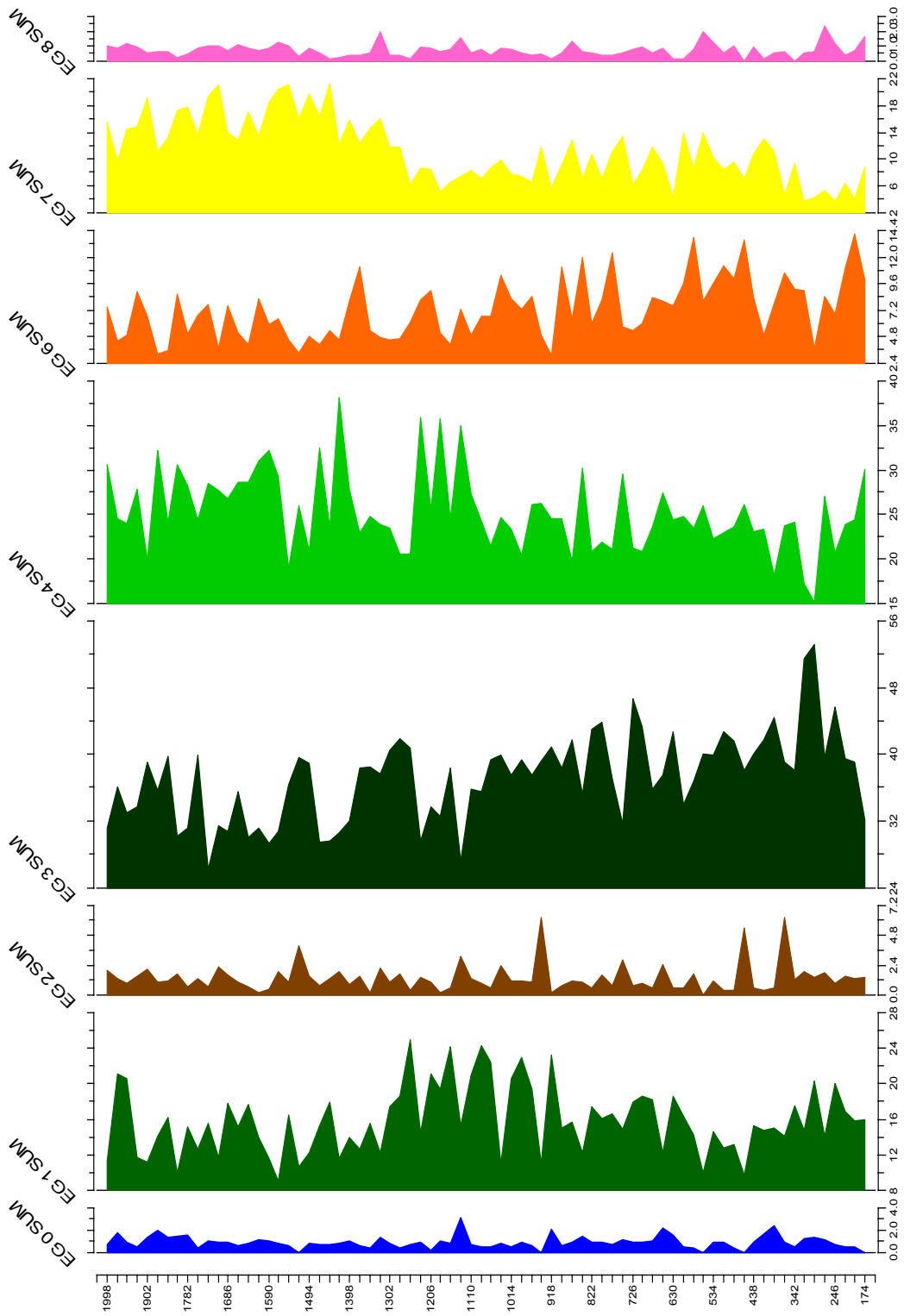
Figure C3. North Flat Lake relative pollen abundances of ecosystem groups (%).
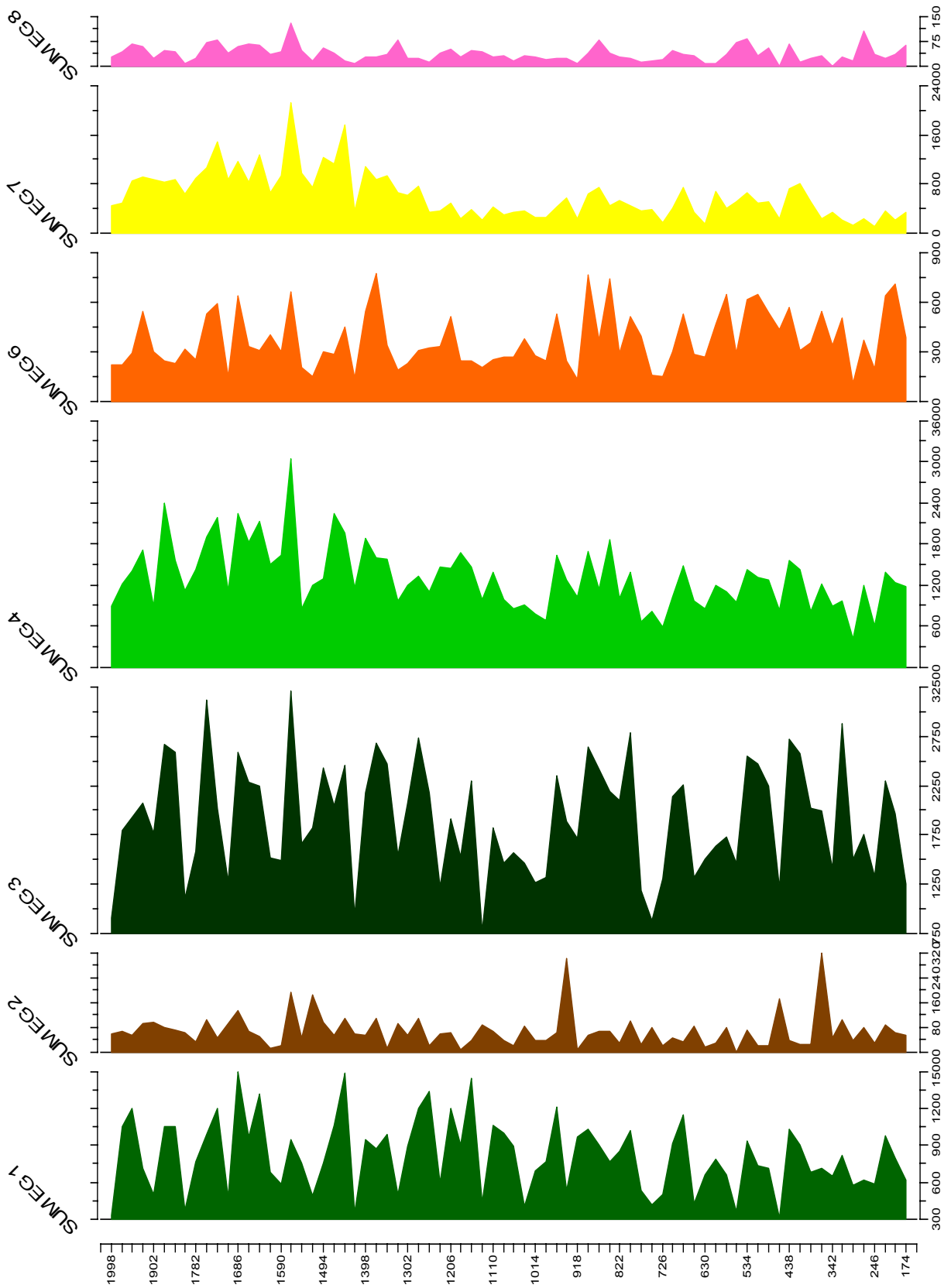
Figure C4. North Flat Lake pollen accumulation rates of ecosystem groups (%).
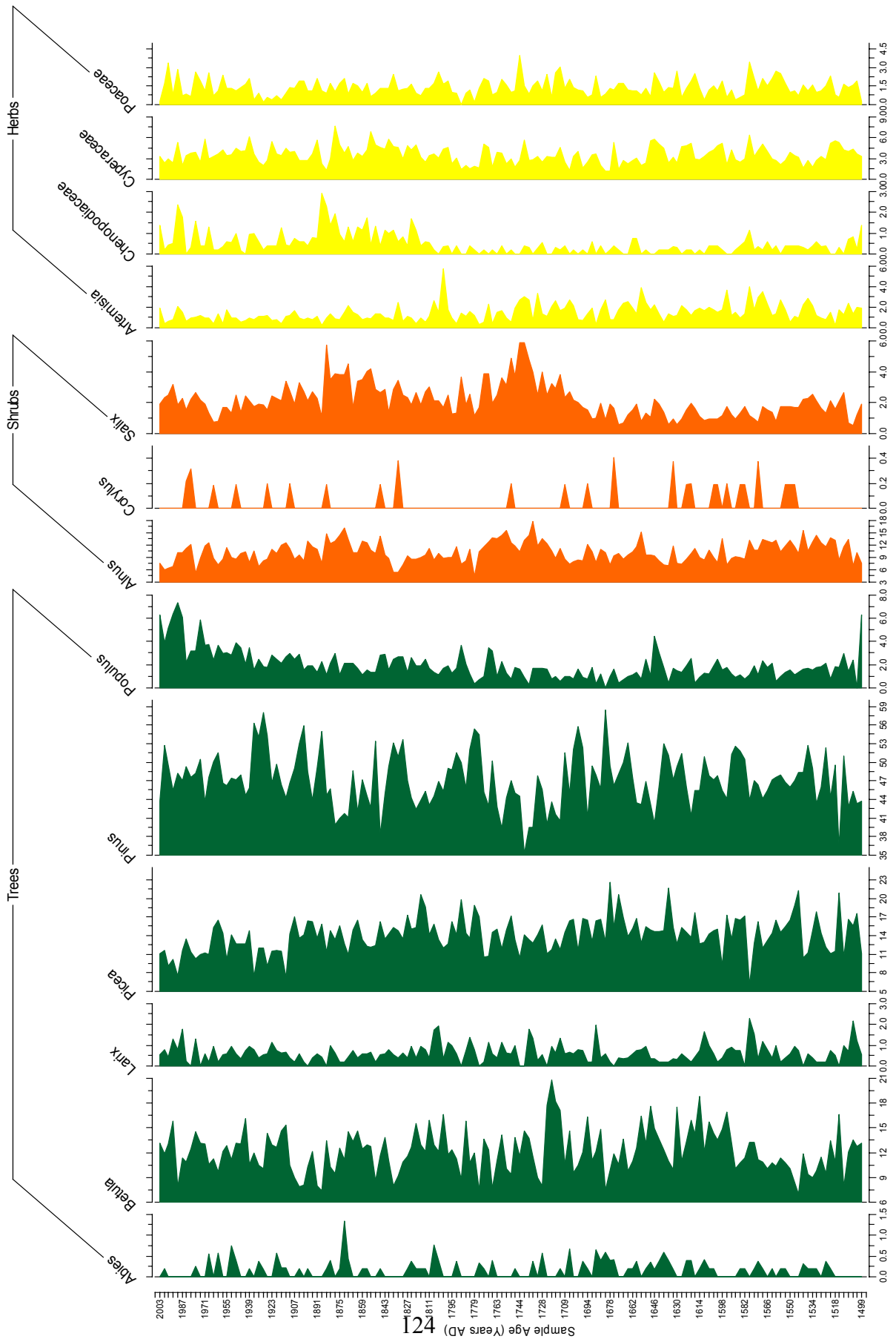
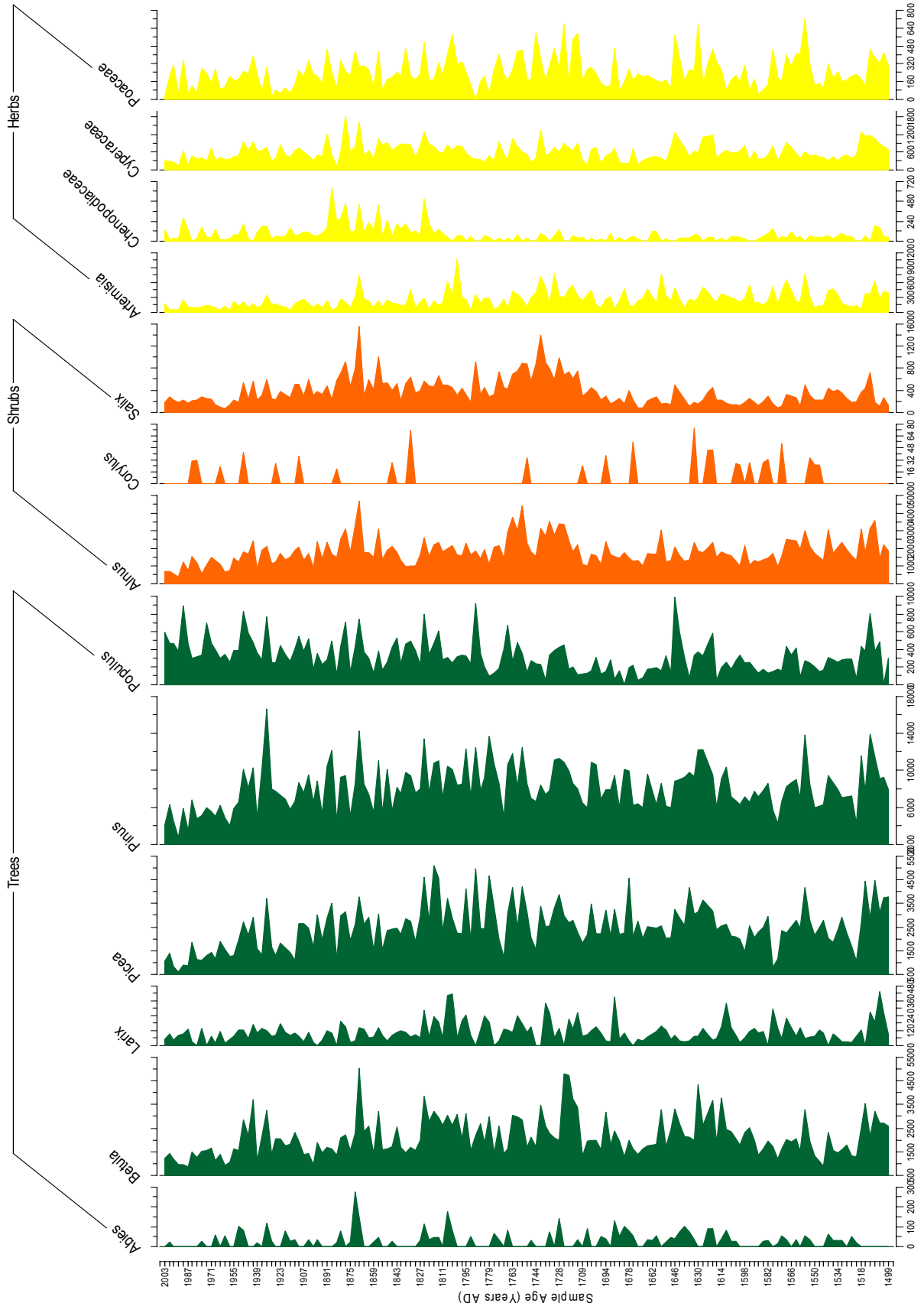Figure C5. L03 relative pollen abundances (%).
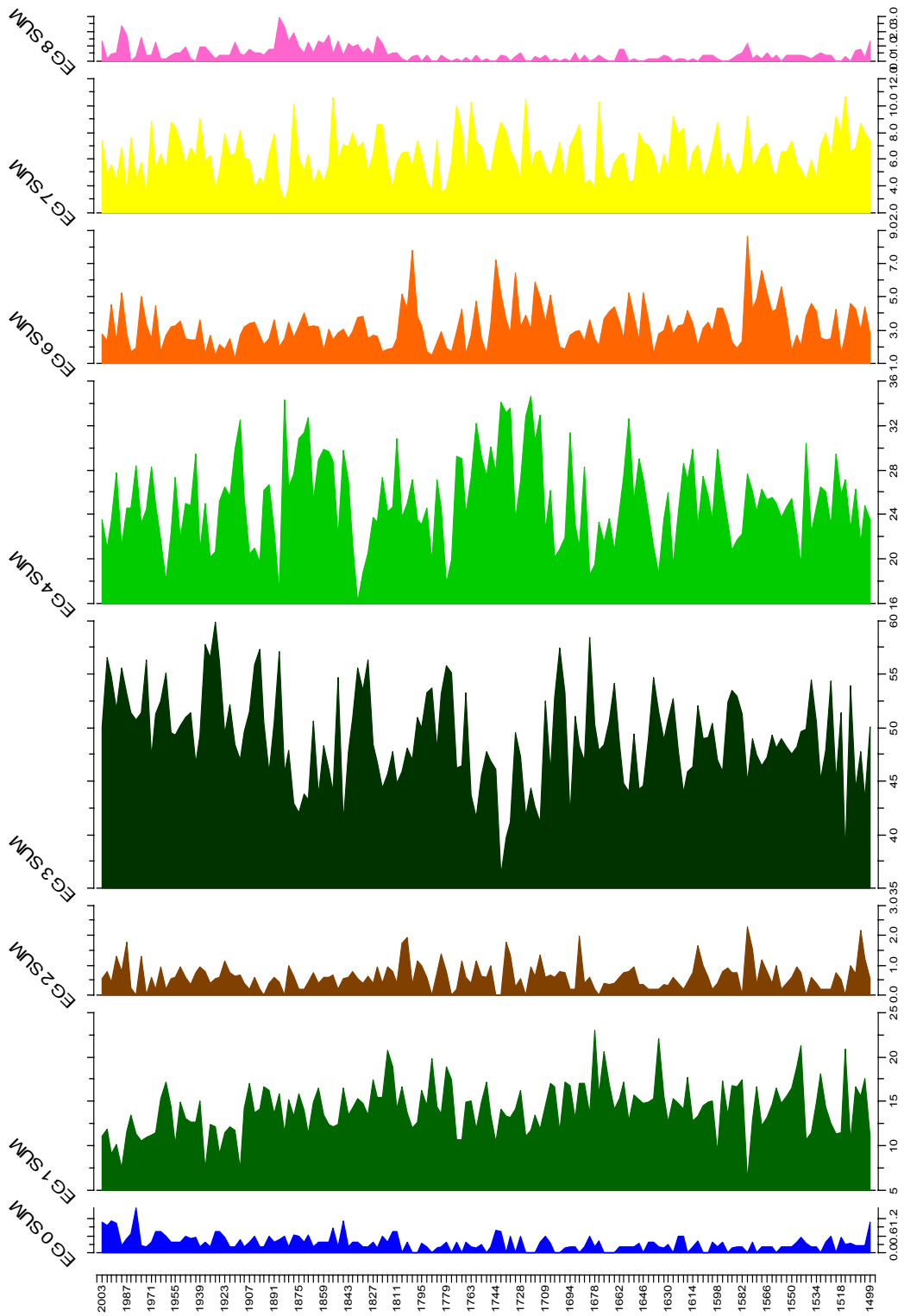
Figure C6. L03 pollen accumulation rates.

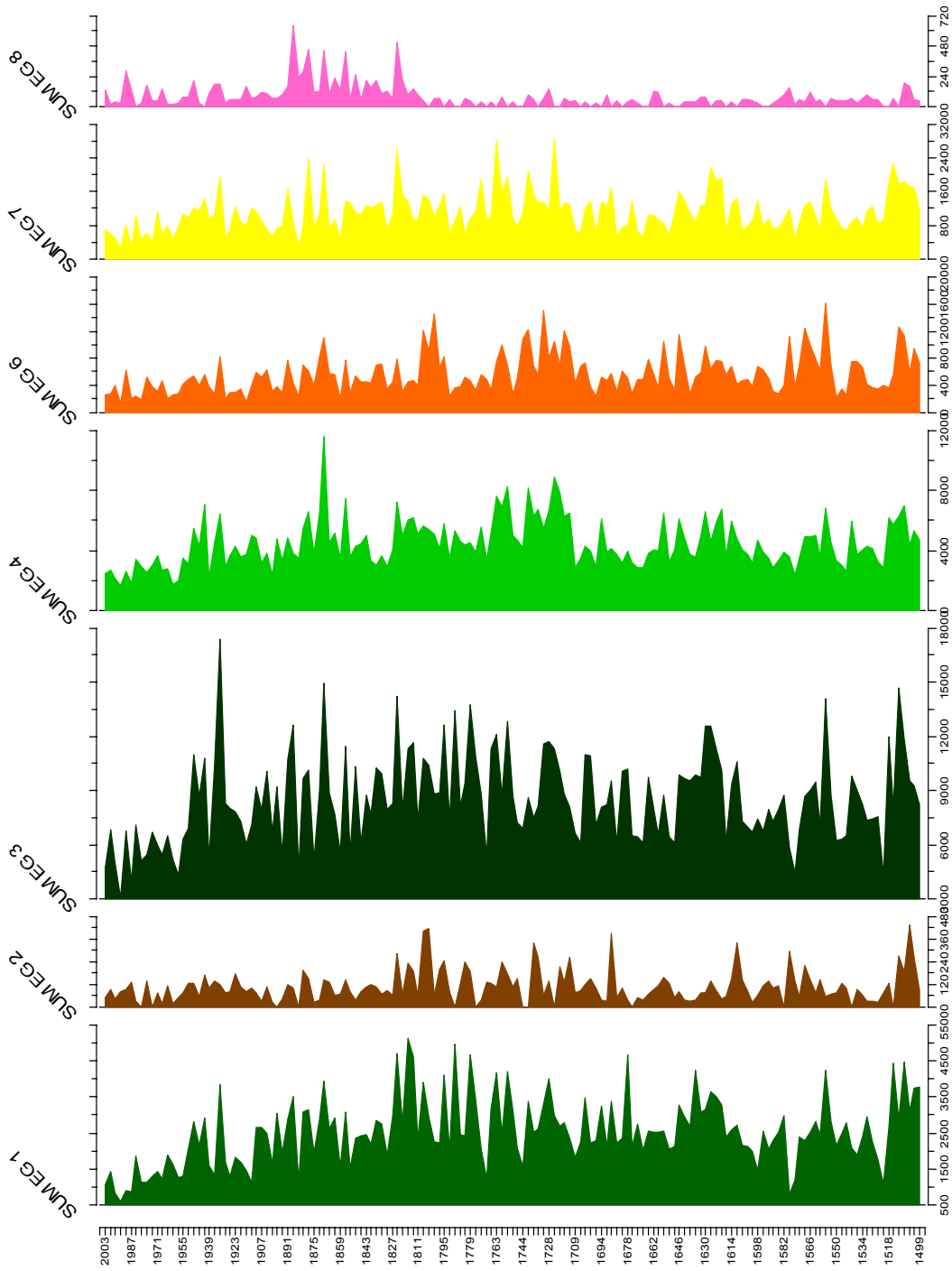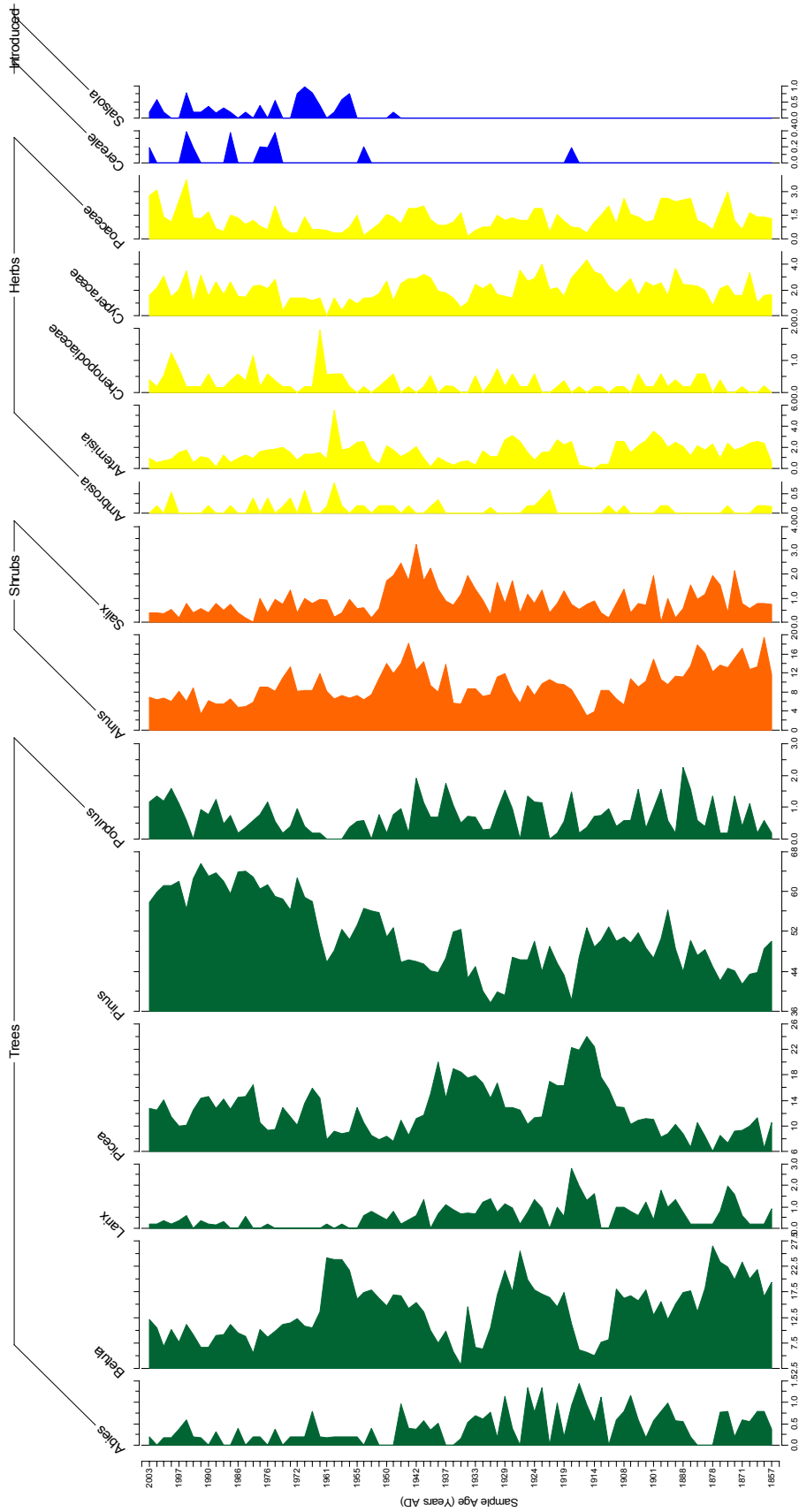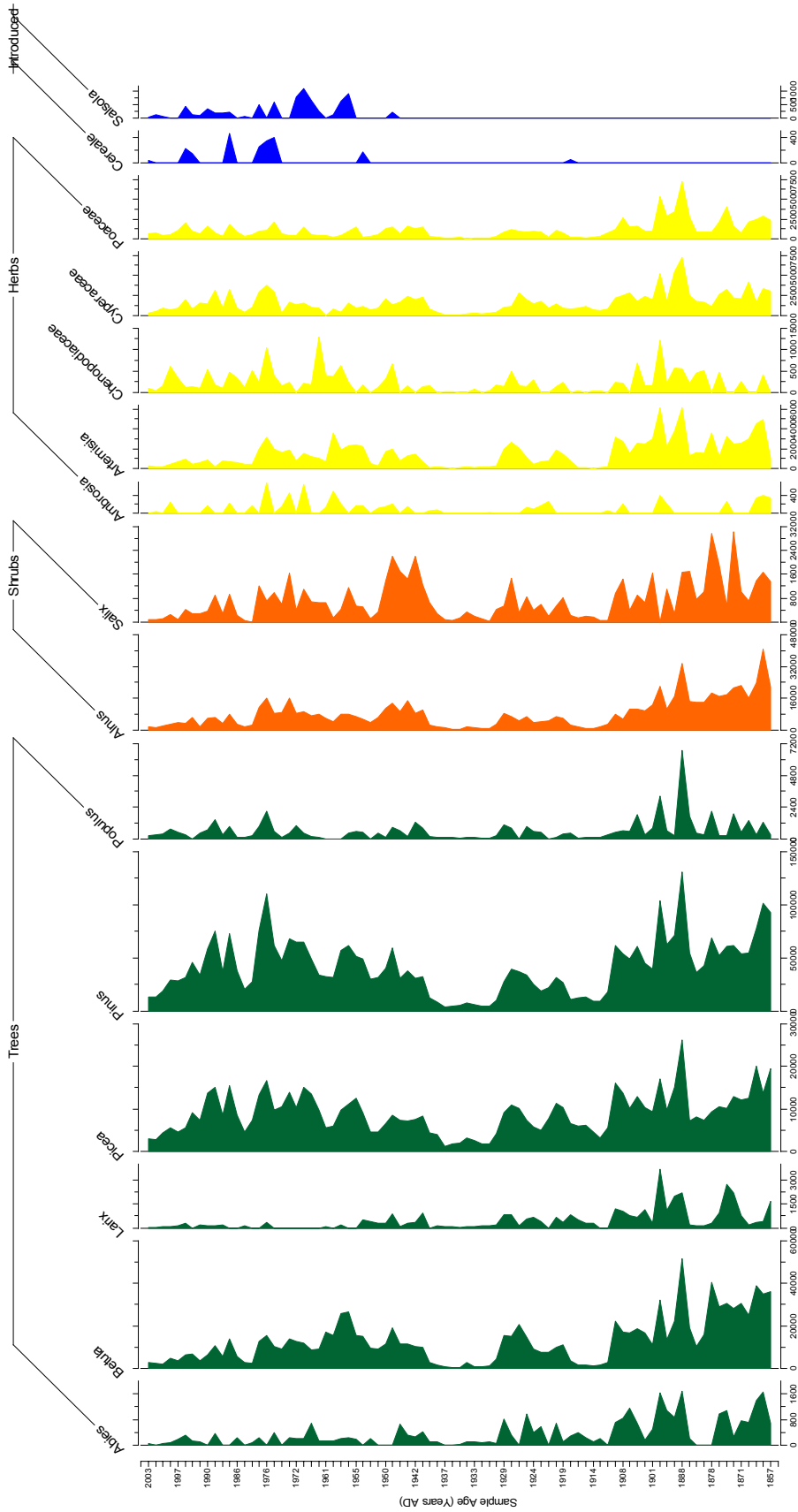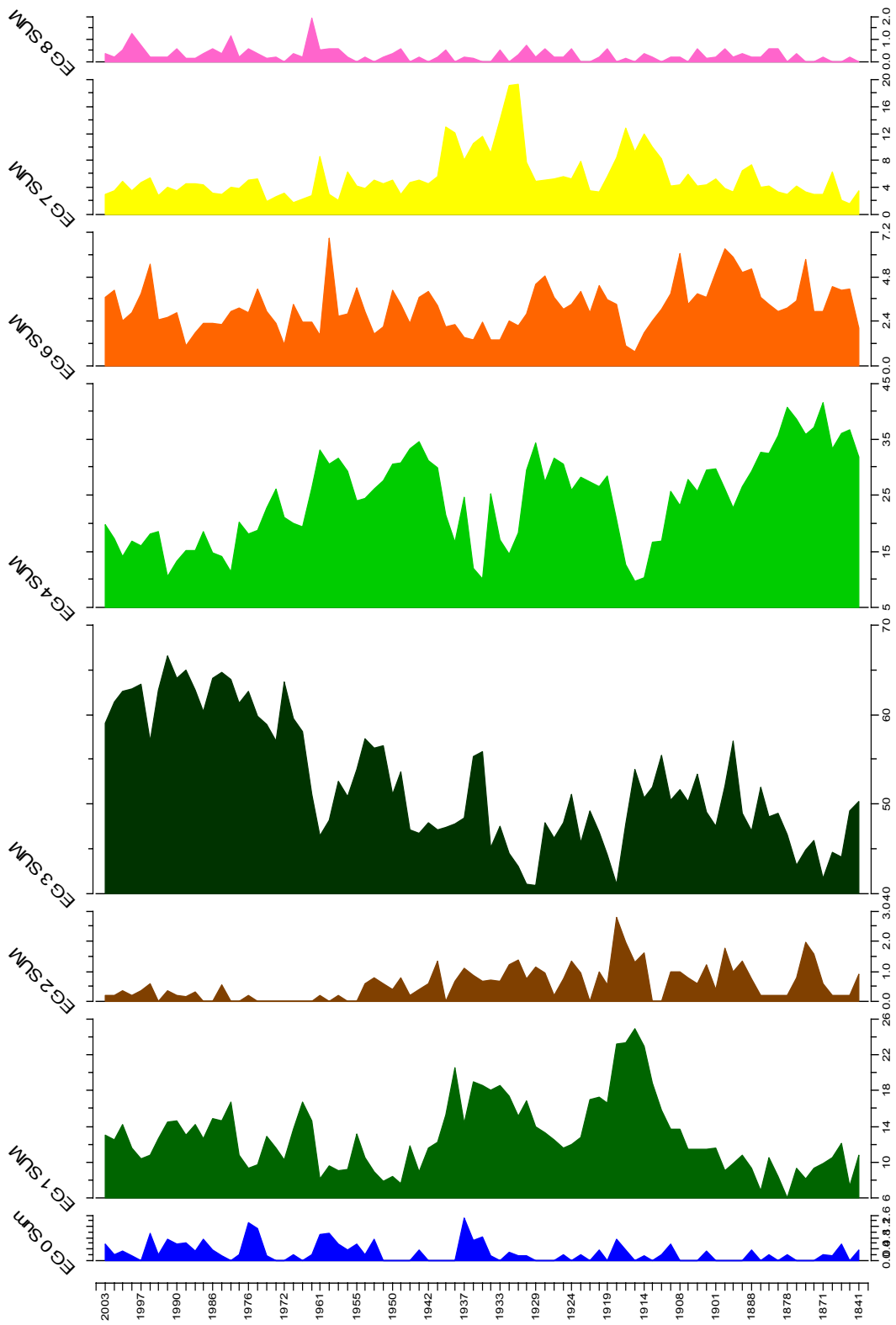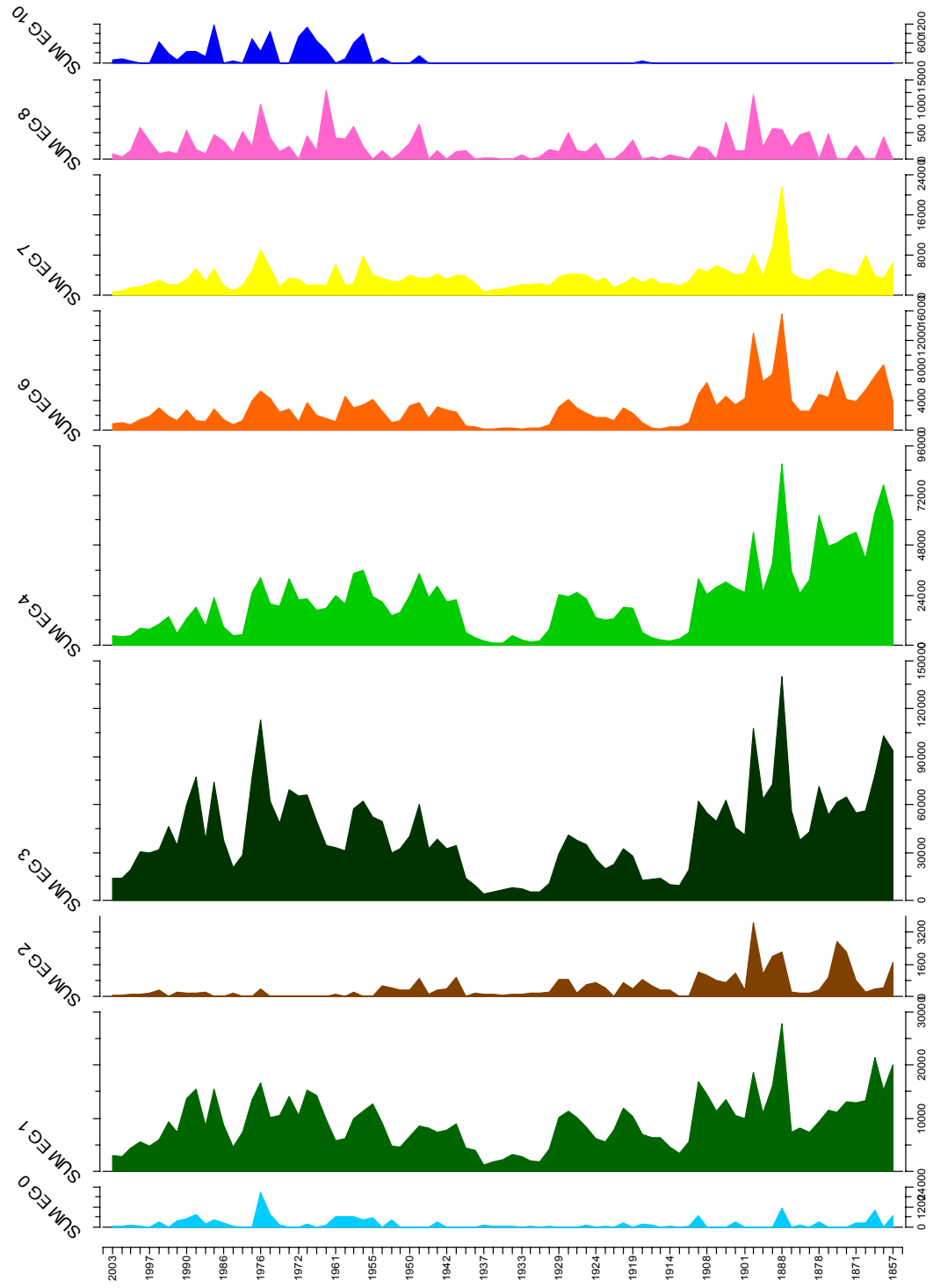Figure C7. L03 relative pollen abundances of ecosystem groups (%).

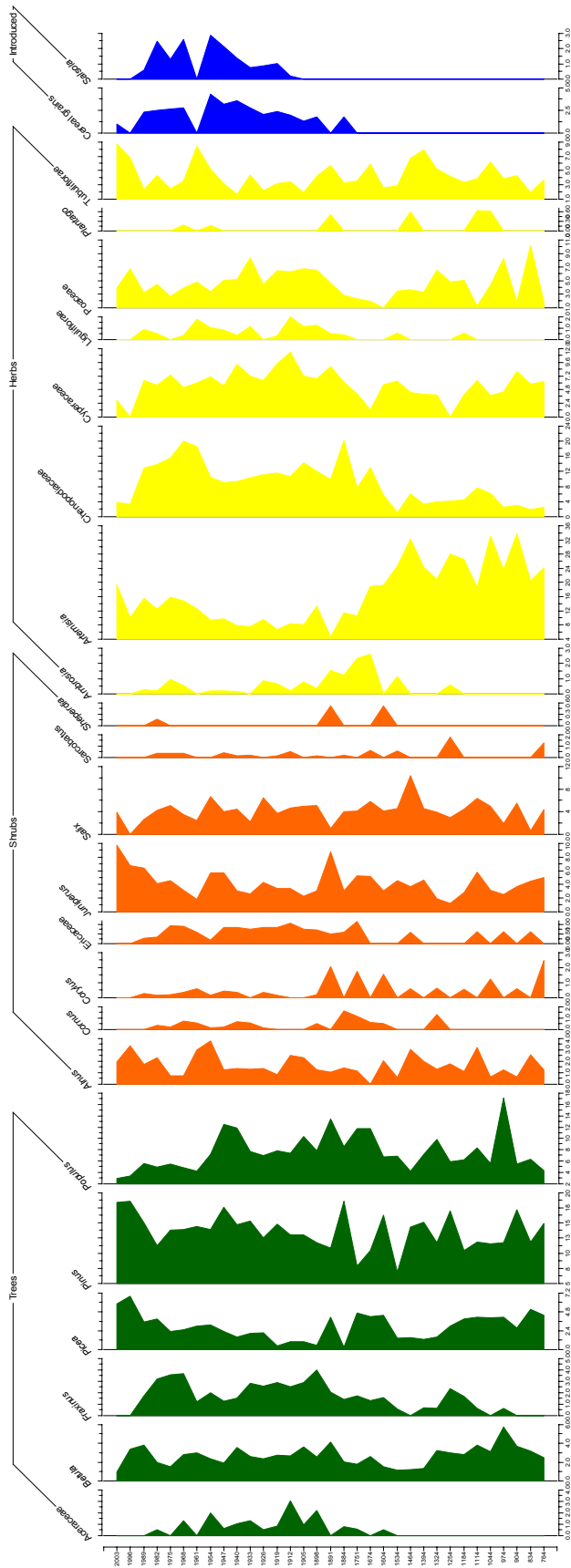Figure C8. L03 pollen accumulation rates of ecosystem groups (%).

Figure C9. L02 relative pollen abundances (%).

Figure C10. L02 pollen accumulation rates.

Figure C11. L02 relative pollen abundances of ecosystem groups (%).

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Figure C12. L02 pollen accumulation rates of ecosystem groups (%).
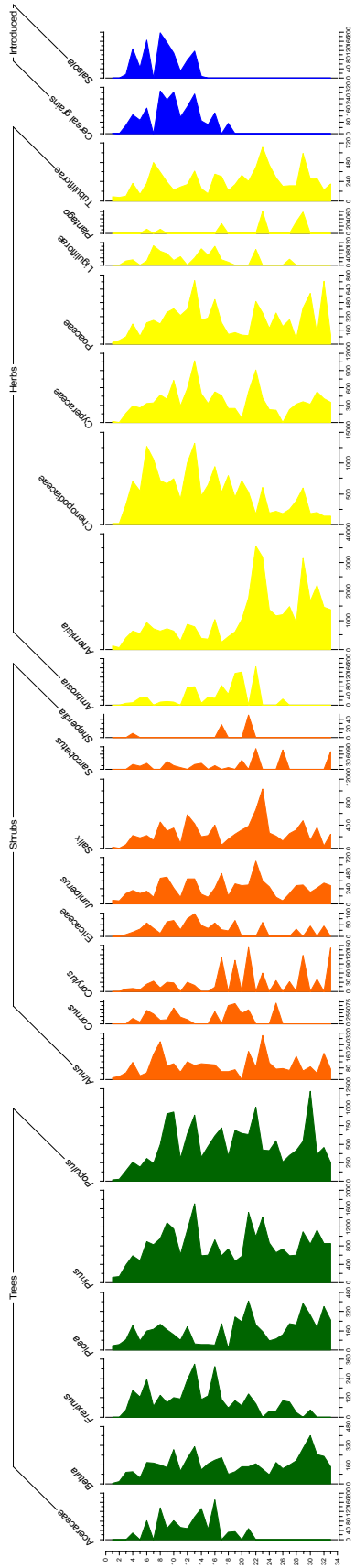
Figure C13. Deep Lake relative pollen abundances (%).

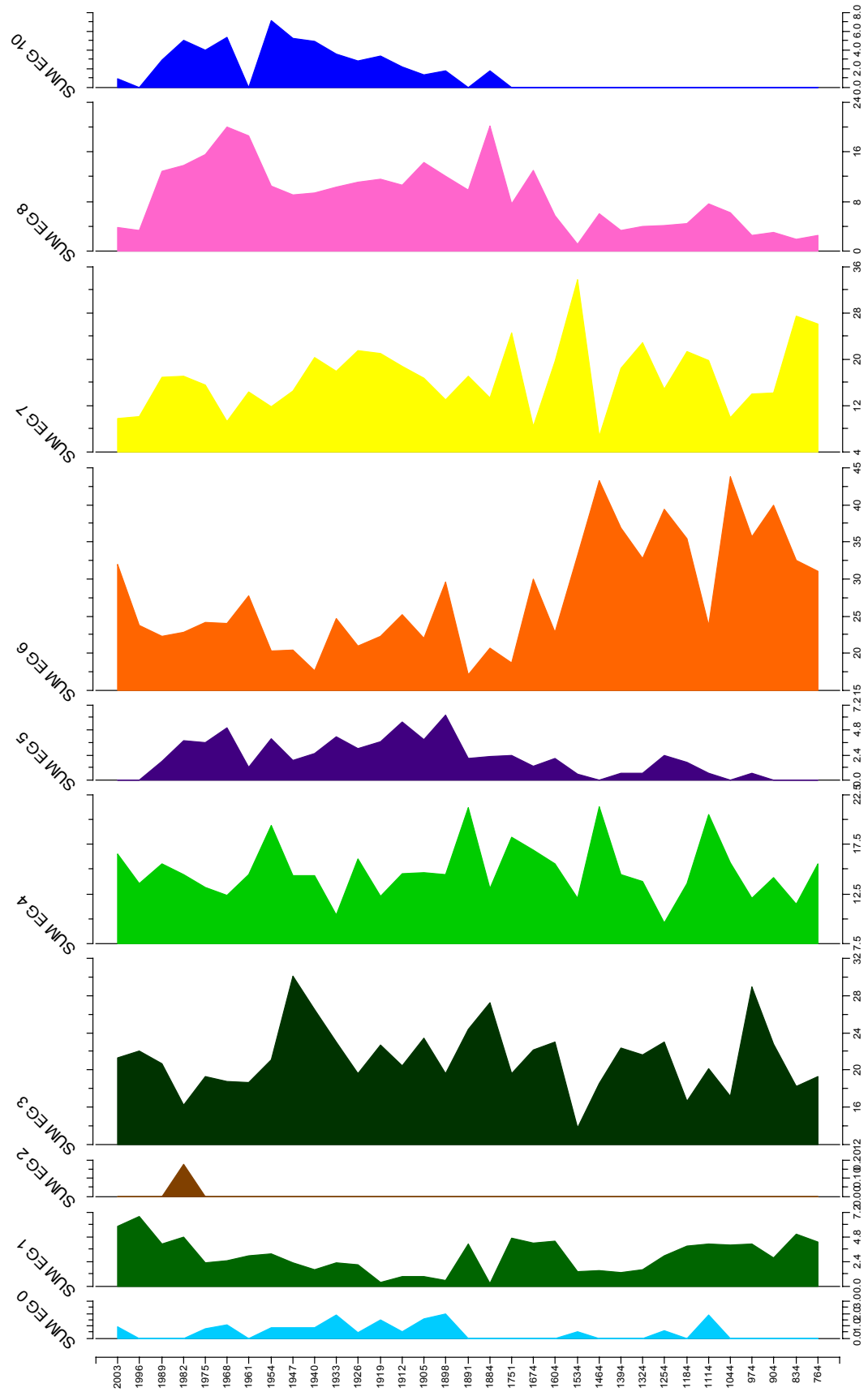Figure C14. Deep Lake pollen accumulation rates.

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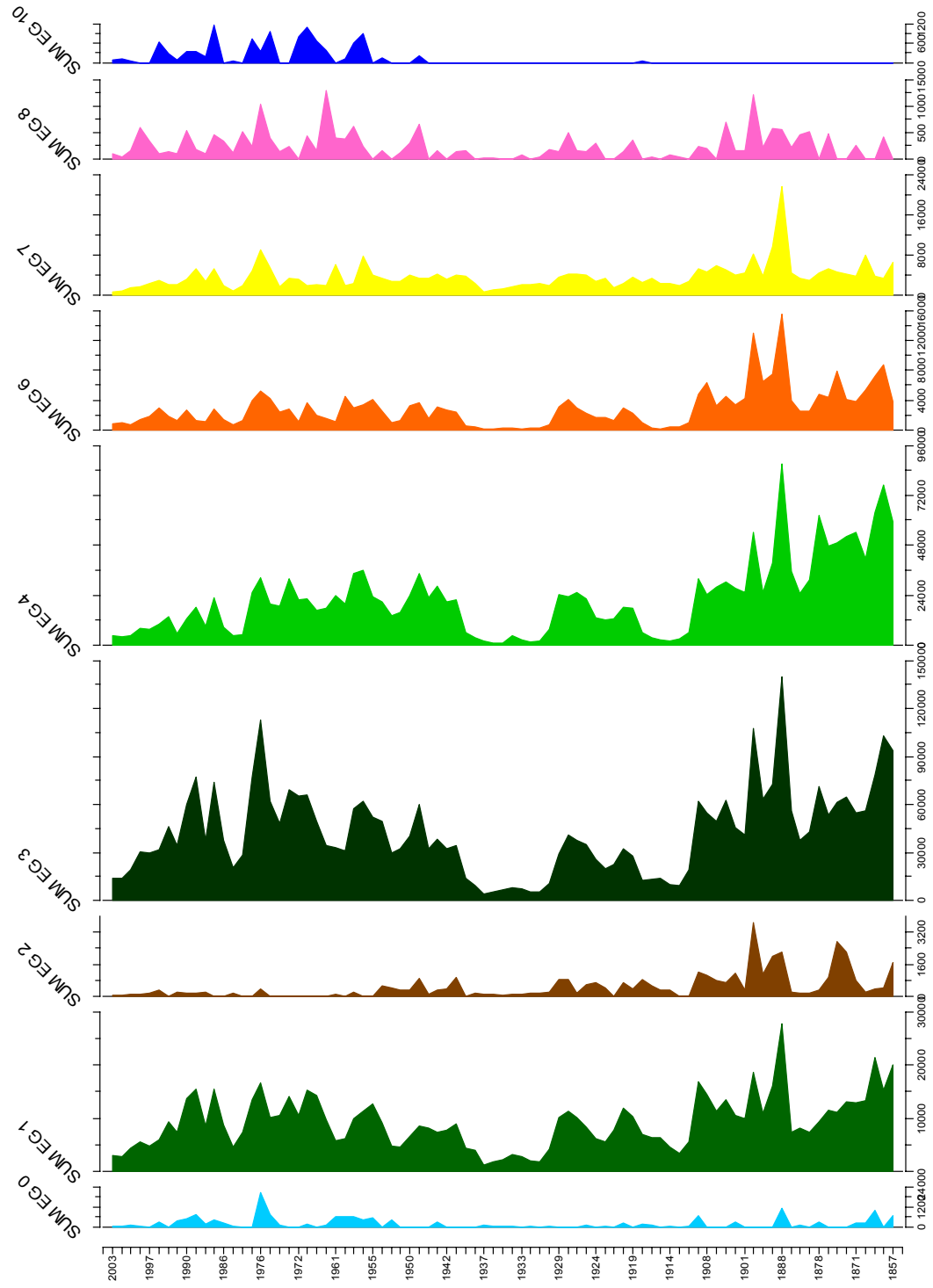Figure C15. Deep Lake relative pollen abundances of ecosystem groups (%).

Figure C16. Deep Lake pollen accumulation rates of ecosystem groups (%).

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