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Temporal Patterns of Wildfire Activity in Areas of Contrasting Human Influence in the Canadian Boreal Forest

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Abstract: The influence of humans on the boreal forest has altered the temporal and spatial patterns of wildfire activity through modification of the physical environment and through fire management for the protection of human and economic values. Wildfires are actively suppressed in areas with higher human influence, but, paradoxically, these areas have more numerous ignitions than low-impact ones because of the high rates of human-ignited fires, especially during the springtime. The aim of this study is to evaluate how humans have altered the temporal patterns of wildfire activity in the Canadian boreal forest by comparing two adjacent areas of low and high human influence, respectively: Wood Buffalo National Park (WBNP) and the Lower Athabasca Plains (LAP). We carried out Singular Spectrum Analysis to identify trends and cycles in wildfires from 1970 to 2015 for the two areas and examined their association with climate conditions. We found human influence to be reflected in wildfire activity in multiple ways: (1) by dampening (i.e., for area burned)—and even reversing (i.e., for the number of fires)—the increasing trends of fire activity usually associated with drier and warmer conditions; (2) by shifting the peak of fire activity from the summer to the spring; (3) by altering the fire-climate association; and (4) by exhibiting more recurrent (<8 year periodicities) cyclical patterns of fire activity than WBNP (>9 years).

Keywords: Wildfire; Wildland fire; forest fire; boreal forest; fire management; human influence; climate

1. Introduction

Wildfire is a critical phenomenon maintaining the ecological processes and integrity of the Canadian boreal forest [1]. Although most fire regimes in Canada are characterized by infrequent, high-intensity, extensive fires occurring mostly between May and August, there is great variability in the components of the fire regime across spatial and temporal scales [2]. Understanding the spatio-temporal patterns of fire occurrence and area burned is thus of foremost interest in Canada in ecological, social, and economic terms. Wildland fires burn on average between 1 to 3 million ha annually in Canada, affecting biological diversity [3,4], ecological services [5,6], and forest resources [7], and require costly fire management strategies for infrastructure and community protection [8,9].

Fire activity, which is usually measured as the number of fires and the total area burned, is driven by weather, climate [10,11], vegetation type [12,13], topography, human activities [8,14,15], and complex interactions among these factors. Globally, wildfire dynamics have been altered by human

activities for millennia through people setting (accidental or deliberate) ignitions that add to the ones caused naturally by lightning, and by modifying the landscape through their activities, increasing access to wildlands, and by altering the arrangement, continuity, amount, structure, and distribution of fuels (i.e., flammable biomass). These changes, combined with climate change, have modified the components of the fire regime: severity, likelihood, seasonality, size, frequency, and intensity of fires [13,16–20].

Evidence suggests that fire suppression practices also have an important effect on the fire–weather relationship, potentially undermining the reliability of weather-based predictions. Current ignition rates in France, for example, are not as high as they were during the pre-suppression period, even under similar weather conditions [21]. Fire regimes in Catalonia, Spain, cannot be efficiently predicted unless fire suppression activities, in addition to climatic variables, are taken into account [22]. In the U.S. Rocky Mountains, alternating periods of fire–climate relationship strength were reported for the past century, suggesting that the interaction of climatic and non-climatic factors, such as fire suppression, is highly complex and needs to be assessed to improve our understanding of fire activity [23].

Over the last century, fire management activities in the Canadian boreal forest have shaped fire activity through aggressive suppression efforts and preventive measures. However, fire management has not been uniform over space and time because deploying resources to prevent and attack fires involves balancing potential economic, social, and ecological impacts, which can sometimes be conflicting [24–27]. To better reflect regional priorities, most of Alberta's forested land surface has been divided into ten Wildfire Management Areas [28] that are managed by the provincial government. Fire management in Alberta has increased the containment (i.e., extinguishment before they reach 2 ha in size) of fires from 75% in 1998 to 93% in 2015 [29]. Regardless of technological advances and preventive measures, large fire events still occur in Alberta. Such is the case of the Horse River fire in Fort McMurray, Alberta (spring 2016; 580,633 ha burned), which caused the evacuation of 80,000 people and was the costliest natural disaster in Canada, with an estimated damage worth of CAN$10.9 billion [30,31]. In contrast, National Parks within Alberta are not included in the provincial Wildfire Management Areas because the administration falls under federal jurisdiction. In these parks, unlike the rest of forested Alberta, the ecological role of fires is favored and wildfires are only supressed when they pose a risk to surrounding inhabited areas and areas containing rare natural resources [32].

Although it is well recognized that human influence can alter fire activity in the boreal forest, the magnitude and direction of recent changes remain largely undocumented. The main goal of this study is to assess how human influence has affected the fire regime of two contrasting areas in the Canadian boreal forest over the past few decades. To achieve this goal, we analyzed the changes in the number of fires and area burned (fire activity) over time and their relationships with climate in two contiguous regions of Alberta with contrasting human influence (fire management and human land use). First, to establish whether fire activity has changed in each region, we analyzed annual trends of the number of fires and area burned, from 1970 to 2015, and compared them while distinguishing natural from anthropogenic fires. Secondly, to determine if the fire–climate relationships remain coherent despite the dissimilar human influence, we compared these relationships between regions. Finally, to better understand the correlations between fire activity and climate, we characterized the cyclical patterns of the number of fires, area burned, and climate, and compared them between regions in terms of the duration of their periodicities.

2. Materials and Methods

2.1. Study Areas

We chose two adjacent study regions located in the northeastern corner of the province of Alberta and a southern portion of Northwest Territories, Canada, that differ in their level of human influence, including wildfire management (Figure 1): Wood Buffalo National Park (WBNP, 4.3 Mha) and the Lower Athabasca Plains (LAP, 7.9 Mha). Both regions are located within the Boreal Forest Natural

Region (BFNR), which covers approximately 58% of Alberta. The topography is mostly flat to gently hilly, and the vegetation is represented by four dominant types: upland deciduous, coniferous, mixed forests, and wetlands. The most common tree species found are black spruce (*Picea mariana* (Mill.) B.S.P.), white spruce (*P. glauca* (Moench) Voss), jack pine (*Pinus banksiana* Lamb.), trembling aspen (*Populus tremuloides* (Michx.)), balsam poplar (*P. balsamifera* L.), and eastern larch (*Larix laricina* (Du Roi) K. Koch) [33].
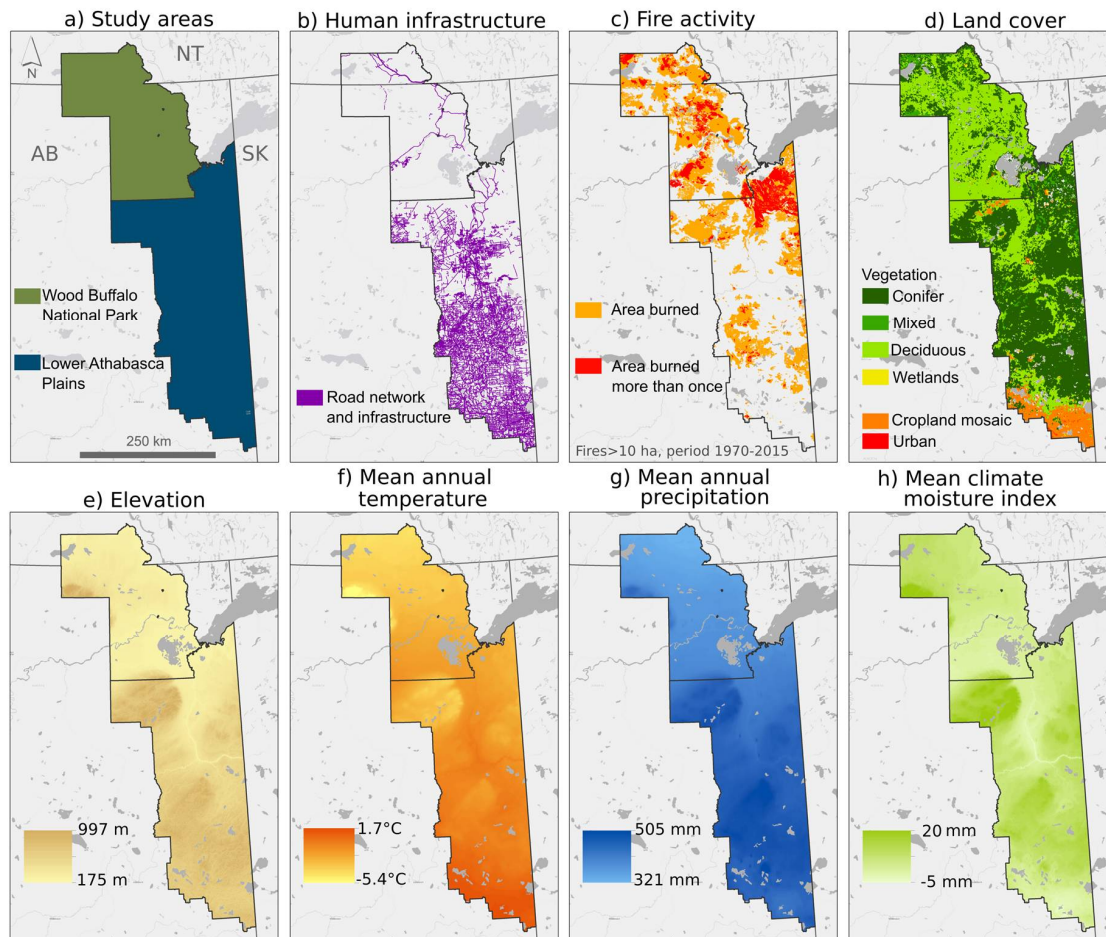

Figure 1. Maps showing (**a**) the location of the areas of interest (53.63° N, 110° W, 60.70° N, 115.60° W): Wood Buffalo National Park, which occupies a portion of Alberta (AB) and Northwest Territories (NT), and Lower Athabasca Plains, which borders with the province of Saskatchewan (SK), (**b**) Human infrastructure cover (30-metre-resolution, Landsat; [34]), (**c**) Area burned from 1970–2015 (one-kilometer resolution), (**d**) Land cover (Global Land Cover Characterization Project, one-kilometer resolution, AVHRR; [35]), (**e**) Elevation, (**f**) Mean annual temperature, (**g**) Mean annual precipitation, and (**h**) Mean climate moisture index (precipitation minus potential evapotranspiration, mm, 1° latitude by 1° longitude resolution; [36]).

Although WBNP and LAP are very similar in terms of topography and vegetation composition, they are subjected to contrasting levels of human influence. Established in 1922, WBNP is a UNESCO (United Nations Educational, Scientific and Cultural Organization) world heritage site where the human influence is remarkably low; less than one percent of its area has been modified by human activities, which mainly consist of two roads (Table 1, Figure 1b). In contrast, LAP has almost 10 percent of its area destined to agriculture, tree harvesting, oil-and-gas exploration, and other rural and industrial activities. Comparatively, LAP also possesses a more extensive road network and more human settlements (Table 1, Figure 1b) [33,34]. Despite belonging to the same land management unit,

we excluded the portion of LAP located on the north side of Lake Athabasca, because it is located in the Canadian Shield, which represents a topo-edaphic setting that differs substantially from the rest of the study area and WBNP, both located in the Boreal Plain.

Table 1. Area occupied or modified by the leading human activities in Wood Buffalo National Park (WBNP) and Lower Athabasca Plains (LAP).

Region	WBNP Area kha (%)		LAP Area kha (%)	
Total	4266	(100)	7932	(100)
Cultivation	0		134.80	(3.16)
Harvested (cut blocks)	0		111.33	(2.61)
Mining	0		32.42	(0.76)
Seismic lines	0		29.86	(0.70)
Industrial-rural	0		23.90	(0.56)
Roads and vegetated margins	0.85	(0.02)	15.36	(0.36)
Urban	0		2.58	(0.06)
Total human-modified area	0.85	(0.02)	350.25	(8.21)

Fire management also differs between these regions. Fires in WBNP are not actively suppressed unless they pose an imminent threat to infrastructure within the park or neighbouring communities, leaving wildfires to fulfill their "natural" role. In contrast, LAP includes the community of Fort McMurray and most of the Lac La Biche Alberta Wildfire Management areas, where there is a strict policy to suppress and prevent fires. On average, during the period 1970–2015, lightning-caused fires in WBNP are larger than the ones in LAP (Table A1), whereas anthropogenic ones are larger in LAP. Human contribution to area burned is so prominent in LAP that the area burned by human-caused fires exceeds the area burned by lightning-caused fires in this region (Table A1). Summer is the season with the highest fire activity (number of fires and area burned; Figure 2) in both regions, but the human contribution to fires is considerably higher during the spring in LAP than in WBNP.
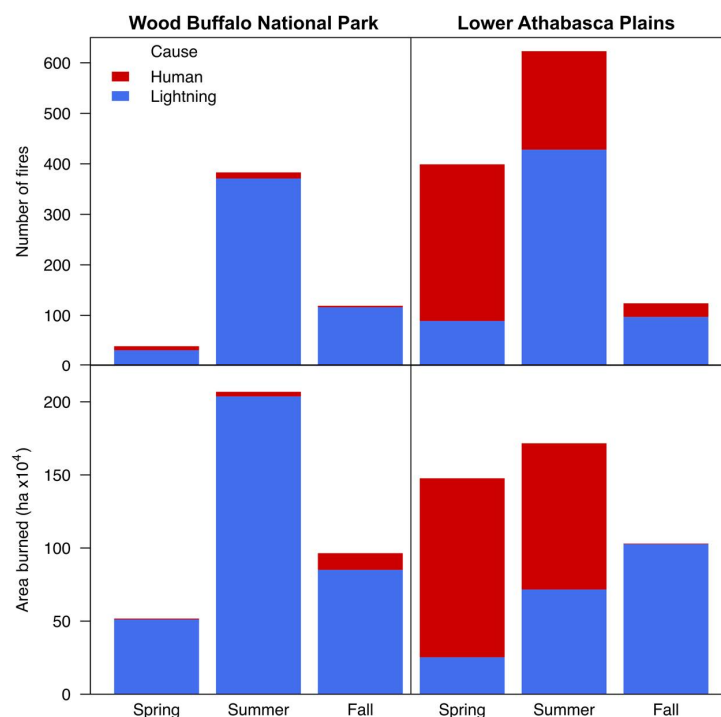

Figure 2. Number of fires and area burned in Wood Buffalo National Park and Lower Athabasca Plains by season (spring, summer, and fall) and cause of ignition (lightning or human). Information based on fires ≥10 ha from 1970–2015.

2.2. Fire Variables

We obtained the historical fire records from the Canadian National Fire Database [37] from which we derived the number of fires and area burned (ha) during the fire season (1 March to 31 October) [38] for the period 1970–2015. Although the database extends earlier than 1970, the analysis was limited to this time period because the data recording and methods of detection during the contemporary era were more reliable and consistent than those of the earlier period [24,27,39]. In addition, we only included fires ≥10 ha because they are less likely to go undetected or unreported than fires <10 ha. The fires were stratified by area (WBNP or LAP) and by cause (human or lightning) and summarized into annual time series using the total number of fires and total area burned (log transformed) during the fire season.

2.3. Fire-Climate Variables

In order to uncover possible relationships with the fire activity variables (area burned and number of fires), we built mean annual time series of climate and fire danger indexes from the Canadian Fire Weather Index System (FWIS) [40] (Table 2). We used the records from 67 weather stations located in WBNP and LAP for the period 1970–2015 [41]. Climate variables include annual means of temperature (°C), relative humidity (%), wind speed (km/h), and 24-h precipitation (mm), as well as codes and indices from the FWIS [40]: Fine Fuel Moisture Code (FFMC), Duff Moisture Content (DMC), Drought Code (DC), Initial Spread Index (ISI), Buildup Index (BUI), Fire Weather Index (FWI), and Daily Severity Rating (DSR). Indices and codes are calculated based on weather measurements taken at noon local standard time (LST) and the FWIS moisture codes from the previous day (Table 2).

Table 2. Climate variables and Fire Weather Index System codes and indices used (Modified from Van Wagner [40]).

Acronym	Name	Units	Description
TEMP	Temperature	°C	A measure of heat present in the air
PRECIP	Precipitation	mm	A form of water, such as rain, snow etc. that condenses from the atmosphere and fall to the Earth
RH	Relative Humidity	%	Amount of water vapor present in air
WINS	Wind Speed	km/h	Velocity of air flow
FFMC	Fine Fuel Moisture Code	unitless	Moisture contained in the upper soil layer (litter and fine fuels)
DMC	Duff Moisture Code	unitless	Moisture for the loose organic layers of the soil, including medium-sized woody debris
DC	Drought Code	unitless	Moisture in deep compacted organic layer and large woody debris
ISI	Initial Spread Index	unitless	The expected rate of spread based on FFMC and wind speed
BUI	Buildup Index	unitless	Proxy for the fuel load available for combustion. Based on DMC and DC
FWI	Fire Weather Index	unitless	Reflects fire intensity and fire danger in forested areas. Based on ISI and BUI
DSR	Daily Severity Rating	unitless	Exponential transformation of FWI indicating severe conditions when DSR >2

2.4. Statistical Analysis

We searched for linear trends in the time series to identify overall changes in the number of fires and area burned during the 1970–2015 period. By decomposing the time series, we were able to

separate them into their additive components: non-linear trend, oscillations (cyclical), and white noise. The non-linear trend was subtracted from the original time series as a "pre-whitening" step, which reduces the occlusion of the remaining components; in this way, we were able to identify oscillation frequencies and calculate their periodicities (years between peaks). Finally, we ran correlation tests between the fire-climate and fire activity time series in order to identify potential relationships between them. If a relationship was identified, we described its nature (positive, negative), strength, and periodicity (through their regular oscillations). All analyses were performed using R [42].

2.4.1. Linear Trend Detection

We tested the time series for autocorrelation processes, after which we ran a phase-randomized version of the Mann-Kendall trend test (slope different from 0: $p \leq 0.05$, H_0: $\beta_1 = \beta_2$, H_a: $\beta_1 \neq \beta_2$) to find a significant linear trend. The Theil-Sen slope method was employed to calculate the slope value (β).

Some time series showed autocorrelation processes (aka. "red noise"), for which the magnitude and order were calculated. This was achieved by means of the autocorrelation and partial autocorrelation functions using the *Acf* function of the "forecast" *R* package [43] (Figures A1 and A2). We found autocorrelation processes in the number of fires and area burned for both lightning-caused fires (first order autoregressive model, AR1 = 0.34) and human-caused fires (autoregressive-moving-average model, ARMA (3, 0), $p = 0.42$) in WBNP. In LAP, only area burned by human-caused fires and the total (L + H) showed autocorrelation ARMA (6, 0). To account for the serial correlation, we employed a phase-randomization method for the hypothesis testing of the trend, which is suitable for non-normal, autocorrelated data, and is robust against outliers (i.e., influential or extreme data). This method consists of the creation of surrogate time series (randomized versions of the original) to create a distribution which is then compared to the original time series to determine its significance. By doing so, we avoided spurious regressions due to the lack of error independence and unequal variances [44–46] and obtained a robust estimate of parameters of the regression by bootstrapping [47]. We employed the *MKcorr.test* function contained in the "MKCorr R" package [48].

2.4.2. Time Series Decomposition

Next, we separated the time series (number of fires, area burned, climate and FWIS indices) into their additive components: non-linear trend, oscillations (regular cycles), and white noise (random signal; see example in the appendix) by using an iterative Singular Spectrum Analysis (SSA, [49]) included in the "Rssa" package [50] in R. SSA is an adaptive non-parametric method ideal for short, noisy time series. This method does not require a priori knowledge of the model to be fitted (e.g., linearity, normality, and stationarity of the residuals, or the number and value of the contained periodicities), making it an advantageous technique to explore and analyze data when the parameters are unknown.

The separation of the components was achieved by running the decomposition process twice (hence the term "iterative"): first, we ran the analysis to extract the non-linear trend and, second, we subtracted this trend (detrending) from the original time series and ran the decomposition process again to extract the oscillatory (cyclical) components. This step also reduces the red noise significantly, so that the oscillations detected are unlikely to be autocorrelation processes [51]. Each iteration requires "windows" (adjacent values) of different lengths (number of values) to establish the resolution and minimum periodicity to detect. We used a small window ($L = 12$) to extract the non-linear trend, and a larger window ($L = 24$) on the detrended time series to extract the cyclical components [49]. We calculated the periodicities of the cyclical components originating from the eigenvectors that explained most variance (>20%) according to the SSA. This was achieved through the Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT; [52]) using the function *parestimate* in the "Rssa" package and confirmed with the spectrum (*mvspec* function, "astsa" package [53]). As a result, we obtained a new set of time series produced for the two study areas (WBNP and LAP), the

three ignition causes (lightning, human, lightning + human), the two fire variables (number of fires and area burned), the eleven fire-climate variables, and the two SSA derived outputs (one non-linear-trend and one detrended time series). Non-linear trends, unlike linear ones, may show changes over time according to different rates that might not be detected with the Mann-Kendall test, but they may still represent a relevant pattern in the time series.

2.4.3. Cross-Correlations of Time Series

In order to evaluate the correlations of fire activity time series between areas and fire activity series with fire-climate variables, we calculated the Kendall rank correlation coefficients and their significance from the detrended time series. We carried out correlations for two different time lags (zero and one year) to test for current and delayed effects of climate on fire, respectively.

We used a non-parametric "randomized-phase surrogate" technique for significance testing to reduce type-1 errors. This test employs the Fourier transform to generate a large number of random time series (called surrogates) with the same spectral properties as one of original (and thus, the same autocorrelation, if present) but with random phases. Then, the correlation between the two original time series is compared to a distribution of correlations produced by the surrogate series to obtain the statistical significance [54,55]. This analysis was performed using the *surrogateCor* function contained in the package "astrochron" [56] in R with 2000 random surrogate series.

3. Results

Fire activity from 1970 to 2015 has increased in WBNP in both the number of fires ($\beta = 0.30$, $p < 0.01$, Figure 3a) and area burned ($\beta = 0.14$, $p < 0.01$, Figure 3c), while in LAP, there is a statistically significant decrease in the number of fires ($\beta = -0.21$, $p = 0.01$, Figure 3b), and no overall change in area burned ($\beta = 0.02$, $p > 0.05$; Figure 3d). Lightning-caused fires were responsible for raising the number of fires in WBNP ($\beta = 0.28$, $p < 0.05$), whereas anthropogenic fires remained low ($\beta = 0$, $p > 0.05$) and their area burned unchanged ($\beta = 0$, $p > 0.05$; Figure 3a,c). Fire activity in WBNP exhibited nonlinear trends, indicating that the increase was faster during the second half of the time period than the first half. Although the non-linear trends suggest a decline in the number of fires caused by lightning or humans in LAP, neither of them were statistically significant ($\beta = 0$, $p > 0.05$ and $\beta = -0.9$, $p > 0.05$ respectively), but their sum (L + H) was (Figure 3b).

In general, a warming and drying climate trend was found over the 46 years studied in both WBNP and LAP, with faster changes in WBNP (Table 3). Most of the fire-climate time series showed some change (linear trend) over the same period that would lead to an increased wildfire activity, but this is only observed in WBNP. In general, for both WBNP and LAP, we found a declining trend in PRECIP, RH, and WINS, and an increasing trend for FFMC, DMC, DC, and BUI. Only ISI did not change overall in any of the areas. Although we did not find a linear trend for temperature in LAP, the non-linear trend extracted by SSA does show an increase (Figure A3), as well as for FWI and DSR in WBNP. The most drastic increase in both areas was observed in the Drought Code, which indicates moisture deficits in the deeper soil levels (Table 3).
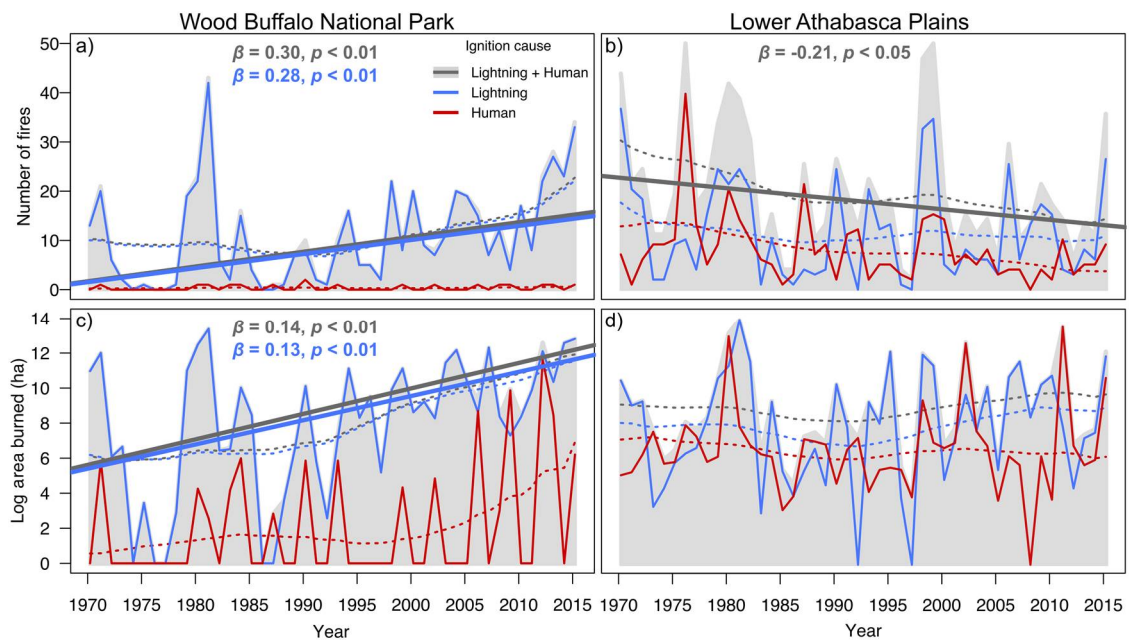
Figure 3. Time series representing the number of fires (**a**,**b**) and area burned (**c**,**d**) for the period 1970–2015 in Wood Buffalo National Park (**a**,**c**) and Lower Athabasca Plains (**b**,**d**). Thin solid lines and shaded background indicate raw time series, dotted lines show the non-linear trend extracted by Singular Spectrum Analysis, and solid straight lines display the significant linear trends obtained by the Mann-Kendall trend test. Different colors indicate the cause of ignition. Theil-Sen's slopes (*β*) and trend significance by Mann-Kendall are shown.

Table 3. Theil-Sen slope values (*β*) and significance by a random-phase Mann-Kendall trend test (* ≤0.05, ** ≤0.005) for the fire-climate variables in Wood Buffalo National Park (WBNP) and Lower Athabasca Plains (LAP). Values were calculated from annual time series.

Acronym	Name	WBNP	LAP
TEMP	Temperature	0.03 **	0.01
PRECIP	Precipitation	<−0.01 *	−0.01 **
RH	Relative Humidity	−0.15 **	−0.06 **
WINS	Wind Speed	−0.10 **	−0.03 *
FFMC	Fine Fuel Moisture Code	0.07 *	0.07 **
DMC	Duff Moisture Code	0.30 **	0.23 **
DC	Drought Code	2.83 **	3.23 **
ISI	Initial Spread Index	0	0
BUI	Buildup Index	0.44 **	0.42 **
FWI	Fire Weather Index	0.04	0.06 **
DSR	Daily Severity Rating	0.02	0.02 *

Cross-correlations of detrended time series between regions indicated a similar pattern of fire activity regardless of the differences in human influence. Lightning-caused fire time series correlations (for both number of fires and area burned) showed the highest coefficients, whereas human-caused fires showed the lowest (Table 4).

Table 4. Correlation coefficient table for the number of fires (upper-right) and area burned (lower left, shaded) of the fire activity time series in Wood Buffalo National Park (WBNP) and Lower Athabasca Plains (LAP). Significance was calculated by a random-phase test (* ≤0.05, ** ≤0.005). Letters following area name indicate ignition cause: Lightning (L) and human (H).

Region		WBNP			LAP		
	Cause	L + H	L	H	L + H	L	H
WBNP	L + H	1	0.96 **	0.17 *	0.31 **	0.36 **	0.08
	L	0.94 **	1	0.13	0.30 **	0.35 **	0.09
	H	0.09	0.04	1	0.18	0.24 *	−0.07
LAP	L + H	0.26 *	0.25 *	0.10	1	0.68 **	0.37 **
	L	0.33 **	0.32 **	0.09	0.76 **	1	0.06
	H	−0.01	−0.01	0	0.29 *	0.09	1

Although the association of fire activity with fire climate was similar in both regions (we observed significant correlations with similar coefficient values for both the number of fires and area burned time series; Table 5), we noted that: (1) mean annual temperature was only correlated with lightning-caused fires in WBNP and human-caused fires and area burned in LAP, (2) mean annual precipitation was associated with lightning-caused fire activity but not human-caused fires in both areas, (3) human-caused fires in WBNP do not have any association with fire-climate, and (4) lightning-caused fires only correlated with temperature and relative humidity in WBNP. We only found three one-year lagged correlations: between the number of human-caused fires in LAP with wind speed ($\tau = -0.30$, $p < 0.005$), and area burned by lightning ignitions with precipitation in WBNP ($\tau = -0.26$, $p < 0.05$) and temperature in LAP ($\tau = 0.29$, $p < 0.005$).

Table 5. Kendall-correlation coefficient table for the relationship between the number of fires and area burned with fire-climate time series at lag 0 (i.e., current year) in Wood Buffalo National Park (WBNP) and Lower Athabasca Plains (LAP). Significance was calculated using a random-phase test (* ≤0.05, ** ≤0.005).

	Number of Fires						Area Burned					
Region	WBNP			LAP			WBNP			LAP		
Ignition cause	L + H	L	H	L + H	L	H	L + H	L	H	L + H	L	H
Temperature	0.20 *	0.19 *	0.17	0.20	0.12	0.23 *	0.07	0.07	0.1	0.10	0.09	0.17 *
Precipitation	−0.29 *	−0.27 *	−0.02	−0.22 *	−0.21 *	−0.14	−0.23 *	−0.25 *	0.07	−0.20 *	−0.21 *	−0.14
Relative humidity	−0.24 *	−0.23 *	−0.05	−0.20	−0.13	−0.18 *	−0.21	−0.22 *	−0.03	−0.27 *	−0.24 *	-0.22 *
Wind speed	−0.14	−0.15	−0.05	−0.18	−0.07	−0.2 *	−0.27	−0.23	−0.09	−0.02	−0.01	−0.12
FFMC	0.26 *	0.24 *	0.1	0.23 *	0.22 *	0.15	0.20	0.20 *	0.05	0.29 *	0.27 *	0.19 *
DMC	0.33 *	0.32 **	−0.01	0.27 *	0.03 *	0.21 *	0.37 **	0.40 **	−0.06	0.40 **	0.34 **	0.30 **
DC	0.34	0.34 **	0.04	0.23 *	0.25 *	0.18 *	0.36 *	0.40 **	−0.02	0.24 *	0.26 **	0.27 *
BUI	0.20 *	0.35 **	0	0.30 *	0.26 *	0.2 *	0.37 **	0.40 **	−0.03	0.40 **	0.35 **	0.30 *
ISI	0.21 *	0.20 *	0.10	0.28 *	0.30 *	0.1	0.23 *	0.26 *	0.07	0.40 **	0.32 **	0.21 *
FWI	0.30 *	0.30 *	0.06	0.31 *	0.30 *	0.16	0.36 **	0.40 **	0.01	0.44 **	0.36 **	0.30 **
DSR	0.28 *	0.26 *	0.01	0.34 **	0.30 **	0.20	0.37 **	0.40 **	0.02	0.44 **	0.35 **	0.31 **

Fire activity in WBNP was characterized by longer and more acute periodicities than the ones found in LAP. We observed that the number of fires and area burned by lightning in WBNP showed strong activity peaks every ~12 years, whereas in LAP, weaker oscillations (i.e., under eight years) were most frequent. Anthropogenic ignitions in both areas mostly displayed high frequency (short periods) oscillations (~3–6 years); however, area burned by humans also showed strong oscillations every ~11 years (Figure 4).
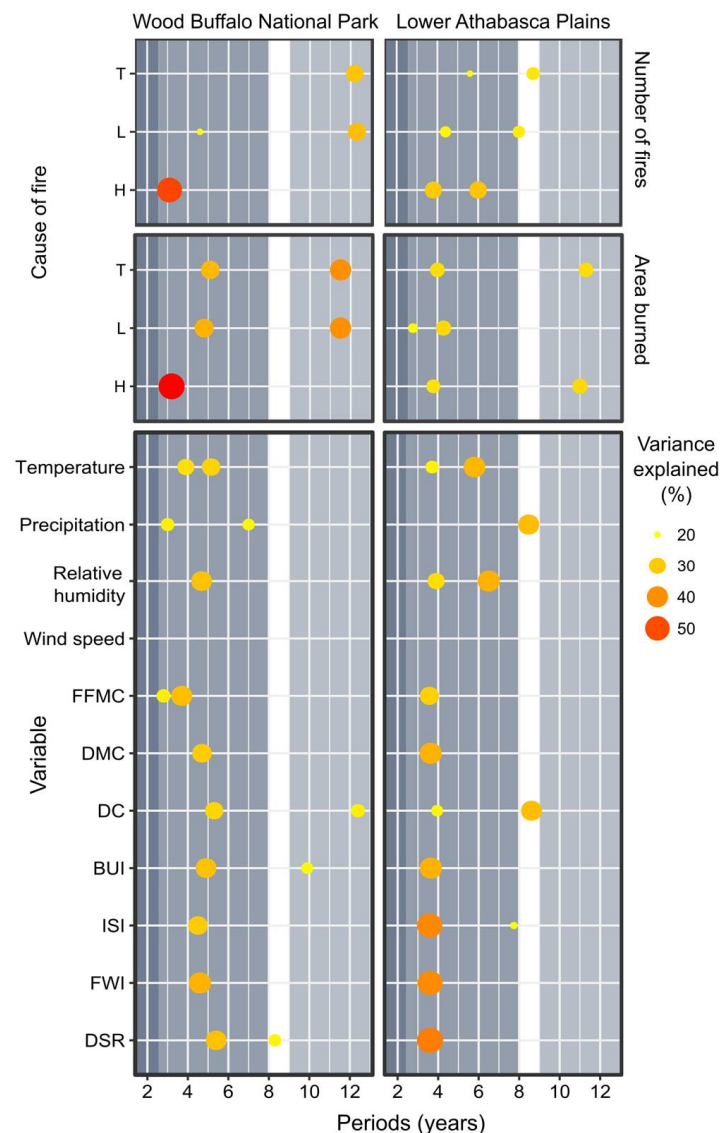
Figure 4. Periodicities (i.e., duration of oscillations) of the fire activity and fire-climate variables, calculated for the cyclical components found in the time series. Size and color of the points indicate the variance explained by the eigenvectors from which the oscillations were extracted during SSA. Shading corresponds to the "typical" climatic teleconnection domains: Quasi-Biennial Oscillation (2–2.5 years, dark grey), El Niño Southern Oscillation (2.5–8 years, moderate grey), and a quasi-decadal oscillation (9–13 years, light grey).

Fire-climate oscillations were very similar between regions, with the strongest periodicities (i.e., higher variance explained) falling under the ENSO domain (2.5–8 years) and aligning with many of the periodicities of fire activity (between 3–6 years). Most of the strongest fire-climate periodicities were found at around four years. With the exception of DC (an index of drought involving precipitation and temperature) and BUI (calculated through DC and DMC), we did not detect strong long periodicities (over nine years) from the fire-climate time series (Figure 4).

4. Discussion

Human activities have been continuously altering the dynamics of the boreal forest in Alberta over the past few decades, and have generated recognizable spatial and temporal patterns of wildfire activity. In the 1970–2015 period, we found increasing fire-conducive climatic trends in both study

areas that were reflected in occurrence and area burned increases only in the region with the lowest human interference (WBNP), which agrees with findings reported across Canada [57–59]. In contrast, we observed a dampening effect of fire activity in the region with the most human impact (LAP), resulting in a decline in the number of fires and no overall change (no trend) in the area burned. Previous studies also suggest that although area burned has increased due to the changing climate in the boreal forest, this is not necessarily the case in areas of higher human influence [60,61].

The main causes limiting the potential area burned under high human influence are: (1) the strong prevention and fire suppression policies, (2) improved accessibility, (3) the location of the human ignitions (i.e., closer to human infrastructures), and (4) land-use change. The first cause is a consequence of two of the objectives of fire suppression in Alberta: reducing the spread of fires before 10 AM of the following day and preventing them from attaining 2 ha in size [28], which results in fewer escaped fires (i.e., defined here as fires ≥10 ha). In addition, the widespread road network facilitates access for fire-management activities to take place. Although human ignitions might increase over time, they also have a tendency to cluster in the wildland-urban interface (WUI; [61,62]), where fire detection and initial attack are more efficient, impeding their further growth in spite of fire-prone weather conditions. Finally, conversion of forested areas to agricultural, urban, and petrochemical mining land uses has altered the vegetation's structure and composition. These changes, in turn, have impacted the burn rates and ignition likelihood, and the increased fragmentation has reduced vegetation continuity, countering potential area burned [15,62–67].

Wildfire suppression practices, in conjunction with other human-induced changes, have the potential to not just slow down, but also to reverse trends in fire activity; hence, non-climatic factors have the potential to alter fire-climate relationships. Such cases have been reported in France, where recent fire activity stopped tracking climatic trends and decreased along with major changes in fire suppression policy [21,68], and in South Africa, where land-use changes mediated the relationship between climate and area burned [69].

Unlike trends, overall annual fluctuation patterns of wildfire activity exhibited some similarities between regions, regardless of the level of human influence. This is because climate and lightning still persist as dominant factors regulating the totality of fire activity in the boreal forest [70–72]. We further support this observation, given that wildfire activity was similarly related to climate in both regions. In general, peaks of fire activity tracked a drier and warmer climate in both areas. We also found that temperature and relative humidity did not correlate to the number of lightning-caused fires in LAP, whereas they did in WBNP, suggesting that non-climatic factors (i.e., fire management, land-use change, road density) might have interfered with those relationships [21,73].

Anthropogenic fire activity is associated with the same climatic variables as lightning-caused fire activity, with only very few exceptions. Most notably, we observed a lack of association between anthropogenic fires and precipitation that might indicate that more of these fires may occur in years with higher soil moisture conditions than lightning-caused fires. This observation has also been reported before in the U.S. [74], where the authors concluded that anthropogenic ignitions can occur in a broader range of moisture environments than lightning-caused fires, thereby resulting in a wider wildfire "niche". In addition, the shift of the peak of anthropogenic fire activity from the summer to the spring, accompanied by a longer fire season length [20,74–76], might have caused anthropogenic and lightning fires associated with different climatic conditions within the year. This means that even if precipitation was higher overall during the year, the actual precipitation events might have been clustered to only the season where they could limit lightning-caused fires (summer), but not anthropogenic fires (spring).

We found periodicities that suggest a match with different teleconnections' oscillatory patterns. Large-scale climatic patterns (teleconnections) and their interactions influence weather and local climate, and consequently, fire activity in Canada [77,78]. Wildfire cycles under higher human influence (LAP), as well as most fire-climate periodicities, were predominantly characterized by shorter periods (<8 years) compared to longer periods under low human influence (WBNP; >9 years).

The short periodicities of fire activity under high human influence suggest a higher susceptibility to Quasi-biennial and el Niño Southern Oscillations (QBO and ENSO, 2–2.5 and 2.5–8 years), whereas under lower human influence (WBNP), they seem to respond to ENSO and a quasi-decadal oscillation (Pacific Decadal Oscillation + sunspot cycle, 9–13 years) [79]. We also found traces of larger oscillations in WBNP (<15 years, not shown) that are usually associated with the PDO and IPO (Pacific Decadal and Pacific Interdecadal Oscillations), but due to the short time series we used, the signals were weak and possibly spurious. The absence of long fire-climate periodicities explaining area burned by humans in LAP at 10–12 years, might be a result of coinciding peaks of short oscillations of different periodicity that may create longer, stronger oscillations. These kinds of interactions have been documented for longer-term climatic patterns, when negative phases of ENSO and PDO concur with positive AMO phase, increasing the occurrence of fires in Colorado [80], or when positive ENSO and PDO phases coincide in the Rocky Mountains [81] in the U.S. In order to support these partial observations, future research with longer, seasonal time series are required.

The creation of Wood Buffalo National Park almost a century ago gave us the opportunity to compare this area of very low human impact with the adjacent area under a strong anthropogenic transformation in the same ecological region, avoiding the conflation of human influence with other factors. Furthermore, we used a temporal and spatial extent that allowed us to distinguish more directly the effect of human influence on fire activity in the short term (years to decades) [57,62,70], which generates useful information for land managers. Understanding the temporal patterns of fire activity helps fire management agencies assign and efficiently distribute material and human resources to fight and prevent fires. For example, in the province of Alberta, increasing attention is being given to the earliest part of the fire season (i.e., spring), when numerous human ignitions often coincide with the early onset of warm weather due to a lengthening of the fire season that has resulted in large and destructive wildfires (e.g., the Fort McMurray fire of 2016) [82].

5. Conclusions

Over the 46-year period studied (1970–2015), we observed how wildfire activity patterns in the boreal forest have been shaped by the continuously increasing influence of humans, potentially creating a novel fire regime through the modification of the seasonality, size, and frequency of fires. In our area of study, under high human influence, fire activity (area burned and number of fires) peaks in the spring instead of the summer, burning rates are lower, on average, and fewer fires over 10 ha occur than in the more natural area. Analyses used mostly non-parametric statistical techniques that are suitable for the highly variable and stochastic nature of the data. We showed how human influence affects fire activity by changing its trends and cyclical patterns, and how anthropogenic wildfire activity generates temporal patterns and associations with climate distinctive (albeit similar) from those associated with lightning wildfire activity. In general, although northern Alberta is subjected to drier and warmer climatic conditions, in areas of a high anthropogenic footprint, human influence appears to dampen and reverse the expected fire activity trends and affect the cyclical nature of fire occurrence. These rapid changes pose a new set of challenges for managers and researchers who try to understand and predict the impact of altered fire regimes on the diversity, structure, and future fire activity of a boreal forest. Our results further emphasize the importance of explicitly incorporating the multi-faceted human impact to improve our understanding of fire activity, how it is affecting the fire regime at different spatial and temporal scales, and to produce more accurate predictive models of fire activity.

map, Karen Blouin for proofreading, and Filmer Chu for our long discussions over the potential applications of time series analysis.

Author Contributions: M.D.F. conceived the original idea and supervised this project. R.C.-R. designed and performed the data analysis; R.C.-R. and M.-A.P. interpreted the results and wrote the paper.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.
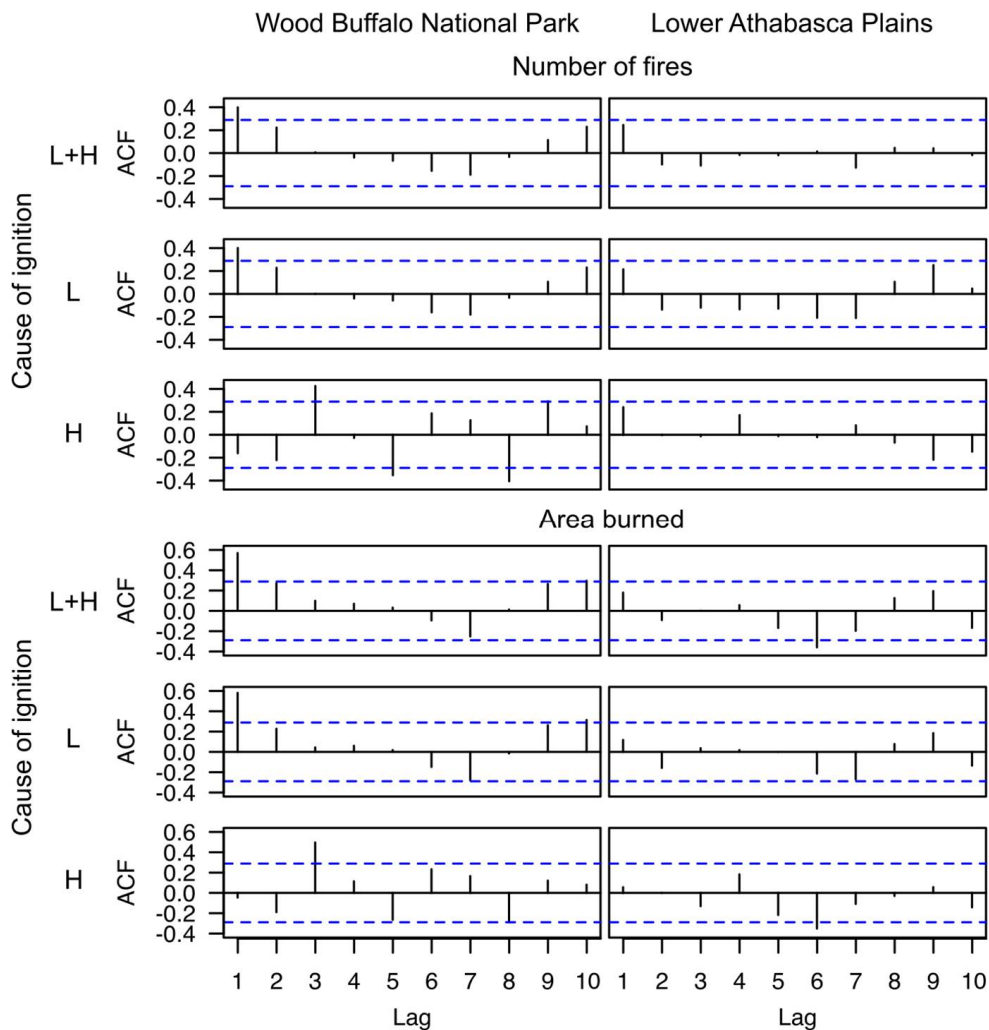
Appendix

Figure A1. Autocorrelation plots for the number of fires and area burned (log transformed) time series in Wood Buffalo National Park and Lower Athabasca Plains.
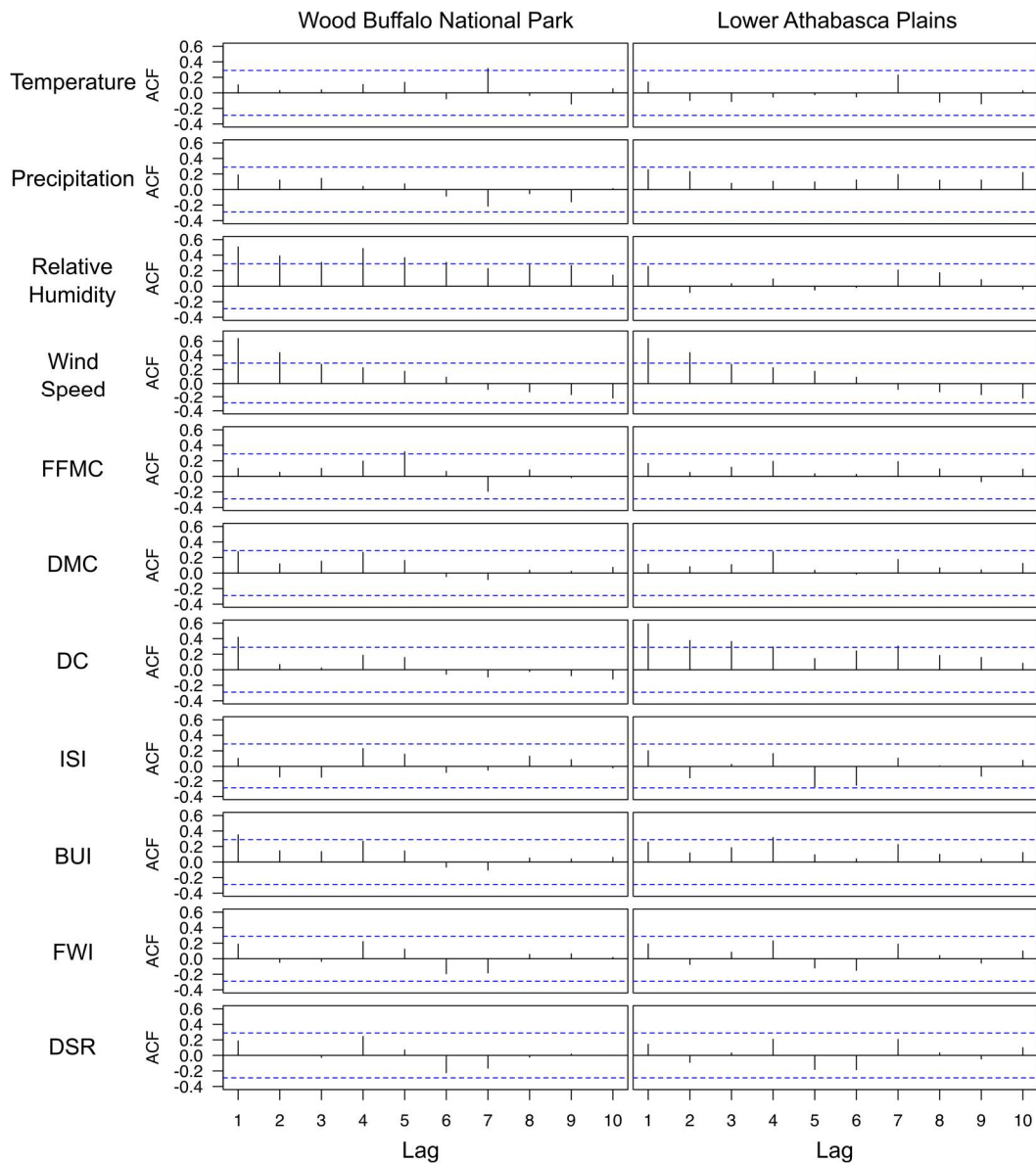
Figure A2. Autocorrelation plots for the fire-climate (climate and Fire Weather Index System) time series in Wood Buffalo National Park and Lower Athabasca Plains.

Table A1. Fire statistics in Wood Buffalo National Park (WBNP) and Lower Athabasca Plains (LAP) from 1970 to 2015. Letters L and H indicate lightning and human-caused fires, respectively.

Region	WBNP			LAP		
Cause	L + H	L	H	L + H	L	H
Number of fires	541 (100%)	518 (95.75%)	23 (4.25%)	1146 (100%)	614 (53.60%)	532 (46.40%)
Proportional number of fires (fires per 100 kha)	12.70	12.14	0.54	14.44	7.74	6.70
Area burned (ha × 10⁴)	355.08 (100%)	339.87 (95.70%)	15.21 (4.30%)	422.39 * (100%)	199.56 (47.25%)	222.83 (52.75%)
Mean fire size (ha)	7332.51	6978.90	353.60	7384.40	4411.42	2972.98

Note: Information shown here is for fires ≥10 ha. Based on the National Fire Database [37]. * The Horse River fire (Fort McMurray) in 2016, increased this value by 13% in just one year.
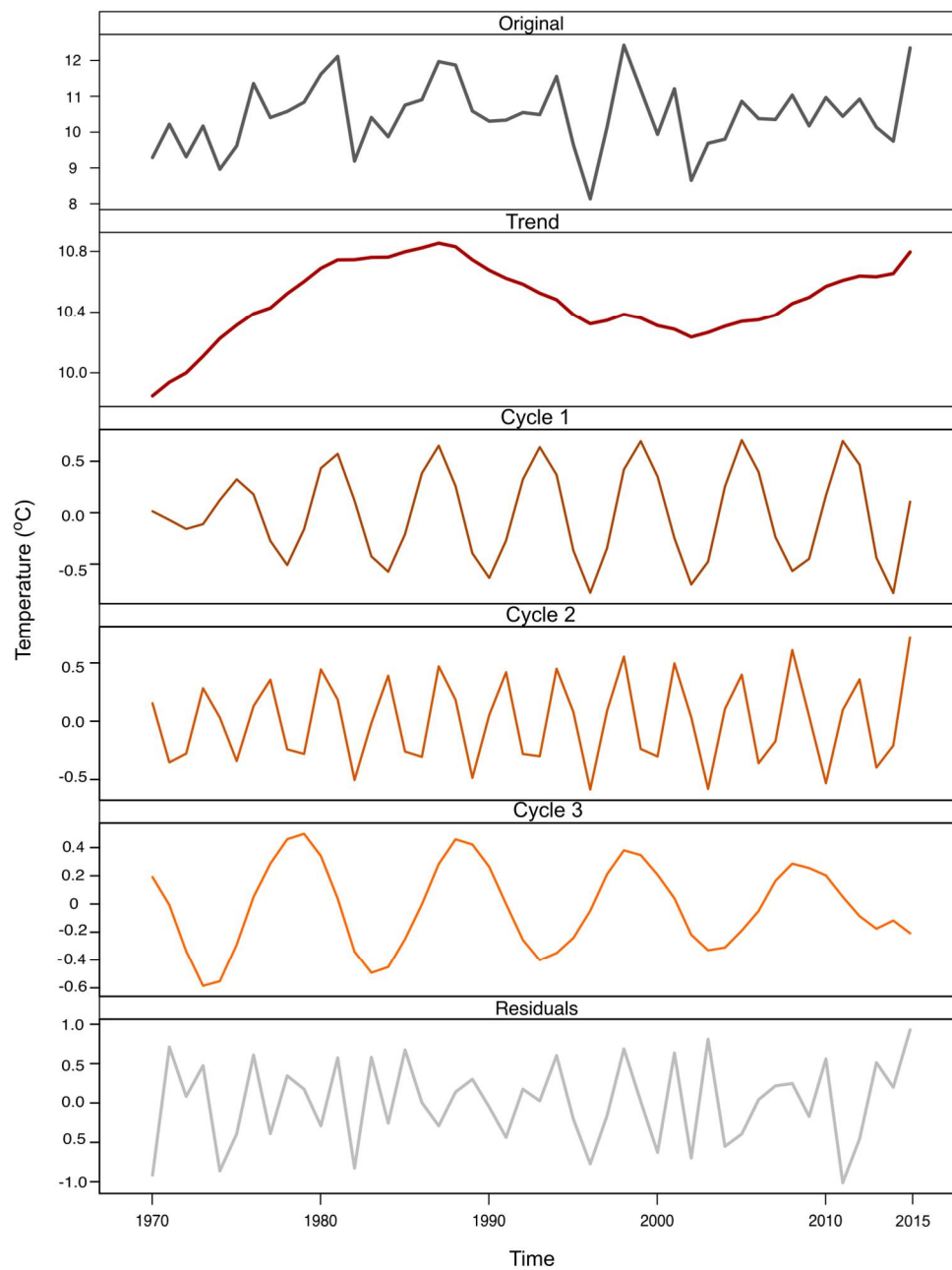
Figure A3. Example of decomposition by Singular Spectrum Analysis for temperature time series in Lower Athabasca Plains, showing its additive components: trend, cycles (oscillations), and residuals (white noise, random). In this case, the trend is upward non-monotonic and each cycle has a distinctive periodicity of 5.8, 3.7, and 9.5 years, respectively.

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