

1 Presence of rapidly degrading permafrost plateaus in 2 southcentral Alaska

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16 **Abstract.** Permafrost presence is determined by a complex interaction of climatic, topographic,
17 and ecological conditions operating over long time scales. In particular, vegetation and organic
18 layer characteristics may act to protect permafrost in regions with a mean annual air temperature
19 (MAAT) above 0 °C. In this study, we document the presence of residual permafrost plateaus on
20 the western Kenai Peninsula lowlands of southcentral Alaska, a region with a MAAT of 1.5±1
21 °C (1981 to 2010). Continuous ground temperature measurements between 16 September 2012
22 and 15 September 2015, using calibrated thermistor strings, documented the presence of warm
23 permafrost (-0.04 to -0.08 °C). Field measurements (probing) on several plateau features during
24 the fall of 2015 showed that the depth to the permafrost table averaged 1.48 m but was as
25 shallow as 0.53 m. Late winter surveys (drilling, coring, and GPR) in 2016 showed that the
26 average seasonally frozen ground thickness was 0.45 m, overlying a talik above the permafrost
27 table. Measured permafrost thickness ranged from 0.33 to > 6.90 m. Manual interpretation of
28 historic aerial photography acquired in 1950 indicates that residual permafrost plateaus covered
29 920 ha as mapped across portions of four wetland complexes encompassing 4,810 ha. However,

30 between 1950 and ca. 2010, permafrost plateau extent decreased by 60 %, with lateral feature
31 degradation accounting for 85 % of the reduction in area. Permafrost loss on the Kenai
32 Peninsula is likely associated with a warming climate, wildfires that remove the protective forest
33 and organic layer cover, groundwater flow at depth, and lateral heat transfer from wetland
34 surface waters in the summer. Better understanding the resilience and vulnerability of
35 ecosystem-protected permafrost is critical for mapping and predicting future permafrost extent
36 and degradation across all permafrost regions that are currently warming. Further work should
37 focus on reconstructing permafrost history in southcentral Alaska as well as additional
38 contemporary observations of these ecosystem-protected permafrost sites lying south of the
39 regions with relatively stable permafrost.

40 **1 Introduction**

41 Permafrost is a major component of the cryosphere in the northern hemisphere, covering ~24%
42 of the terrestrial landscape (Brown et al., 1998). Permafrost is defined as ground that remains at
43 or below 0 °C for at least two consecutive years (Van Everdingen, 1998). Four zones describe
44 the lateral extent of permafrost ~~regions~~: continuous (90-100%), discontinuous (50-90%),
45 sporadic discontinuous (10-50%), and isolated discontinuous (< 10%). This zonation typically
46 represents the north to south changes in spatial distribution for terrestrial permafrost in high
47 latitudes. Mean annual ground temperatures (MAGT) in the continuous permafrost zone can be
48 as cold as -15 °C, fall within a narrow range around -2 °C in the discontinuous permafrost zone,
49 and can be warmer than -1 °C in sporadic and isolated permafrost zones (Smith and
50 Riseborough, 2002; Romanovsky et al., 2010; Smith et al., 2010). In the absence of extensive
51 ground temperature data, researchers have estimated the southern limit of permafrost in northern
52 high latitudes with continental-scale patterns of air temperature isotherms (Brown, 1960, 1970;
53 Ferrians, 1965; Brown et al., 1998). However, in reality complex interactions between climatic,
54 topographic, hydrologic, and ecologic conditions operating over long time scales regulate

55 permafrost presence and stability (Shur and Jorgenson, 2007). Due to these interactions,
56 permafrost may persist in regions with a mean annual air temperature (MAAT) above 0 °C, and
57 it may degrade in regions with a MAAT below -10 °C (Jorgenson et al., 2010). Thus, the extent
58 and dynamics of permafrost and permafrost-related landscape features remain poorly mapped
59 and modelled at sufficiently fine resolution needed for predicting the impact of climate change
60 on specific local landscapes, which is necessary for many decision makers.

61 Permafrost warming, degradation, and thaw subsidence can have significant implications
62 for ecosystems, infrastructure, and climate at local, regional, and global scales (Jorgenson et al.,
63 2001; Nelson et al., 2001; Schuur et al., 2008). In general, permafrost in Alaska has warmed
64 between 0.3 °C and 6 °C since ground temperature measurements began between the 1950s and
65 1980s (Lachenbruch and Marshall, 1986; Romanovsky and Osterkamp, 1995; Romanovsky et
66 al., 2002; Osterkamp, 2007; Romanovsky et al., 2010). Warming and thawing of near-surface
67 permafrost may lead to widespread terrain instability in ice-rich permafrost in the Arctic
68 (Jorgenson et al., 2006; Lantz and Kokelj, 2008; Gooseff et al., 2009; Jones et al., 2015;
69 Liljedahl et al., 2016) and the sub-Arctic (Osterkamp et al., 2000; Jorgenson and Osterkamp,
70 2005; Lara et al., 2016). Such land surface changes can impact vegetation, hydrology, aquatic
71 ecosystems, and soil-carbon dynamics (Grosse et al., 2011; Jorgenson et al., 2013; Kokelj et al.,
72 2015; O'Donnell et al., 2011; Schuur et al., 2008; Vonk et al., 2015). For example, in boreal
73 peatlands, thaw of ice-rich permafrost often converts forested permafrost plateaus into lake and
74 wetland bog and fen complexes (Camill, 1999; Jorgenson et al., 2001; Payette et al., 2004;
75 Quinton et al., 2011; Lara et al., 2016; Swindles et al., 2015). Furthermore, the transition from
76 permafrost peatlands to thawed or only seasonally frozen peatlands can have a positive or a
77 negative feedback on regional and global carbon cycles depending on permafrost conditions and

78 differential effects of thaw on net primary productivity and heterotrophic respiration (Turetsky et
79 al., 2007; Swindles et al., 2015), as well as on the degree of loss of the former deep permafrost
80 carbon pool (O'Donnell et al., 2012).

81 In Alaska, a variety of permafrost conditions shape roughly 80% of the landscape (Jorgenson
82 et al., 2008). Shur and Jorgenson (2007) proposed five classes of permafrost that describe the
83 interaction of climatological and ecological processes. Arranged from coldest to warmest, these
84 permafrost classes are as follows: climate-driven; climate-driven but ecosystem-modified;
85 climate-driven but ecosystem-protected; ecosystem-driven; and ecosystem-protected.
86 Ecosystem-protected permafrost is the warmest and most vulnerable of the five classes of
87 permafrost and characterizes the sporadic and isolated permafrost zones. It comprises residual
88 permafrost that persists due to favourable ecosystem factors under a climate that is not conducive
89 to its formation. Press disturbances, associated with warming air temperatures and increases in
90 precipitation (especially snow), and pulse disturbances, such as fire or human activities, can
91 trigger immediate ecosystem modification and permafrost thaw in these regions (Shur and
92 Jorgenson, 2007).

93 Since permafrost acts as a sentinel, integrator, and regulator of climate change, improved
94 understanding of its distribution and dynamics is essential, particularly along the southern
95 permafrost boundary (Lunardini, 1996). Southcentral Alaska, a region with a MAAT ~ 2 °C, is
96 typically mapped as being within the permafrost-free zone (Ferrians, 1965; Brown et al., 1998;
97 Pastick et al., 2015). However, ecosystem-protected permafrost persists in southcentral Alaska
98 in regions with present-day climatic conditions that are no longer conducive to its formation
99 (Shur and Jorgenson, 2007). Isolated permafrost patches in southcentral Alaska exist on the
100 western Kenai Peninsula Lowlands (Berg et al., 2009; Hopkins et al., 1955; Jorgenson et al.,

2008) and in the vicinity of Anchorage (Jorgenson et al., 2003; Kanevskiy et al., 2013). Enhanced insight into the resilience and vulnerability of ecosystem-protected permafrost is important due to its utility as a climate indicator and a forecaster of the environmental consequences expected to arise from permafrost thaw elsewhere in the boreal forest where MAAT is expected to warm beyond 0 °C in the coming decades (Beilman et al., 2001). Nevertheless, to date, detailed studies of these southcentral Alaska ecosystem-protected permafrost deposits have remained limited (Kanevskiy et al., 2013).

In this study, we document the presence of rapidly degrading permafrost plateaus on the western Kenai Peninsula lowlands of southcentral Alaska (Fig. 1), a region with a MAAT of 1.5±1 °C (Fig. 2). In mid-September 2012, we conducted field studies at several black spruce plateaus located within herbaceous wetland complexes. Continuous ground temperature measurements between 16 September 2012 and 15 September 2015 confirmed the presence and degradation of permafrost. Probing, drilling, coring, and ground-penetrating radar surveys conducted in the summer, fall, and winter seasons provided additional information on the geometry of the frozen ground below the forested plateaus. We also used historic aerial photography and high-resolution satellite imagery from 1950, 1984, 1996, and ca. 2010 to map decadal-scale changes in the aerial extent of the residual permafrost plateaus in portions of four wetland complexes on the western Kenai Peninsula. This study aims to document and incorporate the loss of ecosystem-protected permafrost into the overall understanding of landscape dynamics on the western Kenai Peninsula lowlands. More importantly, insights into its stability will enhance mapping and predicting current and future permafrost extent along the southern fringe of the circumpolar permafrost region.

123 **2 Study Area**

124 The western Kenai Peninsula lowlands are located in southcentral Alaska, between 59.6 and 61.0
125 °N, and are generally less than 100 m asl (Fig. 1). The lowlands experience a semi-continental
126 climate due to a rain shadow produced by the Kenai Mountains to the east and the presence of
127 Cook Inlet to the west and north, and Kachemak Bay to the south (Jones et al., 2009). Regional
128 MAAT for 1981-2010 is 1.5 °C, with a mean annual precipitation of 441 mm
129 (<http://www.ncdc.noaa.gov/crn/observations.htm>). The lowlands represent a unique landscape
130 where two major glacial ice fields converged during the Late Wisconsin, 25,000–21,000 kya
131 (Reger et al., 2007). The modern topography, composed of moraines, outwash fans, kettle lakes,
132 kames, and eskers, is indicative of this glacial history (Hopkins et al., 1955). During the
133 Holocene, the Kenai Peninsula lowlands have succeeded to boreal forest, muskeg, and wetlands
134 laced with rivers and creeks and dotted with lakes (Anderson et al., 2006; Reger et al., 2007).
135 Pastick et al. (2015) recently mapped this region as being permafrost-free in the upper one meter
136 of the ground surface.

137 The Kenai lowlands are situated in an ecotone between the coastal temperate rainforest
138 and interior boreal forest. Species assemblages depend on topography and disturbance history,
139 as well as their location relative to the rain shadow. Black spruce (*Picea mariana*), white spruce
140 (*Picea glauca*), Sitka spruce (*Picea sitchensis*), Lutz spruce (*Picea x lutzii*, hybrid of white and
141 Sitka spruce), paper birch (*Betula kenaica*), alder (*Alnus sp.*), black cottonwood (*Populus*
142 *trichocarpa*), and aspen (*Populus tremuloides*) all occur within various forest stand types.
143 Herbaceous and woody wetland complexes intermingle with these forests in low-lying areas and
144 river corridors. Within wetland complexes, elevated forested plateaus, primarily black spruce
145 but with some paper birch and cottonwood and an understory of dwarf shrubs, exist where the

146 ground surface has been elevated above the regional water table. We suspected these features
147 were associated with a volumetric expansion of freezing peat, forming a permafrost plateau, an
148 elevated permafrost feature associated with frost heave (Zoltai, 1972). These features are the
149 focus of our studies on the Kenai Peninsula.

150 **3 Methods**

151 In September 2012, we conducted field studies at a number of black spruce plateaus located
152 within herbaceous wetland complexes (Fig. 3). These studies documented frozen ground below
153 an unfrozen layer with thicknesses ranging from 0.49 to >1.00 m. The plateau features tended to
154 have sharply defined scalloped edges, marginal thermokarst moats, and collapse-scar depressions
155 on their summits (Fig. 3). These traits were characteristic of the permafrost features described
156 by Hopkins et al. (1955) on the Kenai Peninsula and similar to permafrost plateaus across colder
157 boreal regions (Zoltai, 1972; Thie, 1974; Jorgenson et al., 2001; Camill, 2005; Sannel et al.,
158 2015). To answer whether the frozen ~~ground~~ deposits encountered at the black spruce plateaus
159 were indeed permafrost, we collected continuous ground temperature measurements for three
160 years, measured late-summer thaw depths, mechanically drilled and cored for the base of the
161 frozen ground, imaged the subsurface with ground-penetrating radar (GPR), and analysed a time
162 series of high-resolution remotely sensed imagery. We describe these research efforts in more
163 detail below.

164 **3.1 Field Instrumentation and Surveys**

165 To confirm the presence or absence of permafrost, we installed data loggers on 12 September
166 2012 at one ground temperature monitoring site in the Browns Lake and three in the Watson
167 Lake area (Fig. 1). We used a 5-cm diameter Kovacs Enterprise ice auger to drill the boreholes

168 and cased the holes with a 4.5 cm outer-diameter PVC tube from the base of the borehole to
169 within 10 cm of the surface. We instrumented each site with a 4-channel Hobo data logger
170 (Onset U12-008) buried below the ground surface (bgs). The data loggers recorded hourly
171 ground temperature at four depths from 0.10 m to 3.00 m bgs using Hobo TMC1-HD and
172 TMC2-HD thermistors (Table 1). The manufacturer-specified accuracy of the thermistors is +/-
173 0.25 °C. Prior to deployment, we placed the data logger thermistors in a 0 °C ice bath for up to
174 45 minutes to estimate a calibration factor for post-processing of the data following download in
175 the field. This calibration increased the accuracy of the ground temperature data to better than
176 +/- 0.05 °C on average and is similar to improvements recorded for other measurement systems
177 (Sannel et al., 2015; Cable et al., 2016). We post-processed all data prior to summarizing the
178 hourly ground temperature data into daily, monthly, and annual means.

179 Additional field surveys at each study site provided information on the geometry of the
180 frozen ground distribution and deposit types. We used a tile probe to measure the depth to
181 frozen sediments at each ground temperature monitoring location in mid-September 2015
182 (limited to 2.2 m bgs). At the two forested plateaus in the Watson Lake wetland complex, we
183 selected tile probing locations randomly and split between hummock and depression
184 microtopography. At the Browns Lake site, we recorded this depth at three points every meter
185 along a 100 m transect across the plateau feature. In addition, we collected a topographic profile
186 of the primary Browns Lake plateau using a Leica survey-grade differential GPS (dGPS) system
187 (+/- 0.02 m vertical accuracy) on 09 October 2015 to adjust the probing measurements relative to
188 the local topography. An additional dGPS profile was acquired on 19 February 2016 at an
189 adjacent plateau to provide more relative feature height information in the wetland complex. At
190 both the Browns Lake and Watson Lake locations, we measured the frozen ground thickness

191 using the Kovacs Enterprise ice auger system powered by an 18V portable drill. At Browns
192 Lake, we also collected a core for visual analysis of the frozen ground deposit using a SIPRE
193 permafrost corer with an engine auger head. We calculated the excess ice fraction (EIF) for
194 three sites at the Browns Lake plateau for which we had detailed height, depth to permafrost
195 table, and permafrost base information following Lewkowicz et al. (2011) to enable comparison
196 of EIF with previously studied permafrost plateaus.

197 Implementation of GPR allowed us to image certain characteristics of the frozen ground
198 along the primary Browns Lake plateau feature. We used a shielded 100-MHz Mala antenna in
199 July 2014 and Sensors & Software 100-MHz unshielded bi-static antennas in common-offset
200 configuration in February 2016. We processed the data using commercially available Reflex-W
201 processing software (Sandmeier, 2008). Basic processing steps included dewow, time-zero
202 correction, removing bad traces, and bandpass filtering (40-67.2-128-369 MHz for Mala; 25-50-
203 200-400 MHz for Sensors & Software). Additional processing steps included an average
204 background subtraction with a running window of 20 to 100 traces to reduce noise from surface
205 multiples, where applicable, and variable gain for viewing purposes. Care was taken during
206 processing to preserve any flat-lying reflectors. Finally, we corrected the radargrams using the
207 dGPS surface topography and converted two-way travel time to depth using an estimated
208 average subsurface velocity of 0.038 m ns^{-1} calibrated to average direct probe depths.

209 **3.2 Remotely Sensed Imagery and Change Detection**

210 Historic aerial photography and contemporary high resolution satellite imagery acquired between
211 1950 and ca. 2010 provided an estimated extent of forested plateaus centred on four wetland
212 complexes on the western Kenai Peninsula lowlands. We selected four change detection study
213 areas (Fig. 1) based on the presence of forested, plateau features surrounded by herbaceous

214 wetland vegetation that likely indicated permafrost presence in the boreal wetlands on the Kenai
215 Peninsula (Hopkins et al., 1955). Arranged from north to south, these included portions of the
216 Mystery Creek, Watson Lake, Browns Lake, and Tustumena Lake wetland complexes (Fig. 1).
217 Mapping forested plateau features and their change over time is a common method for detection
218 of permafrost thaw in boreal wetlands. The land cover change associated with conversion of a
219 forested permafrost plateau to a lake or herbaceous wetland (i.e. bog or fen) is readily detectable
220 in high-resolution remotely sensed imagery (Thie, 1974; Camill and Clark, 1998; Osterkamp et
221 al., 2000; Jorgenson et al., 2001; Payette et al., 2004; Quinton et al., 2011; Lara et al., 2016).

222 We overlaid a 25-km² square study area at each of the potential permafrost areas and
223 clipped the wetland extent as defined by the 2001 National Land Cover Dataset for Alaska
224 (<http://www.mrlc.gov/nlcd2011.php>) to define the mapping area. Panchromatic, Digital
225 Orthophoto Quadrangle (DOQs) images were produced at a spatial resolution of 1.0 m for the
226 entire Kenai Peninsula between July and August 1996. The DOQs provided the base upon which
227 to georegister the other remotely sensed image datasets that consisted of panchromatic aerial
228 photos collected in August 1950 (1:40,000 scale), color-infrared aerial photos acquired in 1984
229 (1:62,500 scale), and panchromatic high-resolution satellite images (< 1 m spatial resolution)
230 acquired in ca. 2010. The mean RMS error associated with image georegistration was 1.82 m
231 and ranged from 1.32 m to 2.61 m and all images were sampled to a ground resolution of 1 m.
232 Following image registration, we manually digitized forested plateaus in a Geographic
233 Information System (ArcGIS v. 10.1) at a mapping scale of 1:1,000 (Fig. 4). The high-spatial
234 resolution, georegistered remotely sensed datasets allowed for the assessment of residual
235 permafrost plateau extent in four time slices (1950, 1984, 1996, ca. 2010) and change rates

236 across three decadal-scale time periods: (1) 1950 to 1984 (34 years), (2) 1984 to 1996 (12 years),
237 and (3) 1996 to ca. 2010 (14 years).

238 **3.3 Climate and Weather Data**

239 We compiled climate and weather data from two regional stations to provide context for
240 interpreting the ground thermal regime data and changes mapped in the remotely sensed data.
241 We compiled hourly air temperature data from Kenai Municipal Airport (WBAN: 26523) for
242 1948 - 1971 and 1973 – Present and sub-hourly air temperature data from the Kenai 29 ENE
243 station (WBAN:26563) located at the Alaska Department of Fish and Game Moose Research
244 Center (MRC) from September 2010 - Present. Since the MRC station is more representative of
245 the field study sites, we reconstructed the temperature record for MRC back to 1948 using a
246 linear regression function found between Kenai and MRC daily mean temperatures as
247 summarized from hourly and sub-hourly measurements. The regression equation was calculated
248 by comparing daily mean temperature for 1 January 2012 to 31 December 2015, and validated
249 against daily mean temperatures at the MRC for 1 September 2010 to 31 December 2011.
250 Lastly, we acquired daily snow depth totals recorded at the MRC from September 2012 –
251 September 2015 (<http://wcc.sc.egov.usda.gov/nwcc/site?sitenum=966>).

252 **4 Results**

253 **4.1 Ground thermal regime of southcentral Alaska permafrost**

254 Calibrated ground temperature records collected between 16 September 2012 and 15 September
255 2015 at one forested plateau near Browns Lake and two forested plateaus near Watson Lake
256 confirmed the presence of near-surface permafrost on the western Kenai Peninsula lowlands
257 (Fig. 5a-5c). Over this time period, the MAGT of permafrost at 1 m bgs ranged from -0.04 °C to

258 -0.08 °C (Table 1). At the Browns Lake PF1 and the Watson Lake PF2 sites, permafrost at 2.0 m
259 bgs had a MAGT between -0.06 °C and -0.08 °C. At the Browns Lake PF1 site, permafrost at
260 3.0 m bgs had a MAGT between -0.07 °C and -0.08 °C (Table 1). We detected no permafrost at
261 a black spruce forested, non-plateau site near Watson Lake between September 2012 and August
262 2014 (Fig. 5d).

263 During the three-year observation period, an increase in near-surface ground
264 temperatures was recorded at all three permafrost sites in response to increases in air temperature
265 (Table 1, Fig. 5). The ground temperature at 0.5 m depth was substantially below 0 °C at all
266 three sites during the 2012-2013 winter with minimum temperatures between -1.33 °C (Browns
267 Lake) and -2.5°C (Watson Lake PF2). In the 2013-2014 winter, the ground at 0.5 m depth was
268 barely frozen at the Browns Lake and Watson Lake PF1 sites (Fig. 5a and 5b), with minimum
269 winter temperatures at -0.32 °C and -0.2 °C, respectively. The increase in summer ground
270 temperatures at 0.5 m depth was also substantial. By the end of the 2012 warm period, this
271 temperature was above 0 °C only at the Browns Lake site (the maximum was at 0.4 °C). At the
272 Watson Lake PF1 and PF2 sites the temperature at 0.5 m depth was just below 0 °C and never
273 exceeded the thawing threshold, indicating that the maximum summer thaw (the active layer
274 thickness) was just below 0.5 m during 2012. However, during the summer of 2013 and 2014,
275 the active layer thickness was more than 0.5 m at both of these sites and the maximum
276 temperatures in 2014 exceeded 1°C at the Watson Lake sites (Fig. 5b and 5c). At the Browns
277 Lake site the temperature at a 0.5 m reached almost 2 °C before the thermistor malfunction. The
278 ground temperature warming at 0.5 m depth continued in 2015 (Fig. 5b and 5c).

279 The increase in the shallow ground temperatures triggered warming in the near-surface
280 permafrost at all three permafrost sites (Fig. 6). This warming was strong enough to initiate top-

281 down permafrost thaw at the Watson Lake PF1 site in the fall of 2014 (Fig. 6b). Sensor failure
282 during the winter of 2014/2015 prevented further observations of ground temperature at this site
283 following thaw that winter. At the Watson Lake PF2 site **bottom up permafrost thaw** was
284 detected during the fall of 2015 and likely associated with groundwater flow or degradation of
285 the permafrost in the thermokarst moat that borders the plateau. At the Browns Lake site
286 permafrost persisted at the depths between 1 and 3 m bgs over the three-year observation period
287 (Fig. 6a). However, MAGT warmed by 0.02 to 0.01 °C at all three depths during the observation
288 period. The temperature at 1 m bgs is only -0.04 °C now.

289 **4.2 Depth to permafrost table and permafrost thickness**

290 The thaw depth at our data logger observation sites as measured with the tile probe on 16
291 September 2015 was 0.64 m for the Watson Lake PF1 site (n = 3), 0.53 m for the Watson Lake
292 PF2 site (n = 6), and 0.57 m for the Browns Lake PF1 site (n = 6). More systematic probing at
293 all three sites on 16 September 2015 showed that the average depth to the permafrost table where
294 detectable (max probe length = 2.20 m) was 1.48 m (n = 222). However, probing did not
295 encounter frozen ground in the upper 2.20 m of the ground surface at an additional 140
296 measurement points, mostly associated with collapse-scar features and thermokarst moats. In
297 general, depth to the permafrost table depended on the local topographic conditions at each site.
298 **Hummocks** (n = 164) tended to have a shallower depth to the permafrost table where
299 measureable (average of 1.12 m), while depth to the permafrost table measurements in
300 depressions (n = 58) was larger (average of 1.53 m).

301 The measurements of the depth to permafrost table were complemented with mechanical
302 **drilling, coring**, and GPR surveys in July 2014, September 2015, and February 2016 to constrain
303 permafrost thickness at the field observation sites. The most detailed measurements were

304 collected at the Browns Lake PF1 plateau feature (Fig. 7a). At this site, we conducted a
305 topographic survey of the plateau feature to plot depth to permafrost table along with ~~seasonally~~
306 ~~frozen~~ depth and constraints on permafrost thickness in relation to the relative ground surface
307 elevation along a 100 m transect (Fig. 7b). The relative mean elevation of the plateau above the
308 surrounding wetland area was 0.49 m (not including the collapse-scar bog in the center), with a
309 maximum along the transect of 0.95 m, and a maximum across the feature of 1.3 m. A
310 topographic survey on an adjacent plateau feature produced a mean relative height of 0.59 m and
311 a maximum of 1.81 m. We measured permafrost thickness at five locations and minimum-
312 limiting permafrost thicknesses at another five locations along the Browns Lake primary plateau
313 feature, with one limiting thickness measurement at an adjacent plateau feature using the Kovacs
314 auger. The base of the permafrost at the two marginal plateau measurement sites at the primary
315 plateau feature indicated a permafrost thickness of 0.45 and 0.33 m (Fig. 7b). At the three
316 interior plateau measurements points, permafrost was 5.57 to 5.65 m thick. At one of these
317 locations (0.98 m relative height), we acquired a core that consisted of frozen peat from 0.48 m
318 bgs down to 5.69 m bgs, overlying 0.25 m of unfrozen peat, with unfrozen mineral sediment at
319 the base. At the other five locations where the bottom of permafrost was not reached, drilling
320 operations documented permafrost at least down to between 3.5 and 4.0 bgs (Fig. 7b), and
321 contained frozen peat as well. The EIF for the three interior measurements points on the Browns
322 Lake plateau, where we had information on relative height, depth to permafrost table, and depth
323 of permafrost base, ranged from 0.09 to 0.13. At an adjacent plateau (not shown) the minimum
324 permafrost thickness was 6.90 m bgs, at which point we ran out of auger flight extensions. At
325 Watson Lake PF1, drilling efforts detected permafrost base between 1.30 and 1.50 meters bgs.
326 At the Watson Lake PF2 site, the permafrost base was between 1.96 and 2.04 m bgs.

327 GPR surveys conducted in July 2014 and February 2016 provided more continuous
328 information on the geometry associated with the permafrost table in the residual plateaus on the
329 primary Browns Lake plateau feature (Fig. 8). The topography-corrected radargrams show a
330 prominent reflector between 1 – 3 m depth that coincides with the permafrost table in both the
331 summer (Fig. 8a) and winter (Fig. 8b) survey. The center portion of both images is characterized
332 by moderately continuous and chaotic reflectors (Neal, 2004) as expected for records in unfrozen
333 peat sequences (Parsekian et al., 2010) associated with the collapse-scar bog. The areas
334 underlain by permafrost (i.e. 0 – 30 m, 60 – 90 m) show subdued reflection events deeper than
335 the permafrost table; however, we were unable to image the permafrost base. Our interpretation
336 of these radargrams provides lateral subsurface information on the presence of a talik overlying
337 the permafrost table.

338 **4.3 Remote identification of permafrost plateaus**

339 In 1950, residual permafrost plateau extent accounted for 920 ha of the 4,810 ha (19.1%) of
340 wetlands mapped within four change detection areas (Fig. 1, Table 2). Between 1950 and 1984,
341 permafrost plateau extent decreased to 750 ha, at an average rate of 5.1 ha yr⁻¹ (Table 3).
342 Between 1984 and 1996, permafrost extent dropped to 520 ha, at an average rate of 18.8 ha yr⁻¹,
343 the greatest rate documented in our study periods. Between 1996 and 2010, permafrost features
344 continued to degrade at a rate of 9.5 ha yr⁻¹ so that by 2010, only 370 ha of the permafrost
345 features remained. Thus, between 1950 and ca. 2010, 60% of the residual permafrost plateaus
346 disappeared in our mapped study areas (Fig. 9).

347 Assessment of change in the four wetland complexes showed differences in the extent
348 and change rate of residual permafrost plateaus overtime. The Mystery Creek study area had the
349 most extensive permafrost plateau coverage (32.8 % of the wetland area analysed) in the 1950s

350 relative to the Watson Lake (9.8 %), Browns Lake (11.1 %), and Tustumena Lake (15.8 %) study
351 areas (Table 2). By ca. 2010, permafrost plateau extent in each of the study areas diminished to
352 a cover of 14.8 %, 3.5 %, 3.8 %, and 5.2 %, respectively. Thus, there was a loss of 54.8 % of the
353 plateau extent in the Mystery Creek study area, 64.7 % in the Watson Lake study area, 65.5 % in
354 the Browns Lake study area, and 66.9 % in the Tustumena Lake study area between 1950 and ca.
355 2010. These changes equate to loss rates of 0.9 % yr⁻¹ for Mystery Creek and 1.1 % yr⁻¹ for the
356 Watson, Browns, and Tustumena Lake study areas (Table 3). Mean area loss for all four sites
357 was 0.8 % yr⁻¹ between 1950 and 1984. During this time, loss rate was greatest for Watson Lake
358 and Brown Lake and least for Mystery Creek. Mean loss rate for all four sites increased to 2.3 %
359 yr⁻¹ between 1984 and 1996. During this time, loss rates were greatest in the north and least in
360 the south with Mystery Creek and Tustumena Lake losing 3.0 % yr⁻¹ and 1.2 % yr⁻¹, respectively.
361 Average loss rates decreased to 1.8 % yr⁻¹ between 1996 and 2010, with the three most northern
362 sites losing approximately 1.2 % yr⁻¹, while the Tustumena Lake study area lost 3.2 % yr⁻¹. In
363 terms of plateau area lost per year within the three time periods, Mystery Creek (13.8 ha yr⁻¹),
364 Watson Lake (1.6 ha yr⁻¹), and Browns Lake (1.3 ha yr⁻¹) experienced the greatest areal loss rate
365 during the 1984 to 1996 time period. At the Tustumena Lake study area, the greatest rate of
366 plateau extent loss (4.6 ha yr⁻¹) occurred between 1996 and ca. 2010 (Table 3).

367 We also assessed whether the permafrost degradation occurred along the perimeter of the
368 plateau (marginal), whether degradation was internal to the plateau, or if complete degradation of
369 a plateau occurred. Between 1950 and 2010, 85 % of the degradation occurred as lateral thaw
370 along the plateau margins, while internal thaw and complete loss of features accounted for 1.5 %
371 and 13.4 %, respectively. Lateral loss of permafrost was greatest in the Watson Lake study area
372 (90.9 %) and least (77 %) in the Browns Lake study area. Both Mystery Creek and Tustumena

373 Lake shared a lateral loss of 86 %. Mystery Creek saw the greatest percent of internal collapse
374 loss (3.3 %) compared to Tustumena (1.7 %) and Watson and Browns Lake (both <1 %). The
375 complete loss of permafrost features was greatest in Browns Lake (22.4 %) and least in Watson
376 Lake (8.3 %). Mystery Creek and Tustumena Lake had 10.5 % and 12.3 %, respectively, of their
377 permafrost plateaus disappear in the form of complete feature loss. During the period of
378 remotely sensed observations complete feature loss increased from 6.7 % (1950 to 1984) to 21.0
379 % (1996 to ca. 2010) of the detected change, while lateral feature loss decreased from 91.0 %
380 (1950 to 1984) to 78.1 % (1996 to ca. 2010) of the detected change, likely highlighting the role
381 of fragmentation promoting complete feature degradation.

382 **4.4 Climate and Weather Data**

383 The MAAT of the western Kenai Peninsula lowlands between 1981 and 2010 was 2.22 °C for
384 the Kenai Municipal Airport and estimated to be 1.79 °C for the MRC station. There was
385 significant correlation between Kenai daily mean air temperature and the MRC daily mean air
386 temperature for the 2012-2015 period ($r^2 = 0.97$). The regression equation performed well during
387 validation tests ($r^2 = 0.95$) and was therefore used to estimate daily temperature data for the MRC
388 station back to July 1948. Mean annual air temperature has increased by 0.4 °C since 1950, with
389 a step increase occurring in 1976 associated with the Pacific Decadal Oscillation (PDO)
390 (Hartmann and Wendler, 2005) (Fig. 2). Between July 1948 and December 1976, MAAT was
391 0.83 °C and 0.29 °C for Kenai and MRC, respectively. Following the PDO shift MAAT
392 increased to 1.97 °C and 1.51 °C for Kenai and the MRC, respectively (Fig. 2). Prior to the PDO
393 shift, 18 (MRC) and 6 (Kenai) out of 27 years had a MAAT below freezing and after the PDO
394 shift, only 10 (MRC) and 0 (Kenai) out of 39 years had a MAAT below freezing. MAAT at the
395 MRC station was 0.88 °C (2012), 2.58 °C (2013), and 3.24 °C (2014) during our three-year

396 ground temperature observation period of 16 Sept 2012 to 15 Sept 2015. Therefore, our
397 observations during 2014 and 2015 occurred during a period with anomalously high MAAT
398 relative to the previous climate normal period, with more warming in the winter than the summer
399 months (Table 1). Additionally, between 1948 and 2015, warm season (May-Sept) air
400 temperatures increased by $0.02\text{ }^{\circ}\text{C yr}^{-1}$ for both the Kenai and MRC station, while winter season
401 (Oct-April) air temperature increased by $0.04\text{ }^{\circ}\text{C yr}^{-1}$ (Table 4).

402

403 **5 Discussion**

404 **5.1 Presence of ecosystem-protected permafrost in southcentral Alaska**

405 Our permafrost data for the residual permafrost plateaus on the Kenai Peninsula are the first such
406 observations for isolated permafrost bodies in southcentral Alaska (Osterkamp, 2007). Based on
407 the five classes of permafrost proposed by Shur and Jorgenson (2007), the permafrost present in
408 wetland complexes of the western Kenai Peninsula lowlands is ecosystem-protected. The
409 permafrost on the Kenai Peninsula is extremely warm, with a MAGT that ranges from -0.04 to -
410 $0.08\text{ }^{\circ}\text{C}$ (Table 1; Fig. 6). Permafrost at all ground temperature monitoring sites and depths from
411 1.0 to 3.0 m were near the phase-equilibrium temperature. Latent-heat effects associated with
412 unfrozen water content in permafrost and with seasonal phase changes in the active layer can
413 buffer the ground thermal regime from changes in air temperature at warm permafrost sites
414 (Romanovsky and Osterkamp, 2000) and in part can explain the persistence of ecosystem-
415 protected permafrost on the Kenai Peninsula (Shur and Jorgenson, 2007; Jorgenson et al., 2010).
416 Even though we calibrated all thermistors prior to installation, the ability to resolve such warm
417 permafrost temperatures and their change over time using temperature alone is somewhat
418 limiting. Thus, future measurements at the residual permafrost plateau sites in southcentral

419 Alaska will be accompanied by the addition of soil moisture probes as well as borehole, nuclear
420 magnetic resonance (NMR) which provides a direct measure of liquid water content (Parsekian
421 et al., 2013).

422 **Field** surveys that included probing, drilling, coring and GPR provided additional
423 information on the vertical and spatial distribution of the warm permafrost on the western Kenai
424 Peninsula lowlands. The average active layer thickness at our permafrost plateau ground
425 temperature observation sites was 0.58 m. We chose these sites for initial instrumentation in
426 September 2012 based in part on the relatively shallow depth to the frost table. More
427 comprehensive probing in September 2015 revealed that the average depth to the permafrost
428 table was 1.48 m (n=222) as averaged across three plateaus. At the Brown Lake plateau, a talik
429 overlying the permafrost table was present in February 2016. Average permafrost thickness at
430 this feature was 5.61 m thick, whereas at an adjacent feature it was more than 6.90 m, the
431 maximum depth of our auger flights. GPR survey data confirmed the presence of a continuous
432 surface talik at the Browns Lake site (Fig. 8); however, we were unable to image the base of the
433 permafrost using solely GPR, as similarly described by Lewkowitz et al. (2011). EIF was 0.09
434 to 0.13 for three measurement sites on the primary Browns Lake plateau feature. In comparison,
435 Allard et al. (1986) studied similar peat plateau features in Canada which typically were as high
436 as one-third the thickness of permafrost or an EIF of 0.33. Lewkowitz et al. (2011)
437 demonstrated that features with EIF values below **0.33** likely results from ice-poor permafrost
438 and/or a **high unfrozen water content of the permafrost.** Based on visual interpretation of the
439 permafrost peat core acquired in February 2016, the permafrost deposit consists entirely of
440 **frozen peat that appears to be ice-rich, with a number of ice bands, ice lenses, and ice inclusions.**
441 This evidence combined with the low EIF values and the flat-line ground temperature data

442 suggest high unfrozen water content associated with degrading permafrost on the Kenai
443 Peninsula.

444 5.2 Extent and change in residual permafrost plateaus since the 1950s

445 While previous reports of permafrost on the Kenai Peninsula exist (~~Hopkins et al., 1955;~~
446 ~~Jorgenson et al., 2008~~), they were restricted to the wetland complex (~~Mystery Creek~~) north of
447 Sterling (Berg et al., 2009). Information on its dynamics here and elsewhere was lacking. Our
448 analysis of remotely sensed imagery and field surveys identified residual permafrost plateaus in
449 three additional wetland complexes where it had not been previously identified (Fig. 1 and Fig.
450 9) and indicates that the state of permafrost within the Kenai lowlands is highly dynamic. In
451 1950, forested permafrost plateau extent accounted for 19 % of the land cover in the 4,810 ha of
452 wetland complexes analysed in the four change detection study areas. In each of the wetland
453 areas analysed, permafrost plateaus accounted for more than 10 % of the area in 1950. However,
454 inferred permafrost extent decreased by 60 % between 1950 and ca. 2010, and its lateral
455 coverage dropped below 5 % in three of the four study areas (Table 2).

456 The residual permafrost plateaus documented in this study share similar attributes to
457 features elsewhere in boreal peatlands for which permafrost degradation has been inferred due to
458 the ease of remotely detecting the conversion from forested permafrost plateau to non-permafrost
459 herbaceous wetland or waterbody (~~Jorgenson et al., 2001~~). Thie (1974) inferred a permafrost
460 plateau loss rate of 0.47 % yr⁻¹ between 1800 and 1960 for a 130,000 ha area of southern
461 Manitoba. In Québec, Canada, a 13 ha peat bog lost 1.80 % yr⁻¹ between 1957 and 2003 (Payette
462 et al., 2004). In the Northwest Territories, Canada, Quinton et al. (2011) reported a loss rate of
463 0.62 % yr⁻¹ between 1947 and 2008 across a 100 ha study area. In Interior Alaska (Tanana
464 Flats), Jorgenson et al. (2001) reported a loss rate of 0.76 % yr⁻¹ for birch forested permafrost

465 plateaus between 1949 and 1995 using a point sampling method within a 260,000 ha wetland
466 area. Lara et al. (2016) recently updated these numbers for the Tanana Flats by manually
467 digitizing features with methods similar to ours and demonstrated that birch forest plateaus
468 decreased at a much slower rate of $0.12\% \text{ yr}^{-1}$, and that black spruce forested permafrost plateau
469 features appeared to be stable. Thus, the loss rate of $1.0\% \text{ yr}^{-1}$ that we report for the 4,810 ha
470 mapped on the western Kenai Peninsula Lowlands between 1950 and ca. 2010 are the second
471 fastest change rates reported thus far in boreal peatlands.

472 **5.3 Drivers of permafrost loss**

473 Permafrost on the Kenai Peninsula is likely degrading as a result of warming air temperatures
474 ($+0.4\text{ }^\circ\text{C decade}^{-1}$ since 1950), especially where warming during the winter season likely
475 exacerbates these effects (Table 4). During our three-year observation period as well as since the
476 1950s, warming in the winter has been more pronounced than in the summer (Table 1 and Fig. 2)
477 and 2014 and 2015 had a MAAT **roughly double** the 1981 to 2010 climate normal period. Storm
478 systems regularly bring warm air masses ($> 4\text{ }^\circ\text{C}$) to the region during the winter. Air
479 temperature warming during the winter months has decreased the number of freezing degree
480 days which means that the ground freezes to a much lesser degree in the winter (Fig. 2, Table 1).
481 Therefore ground temperatures decreased less over the winter period (Table 1 and Fig. 5),
482 potentially leading to talik development. Previous research on permafrost plateaus in colder
483 regions indicate that preferential warming in the winter and increased snow accumulation leads
484 to enhanced permafrost thaw in boreal peatlands (Camill, 2005; Osterkamp, 2007). Since the
485 Kenai Peninsula lowlands experience a semi-continental climate due to the rain shadow
486 produced by the Kenai Mountains, a lack of winter snow fall may have contributed to permafrost
487 persistence in this region by allowing relatively cold winter air temperatures to propagate into the

488 sub-surface. Thus, talik formation and permafrost degradation at our study sites in southcentral
489 Alaska are likely being driven for the most part by winter fire
490 air temperature warning (Fig. 2).

491 The increase in permafrost loss rate in southcentral Alaska following the 1980s is likely
492 due to the combined effects of forest fires and a shift in the PDO after 1976. The respective
493 pulse and press disturbances may have promoted large areas of permafrost already close to
494 thawing, to quickly thaw, leaving only colder permafrost and permafrost with intact peat and
495 forest cover. Fire can be an important driver of permafrost thaw (Yoshikawa et al., 2002) and
496 thermokarst development (Jones et al., 2015). The Kenai Fire of 1947 burned the majority of the
497 Mystery Creek study area, all of the Watson Lake study area, and the majority of the Browns
498 Lake study area. We saw evidence of this fire at numerous sites within the Watson Lake and
499 Browns Lake study areas. Watson Lake and Browns Lake subsequently had the two greatest loss
500 rates between 1950 and 1984 and may be related to the 1947 fire. However, the presence of
501 black spruce burn poles were not found on all permafrost plateaus visited indicating that the
502 burning was likely relatively patchy in the wetlands. At Browns Lake, permafrost islands that
503 did not burn in 1947 exhibited less degradation, had thicker permafrost, denser tree cover, and
504 larger trees than the islands that burned. Large portions of the Tustumena Lake study area
505 burned in the 1996 Crooked Creek Fire and 2005 Fox Creek Fire. These fires likely damaged,
506 and partially removed the protective ecosystem cover (black spruce forest and peat), and
507 degraded several permafrost plateau features. This resulted in the Tustumena study area having
508 the highest change rate for the latter time period and 77 % of the plateau loss that occurred
509 between 1996 and ca. 2010 study area did so in areas that burned in the 1996 and 2005 fires.

510 We documented bottom-up permafrost degradation over the short period of direct
511 measurements between 2012 and 2015. The bottom-up permafrost thaw observed at the Watson
512 Lake PF2 site indicates that the flow of groundwater below the permafrost plateaus could be
513 responsible for degradation (Walters et al., 1998). In addition, analysis of the remotely sensed
514 imagery for the four select wetland complexes primarily documented lateral permafrost
515 degradation since the 1950s as inferred by the conversion of forested plateau margins to
516 herbaceous wetland vegetation. This type of feature loss accounted for 85% of the change
517 between 1950 and ca. 2010. This pattern of loss was further observed in the field through the
518 presence of thermokarst moats and drowning black spruce trees along the margins of the
519 permafrost plateaus (Fig. 3). This is similar to the dominant processes documented in more
520 northerly boreal peatlands with permafrost plateaus (Thie, 1974; Camill and Clark, 1998;
521 Osterkamp et al., 2000; Jorgenson et al., 2001; Payette et al., 2004; Quinton et al., 2011; Lara et
522 al., 2015). These findings highlight the importance of groundwater flow and also the impact of
523 saturated herbaceous wetlands that absorb heat during the summer that likely degrades
524 permafrost along the peat plateau margins (Walters et al., 1998). It is possible that lateral
525 permafrost degradation caused by these processes are overwhelming the protection provided by
526 the ecosystem cover for permafrost stability on the Kenai Peninsula lowlands. Future research is
527 required to more fully understand the role of groundwater movement on permafrost instability in
528 the study region.

529 **5.4 Proposed history of permafrost on the Kenai Peninsula**

530 During the Last Glacial Maximum (LGM), northern hemisphere permafrost extended much
531 further south than present day (Lindgren et al., 2015). However, permafrost history in
532 southcentral Alaska is poorly constrained. Even though the western Kenai Peninsula lowlands

533 were almost completely glaciated during the LGM (Reger et al., 2007), the permafrost features
534 identified in this study occur in glaciolacustrine or glaciofluvial wetland complexes that were
535 either not glaciated during the LGM (Mystery Creek) or became deglaciated before 16,000 cal
536 yrs BP (Reger et al., 2007). Perhaps permafrost formed on the Kenai Peninsula during
537 deglaciation or shortly thereafter during the Younger Dryas 12,900 to 11,700 years ago (Jones et
538 al., 2009). However, this permafrost would have likely thawed during the Holocene Thermal
539 Maximum (Zoltai, 1972; Kaufman et al., 2004). As the regional climate became cooler and
540 wetter, between 8,000 and 5,000 years ago, *Sphagnum* accumulation and preservation on the
541 western Kenai Peninsula lowlands may have promoted more widespread permafrost aggradation
542 (Jones et al., 2009). Following this period, the peatlands may have progressively froze, heaving
543 the permafrost plateaus above the water table, drying the peat-rich soils, promoting growth of
544 black spruce, and creating a buffer layer protecting the underlying permafrost (ecosystem-
545 protected) from the unfavourable climate for permafrost that currently exists today (Zoltai, 1972,
546 1995; Payette et al., 2004; Camill, 2005). Growth of permafrost and heaving the peatland
547 surface above the water table could explain low peat accumulation rates calculated in many
548 Kenai Peninsula peatlands between 3,300-2,000 years ago (Jones and Yu, 2010; Jones et al.,
549 2014). This also coincides with widespread neoglaciation on the Kenai Peninsula 3,000 to 1,500
550 years ago (Wiles and Calkin, 1994, Barclay et al., 2009). Alternatively, the Little Ice Age (365 -
551 165 years ago), promoted shallow permafrost formation in areas that were predominantly
552 unfrozen throughout the Holocene (Romanovsky et al., 1992; Jorgenson et al., 2001), and thus,
553 could account for the presence of residual permafrost on the Kenai Peninsula. The widespread
554 loss of permafrost plateaus in central Alaska may be a result of degradation of Little Ice Age

555 permafrost (Jorgenson et al., 2001). The age, history, and future trajectory of permafrost on the
556 western Kenai Peninsula lowlands require further study.

557 **5.5 Landscape dynamics and permafrost thaw on the western Kenai Peninsula lowlands**

558 Previous and ongoing land cover change on the western Kenai Peninsula lowlands are primarily
559 in response to the interaction of climate change and human development. Increases in summer
560 air temperature and late-summer droughts, along with human disturbance, have been linked to
561 the massive spruce bark beetle (*Dendroctonus rufipennis*) outbreak of the late 1990s (Berg et al.,
562 2006; Sherriff et al., 2011), which led to subsequent timber salvage (Jones, 2008). Berg and
563 Anderson (2006) caution that overall drier conditions on the western Kenai Peninsula, combined
564 with standing dead spruce stands, may alter the future fire regime of this region. Wetland drying
565 (Klein et al., 2005) and establishment of woody vegetation in wetlands (Berg et al., 2009) may
566 be attributed to warmer air temperatures and decreases in precipitation. Furthermore, tectonic
567 activity associated with the Great Alaska Earthquake of 1964 caused the western Kenai
568 Peninsula to lower in elevation by 0.7 to 2.3 m (Plafker, 1969), while the northern portion of the
569 peninsula subsequently uplifted 0.8 – 0.9 m (Cohen and Freymueller, 1997), potentially altering
570 groundwater flow paths (Gracz, 2011).

571 In our study, we document and incorporate the loss of ecosystem-protected permafrost in
572 the overall understanding of landscape dynamics on the western Kenai Peninsula lowlands. The
573 degradation of permafrost can impact terrestrial and aquatic ecosystems, hydrology,
574 infrastructure, and carbon cycling on the Kenai Peninsula (Schuur et al., 2008; Grosse et al.,
575 2011; Jorgenson et al., 2013; Kokelj et al., 2015; Vonk et al., 2015). Permafrost degradation
576 within the wetlands is responsible for a shift from black spruce forest plateaus to fen and bog
577 wetland ecosystems at a mean rate of 9.2 ha yr⁻¹ since the 1950s in the four change detection

578 study areas. Permafrost plateaus redirect surface and near-surface drainage in boreal wetlands
579 (Quinton et al., 2011), and the thaw subsidence of these features increases drainage network
580 connectivity (Beilman and Robinson, 2003), and alters the local hydrological cycle (Hayashi et
581 al., 2007). Thus, the loss of permafrost and/or changes in seasonally frozen ground phenology
582 could in part be aiding in observations of terrestrial and aquatic changes that have occurred on
583 the Kenai Peninsula during the past several decades. Further work is required to better
584 understand the past influence of permafrost on the Kenai Peninsula as well as the future loss of
585 these warm permafrost deposits.

586 **6 Conclusions**

587 Based on our ground data and remotely sensed observations, we found that peatland permafrost
588 is currently more extensive than previously reported in southcentral Alaska, a region with a
589 MAAT of 1.5 °C. Warm permafrost (-0.04 to -0.08 °C) persists on the western Kenai Peninsula
590 lowlands in forested (black spruce), peat plateaus found in glaciolacustrine and glaciofluvial
591 wetland complexes. At our field study sites, the depth to permafrost table on the peat plateaus
592 averaged 1.48 m in September 2015, but was as shallow as 0.53 m. Permafrost thickness ranged
593 from 0.33 m to greater than 6.90 m. Field surveys conducted in February 2016 documented the
594 presence of a surface talik overlying the permafrost table. In 1950, residual permafrost plateaus
595 covered 19 % of the 4,810 ha wetland area mapped in our study. Within our changed detection
596 study areas, 60 % of the permafrost plateaus present in 1950 had degraded by ca. 2010. In most
597 cases, permafrost degradation equated to the loss of forest and its replacement by bog or fen
598 vegetation, preferentially occurring along permafrost plateau margins. Permafrost loss on the
599 Kenai Peninsula is likely associated with a warming climate, particularly during the winter

600 season, wildfires that remove the protective ecosystem cover, groundwater flow at depth, and
601 lateral heat transfer from wetland surface waters in the summer. Future studies on the residual
602 permafrost plateaus on the Kenai Peninsula will provide further insight for mapping and
603 predicting permafrost extent across Boreal permafrost regions that are currently warming.

604 **7 Data availability**

605 All data available upon request to the corresponding author.

606 **8 Author contribution**

607 B.M. Jones devised the study design and prepared the manuscript with contributions from all co-
608 authors. B.M. Jones, C.A. Baughman, V.E. Romanovsky, E.L. Babcock, A.D. Parsekian, M.C.
609 Jones, and E.E. Berg contributed to field instrumentation and field studies. B.M. Jones, C.A.
610 Baughman, and G. Grosse conducted and contributed to remote sensing analysis. C.A.
611 Baughman compiled and interpolated regional weather and climate station data. All co-authors
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619 use of trade, product, or firm names is for descriptive purposes only and does not imply
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865 **Tables**

866 Table 1. Mean annual ground temperature data for four observation sites on the Kenai Peninsula lowlands. Browns Lake PF1,
 867 Watson Lake PF1, and Watson Lake PF2 represent permafrost plateaus and the Watson Lake non-PF site a black spruce forested non-
 868 plateau site. Sensor depths that were perennially frozen in a given year are in bold. Mean annual air temperature (MAAT), thawing
 869 and freezing degree days (TDD and FDD), and average winter snow depth (MASD) are from the Kenai 29 ENE AWS 702590 weather
 870 station.
 871

9/16/2012 - 9/15/2013

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50	-0.02	10	0.34	10	0.05	25	0.94				
100	-0.06	25	-0.09	50	-0.30	50	0.42	0.88	1865.9	1544.3	19.3
200	-0.08	50	-0.20	100	-0.08	100	0.14				
300	-0.08	100	-0.08	200	-0.06	130	0.16				

9/16/2013 - 9/15/2014

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50*	0.17	10	0.93	10	0.86	25	0.57				
100	-0.06	25	0.40	50	-0.07	50	0.32	2.58	2066.6	1123.4	8.3
200	-0.06	50	-0.02	100	-0.08	100	0.14				
300	-0.08	100	-0.06	200	-0.08	130	0.14				

*Thermistor failed on 24 August 2014

9/16/2014 - 9/15/2015

Browns Lake PF1		Watson Lake PF1		Watson Lake PF2		Watson Lake non-PF		KENAI 29 ENE AWS 702590 Met Station Data			
Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	Sensor depth (cm)	MAGT (°C)	MAAT (°C)	TDD Sums	FDD Sums	MASD (cm)
50*	---	10*	---	10	1.53	25*	---				
100	-0.04	25*	---	50	0.14	50*	---	3.24	2009.8	829.1	2.7
200	-0.06	50*	---	100	-0.07	100*	---				
300	-0.07	100 [#] *	---	200 [#]	-0.07	130*	---				

*Thermistor or data logger failure

[#]Permafrost thaw during observation period

872

873 Table 2. Permafrost plateau extent mapped in each study region in 1950, 1984, 1996, and ca. 2010. Analyzed wetland area for each
 874 study region is given along with the number of features, total plateau area, mean plateau area, and plateau extent for each image
 875 observation year. In ca. 2010, images were acquired in 2011 (Mystery Creek and Watson Lake), 2012 (Tustumena Lake), and 2013
 876 (Browns Lake).
 877

Study Region	Wetland Area (ha)	1950				1984				1996				ca. 2010			
		Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)	Number of Features	Total Plateau Area (ha)	Mean Plateau Area (ha)	Plateau Extent (%)
Mystery Creek	1562.0	212	511.5	2.4	32.7	237	457.7	1.9	29.3	335	292.6	0.9	18.7	321	232.3	0.7	14.9
Watson Lake	904.2	44	86.6	2.0	9.6	55	54.0	1.0	6.0	68	35.4	0.5	3.9	67	29.8	0.4	3.3
Browns Lake	1013.0	102	111.9	1.1	11.0	117	67.2	0.6	6.6	107	51.2	0.5	5.1	89	38.6	0.4	3.8
Tustumena Lake	1333.4	92	210.2	2.2	15.8	150	168.6	1.1	12.6	183	143.5	0.8	10.8	206	69.9	0.3	5.2
All Sites	4812.7	450	920.2	2.0	19.1	559	747.5	1.3	15.5	693	522.6	0.8	10.9	683	370.6	0.5	7.7

878

879

880 Table 3. Change in the extent of permafrost plateaus for each of the study regions between 1950
 881 and ca. 2010, 1950 and 1984, 1984 and 1996, and 1996 and ca. 2010. Change is reported in
 882 aerial units per year, proportional area change, percent change per year, and by the type of
 883 change. Change type refers to whether the plateau loss occurred along the periphery of a feature
 884 (lateral), in the centre of a feature (internal), or whether complete loss of a feature occurred. In
 885 ca. 2010, images were acquired in 2011 (Mystery Creek and Watson Lake), 2012 (Tustumena
 886 Lake), and 2013 (Browns Lake).
 887

1950 to ca. 2010						
Study Area	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-4.6	-0.3	-0.9	86.2	3.3	10.5
Watson Lake	-0.9	-0.1	-1.1	90.9	0.8	8.3
Browns Lake	-1.2	-0.1	-1.0	77.2	0.3	22.4
Tustumena Lake	-2.3	-0.2	-1.1	86.0	1.7	12.3
All Sites	-9.2	-0.2	-1.0	85.1	1.5	13.4

1950 to 1984						
Study Area	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-1.6	-0.1	-0.3	88.8	5.2	5.9
Watson Lake	-1.0	-0.1	-1.1	91.7	1.4	6.9
Browns Lake	-1.3	-0.1	-1.2	89.0	0.6	10.1
Tustumena Lake	-1.2	-0.1	-0.6	94.1	2.1	3.8
All Sites	-5.1	-0.1	-0.6	91.0	2.3	6.7

1984 to 1996						
Study Area	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-13.8	-0.9	-3.0	87.1	1.8	11.2
Watson Lake	-1.6	-0.2	-2.9	88.7	0.6	10.7
Browns Lake	-1.3	-0.1	-2.0	84.0	0.1	16.0
Tustumena Lake	-2.1	-0.2	-1.2	85.1	2.9	12.0
All Sites	-18.7	-0.4	-2.5	86.2	1.3	12.5

1996 to ca. 2010						
Study Area	Area Change (ha yr ⁻¹)	Proportional Area Change (ha yr ⁻¹ 100 ha ⁻¹)	Percent Change (% yr ⁻¹)	Change Type		
				Lateral (%)	Internal (%)	Complete (%)
Mystery Creek	-4.0	-0.3	-1.4	82.7	3.0	14.3
Watson Lake	-0.4	-0.1	-1.1	92.2	0.5	7.3
Browns Lake	-0.7	-0.1	-1.4	58.7	0.1	41.2
Tustumena Lake	-4.6	-0.3	-3.2	78.7	0.2	21.1
All Sites	-9.5	-0.2	-1.8	78.1	1.0	21.0

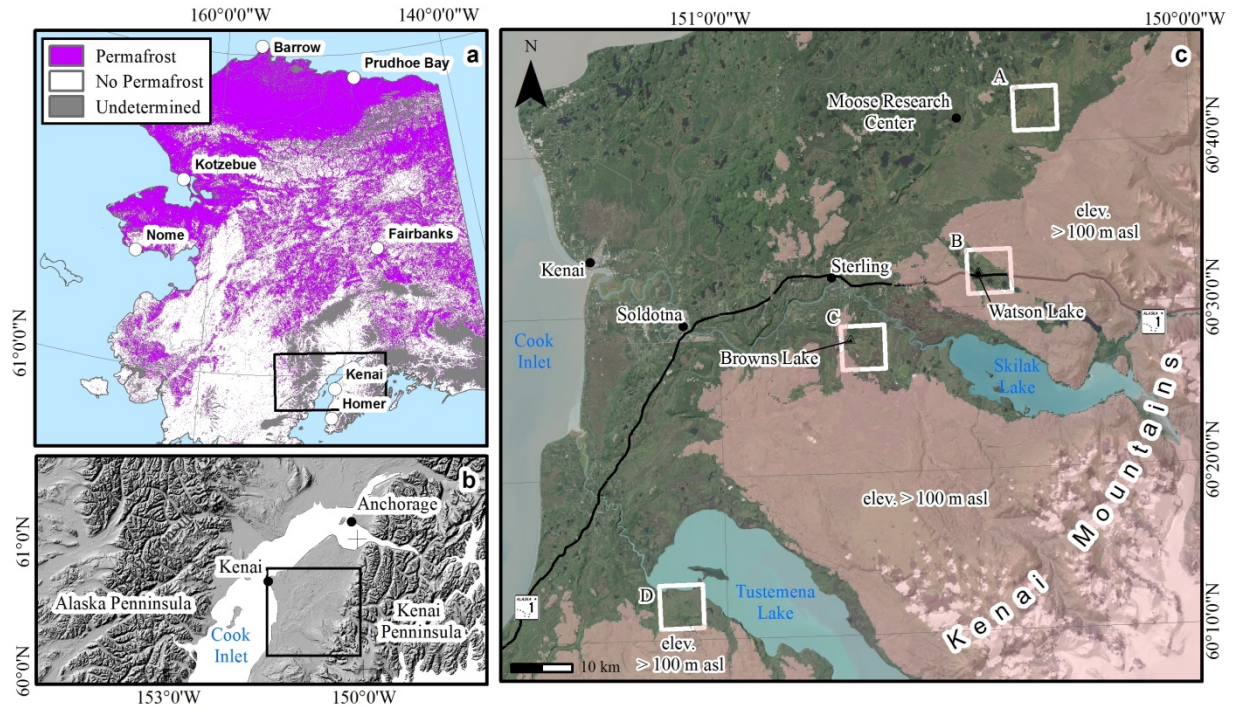
888

889 Table 4. Mean annual, mean summer (May to September), and mean winter (October to April)
 890 air temperature for the three remotely sensed image observation periods compiled from the
 891 Kenai Municipal Airport (WBAN 26523) and estimated from the MRC station (Kenai 29 ENE -
 892 AWS 702590).
 893

**Mean Annual Air Mean Summer Air Mean Winter Air
 Temperature (°C) Temperature (°C) Temperature (°C)**

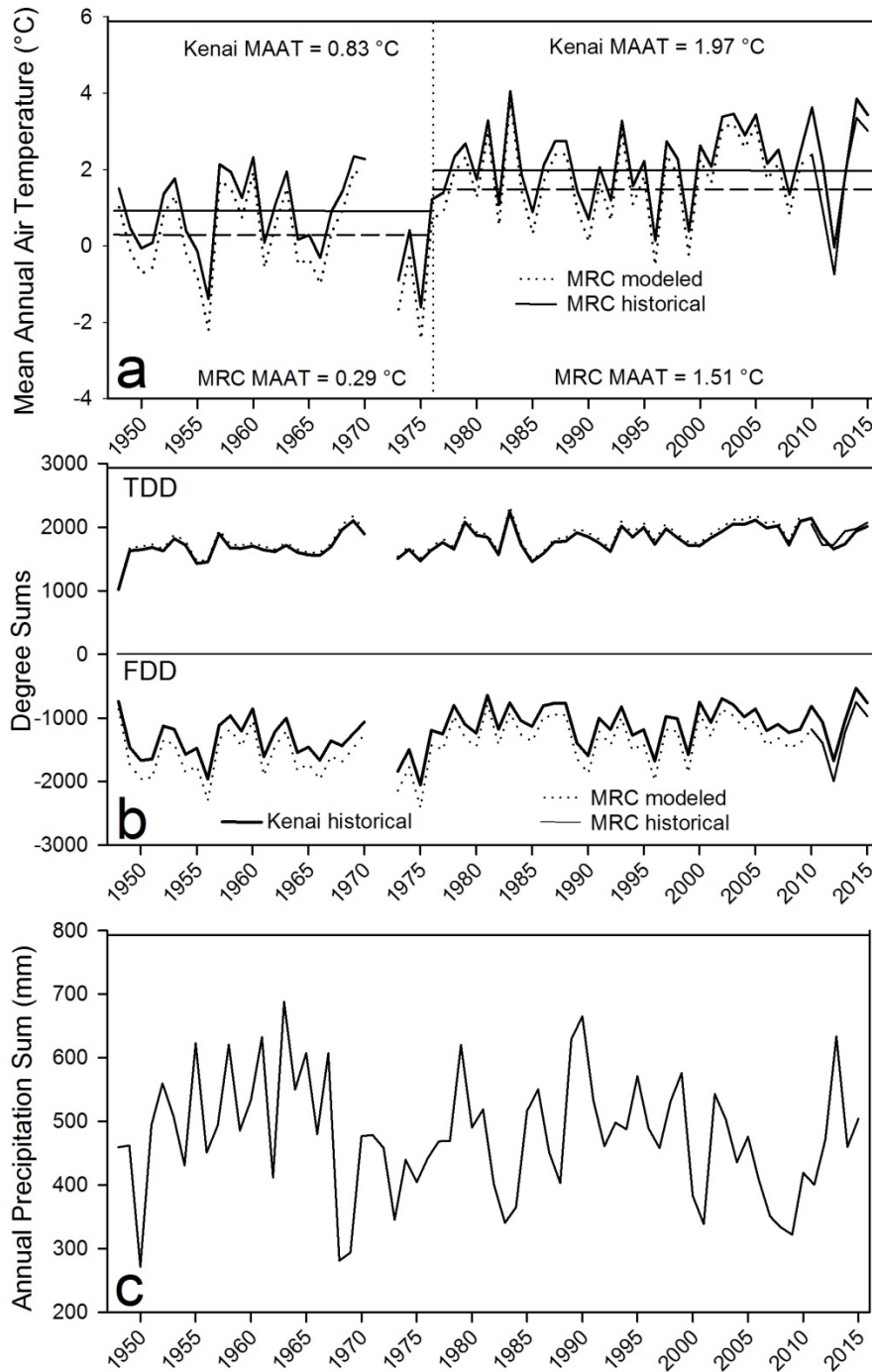
Remote Sensing Time Period	Mean Annual Air Temperature (°C)		Mean Summer Air Temperature (°C)		Mean Winter Air Temperature (°C)	
	Kenai Airport	MRC	Kenai Airport	MRC	Kenai Airport	MRC
1950 to 1984	1.12	0.59	9.92	10.39	-5.29	-6.54
1984 to 1996	1.77	1.31	10.28	10.78	-4.37	-5.52
1996 to 2015	2.34	1.86	10.81	11.31	-3.77	-4.95

894



896

897 Figure 1: Study area figure. (a) Recent permafrost map of Alaska (Pastick et al., 2015)
 898 indicating permafrost presence (purple) and absence (white) in the upper one meter of the ground
 899 surface. (b) Hillshade relief image showing a portion of southcentral Alaska. The study region
 900 on the Kenai Peninsula lowlands is shown with the black box outline. (c) The portion of the
 901 Kenai Peninsula lowlands where field studies and remotely sensed observations were conducted.
 902 Ground temperature observations were collected at the Browns Lake and Watson Lake sites.
 903 The remote sensing change detection areas are shown with a white box: (A) Mystery Creek, (B)
 904 Watson Lake, (C) Browns Lake, and (D) Tustumena Lake wetland complexes.



905

906 Figure 2: a) Historical (1948-2015) mean annual air temperature compiled from Kenai
 907 Municipal Airport (WBAN 26523) hourly surface data and interpolated (broken) and measured
 908 (solid) mean annual air temperature for the MRC station (Kenai 29 ENE AWS 702590). b)
 909 Thawing degree day (TDD) and freezing degree day (FDD) sums for 1948-2015 derived from
 910 historical and interpolated daily mean temperature. c) Cumulative annual precipitation data from
 911 the Kenai Municipal Airport (WBAN 26523) between 1948 and 2015.



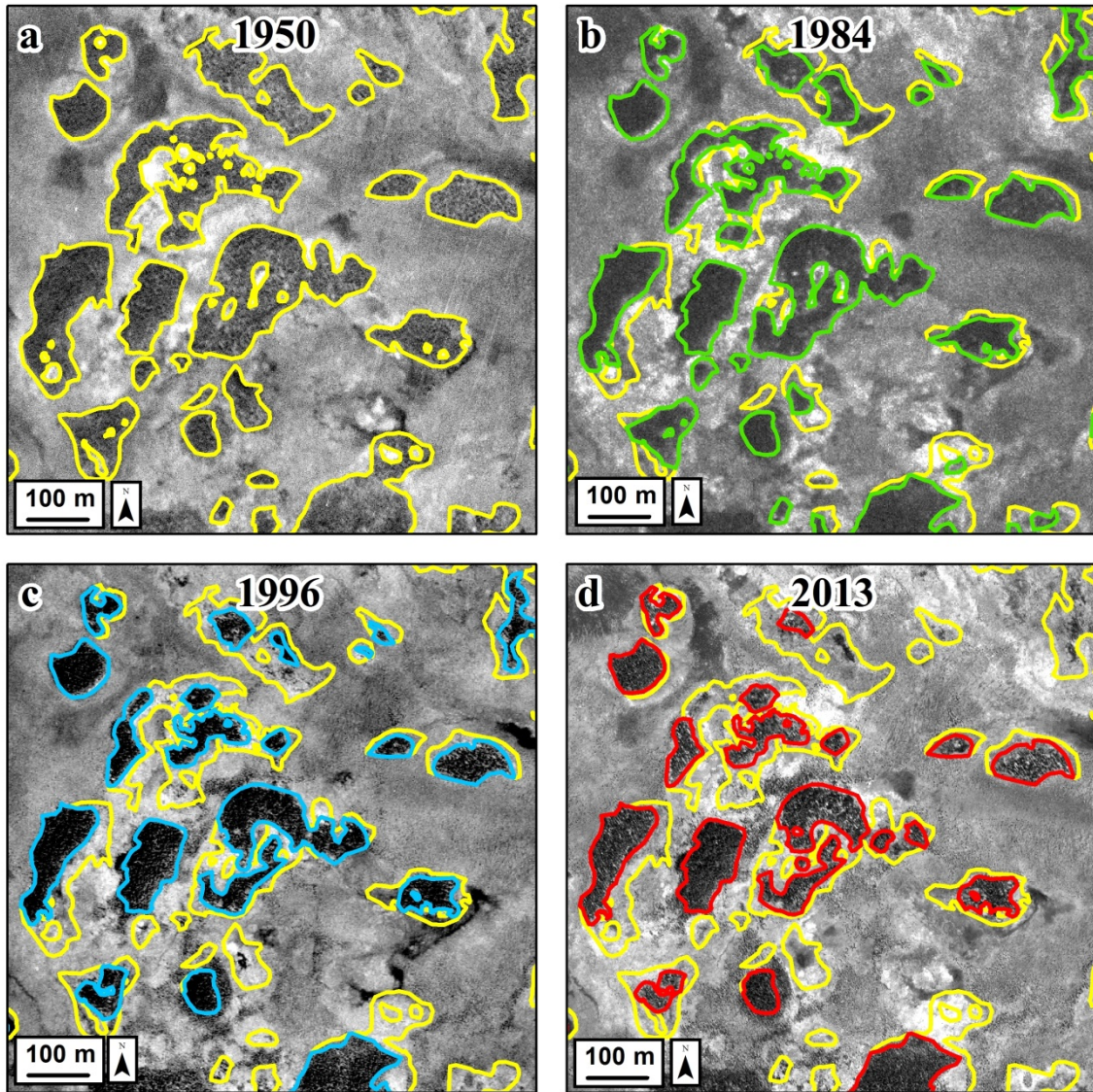
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913

914 Figure 3: Field photos of residual permafrost plateau landforms and thermokarst on the western
915 Kenai Peninsula lowlands. (a) A forested permafrost plateau in the Browns Lake wetland
916 complex. A thermokarst moat and drowning black spruce trees in the (b) Browns Lake and (c)
917 Watson Lake wetland complexes.

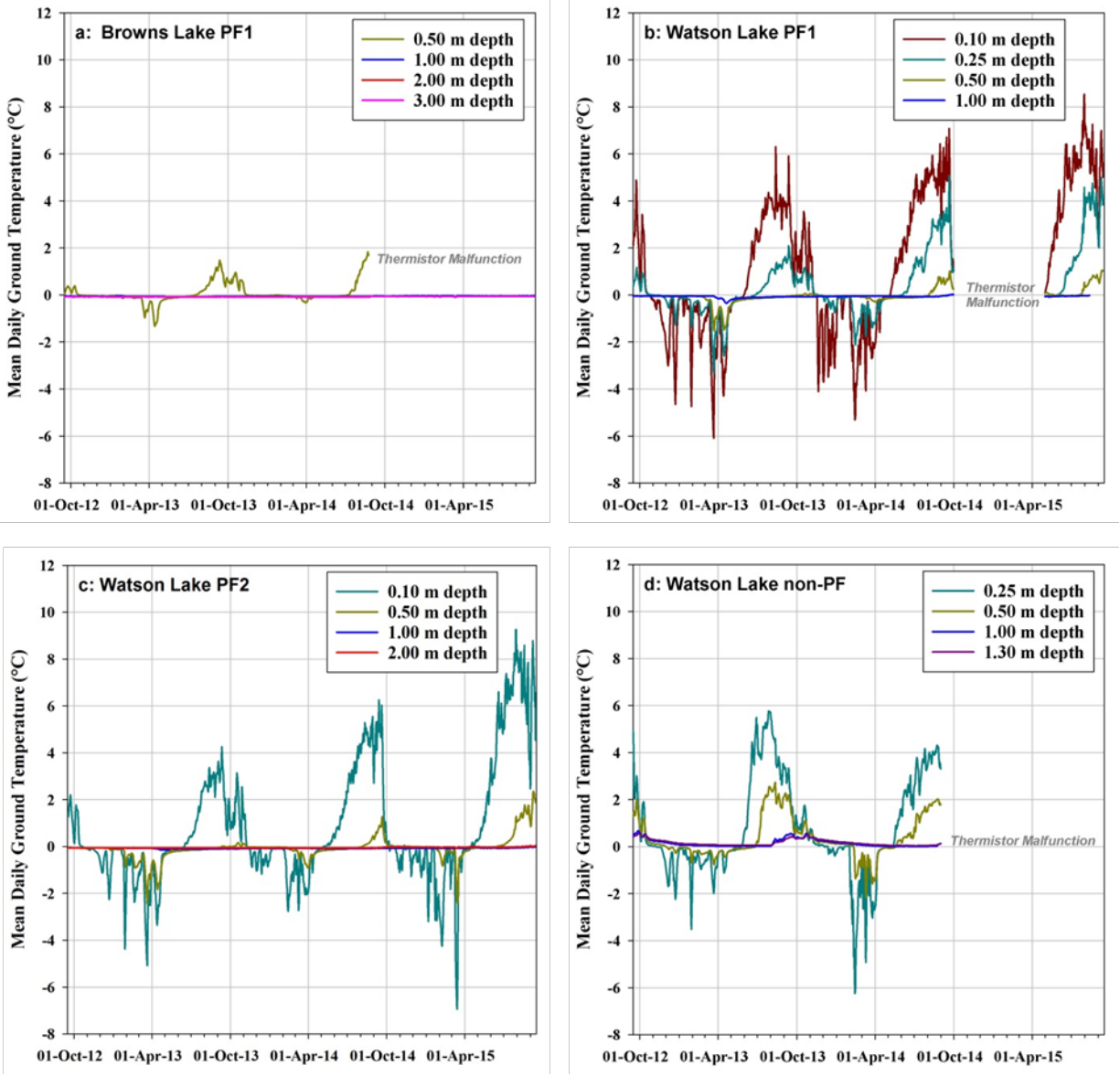
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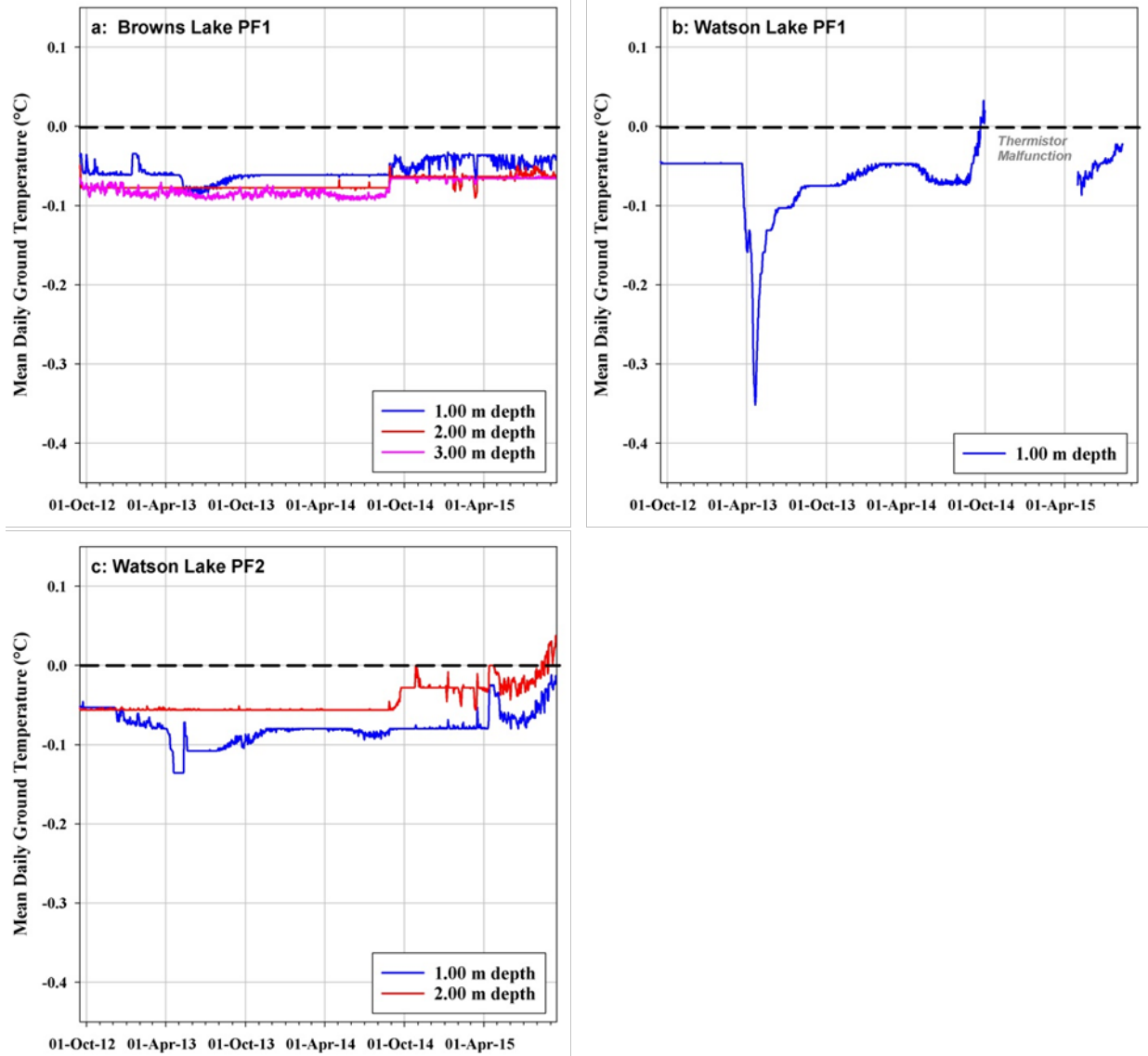
920

921 Figure 4: Time series documenting the extent of a subset of permafrost features in the Browns
 922 Lake wetland complex in (a) 1950, (b) 1984, (c) 1996, and (d) 2013. Permafrost plateau extent
 923 in 1950 is shown as a yellow polygon in each frame and other time slices outlined as green
 924 (1984), blue (1996), and red (2013).



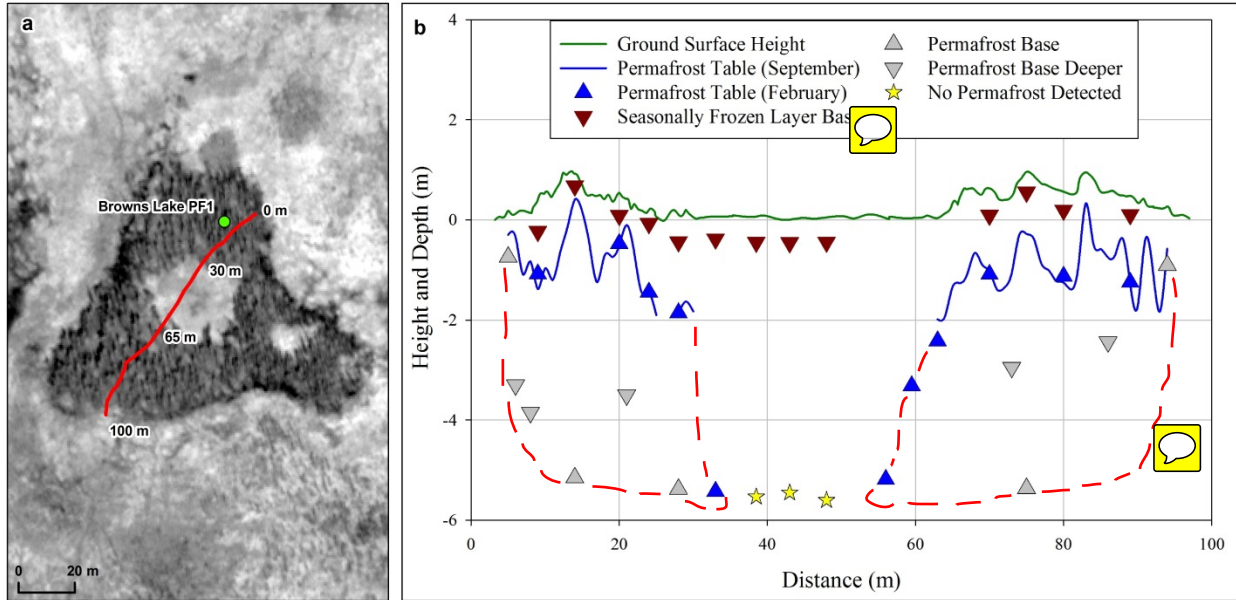
926

927 Figure 5: Mean daily ground temperature data plots for the four shallow boreholes on the
928 western Kenai Peninsula lowlands for the period of 16 September 2012 to 15 September 2015:
929 (a) Browns Lake PF1 site, (b) Watson Lake PF1 site, (c) Watson Lake PF2 site, and (d) Watson
930 Lake non-PF site. All axes scales are the same but sensor depths vary among sites based on site
931 characteristics. Missing data indicates sensor or thermistor failure.
932



933

934 Figure 6: Mean daily ground temperature data plots indicating the presence of permafrost on the
 935 western Kenai Peninsula lowlands for the period of 16 September 2012 to 15 September 2015:
 936 (a) Browns Lake PF1 site, (b) Watson Lake PF1 site, and (c) Watson Lake PF2 site. Top-down
 937 permafrost thaw occurred at Watson Lake PF1 during the fall of 2014 and bottom-up permafrost
 938 thaw occurred at Watson Lake PF2 during the fall of 2015.

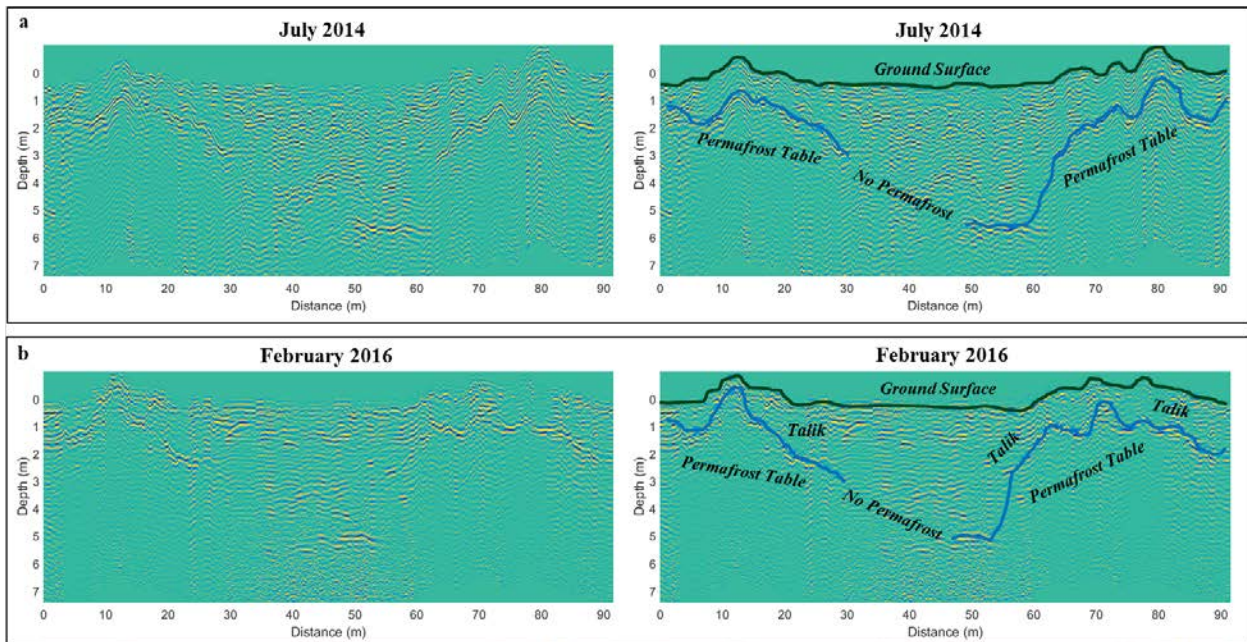


939

940 Figure 7: (a) High-resolution satellite image showing the permafrost plateau in the Browns Lake
 941 wetland complex where detailed field surveys were conducted as well as the location of the
 942 Browns Lake PF1 data logger (green dot). (b) A ~100 m transect across the Browns Lake PF1
 943 permafrost plateau site showing ground surface height above the wetland (green line), depth to
 944 the permafrost table (blue line and blue arrows), permafrost thickness constraints (grey arrows),
 945 seasonally frozen ground depth (maroon arrows), and lack of permafrost (yellow stars) as
 946 measured by probing, drilling, and coring. Locations where the permafrost table exceeded 2.2 m
 947 from the ground surface (limiting depth for September surveys) are indicated with a non-existent
 948 blue line. Locations where the base of the permafrost was encountered are indicated with an
 949 upward looking grey triangle and those locations where it was not encountered, a downward
 950 looking grey triangle.

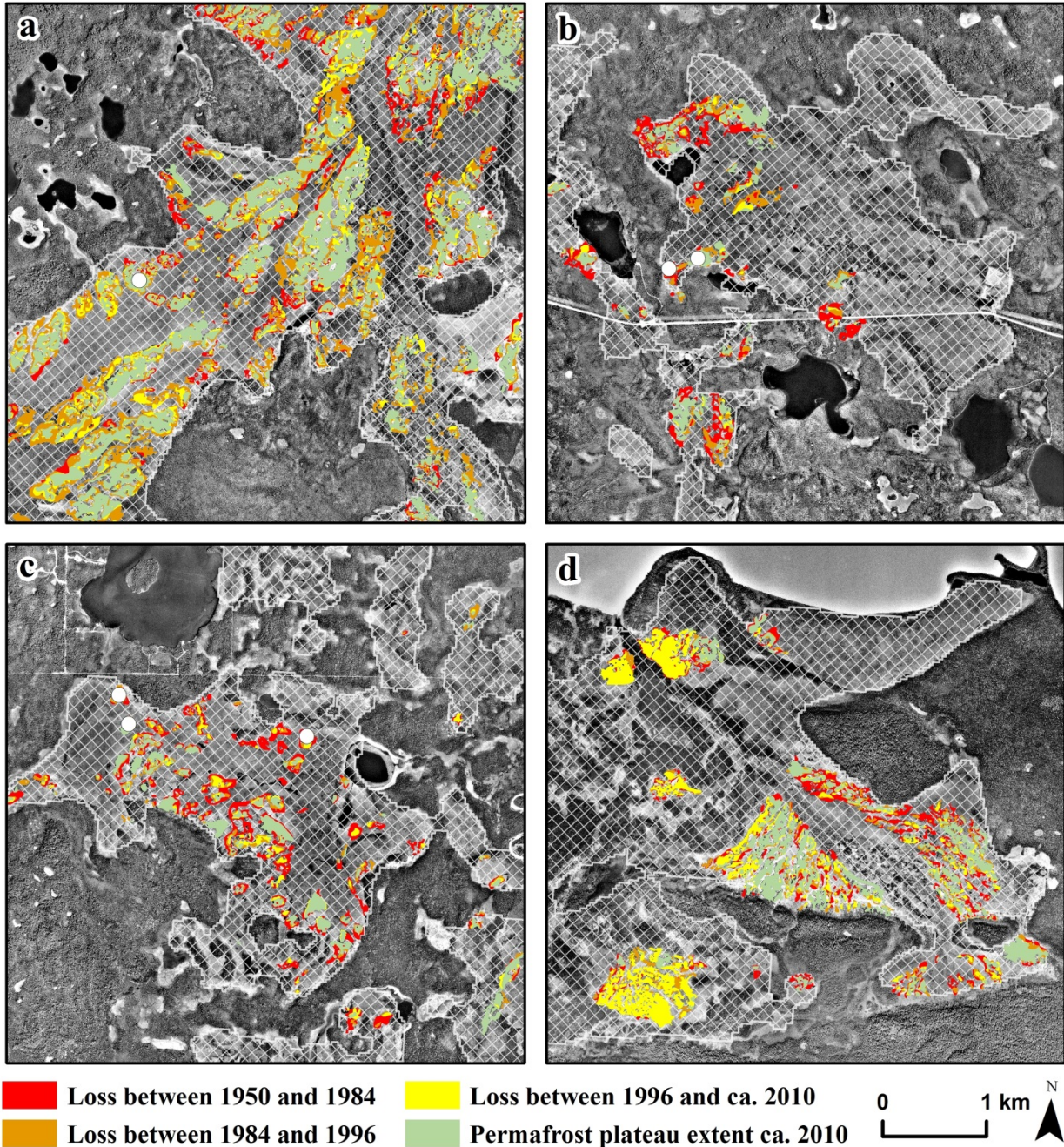
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953

954 Figure 8. GPR profiles at the intensive Browns Lake permafrost plateau (Fig. 7a) from a) late-
955 July 2014 with Mala shielded 100-MHz antennas and b) mid-February 2016 with Sensors &
956 Software unshielded bi-static 100-MHz antennas. Processed radargrams are on the left and
957 processed, interpreted radargrams are on the right. Both summer and winter profiles clearly
958 show reflectors associated with the permafrost table and in the case of (b) show the presence of a
959 talik. However, we were unable to image the permafrost base using GPR. Note that the two
960 GPR transects differ slightly in their orientation across the feature.
961



962

963 Figure 9. Spatial and temporal pattern of permafrost loss within four change detection areas: a)
 964 Mystery Creek, b) Watson Lake, c) Browns Lake, and d) Tustumena Lake. Red indicates feature
 965 loss between 1950 and 1980, orange is feature loss between 1984 and 1996, yellow is feature
 966 loss between 1996 and ca. 2010, and green is ca. 2010 permafrost plateau extent. The white dots
 967 indicate the location of field verified permafrost between 2009 and 2016. The hatched white
 968 polygons indicate the wetland extent where plateau features were mapped in each study area.
 969 Background imagery is the 1996 orthophotography.