



Fire Dynamics in Boreal Forests Over the 20th Century: A Data-Model Comparison

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Fire regimes across the world are expected to be altered by continuing variations in socio-economic conditions and climate. Current global fire-vegetation models are able to represent the present-day fire activity, but it is unclear how well they can simulate past or future scenarios. Here we use sedimentary charcoal-based biomass burning reconstructions to evaluate fire probability and total carbon flux emitted to the atmosphere per year simulated by the dynamic global vegetation model LPJ-GUESS with its incorporated fire model SIMFIRE-BLAZE across the boreal region during the last century. The analyses were run for the whole time period (1900–2000 CE), as well as for the intervals 1900–1950 CE and 1950–2000 CE. The data–model comparison for the 20th century reveals a general disagreement in trends between charcoal reconstructions (with decreasing or stable trends) and simulations (showing an overall increase) at both global (boreal forests) and continental scales (North America and Fennoscandia), as well as for most of the regional sub-areas (Canada, Norway and Sweden). The only exceptions are Alaska and Finland/Russia Karelia, where all the variables increase. Negative correlations between observations and model outputs are also recorded for the two different sub-periods, except for Alaska and North America during the time interval 1900–1950 CE, and Norway and Finland/Russia Karelia between 1950 and 2000 CE. Despite several uncertainties in charcoal records, main differences between modeled and observed fire activity are probably due to limitations in the representation of the human impact on fire regime (especially connected to forest management and landscape fragmentation) in the model simulations.

Keywords: sedimentary charcoal record, biomass burning, fire model, burnt area, carbon flux, Spearman correlation coefficient

INTRODUCTION

Fire is a major disturbance which organizes the physical and biological features of many ecosystems (Goldammer, 2013) and affects the distribution, structure and diversity of vegetation communities and fuel load (Bowman et al., 2009). Simultaneously, the fire regime (defined as the frequency, intensity, magnitude and seasonality of a fire, Krebs et al., 2010) results from complex interactions

between long-term trends in climate and local fuel availability (Heyerdahl et al., 2008) and is also influenced by anthropogenic impacts (Bowman et al., 2011). Additionally, forest fires play a critical role in land-atmosphere carbon exchange and land use emissions, and thus have significant impact on biogeophysical coupling and atmospheric aerosol loads (Sommers et al., 2014; Landry et al., 2015).

Despite the fact that satellite measurements of burned area provide relative good information regarding present-day fires (Giglio et al., 2010) and already show strong temporal trends (Andela et al., 2017), these high quality data only cover a relative short time interval and they do not encompass the range of climate variability expected for the next century. Much less is thus known about long-term fire dynamics, feedbacks and resilience of ecosystems to fire disturbances. By covering a broad range of climatic and environmental conditions and varying intensities of human impact, proxy-based past fire reconstructions are the most promising tools for better evaluating ecosystems' resilience or vulnerability to fire impact and response over long time intervals (Willis et al., 2007). Documenting coherent changes in biomass burning, sedimentary charcoal records are unique among these data sources because of their broad temporal and spatial coverage, which includes reconstructions of fire history at local to global spatial scales and from decadal to millennial temporal scales (e.g., Power et al., 2010; Iglesias et al., 2015).

Charcoal-based studies are a primary source of information about long-term fire dynamics in most terrestrial ecosystems (Tolonen, 1978; Patterson et al., 1987). Charcoal is formed from the incomplete combustion of fuel under reducing conditions. Charcoal particles are carried aloft during the fire, transported by airborne and surficial processes, and incorporated into the sediments where they are preserved. Year by year, lake and bog sediments collect and bury charcoal from local and distant fires (Whitlock and Larsen, 2001; Conedera et al., 2009). Charcoal analysis is based on the assumption that stratigraphic intervals with abundant charcoal particles represent a primary contribution that is deposited mainly through aerial fallout during or shortly after a fire (Whitlock and Larsen, 2001).

Global wildfire models coupled to dynamic global vegetation models (DGVMs) have existed since the 1990s and have advanced rapidly during the last decades (Hantson et al., 2016). However, while these models are largely able to represent present day fire occurrence (Hantson et al., 2020) uncertainty remains regarding their skill at representing changes in fire regime through time (Andela et al., 2017; Forkel et al., 2019). Hence, there is a clear need to evaluate the performance of global fire models over longer periods, for which paleodata-model comparisons are well suited.

Discrepancies between observations and simulations have been underlined by several previous studies. For example, model simulations by Pechony and Shindell (2010) suggest that during the Pre-Industrial period the global fire regime was strongly driven by precipitation, shifting to an anthropogenic-driven regime with the Industrial Revolution. These findings contradict analyses of palaeodata, indicating temperature as the most important driver of long-term changes in biomass burning (Daniau et al., 2012; Power et al., 2013). Additionally,

Marlon et al. (2016) found a disagreement between area burned simulated by the CLIMBA model (Brücher et al., 2014) and sedimentary charcoal-based fire reconstructions over the last 6000 years. Furthermore, contrary to AeroCom 1750 (Dentener et al., 2006) and the Coupled Model Intercomparison Project (CMIP) phase 5 and 6 aerosol emission datasets (Lamarque et al., 2010; van Marle et al., 2017), palaeoenvironmental archives suggest that late Pre-Industrial Holocene (PI) fire activity was similar to present-day (PD) activity, if not higher (Hamilton et al., 2018). According to Hamilton et al. (2018), global aerosol model simulations of the PD/PI ratio in black carbon concentrations using LMfire and SIMFIRE-BLAZE fire emission models are more in line with the trends predicted from palaeofire proxy records than the global aerosol model simulation which uses the CMIP6 fire emissions scenario. Moreover, discrepancies in the Southern Hemisphere fire emissions' trends over the past two centuries are presented by Liu et al. (2021) based on Antarctic and Andean ice records (suggesting that historical fire activity exceeded present-day levels) and the LPJ-LMfire dynamic global vegetation model (simulating an overall decline in fire emissions over the 20th century). Finally, the reconstruction of fire activity based on a 200-year charcoal record from Lake Lading (Indonesia) by Cheung et al. (2021) also contradict assumptions made in current fire emissions estimates and suggest an over-simplification of the spatiotemporal complexity of fire in Equatorial Asia before the 1960s. Despite both palaeofire reconstructions (Marlon et al., 2009b) and ecosystem fire-model studies (Kloster et al., 2012; Knorr et al., 2016a) suggest a rise in frequency and severity of future forest fires linked to rapid and extreme climate variations, a better understanding of the capability of global wildfire models to reproduce reconstructed trends in fire activity is thus needed. As a result of their location at climatically sensitive high northern latitudes, the boreal regions have been suggested to be significantly affected by the ongoing anthropogenic global warming more than other regions worldwide (IPCC., 2014), with a subsequent increase in the frequency, intensity and areal extent of fires (Flannigan et al., 2009b). Furthermore, the occurrence of dry hot summers characterized by high pressure followed by thunderstorms without accompanying rains might increase the chance of lightning, the only natural cause of fire ignition in boreal forests (Veraverbeke et al., 2017). Based on these assumptions, sedimentary charcoal-based fire reconstructions are here compared with natural and anthropogenic fire dynamics simulated by the LPJ-GUESS-SIMFIRE-BLAZE coupled fire-vegetation model for the 20th century (1900–2000 CE) in boreal forests.

LPJ-GUESS-SIMFIRE-BLAZE is a new-generation prognostic wildfire scheme that takes advantage of the detailed horizontal and vertical description of vegetation structure in the DGVM LPJ-GUESS (Smith et al., 2014). Recently the model has been developed in order to enable simulations of fire occurrence, impact and emissions (Rabin et al., 2017; Pellegrini et al., 2018). Different versions of the SIMFIRE model have been used to project past and future fire occurrence (Knorr et al., 2016b,c, 2017) and a better quantification of its skill at simulating longer-term trends is needed.

In order to underline spatial differences in the results, the study area was divided into continental (North American and Fennoscandian boreal forests) and regional (Alaska, Canada, Norway, Sweden, Finland/Russia Karelia) sub-areas. Furthermore, the analyses were run for the whole time period taken into consideration (1900–2000 CE), as well as for two different sub-periods corresponding to the intervals 1900–1950 CE and 1950–2000 CE. The evaluation of model projections that incorporate the behavior and ecosystem effects of forest fires based on proxy-based reconstructions enabled us to highlight the correlation between simulated and reconstructed past fire activity and investigate the possible reasons for differences and similarities between observations and model outputs.

MATERIALS AND METHODS

Charcoal-Based Fire Reconstructions

Variations in biomass burning across the boreal biome (a transcontinental circumpolar band located between 50 and 70°N latitude) were **analyzed** based on 88 sedimentary charcoal records from lakes and peat bogs **characterized** by robust dating control. Even though some geographic areas are less well represented than others, a broad view of boreal forests' fire

activity during the investigated period is provided (**Figure 1**). Charcoal data were selected from the latest version of the Global Charcoal Database (GCD v4.0.6) compiled by the Global Palaeofire Working Group (GPWG¹) or from a previous published synthesis (Molinari et al., 2020). Metadata including detailed information about each record are presented in **Table 1**.

To reconstruct regional and continental composite curves of changes in fire activity over the last century, all charcoal data were first converted to charcoal accumulation rates (CHARs, i.e., the number, area or weight of particles cm⁻² year⁻¹). A standardization procedure was then applied in order to allow comparison within and between charcoal records obtained from various depositional environments and quantified with different laboratory techniques (Power et al., 2008). This technique includes: (1) a min-max rescaling of CHAR values, (2) a Box-Cox transformation to homogenize the within-record variance, and (3) a Z-score conversion using a base period between 1900 and 2000 CE. Palaeofire analyses generally omitted this time interval from the base period because of the large impacts of anthropogenic activities on ignitions and suppressions during the 19th and the 20th century (Power et al., 2008), which, instead, is what we want to capture in this study. Transformed charcoal data were then bootstrap

¹<http://gpwg.org>

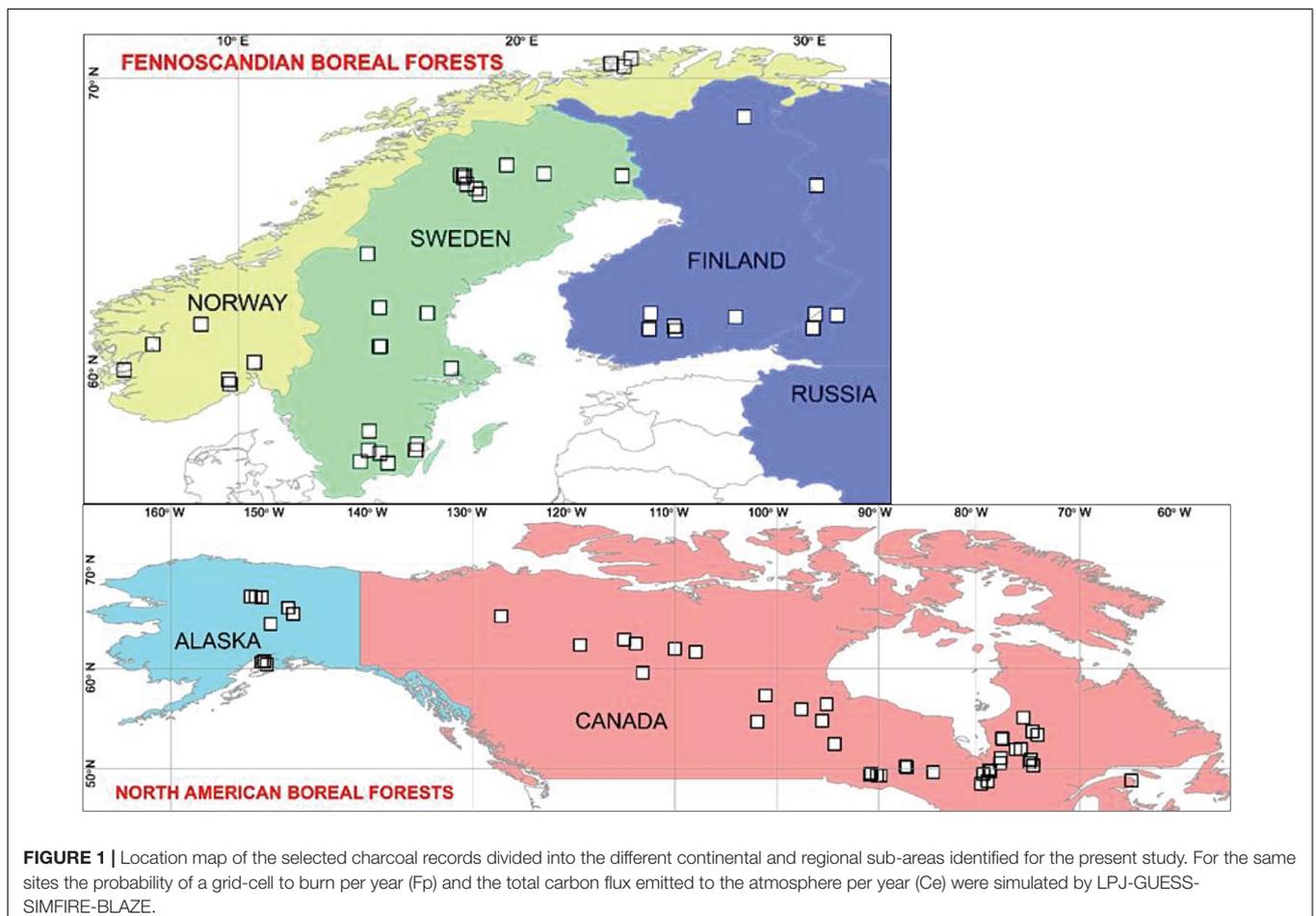


TABLE 1 | Name, source, location, depositional context, time range, and first reference for individual records of Holocene biomass burning in boreal forests.

Site name	Data source*	Country	Lat.	Lon.	Site type	Time range (cal. yr BP)	First references
7-M	GCD v4.0.6	Canada	62.50	-113.72	Lake	6 830 – present	Lynch et al., 2004
Abborrtjärnen	Molinari et al., 2020	Sweden	63.88	14.45	Lake	9 150 – present	Giesecke, 2005
Akkapakte	Molinari et al., 2020	Sweden	66.63	17.68	Bog	2 670 – present	Josefsson et al., 2009
Amont	GCD v4.0.6	Canada	53.73	-74.38	Bog	4 835 – present	Paitre, 2008
Andy Lake	GCD v4.0.6	Canada	61.95	-109.81	Lake	4 475 – present	Lynch et al., 2004
Ängersjötjärn	Molinari et al., 2020	Sweden	62.00	14.87	Bog	1 510 – 160	Karlsson et al., 2010
Arrow	GCD v4.0.6	Alaska	60.75	-150.52	Lake	120 – present	Lynch et al., 2003
Årum	Molinari et al., 2020	Norway	59.48	9.62	Bog	9 675 – present	Bjune et al., 2009
Aval	GCD v4.0.6	Canada	53.42	-73.87	Bog	5 465 – present	Paitre, 2008
Avril Lake	GCD v4.0.6	Canada	49.37	-89.42	Lake	9 990 – present	Senici et al., 2015
Beach	GCD v4.0.6	Canada	65.22	-127.05	Lake	3130 – 0	Rowe et al., 1975
Beaver Lake	GCD v4.0.6	Canada	49.53	-90.4	Lake	11 66 – present	Senici et al., 2015
Ben Lake	GCD v4.0.6	Canada	49.36	-89.77	Lake	10 425 – present	Senici et al., 2015
Bråtamosen	Molinari et al., 2020	Sweden	57.68	14.51	Bog	6 500 – present	Lagerås et al., 1995
Brenda Lake	GCD v4.0.6	Canada	62.35	-119.19	Lake	1 805 – present	Lynch et al., 2004
Bruskardtjorni	Molinari et al., 2020	Norway	61.41	8.66	Lake	11 000 – 0	Bjune, 2005
Code	GCD v4.0.6	Alaska	67.16	-151.86	Lake	7 410 – present	Higuera et al., 2009
Corral Lake	GCD v4.0.6	Canada	57.32	-100.85	Lake	3 350 – present	Lynch et al., 2004
Deuce	GCD v4.0.6	Alaska	66.05	-148.16	Lake	1 270 – present	Lynch et al., 2003
Djäknabygd	Molinari et al., 2020	Sweden	56.62	14.20	Bog	6 000 – present	Lindbladh and Bradshaw, 1998
Dune Lake	GCD v4.0.6	Alaska	64.42	-149.90	Lake	9 220 – present	Lynch et al., 2003
GB2	GCD v4.0.6	Canada	55.10	-75.28	Lake	7 210 – present	Gajewski et al., 1993
Holtjärnen	Molinari et al., 2013	Sweden	60.65	14.92	Lake	10 500 – present	Brown and Giesecke, 2014
Jason Lake	GCD v4.0.6	Canada	61.68	-107.78	Lake	3 135 – present	Lynch et al., 2004
Kapteistjörn	Molinari et al., 2020	Norway	59.33	9.67	Bog	9 500 – present	Molinari et al., 2005
Kilden	Molinari et al., 2020	Norway	70.42	23.36	Bog	9 800 – present	Jensen, 2004
Kirjvalampi	Molinari et al., 2020	Finland/Russia Karelia	61.73	30.76	Lake	3 290 – present	Alenius et al., 2004
Klotjärnen	Molinari et al., 2020	Sweden	61.81	16.53	Lake	9 500 – present	Brown and Giesecke, 2014
Kuusivaara_Betula	Molinari et al., 2020	Sweden	66.67	23.30	Bog	7 900 – 0	Seegerström et al., 2008
Kuusivaara_Picea	Molinari et al., 2020	Sweden	66.67	23.30	Bog	6 700 – present	Hörnberg et al., 2012
Lac aux Geais	GCD v4.0.6	Canada	49.89	-78.65	Lake	7 172 – 15	Ali et al., 2009
Lac Christelle	GCD v4.0.6	Canada	49.68	-84.23	Lake	8 945 – present	Genries et al., 2012
Lac du Berger	GCD v4.0.6	Canada	49.42	-90.48	Lake	10 090 – present	Senici et al., 2015
Lac du Loup II	GCD v4.0.6	Canada	53.05	-77.4	Lake	7 145 – present	Oris et al., 2014
Lac Francis	GCD v4.0.6	Canada	48.53	-79.47	Lake	7 240 – present	Carcaillet et al., 2001
Lac Garot	GCD v4.0.6	Canada	51.10	-77.55	Lake	7 425 – present	Oris et al., 2014
Lac Huard	GCD v4.0.6	Canada	50.16	-86.83	Lake	11 460 – present	Genries et al., 2012
Lac Jack Pine	GCD v4.0.6	Canada	50.27	-86.96	Lake	8 205 – present	Girardin et al., 2013
Lac Marie-Eve	GCD v4.0.6	Canada	52.03	-75.52	Lake	6 990 – present	Oris et al., 2014
Lac Nano	GCD v4.0.6	Canada	53.02	-77.36	Lake	7 450 – present	Oris et al., 2014
Lac Nans	GCD v4.0.6	Canada	50.37	-74.31	Lake	8 515 – present	Ali et al., 2012
Lac Pessiere_B	GCD v4.0.6	Canada	49.50	-79.24	Lake	7 600 – present	Carcaillet et al., 2001
Lac Profond	GCD v4.0.6	Canada	49.86	-78.61	Lake	7 960 – 10	Ali et al., 2009
Lac Raynald	GCD v4.0.6	Canada	49.80	-78.54	Lake	4 115 – 10	Ali et al., 2009
Lac Richard	GCD v4.0.6	Canada	50.64	-74.68	Lake	8 270 – present	Ali et al., 2012
Lac Schon	GCD v4.0.6	Canada	50.59	-77.57	Lake	7 302 – present	Oris et al., 2014
Lac Trefle	GCD v4.0.6	Canada	51.96	-76.08	Lake	7 170 – present	Oris et al., 2014
Lake Kirkkolampi	Molinari et al., 2020	Finland/Russia Karelia	61.78	30.00	Lake	4 600 – 0	Alenius et al., 2004
Lake Orijärvi	Molinari et al., 2020	Finland/Russia Karelia	61.67	27.23	Lake	9 500 – 25	Alenius et al., 2008
Last Chance	GCD v4.0.6	Alaska	67.08	-150.75	Lake	2 165 – present	Higuera et al., 2009
Lattok Lake	GCD v4.0.6	Sweden	65.96	18.34	Lake	10 000 – present	Carcaillet et al., 2007

(Continued)

TABLE 1 | Continued

Site name	Data source*	Country	Lat.	Lon.	Site type	Time range (cal. yr BP)	First references
Lövnäs Lake	GCD v4.0.6	Sweden	66.31	17.90	Lake	9 500 – present	Carcaillet et al., 2007
Low Impact Area	Molinari et al., 2020	Sweden	66.62	17.82	Bog	2 170 - present	Josefsson et al., 2009
Makkassjön	Molinari et al., 2020	Sweden	66.68	20.58	Bog	10 200 – present	Korsman and Seegerström, 1998
Marrajegge	Molinari et al., 2020	Sweden	66.98	19.28	Bog	7 370 – present	Hörnberg et al., 1999
Munka	Molinari et al., 2020	Sweden	66.55	17.78	Bog	4 125 – present	Josefsson et al., 2009
Nicole Lake	GCD v4.0.6	Canada	62.90	-114.82	Lake	7 965 – present	Lynch et al., 2004
Ninisith Lake	GCD v4.0.6	Canada	59.58	-113.00	Lake	555 – present	Larsen et al., 2000
Northwest Lake	GCD v4.0.6	Canada	52.50	-94.00	Lake	8 700 – 25	Lynch et al., 2004
Notteryd	Original author	Sweden	56.91	14.88	Lake	11 000 – present	Cui, 2013
OK Lake	GCD v4.0.6	Canada	54.80	-95.25	Lake	3 140 – present	Lynch et al., 2004
Oops	GCD v4.0.6	Alaska	65.44	-147.63	Lake	6 410 – present	Finney and Krumhardt, 2004
Oppkuven	Molinari et al., 2020	Norway	60.08	10.52	Bog	5 500 – present	Ohlson and Tryterud, 1999
Paanajarvi Picea	Molinari et al., 2020	Finland/Russia Karelia	66.00	30.00	Bog	1 105 – present	Wallenius et al., 2005
Pas-de-Fond	GCD v4.0.6	Canada	48.81	-78.83	Lake	7 412 – present	Carcaillet et al., 2001
Petit Bouchard	GCD v4.0.6	Canada	48.85	-64.6	Lake	11 128 – 0	Carcaillet et al., 2006
Pieni-Kuuppalampi	Molinari et al., 2020	Finland/Russia Karelia	61.28	29.92	Lake	6 570 – present	Miettinen et al., 2002
Portage	GCD v4.0.6	Alaska	60.72	-150.53	Lake	1 280 – present	Lynch et al., 2003
Raigejegge	GCD v4.0.6	Sweden	66.16	18.21	Lake	7 500 – present	Carcaillet et al., 2007
Råshult	Molinari et al., 2020	Sweden	56.62	14.20	Bog	3 780 – 0	Lindbladh and Bradshaw, 1995
Rock	GCD v4.0.6	Alaska	60.42	-150.25	Lake	915 – present	Lynch et al., 2003
Scotty Lake	GCD v4.0.6	Canada	54.72	-101.68	Lake	8 110 – present	Lynch et al., 2004
Skallskog large	Molinari et al., 2020	Sweden	60.64	14.87	Bog	1 450 - present	Seegerström and Emanuelsson, 2002
Skallskog small	Molinari et al., 2020	Sweden	60.64	14.87	Bog	1 045 - 17	Seegerström and Emanuelsson, 2002
Skärsgölarna	Molinari et al., 2020	Sweden	57.02	16.12	Bog	7 465-present	Lindbladh et al., 2003
Sky Lake	GCD v4.0.6	Canada	56.48	-94.78	Lake	7 480 – present	Lynch et al., 2004
Small Lake	GCD v4.0.6	Canada	49.58	-90.39	Lake	9 840 – present	Senici et al., 2015
Stavsåkra	Molinari et al., 2020	Sweden	56.56	15.16	Bog	10 500 – 20	Olsson et al., 2010
Storasjö	Molinari et al., 2020	Sweden	57.01	14.48	Bog	11 000 – present	Olsson et al., 2010
Sundm	Molinari et al., 2020	Norway	70.70	23.60	Bog	6 580 – present	Jensen, 2004
Trettetjorn	Molinari et al., 2020	Norway	60.72	7.00	Lake	12 000 - present	Bjune et al., 2005
Twin Lake	GCD v4.0.6	Canada	50.94	-74.56	Lake	8 515 – present	Ali et al., 2012
Two Hill Lake	GCD v4.0.6	Canada	55.98	-97.28	Lake	930 – present	Lynch et al., 2004
Vatnan5	Molinari et al., 2020	Norway	70.53	22.90	Bog	5 900 – 0	Vorren, 2005
Vesijako	Molinari et al., 2020	Finland/Russia Karelia	61.35	25.10	Bog	5 440 – present	Clear, 2013
Vestre Oykjamyrtn	Molinari et al., 2020	Norway	59.82	6.00	Lake	11 000 – present	Bjune, 2005
Viherraisenneva	Molinari et al., 2020	Finland/Russia Karelia	61.25	24.23	Bog	10 305 – 100	Jauhainen et al., 2004
Wild Tussock	GCD v4.0.6	Alaska	67.13	-151.38	Lake	7 830 – present	Higuera et al., 2009

*GCD v.4.0.6: version 4.0.6 of the Global Charcoal Database compiled by the Global Palaeofire Working Group (<http://gpcwg.org>); Molinari et al. (2020). Fire-vegetation interactions during the last 11,000 years in boreal and cold temperate forests of Fennoscandia. *Quaternary Sci. Rev.* 241, 106408.

re-sampled 1000 times with a moving window procedure using non-overlapping bins of 1-yr. Re-sampled time series were then smoothed using a LOcally WEighted regression Scatterplot Smoother (LOWESS) with a window half-width of 10 years. Charcoal composite series mean and 97.5% confidence intervals (hereafter CI) were calculated by averaging the smoothed and bootstrapped data series (Daniau et al., 2012). For each sub-area taken into consideration, composite curves were finally produced with the method implemented in

the R (R Core Team, 2016) package “paleofire” version 1.2.4 (Blarquez et al., 2014).

LPJ-GUESS-SIMFIRE-BLAZE Fire Model Description

We used the LPJ-GUESS-SIMFIRE-BLAZE model to perform a transient simulation over the last century of vegetation and fire dynamics as influenced by changes in climate, land use and

population density. Here, the empirical fire model SIMFIRE (SIMple FIREmodel, Knorr et al., 2014) produces an annual burned area for each grid-cell ($0.5^\circ \times 0.5^\circ$) containing a charcoal record based on fire weather, fuel continuity, fire-biome and human population density. Using a monthly fire climatology, daily values of burned area (as fraction of grid-cell) are computed and used as a fire probability for the combustion model BLAZE (Blaze-Induced Land-Atmosphere Flux Estimator, Rabin et al., 2017). In LPJ-GUESS (Smith et al., 2001, 2014) natural vegetation is represented by a multitude of patches with different “time since last disturbance” to account for cohorts of different age and height. Each patch is tested against the aforementioned fire probability on a daily basis. In case of a successful ignition, the whole patch is affected by fire and BLAZE simulates fire driven fluxes within the biosphere (live to litter) and from the biosphere to the atmosphere. The combustion model computes survival-probabilities for stands of trees based on vegetation properties (like height or diameter-at-breast-height, DBH) and potential fire-line intensity [based on a revised set of FullCAM parameters following Surawski et al. (2012)] derived from available fuels and local meteorology. In the event of a fire, the stochastic survival of each tree is tested individually. Total carbon fluxes (the total amount of C emitted by fire to the atmosphere) are then computed from the amount of tree-deaths and as fractions of above-ground litter combusted based on the fire-line intensity. SIMFIRE-BLAZE incorporates the HYDE 3.1 population density dataset (Klein Goldewijk et al., 2011) within LPJ-GUESS.

Patterns and annual cycles of burned area and carbon emissions within the range of satellite-based observations have been previously demonstrated by Kloster et al. (2004) to be reasonably simulated by the Arora and Boer (2005) fire model implemented in the Community Land Model (CLM-CM).

Comparison Between Model Outputs and Charcoal Data

For each grid-cell containing a charcoal record, the probability to burn per year (fraction year⁻¹, hereafter fire probability F_p) and the total carbon flux emitted to the atmosphere per year (kg C m⁻² year⁻¹, hereafter carbon emitted C_e) simulated by LPJ-GUESS-SIMFIRE-BLAZE during the period 1900–2000 CE were treated analogously to sedimentary charcoal data in order to estimate regional and continental fire activity. To reduce the high year-to-year variability, a 10-yr running mean filter was applied before the Z-scores were derived. This same data processing minimized inconsistencies in the statistical analysis and maximize comparability between the different datasets. In this way, discrepancies in the data-model comparison can only be explained by model deficiencies.

In order to evaluate the agreement between reconstructed and modeled fire dynamics in boreal forests since the beginning of the 20th century, we calculated the Spearman's rank correlation coefficient (Spearman, 1904) between Z-scores of transformed charcoal influxes (hereafter tCHAR Z-scores) and Z-scores of transformed model output of fire probability (hereafter tFp Z-scores) or carbon emitted (hereafter tCe Z-scores) for the boreal forests as well as for each region and continent. The

Spearman correlation measures the strength of the monotonic relation between two variables, is robust to the presence of outliers, especially when there is sufficient sample size, and is applicable for any continuous or ordinal scale (Sheskin, 2007). The statistical analyses were run for the whole time period taken into consideration (1900–2000 CE), as well as for the two different sub-periods (1900–1950 CE and 1950–2000 CE).

RESULTS

Observed Boreal Forest Fire Dynamics

Reconstructions of fire activity across the boreal forests based on sedimentary charcoal records during the period 1900–2000 CE show different trajectories (Figure 2 and Table 2).

In Alaska (Figure 2A), despite a downturn between 1910 and 1920 CE, a general increasing trend is recorded until 1980 CE. Then tCHAR Z-scores progressively decrease, with only a slight increase between 1998 and 2000 CE. In Canada (Figure 2B), charcoal values show a decrease during the period 1900–1955 CE, while two peaks (followed by downturns) are registered around 1965 and 1985 CE. An increase is recorded between 1998 and 2000 CE. The charcoal composite curves for North America (Figure 2F) and for the whole boreal forests (Figure 2H) record values around the long-term mean between 1900 and 1990 CE. A decreasing trend characterize the following years, with a little increase between 1998 and 2000 CE.

Despite large uncertainties, tCHAR Z-scores for Norway (Figure 2C) show a decreasing trend during the first half of the 20th century, increasing values between 1950 and 1985 CE and a decrease at the end of the century. Sweden (Figure 2D) and Fennoscandia (Figure 2G) document decreasing charcoal trends between 1900 and 1930 CE. Increasing values are recorded during the period 1930–1960 CE, followed by a decrease with a minimum at 2000 CE. After increasing values at the beginning of the century, Finland/Russia Karelia (Figure 2E) registers a general decreasing trend between 1905 and ca 1930 CE. Increasing charcoal values are recorded until 1990 CE, followed by a decrease.

Simulated Boreal Forests Fire Dynamics

Changes in tFp and in tCe Z-scores simulated by LPJ-GUESS-SIMFIRE-BLAZE during the period 1900–2000 CE show a general progressive rise toward the end of the 20th century for all the areas taken into consideration (Figure 2 and Table 2). Large oscillations occur as a direct consequence of climatic drivers.

Comparison Between Observed and Simulated Boreal Forests Fire Dynamics

Observed and modeled boreal forest fire activity since the beginning of the 20th century are compared by investigating trends in tCHAR, tFp and tCe Z-scores transformed time series (Table 2). For the whole time period taken into consideration (1900–2000 CE) as well as for the two different sub-periods (1900–1950 CE, 1950–2000 CE), the Spearman rank correlation coefficient (Spearman, 1904) is also calculated.

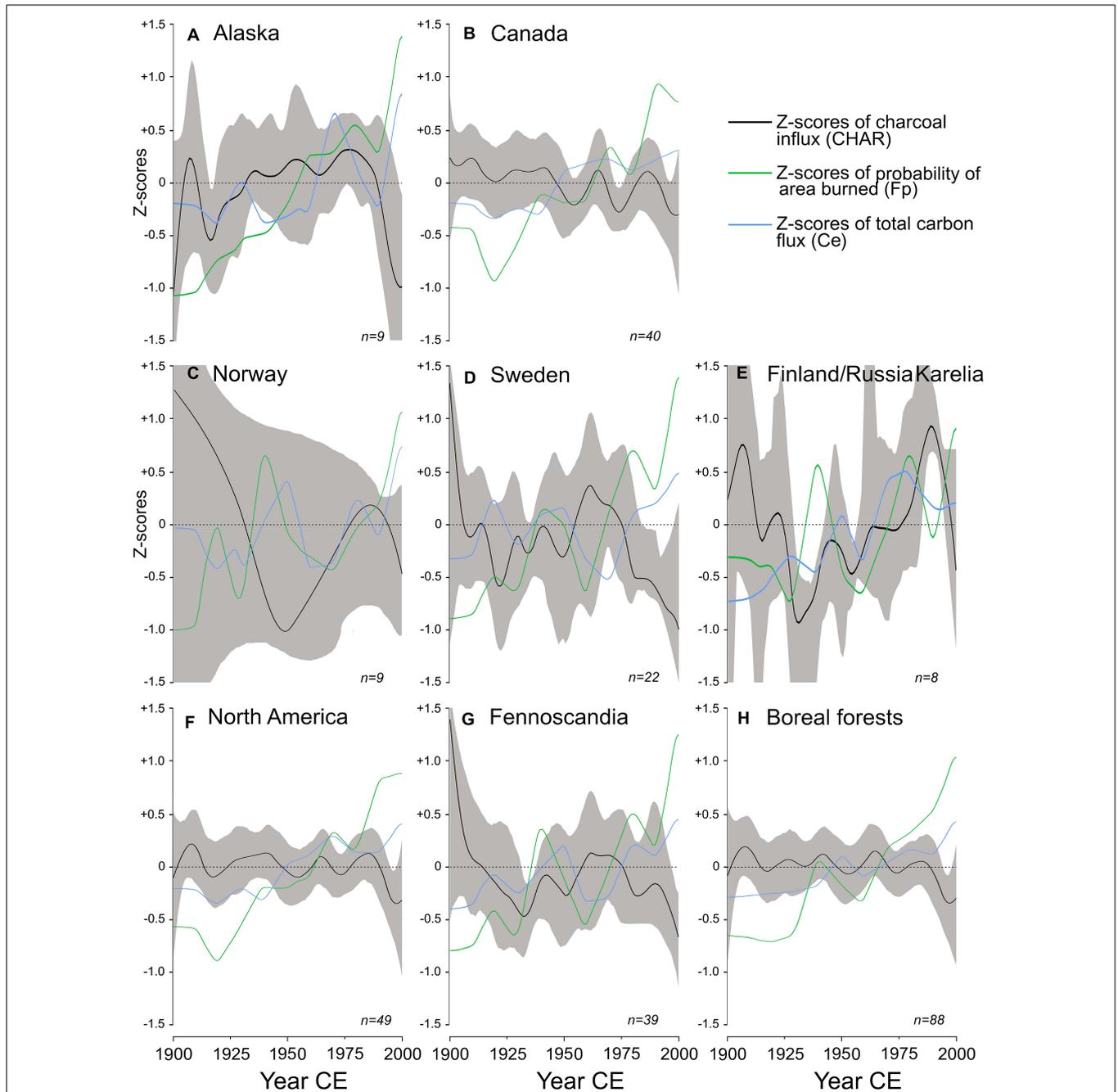


FIGURE 2 | Reconstructed charcoal-based and modeled (probability of annual area burned and total carbon flux emitted per year) boreal forests fire dynamics for the 20th century for **(A)** Alaska, **(B)** Canada, **(C)** Norway, **(D)** Sweden, **(E)** Finland/Russia Karelia, **(F)** North America, **(G)** Fennoscandia, and **(H)** boreal forests, with the number of site contributing to the analysis for each sub-area. The composite curves have been smoothed using a 10-year window half width. Bootstrap 97.5% CI from resampling by charcoal records are shown as gray shadings.

In Alaska, based on 9 sites, an increasing trend in tCHAR (not-significant), tFp and tCe Z-scores is recorded when the whole 20th century is considered and, only in tCHAR and tFp, during the time interval 1900-1950 CE. These results are confirmed by the statistical analyses, indicating positive correlations (only significant among tCHAR and tFp, **Table 3**) for these time

periods. Instead, during the second half of the 20th century the correlation between observations (decreasing) and simulations (increasing) is negative (**Tables 2, 3**).

For what concerns North America, on a total of 49 sites, an agreement between the different trends (all increasing but significant only for tFp) is recorded during the time interval

TABLE 2 | Trends of fire activity in boreal forests for the 20th century expressed by mean (standard deviation, sd) Z-score of transformed charcoal influx (tCHAR), mean (standard deviation, sd) Z-score of transformed fire probability (tFp) and mean (standard deviation, sd) Z-score of carbon emitted (tCe).

Region/continent	Variable	Time period (year CE)			
		1900–2000	1900–1950	1950–2000	
Alaska	tCHAR	trend	increasing	increasing	decreasing
		p -value [R ²]	0.421 [0.007]	<< 0.001 [0.300]	<< 0.001 [0.445]
		mean (sd)	−0.05 (+ 0.34)	−0.11 (+ 0.28)	+ 0.02 (+ 0.38)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.950]	< <0.001 [0.979]	<< 0.001 [0.686]
		mean (sd)	−0.13 (+ 0.63)	−0.69 (+ 0.27)	+ 0.40 (+ 0.34)
	tCe	trend	increasing	decreasing	increasing
		p -value [R ²]	< <0.001 [0.380]	0.064 [0.069]	0.001 [0.193]
		mean (sd)	−0.04 (+ 0.32)	−0.23 (+ 0.11)	+ 0.15 (+0.35)
Canada	tCHAR	trend	decreasing	decreasing	decreasing
		p -value [R ²]	<< 0.001 [0.445]	< <0.001 [0.353]	0.770 [0.002]
		mean (sd)	+ 0.01 (+ 0.15)	+ 0.11 (+ 0.08)	−0.09 (+ 0.14)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.791]	0.001 [0.195]	<< 0.001 [0.845]
		mean (sd)	−0.07 (+ 0.50)	−0.45 (+ 0.26)	+ 0.30 (+ 0.39)
	tCe	trend	increasing	increasing	increasing
		p -value [R ²]	< <0.001 [0.770]	0.029 [0.095]	< <0.001 [0.317]
		mean (sd)	−0.01 (+ 0.22)	−0.22 (+ 0.10)	+ 0.19 (+ 0.05)
North America	tCHAR	trend	decreasing	increasing	decreasing
		p -value [R ²]	<< 0.001 [0.184]	0.837 [0.001]	0.017 [0.112]
		mean (sd)	+ 0.01 (+ 0.12)	+ 0.06 (+ 0.09)	−0.04 (+ 0.13)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.890]	< <0.001 [0.440]	<< 0.001 [0.909]
		mean (sd)	−0.09 (+ 0.52)	−0.51 (+ 0.23)	+ 0.32 (+ 0.36)
	tCe	trend	increasing	increasing	increasing
		p -value [R ²]	< <0.001 [0.784]	0.073 [0.065]	< <0.001 [0.354]
		mean (sd)	−0.02 (+ 0.23)	−0.23 (+ 0.08)	+ 0.19 (+ 0.09)
Norway	tCHAR	trend	decreasing	decreasing	increasing
		p -value [R ²]	<< 0.001 [0.266]	<< 0.001 [0.978]	<< 0.001 [0.631]
		mean (sd)	−0.03 (+ 0.65)	+ 0.23 (+ 0.76)	−0.30 (+ 0.39)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.420]	< <0.001 [0.714]	<< 0.001 [0.659]
		mean (sd)	−0.17 (+ 0.52)	−0.33 (+ 0.58)	−0.02 (+ 0.40)
	tCe	trend	increasing	increasing	increasing
		p -value [R ²]	< <0.001 [0.151]	0.021 [0.106]	< <0.001 [0.297]
		mean (sd)	−0.06 (+ 0.28)	−0.11 (+ 0.23)	+ 0.004 (+ 0.31)
Sweden	tCHAR	trend	decreasing	decreasing	decreasing
		p -value [R ²]	<< 0.001 [0.228]	< 0.001 [0.246]	<< 0.001 [0.708]
		mean (sd)	−0.16 (+ 0.39)	−0.10 (+ 0.36)	−0.23 (+ 0.41)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.790]	< <0.001 [0.890]	<< 0.001 [0.791]
		mean (sd)	−0.10 (+ 0.58)	−0.46 (+ 0.37)	+ 0.25 (+ 0.53)
	tCe	trend	increasing	increasing	increasing
		p -value [R ²]	< 0.001 [0.137]	<<0.001 [0.487]	< <0.001 [0.513]
		mean (sd)	−0.06 (+ 0.26)	−0.06 (+ 0.20)	−0.04 (+ 0.30)
Finland/Russia Karelia	tCHAR	trend	increasing	decreasing	increasing
		p -value [R ²]	0.060 [0.035]	<< 0.001 [0.491]	<< 0.001 [0.489]
		mean (sd)	−0.01 (+ 0.46)	−0.13 (+ 0.49)	+ 0.10 (+ 0.42)
	tFp	trend	increasing	increasing	increasing
		p -value [R ²]	<< 0.001 [0.336]	< 0.001 [0.249]	<< 0.001 [0.651]
		mean (sd)	−0.10 (+ 0.43)	−0.23 (+ 0.35)	+ 0.02 (+ 0.47)
	tCe	trend	increasing	increasing	increasing
		p -value [R ²]	< <0.001 [0.816]	<<0.001 [0.846]	< 0.001 [0.245]
		mean (sd)	−0.14 (+ 0.38)	−0.45 (+ 0.21)	+ 0.16 (+ 0.24)

(Continued)

TABLE 2 | Continued

Region/continent	Variable		Time period (year CE)		
			1900–2000	1900–1950	1950–2000
Fennoscandia	tCHAR	trend	decreasing	decreasing	decreasing
		p -value [R^2] mean (sd)	<< 0.001 [0.188] –0.08 (+ 0.32)	<< 0.001 [0.474] –0.04 (+ 0.40)	<< 0.001 [0.387] –0.13 (+ 0.20)
	tFp	trend	increasing	increasing	increasing
		p -value [R^2] mean (sd)	<< 0.001 [0.692] –0.11 (+ 0.51)	< 0.001 [0.767] –0.38 (+ 0.39)	<< 0.001 [0.808] + 0.14 (+ 0.47)
	tCe	trend	increasing	increasing	increasing
		p -value [R^2] mean (sd)	< 0.001 [0.493] –0.07 (+ 0.23)	<< 0.001 [0.798] –0.16 (+ 0.18)	< 0.001 [0.542] + 0.01 (+ 0.24)
Boreal forests	tCHAR	trend	decreasing	decreasing	decreasing
		p -value [R^2] mean (sd)	<< 0.001 [0.300] + 0.01 (+ 0.11)	0.210 [0.032] + 0.06 (+ 0.06)	<< 0.001 [0.341] –0.03 (+ 0.13)
	tFp	trend	increasing	increasing	increasing
		p -value [R^2] mean (sd)	<< 0.001 [0.879] –0.10 (+ 0.49)	< 0.001 [0.707] –0.45 (+ 0.28)	<< 0.001 [0.954] + 0.24 (+ 0.39)
	tCe	trend	increasing	increasing	increasing
		p -value [R^2] mean (sd)	< 0.001 [0.891] –0.04 (+ 0.19)	<< 0.001 [0.683] –0.19 (+ 0.10)	< 0.001 [0.724] + 0.11 (+ 0.12)

Significant ($p < 0.05$) increasing trends have a red background while significant decreasing trends have a blue background.

1900–1950 CE (Table 2). The statistical analyses confirm these results, showing a positive correlation (only significant among tCHAR and tFp) for charcoal data and model outputs during this period (Table 3). On the contrary, observations decrease and simulations increase between 1900 and 2000 CE and for the second half of the 20th century (Table 2), with a negative correlation between the variables (Table 3).

In Canada (40 sites), Sweden (22 sites), Fennoscandia (39 sites) and for the whole boreal forests (88 sites) observations (increasing, but non-significantly for Canada between 1950 and 2000 CE and for the whole boreal forests between 1900 and 1950 CE) and simulations (decreasing) follow opposite trends during the 20th century as well as for the two distinct periods (Table 2). Despite that, in Canada a positive non-significant correlation exists among tCHAR and tFp and tCe during the first half of the 20th century (Table 3), while in the whole boreal forests a positive non-significant correlation is registered between tCHAR and tFp for the period 1900–1950 CE.

In Norway, based on 9 sites, tCHAR, tFp, and tCe record an increasing trend during the second half of the 20th century. These results are confirmed by the statistical results, showing a positive relationship between the variables (only significant between tCHAR and tFp, Table 3). Instead, during the two different time intervals the correlations among observations (decreasing) and simulations (increasing) are negative (Tables 2, 3).

For Finland/Russia Karelia, based on 8 sites, observed and modeled data show an analogous (increasing, non-significantly for tCHAR between 1900 and 2000 CE) trend when the whole 20th century and during the second half of the 20th century (Table 2). This is in agreement with the Spearman rank correlation analyses indicating positive correlations (non-significant for tCHAR-tCe between 1900 and 2000 CE) among the variables during these periods (Table 3).

DISCUSSION

Uncertainties in Observed Fire Dynamics

Granted all simplifications, generalizations and uncertainties in LPJ-GUESS-SIMFIRE-BLAZE structure, processes and input data (Hamilton et al., 2018), the use of sedimentary charcoal data to evaluate fire model simulations requires a careful consideration of the uncertainties connected to palaeofire data. In fact, even if time series of sedimentary charcoal abundance have become a widely used tool for reconstructing long-term trends in biomass burning (Whitlock and Bartlein, 2004), interpretation rests on understanding the source area of charcoal particles (i.e., the area burned and the distance to the site) and the ability to accurately infer other properties of the fire regime, such as frequency, intensity, and fuel type (Lynch et al., 2004). Constraining the charcoal source area is not a trivial task because charcoal abundance is influenced by vegetation, fire climate, and fire weather as well as site-specific processes related to charcoal deposition and burial (Clark, 1998). Despite advances in model-data integration (e.g. Higuera et al., 2007, 2011; Kelly et al., 2013) have helped validate charcoal-based fire reconstructions and identify uncertainties associated with natural (e.g., charcoal production, transport, and deposition) and analytical processes, reconstructing the area burned thus remains a challenge (Hennebelle et al., 2020). Furthermore, variability in the charcoal record comes from a variety of sources, including temporal variations in primary charcoal production, transport, and deposition; bioturbation and addition of secondary (remobilized) charcoal; differences in sampling, chemical treatment, and charcoal identification and quantification that can obscure the relationship between charcoal accumulation rates and fire (Iglesias et al., 2015). More specifically for our study, the uppermost sediments of the

TABLE 3 | Results of Spearman rank correlation analyses (*R*s) and significance level (*p*).

Region/continent	Correlations	Time period (year CE)					
		1900–2000		1900–1950		1950–2000	
		<i>R</i> s	<i>p</i>	<i>R</i> s	<i>p</i>	<i>R</i> s	<i>p</i>
Alaska	tCHAR-tFP	+ 0.33	< 0.001	+ 0.49	< 0.001	– 0.15	0.294
	tCHAR-tCe	+ 0.15	0.150	– 0.09	0.527	– 0.05	0.722
Canada	tCHAR-tFP	– 0.47	<< 0.001	+ 0.26	0.071	– 0.01	0.889
	tCHAR-tCe	– 0.55	<< 0.001	+ 0.27	0.065	– 0.07	0.612
North America	tCHAR-tFP	– 0.22	0.025	+ 0.45	< 0.001	– 0.12	0.382
	tCHAR-tCe	– 0.33	< 0.001	+ 0.19	0.174	– 0.26	0.069
Norway	tCHAR-tFP	– 0.48	<< 0.001	– 0.84	<< 0.001	+ 0.47	< 0.001
	tCHAR-tCe	– 0.22	0.027	– 0.25	0.075	+ 0.16	0.269
Sweden	tCHAR-tFP	– 0.53	<< 0.001	– 0.43	0.002	– 0.83	<< 0.001
	tCHAR-tCe	– 0.87	<< 0.001	– 0.60	<< 0.001	– 0.95	<< 0.001
Finland/Russia Karelia	tCHAR-tFP	+ 0.22	0.026	– 0.20	0.162	+ 0.50	< 0.001
	tCHAR-tCe	+ 0.10	0.326	– 0.70	<< 0.001	+ 0.40	0.003
Fennoscandia	tCHAR-tFP	– 0.45	<< 0.001	– 0.50	<< 0.001	– 0.70	<< 0.001
	tCHAR-tCe	– 0.67	<< 0.001	– 0.41	0.003	– 0.95	<< 0.001
Boreal forests	tCHAR-tFP	– 0.33	< 0.001	+ 0.24	0.098	– 0.42	0.002
	tCHAR-tCe	– 0.50	<< 0.001	– 0.12	0.395	– 0.56	< 0.001

Shown are the values of the correlations between Z-scores of transformed charcoal influxes (tCHAR) and Z-scores of transformed model outputs of fire probability (tFp) or carbon emitted (tCe) for each continent/region taken into consideration. Significant ($p < 0.05$) positive values are highlighted in green, while not-significant ($p > 0.05$) positive values are in black. Significant negative values are highlighted in yellow, while not-significant negative values are in gray.

charcoal records might be less tightly constrained due to: (1) the difficulty to fully recover sediment/water interface during coring, (2) the high water content which tend to lower charcoal concentrations, and (3) the potential impact of human activities on catchment processes and sedimentation (Gale, 2009). Despite the recent development of Bayesian age-models (Blaauw et al., 2020), uncertainties in charcoal records can also be associated with a poor chronological control for recent times (where most of the dating are based on radiocarbon results) and to the different processes of charcoal production, transportation and deposition in the catchments, partially solved by field experiments that enable a better understanding of charcoal accumulation through time (Higuera et al., 2007; Hennebelle et al., 2020). Although charcoal is a proxy of carbon released by biomass burning, sedimentary-based reconstructions are currently insufficient for providing quantitative estimates of carbon released by fires because the links between stratigraphic charcoal and gaseous carbon fluxes are difficult to assess (Carcaillet et al., 2002). In boreal forests carbon release comes primarily from the ground layer (woody debris, humus, peat), which is more susceptible to becoming completely consumed than is the aboveground biomass (Kasischke et al., 2000). Finally, our analyses are based on charcoal records primarily collected from Canada (40 sites) and Sweden (22 sites), and this may have partly biased the results because some trends might be less robust than others.

Drivers of Observed and Simulated Fire Dynamics

The decline in fire activity over the 20th century shown by our charcoal-based reconstructions for most of the boreal

regions taken into consideration reiterate the results of previous palaeoecological studies at the global scale (Marlon et al., 2009a), in Australia (Mooney et al., 2011), in Europe (Molinari et al., 2013) and in the Americas (Power et al., 2013). A number of causes have been suggested for this downturn, including: (1) land-use change, resulting in landscape fragmentation and a generally less flammable fuel (Pyne and World, 1995), (2) active fire suppression management policies (Granström and Niklasson, 2008; Marlon et al., 2009a), and (3) an economic and cultural transition from traditional fire practices (such as slash-and-burn cultivation) to modern agriculture and forestry activities, especially in Fennoscandia (Wallenius, 2011). On the contrary, the increase in fire probability and, thus, in carbon emitted simulated by LPJ-GUESS-SIMFIRE-BLAZE are the result of the factors which determine the probability of a grid-cell to burn per year, such as: (1) the shift of many grid-cells taken into consideration from tundra to boreal fire-biome with a different flammability due to a change in CO₂-fertilization and climate (rise in both total annual precipitation and temperature), leading to an increase in the maximum annual fAPAR (fraction of Absorbed Photosynthetically Active Radiation, a proxy for the amount of vegetation growing in a grid-cell), and (2) a rise in the maximum annual Nesterov index, which is a proxy for fire-weather conditions and the curing of fuels. Both these factors lead to higher amounts of fuels and more fire-promoting weather conditions with a consequent increase of fire occurrence. So, when looking only into climatic drivers, an increase in boreal forest fires is expected under present and future climate change (Flannigan et al., 2005, 2009a; Ali et al., 2009). This is probably the reason of the agreement between trends in sedimentary charcoal data and

model outputs during the 20th century in Alaska, a region where fire activity was mainly driven by warm temperatures and vegetation flammability (Hoecker and Higuera, 2019). The good correlation between observations and simulations detected in Finland/Russia Karelia is instead probably due to reworking of charcoal particles in the uppermost levels of the sequences due to ditching and clearcutting in the forests (Pitkänen and Huttunen, 1999).

Reasons for Data-Model Divergence

The influence of anthropogenic factors (e.g., fire suppression, forest management and ignition control) on boreal fires dynamics is likely to be the main cause of the data-model disagreement. In Canada, the decrease in charcoal-based reconstructions during the first half of the 20th century is mainly the result of forest management (Bergeron et al., 2001). For the same period, a gradual abandonment of slash-and-burn cultivations in Norway and Finland/Russia Karelia (Lehtonen and Kolström, 2000; Rolstad et al., 2017), and of an early use of fire management practices in Sweden (Zackrisson, 1977; Granström and Niklasson, 2008) resulted in a similar decrease in these regions. The good correspondence between fire dynamics observations and simulations in Alaska and in North America is instead connected to a rise in wildfire extent due to an earlier impact of climate warming in these northern latitude areas (Chapin et al., 2008; Kelly et al., 2016). Regarding the second half of the 20th century, the negative correlation between sedimentary charcoal trends and model projections recorded in Alaska and Canada is primarily related to the high efficiency of active fire suppression policies thanks to increased landscape fragmentation (Weir et al., 2000; Kasischke et al., 2010). For Canada this is in contrast with the data included in the Large Fire Database (LFDB, which includes information on fires larger than 200 ha in area) indicating, as suggested by LPJ-GUESS-SIMFIRE-BLAZE outputs, a general increase in area burned during the period 1959–1997 CE (Stocks et al., 2003). Discrepancies between charcoal-based reconstructions and simulations are also registered in Sweden, where the decline in forest fires is linked to both active fire suppression (Niklasson and Granstrom, 2000) and climate variations [particularly water availability as suggested by Drobyshev et al. (2012)]. Norway and Finland/Russia Karelia are the only sub-areas where both observations and model projections register an increase probably connected to a comeback of prescribed burning practices for biodiversity goals (Bleken et al., 1997; Lindberg et al., 2000) or to sediment remixing at the top of the sequences due to forest management (Pitkänen and Huttunen, 1999).

Implications for Future Data-Model Improvements

As in most fire models (Hantson et al., 2016), the only anthropogenic driver mediating fire probability (and thus carbon emitted) in LPJ-GUESS-SIMFIRE-BLAZE is human population density which, in the high latitudes investigated by the present study, is at very low levels and its general mild increase toward the

end of the century is outcompeted by the climatic drivers which promote a rise in fire probability. However, even under these low population densities, people can have large-scaled impacts on fire occurrence as indicated in the previous subsection. Detailed representation of forest management (and the associated stand structure) and landscape fragmentation (and their absence in the past) should be taken into account in high-latitudes fire-simulations for a better representation of the human impact on fire regime. Furthermore, a more detailed simulation of fires in the boreal vegetation, especially peatland and shrubs, with a special focus on soils, is needed to more accurately represent fires in these regions. The same goes for the representation of fire and forest management (e.g., fire prevention, prescription). While, in fact, the impact of such factors on the global scale is probably small, it is clear that in practise these can override the predominant climate signal currently simulated by LPJ-GUESS-SIMFIRE-BLAZE on a regional scale.

This study further indicates the need for additional sampling and high-resolution analyses of charcoal records from areas inadequately represented by the present dataset and covering the more recent years (i.e., the beginning of the 21st century). Due to the low number of charcoal records available for the last 20 years, it was in fact impossible to perform the statistical analyses beyond the end of the 20th century. Despite that, the rise in both charcoal-based reconstructions and model outputs at the end of the study period in Alaska, Canada, North America and for the whole boreal forests (**Figures 2A,B,E,H**) make us assuming increasing trends until the present time as already suggested by Turetsky et al. (2011), Sanford et al. (2015), and Tymstra et al. (2020). On the contrary, the decline in charcoal-based reconstructions register in Fennoscandia (**Figures 2C–E,G**), probably connected to the effectiveness of fire suppression policies in the modern forests to support a growing timber industry that makes large fire events rare in these regions (Pinto et al., 2020), is in contrast with an increasing fire risk in these areas raised by the outbreak of exceptionally large fires in Sweden in recent years, and especially during summers 2014 and 2018 (San-Miguel-Ayanz et al., 2019). A better understanding of the spatio-temporal variability of fire activity is thus needed in order to maximize the possibility of data-model comparison and better evaluate the ability of ecosystem models to more realistically simulate future biomass burning.

CONCLUSION

Our results show how palaeofire proxies can be used to evaluate fire projections made by global fire-vegetation models. A general disagreement is highlighted for the boreal region, where LPJ-GUESS-SIMFIRE-BLAZE simulates an increasing and sedimentary charcoal records a decreasing in fire activity over the 20th century. The present study demonstrates that socio-economical drivers of human behavior and forest management can override broad climate patterns, at least in these areas. Therefore, past and future projections in fire occurrence are still very uncertain and should take into account the specifics of

the region (e.g., peatlands) and its particular vegetation. Additional improvements about these processes that are not yet completely understood are essential to better understand the complex interactions between climate, meteorology, vegetation, humans and fire. This enhanced understanding necessitates a closer collaboration between palaeoecologists and modelers.

DATA AVAILABILITY STATEMENT

Sedimentary charcoal data used in this analysis are either stored in the Global Charcoal Database (<http://gpwg.org>) and accessible through the paleofire package (Blarquez et al., 2014) for R (R Core Team, 2016) or are available upon request. Model output is available upon request.

AUTHOR CONTRIBUTIONS

CM conceived and designed the study, compiled and analyzed the charcoal data, made the figures, and drafted the manuscript. LN

and SH performed the model simulation, helped interpreting the results, and contributed drafting the manuscript. All authors read and approved the final manuscript.

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