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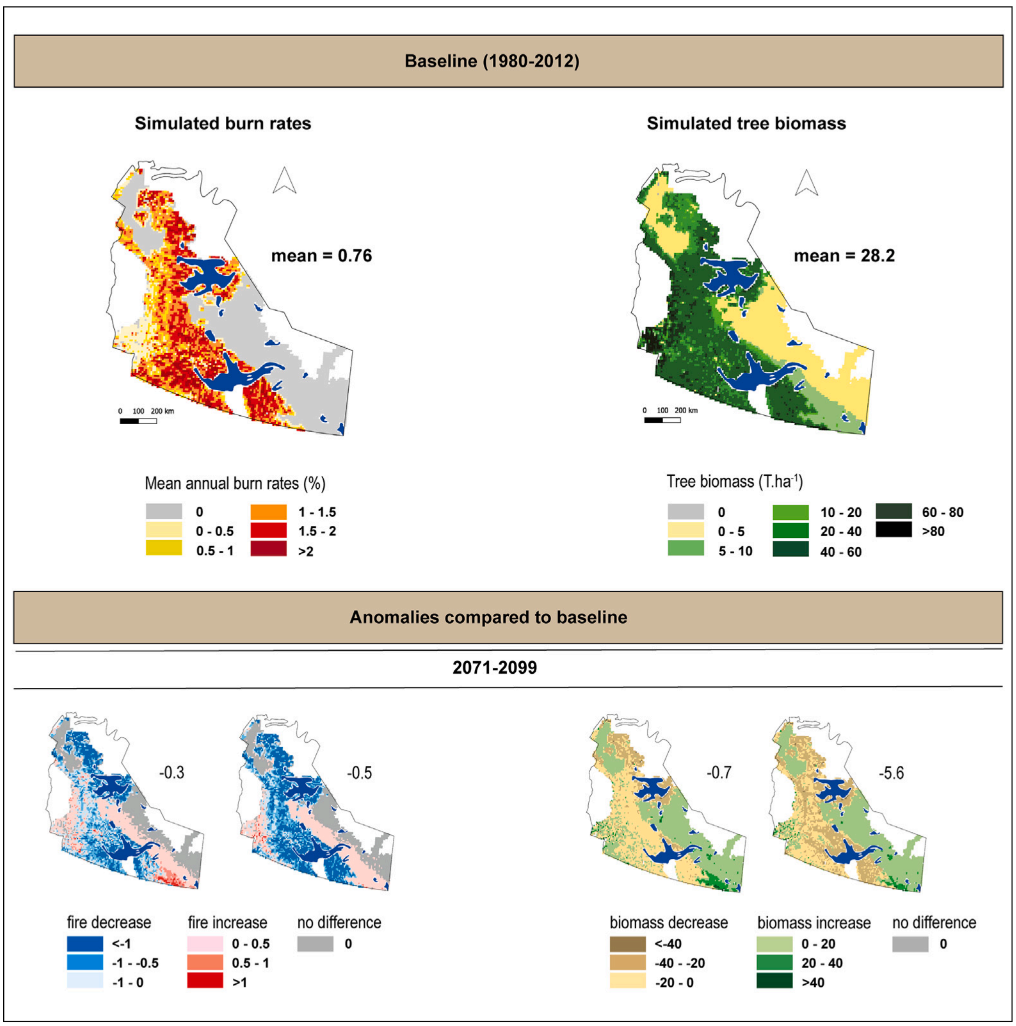

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dorian.gaboriau@uqat.ca

Highlights

Burn rates will decline during the 21st century in most of the NT

Tree composition and biomass will be limiting drivers of future burning

Burn rates will decline where black spruce biomass will decrease

Increased needleleaf biomass will enhance fire activity in southeastern NT

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Dorian M. Gaboriau,[1,2,9,*] Émeline Chaste,[3,4] Martin P. Girardin,[2,5] Hugo Asselin,[2,6] Adam A. Ali,[7] Yves Bergeron,[1,2] and Christelle Hély[7,8]

SUMMARY

Dry and warm conditions have exacerbated the occurrence of large and severe wildfires over the past decade in Canada's Northwest Territories (NT). Although temperatures are expected to increase during the 21st century, we lack understanding of how the climate-vegetation-fire nexus might respond. We used a dynamic global vegetation model to project annual burn rates, as well as tree species composition and biomass in the NT during the 21st century using the IPCC's climate scenarios. Burn rates will decrease in most of the NT by the mid-21st century, concomitant with biomass loss of fire-prone evergreen needleleaf tree species, and biomass increase of broadleaf tree species. The southeastern NT is projected to experience enhanced fire activity by the late 21st century according to scenario RCP4.5, supported by a higher production of flammable evergreen needleleaf biomass. The results underlie the potential for major impacts of climate change on the NT's terrestrial ecosystems.

INTRODUCTION

Fires provide essential ecosystem functions in boreal forests by influencing tree regeneration, nutrient cycling, and climate regulation.[1,2] However, recent extreme weather events have contributed to increase the occurrence of large fires (>200 ha) over the past decade, especially in the northwestern North American boreal forest,[3] causing significant damage to forests and human infrastructures. Among several examples in boreal Canada, several million hectares burned in the Northwest Territories (NT) in 2014 during high temperatures, dry conditions and numerous lightning strikes.[4–6] Under similar meteorological conditions, more than 630,000 ha of forest burned near Fort McMurray in Alberta in 2016, which involved significant economic losses and damage to houses and mining infrastructures, despite unprecedented firefighting expenditures.[7,8] In 2017 and 2018, British Columbia experienced its worst fire seasons in at least 50 years, with over 1.2 million hectares burned in those two consecutive years.[9,10] In addition to their economic and social consequences, warming and large fires affect boreal forest health, productivity, and carbon stocks across the Northern Hemisphere.[1,11] Under such circumstances, it is crucial to understand the consequences of additional warming on fire activity, particularly on area burned, in the Canadian boreal forest.

As climate change is particularly intense and rapid at northern latitudes,[12,13] the dynamics of tree vegetation and natural disturbances in the boreal ecosystem are largely affected.[14–16] Climate models predict warmer temperatures and more frequent and/or severe droughts over the 21st century.[13,17] Projections are more uncertain for precipitation, but a 10–30% increase is likely in northwestern Canada by the end of the century.[12,18] Climate models also suggest that winters could be shorter and milder, with reduced depth and duration of the snow cover promoting vegetation drying earlier in the year and therefore a longer fire season.[19–21] Lightning strikes related to air mass convergence and atmospheric instability are also expected to occur more often and thus to promote fire ignition.[5,6,22–24] For all the above reasons, increases in the frequency of severe fires,[25,26] area burned,[15,16,27,28] and days of fire spread[29] can be anticipated for the coming century.

To fully understand how fire regimes might evolve in the future, it is necessary to consider the effects of climate change on tree vegetation, including fuel load and forest composition. However, research so far has overlooked how vegetation changes could modulate fire activity. Consequently, we lack understanding

[1]Institut de recherche sur les forêts, Université du Québec en Abitibi-Témiscamingue, 445 Boulevard de l'Université, Rouyn-Noranda, QCJ9X 5E4, Canada

[2]Centre for Forest Research, Université du Québec à Montréal, P.O. Box 8888, Stn. Centre-ville, Montréal, QCH3C 3P8, Canada

[3]Université de Lorraine, AgroParisTech, INRAE, SILVAE, 54000 Nancy, France

[4]Now at: CIRAD, UMR Eco&Sols, University Montpellier, CIRAD, INRAE, Institut Agro, IRD, Montpellier, France

[5]Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 rue du PEPS, P.O. Box 10380, Stn. Sainte-Foy, Québec, QCG1V 4C7, Canada

[6]École d'études autochtones, Université du Québec en Abitibi-Témiscamingue, 445 Boulevard de l'Université, Rouyn-Noranda, QCJ9X 5E4, Canada

[7]ISEM, University Montpellier, CNRS, IRD, EPHE, Montpellier, France

[8]École Pratique des Hautes Etudes, PSL University, Paris, France

[9]Lead contact

*Correspondence: dorian.gaboriau@uqat.ca

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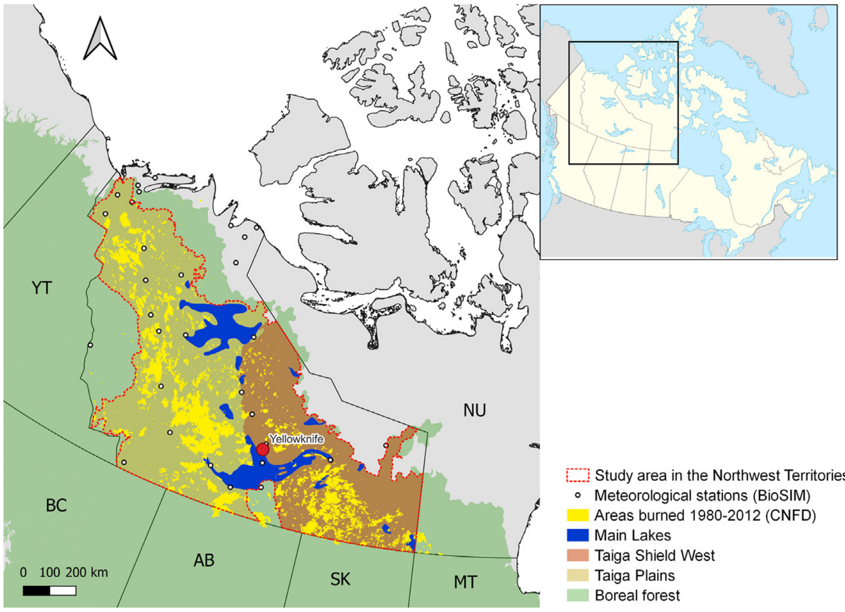

Figure 1. Location of the study area covering two ecoregions[52] in the boreal forest of the Northwest Territories (NT), Canada, as well as burned areas extracted from the Canadian National Fire Database for the 1980–2012 period

of how the climate-vegetation-fire nexus might respond to climate changes.[16,28] Interactions between climate conditions and vegetation characteristics determine the regime of natural disturbances because temperature and moisture conditions modulate tree growth,[30] as well as mortality rates and fuel loading.[31–33] Hence, a modification of the forest structure or composition might create negative feedbacks on wildfire activity.[34,35] For instance, broadleaf tree species, both better adapted to warmer temperatures and less flammable than needleleaf tree species,[36] could dampen the forcing effect of climate on wildfire regimes.[35,37] Long and severe droughts could hamper the growth of tree species vulnerable to water-stress, even causing their mortality, leading to open landscapes, limiting fire ignition and spread.[38,39] Although some studies included vegetation structure and composition as drivers of fire ignition and spread,[37,40] modeling frameworks often take the form of linear combinations of annual area burned over a given region with sets of predictors that can include seasonal means of daily drought severity and temperature.[15,41] Underestimating the interactions within the climate-vegetation-fire nexus, is oversimplistic and omits the effects of changing vegetation attributes on wildfire regimes,[42] and the effects of fires on vegetation structure or composition. This is particularly relevant in the boreal context, where short intervals between large fires increase the probability of dominance by pioneer and less fire-prone broadleaf tree species,[43,44] or even regeneration failure leading to landscape opening,[45–47] which may feedback negatively on fire activity. Mechanistic models, such as Dynamic Global Vegetation Models (hereafter DGVMs), include the climate-vegetation-fire nexus through main ecophysiological processes, therefore addressing some of the feedbacks between fire and climate but also fire and vegetation, which improves our representation of ecosystem functioning.[48,49] Fire modules within DGVMs more realistically simulate fire regimes and vegetation dynamics in response to climate change[34,50,51] than statistically generalized linear or non-linear models.

In this study, we performed temporal and spatial simulations of future fire activity and vegetation dynamics in the boreal forest of the Northwest Territories (hereafter NT), Canada (Figure 1), whereas accounting for climate change based on two IPCC radiative forcing scenarios (Representative Concentration Pathways 4.5 and 8.5; hereafter, RCP4.5 and RCP8.5). We used the LPJ-LMfire model to project annual burn rates and genus-specific vegetation attributes of the four main boreal tree genera (*Picea*, *Pinus*, *Abies* and *Populus*) from the mid-20th century to the late-21st century, using an ensemble of climate simulations driven by the two radiative forcing scenarios. Among the DGVMs, the LPJ-LMfire model includes processes that simulate natural wildfires independently of fire statistics observations,[53] e.g. fuel moisturizing and drying, fuel load increase, lightning-based ignition probability, fuel consumption, and wind-driven rate of spread. Hence,

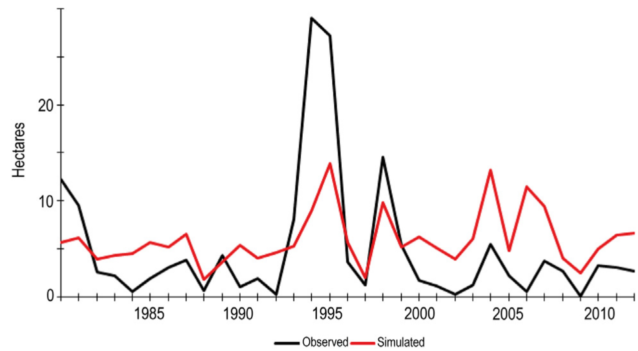

Figure 2. Observed (Canadian National Fire Database) and LPJ-LMfire-simulated annual area burned from 1980 to 2012 (validation phase) in the study area

LPJ-LMfire may be used to perform a comprehensive analysis of fire activity in a context of climate change for different time horizons.

Using the LPJ-LMfire model, this study provides evidence that burn rates will decrease overall by the end of the 21st century over most of the NT, despite some regional disparities. This unexpected result can be explained by decrease biomass of needleleaf tree species and, to a lesser extent, by an increase of less fire-prone broadleaf species across the landscape. In the meantime, increased *Picea* biomass in eastern NT will promote fire occurrence in regions that used to be rarely affected.

RESULTS

Predictive capabilities of the LPJ-LMfire model

From 1980 to 2012, 16.5 million hectares burned in the study area according to the Canadian National Fire Database (hereafter CNFD), while the LPJ-LMfire model simulated 17.4 million hectares burned during the same period. The interannual variation in areas burned was relatively well simulated by LPJ-LMfire, compared with observations (Figure 2; $r_s = 0.53$, $p = 0.001$). Large fire years (such as 1980, 1994, 1995 or 1998) were less well simulated by the model in terms of magnitude, especially because these events are generally related to sporadic short term and local scale extreme weather conditions, which are difficult to capture in areas with a low density of weather stations needed for computation of the historical climatological baseline. Spatially, the average annual burn rates observed within the CNFD and simulated by LPJ-LMfire were 0.52% and 0.69% per year, respectively, from 1980 to 2012 (Figure 3). The fire module overestimated fire activity in the northern and southwestern parts of the study area, while it underestimated fire activity in southeastern NT (Figure 3). Observed and simulated annual burn rates differed by less than 0.5% for half of the study area. As suggested by historical observations from 1980 to 2012 (Figure 1) and as shown in LPJ-LMfire simulations (Figure 3), the Taiga Plains ecoregion was more exposed to area burned than the Taiga Shield ecoregion.

The average tree biomass simulated by LPJ-LMfire in 2000 in the study area was 25.8 T ha^{-1}, similar to the 23.5 T ha^{-1} estimate of Global Forest Watch (hereafter GFW) for the same year (Figures 3 and S4 for the results at a 10-km resolution). The observed southwest-northeast gradient of tree biomass decline in the study area was reproduced by the model, but steeper. Tree biomass was underestimated in the Taiga Shield West and mostly overestimated in the Taiga Plains, suggesting more disparities at the sub-regional level (Figure 3).

Future trends in climate, fire activity and vegetation

As revealed by the two general circulation models (hereafter GCMs) and the two regional climate models (hereafter RCMs) that we used in LPJ-LMfire, mean annual temperatures in the NT are projected to increase by 5°C–9°C in 2070–2099, under RCPs 4.5 and 8.5 respectively, in comparison with the baseline period (1951–1980) (Figure S5). Future temperatures seem to reach a plateau in the late 21st century under the RCP4.5, whereas the temperature increase is constant under RCP8.5. Monthly mean rainfall is projected to increase by 2071–2099 for both climate scenarios, but more so for RCP8.5 (16 mm) in comparison with RCP4.5 (7 mm) (Figure S5). Annual burn rates simulated in the study area up to 2099 by LPJ-LMfire differ

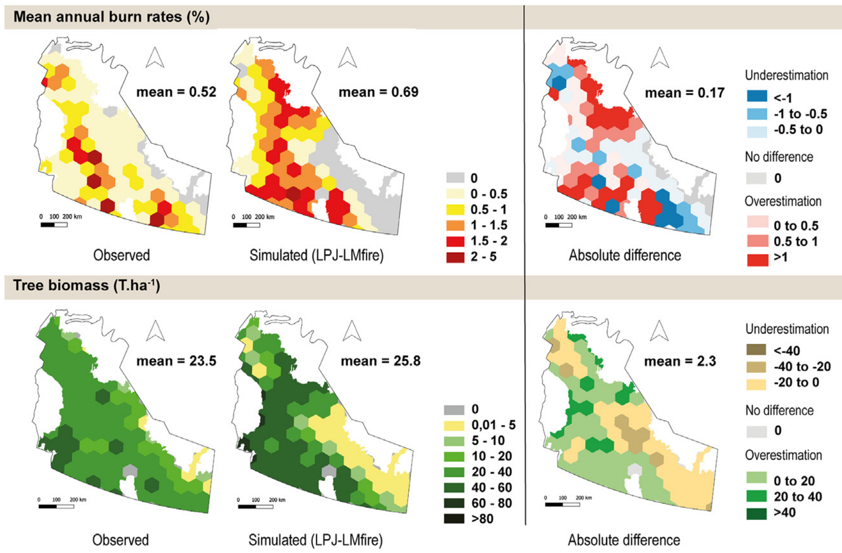

Figure 3. Observed and LPJ-LMfire-simulated mean annual burn rates from 1980 to 2012 (validation phase) and averaged tree biomass (T.ha^{-1}) in 2000 for the 116 cells covering the study area

Absolute differences between simulated and observed values are shown on the right panel.

among time horizons and NT sub-regions, as well as between climate change scenarios. Averaged over the whole study area and starting from a baseline of 0.69% yr^{-1} (1980–2012), annual burn rates are projected to decrease to 0.37% yr^{-1} by 2071–2099 under RCP4.5 and to 0.22% yr^{-1} under RCP8.5 (Figures 4 and S6 for projections at a 10-km resolution). The future decrease in wildfire activity is hence particularly accentuated under the warmest climate change scenario (RCP8.5). We note that spatial disparities characterize future annual burn rates, and that predicted changes in fire activity will not be uniform among NT sub-regions. Temporal series of annual burn rates simulated by LPJ-LMfire show that the decrease in burn rates will affect northwestern and southwestern NT by the mid-21st century (Figures 4 and 5). With the RCP8.5 scenario, burn rates could drop below 1% yr^{-1} in areas that experienced burn rates of up to 2% yr^{-1} during the 1980–2012 baseline period. The opposite trend is simulated by LPJ-LMfire in the southeastern part of the NT, where annual burn rates could be doubled by the end of the 21st century under RCP4.5, in comparison with the baseline period (Figures 4 and 5). In central NT, annual burn rates will be stable (RCP4.5) or will slightly decline (RCP8.5).

The overall mean tree biomass simulated by LPJ-LMfire within the study area will decrease from 25.8 T ha^{-1} during the baseline period to 17.6 T ha^{-1} and 17.3 T ha^{-1} by 2040, under RCP4.5 and RCP8.5, respectively (Figure 4). After that period, tree biomass will increase to reach 20 or 24 T ha^{-1} by the end of the century under RCP 4.5 and RCP8.5 respectively, but not reaching the levels observed during the 1980–2012 period (Figures 4 and S6).

As for annual burn rates, future changes in tree biomass will vary at the sub-region level. Northern and southwestern NT will present a 20–40 T ha^{-1} decrease during the 21st century from their 40–60 T ha^{-1} baseline biomass. Conversely, tree biomass will increase by 12 T ha^{-1} in average in eastern NT for both RCPs. Future tree biomass in the NT will also vary according to the four genera simulated by the model. *Picea*, *Populus* and *Pinus* PFTs will respond differently to future climate change in terms of biomass (Figures 5 and 6). The main changes will be in *Picea*, which currently dominates the landscape in the study area. *Picea* biomass will largely increase from 5 to 10 to 20 T ha^{-1} under RCP4.5 in the northern, central and southeastern parts of the study area. The RCP8.5 scenario shows similar trends but a less pronounced increase in *Picea* biomass over time and a stabilization during the last three decades of the 21st century. The biomass of *Picea* will even decrease by almost 10 T ha^{-1} in southwestern NT. The LPJ-LMfire model predicts that the *Populus* biomass might increase by 2–6 T ha^{-1} depending on NT sub-regions and RCPs. The *Populus* biomass will increase more under RCP8.5. *Pinus*, which currently occupies southwestern NT, is projected to undergo changes that are opposite those of *Picea* in many areas. The proportion of *Pinus* is expected to decrease in the southwest NT whereas it will increase from southeast to northwest. Hence,

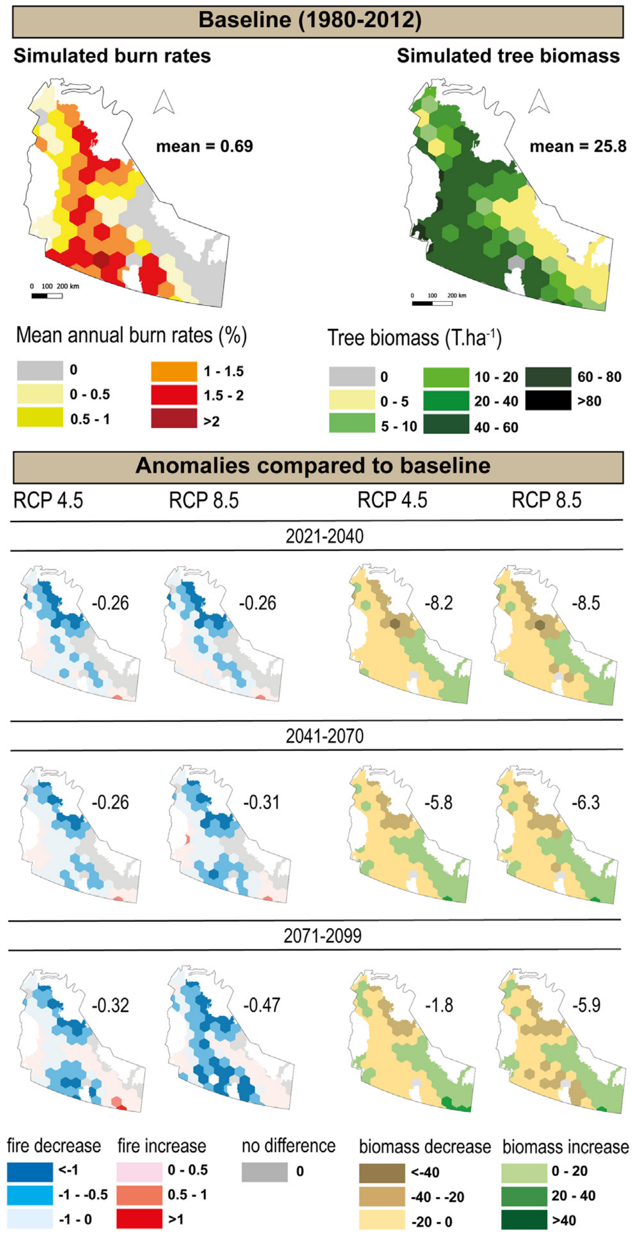

Figure 4. Anomalies in annual burn rates (in %; left panels) and tree biomass (T.ha^{-1}; right panels) over 2021–2040, 2041–2070, and 2071–2099 time horizons from climate scenarios RCP4.5 (average of model results from LPJ03, 09, 15) and RCP8.5 (average of model results from LPJ06, 12, 18)

For each of the 116 cells covering the study area, the anomaly for a given variable, time horizon and RCP scenario is the difference between LPJ-LMfire values simulated for that time horizon and RCP, and simulated for the baseline period (1980–2012).

Pinus will remain stable at the NT scale during the 21st century. As for *Abies*, which is currently present only sporadically in south-central NT, LPJ-LMfire simulates a minor increase of its presence throughout south-eastern NT.

DISCUSSION

Until recently, modeling frameworks of North American boreal forests disturbances have tended to overlook how changes in vegetation attributes could affect natural wildfire regimes under climate change.[54] Our results suggest that interactions within the climate-vegetation-fire nexus could play a critical role in

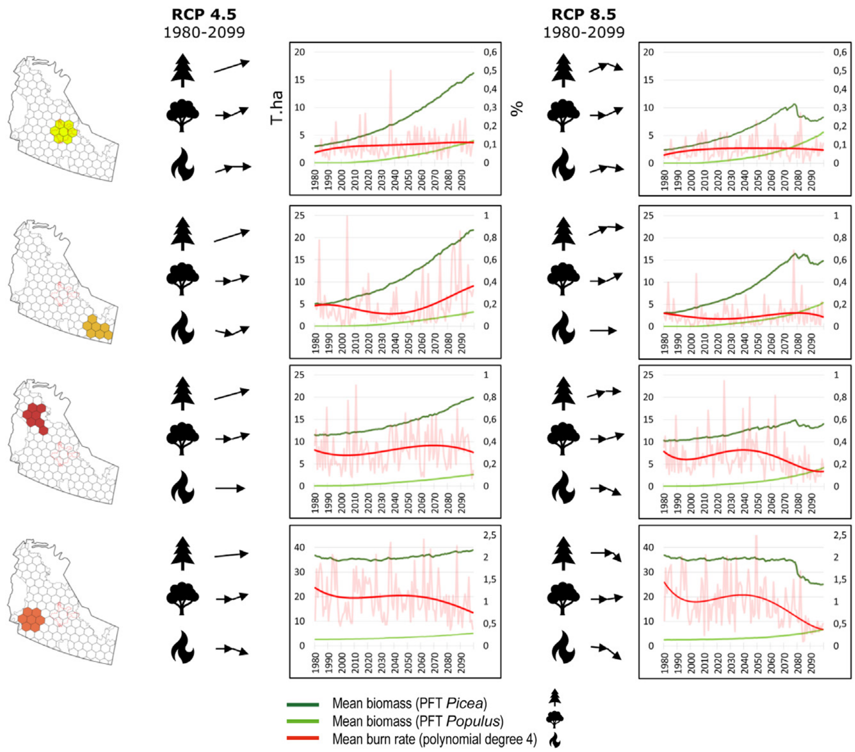

Figure 5. Sub-regional time-series (1980–2099) of LPJ-LMfire-simulated mean annual burn rates and tree biomass for *Picea* and *Populus* PFTs

From top to bottom, the areas represent the central, southeastern, northwestern, and southwestern parts of the Northwest Territories. Beyond the differences for a given sub-region between RCP4.5 and RCP8.5 scenarios, these time-series show the high variability that exists within the studied region and reveal an overall longitude trend.

reshaping NT's future boreal fire activity. The modeling experiment based on the LPJ-LMfire model suggests an overall decrease in annual burn rates during the 21st century in the NT, concomitant with lower tree biomass, especially under RCP8.5. Despite rising temperatures, changes in vegetation composition and structure might become a limiting driver of fire ignition and spread in the future (Figure 5). As such, the recent increase in burn rates observed during the last decades, could be only transitory.[4] This result contrasts with previous climate-only projections of fire activity, suggesting an increase in area burned and fire severity in northwestern Canada over similar temporal horizons.[16,25–27] The difference with our results may be explained by the modeling approach based on warming-induced changes and their effects on tree vegetation of various PFTs in the model, with consequences on future fire regimes. Although a decline of future burn rates is expected at the NT scale by the end of the 21st century, the southeastern part of the study area might actually experience an increase in fire activity, especially under RCP4.5, because of an increase in conifer biomass.

Climate forecasts clearly show that temperatures and precipitation will rise in the NT, with direct consequences for tree biomass, composition, and natural disturbances. The difference between RCP4.5 and RCP8.5 is the speed and intensity of the changes in climate conditions, which are faster and stronger in the more pessimistic RCP8.5 scenario. Based on bioclimatic parameters used as thresholds for the establishment of plant functional types, rising temperatures might be favorable to broadleaf tree species (PFT *Populus*) growth and expansion northward, regardless of the NT region and the climate change scenario.[55] Broadleaf tree species are known to grow faster than coniferous species under warmer conditions and this growth will likely be even faster if future conditions are both warmer and wetter.[55,56] These projections are in line with those of a recent study using the UVAFME individual tree-based forest model for boreal Alaska and western Canada.[37] They underlined that climate change will decrease tree biomass, especially for conifers, but increase the proportion of deciduous tree species in many boreal regions,[57] which in turn will limit fire occurrence and intensity, despite fuel drying. Conversely to broadleaf tree species, the

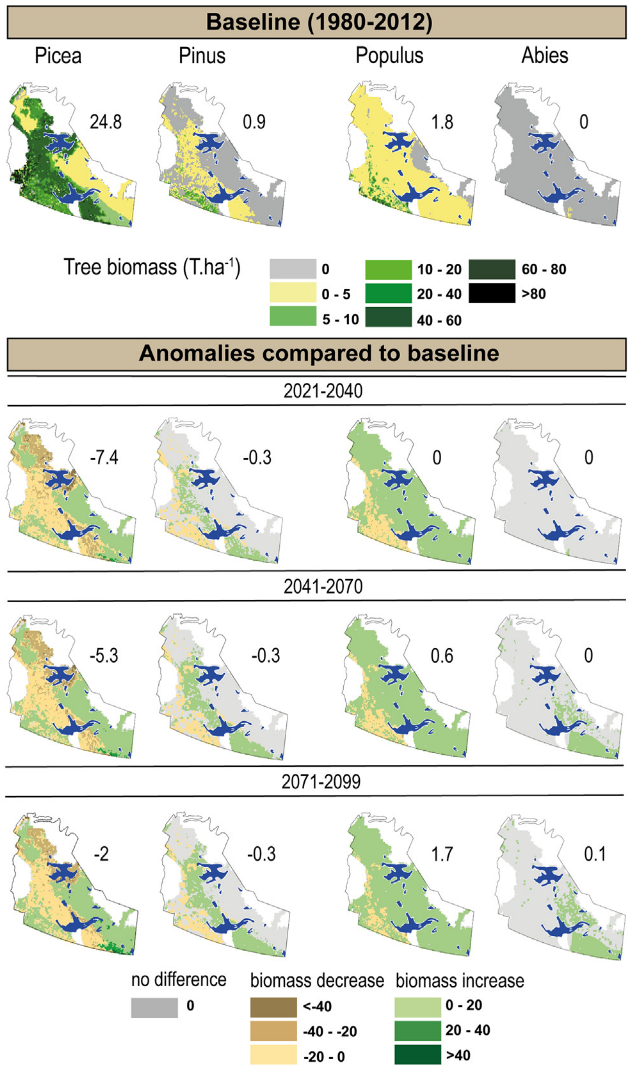

Figure 6. Tree biomass (T.ha^{-1}) simulated for the baseline period (1980–2012) for each plant functional type (*Picea*, *Populus*, *Pinus*, *Abies*) and predicted changes over 2021–2040, 2041–2070, and 2071–2099 time horizons for climate scenario RCP4.5 compared to the baseline period

Values represent absolute differences between the mean biomass of the simulated period and the baseline.

LPJ-LMfire model suggests a climate-induced decrease in *Picea*, especially by the end of the 21st century and under RCP8.5. Warmer temperatures at the end of the century could be a limiting factor for the expansion of *Picea*, this PFT stagnating or even decreasing in the southwestern part of the study area, but such decline is not simulated under RCP4.5. Hence, climate change could limit conifer tree productivity and cause vegetation dieback decreasing forest cover.[35,58] Under the higher emission scenario, the model suggests a decrease in burn rates by the end of the 21st century because of reductions of fuel load, mainly driven by a decrease in the percentage of *Picea* cover. These results are consistent with the multi-millennial climate-fire-vegetation histories inferred from recent palaeoecological reconstructions in central NT.[59] High biomass burning by large wildfires occurred during the Holocene Thermal Maximum (HTM; ca. 7000-5000 years ago) when the landscape was characterized by high fuel abundance, especially of fire-prone spruce.[59,60] In contrast, palaeoecological proxies revealed that after 4000 years cal. BP, a decline in fire size and/or severity as well as biomass burned was recorded, in relation with lower fuel abundance and increased proportion of broadleaf tree species in the landscape. The projections obtained from the LPJ-LMfire model highlight the importance of simultaneously considering changes in climate conditions and tree vegetation (composition and biomass) in modeling studies of future burn rates in boreal ecosystems. Using DGVMs to simulate the full system response (vegetation-fire-climate nexus) is essential to appropriately apprehend future fire regimes within the boreal forest ecosystem. The LPJ-LMfire model was able to account for the interactions between climate, vegetation, and fire dynamics, and thus provide more accurate projections than models based exclusively on climate.

Limitation to the study

Although highlighting new insights on future fire activity in the NT, we recognize some limitations of our approach associated with the available datasets and the current version of LPJ-LMfire. Indeed, LPJ-LMfire simulations of mean annual burn rates and tree biomass are representative of observed data at the scale of the NT boreal forest for the period 1980–2012, despite disparities within regions in the study area. The sampling dataset used to estimate tree biomass (i.e., observed data) is often less accurate at high latitudes where data are scarcer.[61,62] A previous study, reporting vegetation structure in terms of basal area instead of biomass,[37] also under- or overpredicted total basal area in the Taiga Shield West and Taiga Plains ecoregions. Our underestimation of tree biomass in some areas, such as in eastern NT, may alternatively stem from the absence of some PFTs, such as *Betula*, in the LPJ-LMfire model. As birch abundance is currently quite low in the NT, we used the generic broadleaf PFT that is closely related to aspen.[51] Comparisons between observed and simulated values show that although simulated burn rates and tree biomass are close to the observed values regionally, differences are more important at finer spatial scales, highlighting more difficulty to accurately predict tree biomass.

The lightning data required as input to the LPJ-LMfire model was considered as constant because previous results for eastern Canada have shown very similar results between constant and increasing flash simulations.[34] However, an increase in lightning strike flashes could be expected along with more precipitation, as previously suggested.[6,24] The LPJ-LMfire model showed limited ability to simulate the most extreme wildfire years historically observed in the NT[4] and archived in the CNFD (Figure 2). Indeed, because of their non-linear nature, extreme fire events are difficult to predict. It therefore seems necessary to improve the performance of the LPJ-LMfire model to simulate such events by expanding the time window of comparison between observed and simulated data and likely the performance of the weather generator embedded in LPJ-LMfire. Differences between observed and simulated extreme fire year events may also have been because of the spatial scale of analysis. In the LPJ-LMfire model, fire is a spatial process, but it does not involve neighboring pixels, which may underestimate large fire events, especially when simulations are performed over relatively small areas. Future DGVM versions should provide spatially explicit processes such as disturbances (e.g., fire and insect outbreaks) that could propagate over the entire grid surface. Models used to explore high latitude environments should also be coupled with permafrost-specific hydrological modules[63,64] and peatland modules[65] to better take into account local surface moisture anomalies influencing fire occurrence more accurately,[50,66] processes not being included in the present version of LPJ-LMfire. Future studies could also use other climate databases relying on different or larger numbers of meteorological stations to represent local climate gradients more adequately, which may influence simulations of vegetation dynamics and fire ignitions.

Conclusions

Given the socio-economic consequences of large fires,[67–69] the threats they pose to the health and safety of Indigenous communities[70–72] and their access to ecosystem services,[73–75] our projections of climate change, vegetation dynamics and fire activity in the NT demonstrate the urgent need to develop preventive measures for limiting the future consequences of fire regime changes.[76] Our simulations for the latter half of the 21st century suggest reduced fire activity because of decreased proportion of needleleaf tree species, except in the southeastern part of the study area where the reverse trend could occur. The consequences of climate change on tree biomass and fire activity dynamics will need to be integrated in long-term forest management and land-use planning strategies.

STAR★METHODS

Detailed methods are provided in the online version of this paper and include the following:

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SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.isci.2023.106807.

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AUTHOR CONTRIBUTIONS

D.M.G., E.C., M.P.G., H.A., A.A.A., Y.B., and C.H. designed the study. D.M.G performed the simulations following the methodology and the analysis protocol developed by E.C., C.H., and M.P.G. D.M.G. interpreted the results and wrote the manuscript with contributions from all co-authors.

DECLARATION OF INTERESTS

The authors declare no competing interests.

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STAR★METHODS

KEY RESOURCES TABLE

REAGENT or RESOURCE	SOURCE	IDENTIFIER
Software and algorithms		
BioSIM v.11	Natural Resources Canada Régnière et Saint Amant 2014	https://cfs.nrcan.gc.ca/projets/133
R v. 4.2.0. Statistics programmation	Comprehensive R Archive Network (CRAN)	https://cran.r-project.org/bin/windows/base/
QGIS v. 3.24. GIS software	Quantum Gis	https://qgis.org/
LPJ-LMfire source code	Sitch et al.[77] Chaste et al.[34]	https://github.com/ARVE-Research/LPJ-LMfire/tree/canada/src
Bioclimatic parameters for PFTs	Thompson et al., 1999	https://pubs.usgs.gov/pp/p1650-a/
LPJ-LMfire NetCDF files	Outputs from LPJ-LMfire produced in this study	https://zenodo.org/deposit/6078609

RESOURCE AVAILABILITY

Lead contact

Further information and requests for resources should be directed to and will be fulfilled by the lead contact, Dorian M. Gaboriau (dorian.gaboriau@uqat.ca).

Materials availability

The source code of the LPJ-LMfire model is available at the following address: https://github.com/ARVE-Research/LPJ-LMfire/tree/canada/src.

Data and code availability

Datasets generated in this study, i.e., LPJ-LMfire NetCDF files, have been deposited to: https://zenodo.org/deposit/6078609.

METHOD DETAILS

Study area

The study area covers 821,000 km^2 of boreal forest or 61% of the Northwest Territories (NT), Canada, in the Taiga Plains and Taiga Shield West ecoregions[52] (Figure 1). Forests are dominated by needleleaf tree species – mostly black spruce (*Picea mariana*(Mill.) B.S.P.) and jack pine (*Pinus banksiana* Lamb.) – and broadleaf tree species – mostly trembling aspen (*Populus tremuloides* Michx.).[62] The study area is currently outside the distribution of balsam fir (*Abies balsamea* L.(Mill)), located further south from northern Alberta to the Atlantic provinces. Tree biomass declines along a decreasing temperature gradient from southwest (<50 T ha^{-1}) to northeast (<20 T ha^{-1}),[78,79]while the fire return interval increases along the same gradient.[80,81] The fire season extends from May to September, with very large (>20,000 ha) lightning-induced wildfires occurring essentially during warm and dry summers.[6,82,83] Human-caused fires represented only 1% of the total area burned from 1980 to 2012 in the study area and they were mainly located near populated areas.[84]

LPJ-LMfire model

LPJ-LMfire is designed to simulate vegetation dynamics and fire events in response to changes in climate, carbon dioxide (CO_2) concentration, and lightning events.[53] The model was initially parameterized and validated for Alaska,[53] Europe,[85] and then for the boreal forest of eastern Canada.[51] Vegetation is defined according to four plant functional types (hereafter PFTs): *Picea*, *Abies*, *Pinus*, and *Populus*, which correspond to the main tree genera in the Canadian boreal forest. A PFT corresponds to a group of species with common physical and morphological characteristics, responding comparably to environmental conditions and sharing similar roles (e.g., regeneration, succession, mortality) in the forest ecosystem.[86,87-] *Betula* and *Larix* PFTs are not parametrized in the model, but these genera have low abundance in the NT.[62]

For the establishment of PFTs in the model, bioclimatic conditions, such as minimum or maximum temperature thresholds, constrain potential growth, while specific fire tolerance (e.g., in terms of flammability or regeneration) are defined for each PFT (Table S1) and participate to the forest response in terms of composition and structure. Further details on the processes related to the PFTs included in the model are described in Figure S2A.

The LPJ-LMfire model simulates the response of vegetation, fire and their interactions to climate at a 10-km resolution[51] based on ecophysiological, biophysical and hydrological parameters, distributed within the model in different modules describing the processes related to terrestrial ecosystem functioning including natural disturbances. The model simulates the growth of aboveground vegetation in terms of composition (i.e., PFT presence) and some structural and functioning variables: biomass, net primary productivity, cover percentage, tree density, crown area and leaf area index for each PFT, and carbon fluxes at the stand level, varying annually with respect to the processes calculated daily. Most processes are calculated at a daily time-step (e.g., photosynthesis, stomatal regulation, soil hydrology, autotrophic respiration, phenology, decomposition, fire occurrence), while others have an annual time-step (e.g., germination, reproduction, tree mortality and litterfall) or an annual report (burned area and fire impacts based on PFT resistance) (Figure S2B). For fire ignition, the probability that a lightning strike will result in an ignition depends on the ratio of dead versus live fuel loads, as well as their moisture, which must be lower than the threshold set for fuel moisture of extinction. The ignition probability is also modulated by an ignition efficiency parameter specific to each PFT (i.e. representative of flammability) and the pixel proportion already burned to date.[53] The LPJ-LMfire fire module[53] simulates fire ignition based on estimations of daily lightning strikes, available fuel, and its desiccation state on each cell of 10 × 10 km resolution, without considering fire spread through neighboring cells. Fire spread, intensity, and carbon emission depend on the litter fuel load, its bulk density, its moisture, and on wind speed.[51,53] Fire extinguishment is determined by changes in weather and/or fuel conditions (amount and desiccation).[77] Therefore, the proportion of area burned within each grid pixel varies with tree biomass, forest structure, composition, and desiccation, and we computed burn rates as the annual proportion of the study area burned.

Model inputs

We aimed to reproduce the natural functioning of boreal forest ecosystems considering interactions between climate, vegetation, and lightning-ignited fires >1 ha. We did not consider human disturbances such as forest management and fire control efforts in the simulations due to the low human population density and limited forest and fire management in the study area.[88,89] The datasets used as input to run the LPJ-LMfire model are described below and based on the methodology of Chaste et al. (2018, 2019),[34,51] adapted to the study area.

(i) For phases of model spinup and validation (1980–2012), we used historical 1901–2012 monthly observations of daily temperature (°C), precipitation (mm), wind speed (km h^{-1}), total cloud cover (%), and relative humidity (%) obtained from the BioSIM software for each 10-km grid cells.[90] The software interpolates daily data from the four closest weather stations of the Environment and Climate Change Canada's network to each grid cell, adjusting each location for elevation and coordinates differentials with nearest weather stations using an inverse-distance weighting procedure. Besides, 1950–2099 monthly climatology for the projection experiment were obtained from the Regional Climate Modeling and Downscaling Project conducted by the CORDEX working group[91] and developed for phase 5 of the coupled model comparison (CMIP5). Two GCMs were used as boundary conditions for two RCMs, each forced by two representative concentration pathways (hereafter RCPs). The six climate scenarios produced (Table S3) were used as LPJ-LMfire inputs for simulating a wide range of variability in vegetation and fire responses to climate change in the study area. Among Earth system climate models, we selected the Canadian and European GCMs – CanESM2[92,93] and EC-EARTH[94] – and among RCMs – CanRCM4 and the Rossby Center Regional Climate Model version 4 (RCA4).[95] The RCPs used herein represent medium-low and high emission radiative forcing scenarios from IPCC AR5 projections (RCP4.5 and RCP8.5).[96] The radiative forcing values of RCP4.5 and RCP8.5 are 4.5W/m^2 (650 ppm CO_2 equivalent) and 8.5W/m^2 (1300 ppm CO_2 equivalent) at the end of the 21st century, respectively.[97] All climate model data were corrected for drift using the methodology described by Chaste et al. (2019).[34]

(ii) Time-series of monthly lightning flash densities (number day^{-1} km^{-2}) were used in the calculation of the fire ignition probability in the LPJ-LMfire model. Lightning flash densities were calculated based on the Canadian Lightning Detection Network (CLDN) dataset, which covers the period 1999–2010.[98]Since a recent LPJ-LMfire experiment in eastern Canada showed that constant and increasing lightning activity produced the same results in terms of fire activity and vegetation changes (see Chaste et al. 2019, Figure S9),[34] we only present the constant scenario ($Flashes_{constant}$). In the $Flashes_{constant}$ scenario, we applied a constant lightning flash density from 1950 to 2099 that varied spatially through years. The time-series were constructed by randomly selecting monthly values from the 12 years of monthly CLDN time-series. Monthly lightning densities are converted to daily values by the LPJ-LMfire weather generator module by distributing lightning flash occurrence over rainy days.[34]

(iii) Annual atmospheric CO_2 concentrations were provided to LPJ-LMfire from 1950 to 2099[53,97] and ranged from 310.7 ppm in 1950 to 537.8 ppm in 2099 for RCP4.5, and 926.7 ppm in 2099 for RCP8.5.

(iv) Static maps of environmental constraints such as soil particle size distribution (%) and coarse sediment volume fraction (%),[99] elevation (meters), slope (degrees),[100] and water fraction (%)[101] were provided to LPJ-LMfire.

(v) PFT-specific bioclimatic parameters were also provided as inputs to the model (more details in Table S1 and Figure S2A).

QUANTIFICATION AND STATISTICAL ANALYSIS

Simulation protocol and experiments

Each LPJ-LMfire simulation experiment includes two phases. The 1120-year-long initial phase (spinup phase) is the time for vegetation to grow on bare soils and to reach an equilibrium with climatic conditions, atmospheric CO_2 concentrations, and potential fire occurrences. The spinup climate dataset for each grid cell corresponds to a detrended climatology from 1901 to 2012 obtained from the interpolated weather data from meteorological stations over the 10-km layer using BioSIM (Figure 1), and repeated 10 times.[51] The second simulation phase (validation phase), starting just after the end of the spinup phase corresponding to the baseline period, is a transient run of the model from 1950 to 2012 using historical monthly observations based on the CORDEX datasets.[102,103] The projection experiment includes six runs, each using a transient climate dataset for this second phase based on one of the two radiative forcing scenarios (RCP4.5 and RCP8.5) applied on the combined GCMs and RCMs (Table S3). Simulations of vegetation dynamics in the LPJ-LMfire model were performed using the climatic datasets and LPJ-LMfire parameters from Chaste et al. (2018).[51]

LPJ-LMfire validation

We followed the methodology of Chaste et al. (2018)[51] to temporally and spatially compare simulated (LPJ-LMfire) and observed burn rates (%) for lightning-induced fires >1 ha from the Canadian National Fire Database (hereafter CNFD).[84] We averaged simulated and observed burn rates from 1980 to 2012 into 116 cells defined by Héon et al. (2014)[104] and covering the study area. The cells not intersected by the study area boundaries are 10,000 km^2 in size. Measures from cells intersecting study area boundaries were assigned to their respective areas. Then, we measured the absolute difference between the two data products. We also compared time-series of simulated and observed burn rates for the same period (1980–2012) and we measured the Spearman rank correlation between the two datasets with a 95% confidence interval (Figure 2; $r_s = 0.53$, $p = 0.001$).

We compared tree biomass (T.ha^{-1}) simulated by the LPJ-LMfire model with the aboveground live woody biomass density map published by Global Forest Watch (GFW) at a global scale and available only for the year 2000.[78] This reference map of carbon density values of aboveground live woody biomass has been produced with the methodology developed by Baccini et al. (2012)[61] and relied on remote-sensing data[105] as well as geomorphological, topographic and climate data.[106–108] We resampled the GFW original 30-m resolution data product at a 10-km resolution by averaging tree biomass for each cell. Then, for LPJ-LMfire and GWF reference maps, we aggregated the tree biomass pixel values to hexagonal cell resolution in order to report one average value for each one of the 116 cells covering the study area. We measured the absolute difference between each cell pair of the two data products.

Projections

To report warming in each of the six climate scenarios used as inputs in LPJ-LMfire, we computed annual mean temperatures (°C), monthly mean rainfall (mm/100 km^2) and cloud-to-ground lightning strike flashes per 100 km^2 (km^2 d^{-1}(log10scale)) from 1950 to 2099. To predict future fire and vegetation dynamics responses to climate change, based on LPJ-LMfire outputs we computed annual burn rates (%), as well as total tree biomass (T.ha^{-1}) for the four PFTs and for the following time horizons: 2021–2040, 2041–2070, and 2071–2099, averaging the outputs of the three models corresponding to RCP4.5 and RCP8.5 (Table S3). Then, we measured the anomalies between the three horizons and the baseline (1980–2012), and we interpreted absolute gains and losses in terms of burn rates and tree biomass for each PFT. We also extracted sub-regional time-series of LPJ-LMfire simulated mean annual burn rates and tree biomass for PFTs *Picea* and *Populus*, for RCP4.5 and RCP8.5 and for the 1980–2099 period in order to apprehend sub-regional variability level.