

# Environmental and Hunter-Gatherer Responses to the White River Ash East Volcanic Eruption in the Late Holocene Canadian Subarctic

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**ABSTRACT.** The eastern lobe of the Alaskan White River Ash volcanic event of AD 846–848 blanketed portions of Yukon and Northwest Territories, Canada, in 5 to 50 cm of tephra. The eruption has been linked to concurrent changes among hunter-gatherers, including the spread of new technologies and the continent-wide migration of a group of Dene ancestors from Subarctic Canada to the United States. We use published palaeoenvironmental data (primarily pollen and charcoal profiles) as well as studies of modern ash fall ecology and human health hazards associated with eruptions to reconstruct effects of the White River Ash east event on northern hunter-gatherer subsistence. While many components of local ecosystems appear to have rebounded quickly from ash deposition, we deduce a more pronounced impact on the important game species of caribou and salmon, the seasonal migration paths of which were intersected by thick deposits of ash. A trophic model informed by palaeoenvironmental data and ethnohistoric records suggests that negative biological effects of the ash temporarily pushed hunter-gatherer populations to neighbouring and less affected kin groups for up to 100 years. This synthesis contextualises archaeological theories of human responses to ecological disturbance events in circumpolar landscapes.

**Key words:** Subarctic; hunter-gatherer; volcano; tephra; White River Ash; ethnohistory; pollen; ecology; disaster; palaeoenvironment; archaeology

**RÉSUMÉ.** Le lobe occidental du dépôt de cendres volcaniques White River Ash, en Alaska, remontant aux années 846–848 A.D., a recouvert certaines parties du Yukon et des Territoires du Nord-Ouest, au Canada, d'une couche de téphra de 5 à 50 cm. Cette éruption a été liée à des changements simultanés chez les chasseurs-cueilleurs, dont l'adoption de nouvelles technologies et la migration à l'échelle du continent d'un groupe d'ancêtres dénés, de la zone subarctique canadienne jusqu'aux États-Unis. Nous avons publié des données paléoenvironnementales (principalement des profils de pollen et de charbon de bois) ainsi que des études d'écologie moderne de chutes de cendres et de dangers pour la santé des êtres humains découlant d'éruptions afin de reconstituer les effets du dépôt occidental White River Ash sur la subsistance des chasseurs-cueilleurs nordiques. Même si de nombreuses composantes des écosystèmes locaux semblent s'être remises rapidement des dépôts de cendres, nous déduisons que les répercussions ont été plus prononcées sur les espèces de gibier de caribou et sur le saumon, dont les voies de migration saisonnière croisaient les épais dépôts de cendres. Un modèle trophique établi à l'aide de données paléoenvironnementales et d'enregistrements ethnohistoriques suggère que les effets biologiques négatifs des cendres ont poussé temporairement les populations de chasseurs-cueilleurs chez des groupes apparentés avoisinants et moins touchés pendant une centaine d'années. Cette synthèse met en contexte les théories archéologiques se rapportant aux réactions humaines vis-à-vis d'événements de perturbation écologique dans les paysages circumpolaires.

**Mots clés :** subarctique; chasseur-cueilleur; volcan; téphra; White River Ash; ethnohistoire; pollen; écologie; catastrophe; paléoenvironnement; archéologie

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## INTRODUCTION

Large-scale natural disturbances in the past have garnered archaeological interest as catalysts of change. Volcanic eruptions, earthquakes, and tsunamis have been portrayed as stimuli of new modes of cultural resilience (Jacoby et al., 1999; Williams, 2002; Losey, 2005; Elson et al., 2007; Sheets, 2007; Begét et al., 2008; Fitzhugh, 2012; Torrence, 2016; Mohlenhoff and Butler, 2017) and as instigators of unrest, conflict, and forced relocation (MacKie, 1961; Black, 1975; Dumond, 1979; Sheets et al., 1991; Cronin and Cashman, 2007; Riede, 2016a). Studies of past disasters are best supported by accurate reconstructions of an event's ecological parameters, including magnitude, duration, impact on flora and fauna, and implications for human access to food, water, and shelter (Grattan, 2006; VanderHoek, 2009; Riede, 2014; Mulliken, 2016). This paper investigates a hypothesis that a late Holocene volcanic eruption in Subarctic Canada spurred human population displacement and technological change (Hare et al., 2012; Kristensen et al., 2019a). We examine impacts of the eruption on hunter-gatherers and their trophic pyramid, including flora (based on pollen and charcoal records) and fauna (fish and ungulates based on ancient DNA and studies of modern ash falls), as well as human health (based on records of pre-contact [the time period prior to European arrival in the 1800s] physiology and modern disaster studies). This research helps contextualise a large-scale disturbance event that has been implicated in archaeological theories without thorough investigation of its biological effects.

The White River Ash east (WRAe) volcanic eruption originated in the Wrangell volcanic field (Fig. 1) near Mount Churchill in Alaska (Lerbekmo and Campbell, 1969; Lerbekmo et al., 1975; McGimsey et al., 1992; Richter et al., 1995; Robinson, 2001; Preece et al., 2014). The Plinian eruption (Volcanic Explosivity Index or VEI of 6.0) produced an estimated 47 km<sup>3</sup> of bulk ejecta (22.5 km<sup>3</sup> dense rock equivalent [DRE]) that spread east across southern Yukon and the Northwest Territories (NWT) (Lerbekmo, 2008). The WRAe event is dated to AD 846–848 or 1104–1102 calendar years before present (cal yrs BP) based on preserved cryptotephra horizons in European bogs and Greenlandic ice cores (Jensen et al., 2014). It is thought that the eruption occurred in late fall or early winter because of 1) the typically westerly wind patterns during that season (Hanson, 1965; West and Donaldson, 2002), 2) the preservation of ash on steep slopes that would only occur if covered by snow (Hanson, 1965; Lerbekmo and Campbell, 1969), and 3) the preservation of fractured clasts of ash and pumice in floodplain deposits, which implies relatively rapid freezing of ash sediment in some areas immediately prior to snowfall (West, 2007).

The WRAe event ranks among the five largest eruptions in North America during the past 10 000 years (VanderHoek and Nelson, 2007). In a comparison of ejecta volume, WRAe lies between the Mount Mazama (U.S.) eruption at 7630 cal yrs BP (VEI = 7.0, > 180 km<sup>3</sup> of bulk ejecta,

50 km<sup>3</sup> DRE) (Lidstrom, 1971; Bacon, 1983; Zdanowicz et al., 1999; Egan, 2016) and the AD 1883 eruption of Krakatau in Indonesia (VEI = 6.0, 19 km<sup>3</sup> of bulk ejecta, 12 km<sup>3</sup> DRE) (Rampino and Self, 1982; Mandeville et al., 1996). Five to 50 cm of WRAe tephra fell across a Yukon landscape (Fig. 1) in which archaeologists have uncovered a long history of hunter-gatherer occupation extending from 13 000 yrs BP to European contact at roughly 150 yrs BP (Workman, 1978; Hare, 1995; Thomas, 2003; Easton, 2007; Easton et al., 2011; Castillo, 2012). Aside from its value as a chronostratigraphic marker (Davies et al., 2016), WRAe has received comparatively little attention from ecologists (Kuhn et al., 2010; Bunbury and Gajewski, 2013; Hutchinson et al., 2019).

Archaeologists have implicated WRAe tephra as a stimulus of cultural change in the Canadian Subarctic (Workman, 1974, 1979; Ives, 1990; Clark, 1991; Hare et al., 2012; Mullen, 2012; cf. Gordon, 2012). The event has assumed continental importance as a proposed trigger for the migration of Dene ancestors over a linear distance of 3000 km from northern Canada into the U.S. Great Basin and Southwest (Haskell, 1987; Ives, 2003, 2010, 2014; Magne and Matson, 2010; Magne, 2012; Seymour, 2012; Hill and Trabert, 2018).

Our objective here is to reconstruct the biological effects of the WRAe event. We rely principally on published pollen and charcoal records that capture conditions before and after the WRAe event and have been sufficiently studied to warrant a synthesis indicative of trends across the study area. Regional diatom, chironomid, ostracod, and isotope records that span the Holocene epoch (Bradbury and Whiteside, 1980; Anderson et al., 2005, 2007, 2011; Chakraborty et al., 2010; Bunbury and Gajewski, 2012, 2013; Rainville, 2016) are not discussed to the same extent as the pollen and charcoal records because their limited geographic distribution prevents an informative regional synthesis. Pollen and charcoal research in the study area has been conducted in a variety of habitats, elevations, and thicknesses of tephra deposition and reveals diverse impacts of the eruption. Pollen and charcoal syntheses are followed by a discussion of hunter-gatherer subsistence and trophic links between tephra and major game species.

This synthesis contributes to broader theories and international studies of human resilience and adaptability to natural disturbances, which are often portrayed as uniformly devastating disasters (Sheets, 1980; Bawden and Reycraft, 2000; Nunn, 2000; Torrence and Grattan, 2002; Williams, 2002; Losey, 2005; Bradtmöller et al., 2017; Fitzhugh et al., 2019; Torrence, 2019). This work highlights temporal gaps in archaeological research of natural disturbances, which modern analogues can only partially address. The ability to understand palaeoenvironmental impacts on people depends in part on the availability of high-resolution records that reveal changes that influenced human survival on the order of weeks, months, and years, as opposed to the scale of decades and centuries targeted by most palaeoenvironmental research.

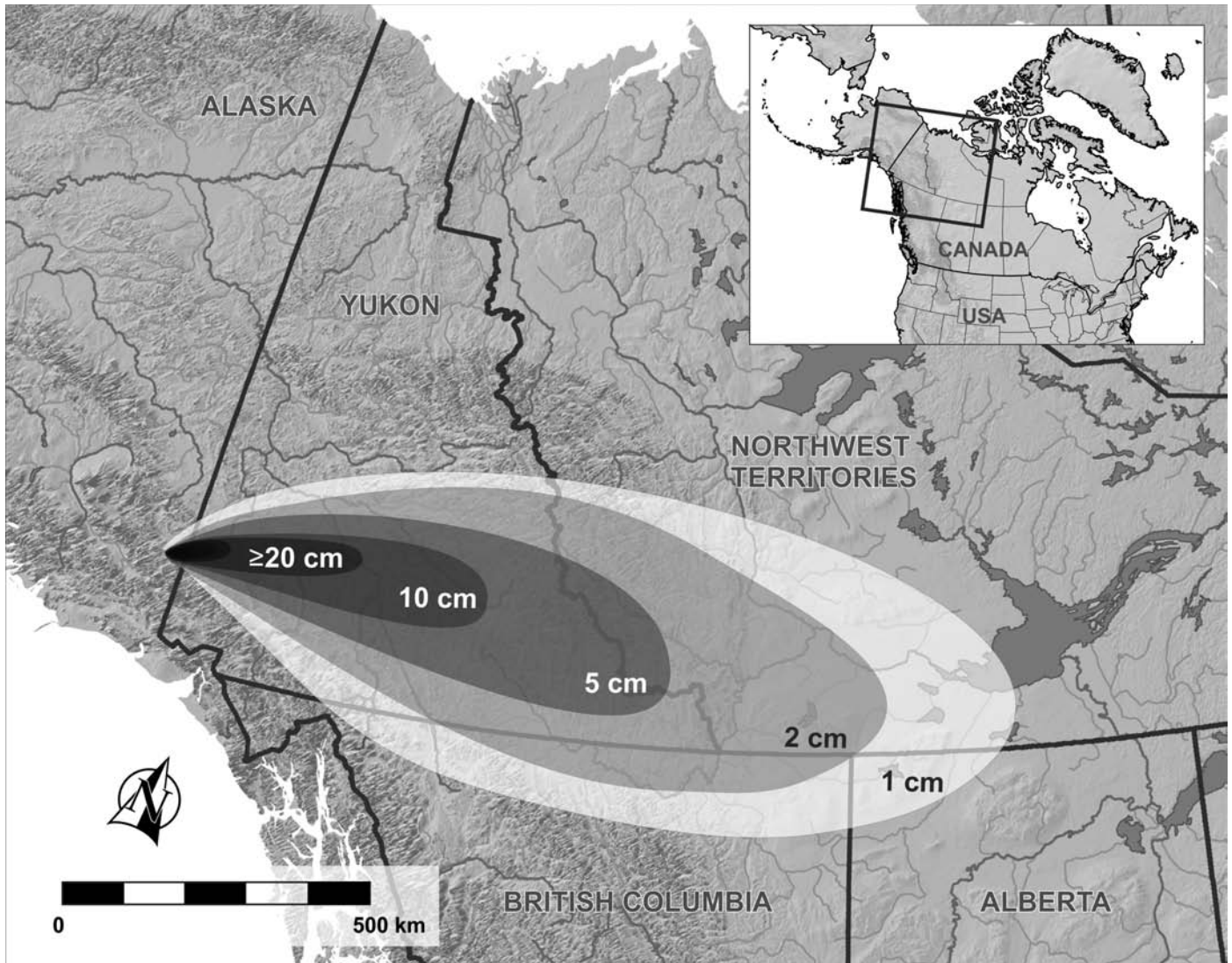


FIG. 1. Study area and inferred WRAe tephra isopachs (adapted from Lerbekmo, 2008). Isopachs are lines joining a common thickness of ash, here based on terrestrial sediment records. These isopachs are post-compression; tephra compresses up to 50% in the decades following deposition (Aramaki, 1956; Gorshkov and Dubik, 1970:283; Riehle, 1973; Hildreth and Drake, 1992; Guichard et al., 1993; Larsen and Eiriksson, 2008; Blong and Enright, 2011; Engwell et al., 2013) although the compression ratio of WRAe is unknown. The isopachs mark occurrences of visible tephra. It is likely that the ashfall extent is much greater, but would only be detectable by cryptotephra occurrence. Delineation of the ashfall through mapping cryptotephra occurrence remains to be done in this region.

## PALAEOENVIRONMENTAL RECORDS

### *Pollen: Methods and Limitations*

Published pollen records from lakes, peatlands, and wetlands are the primary sources of data used here to infer vegetation change associated with the WRAe eruption (Fig. 2). From a total of 55 pollen diagrams in the study area (Table 1), we excluded 21 because they lacked temporal resolution (e.g., visible tephra were not detected, they lacked bracketing radiocarbon dates, or the cores failed to penetrate through the ash, making it impossible to evaluate changes before and after the event). We input the remaining 34 pollen diagrams into CorelDRAW design software to visually extract the WRAe interval and evaluate relative percentage changes to pollen taxa before and after the tephra.

Pollen sums were recorded to evaluate comparability but were not standardized across the dataset: they ranged from minimums of 150 grains per sample to 500. Particularly low pollen sums (e.g., < 100) might not capture minor elements of pollen assemblages (see Beaudoin and Reasoner, 1992). Pollen sums on diagrams generally included pollen from upland vegetation comprising trees, shrubs, herbs, and grasses, and excluded aquatics and non-pollen palynomorphs, such as *Sphagnum* spp. spores. Most of the tree and shrub taxa are wind pollinated although typical dispersal distances vary between taxa. We consider this bias towards upland terrestrial taxa acceptable since we are interested in trophic links largely based on terrestrial ecosystems. Eleven terrestrial taxa were present in enough diagrams to warrant comparison: *Pinus* spp. (pine), *Picea* spp. (spruce), *Betula* spp. (birch), *Populus* spp. (poplar/aspens), *Alnus* spp. (alder), *Salix* spp. (willow), *Juniperus*

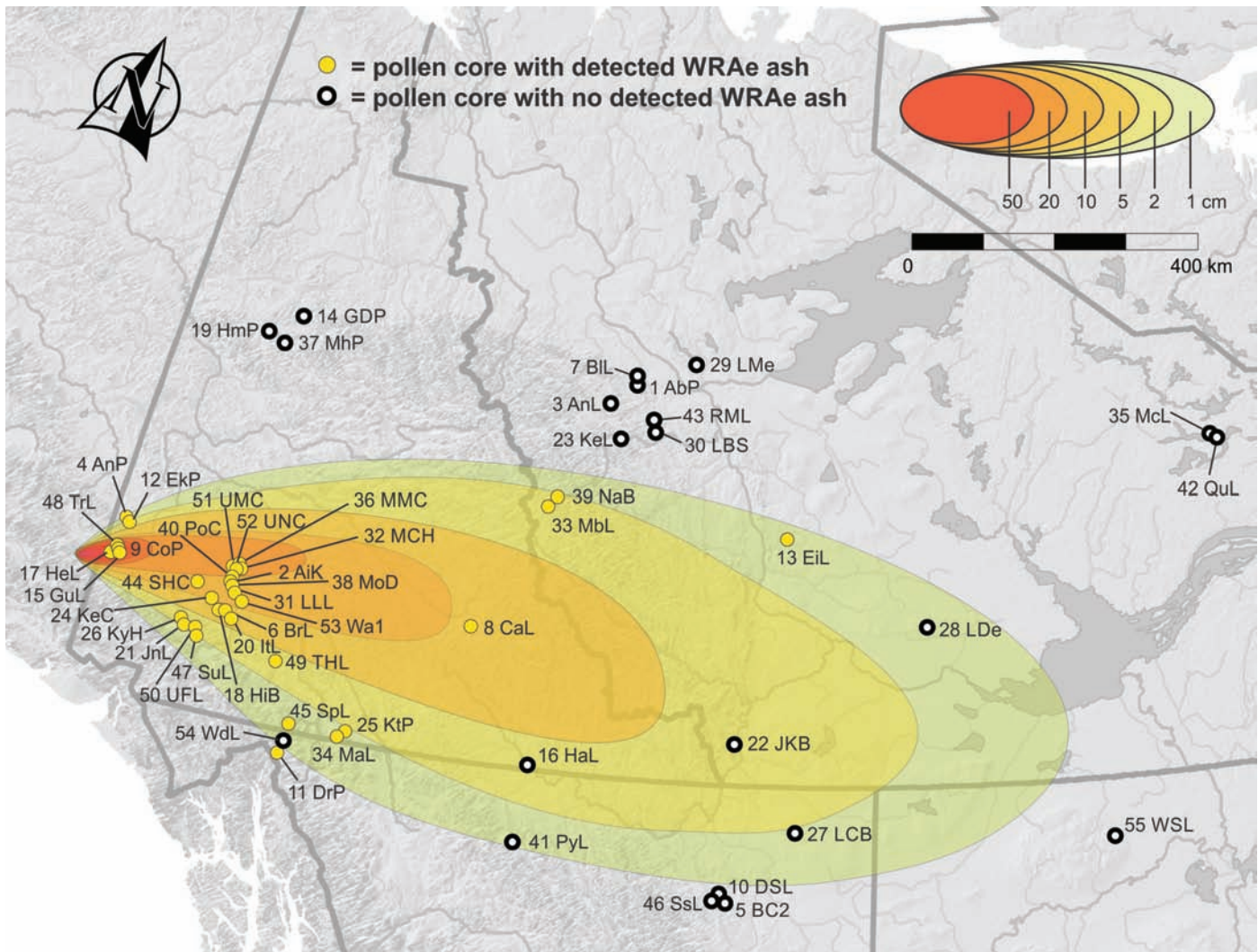


FIG. 2. Pollen cores utilized in this study. Names and references of core locations are listed in Table 1.

spp. (juniper), Ericaceae (heather), Cyperaceae (sedge), Gramineae (grass), and *Artemisia* spp. Note that Gramineae is now referred to as Poaceae but we have used the plant taxon names as given in the publications rather than update the nomenclature to reflect current taxonomy. *Sphagnum* spp. spores were generally presented in diagrams separate from the taxa above; we include them here as the twelfth taxon in our comparison.

We recorded pollen changes in five broad categories to retain some quantitative value despite disparate datasets: major increase (> 20% increase in the pollen of a specific taxon in the core sampling intervals that span the WRAe), minor increase (5% to 20%), no significant change (−5% to 5%), minor decrease (−5% to −20%), and major decrease (< −20%). Note that due to closure on the percentage values (i.e., that the percentage of one taxon influences the percentage of the others in order to close at 100%), changes in pollen percentages may reflect changes in the input of pollen from other taxa included in the pollen sum, rather than a change in the input of pollen from the taxon under consideration. Figure 3 contains two annotated pollen

diagrams to illustrate the method. Attempts were made to ensure that the percentage changes in taxa were recorded from before WRAe to immediately after the WRAe tephra (as opposed to changes in relative pollen percentages within tephra bands, which may be more heavily influenced by pollen preservation patterns during deposition as opposed to changes in plant communities). However, the ability to target the precise interval of ash fall is hindered by processes of re-deposition (e.g., re-activation of ash by wind), which can be difficult to distinguish in the stratigraphic record.

Pollen diagram syntheses are subject to limitations. Researchers sampled cores at different intervals (1 to 10 cm), therefore some diagrams capture plant communities immediately before and after WRAe while others predictably have lags. In the vast majority of studies, researchers investigated broader climate and vegetation changes through the Late Pleistocene and Holocene intervals and utilized the WRAe tephra as a chronostratigraphic marker, not as a potential catalyst of vegetation change. None of the studies incorporated high-resolution sampling through the WRAe interval, so fine-scale ash-driven change

TABLE 1. Pollen extraction locales evaluated in this study. The entries highlighted in grey contain sufficient chronological control to evaluate changes in vegetation before and after the WRAe.

No.	Abb.	Name	Reference
1	AbP	Abbey Pond, NWT	Szeicz and MacDonald, 2001
2	AiK	Aishihik Kettle, YT	Wang, 1989
3	AnL	Andy Lake, NWT	Szeicz et al., 1995
4	AnP	Antifreeze Pond, YT	Vermaire and Cwynar, 2010
5	BC2	BC2, BC	Pisarcic et al., 2003
6	BrL	Bear Lakes, YT	Wang, 1989
7	BL	Bell's Lake, NWT	Szeicz et al., 1995
8	CaL	Candelabra Lake, YT	Cwynar and Spear, 1995
9	CoP	Cotton Pond, YT	Birks, 1980
10	DSL	Dead Spruce Lake, BC	Pisarcic et al., 2003
11	DrP	Drizzle Pond, BC	Spear and Cwynar, 1997
12	EkP	Eikland Pond, YT	Vermaire and Cwynar, 2010
13	EiL	Eildun Lake, NWT	Slater, 1985
14	GDP	Gray Day Pond, YT	Cwynar and Spear, 1991
15	GuL	Gull Lake, YT	Birks, 1980
16	HaL	Hail Lake, YT	Cwynar and Spear, 1995
17	HeL	Heart Lake, YT	Birks, 1980
18	HiB	High Bog, YT	Wang, 1989
19	HmP	Honeymoon Pond, YT	Cwynar and Spear, 1991
20	ItL	Ittlemit Lake, YT	Wang, 1989
21	JnL	Jenny Lake, YT	Stuart et al., 1989
22	JKB	John Klondike Bog, NWT	Matthews, 1980
23	KeL	Keele Lake, NWT	Szeicz and MacDonald, 2001
24a	KeC	Kettle Camp, YT (bottom)	Campbell, 1999
24b	KeC	Kettle Camp, YT (slope)	Campbell, 1999
25	KtP	Kettlehole Pond, YT	Cwynar, 1988
26	KyH	Keyhole Pond, YT	Whittmire, 2001
27	LCB	Lac Ciel Blanc, BC	MacDonald, 1983
28	LDe	Lac Demain, NWT	MacDonald, 1987
29	LMe	Lac Meleze, NWT	MacDonald, 1987
30	LBS	Little Bear River, NWT	Hughes et al., 1993
31	LLL	Long Lost Lake, YT	Keenan and Cwynar, 1992
32	MCH	Mackintosh Creek HBI, YT	Beaudet, 1986
33	MbL	Marahbodd Lake, NWT	Rainville, 2015
34	MaL	Marcella Lake, YT	Anderson et al., 2005
35	McL	McMaster 3, NWT	Moser and MacDonald, 1990
36	MMC	Middle Mackintosh Creek, YT	Wang, 1989
37	MhP	Monkshood Pond, YT	Cwynar and Spear, 1991
38	MoD	Moose Depression, YT	Wang, 1989
39	NaB	Natla Bog, NWT	MacDonald, 1983
40	PoC	Polecat Lake, YT	Wang, 1989
41	PyL	Pyramid Lake, BC	Mazzucchi, 2000
42	QuL	Queens Lake 4, NWT	Moser and MacDonald, 1990
43	RML	Rouge Mountain Lake, NWT	Szeicz and MacDonald, 2001
44	SHC	Shaky Hand Creek, YT	Campbell, 1987
45	SpL	Spirit Lake, YT	Rainville, 2015
46	SsL	Sunset Lake, BC	Pisarcic, 2001
47	SuL	Sulphur Lake, YT	Lacourse and Gajewski, 2000
48	TrL	Triangle Lake, YT	Birks, 1980
49	THL	Two Horseman Pond, YT	Keenan and Cwynar, 1992
50	UFL	Upper Fly Lakes, YT	Bunbury and Gajewski, 2009
51	UMC	Upper Mackintosh Creek, YT	Wang, 1989
52	UNC	Upper Nisling Valley, YT	Wang, 1989
53	WaL	WA01, YT	Rainville and Gajewski, 2013
54	WdL	Waterdevil Lake, BC	Cwynar, 1993
55	WSL	Wild Spear Lake, AB	MacDonald, 1987

has not been captured. Interpretations of WRAe impacts presented below are largely our own (cf. Birks, 1980; Slater, 1985; Rainville, 2016). Lastly, in six instances when tephra were either very diffuse or not detected, bracketing radiocarbon dates enabled evaluation of the WRAe interval, although these radiocarbon dates and their interpretation are subject to error. Despite these limitations, a regional synthesis offers opportunities to investigate patterns of tephra impacts on vegetation.

### Pollen: Results

Vegetation responses to the eruption were variable (Figs. 4 and 5). Of the 345 evaluations of taxa (Table 2), the most common response to the WRAe was no significant change (65.8%). Pioneer species that would predictably respond well to ash disturbances (e.g., *Salix* and *Alnus* spp.) do not exhibit consistent positive responses to WRAe (Fig. 4), which suggests that ecological effects of the tephra were neither drastic nor uniform. Pollen records north of the WRAe lobe (Fig. 2) suggest that some vegetation changes may be either independent from the ash or occurred on regional scales that extended beyond the ash footprint.

Two taxa display informative trends. Within tephra depths of 2 cm or greater, *Picea* spp. pollen predominantly decreases (Fig. 4); within tephra zones of 5 cm or greater, Cyperaceae pollen predominantly increases (Fig. 5). Although it is wind-dispersed, *Picea* spp. pollen tends not to travel long distances and is therefore indicative of local pollen production, as opposed to *Pinus* spp. pollen, which travels long distances (Davis and Goodlett, 1960; Janssen, 1966; Campbell et al., 1999). The relatively consistent decrease in *Picea* spp. pollen indicates either an increase in tree mortality or a decrease in tree viability. Cyperaceae includes upland and wetland sedges in the study area, both of which produce pollen that tends not to travel far (Ritchie and Lichti-Federovich, 1967; Sugita et al., 1999).

### Pollen: Discussion

Research on the impacts of modern eruptions provides analogues for interpretation of WRAe pollen results. Impacts on modern vegetation generally vary depending on the thickness of airborne tephra, grain size, and distance from the vent (tephra tends to be thick, large in grain size, and continuous close to the vent, whereas it becomes thinner, smaller in grain size, and discontinuous farther away). Four to 15 cm of tephra from the 1980 Mount St. Helens eruption in Washington, U.S., killed a large percentage of understory plants and decreased the productivity of conifers and deciduous trees through leaf abscission and photosynthetic disruptions (Black and Mack, 1984; Hinkley et al., 1984; Antos and Zobel, 2005). Tree mortality was limited to a small percentage of mature conifers in the vicinity of the vent (Segura et al., 1994) although some mature trees of species like Douglas fir (*Pseudotsuga menziesii*) can survive over a metre of tephra deposition (Yamaguchi, 1985). Four to five cm of Mount St. Helens tephra killed most mosses but herbs persisted; the response of shrubs and small

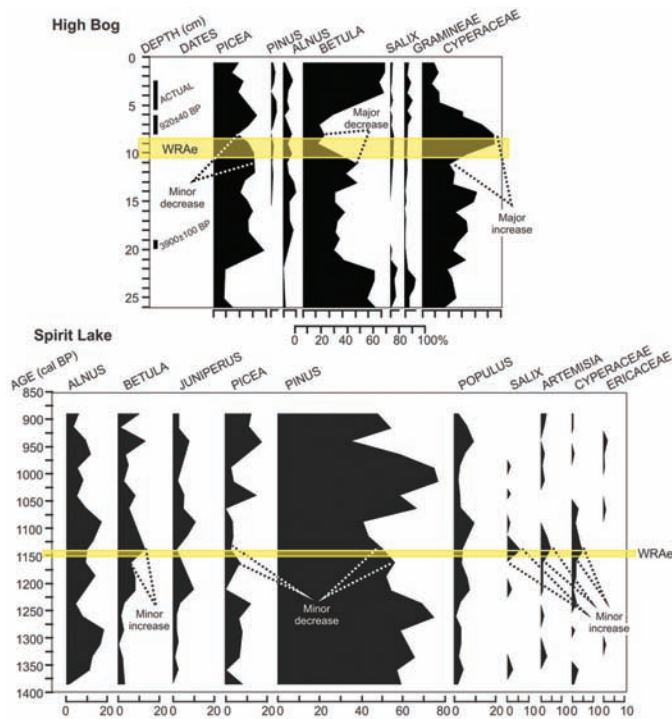


FIG. 3. Annotated pollen diagrams that illustrate the selection of WRAe intervals based on reported depths of tephra layers and age curve calibrations as reported by authors, in this case, Wang (1989) for High Bog (above) and Rainville (2015) for Spirit Lake (below). The categories of change are based on pollen percentages; some examples of minor and major increases and decreases are annotated. This process was completed for the 34 pollen diagrams highlighted in Table 1.

trees to tephra was diverse and depended on local habitats and distance from the vent.

In a circumpolar environment, 10 cm of ash from the 1907 eruption of Ksudach volcano in Kamchatka eliminated lichen and moss but herbs, shrubs, and trees generally persisted in conditions with less than 30 cm of tephra (Grishin et al., 1996). Grishin (1996) documented an 8% decrease in forest stands under 3 cm of tephra and a 20% decrease in forest stands under 10–12 cm of tephra 10 years after the Tolbachik eruption of 1975–76 in Kamchatka. Griggs (1922) noted a similar widespread destruction and delayed regrowth of low-lying understory vegetation like moss and reindeer lichen (*Cladonia rangiferina*) following the 1912 Novarupta-Katmai eruption in Alaska. Long et al. (2014) found that, in areas of 14–50 cm of tephra deposition from Mount Mazama at ca. 7630 BP, arboreal species were minimally affected while the understory took 50–100 years to recover. In an experimental study in Hokkaido, Japan, Hotes et al. (2004) found that mosses had difficulty re-establishing in tephra more than 6 cm thick, but most other mire vegetation taxa were not significantly depressed, particularly when tephra deposition occurred at the end of a growing season.

Environments with more uniform relief, like meadows or clear-cut forests, tend to experience greater damage with more delayed regrowth, while tephra that interacts with snow often develops an impenetrable crust, which can delay

TABLE 2. Evaluations of plant taxa by category.

Category	# of evaluations	%
Major increase	5	1.4
Minor increase	57	16.5
No significant change	227	65.8
Minor decrease	44	12.8
Major decrease	12	3.5
Total	345	

recovery of plants like mosses for over 40 years (Antos and Zobel, 2005:56; Ayris and Delmelle, 2012). Some studies (Magnusson, 1994; Aradóttir et al., 2010) suggest that terrestrial mosses and lichens may have been severely affected after WRAe but this is not detectable in pollen records. Lichens do not have reproductive structures that are detectable in pollen records so they cannot be assessed by this method. Mosses reproduce by spores but most palynologists do not record moss spores to a taxonomic level lower than Bryophyte. A few taxa, such as *Sphagnum* and *Lycopodium*, are, however, readily identifiable to genus level, and these may be tallied in pollen analyses. *Sphagnum* spores are commonly present in peatland samples, especially if the peatland is ombrotrophic because bogs are generally *Sphagnum*-dominated. Fluctuations in the abundance of *Sphagnum* spores may be indicators of moisture status of the peatland (i.e., wetter or drier intervals). As such, their abundance is tied to local moisture conditions in the peatland, controlled in part by topography, but which can reflect either increased atmospheric input or changes in run-off. In instances where moss spores are recorded (in the *Sphagnum* spp. examples above), input from terrestrial mosses is generally not recorded, so it remains difficult to assess terrestrial changes associated with tephra (and cascading trophic impacts up to game animals). However, tephra does increase water retention in soils, preventing evaporation and slowing runoff, which presumably favoured a variety of bryophytes.

The Yukon pollen studies fail to indicate widespread, uniform, and marked vegetation changes associated with the WRAe event. Based on studies of modern eruptions, this result is likely attributable to the facts that 1) much of the pollen research has been undertaken in regions outside of the main fallout zone (with less than 5 cm of tephra) where ash did not significantly impede regrowth of most woody plant species; 2) many of the pollen records are from areas characterized by high topographic relief, which would have facilitated erosion of unconsolidated tephra and limited its disturbance on plants; 3) most vegetation appears to have recovered within several decades (conifer tree ring data from Mount St. Helens, Washington, suggest the recovery of surviving trees to normal growth patterns in about a decade [Yamaguchi and Lawrence, 1993]) but disturbance on this time frame is nearly impossible to detect in these pollen records, most of which were sampled at temporal intervals too large to reveal subdecadal perturbations; and 4) low-lying understory like terrestrial mosses and lichens were the most significantly disturbed by

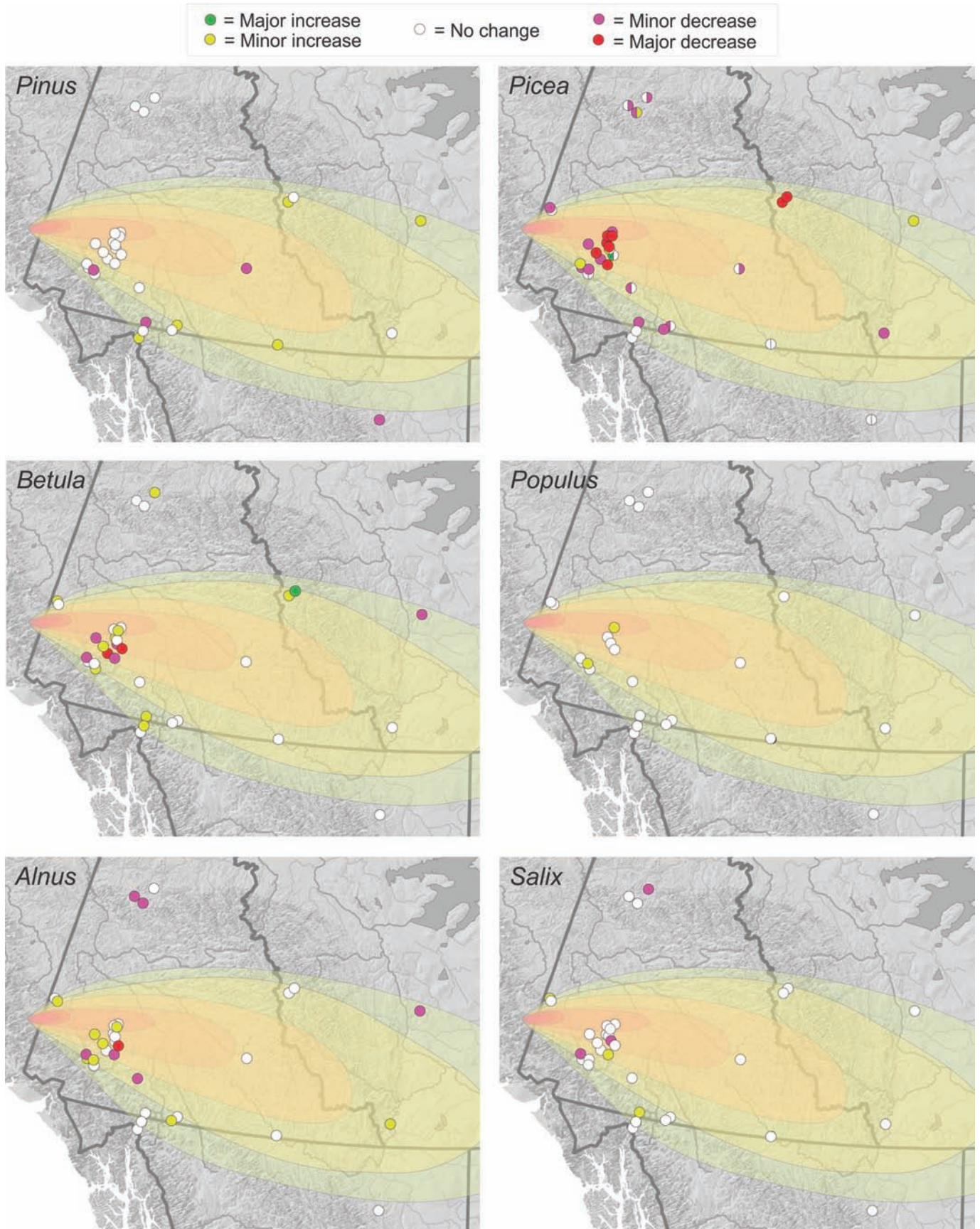


FIG. 4. Changes in pollen percentages for trees and large shrubs before and after the WRAe. Note that some researchers distinguished *P. glauca* from *P. mariana*, in which case the left portion of a split circle symbol represents *P. mariana* and the right portion represents *P. glauca*.

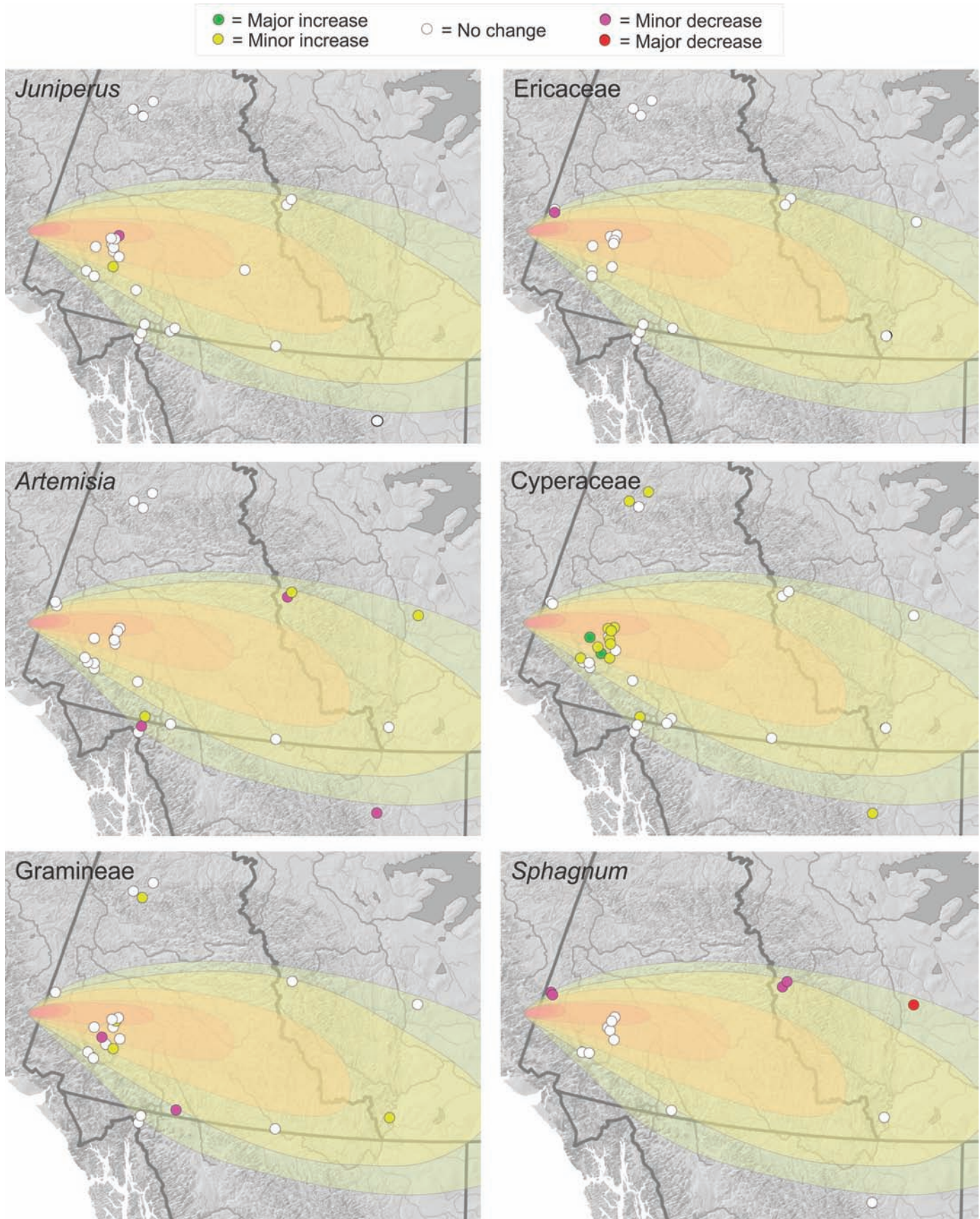


FIG. 5. Changes in pollen percentages for small shrubs, herbs, grasses, and mosses before and after the WRAe event.



tephra but the signals of these vegetation components are not detectable in pollen studies.

However, observable trends in spruce and sedges warrant discussion. Increased forest fires associated with tephra deposition (Long et al., 2014; Egan et al., 2016) may have decreased spruce populations. It is possible that tephra converted some landscapes (e.g., black spruce muskeg) into habitats more favourable to non-spruce species. If WRAe tephra was deposited in late fall or early winter (Hanson, 1965; Lerbekmo and Campbell, 1969; West and Donaldson, 2002; West, 2007), spruce may have experienced increased mortality associated with snow breakage (tephra is denser than snow and would significantly increase the weight of snow burdens). Because of branch growth patterns, pine trees are often more susceptible to snow damage than spruce (Elfving et al., 2001; Quine and Gardiner, 2007); predictably, both spruce and pine pollen would decrease after WRAe if snow burdens had a significant effect on mortality and stand composition. Two variables may explain why only spruce appears to decrease following WRAe: 1) since pine pollen travels greater distances, it does not reflect local conditions to the extent that spruce pollen does; and 2) pines thrive following fires, which may explain a quicker regional recovery than spruce and result in difficulty detecting a shorter term decrease in pine. Regardless, if WRAe fell in winter, snow loading, especially in areas exceeding 10 cm of tephra, would likely cause notable conifer damage (for studies of the importance of snow damage in boreal forest ecology see Pruitt, 1958; Päätaalo et al., 1999; Hanewinkel et al., 2008; Teste and Lieffers, 2011). In addition, black spruce trees have shallow, adventitious roots compared to pine and may have experienced more notable disruptions to growth processes following the deposition of a tephra layer that altered permeability and the near-surface movement of ground water. The cumulative effects of fire, snow and tephra loading, and the alteration of soil permeability may explain a decrease in spruce pollen.

An increase in sedges (Cyperaceae) at some localities in central and southern Yukon may relate to deposition of a horizon with poor permeability that reduced infiltration, increased water retention, and increased nutrient loading (including phosphorous) that favoured sedges (Major and Yamakoshi, 2005; Hughes et al., 2013; Egan et al., 2016). Since sedges are perennials that experience strong regrowth following annual die back, a different ecological response than spruce is expected. The decrease in spruce and increase in sedge appear directly related at several localities (Figs. 4 and 5). Birks (1980) documented the colonization of thick WRAe pumice and ash layers by Cyperaceae-dominated assemblages; it appears that this occurred at a number of regions across Yukon (Fig. 5). Increases in sedges and grasses have been linked to tephra deposition and an inferred increase in soil wetness in other northern forest habitats (Mehring et al., 1977b; Mack et al., 1983; Heinrichs et al., 1999; Lotter and Birks, 1993; Egan, 2016). Payne and Egan (2019) noted an increase in Cyperaceae

pollen in Washington following the Mazama tephra fall. The pollen diagrams of Mehringer et al. (1977a) and Blinman et al. (1979) at separate locales in Montana suggest that pine, *Artemisia* spp., and grass (Gramineae) pollen may have increased following Mazama ash deposition. Snow breakage, forest fires, and increased saturation of sediments associated with tephra may have led to a decrease in coniferous taxa (spruce and pine) followed by a rapid increase in sedges and pine in some habitats.

Keller-Pirklbauer et al. (2007) found that tephra accumulation led to permafrost aggradation in Iceland, and it is likely that similar conditions prevailed following WRAe deposition in Yukon and the NWT, which are high-latitude areas characterized by permafrost. The expansion of permafrost layers and ground ice in wetlands may have also favoured sedge growth and hindered spruce regrowth. This pattern would be predictably more exaggerated in colder, high-altitude regions. Alpine areas, including those of the Mackenzie Mountains, may have been more susceptible to long-term vegetation change because of slower ecological succession in response to tephra (Arnalds, 2013), permafrost aggradation, as well as a lower and more uniform vegetation canopy (alpine meadows vs. lower valley forests) that was more consistently smothered by tephra (see Kershaw and Gill, 1979 for a discussion of the impact of WRAe tephra on permafrost aggradation and palusa formation in an alpine region of the western NWT in the current study area).

In summary, pollen data demonstrate that most taxa were not significantly influenced over long time periods by the WRAe event. Where changes were noted, responses were quite variable even within tens of kilometres, which is indicative of diverse impacts that were likely dependent on different local ash thicknesses, basin sizes, elevations, erosion patterns, and forest canopy. Patches of biota that persisted probably served as nuclei of revegetation. Within the 5 cm tephra isopach in particular, sedge pollen increases while spruce decreases at some localities. Plant community canopies appear to have opened up, particularly within 300 km of the WRAe origin. The WRAe-related pollen fluctuations are unlike those that occurred during other narrow Holocene time intervals (e.g., a 100-year time span); there do not appear to be similar patterns of spruce decrease and sedge increase over such a large area. Relatively small and frequent ecological events like forest fires may have pre-adapted local biota to disturbances, but modern studies and the current regional pollen review point to the WRAe event as a disturbance factor that created mosaic environments on a much larger spatial extent than wildfires.

#### *Charcoal: Methods and Limitations*

Charcoal generated by forest fires is introduced to lakes and bogs through runoff and aerial transport and can serve as a proxy indicator of climate, anthropogenic burning, and large-scale disturbances such as fires associated

TABLE 3. Charcoal extraction locales and diagrams evaluated in this study.

No.	Abb.	Name	Reference
26	KyH	Keyhole Pond, YT	Gajewski et al., 2014
33	MbL	Marahbodd Lake, NWT	Rainville, 2015
34	MaL	Marcella Lake, YT	Edwards et al., 2015
45	SpL	Spirit Lake, YT	Rainville, 2015
47	SuL	Sulphur Lake, YT	Lacourse and Gajewski, 2000
50	UFL	Upper Fly Lakes, YT	Bunbury and Gajewski, 2009
53	Wa1	WA01, YT	Rainville and Gajewski, 2013
57	BbL	Burnt Bowl Lake, YT	Marcantonio, 2007
58	SmL	Salmo Lake, YT	Edwards et al., 2015
59	DfL	Dragonfly Lake, YT	Edwards et al., 2015
60	HcL	Haircut Lake, YT	Edwards et al., 2015
61	YK1	YK1, YT	Pellow, 2006
62	YK3	YK3, YT	Pellow, 2006
63	YK5	YK5, YT	Pellow, 2006
64	SyL	Spindly Pine Lake, YT	Prince et al., 2018

with tephra deposition (Patterson et al., 1987; Gardner and Whitlock, 2001). Researchers have linked fires to tephra in palaeoenvironmental studies because of intense lightning associated with ash clouds during the eruptive event (Wilcox, 1959; Thorarinsson, 1979; Hoblitt, 1994; Beierle and Smith, 1998; Hallett and Walker, 2000; McNutt and Davis, 2000) and plant desiccation in the following months or years (Wilmshurst and McGlone, 1996; Long et al., 2014). Needle fall, dead-standing timber, and the desiccation of shrubs and herbs increase fuel loads (Long et al., 2011).

Microcharcoal (< 100 µm) can be transported large distances by winds and runoff (Clark, 1988) and tends to indicate larger regional trends associated with fire activity (Patterson et al., 1987). Macroscopic charcoal (> 100 µm) provides more local indications of forest fires (Gardner and Whitlock, 2001). We amassed both micro- and macrocharcoal data from cores from publications and dissertations (Table 3) for input into design software to extract the WRAe interval and evaluate fire frequency and regional trends during and shortly after the tephra. Charcoal levels (as measured in particles/cm<sup>2</sup>/year or particles/gram dry weight/year) were classified in five broad categories within or immediately above tephra for comparative purposes: major increase (> 50% increase in the charcoal particles), minor increase (20% to 50%), no significant change (−20% to 20%), minor decrease (−20% to −50%), and major decrease (< −50%).

As in the synthesis of pollen studies, researchers sampled cores at different intervals (1 to 5 cm), so some diagrams capture immediate changes while others have lags. In the majority of studies, researchers were investigating broader Holocene climate and vegetation changes and therefore did not discuss direct associations of charcoal and tephra.

#### Charcoal: Results

Charcoal records, like the pollen studies, are variable across the study area (Fig. 6) although most micro- and macrocharcoal studies demonstrate minor or major

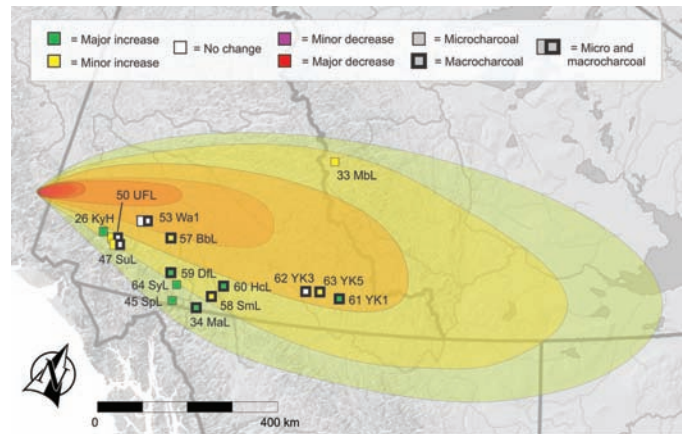


FIG. 6. Charcoal locations and results. Names and references of these locations are given in Table 3.

increases following the WRAe event, which suggests increases in both local and regional fire regimes. However, some habitats (e.g., those at high altitudes or with relatively small catchment basins like Upper Fly Lake, Sulphur Lake, and YK3) appear to have undergone no visible change in fire dynamics. In virtually all cases, the abundance of charcoal following WRAe is not unique in the Holocene fire history of each study site, but no other narrow time interval across the whole study area occurs in which fires appear to have been as common as that following the WRAe event.

#### Charcoal: Discussion

Long et al. (2014) and Egan et al. (2016) linked Mount Mazama tephra deposition to local and regional fires that were presumably promoted by increased fuel loads associated with plant mortality or stress. Their results were not uniform, however, with some localities displaying little or no connection between tephra deposition and ensuing fires. Studies of links between modern eruptions and fires are rare and would perhaps be less informative as analogues because of modern fire suppression (wildfire-fighting efforts) and a host of other factors that limit the extent of recent forest fires (e.g., transportation networks and commercial logging). However, charcoal results from Yukon (though biased toward the southern portion of the study area) do demonstrate a consistent increase in forest fires following deposition of WRAe tephra (Fig. 6).

When combined with pollen syntheses, the charcoal results suggest that landscapes immediately following the WRAe eruption were not uniformly altered although some experienced a decrease in forest cover and an increase in sedge meadows. Some habitats do not appear to have experienced much change (e.g., small and isolated catchment areas where the probability of fires remained low). The tephra, like other natural large-scale disturbances, probably enhanced environmental patchiness with more local diversity of habitats. Long et al. (2014) view volcanic disturbances as additive through the creation of new habitats and the re-initiation of ecological succession

across landscapes, which the current pollen and charcoal studies support. However, the spatial extent of landscape disturbance may have presented challenges up the trophic pyramid to fauna and people.

### HUMAN SUBSISTENCE FOLLOWING WRAe

We here bridge palaeoenvironmental studies and archaeology through trophic links from vegetation to game animals and hunter-gatherers. This bridge extends over a temporal gap from palaeoenvironmental studies (that reveal century-scale changes) to meaningful time frames for humans and animals (weeks, month, years, and decades). We begin with a summary of human subsistence based on ethnohistoric and archaeological records to focus the ensuing discussion of ecological impacts on important prey species. While climatic records do illustrate some changes in the study area in late Holocene times (Chakraborty et al., 2010; Anderson et al., 2011; Bunbury and Gajweski, 2012; Gajweski et al., 2014), it is not expected that these changes would have significantly altered animal distributions (e.g., migratory paths of caribou or salmon) from the time of the WRAe eruption to the interval represented by ethnohistoric records (from AD 846–848 to the AD 1700–1800s). The WRAe event occurred during the global Medieval Warm Period, which may have involved increased summer and winter temperatures in the study area (Bunbury and Gajweski, 2009) that caused more frequent winter thawing, increased snowfall, and elevated stresses on cold-adapted species in the Yukon (Kuhn et al., 2010). Archaeological records generally fail to illustrate major changes in distributions of important food animals over the past 1000 years but it is worth a cautionary note that the Medieval Warm Period and ensuing phases of regional Little Ice Age advances between AD 900 and 1900 may limit the extension of ethnohistoric records to the time of the WRAe event.

#### *Ethnohistoric Records and Subsistence*

The WRAe tephra dispersed across the territories of what were probably several different hunter-gatherer groups based on contact-era distributions (Fig. 7). Figure 8 compares subsistence models of those groups and the neighbours with whom they may have interacted. Models of hunter-gatherer seasonal rounds (the shift from one resource and resource extraction area to another throughout the year) are built from ethnographic records and oral histories (Dawson, 1889; Pike, 1896; Emmons, 1911, 1991; Osgood, 1936; McClellan, 1953, 1975; Honigmann, 1954; Krause, 1956; Teit, 1956; de Laguna, 1972; Gillespie, 1981; Albright, 1982; Grinčev, 2005; Legros, 2007; Andrews et al., 2012b) and archaeological records (MacNeish, 1951, 1954, 1960, 1964; Workman, 1978; Shinkwin, 1979; Ives and Sinopoli, 1980; Clark, 1982; Clark and Morlan, 1982; Morrison, 1984, 1987; Hanks and Winter, 1991; Hare, 1995;

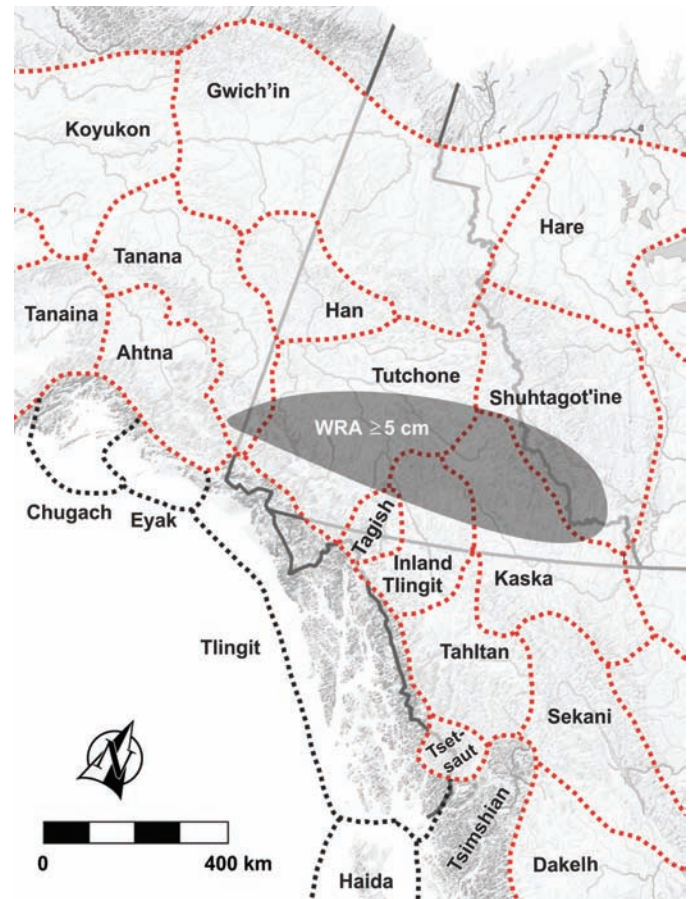


FIG. 7. Approximate First Nations territories at European contact (adapted from Ives, 1990 and de Laguna, 1972) and the WRAe tephra footprint equal to or greater than 5 cm in thickness (based on Lerbekmo, 2008). Botanical and faunal studies of recent eruptions indicate that the most significant impacts of ash are in tephra zones of 5 cm depth or greater (Capps, 1915; Kurenkov, 1966; Mack, 1981; Seymour et al., 1983; Black and Mack, 1984; Hinckley et al., 1984; Martin et al., 1984; Antos and Zobel, 1985; Tsuyuzaki, 1995; Grishin et al., 1996; Dale et al., 2005; Talbot et al., 2010; Flueck, 2016). Athapaskan (Dene) territories are bordered by red.

Gordon, 1996; Holmes, 2001; Thomas, 2003; Farnell et al., 2004; Hare et al., 2004, 2012; Dixon et al., 2005; Easton, 2007; Richards et al., 2007; Corr et al., 2008; Potter, 2008; Andrews et al., 2012a).

In what is now southern and central Yukon, people relied on seasonal migrations of caribou and salmon, both of which have roughly north-south migratory paths that would have been intersected by WRAe tephra (Fig. 9). Barren-ground caribou (*Rangifer tarandus groenlandicus*) herds that exceeded 500 000 animals historically migrated from calving grounds in the north each fall to feed in sheltered forests of central and southern Yukon over winter (Valkenburg et al., 1994; Boertje and Gardner, 2000). Scattered herds gathered together in spring to return to northern tundras to calve. Woodland caribou (*R. t. caribou*) live throughout southern and central Yukon and northern British Columbia and have much smaller geographic territories but still migrate seasonally from forested valleys in winter to alpine meadows in summer. Both barren-ground and woodland caribou rely on lichens and sedges as

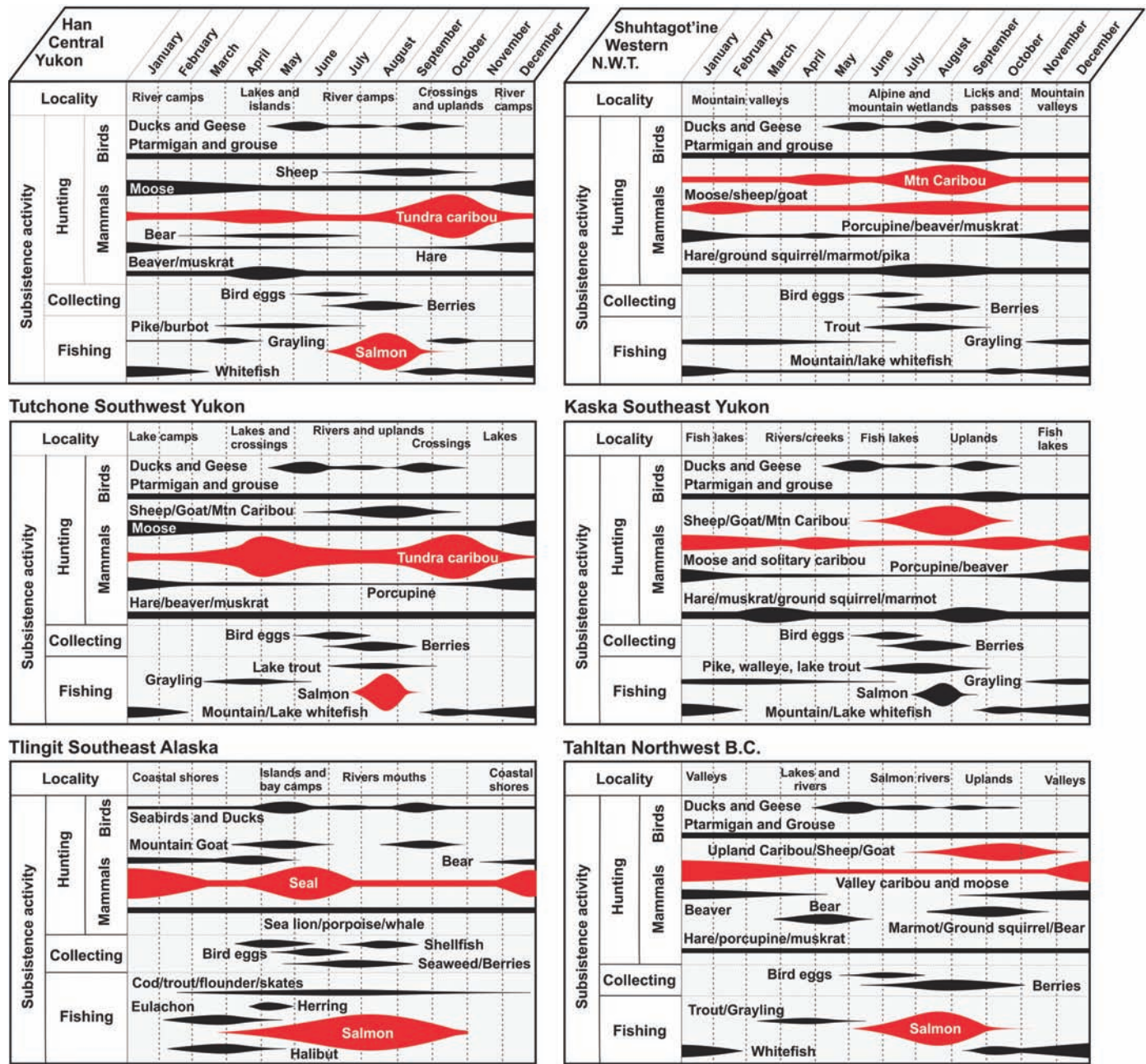


FIG. 8. Generalised human seasonal rounds in the study area shortly before European contact. Major or key resources are in red. We accounted for contact-era increases in attention to small fur-bearing mammals and the utilization of fisheries to support dogs (both of which assumed greater importance during the fur trade) and for early ethnographic biases towards subsistence pursuits with complex socio-political dimensions (e.g., ungulate hunting tended to receive more early ethnographic attention than snaring birds although both pursuits seasonally sustained populations). Archaeological data informed these models with acknowledgement that preservation biases may exaggerate the importance of large animals.

principal food sources. Salmon enter the Yukon from the Pacific Ocean primarily via the Yukon and Alsek Rivers (Fig. 9). Several species of salmon (Chinook [*Oncorhynchus tshawytscha*], chum [*O. keta*], and coho [*O. kisutch*]) spawn along Yukon riverbeds from June until mid-October (Scribner et al., 1998; Brown et al., 2017; Cunningham et al., 2018). Major salmon fisheries in the study area also occur along the Stikine River in northern British Columbia.

The diet of neighbours of people impacted by WRAe tephra differed. In the absence of large barren-ground caribou herds, the Tahltan and Kaska hunted isolated

moose (*Alces alces*) and caribou in valleys, and upland populations of bighorn sheep (*Ovis canadensis*), mountain goat (*Oreamnos americanus*), woodland and mountain caribou, and marmot (*Marmota caligata*) (Fig. 8). Salmon do not spawn in the Mackenzie River Basin where the Shuhtagot'ine and others relied more heavily on upland ungulates and small game, such as marmot, ground squirrel (*Spermophilus parryii*), hares (*Lepus americanus*), beaver (*Castor canadensis*) and muskrat (*Ondatra zibethicus*). From rivers and wetlands, the people harvested birds and freshwater fish, such as whitefish (*Coregonus* spp.), pike

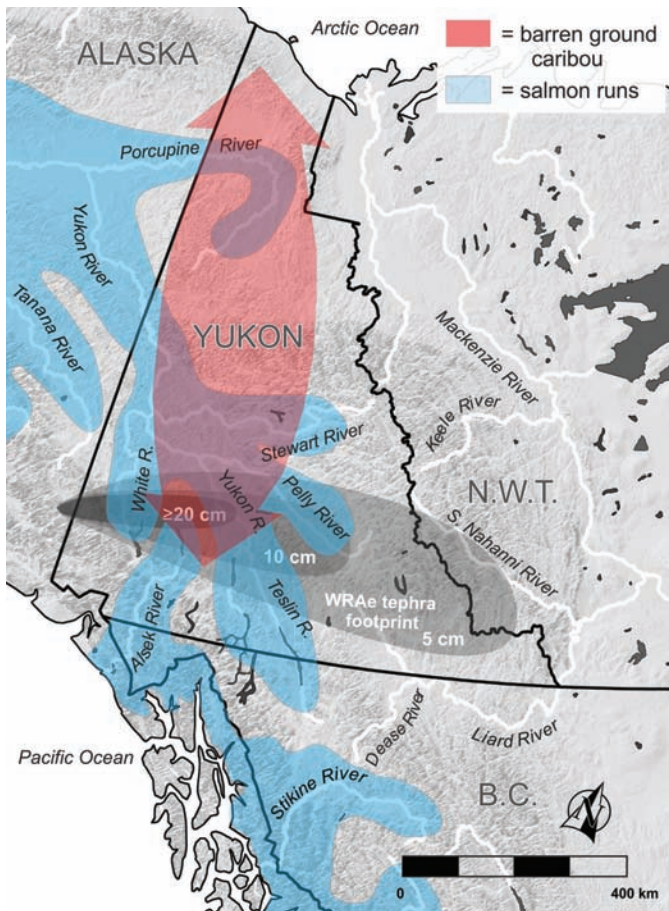


FIG. 9. Rivers mentioned in text and generalised outlines of the barren ground caribou migration path and the most productive salmon spawning areas in Yukon and northwest British Columbia.

(*Esox lucius*), lake trout (*Salvelinus namaycush*), inconnu (*Stenodus leucichthys*), walleye (*Sander vitreus*), and burbot (*Lota lota*) (Gillespie, 1981; Andrews et al., 2012a). The coastal Tlingit people exploited seasonal availabilities of sea mammals and a variety of marine fish species (Fig. 8) (de Laguna, 1972). In virtually all of the study area, small to medium mammals and a variety of birds were hunted or snared throughout the year. Beaver and whitefish were important sources of fat in winter across the Subarctic, which factored heavily into hunter-gatherer attraction to valleys and fish lakes during this season.

The effects of WRAe ash on populations of fish and game in southern and central Yukon have not been well addressed (cf. Mulliken, 2016). The data sources utilized below to assess impacts of the ash are from Yukon caribou ancient DNA (aDNA) and studies of modern eruptions and their impacts on wild animals and livestock.

### Ungulates

On the basis of aDNA from Holocene caribou remains, Kuhn et al. (2010) concluded that populations in southwest Yukon were partially replaced by new caribou populations following the WRAe event, although this may

be attributable to concurrent climatic changes (i.e., the Medieval Warm Period). WRAe may have induced caribou mortality by hindering access to their principal food supply (reindeer lichen) when migratory herds wintered in southern forests. If the ash fell in winter, immediate impacts on the lichen food supply may have been delayed until the following winter when lichen abundance was reduced (although ash may have made lichen harder to access immediately after deposition). In studies of modern ash falls, Alaskan caribou have been found to undergo drastic tooth wear from grit that led to mortality (Hubbard, 1938:57). In Kamchatka, reindeer deaths in ash-covered ranges were attributed to the ingestion of coarse ash while feeding (VanderHoek, 2009:166). Ash ingestion leads to rumen blockage and inanition (exhaustion from lack of nourishment) in addition to depressed fur production, chronic bronchitis, pneumoconiosis, silicosis, and corneal abrasion (blindness) (Gregory and Neall, 1996). Griggs (1922) argued that the destruction of reindeer lichen by tephra from the 1912 Katmai eruption in Alaska led to widespread caribou mortality. Eruptions in Kamchatka in 1953 and 1975 similarly caused widespread caribou malnutrition because of lack of access to meadows, in some cases involving over 70% mortality in a herd (VanderHoek, 2009:166).

Caribou mobility drops in winter when their biological response to a disturbance event may be more akin to livestock, which have been studied more extensively following modern eruptions. Fluorine released during volcanic events is captured by plants and transmitted to livestock, often leading to rapid fluoride contamination and osteofluorosis or dental fluorosis (Óskarsson, 1980; Araya et al., 1993; Cronin et al., 2003; Flueck, 2016). The abundance of fluorine released is related to specific magma compositions and it is not currently known if WRAe was associated with high levels of fluorine that could have caused fluoride contamination. Toxic levels of fluoride cause bone deformation and wear on articular surfaces (erosion of bone joints). Mortality linked to dental fluorosis (pathological tooth wear and severe ablation leading to malnutrition) has been noted in wild deer populations in Chile following eruptions (Flueck, 2014), while osteofluorosis has been implicated in livestock mortality after ash falls in Chile (Araya et al., 1993) and New Zealand (Cronin et al., 2003). Records of tephra-induced livestock mortality from around the world (often in areas subjected to less than 5 cm of tephra before compression) (Table 4) indicate that a variety of large herbivore species can be affected. Following the 1970 Hekla eruption in Iceland, adult sheep mortality due to fluorosis below 1 mm of tephra was 3% while that of lambs was 8%–9% (Thorarinsson, 1979:146). Thorarinsson (1979) noted that fluorosis is more severe with distance from the eruption because fine particles are more likely to adhere to vegetation and bind to water. These conditions can persist for over a decade but ash mobilization events (e.g., windstorms) can re-introduce tephra effects for centuries (Wilson et al., 2011a).

TABLE 4. Examples of recorded livestock mortality due to tephra following volcanic eruptions.

Eruption	Year	Livestock loss	Reference
Paricutin, Mexico	1943–52	~4500 cattle 500 horses	Rees, 1970
Mt Hudson, Chile	1991	~1 million sheep	Wilson et al., 2011b
Laki, Iceland	1783	10 263 cattle 186 638 sheep 27 256 horses	Thorarinsson, 1979
Hekla, Iceland	1970	15 600 sheep	Thorarinsson, 1970
Chaitén, Chile	2008	25 000 sheep	Craig et al., 2016

Fluorosis and the biological impacts of tephra in general are difficult to reconstruct for pre-contact eruptions because they are related to compositions specific to each tephra fall and local soil characteristics (Ayrís and Delmelle, 2012). However, agricultural studies and DNA research suggest that wintering barren-ground caribou and resident woodland caribou (as well as moose, bighorn sheep, and mountain goat) exposed to over 1 cm of tephra were negatively affected through inescapable ash ingestion. Lichen feeders and grazers were presumably more negatively affected than browsers. Prolonged exposure by caribou and other ungulates to volcanic ash would have led to malnutrition (e.g., related to fluorosis, rumen blockage, or tooth wear), depressed breeding success, or mortality. Summer erosion in high relief areas would have exposed lichens and sedges in some habitats, which may have altered caribou ecology without significantly depressing nutrition. Ancestral migration paths would have seasonally brought caribou into the WRAe footprint (Fig. 9) and introduced biological challenges, particularly to pregnant females prior to spring calving.

To extend up the trophic chain from our pollen synthesis, decreased spruce and increased sedge (Figs. 4 and 5) following the WRAe may have produced habitats that favoured the recovery of summer ungulate food supplies within several decades. However, lichen communities can take over 100 years to become established after disturbance events in Subarctic environments (Rupp et al., 2006; Payette and Delwaide, 2018); for example, in Alaska's boreal forest, lichens took over 80 years after forest fires to return to sufficient abundance to attract grazing caribou (Collins et al., 2011). Woodland caribou favour old-growth forest where lichen is abundant, so disturbance events like ash deposition and associated forest fires would reset stages of ecological succession with prolonged impacts on caribou. Caribou adapted to alpine habitats in Yukon and the western NWT (e.g., the Mackenzie Mountains) may have also experienced delayed recovery because of their reliance on meadows that were susceptible to more uniform impacts of tephra and permafrost aggradation that altered plant communities. Letts et al. (2012) noted no significant change in aDNA of woodland caribou in the western NWT following the WRAe event, which indicates genetic continuity although their ecology may have been disrupted. We estimate that it minimally took several human generations

(50–100 years) for caribou to return to pre-WRAe abundance and to re-establish predictable migratory paths that humans seasonally exploited. This timescale is based on the estimated recovery of moss and lichen communities after the initial tephra fall and re-mobilisation events (Rupp et al., 2006; Collins et al., 2011; Payette and Delwaide, 2018), the general hiatus of over a century in southern Yukon ice patch artifacts and dated faunal remains (a repository of organic hunting artifacts and animal remains preserved at high altitudes) following WRAe (Hare et al., 2012), and other work that estimated the recovery of caribou from circumpolar eruptions (VanderHoek, 2009:289). In the weeks and months after ash deposition, caribou populations were probably stressed because of hindered food access, which would have altered both their daily movement patterns and their once predictable foraging territories through the following winter and summer.

### *Fish*

Tephra and ensuing erosion can lead to fish mortality related to suffocation, as well as changes in channel morphology (gravel spawning beds), riparian vegetation, and habitat availability (Lallement et al., 2016). A principal impact on anadromous fish like salmon is through turbidity. Suspended ash coats or abrades gills (Newcomb and Flagg, 1983), impedes homing behaviours used to relocate ancestral spawning beds (Whitman et al., 1982), decreases egg survival, reduces soluble oxygen (Ward et al., 1983), and depresses invertebrate and algae populations, such as amphipods, chironomids, and diatoms, upon which fish directly or indirectly rely (Kurenkov, 1966; Abella, 1988; Hutchinson et al., 2019). Acidity associated with volcanic emissions and tephra can also alter pH and aluminum toxicity that harms invertebrates and fish (Birchall et al., 1989; Birks and Lotter, 1994; Telford et al., 2004; Schaefer et al., 2008; Wall-Palmer et al., 2011). The WRAe tephra, however, is from a volcanic vent and eruption type—a high-silica adakitic vent producing a water-rich phreatomagmatic eruption (Lerbekmo, 2008; Preece et al., 2014)—that is not typically associated with high levels of sulphur dioxide (see Jensen et al., 2014), which is a major contributor to acid rain (Ayrís and Delmelle, 2012). Decreased riparian vegetation is one factor that led to high water temperatures and elevated mortality of juvenile salmon after the Mount St. Helens 1980 eruption (Martin et al., 1986). However, nutrient- and iron-rich ash deposition has been linked to phytoplankton blooms (Olgun et al., 2013) and zooplankton productivity (Bisson et al., 2005), which in turn promote the rapid recovery of fish communities (Parsons and Whitney, 2012), although some tephra may lead to anoxic events from over-nutrientification (Bisson et al., 2005; Ayrís and Delmelle, 2012).

Eicher and Rounsefell (1957) and Kurenkov (1966) noted sharp declines in salmon populations in Alaska and Kamchatka due to suffocation following tephra deposition but recovery within three years, in some cases leading to salmon populations larger than pre-ash times. Ball (in

Evermann, 1914) reported the suffocation of 4000 salmon in one stream in 1913 following the Katmai eruption in 1912 (due to turbid waters) while Evermann (1914) noted the destruction of salmon spawning beds by tephra. Both of these observations were made in water bodies over 100 km from the volcano (these areas were exposed to 3–20 cm of tephra based on isopachs from Hildreth and Fierstein (2012:10). Bisson et al. (1988) noted immediate declines followed by sharp increases in fish productivity attributed to an abundance of food resources for salmon after the Mount St. Helens 1980 eruption. In general, fish populations in mountain waterways decrease but rebound quickly to pre-eruption levels (Bisson et al., 2005), possibly because of high spring and summer meltwater levels that flush ash downstream and out of fluvial systems.

Extrapolating modern fish studies to the WRAe event is difficult because salmon ecology in the upper Yukon River is quite different from systems analysed after modern eruptions. Of direct relevance, Bunbury and Gajewski (2013) studied impacts of the WRAe on aquatic environments in southwest Yukon and concluded that, in systems with moderate to large catchment basins, chironomid communities often displayed significant reductions indicative of negative WRAe impacts on organisms that support fish. In some cases, chironomid communities took 100 years to recover from the WRAe. Hutchinson et al. (2019) detected distinct changes in diatom communities after the WRAe event in a lake in the Northwest Territories over 1200 km from the volcano.

We expect that Yukon salmon populations were reduced in the 5 cm or more tephra isopach because of suspended ash particles, sediment loads, and a loss of riparian vegetation that regulated temperatures of spawning beds and smolt development. The pollen studies are informative because spruce appears to have decreased post-WRAe; it plays an important role maintaining fish habitat and water temperatures through the provision of shade, predator refuge, and erosion control. The 20 cm tephra isopach crosses the Yukon River and the 10 cm isopach crosses portions of the Pelly, Teslin, and Alsek Rivers (Figs. 1 and 9). The introduction of this much ash may have raised turbidity to lethal levels for fish in important fishing grounds for people in that region and downstream from it, although large percentages of ash deposited in winter may have flushed through the Yukon Basin prior to summer salmon runs.

Perhaps more significantly, the timing and location of salmon runs would have been less predictable due to population changes, large-scale erosion events that altered river bed and bank morphology, and straying or homing issues (Whitman et al., 1982; Leider, 1989). Reductions in anadromous fish productivity due to ash remobilization events probably lasted 10 years. This is based on modern studies of salmonid depression for roughly three to eight years following smaller northern eruptions (Ball in Evermann, 1914; Eicher and Rounsefell, 1957; Kurenkov, 1966), an expected 5- to 10-year episode of ash flushing and

stabilisation after the WRAe (cf. Wilson et al., 2011a), and the roughly 5-year life cycle of salmon (i.e., five years of ash flushing through rivers would influence the population of salmon that returns to ancestral spawning beds for an additional five years).

Landlocked (or non-diadromous) fish like whitefish and lake trout may have been locally eradicated for centuries because of turbidity and changes in lake pH, as is inferred to have occurred in New Zealand where lakes still have not been recolonized by non-diadromous fish more than 1000 years after a major ash fall (McDowall, 1996). Hutchinson et al.'s (2019) high-resolution study in the NWT indicates that less than 5 mm of WRAe tephra caused a significant though short-lived change in pH and diatom communities. Lakes in Alaska were also determined to undergo steep decreases in productivity (based on carbon and nitrogen isotopes) due to tephra deposition during Holocene volcanic events (Misarti, 2007). Changes in pH and turbidity due to ash and intensified sediment yields (Kadomura et al., 1983; Major et al., 2000; Waythomas et al., 2010) may have pushed lake fish populations to different habitats, making access to fish unpredictable for people. Species like whitefish and inconnu can migrate long distances from the Mackenzie Mountains across the Mackenzie Basin (Helm, 1981; Stephenson et al., 2005; McPhail, 2007), which would expose them to impacts arising from 1 to over 5 cm of ash fall. Ash deposition in winter when lakes and many rivers were capped with ice may have rendered ash impacts negligible until the spring melt, which appears to have lessened the impact of tephra on fish after the 1980 Mount St. Helens eruption (Bisson et al., 2005). However, winter tephra deposition would presumably concentrate ash impacts within the vulnerable spring spawning season of many Mackenzie and Yukon basin fish.

#### *Rodents, Birds, and Plant Foods*

Aside from fish and ungulates, very few studies have systematically analysed tephra-related changes to species that were valuable to pre-contact people, such as rodents (e.g., porcupine [*Erethizon dorsatum*], muskrat, beaver, and marmot), birds (e.g., ptarmigan [*Lagopus* spp., grouse [*Tetraoninae*], and geese [*Anser* spp.]), and berries. Small mammal communities in tephra fall zones appear minimally affected because of the ability to survive in and quickly recolonize from small refugia (Crisafulli et al., 2005). This lower impact is partially due to higher reproductive rates than large mammals. For example, hare populations fluctuate widely from year to year in boreal ecosystems, which humans were aware of and adapted to through changes in hunting patterns; we predict a minor disruption to the cyclical rise and drop in hare abundance. Ptarmigan mortality was noted as severe after the Katmai eruption of 1912 (Ball in Evermann, 1914:62–63), and Thorarinsson (1979:137) described mass kills of ptarmigan following the 1693 eruption of Hekla volcano in Iceland. Ash falls may have also disoriented migratory waterfowl

if the falls occurred during spring or autumn migration. Changes to lake productivity and water quality (especially in small water bodies) would have also affected some waterfowl species.

Hunn and Norton (1984) documented a sixfold decrease in berry productivity (mountain huckleberry, *Vaccinium membranaceum*) under an average of 32 mm of tephra from Mount St. Helens. This decline was attributed to significant decreases in insect pollinators (Cook et al., 1981) and may relate to the timing of the 1980 eruption in May, an important season for pollination (Hunn and Norton, 1984). Despite reports of local decreases in ground birds and berries, most small animal and plant food species likely recolonized tephra-coated landscapes quickly but in spatial patterns that may have taken years for people to relocate. In summary, animal movements, productive berry grounds, leks (where ground-dwelling birds gather), and the timing of other animal congregations and plant availability were less predictable for weeks, months, and possibly decades following ash deposition.

#### EFFECT OF WRAe ON HUMAN HEALTH

Global studies of eruption impacts on human health enable some extrapolations to hunter-gatherers. Fatalities related to volcanic eruptions are most commonly linked to pyroclastic density currents consisting of ash and hot gas driven by dynamic pressure and gravity (Baxter and Horwell, 2015). The average extent of density currents is not well-known but the comparatively small eruption of Mount St. Helens in 1980 produced a blast zone extending 28 km from the summit (which killed 57 people) and the Merapi eruption in Indonesia in 2010 produced a pyroclastic density current that extended 17 km (causing close to 200 human deaths) (Jenkins et al., 2013). Ash flow deposits from the Aniakchak eruption of 3700 BP (Kaufman et al., 2012) in Alaska extend 80 km from the caldera (Miller and Smith, 1977).

Although the full extent of pyroclastic density currents associated with WRAe are not known, it is reasonable to conclude that pyroclastic flows and associated density currents were small (Lerbekmo and Campbell, 1969; Richter et al., 1995; Lerbekmo, 2008). Associated human fatalities would be minimal unless specific task groups were moving within 10 km of Mount Churchill at the time of the eruption or were camped in neighbouring valleys. Population densities of hunter-gatherers in the vicinity of Mount Churchill and the St. Elias Mountains (the origin of the WRAe event) were predictably low, especially in winter when hunter-gatherers tended to reside at lower altitude fish lakes, rivers, and coastal shores (Fig. 6). Workman (1974) postulated a population density of one person per 100 to 250 km<sup>2</sup> in the general study area (southern and central Yukon) and suggested that virtually no one resided within a danger zone of pyroclastic density currents, dubbed glowing ash clouds by Workman (1974). Modern eruption data

support Workman's (1979:348–349) notion that the WRAe did not cause human mortality in Yukon and that volcanic impacts on human biology would have most likely been limited to regions that experienced fine-grained tephra falls.

Ash falls are generally not a cause of mortality (Wilson et al., 2015) and when implicated in human deaths tend to relate to roof collapse and particle loading exaggerated by rainwater (Baxter and Horwell, 2015). Tephra is an unlikely cause of immediate death in pre-contact times given that most structures were small and could adequately shed snow burdens. More significant are chronic respiratory and eye issues associated with prolonged exposure to ash (from the initial deposit and during remobilization events). Airborne tephra can lead to potentially fatal silicosis, particularly if tephra contains cristobalite, a polymorph of silica formed at very high temperatures (Baxter et al., 1981; Horwell et al., 2014). Cristobalite has not been noted in WRAe (Preece et al., 2014) and is unlikely to have been present. Modern studies suggest that respiratory hazards of tephra among healthy people are minimal (Gudmundsson, 2011; Baxter and Horwell, 2015), but a few variables temper extrapolations of these studies to pre-contact times. First, if WRAe tephra fell in winter, relative air moisture would be low and the amount of dangerous respirable crystalline silica (Horwell et al., 2012) would be high. Second, most modern studies are in urban settings where ash is cleared so exposure tends to be short-lived; hunter-gatherers were much more mobile, which may have increased exposure to tephra. Third, respiratory issues associated with tephra are exacerbated among people with pre-existing conditions (Baxter et al., 1981); in urban settings, this is often due to smoking or regular exposure to airborne pollutants. In pre-contact times, some hunter-gatherers had respiratory issues associated with regular smoke inhalation in closed settings due to the need for indoor fires much of the year. Studies of pre-contact populations in North America indicate that respiratory illnesses were common and are attributed to poor indoor air quality and airborne pathogens (Keenleyside, 1998; Merrett and Pfeiffer, 2000; Lambert, 2002; Roberts, 2007). For example, Zimmerman and Aufderheide (1984) documented severe anthracosis in the preserved lungs of pre-contact women from ca. AD 1500 in northern Alaska, which they attribute to prolonged smoke exposure. Constant exposure to indoor wood or turf fires causes pulmonary diseases (e.g., chronic bronchitis) that have been linked to morbidity and mortality in some populations (Cleary and Blackburn, 1968; Pandey, 1984; Larson and Koenig, 1994; Bruce et al., 2002).

We suggest that Subarctic people who relied on wood fires for indoor heating in small enclosed spaces for over five months of the year were prone to respiratory diseases. Over 5–10 cm of tephra would aggravate health issues for much of this population. Biological impacts of tephra are influenced by height above ground level so we presume that children and domestic dogs would have been particularly susceptible to respiratory stress associated with thick tephra. We conclude that tephra exceeding



5 cm introduced respiratory issues that would have been actively avoided by pre-contact people for over five years until sufficient ash had been flushed through the ecosystem or stabilized. This conservative estimate is based largely on Wilson et al. (2011a), who documented ash storms that continued for 20 years after an eruption much smaller than WRAe in Chile—the 1991 eruption of Mount Hudson, VEI = 5, 4.3 km<sup>3</sup> bulk ejecta, and 2.7 km<sup>3</sup> DRE (Kratzmann et al., 2009). The pervasive impacts of finer ash fall and smoke from forest fires may also have been challenging for populations in more distant locations of the WRAe footprint in the NWT (cf., Thorarinsson, 1979; Óskarsson, 1980).

Ash falls would have contaminated some water sources but not to the same extent as has been presumed following large-scale eruptions in more arid regions like the Northern Plains of the United States (Oetelaar and Beaudoin, 2005). Human fluorosis has been linked to contaminated groundwater, which serves as the major route of intake of volcanic fluorine by people, as opposed to cascade effects; that is, fluorine is not significantly transmitted from prey to predator (D'Alessandro, 2006). However, volcanic fluorine contamination is more commonly linked to rock-water interactions or degassing; fluorine contamination of water supplies from tephra generally does not result in chronic exposure to humans (D'Alessandro, 2006). Human fluorosis was noted among several families following the 1783 Laki eruption in Iceland with some bone and teeth deformation but this occurred among sedentary farmers with diets and water supplies that were much more spatially limited than pre-contact hunter-gatherers. It is unlikely that fluorine water contamination was a significant issue for people following the WRAe eruption, given their mobile lifestyle and abundant snow deposits and flowing water. It is likely, though, that ash was regularly ingested from drinking water, which may have had notable, though non-fatal, mechanical impacts on internal organs and teeth (e.g., increased tooth wear). We hypothesize that ash inhalation significantly harmed human populations because of mechanical irritation during tephra deposition and in the following weeks, months, and years.

## GENERAL DISCUSSION AND SYNTHESIS

We infer effects of a volcanic eruption on hunter-gatherers in circumpolar landscapes by reconstructing trophic links from plant communities to major prey species and up to people. The severity of disturbance induced by the WRAe tephra fall appears variable across different habitats and in some ways resembles that of severe forest fires. However, the charcoal and pollen records suggest that impacts extended across thousands of square kilometres as opposed to the generally smaller extent of wildfires, and the ash itself had other deleterious consequences. Overall, the diversity of local responses to tephra likely created a mosaic or patchwork environment with different

implications for fauna with small versus large territories and resident versus migratory species. The effect of the widespread disturbance caused by WRAe is perhaps best illustrated in caribou DNA that suggests partial population replacement following the eruption (Kuhn et al., 2010). Because caribou were a principal prey species across Yukon (Fig. 8), it is probable that WRAe had a significant negative impact on people for several generations while caribou recovered. An expansion of sedge meadows (as suggested by pollen records) may have facilitated caribou recovery but slow recovery of lichen communities (based on studies of modern eruptions) in critical winter habitat may have slowed recovery and elevated winter mortality of caribou. An alteration of migratory paths to avoid the ash would have left caribou less predictable to hunter-gatherers. These negative impacts on subsistence were compounded through what we argue was a decrease in salmon populations and the predictability of their migratory runs, which may have lasted for a decade because of lethal turbidity, changes in river bank morphology, and homing issues. The WRAe footprint extends across migratory paths of caribou and salmon (Fig. 9), which would have seasonally reexposed key prey species to ash and its negative biological consequences. Widespread forest fires may have further lessened the ability of hunter-gatherers to persist in portions of southern and central Yukon (Fig. 10).

WRAe tephra was likely a discontinuous layer that fell on topographically diverse areas with a resultant range of effects (Fig. 11). High-elevation areas with more continuous permafrost and a more uniform vegetation canopy (e.g., alpine meadows) may have experienced more prolonged impacts than lower-elevation areas that hosted more diverse vegetation canopies, discontinuous permafrost, and higher microscale vertical relief (which promoted more rapid erosion and flushing of tephra). High-elevation regions may have experienced more drastic changes to ecological succession than lower-elevation areas. However, variables that spatially concentrate tephra (e.g., erosion toward fish-bearing lakes and tributaries) would exacerbate effects. Ecological impacts are also influenced by tephra grain size with evidence that some toxic effects for fish and mammals are linked to smaller tephra particles, which are typically deposited farther from the vent (Thorarinsson, 1979; Óskarsson, 1980). Coupled with more continuous permafrost, a more uniform vegetation canopy, and slower succession at high-elevation areas (Arnalds, 2013), such as alpine meadows in the Mackenzie Mountains (see Kershaw and Gill, 1979; Rainville, 2016), the eastern reaches of the WRAe footprint may have experienced more significant impacts on flora and fauna than neighbouring lower-elevation areas to the west with thicker deposits (e.g., along Pelly River).

WRAe tephra in the NWT likely affected vegetation and game animals. Fine-grained ash is susceptible to intense compaction (Antos and Zobel, 2005), which limits oxygen flow and hinders vegetation regrowth. It also has an increased likelihood of adsorbing volatiles that alter pH

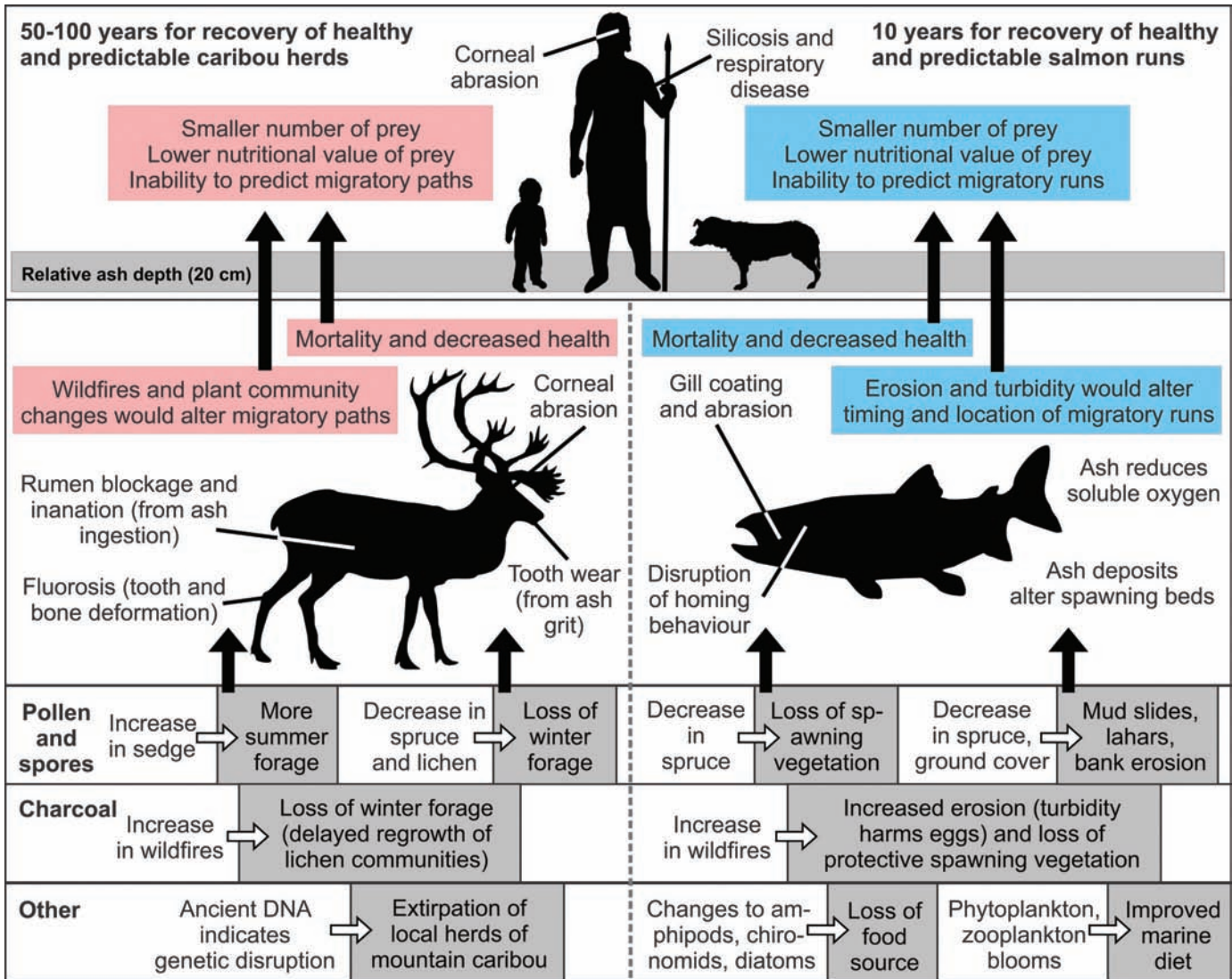


FIG. 10. Schematic of trophic impacts of the White River Ash east eruption in southern and central Yukon.

(Smith et al., 1993; Payne and Blackford, 2008) and adhere to vegetation (Thorarinsson, 1979; Óskarsson, 1980). Based on these studies, eastern reaches of the WRAe tephra footprint (e.g., places with 0.5–1 cm of tephra) may have experienced ecological impacts that rivalled areas closer to the vent. We expect there to have been negative impacts on freshwater fish (including inconnu and whitefish, a fall spawner with runs that involve millions of individuals; (Bond, 1980) and waterfowl, both of which were crucial to people in the Mackenzie Basin (Helm, 1981). Moose and bison in the Mackenzie Basin may have also been affected through their seasonal reliance on aquatic vegetation and meadow habitats. Consequently, there are reasons to suspect that Dene populations of the NWT were adversely affected.

One element of successful hunter-gatherer food procurement in Subarctic landscapes involved the periodic aggregation of people to seasonal pulses in biological productivity (such as caribou and salmon migration) that sustained large gatherings vital for information sharing about regional resources, marriage arrangements, and

ceremonial life. We hypothesize that both caribou and salmon (as well as small mammals and birds) were both scarcer and less predictable in portions of Yukon because of large-scale landscape changes induced by the ash. It may have taken up to a century for human populations to return to the 5 cm or more tephra footprint and resume former patterns of subsistence. This estimate is supported by a roughly century-long hiatus of ice patch artifacts in southern Yukon (Hare et al., 2012) and by Mullen’s (2012) work on radiocarbon dates and population history following the WRAe. Mullen (2012) concluded that an exodus occurred after WRAe, based on radiocarbon-dated occupations, but because of error ranges in radiocarbon dates, it is not currently possible to say how long an interval of abandonment or population decline lasted. It is probable that smaller local groups, task groups, or scouting parties occasionally entered the tephra fallout area (perhaps for decades following the eruption) to reconnoitre their homeland and exploit resources that persisted or had recolonized patchwork landscapes.

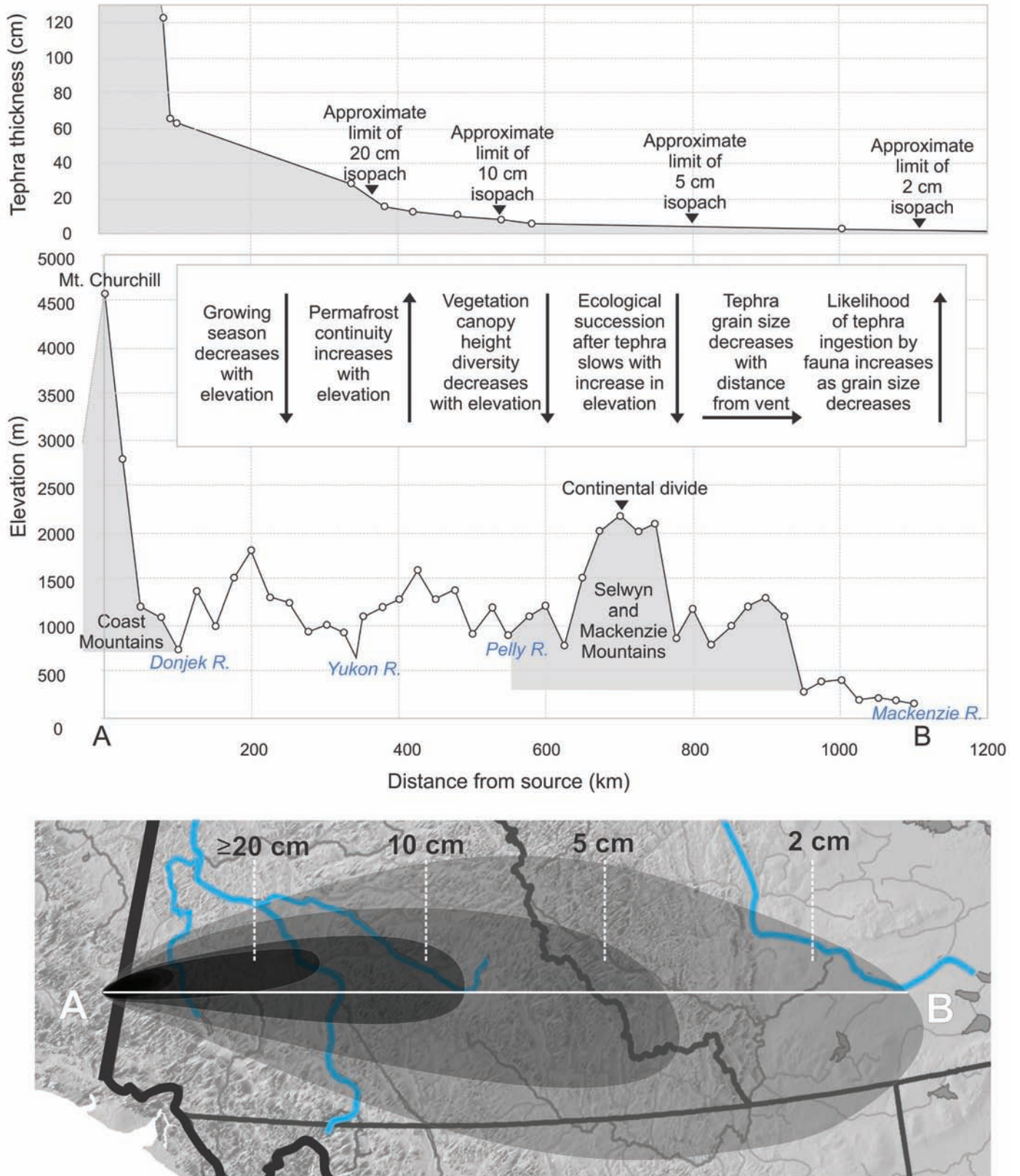


FIG. 11. Schematic of tephra thickness (top) with distance from the source (from Robinson, 2001) and a general landscape elevation profile (middle) along a transect from the WRAe source to the Mackenzie River (bottom) (the isopachs at bottom are adapted from Lerbekmo, 2008).

The stability of the trophic pyramids of neighbouring hunter-gatherers undoubtedly influenced the directions in which displaced people turned following a natural disturbance. We expect that people who temporarily left the tephra fallout area would rely on neighbours, as occurred historically in times of need (McClellan, 1975). Derry (1975) suggested that WRAe forced people north into central and northern Yukon. While the movement north of some social units may have taken place, in a purely ecological sense, people would have faced challenges seeking support from neighbouring kin in that direction. Northern neighbours were also experiencing related stresses on their major food supplies of salmon and caribou, which, because of their migratory paths, seasonally entered the WRAe footprint to the south. However, the WRAe event likely had minimal effects on the subsistence of hunter-gatherers south and west of the WRAe footprint (Fig. 8), such as the Tlingit in southeast Alaska and Tahltan in northwest British Columbia. These were logical places to seek refuge from an ecological perspective, as were regions southeast of the ash fall zone.

Neighbours in regions southeast of the WRAe zone, historically inhabited by the Sekani, Dene Tha', and Danezaa of northeast British Columbia and northwest Alberta, could have harboured groups affected in the more easterly footprint of the ash fall. Apachean ancestors share close, recent ties with the eastern branch of the Dene languages (those of the Peace and Mackenzie basins) (Krauss and Golla, 1981; Malhi et al., 2003; Achilli et al., 2013; Snoek, 2015); microbands of prototypical speech communities of the eastern Dene divisions described by Snoek (2015) may have been among those displaced in the wake of WRAe.

We envision two major alternatives for ancestral populations of Dene (Athapaskan) hunter-gatherers who temporarily left the WRAe footprint: 1) to have sought assistance from communities in which ties of kinship existed, or 2) to have sought support where alliances such as trading partnerships had been previously established. These strategies were not mutually exclusive. Historically, northern Dene communities explored various options in kinship and residence, with marriage practices ranging from endogamy to exogamy (Ridington, 1968, 1969; Asch, 1980, 1988; Ives, 1990, 1998; Legros, 2007). Exogamous strategies promoting external kin ties would have alleviated ecological challenges created by WRAe. Such kin ties were vital in allowing people to gather in larger groups for communal harvesting (i.e., caribou and salmon migrations) or in times of scarcity when it would be necessary to seek help. Similarly, ties established through trading relationships, often involving real affinal or fictive consanguineal kinship, would provide social avenues along which to move away from areas of severe impact.

Cultural perceptions of large-scale events and the social networks on which people relied to cope with them surely shaped responses (Oetelaar and Beaudoin, 2005; Torrence, 2016). The ash cloud of the WRAe event is thought to have extended over 40 km high (Lerbekmo,

2008) and would have been visible on the horizon over 500 km away. For comparison, Wilcox (1959:421) recorded an ash cloud 18–21 km high and 50 km wide roughly 40 minutes after the Mount Spurr eruption of 1953 in Alaska (lightning flashes were recorded every 3 seconds as the ash cloud dispersed downwind). Based on other models of large-scale eruptions (Oetelaar and Beaudoin, 2005) that accounted for ash cloud dispersal (Hooper et al., 1980), sound emanation (Fairfield, 1982; Simkin and Fiske, 1983), and light transmission (Lamb, 1970; Cook et al., 1981), it may have taken as little as one hour for thunderous booms and 10 hours for the WRAe ash cloud (and accompanying lightning) to descend across Yukon and the NWT. Ash clouds over southern Yukon would have blocked out the sun with a darkness akin to night time for several days. See Griggs (1922:9–11) for a description of the several days of darkness on Kodiak Island over 100 km from the source of the 1912 Katmai eruption, and Blong (1982) for accounts of the three to four days of darkness reported after the Matapen-Tibito eruption in Papua New Guinea in the 1650s or 1660s. This model presumes a single explosive event over a short time frame—Lerbekmo (2008) estimated 70 hours for WRAe. In a landscape where people were accustomed to periods of resource depression (e.g., lean food supplies during portions of the year), they could probably survive on stored food during the days and weeks of out-migration. The event was almost certainly a terrifying spectacle that would be psychologically stressful and confusing, and would have pushed people to fall back on reliable resources and kin networks (cf. Oetelaar, 2015; Riede, 2016b, 2017).

The vulnerability of human populations to large-scale disturbances relates to their capacity to anticipate, cope with, and recover from incidents (Blaikie et al., 1994:9; Losey, 2005; Riede, 2017; Torrence, 2019). Regular forest fires pre-adapted Subarctic hunter-gatherers to landscape disturbances but perhaps not at the scale of the WRAe event. Major volcanic eruptions occur infrequently (e.g., every 500 years) in North America's northwest circumpolar region (Davies et al., 2016) such that they may have been preserved in oral history as powerful phenomena (Moodie et al., 1992; Fast, 2008). The White River Ash north eruption of ~ 1625 BP (Reuther et al., 2020) is pertinent because it preceded the WRAe eruption by roughly 500 years and occurred in a partially overlapping territory (Fig. 12). Dene oral histories of WRAe (Moodie et al., 1992; Fast, 2008) may have embedded moral codes and prescriptions for ecological responses to widespread disturbance events (e.g., Minc, 1986).

The eastward spread of ash, coupled with knowledge of social networks and the habitual ranges of adjacent kin groups, would have determined in what direction displaced people spread. This in turn would have shaped longer-term consequences of the eruption on technological transfer and the potentially permanent migration of some social groups of Dene ancestors to other regions (Ives, 1990; Magne, 2012). The Yukon ice patch data point to a distinct change in weaponry (from the atlatl or spearthrower to the bow

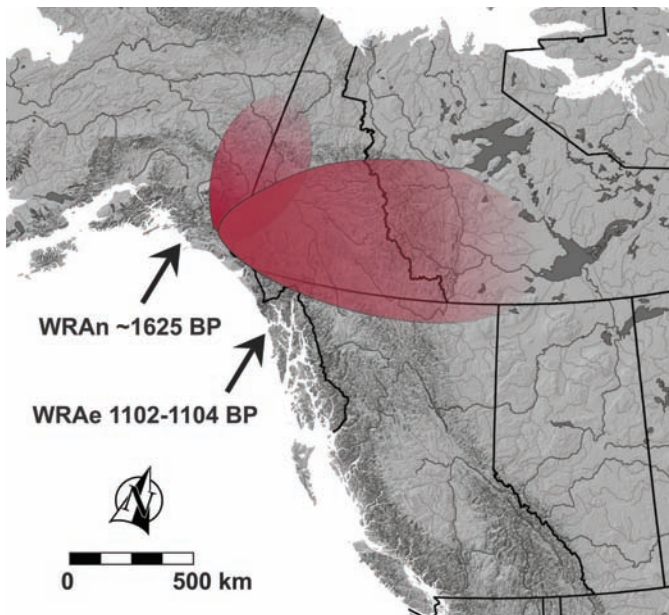


FIG. 12. Comparative plumes and dates of the White River Ash north and east eruptions.

and arrow) from before to after the WRAe eruption, likely because of coastal influences (Hare et al., 2004, 2012), while obsidian data (Kristensen et al., 2019b) bolsters a vector of movement of temporarily displaced people to the southwest, toward Tlingit communities. The distribution of Tertiary Hills Clinker, a partially fused, glassy rock that originates in the NWT (Kristensen et al., 2019a) suggests that the WRAe eruption and its impacts decreased human contact across the Mackenzie Mountains in the eastern portion of the WRAe tephra footprint while groups in the NWT strengthened networks to the east and northeast. It remains possible that some hunter-gatherer social units in the eastern portion of the WRAe footprint moved south and southeast away from tephra impacts. Genetic and linguistic research has affirmed a timing roughly coeval with both WRA eruptions of the southward migration of northern Athapaskan speakers to coastal Washington and California and the Great Basin and Southwest United States (e.g., Krauss and Golla, 1981; Malhi et al., 2003, 2008; Achilli, 2013; Monroe et al., 2013; Ives et al., 2014; Billinger and Ives, 2015; Snoek, 2015; Flegontov et al., 2019). On the basis of current palaeoenvironmental and comparative evidence, the suspicion that WRAe triggered human population movements in northwest North America is warranted. The current paper presents ecological studies of the WRAe event and likely vectors of movement to be tested in the future with archaeological and oral history data (see Moodie et al., 1992; Fast, 2008; Edinborough, 2015).

The Hutchinson et al. (2019) diatom study at Pocket Lake, NWT, illustrates that precise detection of ecological events and their impacts requires sediment core sampling at millimetre-scale intervals. For the time being, we attempt to bridge the temporal gap between most other palaeoenvironmental studies and human adaptation by

linking pollen and charcoal records to major prey species, the seasonal round of hunter-gatherers, and human health. Ultimately, palaeoenvironmental studies, research on modern ash falls, and a trophic approach inform a hypothesis of the ecological parameters of a large-scale disturbance. Future work may reveal human adaptations to this event through social strategies, subsistence, and ideology. This approach complements other studies that have elucidated human responses to eruptions through detailed palaeoclimatological data, radiocarbon dates, demographic models, and changing settlement patterns (Mullen, 2012; Riede et al., 2017; Tremayne and Brown, 2017; Jørgensen and Riede, 2019).

## CONCLUSION

We utilize palaeoenvironmental data (principally pollen and charcoal records) supplemented by studies of modern ash fall ecology to infer effects of the WRAe event at AD 846–848 upon hunter-gatherers in southern and central Yukon. The WRAe event was capable of triggering the temporary movement of people away from the thickest zones of tephra deposition ( $\geq 5$  cm) because of the expected effects of ash on the physiology and ecology of ungulates, fish, and people. People relied on predictable animal aggregations; we argue that the volcanic event stimulated a disruption to patterns of human subsistence in the 5 cm or more tephra footprint, which lasted for up to a century, with notable but shorter-term impacts in the 1–5 cm tephra isopach zone. However, the intervening period of recovery of that subsistence strategy was likely characterized by frequent visits and the persistence of smaller, dispersed social units across a mosaic landscape that the tephra disturbance fostered. Our synthesis addresses misconceptions of the uniformly cataclysmic nature of disturbances and contextualises archaeological inferences of what this volcanic eruption induced, including previously proposed eradications of local human populations, long-term abandonment of landscapes, the migration of groups of Dene people across the continent, and technological change (Workman, 1974, 1979; Derry, 1975; Ives, 1990, 2010; Magne and Matson, 2010; Kristensen et al., 2019a, b). By the same token, our synthesis does suggest that ecological impacts associated with this eruption induced changes in human behaviours with a long-lasting cultural legacy. As with eruptions elsewhere, hunter-gatherer communities responded through increased mobility and the activation of social networks, both of which leave archaeological signatures. Palaeoenvironmental data in the context of trophic links, combined with ethnohistoric and archaeological records of subsistence, offer the means to understand pre-contact human responses to natural disturbances.

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