

<https://doi.org/10.1038/s43247-025-02313-1>

# Integrating fire-smart fuels management with bioenergy benefits remote and Indigenous communities in Canada



Nicolas Mansuy<sup>1</sup>✉, Jennifer Buss<sup>1</sup>, Kelvin Hirsch<sup>1</sup>, Luc Guindon<sup>1,2</sup>, François-Nicolas Robinne<sup>1</sup>, Yan Boulanger<sup>2</sup>, Maude Lussier<sup>3</sup>, Adrian Regos<sup>4</sup>, Claudia Castillo Ayala<sup>1</sup> & Marc-André Parisien<sup>1</sup>

The global urgency of more damaging wildfires calls for proactive solutions. Integrating fire-smart fuels management with bioenergy could reduce wildfire risk while providing feedstock for bioenergy. We explore this strategy in off-grid communities in Canada who are heavily dependent on diesel for their energy needs, many of which are home to Indigenous peoples. Combining national remote sensing data and community-based information, we identify 33 diesel-dependent communities at high wildfire risk due to a large accumulation of undisturbed flammable forest. We demonstrate that 30 of these 33 communities could theoretically meet their annual energy needs by harvesting less than 1 % of the surrounding biomass, which with thoughtful planning could constitute effective fuel treatments. Given the growing wildfire risk and the need for energy security in Indigenous communities, Indigenous leadership, and collaboration with wildland fire agencies, are essential for developing integrated fuel management strategies and identifying synergies with the bioenergy sector.

Globally, wildfire is an increasing threat and costly hazard to human beings, carbon sinks, natural resources, and infrastructure<sup>1,2</sup>. Financial losses due to wildfires are increasing and are estimated to constitute 1–2% of the gross domestic product of most developed countries, with global annualized losses estimated to range from US\$63.5 billion to US\$285 billion<sup>3,4</sup>. Given the increasing cost of wildfire suppression around the world, many governments have been calling for proactive and holistic strategies to mitigate risks<sup>5</sup>. The year 2023 was another record-breaking fire season in many regions across the globe, like the Mediterranean and boreal biomes, experiencing longer and increasingly challenging wildfire seasons driven by more severe and frequent fire-conducive weather and fuel accumulation<sup>6–13</sup>. Population growth, combined with the rapid expansion of the Wildland-Human Interface (WHI; where forest fuels intermingle with or abut housing, industry, and infrastructure) in Canada<sup>14</sup> and around the world<sup>15</sup>, are putting a strain on wildland fire management agencies and local economies, thereby enhancing the need for enhanced safety through wildfire protection.

The year 2023 was Canada's worst wildfire season on record<sup>8,9</sup> accounting for 30% of total carbon emissions from wildfires worldwide<sup>6</sup>. Additionally, over 230,000 people were evacuated from communities due to the potential dangers to life and health and eight firefighters died in the line of duty. Approximately 15 million ha burned across the country, and greatly

surpassing the 10-year average of 2.5 million ha per year<sup>8</sup>. Northern communities in Canada, many of which are home to Indigenous peoples, are disproportionately exposed to wildfire<sup>15</sup>. Indigenous peoples only make up 5% of the population in Canada but 42% of wildfire evacuation events occurred in their communities<sup>14,16</sup>. Approximately 80% of the Indigenous communities in Canada are located in fire-prone forested areas, and 32% of the on-reserve First Nations population reside within the WHI<sup>14</sup>. Many of these remote communities, Indigenous and non-Indigenous, lack up-to-date emergency planning, security infrastructure, have limited evacuation routes, and limited resources and capacity to respond to potential wildfires<sup>17,18</sup>.

In Canada, as in most countries, wildland fire management over the past century has focused primarily on preventing and suppressing wildfires. Although suppression has been effective in many areas of the boreal forest, its efficacy is likely to diminish as wildfire suppression resources become increasingly strained due to projected climate changes<sup>19</sup>. More recently, based on the FireSmart™ Canada guidelines<sup>20</sup>, proactive fuel management measures (e.g., thinning, pruning, surface fuel reduction, species conversation to low flammability trees and shrubs), have been initiated in the WHI to help individuals and communities mitigate the risk of loss from wildfires (Supplementary Table A1). At the landscape level, forest management activities (such as site preparation, regeneration, stand tending,

<sup>1</sup>Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320 122 St, Edmonton, AB, T6H 3S5, Canada. <sup>2</sup>Natural Resources Canada, Canadian Forest Service, Laurentian Forestry Centre, 1055 Du P.E.P.S. Street, Québec, QC, G1V 4C7, Canada. <sup>3</sup>Protective Services Department, Wildfire Mitigation, Squamish-Lillooet, Regional District, Box 219, 1350 Aster Street, Pemberton, BC, V0N 2L0, Canada. <sup>4</sup>Biological Mission of Galicia, Spanish National Research Council (MBG-CSIC), Avda de Vigo s/n, 15705 Santiago de Compostela, Spain. ✉e-mail: [nicolas.mansuy@nrcan-mncan.gc.ca](mailto:nicolas.mansuy@nrcan-mncan.gc.ca)

harvest scheduling and systems, block layout and design, and road construction) when conducted with wildfire in mind can also be used to reduce, isolate, and convert forest fuels and, in turn, decrease the potential area burned by undesirable wildfires<sup>21</sup>. In this study, these two approaches are combined in the term “fire-smart” which refers to fuel management activities taken at both the site and landscape levels to reduce the flammability of forests and other vegetation in and around communities.

Reducing fuel accumulation and disrupting the vertical and horizontal continuity through prescribed burning<sup>22</sup> and mechanical treatments can be a cost-effective strategy for reducing potential wildfire spread and intensity<sup>23–26</sup>. However, unmerchantable biomass from fuel treatments is typically considered a waste product that is disposed of through piling and burning on-site or transported and disposed of off-site to reduce fuel hazard<sup>27,28</sup>. For some communities in Canada, especially those with limited financial resources and capacity, the cost and logistics of disposing of biomass can present considerable challenges<sup>29</sup>. As a result, they may be hesitant to invest in fuel treatment activities, even if they recognize the importance of wildfire risk mitigation.

Bioenergy refers to the production of renewable energy derived from the combustion of organic biomass, accounting for 27% of Canada’s renewable energy supply. This primarily consists of solid biofuels, such as wood chips and pellets, sourced from forest biomass. Currently, the majority of biomass is produced from harvesting and processing residues, but several studies have suggested that non-merchantable biomass from fuel treatment could be used as a feedstock to produce bioenergy in a cost-effective manner<sup>30–33</sup>. For example, initiatives in the southern United States<sup>34</sup> and in European Mediterranean ecosystems have explored the potential of producing bioenergy from fire-prone biomass not only to reduce greenhouse gas (GHG) emissions from wildfires, but also to reduce the vulnerability of rural communities to wildfires<sup>35,36</sup>. In boreal and temperate forests of Canada, the amount of biomass resulting from fuel reduction treatments can be substantial<sup>31</sup>.

For example, it has been estimated that the volume of biomass available from fuel treatments could be 2.5 million oven-dry tonnes (odt) per year in British Columbia and 850,000 odt per year in Alberta<sup>33</sup>. However, to date, no quantitative study in Canada has assessed the amount of biomass surrounding communities vulnerable to wildfire, and whether the biomass collected through fuel management could meet communities’ long-term energy needs. That is, there is still no clear picture of whether fuel treatments could supply enough biomass to support community-based bioenergy strategies while concomitantly mitigating wildfire risk.

The impetus for community-based bioenergy development has increased recently in Canada and represents an opportunity to examine the nexus between fire-smart fuel treatments and bioenergy strategies. In addition to being vulnerable to wildfire, about 70% of remote communities in Canada are off-grid and dependent on local diesel-powered generators as their main source of electricity and heat (Box 1).

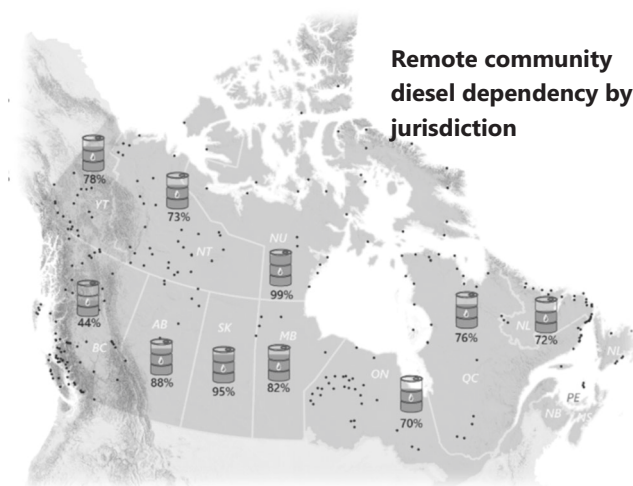
Diesel-dependent communities in Canada are collectively home to some 200,000 people, mostly Indigenous and many of whom face major socio-economic and environmental challenges, such as climate change and energy insecurity<sup>37</sup>. Diesel-dependent remote communities pay approximately 2–6 times more for energy (US\$0.20 kWh<sup>−1</sup> to US\$0.80 kWh<sup>−1</sup>) than the average Canadian, even with subsidies (US\$0.11 kWh<sup>−1</sup>)<sup>38,39</sup>. Wood-based bioenergy in Canada can cost as low as US\$0.07 kWh<sup>−1</sup><sup>138</sup>. For example, in Fort McPherson, Northwest Territories, the costs vary between US\$0.07 kWh<sup>−1</sup> to US\$0.15 kWh<sup>−1</sup> for locally harvested wood chips<sup>40</sup>, and US\$0.50 kWh<sup>−1</sup> for a combined heat and power system in the community of Lac Brochet (Northlands Denesuline First Nation) located in Manitoba<sup>41</sup>. In addition, transitioning from diesel to bioenergy offers many environmental benefits, including reducing GHG emissions and eliminating or reducing local environmental damage such as soil, water and air pollution caused by leaking diesel storage tanks and inefficient generators<sup>42,43</sup>. Bioenergy can also bring socio-economic advantages in terms of job creation and new sources of

## Box 1 | Canada's Diesel-dependent Communities

According to the Remote Communities Energy Database (RCED)<sup>101</sup>, there are 276 remote communities in Canada, defined as permanent or long-term settlements (lasting five years or more) with at least 10 dwellings, not connected to the North American electrical grid or to the piped natural gas network. All-year road access is only available in some of these communities, and over half are fly-in only. About 70% of these communities rely on inefficient diesel generators for electricity, while 13% utilize hydroelectric power and 17% use a mix of other fossil fuels<sup>102</sup>.

Additionally, remote communities depend heavily on fossil fuels for space and water heating, with diesel primarily fulfilling their heating needs.

As of 2020, remote communities in Canada collectively consumed approximately 682 million liters of diesel per year, serving an estimated population of 200,000 people<sup>102</sup>. This consumption translates to around 9 tonnes of CO<sub>2</sub> equivalent emissions per person annually—more than three times the average GHG emissions of Canadian households<sup>103</sup>.



income, as well as the development of new skills that contribute to energy security and sovereignty, and hence to community empowerment<sup>42</sup>. Since 2017, the Government of Canada, has supported over one hundred clean energy projects including bioenergy via its Clean Energy for Rural and Remote Communities program<sup>44</sup> and many fire-prone communities have expressed the need to integrate local biomass management with wildland fire management plans<sup>42</sup>.

As wildfire threatens a growing number of communities across Canada, the integration of fire-smart fuel management and bioenergy can represent a win-win solution for communities that are simultaneously vulnerable to wildfires and face energy insecurity. The aim of this study is to identify pathways for integrating bioenergy development with wildfire mitigation efforts, and specifically: 1) Identify diesel-dependent communities presenting high wildfire risk across Canada; 2) Estimate the amount of biomass available from fuel treatments (BAFT) and fuel treatment area (FTA) at the community level that could be used as feedstock for bioenergy purposes; and 3) Rank priority communities that could also meet their annual energy demand using BAFT. To standardize our spatial analyses across Canada, we have developed a unique framework combining a national environmental remote sensing dataset with community-based data (Fig. 1). To select the communities and identify their energy needs, we used the Remote Communities Energy Database (RCED), which comprises 276 communities as of 2022. Amount of BAFT and FTA were determined with spatial analyses between the national above ground biomass dataset, time since disturbances, and the national WUI layers and 10 km buffers around each community. To determine which communities would benefit the most from using BAFT as feedstock for bioenergy, we performed a hierarchical clustering analysis of the communities. Although the data used are static over time, and do not account for forest regrowth after treatment or disturbances, the study aims to provide an initial national assessment to help identify and prioritize communities where fuel treatments and biomass mobilization could be combined for both wildfire mitigation and bioenergy purposes.

## Results

### Selection of diesel-dependent communities at risk from wildfire

Of the 276 communities available in the RCED in 2022, 201 relied on diesel as their main energy source (filter 1). Then, communities with a population smaller than 100 inhabitants, as well as those lacking both energy use and population information in the RCED, were filtered out (filter 2). If there was no listed population for a community in the RCED, but there was an annual energy demand, the 2021 and 2016 Canada Census were referenced to ensure the population was over 100. To ensure the inclusion of only permanent communities, 9 temporary settlements (e.g., related to mining and oil and gas or temporary subsistence settlements) were removed (filter 3). Lastly, the 41 communities outside of the boundaries of the homogeneous fire regime zones (HFRZ; filter 4) as defined by Boulanger et al.<sup>45</sup> or in coastal areas, within 10-km of an ocean, (25; filter 5) were excluded. This resulted in a total of 53 communities being selected for further analysis, of which all are Indigenous.

Among these 53 communities, we determined that 33 were at a high risk from wildfire (Fig. 2). The risk from wildfire at the community level was assessed by quantifying the accumulation of undisturbed forest area defined as a forest  $\geq 30$  years old within a 10 km buffer around each community as per Parisien et al.<sup>46</sup>. Undisturbed forest area was used here as an indicator of fuel accumulation and therefore if the undisturbed forest area was greater than 90% of the total forested area within the 10 km buffer a community was classified as at high risk from wildfire. Profile details of the 33 selected communities are provided in Table 1.

The 33 selected communities are not evenly distributed across Canada but rather form distinct clusters from the southern limits of the boreal forest to the arctic regions (Fig. 2). The first group is made up of 2 communities in central southern Quebec, plus one in northern Quebec. The second group is made up of 16 communities located in northwestern Ontario and northern Manitoba. The third group composed of 14 communities extends from northern Alberta, Northwest Territories, Yukon and British Columbia.

### Quantifying biomass available for fuel treatment

The amount of BAFT at the community level was estimated from national aboveground biomass<sup>47</sup> older than 30 years old including branches, foliage, bark, and stemwood in  $\text{odt ha}^{-1}$ , and specifically located within the WHI using the national dataset<sup>48</sup>. The BAFT was then calculated by the overlap of these two databases within a 10 km buffer around each community excluding the biomass categorized as nonfuel and the biomass located at least 30 m from water bodies to reduce stress on sensitive riparian ecosystems and water resources<sup>49</sup> (see close-up in Fig. 2).

The amount and density of biomass among the 33 communities selected are highly variable. In addition, the BAFT and the FTA are largely influenced by the extent of the WHI. The mean biomass density is 58  $\text{odt ha}^{-1}$ , the mean BAFT is estimated at 4 Modt for a total of 139 Modt (Table 1). The community with the highest BAFT is Watson Lake, YT (18 Modt) and the community with the least is Shamattawa (0.2 Modt). The total FTA across all 33 communities is 196,328 ha and the average is 5949 ha (Table 1). Watson Lake had the largest FTA (16,278 ha) and Shamattawa had the smallest FTA (482 ha; Table 1). The average percentage of the total biomass within 10 km available for fuel treatment is 27% and there are 3 communities with greater than 50%, Clova (54%); Fort Simpson (60%); and Watson Lake, (58%).

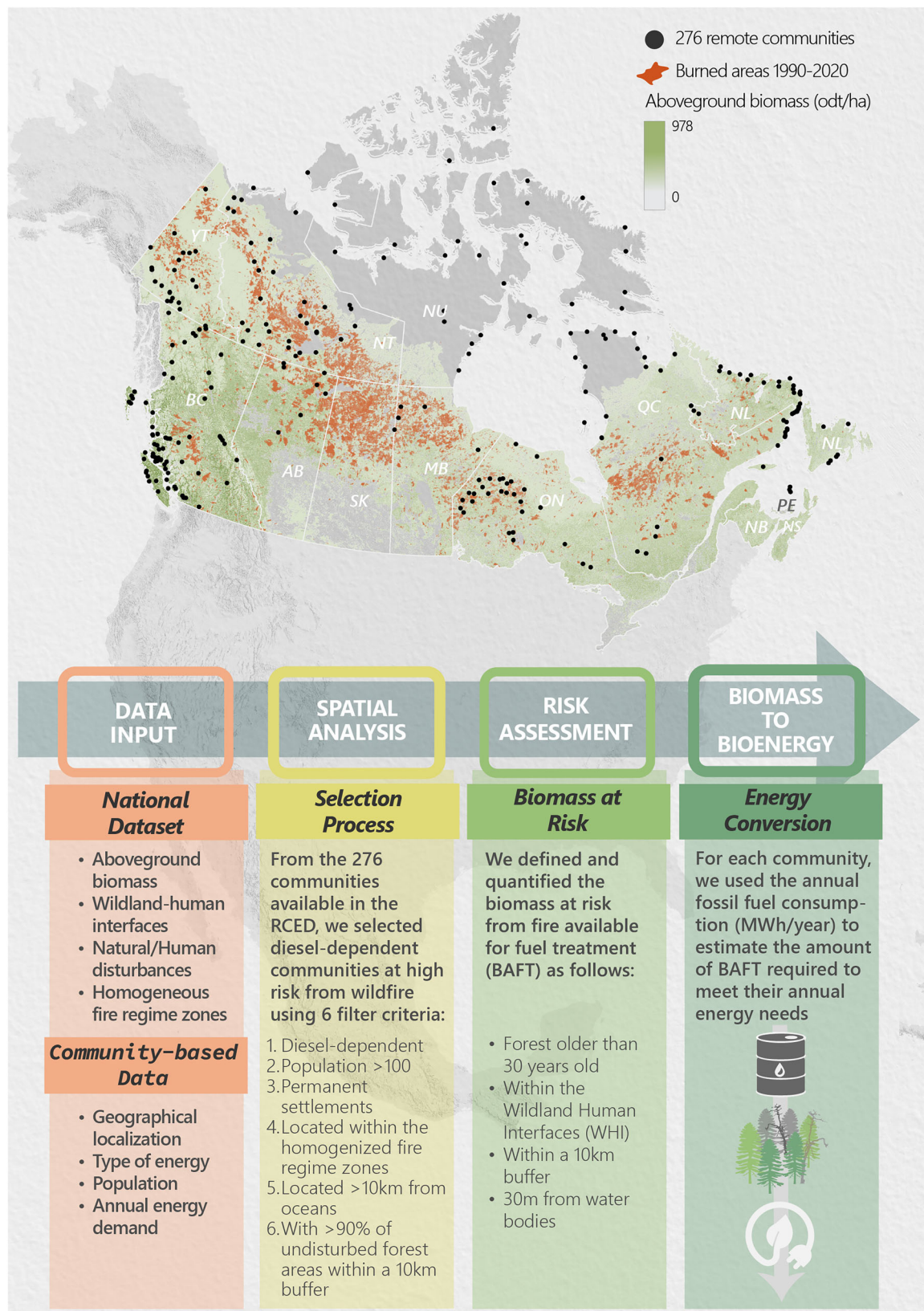
### Potential for meeting annual energy demand

Based on the annual fossil fuel consumption of each community, we estimated that the AED for the 33 communities at high risk from wildfire ranged from 627 to 20,333 MWh  $\text{year}^{-1}$  with an average of 4753 MWh  $\text{year}^{-1}$  (Table 1). The AED is directly proportional to population size; therefore, the highest AED is in Kuujuaq, with a population of 2754. Based on Eqs. (1)–(4), the average theoretical biomass needed to meet AED, across the 33 communities is 897  $\text{odt}$  (Table 1). All 33 communities can theoretically meet their annual energy needs by collecting less than 1% of their BAFT, with an average of 0.06%, minimum of 0.001%, and a maximum of 0.63% (Table 1). This means that all the communities could meet their energy demand for more than 100 years without considering the potential forest regrowth after fuel treatment. In terms of area to be treated, the average theoretical FTA needed across the 33 communities to meet AED is 20 ha (Table 1). Clova had the lowest theoretical FTA needed to meet their AED, 2  $\text{odt}$ , and Kuujuaq had the highest, 104  $\text{odt}$  (Table 1). Most communities (30 out of 33) can also theoretically meet their AED by collecting less than 1% of their FTA per year, with the average being 0.62%, a minimum of 0.01%, and maximum of 7%. Communities that would have to harvest more than 1% of their FTA are Aklavik (2.4%), Kuujuaq (1.9%), and Shamattawa (7.0%). For the communities with the highest AED, which are Fort Chipewyan, Fort Hope, Kuujuaq, Sandy Lake, and Watson Lake, the theoretical percentage of FTA needed to meet AED varies between 0.18% and 1.92% annually (Table 1).

In the operational scenario where we consider that wood pellets are used to meet energy need, the average operational biomass needed to meet AED across the 33 communities increased to 1188  $\text{odt per year}$  (Table 1). All 33 communities would still be able to meet their AED by collecting less than 1% of their BAFT, with the maximum of 0.84% for Shamattawa. The average operational FTA needed across the 33 communities to meet AED is 26 ha, a 6-ha increase from the theoretical estimate (Table 1). Clova's operational FTA need, the lowest of all communities, was the same as their theoretical (2 ha), but Kuujuaq's, the highest, increased from 103 to 137 ha (Table 1). The number of communities that can operationally meet their AED by harvesting less than 1% of their FTA per year decreases to 28 out of 33, with the maximum of 9.31% for Shamattawa (Table 1). The two additional communities that would need to harvest slightly more than 1% of their FTA are D  lne and Fort Good Hope (both 1.1%) (Table 1).

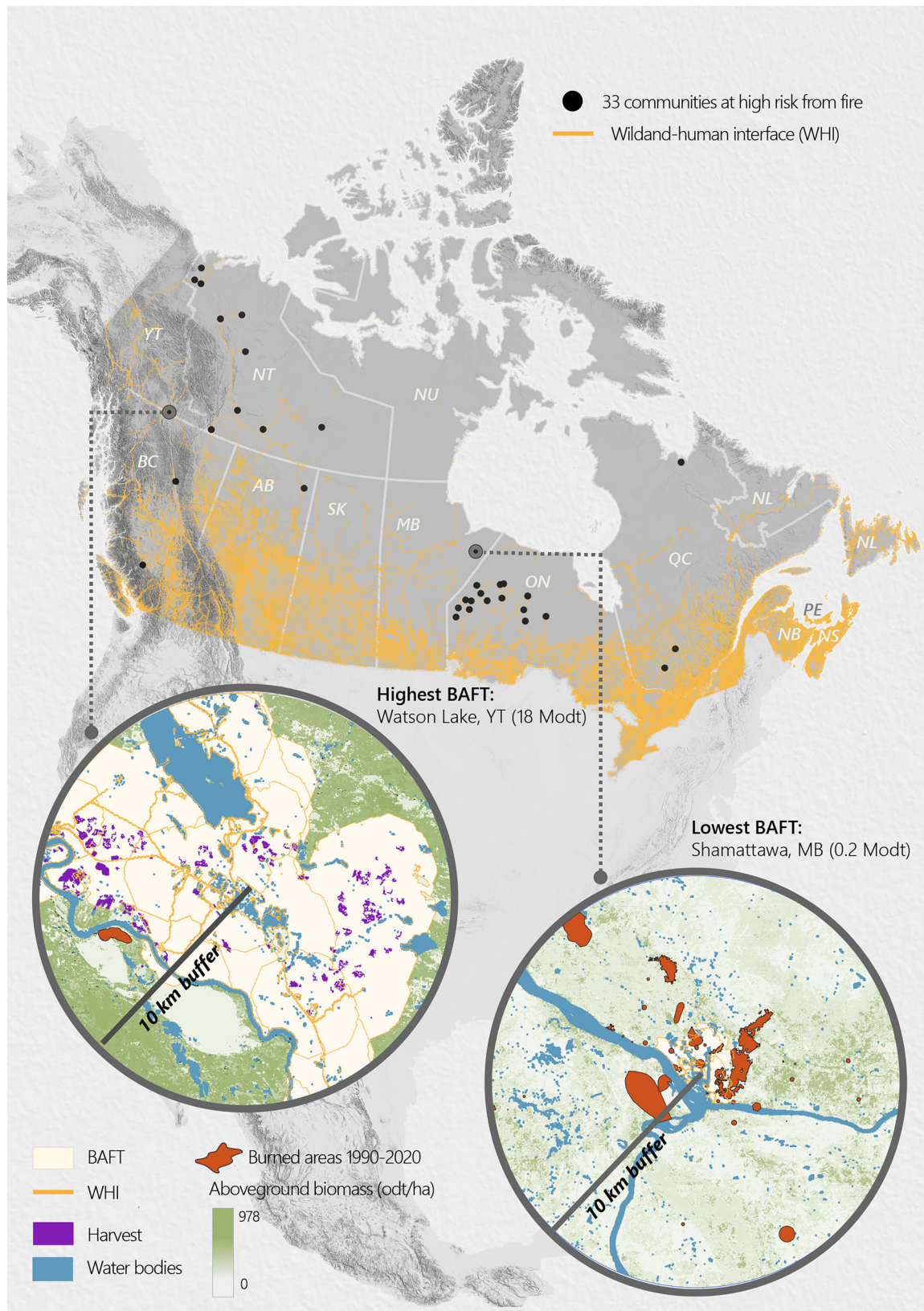
### Suitability of communities for fire-smart bioenergy development

Finally, we performed a hierarchical clustering analysis to identify and rank the communities best suited to a fire-smart bioenergy program (Fig. 3). The first group contains the three highest priority communities (Clova, QC; Fort Simpson, NT; and Watson Lake, YT) given their high percentage of BAFT



**Fig. 1 | Methodology of the study.** The framework integrates a pan-Canadian environmental remote sensing dataset with community-level data. The process consists of three main steps. The first step involves identifying diesel-dependent communities at high wildfire risk across Canada from the Remote Communities Energy Database (RCED) using six specific criteria. The second step aims to quantify the amount of high-wildfire-risk biomass available for fuel treatment (BAFT) and

the corresponding fuel treatment areas for each selected community. The third step aims to calculate the percentage of fuel treatment areas required and the amount of high-wildfire-risk biomass needed to meet the communities' annual energy demand (in MWh year<sup>-1</sup>), based on their current fossil fuel consumption. More details are available in the supplementary information section (Supplementary Fig. A1 and Supplementary Table A2).



**Fig. 2 | National map showing the selection and location of the 33 communities at high risk from wildfire.** The circles below also show a close-up of two communities illustrating the spatial boundaries of the biomass available for fuel treatment (BAFT). BAFT is defined as the accumulation of undisturbed above ground biomass older than 30-years old located within the wildland human interface (WHI) and constrained by a 10 km buffer around the community and excluding biomass located within 30 m of water bodies. The age of the biomass was determined with the time since last disturbance, i.e.

burned or harvested areas. On the left, Watson Lake located in Yukon is the community with the largest amount of BAFT. On the right, Shamattawa, located in Manitoba with the smallest amount of BAFT (see Table 1 for more details of each community; Abbreviations for Canadian provinces and jurisdictions: AB Alberta, BC British Columbia, MB Manitoba, NB New Brunswick, NL Newfoundland and Labrador, NS Nova Scotia, NT Northwest Territories, NU Nunavut, ON Ontario, PE Prince Edward Island, QC Quebec, SK Saskatchewan, YT Yukon).

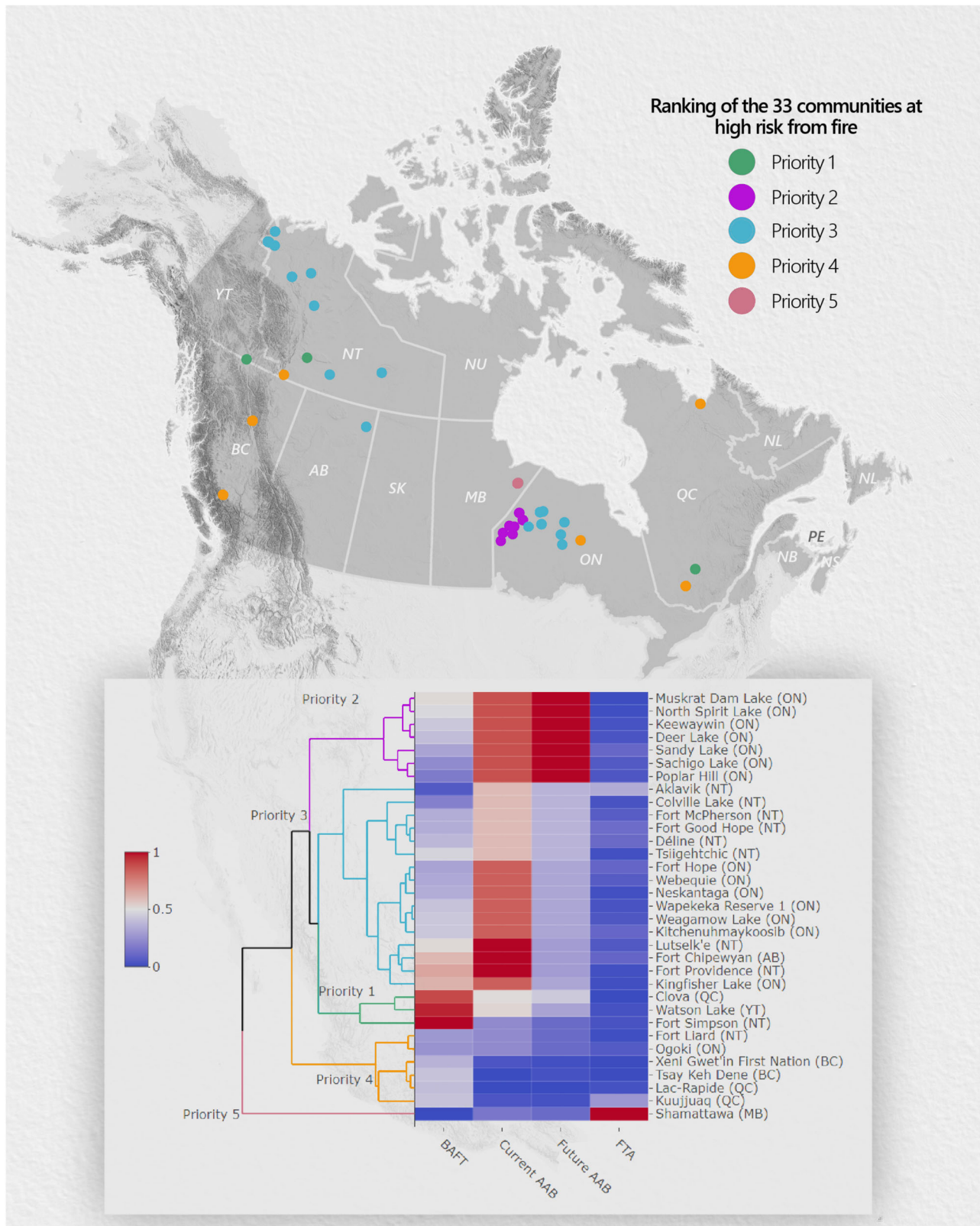
Table 1 | Profiles of the 33 communities at high risk from wildfire

Community profile				Biomass available for fuel treatment (BAFT) and fuel treatment areas (FTA)				Theoretical biomass needs to meet AED (raw biomass)				Operational biomass needs to meet AED (pellets)			
Community <sup>a</sup>	Population (census 2022)	Annual energy demand (MWh yr <sup>-1</sup> )	Total biomass within 10 km (odt)	Total BAFT (odt)	% BAFT of total biomass within 10-km	Mean biomass density (odt ha <sup>-1</sup> )	FTA(ha)	Biomass need (odt yr <sup>-1</sup> )	% of biomass need of total BAFT	Area to be treated annually (ha)	% of FTA to meet AED	Biomass need (odt yr <sup>-1</sup> )	% of biomass need of total BAFT	Area to be treated annually (ha)	FTA needed to meet AED (%)
Aklavik, NT	590	3192	5,840,056	282,425	5	28	893	602	0.213	21	2.372	798	0.283	28	3.140
Clova, QC	100	788	23,015,654	12,420,047	54	83	13,486	149	0.001	2	0.012	197	0.002	2	0.020
Colville Lake, NT	129	627	4,609,341	606,055	13	19	2852	118	0.019	6	0.222	157	0.026	8	0.290
Déline, NT	533	2756	3,041,722	723,866	24	15	4368	520	0.072	35	0.801	689	0.095	46	1.060
Deer Lake, ON	1083	5333	19,743,858	4,929,318	25	80	5516	1006	0.020	13	0.236	1333	0.027	17	0.300
Fort Chipewyan, AB	853	12,843	10,983,172	4,026,595	37	51	7075	2423	0.060	47	0.671	3211	0.080	63	0.890
Fort Good Hope, NT	516	2749	3,064,647	674,561	22	9	6722	519	0.077	57	0.851	687	0.102	76	1.130
Fort Hope, ON	1548	9181 <sup>b</sup>	13,947,827	2,823,776	20	58	4414	1732	0.061	30	0.680	2295	0.081	40	0.900
Fort Liard, NT	500	2279	28,611,263	5,272,283	18	88	5421	430	0.008	5	0.092	570	0.011	7	0.120
Fort McPherson, NT	700	3459	7,355,811	1,617,268	22	24	5999	653	0.040	27	0.450	865	0.053	36	0.590
Fort Providence, NT	695	3123	15,095,833	6,076,099	40	58	9376	589	0.010	10	0.111	781	0.013	13	0.140
Fort Simpson, NT	1202	7529	12,022,865	7,162,220	60	45	14,199	1421	0.020	31	0.220	1882	0.026	41	0.290
Keewaywin, NT	577	3446 <sup>b</sup>	13,976,220	3,720,740	27	71	4747	650	0.017	9	0.190	861	0.023	12	0.260
Kingfisher Lake, ON	535	2724	15,344,688	5,821,303	38	61	8596	514	0.009	8	0.100	681	0.012	11	0.130
Kitchenuhmaykoosib, ON	1156	6402	7,153,687	1,931,046	27	46	3815	1208	0.063	27	0.700	1601	0.083	35	0.920
Kuujuuaq, QC	2754	20,333	8,645,587	2,225,163	26	37	5405	3836	0.172	104	1.924	5083	0.228	137	2.540
Lac-Rapide, QC	854	5082 <sup>b</sup>	26,332,079	6,525,130	25	106	5532	959	0.015	9	0.163	1271	0.019	12	0.220
Lutselk'e, NT	303	1827 <sup>b</sup>	3,427,039	1,097,486	32	24	4158	345	0.031	15	0.359	457	0.042	19	0.460
Muskat Dam Lake, ON	234	1420 <sup>b</sup>	19,778,496	6,375,860	32	73	7841	288	0.004	4	0.051	355	0.006	5	0.060
Neskantaga, ON	237	2122	16,164,314	3,618,821	22	68	4776	400	0.011	6	0.126	531	0.015	8	0.160
North Spirit Lake, ON	440	2637 <sup>b</sup>	20,682,771	6,292,740	30	88	6441	497	0.008	6	0.093	659	0.010	7	0.120
Ogoki, ON	389	2016	5,967,532	1,028,954	17	26	3519	380	0.037	14	0.410	504	0.049	19	0.540
Poplar Hill, ON	601	3588 <sup>b</sup>	22,930,738	2,755,922	12	80	3120	677	0.025	9	0.272	897	0.033	11	0.360
Sachigo Lake, ON	547	3299	12,264,651	1,864,228	15	54	3119	622	0.033	12	0.371	825	0.044	15	0.490
Sandy Lake	2641	12,365	18,264,923	3,618,155	20	80	4049	2333	0.064	29	0.721	3091	0.085	38	0.950
Shamattawa, MB	1443	6330	9,109,537	188,856	2	35	482	1194	0.632	34	7.035	1583	0.838	45	9.310
Tsay Keh Dene, BC	352 <sup>b</sup>	2119	43,240,563	11,047,410	26	155	6433	400	0.004	3	0.040	530	0.005	3	0.050
Tsigehtchic, NT	172	777	4,797,069	1,412,209	29	18	7074	147	0.010	8	0.123	194	0.014	11	0.150
Wapekeka Reserve 1, ON	437	2610	10,198,879	2,617,884	26	40	5861	492	0.019	12	0.210	653	0.025	16	0.280
Watson Lake, YT	790	14,902	30,736,151	17,783,357	58	98	16,278	2812	0.016	29	0.182	3726	0.021	38	0.230
Weagamow Lake, ON	880	4712	12,471,898	3,346,447	27	51	5933	889	0.027	18	0.303	1178	0.035	23	0.390
Webequie, ON	793	3070	7,147,091	1,492,719	21	41	3270	579	0.039	14	0.431	768	0.051	19	0.570
Xeni Gwet'in First Nation, BC	197	1201 <sup>b</sup>	30,621,205	7,162,114	23	116	5560	227	0.003	2	0.401	300	0.004	3	0.050

Key biomass statistics from spatial analyses and the energy conversion are included. See Eqs. (1)–(4) in the methodology section for analyses and energy conversion factors.  
<sup>a</sup>Communities presented in alphabetical order. Abbreviations for Canadian provinces and territories are presented in Fig. 2.  
<sup>b</sup>Annual Energy Demand (AED) estimated based on the population size (Supplementary Fig. A2). Annual energy demand and population values are from the Remote Communities Energy Database.<sup>101</sup>

( $\geq 54\%$ ) of total biomass within 10-km, and low theoretical percentage of FTA needed to meet AED ( $\leq 0.22\%$ ; Table 1). This group is also exposed to a moderate current wildfire risk (AAB of 0.15–0.32%) and future wildfire risk (AAB of 0.23–0.82%; Supplementary Table A3).

The second group includes 7 communities clustered together in Northwestern Ontario with a high current (AAB of 0.52%) and future wildfire risk (AAB of 1.84%). This group also has a low FTA needed to meet AED of less than 0.73%, but less BAFT than the first group (12–32% BAFT)



**Fig. 3 | Hierarchical clustering analysis.** The 33 communities at high risk from wildfire were grouped based on percentage of the BAFT, the theoretical percentage of fuel treatment area (FTA) needed to meet AED, and current (1981–2011) and future

AAB (2011–2041). The map above shows the location of the communities with the priority ranking. See Supplementary Table A3 for the data used in the analysis.

(Table 1). The third group contains 16 communities spread across Canada with moderate-to-high current AAB ranging from 0.36 to 0.59%, and a moderate future AAB ranging from 0.55 to 0.69%. This group has low-to-moderate BAFT (5–40%), and low-to-moderate FTA needed to meet AED (0.10–2.37%; Table 1). The fourth priority group includes 6 communities with a low current and future AAB (both  $\leq 0.23\%$ ), with BAFT less than 27% and low to moderate FTA needed to meet AED (0.04–1.92%; Table 1). Lastly, the fifth priority group includes only one community (Shamattawa, MB), which stands out from the other communities because of its relatively high proportion of FTA needed to meet AED (7.03%; Table 1).

## Discussion

This study presents the first nationwide assessment of the potential of local biomass extraction for bioenergy and wildfire risk mitigation for energy-compromised communities in Canada. Our findings reveal a high wildfire risk among 63% of these diesel-dependent communities, due to the accumulation of undisturbed forest within their vicinity. Although we conducted the analysis on a limited number of off-grid communities, our findings clearly demonstrate that remote off-grid communities, which are predominantly Indigenous, face the dual threats of wildfire and energy insecurity. With impacts of climate change increasing wildfire risks in northern Canada, it is likely that communities not currently deemed high-risk will quickly become vulnerable to wildfires. Therefore, our study highlights the urgent need for adaptive solutions to enhance both the well-being and resilience of these communities. Many of these communities are already marginalized, operating with limited infrastructure and enduring harsh environmental conditions<sup>14</sup>. Moreover, while our study focuses on northern Canadian communities, its implications reach far beyond these regions. The increased wildfire activity in the circumboreal forest has global repercussions, affecting air quality and contributing to GHG emissions worldwide<sup>6,8</sup>.

Additionally, we have shown that the biomass classified as high wildfire risk serves as an abundant local feedstock capable of meeting the bioenergy needs of the 33 diesel-dependent communities selected. Regardless of their energy needs, all communities selected in this study can theoretically meet their AED by harvesting less than 1% of the FTA per year on average. Despite the variability in biomass density between Arctic and southern communities (for example, 28 odt ha<sup>-1</sup> in Aklavik, Yukon, versus 155 odt ha<sup>-1</sup> in Tsay Keh Dene, British Columbia, Table 1), this study shows that even the most remote northern communities have the potential to develop their own local biomass supply chains given the proximity of the hazardous biomass. Given the relatively low community energy needs, the areas to be treated each year at the community level remain relatively small, ranging from 2 ha to 137 ha for an average of 26 ha, and are well below the areas currently reported in the literature. For example, a project in Arizona utilizes the output of fuel treatments on 1100 ha to supply a 3-MW biomass plant, burning 87 odt of woody biomass<sup>32</sup>. In Fort McPherson (NT), annual fuel treatments of 400 odt over 15 ha have been estimated to supply an 85-kW boiler<sup>50</sup>. Despite variability among communities in terms of energy needs and BAFT, biomass sourced from fuel treatment operations can therefore represent a consistent feedstock for their energy needs without compromising the sustainability of the ecosystem. Besides, our estimates of BAFT are likely conservative since they are based on the current above ground biomass inventory and therefore do not include potential increases in volume over time due to forest regrowth nor depletions arising from insect and disease outbreaks, drought, and wildfires.

Thoughtful planning and mobilization of local hazardous biomass can address many challenges in the bioenergy sector. Despite increasing interest in bioenergy projects led by remote and Indigenous communities in Canada, barriers to biomass supply remain. Although Canada has abundant biomass, communities and private companies struggle to develop viable business cases for mobilizing woody biomass as feedstock<sup>51,52</sup>. Key obstacles include the complexity and length of biomass supply chains—some northern communities rely on imported wood pellets transported over 3000 km on variable roads and climate conditions<sup>43</sup>, inertia from utility-owned energy systems, and inconsistent legislation and infrastructure across the country<sup>52</sup>. Utilizing local biomass instead of imported feedstock can not

only reduce these barriers but also reduce transportation costs and associated GHG emissions while creating jobs, generating revenue, and fostering expertise to support community leadership and socio-economic development. Additionally, sourcing feedstock from local biomass can improve bioenergy ecological footprint, which has been scrutinized for its potential impacts on forest ecosystems<sup>53–55</sup>. For remote Canadian communities, where GHG emissions per capita from electricity and heating are three times the national average (Box 1), bioenergy also presents GHG mitigation opportunities. Studies show substantial GHG benefits within 0–20 years for local wood chips and 2–37 years for imported sawmill residue pellets compared to fossil fuels<sup>43</sup>. Using slash piles as feedstock can also mitigate the ecological impacts of slash pile burning, such as soil degradation and immediate GHG emissions, delivering faster GHG savings compared to alternative disposal methods<sup>56</sup>.

Given the substantial amount of BAFT within a 10 bkm radius in most communities, the next steps will require further analysis to determine the optimal fuel treatment at the community level. This treatment should effectively reduce wildfire risk while ensuring there is sufficient biomass to meet the community's bioenergy need. While an abundant literature has shown that thinning and biomass removal can be effective in reducing fire risk, the effectiveness remains variable depending on factors such as fuel load, fire weather, forest type, site characteristics, topography, and treatment intensity and scale<sup>57–61</sup>. Meanwhile, a recent meta-analysis in coniferous forests of the western United States demonstrated that a combination of thinning and prescribed burning can result in a 62–72% reduction in fire severity compared to untreated areas<sup>62</sup>.

The next steps will therefore require spatial planning at the community level to design and optimize fuel treatment and determine which areas to treat with which fuel management technique, what type of fuel to prioritize for disposal, and when to conduct treatments in order to minimize risks. In addition, implementing fuel treatments and biomass operations, such as woody debris collection, drying, processing and storage, will require adapted equipment and logistics due to the remoteness of these communities and their location outside managed forests.

Further economic analyses are also needed to assess cost-sharing opportunities between the bioenergy sector and wildfire risk mitigation strategies. Conceivably, bioenergy could be part of a proactive strategy to offset the cost of fuel treatments and wildfire suppression. In Canada, the total cost of wildfire suppression has risen approximately US\$110 million per decade since 1970, a trend that is expected to continue<sup>63</sup> and has exceeded US\$725 million per year for six of the last ten years<sup>64</sup>. Depending on various factors such as the type of treatment, fuel load, forest age and structure, accessibility, terrain, and specific treatment goals<sup>24–26,65</sup>, the cost of fuel treatments can vary widely from 500 hundreds to over US\$15,000 ha. For example, in the province of British Columbia, where piling and burning of harvest residues to reduce the potential wildfire risk has been mandated for decades<sup>66,67</sup>, efforts are in progress to eliminate the practice by 2030 and instead utilize the material as a feedstock for bioenergy<sup>68</sup>.

Although we are not yet in a position to recommend fuel treatments at the community level, we stress the need to create synergies between the bioenergy sector and those undertaking fire-smart activities in order to design biomass disposal operations based on existing fuel treatment standards. Currently, these standards and guidelines are developed by a variety of organizations, including municipalities, industries, academia, Indigenous organisations, government agencies, non-governmental associations, forest managers, and wildland fire practitioners, but the bioenergy sector is not explicitly mentioned<sup>69</sup>. Fuel treatment prescriptions are also often designed according to a broad range of local factors including biodiversity, water and soil protection, riparian and visual concerns<sup>70,71</sup> and consideration of forest practices legislation, and higher-level plans and land-use objectives of the community<sup>27</sup>. Therefore, engagement and collaboration with communities will be essential to design and integrate effective wildfire mitigation strategies combined with bioenergy development adapted to local needs and context, including scale of the treatment, type of fuel, but also other land uses such as conservation of areas of cultural or ecological importance, and

integration of traditional land use<sup>72</sup>. Also, recent research in Europe underscores the importance of compensating landowners for the wildfire-regulation ecosystem services their activities provide<sup>73</sup>. Similarly, innovative financing instruments, such as payments for ecosystem services schemes, could reward communities for their role in wildfire prevention and incentivize local communities to adopt fuel treatments for bioenergy as a fire-smart strategy.

The relevance of this study's results extends far beyond the local context of northern communities in Canada. Off-grid communities exposed to wildfires are a concern in many parts of the world, particularly in rural areas of low-income and developing countries, but also in developed countries<sup>74</sup>. For example, western U.S. states, which are exposed to increased wildfire activity, have long advocated finding ways to manage the accumulation of woody debris after insect infestations or droughts, with bioenergy production seen as a viable social and economic solution<sup>75,76</sup>. In 2024 the California Department of Conservation and the USDA announced a US \$50 million investment to launch innovative technologies designed to convert biomass into carbon-free energy, with the aim of reducing wildfire risk, improving forest health, reducing GHG emissions and improving air quality in Tribal Lands and prone-fire communities<sup>77</sup>. Australia has tested similar initiatives in remote Indigenous communities<sup>78</sup>. Also, in southern Europe where decades of land abandonment resulted in the accumulation of highly flammable vegetation, bioenergy is considered within fire-smart initiatives to develop fire-resilient landscapes and increase ecosystem services<sup>79,80</sup>.

The approach proposed in this study represents a win-win opportunity that can only be realized with the integration of wildfire risk mitigation and bioenergy planning expertise and, most importantly, community involvement. There is growing acknowledgement of the key role that Indigenous knowledge and stewardship can play in informing land management practices, including mitigation prevention and restoration<sup>81,82</sup>. Indigenous fire stewardship has proven to be an effective way to reduce the risk from wildfire while protecting and restoring biodiversity and cultural values<sup>83,84</sup>. Similarly, recognizing and supporting Indigenous leadership in the development of bioenergy projects is key to unlocking the multiple benefits of clean energy transition in the North and de-risking biomass supply chains<sup>42,85</sup>.

In conclusion, we also stress the need to increase education and funding to enable communities to design cost-effective fuel treatments tailored to their bioenergy needs and infrastructure<sup>86</sup>. Given the complexity of the land-use planning required in wildfire-prone areas, successful implementation of fire-smart fuel management for bioenergy will require empowering communities to strengthen coordination and collaboration with local governments and wildland fire agencies to build capacity to respond to increased wildfire risk.

## Methods

### Selection of the communities

As of 2021, the RCED provides energy profiles and other socio-economic information for 276 remote communities, but the database is not complete because data are missing or not standardized. To homogenize the database and identify which of these communities are both diesel-dependent and at risk from wildfire, we developed a selection procedure based on 6 filters and published literature on wildfire risk. First, we selected the communities with reliance on diesel as their main power source (filter 1). Then, communities with a population smaller than 100 as well as those lacking both energy use and population information in the RCED were filtered out (filter 2). If there was no listed population for a community in the RCED but there was an AED, the 2021 Canada Census were referenced to ensure the population was over 100 inhabitants<sup>87</sup>. If population information was listed but AED was nonexistent, we estimated AED by linear regression between the population size and the AED (Supplementary Fig. A2 in the Supplementary Information section). To ensure the inclusion of permanent communities only, temporary settlements (e.g., related to mining and oil and gas) were removed (filter 3). Then, we removed the communities outside of the

boundaries of the homogeneous fire regime zones (HFRZ; filter 4) as defined by Boulanger et al.<sup>45</sup>. The 16 HFRZ's available across Canada are a key indicator of wildfire exposure at national level since they have been developed based on the annual area burned (AAB) and wildfire occurrence with each zone having similar weather, fuel, and fire regime characteristics<sup>45</sup>. Coastal communities defined as being located less than 10 km of an ocean were excluded (filter 5) due to the impossibility of calculating biomass (within a 10 km buffer) given their proximity to the ocean. Finally, to identify communities at high risk from wildfire, we estimated the accumulation of undisturbed forest (filter 6) based on the method of Parisien et al.<sup>46</sup> and the recommendations of FireSmart Canada. FireSmart Canada and the Government of Alberta<sup>88</sup> suggest a 10 km buffer serves as the FireSmart Community Zone for wildfire planning and protection purposes. If the undisturbed forest area was greater than 90% of the total forested area within 10 km, a community was classified as at high risk from wildfire, as in Parisien et al.<sup>46</sup>. Note that two Ontario communities (Armstrong and Whitesand) had overlapping buffers and therefore were merged into a single buffer, as it was assumed that the proximity of communities would allow them to share any local wood biomass supply for bioenergy, as well as fuel treatment expenditures.

Within each 10-km buffer, undisturbed forest area was identified using the time since last disturbance, namely fire or harvested areas, based on the National Burned Area Composite from the National Wildland Fire Database<sup>89</sup>, the updated version of Canada Landsat Disturbance (CanLaD) from 1985 to 2020<sup>90</sup>, and the most recent national aboveground biomass inventory<sup>47</sup>. Forests younger than 30 years old can burn<sup>91</sup> but are usually less flammable, with a reduced wildfire ignition and propagation potential, than older forests due to having less fuel after disturbance<sup>92,93</sup>. Therefore, we excluded any areas that were burned between 1990 and 2020 in the National Burned Area Composite or harvested between 1990 and 2020 in the CanLaD layer from the undisturbed forest area. Also, any pixel without aboveground biomass was excluded from the undisturbed forest area. All data layers utilized in the analysis are included in the Supplementary information section in Supplementary Table. A2.

### Quantifying biomass available from fuel treatments (BAFT)

BAFT is defined as the accumulation of undisturbed biomass (older than 30-years old) considered to be hazardous due to its proximity to the community and therefore should be targeted in priority for fuel treatment to reduce wildfire risk. In addition to the previously established 10 km buffer around the community, the amount of BAFT was specifically calculated within the WHI at the community level using the national WHI dataset<sup>48</sup> (Fig. 2 and Supplementary material section). The WHI layer used in our analysis is an aggregation of 3 types of anthropogenic interfaces: the wildland–urban interface, the wildland–infrastructure interface, and the wildland–industrial interface. Each interface is defined by the intersection of human-built structures and wildland fuels with a variable-width buffer surrounding human-built structures up to a maximum distance of 2.4 km, determined by the burning potential of the fuel type<sup>48</sup>. BAFT was calculated using a national aboveground biomass dataset in oven dry tonne per hectare (odt ha<sup>-1</sup>)<sup>47</sup>. The aboveground biomass estimate includes branches, foliage, bark, and stemwood from trees in forest stands from 2020 at 30 m resolution. In order to focus on flammable vegetation, biomass characterized as non-fuel was masked and excluded from the analysis. Finally, we excluded biomass located within 30 m of water bodies, a conservative average buffer width used throughout Canada to reduce stress on sensitive riparian ecosystems and water resources<sup>49</sup>.

### Bioenergy meeting community energy needs

To determine the amount of BAFT required to meet the annual energy demand (AED) of each community, biomass and fuel treatment area requirements for energy production were calculated based on their annual fossil fuel consumption (in Megawatt hours per year; MWh year<sup>-1</sup>).

We developed two scenarios to meet the AED of each community - a theoretical one and the other more applied. The theoretical scenario

considers raw biomass without further processing transformations using an energy conversion factor of 5.3 MWh per metric tonne of dry woody biomass (with calorific value of 19 MJ kg<sup>-1</sup> at 0% moisture content), as commonly reported in bioenergy standards<sup>94</sup>. A conversion factor assuming oven-dried wood was used because aboveground biomass estimates are in units of oven-dried tonnes in the national inventory<sup>47</sup>. The theoretical biomass amount needed at the community level was calculated as follows:

$$\text{Theoretical biomass need (odt yr}^{-1}) = \frac{\text{AED (MWh yr}^{-1})}{5.3 (\text{MWh odt}^{-1})} \quad (1)$$

The theoretical FTA needed to meet AED was calculated using the mean biomass density within the FTA of the community as follows:

$$\begin{aligned} \text{Theoretical area to be treated annually (ha yr}^{-1}) \\ = \frac{\text{Theoretical biomass need (odt yr}^{-1})}{\text{Mean biomass density (odt ha}^{-1})} \end{aligned} \quad (2)$$

The theoretical percentage of the FTA to be treated annually was calculated as follows:

$$\begin{aligned} \text{Theoretical percentage of FTA needed to meet AED (\%)} \\ = \frac{\text{Theoretical area to be treated annually (ha)}}{\text{FTA (ha)}} \times 100 \end{aligned} \quad (3)$$

The more applied scenario considers further biomass conversion into the form of commercial pellets, which are commonly used in biomass boilers. An increased energy content was used for premium-grade pellets (5.5 MWh odt<sup>-1</sup>)<sup>95</sup>. It was assumed that the loss of biomass during the pelletization process (i.e. when raw biomass is converted into pellets), was 25%<sup>96</sup>, which was accounted for by increasing the volume of biomass needed to meet AED by 25% (multiplying by 1.25). This also accounts for the portion of aboveground biomass, such as bark and foliage, that is not usable in the pelletization process. Excluding these components helps avoid contamination, reduces ash content, and improves the energy efficiency of the pellets. An energy efficiency of 90% was assumed for biomass boilers based on their current operating average in Canada<sup>31,97</sup>. This was accounted for by increasing the volume of biomass needed by 10% (multiply by 1.10). The equation to calculate the operational biomass need is presented below. The operational area to be treated annually, and percentage of FTA needed to meet AED were calculated using the same steps presented above for the theoretical amounts, using mean biomass density and FTA.

$$\begin{aligned} \text{Operational biomass need (odt yr}^{-1}) \\ = \left( \left( \text{AED (MWh yr}^{-1}) \times \frac{1 (\text{odt})}{5.5 (\text{MWh})} \right) \times 1.10 \right) \times 1.25 \end{aligned} \quad (4)$$

### Hierarchical clustering analysis of the communities

To determine which communities would benefit the most from using biomass from fuel treatments as feedstock for bioenergy, we performed a hierarchical clustering analysis of the communities based on the BAFT, the theoretical percentage of FTA needed to meet AED, and current and future projected annual area burned (AAB). We used the *heatmaply* R package<sup>98</sup> to perform the hierarchical clustering method and the data was scaled by subtracting the minimum and dividing by the maximum of all observations. This transformation brings the data for all variables to a 0 to 1 scale, while preserving the shape of each variable's distribution. The clustering method, centroid, was chosen using the *dendextend* R package<sup>99</sup> and the optimal number of clusters, five, was determined based on a consensus of many methods using the parameters R package<sup>100</sup>. Further details on the cluster analysis, including the R code, is available in the Supplementary information section. For each of the 33 communities, the current and future AAB was estimated from the HFRZ's<sup>45</sup> according to the community's centroid.

Estimates for current (1981–2010) and future (2011–2040) AAB were projected based on a refined version of the multivariate adaptive spline regression models developed by Boulanger et al.<sup>45</sup> for each HFRZ, which estimates monthly AAB from current and future fire-weather and meteorological parameters. End-of-century climate conditions as simulated under the RCP 4.5 were used for future AAB projections.

### Data availability

The data used in this analysis are publicly available from various open-access government sources, including the Government of Canada Open Data portal and Natural Resources Canada's national data repositories. Community dataset were downloaded from the Remote Communities Energy Database <https://open.canada.ca/data/en/dataset/0e76433c-7aeb-46dc-a019-11db10ee28dd>. The Homogenous Fire Regime Zones (HFRZ) calculated with the Canadian National Fire Database were downloaded from <https://open.canada.ca/data/en/dataset/779f9b2d-d010-4ddc-b3b3-57a9ac7631b2>. The Wildland Human Interface dataset was downloaded from the Mapping Canadian wildland fire interface areas project <https://doi.org/10.1071/WF16221> available at <https://osdp-psdo.canada.ca/dp/en/search/metadata/NRCAN-CFS-1-38282>. The aboveground biomass dataset was downloaded from the new The Spatialized Canadian National Forest Inventory data product (SCANFI) available at <https://open.canada.ca/data/en/dataset/18e6a919-53fd-41ce-b4e2-44a9707c52dc>. Canada Landsat Disturbance data (wildfire, harvest, and insect) were downloaded at <https://open.canada.ca/data/en/dataset/660b7c6a-cdec-4c02-90c7-d63e91825c42>. National Burned Area Composite dataset was downloaded from the Canadian Wildland Fire Information System available at <https://cwfis.cfs.nrcan.gc.ca/datamart/metadata/nbac>.

### Code availability

Code and data for replicating the analysis are archived at the Centre for Open Science OSF data repository OSF Fire-smart Bioenergy nexus <https://doi.org/10.17605/OSF.IO/ZQPT5>.

Received: 2 September 2024; Accepted: 17 April 2025;

Published online: 09 May 2025

### References

1. Jones, M. W. et al. Global and regional trends and drivers of fire under climate change. *Rev. Geophys.* **60**, e2020RG000726 (2022).
2. Clarke, H. et al. Forest fire threatens global carbon sinks and population centres under rising atmospheric water demand. *Nat. Commun.* **13**, 7161 (2022).
3. Centre for Research on the Epidemiology of Disasters (CRED). 2021 Disasters in numbers. Available at: <https://www.emdat.be/publications> (2023).
4. Thomas, D. et al. *The Costs and Losses of Wildfires, Special Publication (NIST SP)* (National Institute of Standards and Technology, 2017). <https://doi.org/10.6028/NIST.SP.1215>. Accessed 20 July 2024.
5. Pandey, P. et al. A global outlook on increasing wildfire risk: current policy situation and future pathways. *Trees People* **14**, 100431 (2023).
6. Kolden, C. A. et al. Wildfires in 2023. *Nat. Rev. Earth Environ.* **5**, 238–240 (2024).
7. Dosiou, A. et al. Employing Copernicus Land Service and Sentinel-2 Satellite Mission Data to Assess the Spatial Dynamics and Distribution of the Extreme Forest Fires of 2023 in Greece. *Fire* **7**, 20 (2024).
8. Jain, P. et al. Drivers and Impacts of the Record-Breaking 2023 Wildfire Season in Canada. *Nat. Commun.* **15**, 6764 (2024).
9. Boulanger, Y. et al. The 2023 wildfire season in Quebec: an overview of extreme conditions, impacts, lessons learned and considerations for the future. *Can. J. For. Res.* **55**, 1–21 (2025).
10. Coogan, S. C. et al. Scientists' warning on wildfire – a Canadian perspective. *Can. J. Res.* **49**, 1015–1023 (2019).

11. Turco, M. et al. Exacerbated fires in Mediterranean Europe due to anthropogenic warming projected with non-stationary climate-fire models. *Nat. Commun.* **9**, 1–9 (2018).
12. Tymstra, C. et al. Wildfire management in Canada: Review, challenges and opportunities. *Prog. Disaster Sci.* **5**, 100045 (2020).
13. Velasco Hererra, V. M. et al. Past and Future of Wildfires in Northern Hemisphere's Boreal Forests. *Ecol. Manag.* **504**, 119859 (2022).
14. Erni, S. et al. Exposure of the Canadian Wildland-Human Interface (WHI) and population to wildland fire, under current and future climate conditions. *Can. J. Res.* **51**, 1053–1065 (2021).
15. Tang, W. et al. Global expansion of wildland-urban interface (WUI) and WUI fires: insights from a multiyear worldwide unified database (WUWUI). *Environ. Res. Lett.* **19**, 044028 (2024).
16. Christianson, A. Social science research on Indigenous wildfire management in the 21st century and future research needs. *Int. J. Wildland Fire* **24**, 190–200 (2015).
17. McGee, T. K. Evacuating first nations during wildfires in Canada. *Fire Saf. J.* **120**, 103120 (2021).
18. Tepley, A. J. et al. Wildfire evacuation patterns and syndromes across Canada's forested regions. *Ecosphere* **13**, e4255 (2022).
19. Wotton, B. M. et al. Potential climate change impacts on fire intensity and key wildfire suppression thresholds in Canada. *Environ. Res. Lett.* **12**, 095003 (2017).
20. Partners in Protection. *FireSmart: Protecting Your Community from Wildfire* (Partners in Protection, 1999).
21. Hirsch, K. et al. Fire-smart forest management: a pragmatic approach to sustainable forest management in fire-dominated ecosystems. *Chron.* **77**, 357–363 (2001).
22. Hoffman, C. M. et al. Wildland Fuel Treatments. In: *Encyclopedia of Wildfires and Wildland-Urban Interface (WUI) Fires* (Springer, 2018).
23. Brodie, E. G. et al. Forest thinning and prescribed burning treatments reduce wildfire severity and buffer the impacts of severe fire weather. *Fire Ecol.* **20**, 17 (2024).
24. Martin, K. J. & Jakes, P. J. Costs and effectiveness of fuel treatments in British Columbia's forests. *Policy Econ.* **20**, 88–97 (2012).
25. Huggett, R. J. Jr. et al. Efficacy of mechanical fuel treatments for reducing wildfire hazard. *Policy Econ.* **10**, 408–414 (2008).
26. Kreidler, J. et al. Cost-effective fuel treatment planning: A theoretical justification and case study. *Int. J. Wildland Fire* **29**, 42–56 (2019).
27. Beverly, J. L. et al. Stand-level fuel reduction treatments and fire behaviour in Canadian boreal conifer forests. *Fire* **3**, 35 (2020).
28. Agee, J. K. & Skinner, C. N. Basic principles of forest fuel reduction treatments. *Ecol. Manag.* **211**, 83–96 (2005).
29. Westhaver, A. et al. FireSmart®-ForestWise: Managing wildlife and wildfire risk in the wildland/urban interface—A Canadian case study. In: *Proc. USDA For. Serv.* 347 (USDA, 2007).
30. Campbell, R. M. & Anderson, N. M. Comprehensive comparative economic evaluation of woody biomass energy from silvicultural fuel treatments. *J. Environ. Manag.* **250**, 109422 (2019).
31. Welling, H. H. & Shaw, T. J. *Energy from wood biomass combustion in rural Alberta applications* (Government of Alberta, 2007).
32. Neary, D. G. & Zieroth, E. J. Forest bioenergy system to reduce the hazard of wildfires: White Mountains, Arizona. *Biomass. Bioenergy* **31**, 638–645 (2007).
33. Volpé, S. & Roser, D. *Improving the efficiency of forest biomass supply chains in Canada* (FPInnovations, 2014).
34. Tubbesing, C. L. et al. Characterization of the woody biomass feedstock potential resulting from California's drought. *Sci. Rep.* **10**, 1–14 (2020).
35. Regos, A. et al. Synergies between forest biomass extraction for bioenergy and fire suppression in mediterranean ecosystems: insights from a storyline-and-simulation approach. *Ecosystems* **19**, 786–802 (2016).
36. Verón, S. R. et al. Assessing the potential of wildfires as a sustainable bioenergy opportunity. *GCB Bioenergy* **4**, 634–641 (2012).
37. Reed, G. et al. *For Our Future: Indigenous Resilience Report* (Ottawa, Ontario. Government of Canada, 2024).
38. Touchette, Y. et al. Costing energy and fossil fuel subsidies in Nunavut: a mapping exercise. Available at: [https://wwf.ca/wp-content/uploads/2020/03/Tracking-Diesel-Fuel-Subsidies\\_April-2017.pdf](https://wwf.ca/wp-content/uploads/2020/03/Tracking-Diesel-Fuel-Subsidies_April-2017.pdf) (2022).
39. Lovekin, D. Heerema. The true cost of energy in remote communities. Understanding diesel electricity generation terms and economics, 2nd ed. Available at: <https://www.pembina.org/reports/diesel-cost-backgrounder-2019.pdf> (2019). Accessed 4 January 2021.
40. Sauder, E. A. *Fort McPherson costing associated with community willow harvesting* (FPInnovations, 2012).
41. Aki Energy. *A plan to end diesel dependency* (Winnipeg, 2017).
42. Buss, J. et al. De-risking wood-based bioenergy development in remote and Indigenous communities in Canada. *Energies* **14**, 2603 (2021).
43. Buss, J. et al. Greenhouse gas mitigation potential of replacing diesel fuel with wood-based bioenergy in an arctic Indigenous community: A pilot study in Fort McPherson, Canada. *Biomass. Bioenergy* **159**, 106367 (2022).
44. Government of Canada. Clean Energy for Rural and Remote Communities Program. <http://natural-resources.canada.ca/reducingdiesel> (2023).
45. Boulanger, Y. et al. A refinement of models projecting future Canadian fire regimes using homogeneous fire regime zones. *Can. J. Res.* **44**, 365–376 (2014).
46. Parisien, M. A. et al. Fire deficit increases wildfire risk for many communities in the Canadian boreal forest. *Nat. Commun.* **11**, 1–9 (2020).
47. Guindon, L. et al. A new approach for Spatializing the Canadian National Forest Inventory (SCANFI) using Landsat dense time series. *Can. J. For. Res.* **554**, 793–815 (2024).
48. Johnston, L. M. & Flannigan, M. D. Mapping Canadian wildland fire interface areas. *Int. J. Wildland Fire* **27**, 1–14 (2018).
49. Lee, P., Smyth, C. & Boutin, S. Quantitative review of riparian buffer width guidelines from Canada and the United States. *J. Environ. Manag.* **70**, 165–180 (2004).
50. Varem-Sanders, T. Fort McPherson willow fuelwood project: Physical measurements of existing stands, and estimates of sustainable harvest Rates (2012).
51. Mansuy, N. et al. Woody biomass mobilization for bioenergy in a constrained landscape: A case study from Cold Lake First Nations in Alberta, Canada. *Energies* **13**, 6289 (2023).
52. Menghwani, V. et al. Bioenergy for community energy security in Canada: Challenges in the business ecosystem. *Energies* **16**, 19961073 (2023).
53. Mansuy, N. et al. Salvage harvesting for bioenergy in Canada: From sustainable and integrated supply chain to climate change mitigation. *Wiley Interdiscip. Rev. Energy Environ.* **7**, 1187–1207 (2018).
54. Nicholls, D. et al. International bioenergy synthesis—Lessons learned and opportunities for the western United States. *Ecol. Manag.* **257**, 1647–1655 (2009).
55. Searchinger, T. et al. EU climate plan sacrifices carbon storage and biodiversity for bioenergy. *Nature* **612**, 27–30 (2022).
56. Serra, R. et al. From conventional to renewable natural gas: can we expect GHG savings in the near term?. *Biomass. Bioenergy* **131**, 105396 (2019).
57. Covington, W. W. et al. Thinning and prescribed fire reduce fire hazard in Western United States ponderosa pine forests. *Fire. Ecol.* **2**, 3–19 (1997).
58. Cohen, J. D. et al. *Effects of thinning and similar stand treatments on fire behavior in Western forests*. USDA For. Serv. Proc. RMRS-P-29 (USDA, 2003).

59. Hessburg, P. F. et al. Thinning and prescribed fire effects on overstory tree and snag structure in dry coniferous forests of the interior Pacific Northwest. *For. Ecol. Manage.* (2005).
60. Collins, B. M. et al. Effectiveness of fuel treatments for mitigating wildfire risk and sequestering forest carbon: a case study in the Lake Tahoe Basin. *For. Ecol. Manage.* **323**, 114–125 (2014).
61. Martinson, E. J. & Omi, P. N. Fuel treatments and fire severity: a meta-analysis. *Res. Pap. RMRS-RP-103* (US Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2013).
62. Davis, K. T. et al. Tamm review: A meta-analysis of thinning, prescribed fire, and wildfire effects on subsequent wildfire severity in conifer dominated forests of the Western US. *Ecol. Manage.* **561**, 121885 (2024).
63. Hope, E. S. et al. Wildfire suppression costs for Canada under a changing climate. *PLoS One* **11**, e0157425 (2016).
64. NRCan. Cost of wildland fire protection. <https://natural-resources.canada.ca/climate-change/climate-change-impacts-forests/forest-change-indicators/cost-fire-protection/17783> (2024).
65. Pavel, M. et al. *Operational Manual for Commercial Thinning in British Columbia* (No. 93) (TR, 2021).
66. MacBean, A. P. Silviculture and cutting methods in British Columbia. *Chron.* **25**, 164–169 (1949).
67. Moss, A. *A comparative study of forest policy and management practices in Scotland and British Columbia, with particular reference to the use of Pinus contorta in Scottish forestry* (KB Thesis Scanning Project, 1969).
68. Government of British Columbia. Clean BC Roadmap to 2030. Available at: [https://www2.gov.bc.ca/assets/gov/environment/climatechange/action/cleanbc/cleanbc\\_roadmap\\_2030.pdf](https://www2.gov.bc.ca/assets/gov/environment/climatechange/action/cleanbc/cleanbc_roadmap_2030.pdf) (2022).
69. Partners in Protection. *FireSmart: Protecting Your Community from Wildfire*, 2nd ed. (Partners in Protection, 2003).
70. Gannon, B. M. et al. Prioritising fuels reduction for water supply protection. *Int. J. Wildland Fire* **28**, 785–803 (2019).
71. McCaffrey, S. & Graham, R. Science information for informing forest fuel management in the dry forests of the western United States. *J. Forest.* **105**, 73–76 (2007).
72. Wyncoop, M. D. et al. Getting back to fire sumés: exploring a multi-disciplinary approach to incorporating traditional knowledge into fuels treatments. *Fire Ecol.* **15**, 1–18 (2019).
73. Lecina-Diaz, J. et al. Incorporating fire-smartness into agricultural policies reduces suppression costs and ecosystem services damages from wildfires. *J. Environ. Manage.* **337**, 117707 (2023).
74. International Renewable Energy Agency. Renewable energy for remote communities: A guidebook for off-grid projects. Available at: <https://www.irena.org/Publications/2023/Nov/Renewable-energy-for-remote-communities-A-guidebook-for-off-grid-projects> (2023).
75. Evans, A. M. & Finkral, A. J. From renewable energy to fire risk reduction: a synthesis of biomass harvesting and utilization case studies in US forests. *GCB Bioenergy* **1**, 211–219 (2009).
76. Ganz, D. J. et al. Fire behavior modeling to assess net benefits of forest treatments on fire hazard mitigation and bioenergy production in Northeastern California. In *Butler, Bret W.; Cook, Wayne, comps. The Fire Environment—Innovations, Management, and Policy; Conference Proceedings. 26–30 March 2007; Destin, FL. Proceedings RMRS-P-46CD. 143–157* (U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, 2007).
77. U.S. Department of Energy. DOE announces \$46 Million to explore new technologies that convert carbon and waste into clean energy. Department of Energy. <https://www.energy.gov/articles/doe-announces-46-million-explore-new-technologies-convert-carbon-and-waste-clean-energy>.
78. Trombley, J. B. et al. Utilizing Locally Available Bioresources for Powering Remote Indigenous Communities: A Framework and Case Study. *Energies* **16**, 666 (2023). (2023).
79. Regos, A. et al. Nature-based solutions to wildfires in rural landscapes of Southern Europe: let's be fire-smart. *Int. J. Wildland Fire* **32**, 942–950 (2023).
80. Ascoli, D. et al. Fire-smart solutions for sustainable wildfire risk prevention: Bottom-up initiatives meet top-down policies under EU green deal. *Int. J. Disaster Risk Reduct.* **92**, 103715 (2023).
81. Hoffman, K. M. et al. The right to burn: barriers and opportunities for Indigenous-led fire stewardship in Canada. *FACETS* **7**, 464–481 (2022).
82. Burrows, N. D. et al. Integrating Indigenous knowledge of wildland fire and western technology to conserve biodiversity in an Australian desert. In: *Bridging Scales and Epistemologies: Linking Local Knowledge and Global Science in Multiscale Assessments Conference* (Alexandria, 2004).
83. Mansuy, N. et al. Indigenous protected and conserved areas (IPCAs): Canada's new path forward for biological and cultural conservation and Indigenous well-being. *FACETS* **8**, 1–16 (2023).
84. Lake, F. K. & Christianson, A. C. Indigenous fire stewardship. In: *Encyclopedia of wildfires and wildland-urban interface (WUI) fires* 714–722 (Springer International Publishing, 2020).
85. Bullock, R. C. et al. Open for bioenergy business? Perspectives from Indigenous business leaders on biomass development potential in Canada. *Energy Res. Soc. Sci.* **64**, 101446 (2020).
86. Pacheco, R. et al. Wildfire Education: A Review Across the Globe. In *Fire Hazards: Socio-economic and Regional issues*, (eds. Rodrigo-Comino, J. & Salvati, L.), [https://doi.org/10.1007/978-3-031-50446-4\\_3](https://doi.org/10.1007/978-3-031-50446-4_3) (2024).
87. Statistics Canada. Census Profile, 2021 Census of Population. Available at: <https://www12.statcan.gc.ca/census-recensement/2021/dp-pd/prof/index.cfm?Lang=E> (2022).
88. Government of Alberta. FireSmart Guidebook for Community Protection: A Guidebook for Wildland/Urban Interface Communities (2013). Available at: <https://wildfire.alberta.ca/firesmart/documents/FireSmart-Guide-CommunityProtection-Nov2013.pdf> (2022).
89. Hall, R. J. et al. Generating annual estimates of forest fire disturbance in Canada: the National Burned Area Composite. *Int. J. Wildland Fire* <https://doi.org/10.1071/WF19201> (2020).
90. Guindon, L. et al. Canada Landsat Disturbance (CanLaD): a Canada-wide Landsat-based 30-m resolution product of fire and harvest detection and attribution since 1984. Available at: <https://open.canada.ca/data/en/dataset/add1346b-f632-4eb9-a83d-a662b38655ad>.
91. Parks, S. A. et al. Fine-scale spatial climate variation and drought mediate the likelihood of reburning. *Ecol. Appl.* **28**, 573–586 (2018).
92. Beverly, J. L. Time since prior wildfire affects subsequent fire containment in black spruce. *Int. J. Wildland Fire* **26**, 919–929 (2017).
93. Erni, S. et al. Stand age influence on potential wildfire ignition and spread in the boreal forest of northeastern Canada. *Ecosystems* **21**, 1471–1486 (2018).
94. ForestResearch. Available at: <https://www.forestresearch.gov.uk/tools-and-resources/fthr/biomass-energy-resources/reference-biomass/facts-figures/typical-calorific-values-of-fuels/>. (2024)
95. Natural Resources Canada (NRCan). Solid Biofuels Bulletin No. 2 Primer for solid biofuels. Definitions, classes/grades, and fuel properties. Graded wood pellets. <https://www.nrcan.gc.ca/energy/energy-sources-distribution/renewables/bioenergy-systems/biofuels/solid-biofuels/7399> (2022).
96. Mansuy, N. et al. Sustainable biomass supply chains from salvage logging of fire-killed stands: A case study for wood pellet production in eastern Canada. *Appl. Energy* **154**, 62–73 (2015).

97. Pantaleo, A. M. et al. Small scale biomass CHP: Techno-economic performance of steam vs gas turbines with bottoming ORC. *Energy Procedia* **82**, 825–832 (2015).
98. Galili, T. et al. heatmaply: an R package for creating interactive cluster heatmaps for online publishing. *Bioinformatics*. <https://doi.org/10.1093/bioinformatics/btx657> (2017).
99. Galili, T. dendextend: an R package for visualizing, adjusting, and comparing trees of hierarchical clustering. *Bioinformatics*. <https://doi.org/10.1093/bioinformatics/btv428> (2015).
100. Lüdtke, D. et al. Extracting, computing and exploring the parameters of statistical models using R. *J. Open Source Softw.* **53**, 2445 (2020).
101. Government of Canada. Remote Communities Energy Database. Available at: <https://open.canada.ca/data/en/dataset/0e76433c-7aeb-46dc-a019-11db10ee28dd> (2022).
102. Lovekin, D. Heerema. Diesel, renewables, and the future of Canada's remote communities. Available at: <https://www.pembina.org/blog/remote-microgrids-intro> (2019).
103. Mansuy, N. & Buss, J. Développer la bioénergie pour atténuer les gaz à effet de serre dans les collectivités nordiques et autochtones du Canada. *Climatoscope* **4**, 91–95 (2022).

## Acknowledgements

This project was financed by grant CFS-23-013 from Office of Energy Research and Development (OERD) awarded to Nicolas Mansuy. We would like to thank FireSmart Canada for permission to use their brand. We gratefully acknowledge the Pembina Institute for granting permission to use their data, which are presented in Box 1.

## Author contributions

N.M. secured funding, designed the analyses, and drafted the manuscript. J.B. collected data, led the analysis, and drafted the manuscript. K.H. drafted and reviewed the manuscript. L.G. provided biomass data and reviewed the manuscript. F.-N.R., M.L., and A.R. reviewed the manuscript. Y.B. provided fire data and reviewed the manuscript. C.C.A. designed the figures and reviewed the manuscript. M.-A.P. reviewed the manuscript. All authors contributed to the reviewing, editing, and overall improvement of the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

**Supplementary information** The online version contains supplementary material available at <https://doi.org/10.1038/s43247-025-02313-1>.

**Correspondence** and requests for materials should be addressed to Nicolas Mansuy.

**Peer review information** *Communications Earth & Environment* thanks Kate Magargal and Kamaljit Sangha, reviewer(s) for their contribution to the peer review of this work. Primary Handling Editors: Mengjie Wang. [A peer review file is available].

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