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ARTICLE

Estimating age of rock cairns in southeast Alaska by combining evidence from successional metrics, lichenometry, and carbon dating

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Abstract: We estimated ages of rock cairns in alpine tundra in southeast Alaska by combining information from three general classes of methods, each of them imperfect, but considered together providing better estimates than any of the three alone. We used lichenometry, radiocarbon dating, and five successional metrics: score on a nonmetric multidimensional scaling axis of vegetation composition, cover-weighted average successional class of organisms, overgrowth of contact points between rocks, sum of species cover, and species richness. Lichenometry estimated absolute ages, but with considerable error because we violated key assumptions. Successional metrics provided relative ages, probably with more precision than lichenometry, but did not provide absolute ages. Although the relative age estimates from traditional lichenometry seemed least reliable, collectively they supported the hypothesis of prehistoric origins for the cairns with a range of possible absolute ages of 258–892 years. Similarly, radiocarbon dates for the cairns suggested cairn construction before European settlement, about 450–1500 years B.P. The five successional metrics were in general agreement with each other on relative ages. Combining all methods provided more information than any of the methods alone. We conclude that the cairns were built over a range of times, probably over centuries, most likely 500–1500 years B.P.

Key words: Alaskan native culture, alpine, bryophytes, lichens, plant succession, vegetation.

Résumé : Nous avons évalué les âges de cairns (c.-à-d. amoncellements de pierres) dans la toundra alpine du sud-est de l'Alaska en combinant des informations de trois classes générales de méthodes, chacune d'entre elles imparfaites, mais considérées ensemble, elles produisent de meilleures estimations que n'importe lesquelles des trois seules. Nous avons utilisé la lichénométrie, la datation au carbone 14 et cinq mesures de succession : le score sur un axe de l'échelle multidimensionnelle non métrique de composition végétale, la moyenne pondérée de couverture par classe évolutive d'organismes, la prolifération aux points de contact entre les pierres, la somme de recouvrement des espèces et la richesse spécifique. La lichénométrie a permis d'évaluer les âges absolus, mais avec une marge d'erreur considérable, car nous n'avons pu respecter les hypothèses clés. Les mesures de succession ont donné des âges relatifs, probablement avec plus de précision que par la lichénométrie, mais n'ont pas fourni d'âges absolus. Bien que les estimations d'âges relatifs obtenues au moyen de la lichénométrie traditionnelle aient semblé les moins fiables, collectivement elles ont soutenu l'hypothèse d'origines préhistoriques des cairns avec une gamme d'âges absolus possibles de 258 à 892 ans.

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Également, la datation au carbone 14 des cairns a suggéré que la construction de cairns ait eu lieu avant l'arrivée des Européens, 450 à 1500 ans avant le présent. Les cinq mesures de succession correspondaient généralement entre elles concernant les âges relatifs. L'ensemble de toutes les méthodes a fourni plus d'informations que n'importe laquelle des méthodes seules. Nous concluons que les cairns ont été construits au cours de différents moments, probablement au fil des siècles, très probablement entre 500 et 1500 ans avant le présent. [Traduit par la Rédaction]

Mots-clés : culture autochtone de l'Alaska, zone alpine, bryophytes, lichens, succession végétale, végétation.

Introduction

Rock cairns are found throughout the world. The ages, derivations, and functions of cairns are as varied as the cultures that produced them, but known functions include navigational aids (including trail markers), meat caches, hunting blinds, religious monuments, and property boundaries. In western North America, cairns have been built by livestock herders for navigation and marking boundaries (e.g., Yehle 1989; Boyd et al. 1995; Rosentreter 2004, 2009), by Native Americans for hunting blinds (Rosentreter et al. 2006), in conjunction with vision quests (Minor and Pike 1976), as structures related to shelter (Bettinger and Oglesby 1985; Modoc National Forest 2011), and in modern times as route finders in open country, such as tundra, steppe, and deserts. Land managers frequently wish to know the ages of cairns, but this has been a persistent, difficult problem, so much so that few scientists have been willing to invest time and energy to solve the problem of how to date them.

The numerous cairns found in the alpine regions of the archipelago of southeast Alaska have baffled explorers, scientists, and native peoples alike. A set of these cairns, located at Cross Peak on Baranof Island, exemplifies the problem. These mysterious structures sit near or above the alpine treeline, on the edge of topographic ledges and ridges, and overlook expanses of saltwater straits between islands (Figs. 1 and 2). Numerous hypotheses have been made about their origins and functions, but a convincing explanation remains obscure. To date, no artifacts have been found in, near, or under these cairns. Anthropologists and land managers would like to know their ages, as such knowledge might help to inform us about their origins.

Estimating ages of rock surfaces by geologists, ecologists, and anthropologists has commonly been done by lichenometry — using size of radially growing crustose lichens as a proxy for age and calibrating the size–age relationship by sampling the largest lichens on surfaces of known age. The basic premise is that the diameter of the largest, free-growing lichen colonizing a surface is proportional to the amount of time the surface has been exposed to its environment (Webber and Andrews 1973; Innes 1985; Naveau et al. 2007; Matthews and Trenbirth 2011). By measuring lichen diameters on surfaces of known age (i.e., buildings, bridges, gravestones, landslides), one can calibrate a dating curve for an area of interest (Loso and Doak 2006; Jomelli et al. 2007).

Although lichenometry has been widely applied and is always presented with acknowledgment of its limitations (e.g., Porter 1981; Innes 1985; Bull 1996; Bull and Brandon 1998), some authors have been critical of its application in some cases (Scuderi and Fawcett 2013; Osborn et al. 2015). Few people have applied lichenometry to cairns (but see Rosentreter 2004; Borrero et al. 2011; also popular treatment by Williams 2012). Successful application of lichenometry requires several key assumptions that usually cannot be met for old cairns. The cairns that we studied in southeast Alaska were almost completely covered by lichens and bryophytes, such that the lichens were not free to grow radially.

Fig. 1. Location of the study area, Cross Peak, Baranof Island, Alaska.

Furthermore, the initial condition for a cairn is not usually bare rock, and we had no nearby rock surfaces of known age for calibration.

We sought ways to compensate for these problems, both by modifying lichenometric methods and by applying two other classes of methods: radiocarbon dating of organic matter beneath the cairns and analysis of successional development of the vegetation growing on the cairn. This novel method uses various attributes of successional development of the lichen–plant community to assign relative ages to cairns.

Constructing a cairn buries organic carbon: plants, plant and animal detritus, and lichens. Analysis of carbon isotopes in the buried material might provide dates of construction. Those methods and results for the cairns that we studied will be published in detail elsewhere, but here we include information on carbon dates to evaluate their relationship to other forms of dating.

Fig. 2. Example cairn on Cross Peak at about 700 m above sea level.

When one encounters an historic or prehistoric rock structure in otherwise natural areas, one immediately gets an impression of its age, based on the degree of development of lichens, bryophytes, and vascular plants, as opposed to bare rock, on its surface. Surprisingly, it appears that no one has attempted to develop quantitative metrics of this development on cairns, despite more than a century of focus on plant succession by ecologists. We sought to do this, motivated by problems with applying lichenometry to cairns.

The cairns on Cross Peak support a diverse community of lichens, bryophytes, and a few species of vascular plants. The degree of development of these communities can help us to estimate the relative ages of these structures. We used numerous developmental attributes of the communities, including species composition; representation by primary, secondary, and tertiary colonists; total cover by lichens, bryophytes, and other vegetation; and degree of overgrowth of rock contact points to estimate the relative ages of the cairns.

The purpose of our work was, therefore, to estimate the ages of the cairns by combining information from three general classes of methods, each of them imperfect, but considered together providing better estimates than any of the three alone. This was one aspect of a larger multidisciplinary exploratory study of cairns in southeast Alaska (Hunt et al. 2016).

Study area

We studied cairns on and near Cross Peak at the north end of Baranof Island in southeast Alaska (Fig. 1), overlooking Peril Strait. Cairns were located just above treeline at 640–850 m above sea level (Fig. 2). This peak and ridge system has numerous bedrock exposures of hard, noncalcareous metamorphic rock (amphibolite; Karl et al. 2015). The area has a cold oceanic climate (Table 1). This windswept ridge is frequently free of snow, even for extended periods in winter, as shown by timelapse photography taken by a camera left on site during

Table 1. Location and climate data for our study site (Cross Peak, Baranof Island) and the published lichenometry sites across Alaska: Kenai Peninsula, Wrangell-St. Elias Range, Alaska Range, Central Brooks Range, and the Kigluaik Mountains.

Region	Latitude N	Longitude W	Mean July maximum temperature (°C)	Mean January minimum temperature (°C)	Mean annual precipitation (mm)	Mean annual snowfall (cm)	Reference(s)
Cross Peak	57°30′	135°28′	15	−6	2921	101	ClimateNA (Wang et al. 2016)
Kenai Peninsula	60°60′	149°20′	14	−15	1690	155	Wiles and Calkin 1994; Wiles et al. 2010
Wrangell-St. Elias Range	62°58′	141°56′	21	−25	279	145	Wiles et al. 2010
Alaska Range	62°10′	145°27′	20	−22	381	206	Wiles et al. 2010
Central Brooks Range	67°25′	150°06′	22	−28	365	224	Calkin and Ellis 1980; Wiles et al. 2010
Kigluaik Mountains	65°01′	165°20′	14	−19	432	173	Wiles et al. 2010

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the winter of 2013–2014. The vegetation varies from lichen–bryophyte mats to dwarf ericaceous shrub tundra to krummholz dominated by *Tsuga mertensiana*.

All cairns sampled (25, 39, A, C, E, G, H, and I) were roughly conical or mound shaped (Fig. 2) except for cairn H, which had been disturbed. This sample was chosen arbitrarily but without preconceived bias from the population of about 50 cairns that were relatively large (approximately 1–2 m tall and 2–3 m in diameter) and within 1 km of our basecamp. These cairns, like all of the other cairns at Cross Peak, have spectacular views of the mountains and straits around them. None were built in interior-facing positions.

At an unknown point in time, cairn H had been partially disassembled and the rocks from one side discarded downslope, thus splitting the cairn into two distinct halves. Therefore, we delineated cairn H by its two parts, "H-disturbed" and "H-undisturbed", resulting in a total of nine cairns or partial cairns for analysis.

Methods

Lichenometry

We attempted to compensate for each of three problems with conventional lichenometry as applied to the cairns on Baranof Island. These three problems, and our partial remedies, are described below.

First, we could not meet a standard assumption in lichenometry that the measured lichens are free to grow radially. Instead, because the rock surfaces are so thoroughly covered by lichens and bryophytes, they interact in a complex mosaic with an unknown effect on growth rates. We partially compensated for this by (*a*) searching for lichens that showed the clearest circular growth patterns on the rock, even if contacting other thalli, (*b*) basing our estimates on just the largest diameter of a given thallus, rather than measuring major and minor axes, thus ignoring shorter diameters that might have been caused by growth suppression from contact with other individuals or species, and (*c*) using a variety of lecideoid lichen species, rather than just one species, trading the ability to choose individuals that appeared to be most free to grow, uninhibited by their neighbors, for more variation in growth rate among species.

Second, lichenometry assumes that the rock was bare at the time of its first exposure, but cairns are typically built from rocks already exposed on the surface, rather than freshly quarried rocks. This was certainly true of our study area, where loose rock and small talus slopes are common, providing abundant building materials. Thus, many of the rocks in a cairn would have had preexisting lichens, sometimes quite old, and a newly built cairn will have a mixture of bare and previously colonized surfaces. To reduce this problem, we constructed a "calibration cairn" at Cross Peak. We built this cairn with nearby available rock and then made our standard measurements on it. We used the condition of the lichens on this cairn to calibrate a zero-age point, rather than assuming that all of the lichens on a cairn postdate the cairn construction.

Furthermore, we based our age estimates not on the largest lichen on a cairn but rather on the modal size of the largest lichens. This reduces the problem that the absolute largest lichen on a cairn is likely to predate the cairn, i.e., a lichen present on the cairn at the time of construction could be considerably older than the typical age of the postconstruction colonists. The modal age was identified as the first plateau in a ranked series of lichen sizes on an individual cairn. We assumed that the modal-sized lichen developed from the first wave of recruitment on open space of a newly constructed cairn.

Third, we lacked comparable surfaces of known age from which we could calibrate local growth curves. We therefore applied growth rates from another site in Alaska, the Kenai Peninsula. We chose this site among several candidates as being climatically closest to our study area, as described below.

We measured the maximum diameter of each of the 10 largest crustose lichens on each cairn other than the newly constructed cairn. Lichenometry is most often based on a group of species that are rarely differentiated in lichenometric studies, bright yellow crustose lichens in the *Rhizocarpon geographicum* group (Bradwell 2010). However, due to competition among lichens and with mosses and vascular plants, it was impossible to restrict our measurements to 10 circular individuals in the yellow *Rhizocarpon* group. Consequently, we measured the diameters of the 10 largest, subcircular crustose lichens. These included the *Rhizocarpon geographicum* group (here: *R. eupetraeoides*, *R. geographicum*, and *R. superficiale*) and members of *Lecidea*, in the broad sense. Upon identification in the laboratory, we found that these additional species were included: *Carbonea vorticosa*, *Calvitimela armeniaca*, and *Lecidea lapicida* (all formerly considered *Lecidea*). We used these species to estimate the age of the cairns, assuming that they exhibit similar growth rates as *Rhizocarpon alpicola*, the taxon used in the Kenai Peninsula growth curve (Wiles and Calkin 1994) and a member of the *R. geographicum* group.

Nomenclature follows the North American checklist (Esslinger 2015).

Growth curve selection

We chose the most suitable growth calibration curve for our study area from the five published dating curves for Alaska (Wiles et al. 2010). The growth rates represented by these curves vary tremendously, so we chose the Kenai Peninsula curve as most appropriate, based on climatic similarity to our study area. Both the Kenai Peninsula and our site have oceanic climates with high precipitation (Table 1) (Solomina and Calkin 2003; Shulski and Wendler 2007). Lichens grow more rapidly in wet climates than in dry climates (Armstrong and Bradwell 2010). As such, lichens at our study site and the Kenai Peninsula most likely exhibit similar growth rates. Growth curves from other parts of Alaska were from drier, higher-elevation sites, where lichen growth is slower (Wiles et al. 2010). These sites were the Wrangell-St. Elias Range, Alaska Range, Central Brooks Range, and the Kigluaik Mountains (Table 1).

The dating curve constructed for the Kenai Peninsula was calibrated from tree-ring dated controlled surfaces using the largest-lichen technique (Wiles and Calkin 1994; Solomina and Calkin 2003; Wiles et al. 2010). The equation used to estimate the age of the cairns (A, years) is as follows: $A = 43.95(10^{0.00817D})$, where D is lichen diameter (millimetres).

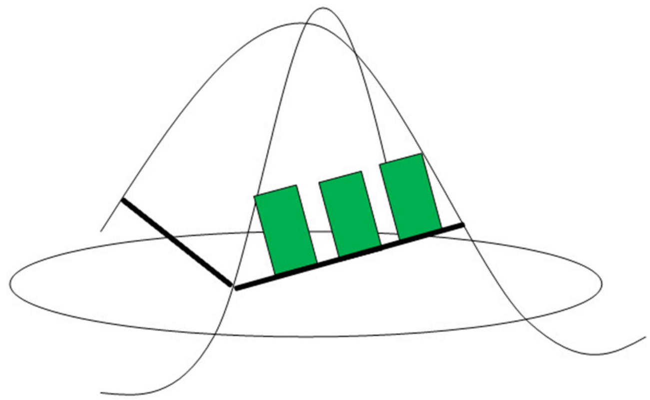
Radiocarbon dating

We also applied radiocarbon dating to estimate the absolute ages of the cairns. This method involved collecting organic sediment samples from beneath select cairns and estimating the age based on the amount of C_{14} in that sample. This presumably provided a maximum age estimate for the cairn. Details of the methods are in Hunt et al. (2016). Cairns C, E, and G were disassembled and sediment samples were collected at the base of these structures. Two samples of organic matter were collected and analyzed for cairn C, three for cairn E, and three for cairn G. The results of the sediment samples were averaged within cairns.

Successional metrics

We inferred the relative age of a surface as a function of attributes of the plant community mosaic (including species diversity, amount of bare rock, and percent cover of primary, secondary, and tertiary colonists) and of overgrowth of rock contact points by single individuals. Initial colonization of vegetation on rock occurs by the establishment of crustose lichens (primary colonists). In time, these primary colonists are overgrown by other lichens and bryophytes (secondary colonists). As more time passes, secondary colonists are overgrown by moss mats, turfs, some large overgrowing lichens (tertiary colonists) and finally

Fig. 3. Diagram of cairn sampling showing three quadrats arrayed along one of four sectors. Within each sector, we recorded percent cover of lichen, moss, and plant species using 20 cm × 50 cm quadrats. Rock fusions and successional relationships ("who-beats-whom" based on overgrowth patterns) were also recorded along each sector line.



vascular plants. Contact points between adjacent rocks are overgrown by one or more individuals.

Community sampling and analysis

We divided each cairn, including the calibration cairn, into four roughly equal-sized triangular sectors (Fig. 3). Within each sector, we recorded percent cover of lichen, bryophyte, and vascular plant species using three 20 cm × 50 cm quadrats arranged at equally spaced intervals on transects along the horizontal midline of each sector for a total of 12 quadrats per cairn (Fig. 3). Cover classes were scored for each species of lichen, bryophyte, and vascular plant using a scale approximating an arcsine square root transformation: trace = 0%–1%, 1 = 1%–5%, 2 = 5%–25%, 3 = 25%–50%, 4 = 50%–75%, 5 = 75%–95%, 6 = 95%–99%, and 7 = 99%–100%.

Because the pace of successional development might depend on slope and aspect of the cairn face, we measured these variables for each quadrat. We then used these to calculate potential direct incident radiation and heat load for each quadrat (McCune 2007).

Acronyms and definitions for successional metrics, as described below, are in Table 2. Each species was assigned to a successional class (Appendix A) based on observing overtopping of one species by another. Primary colonists (score = 1) appeared capable of establishment only on bare rock and included many crustose lichens. Secondary colonists (score = 2) were observed overgrowing primary colonists and included many bryophytes and some lichens of various growth forms, for example the foliose genus *Parmelia* and the crustose genus *Euopsis*. Tertiary colonists (score = 3) were observed overgrowing primary and secondary colonists and consisted of large lichens (e.g., *Peltigera*) and bryophytes (e.g., *Hylocomium*). Finally, vascular plants (score = 4, primarily dwarf ericaceous shrubs) were observed to overgrow all three of the other successional classes. Although we initially assigned species to these classes in the field, we refined them based on tallying and analyzing 903 data points of "who-beats-whom" by observing overgrowth of one species by another at contact points between species.

We then calculated the weighted average colonization score ("ColScore" in Table 2) for each quadrat by averaging the successional class (s_j) of species j in that quadrat, weighting them by their percent cover (c_j), so that ColScore = $(\Sigma s_j c_j)/\Sigma c_j$. Bare rock was considered a separate "species" with a $s_j = 0$. This yielded an index that potentially ranged from zero

Table 2. Definitions, acronyms, and ranges for variables describing vegetation and successional age.

Acronym	Variable	Range	Definition
Lichenom	Lichenometric age (years)	187–892*	Age estimate of a cairn from lichenometry curve based on modal major lichen diameter
SuccScore	Successional score	−2.73–1.43	Position of a quadrat on an NMS axis of vegetation composition (lichens, bryophytes, vascular plants), with zero being the average position of all quadrats on that axis
ColScore	Colonization score	0.21–2.82	Cover-weighted average successional class of organisms in a quadrat
Fusion%	Fusion percentage unweighted	0–92	"Fusions" are overgrowth of contact points between rocks; zero indicates a relatively new cairn; 100 is the maximum possible
Fusion%Wtd	Fusion percentage weighted	0–55	Same as above but weighted by the successional class of the organism fusing the rocks; 100 is the maximum possible
RockSize	Rock size (m)	0.14–0.45*	Average line intercept length of rock from sampling transects
CairnSize	Cairn size (m)	0.89–2.25*	Average length of transect segment, four segments per cairn
SumCover%	Sum species cover (%)	1–229	Sum of species cover in a quadrat after converting cover classes to midpoints and excluding bare rock
SppRich	Species richness (count)	2–33	Number of lichen, bryophyte, and vascular plant species in a quadrat

Note: Ranges excluding the calibration cairn are indicated by an asterisk.

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(a cairn completely composed of bare rock) to 4 (a cairn completely covered by vascular plants).

We also evaluated vegetation development by scoring rock "fusions", overgrowth of contact points between rocks. The idea is that upon initial cairn construction, rock contacts necessarily lacked lichens or mosses growing across contact points. In time, these contact points are overgrown by vegetation. At each point i that our transect line crossed a rock-to-rock contact, we scored whether or not a species had grown continuously across that contact point as $f_i = 1$ or 0, also recording the species j involved. For n points along the line, we then calculated the percentage of rock contacts that were fused. We did this in two ways: unweighted $(100(\Sigma f_i)/n)$ and weighted by the successional class (s_{ij}) of the organism fusing the rocks $(100(\Sigma f_i s_{ij})/(4n))$. Dividing the weighted form by 4 placed the measure on a 0–100 scale, with 100% meaning all contact points were fused by the highest successional class (4), vascular plants.

Total cover and species richness might both be expected to increase over time and thus provide further description of successional development. We therefore calculated for each quadrat the total species richness and total species cover, retaining all species and converting cover classes to midpoints.

We used ordination to extract gradients in species composition from the quadrat data and to relate those gradients to rock fusions, lichenometry dates, and colonization scores. We first performed nonmetric multidimensional scaling (NMS) (Kruskal 1964), based on a data matrix of 96 quadrats × 89 species. Cover classes were used as is to preserve the built-in arcsine square root transformation. We used "autopilot" with the medium setting and Sørensen (Bray–Curtis) distances and Kruskal's strategy 2 for tie-handling in PC-ORD 7 (McCune and Mefford 2016). The best-fit solution was then rotated to align the first axis with age-related variation, as indicated by the successional metrics. Scores on the first axis were then taken as the final successional score ("SuccScore" in Table 2) for each quadrat. These scores were then averaged within each cairn, yielding a cairn-level estimate of vegetational development. Scores were expressed as number of standard deviations from the mean quadrat score of zero.

Results

Lichenometry

Using the modal size of the largest lichens and the Kenai Peninsula growth curve, the estimated minimum ages of cairns 25, 39, A, C, E, G, H-undisturbed, H-disturbed, and I ranged from 187 to 892 years (Table 3). The average estimated age of all cairns, excluding the calibration cairn, was 467 years.

Radiocarbon dates

Sediment samples for radiocarbon dating were collected for cairns A, C, E, and G (Table 3). Radiocarbon dating and traditional lichenometry dating suggested that cairns E and G were among the oldest structures (Table 3). The carbon from cairn A was modern, while C, E, and G gave ages of about 450–1500 years. The radiocarbon ages differed from the lichenometric ages by about 50, 300, and 700 years.

Successional metrics

Results from the newly created calibration cairn demonstrate that at its inception, a cairn will have preexisting colonists. In this case, we found that the new cairn had means of 26% cover and nine species per 20 cm × 50 cm quadrat (Table 3). Old cairns, however, had means of 84%–131% cover and 17–21 species per quadrat. Cover and species richness

Table 3. Age estimates and relative age estimates for each study cairn.

Cairn	Lichen diameter (mm)	Lichenometric age (years)	C_{14} age (years)	Successional score	Rock fusion (%) (unweighted)	Rock fusion (%) (weighted)	Colonization score	Sum cover (%)	Species richness
25	94	258		0.31 (0.36)	55 (13)	31 (7)	2.07 (0.18)	**131 (31)**	**28.0 (3.8)**
39	128	489		0.30 (0.54)	46 (11)	28 (9)	2.04 (0.31)	104 (36)	19.2 (3.1)
A	109	342	modern	0.54 (0.40)	45 (9)	27 (8)	1.92 (0.12)	123 (25)	18.5 (3.5)
C	131	517	472–442	−0.06 (0.55)	33 (13)	19 (11)	1.68 (0.31)	116 (43)	17.3 (4.4)
E	160	**892**	652–597	−0.03 (0.19)	60 (10)	35 (7)	1.81 (0.11)	99 (27)	17.9 (2.4)
G	160	**892**	**1604–1465**	0.13 (0.28)	60 (17)	31 (12)	1.95 (0.20)	99 (15)	20.1 (3.4)
H-undisturbed	95	263		−0.03 (0.35)	67 (0)	33 (0)	1.80 (0.13)	84 (23)	20.0 (2.6)
H-disturbed	77	187		−0.75 (0.51)	0 (0)	0 (0)	1.63 (0.17)	31 (9)	9.3 (2.1)
I	113	368		**0.55 (0.39)**	67 (16)	**39 (12)**	**2.09 (0.33)**	**131 (28)**	26.0 (3.4)
Calibration	113			−1.38 (0.54)	0 (0)	0 (0)	1.05 (0.33)	26 (19)	9.1 (3.7)

Note: "Lichen diam" is the modal major lichen diameter (see Methods). Lichenometric age was calculated from diameter using a lichenometry curve. The remaining variables are expressed as means (standard deviations), averaging across quadrats within each cairn. The successional score is position on an NMS axis of vegetation composition (lichens, bryophytes, vascular plants), with zero being the average position of all quadrats on that axis. Rock fusions are expressed as a proportion of the maximum possible, weighted by the successional class of the organism fusing the rocks, with zero indicating a relatively new cairn. Colonization scores are the weighted average successional class. Successional and colonization scores are unitless indexes of relative age as indicated by community composition. Both cover and species richness are expected to increase over time, at least early in succession. The oldest cairn for each method is indicated in boldface.

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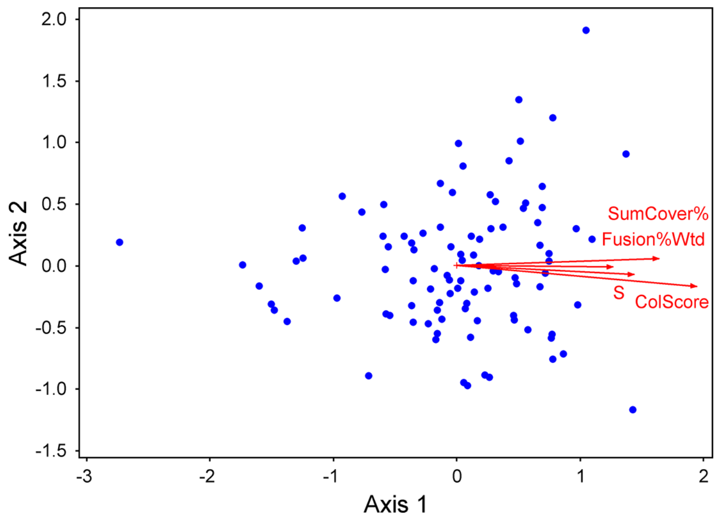
Fig. 4. Axes 1 and 2 of a three-dimensional NMS of quadrats (points) in vegetation space, including lichens, bryophytes, and vascular plants (final stress = 18.4). Radiating lines indicate strength and direction of linear relationships with successional metrics. SumCover%, sum of vegetation cover; Fusion%Wtd, Rock fusion percentage, weighted by successional class; S, species richness; ColScore, cover-weighted average successional class (see Table 2 for more details). Quadrat scores on axis 1 were taken as "successional scores".



on the disturbed cairn were nearly as low as on the newly created cairn, suggesting that the disturbance to cairn H was rather recent, although we cannot estimate that date.

Neither the new cairn nor the disturbed cairn had rock fusions by overgrowing organisms, while older undisturbed cairns generally had many rock contacts spanned (fused) by a single lichen or moss individual. Undisturbed cairns averaged 54% rock fusions, with a weighted score of 30% (Table 3).

Colonization scores on the new and disturbed cairns were near 1, indicating that the communities on these cairns were dominated by primary colonists, mainly crustose lichens. Older cairns had colonization scores near 2 and a blend of primary, secondary, and tertiary colonists. With sufficient time, presumably centuries more, we would anticipate the colonization score to approach 4 as the cairn became covered with soil and vascular plants.

NMS revealed that the variation in vegetation was strongly related to the successional status of the species. We chose a three-dimensional solution from NMS with final stress of 18.4 and representing 54% of the variation in the Sørensen distance matrix. A randomization test showed it highly unlikely to obtain a solution as strong as this by chance ($p < 0.02$). Only one axis was related to successional age-related variables and we rotated the final solution slightly to maximize their relationships with axis 1. The ordination axes were only weakly related to potential direct incident radiation and heat load, so those variables are not discussed further.

The scores on the NMS axis (Fig. 4) were averaged across quadrats within cairns to obtain a successional score for each cairn (Table 3). These indicate the relative age of the cairns, as shown by the extreme negative score for the calibration cairn, the negative score for the disturbed cairn, scores near zero for the average cairn, and scores above zero for cairns with well-developed vegetation including many secondary and tertiary colonists.

All measures of successional development were strongly correlated with NMS axis 1 (successional score), although the lichenometric age estimates were virtually unrelated to the

Table 4. Correlations between NMS axis 1 (successional score) and measures of vegetation and lichenometric age.

Variable	*r*	tau
Lichenom	0.095	0.129
ColScore	0.883	0.650
Fusion%	0.687	0.385
Fusion%Wtd	0.711	0.434
SumCover%	0.810	0.656
SppRich	0.759	0.561

Note: Pearson's correlation (*r*) and Kendall's rank correlation (tau). Potential direct incident radiation, heat load, and slope had negligible correlations with all axes and are not shown. See Table 2 for variable definitions. Because lichenometry was not applied to the calibration cairn, it is not included in statistics for that variable.

Table 5. Matrix of simple correlation coefficients among indicators of cairn age.

	Lichenom	SuccScor	Fusion%Wtd	ColScore	SumCover	SppRich
Lichenom	1					
SuccScore	0.09	1				
Fusion%Wtd	0.37	**0.87**	1			
ColScore	0.04	**0.94**	**0.82**	1		
SumCover	0.16	**0.93**	**0.84**	**0.82**	1	
SppRich	−0.08	**0.84**	**0.87**	**0.83**	**0.89**	1

Note: C_{14} dates were not included because they were not available for most cairns. The strongly interrelated indicators are indicated in boldface.

successional scores, as indicated by the relatively low correlation between lichenometric age and NMS axis 1 (Table 4).

The largest lichens were not necessarily on the most successionally advanced cairns. For example, cairns E and G appeared to be the oldest structures, based on lichen sizes; their successional scores, however, were close to the median. On the other hand, the two methods agreed that cairn H-disturbed was the youngest cairn, other than the calibration cairn. Cairn H-undisturbed appeared to be close in age to cairn H-disturbed, based on the largest lichens, but cairn H-undisturbed was considerably more successionally advanced than cairn H-disturbed. In this case, the successional scores better approximated the ages of the cairns as they appeared in the field. We therefore inferred that the successional scores probably provided more accurate relative ages of the cairns than did the lichenometric ages.

In contrast, the five other indicators of age were in general agreement in contrasting old, disturbed, and new cairns, as shown by the high correlation coefficients among them (Table 5). The weight of evidence suggests collectively that the cairns were built over a long time period with some cairns less advanced successionally than others. Cairn C appeared to be the youngest of the undisturbed cairns, based on the aggregate of community data, while Cairn I appeared to be the oldest and most successionally advanced of the cairns.

Discussion

We used three types of age estimates for the cairns: traditional lichenometry, successional metrics, and carbon dating. Each has flaws, as applied to this particular dating problem, and we concluded that none of the methods alone provided reliable age estimates. Having no "true" age for any except the calibration cairn, we cannot conclude which method was most accurate.

Any dating method that provides absolute age estimates also provides relative age estimates. Although the relative age estimates from lichenometry seemed least reliable (see Methods), collectively the absolute estimates did support the hypothesis of prehistoric origins for the cairns. Based on the Kenai Peninsula growth curve, the undisturbed cairns could potentially be 258–892 years old. Similarly, radiocarbon dates for the cairns suggested cairn construction before European settlement, about 450–1500 years B.P.

Lichenometry

Lichenometric ages were related only weakly to the successional metrics and to ages as inferred from carbon dating. We believe this to be a consequence of violating basic assumptions of lichenometry as described above and that our efforts to compensate for those problems were insufficient to salvage the method for anything more than a general indication of absolute age.

Solomina and Calkin (2003) suggested that lichenometry is less reliable in wetter environments and dating curves are useful for only a few hundred years. With respect to the Kenai Peninsula growth curve, calibration points are well constrained for the past 400 years and are ±20% accurate, but beyond that, application of this curve is less reliable (Wiles et al. 2010). Cairns 39, E, G, and C yielded age estimates greater than 400 years.

Estimates of cairn ages were greatly influenced by the lichen growth calibration curve used. A growth curve from a drier, higher-elevation location in Alaska would have yielded much older ages than those obtained using the Kenai Peninsula curve. Not having a local lichen growth curve, we chose the Kenai Peninsula growth curve based on climatic similarity to our study site (i.e., maritime climate with high precipitation levels). Having a calibration curve for nearby surfaces of known age would have improved the age estimates, but accuracy was further constrained by our violation of the assumptions that the lichens were free to grow radially, without mutual interference, and that the rock was bare at the time of cairn construction.

Radiocarbon dates

Because so few C_{14} dates were available, it was difficult to draw conclusions from those data. We can, however, conclude that the "modern" date obtained for cairn A is misleading because it is at odds with the advanced successional metrics for that cairn. The carbon sample retrieved from that cairn is probably a modern contaminant, possibly from roots, percolation of plant detritus into the cairn, or transport by small mammals.

Successional metrics

Each cairn had been colonized by a diverse community of vegetation composed of lichens, bryophytes, and vascular plants. The degree of colonization and the successional roles of colonists helped us to estimate the relative ages of these cairns.

Five successional metrics were in general agreement with each other on relative ages: successional score based on ordinations, percentage of rock fusions by overgrowing vegetation, colonization score based on the abundance of species weighted by colonization sequence, total percent cover, and species richness.

Because all five successional metrics were strongly intercorrelated, any single one of them could have been used in this case to provide relative age estimates. However, each of the individual metrics has drawbacks that might reduce its performance in other cases.

Species richness was most weakly related to the successional scores. We hypothesize that it will not increase monotonically with age if very old cairns are included. As soil develops on the cairns, many lichen and bryophyte species may be lost with the increasing dominance of a few vascular plant species.

Rock fusions showed promise as an age indicator. Total cover and rock fusion percentages should increase to an asymptote with age, limiting the sensitivity of these metrics with very old cairns. Both of these are, however, easily measured and do not require in-depth training in lichen, moss, or plant identification. Furthermore, our presumed-oldest cairns did not exceed 40% rock fusions, so this indicator could still increase over time before it reached its maximum possible of 100%, or 400% for the weighted form.

The colonization score has the desirable characteristics of taking a value of zero for a cairn of bare rock and a theoretical maximum value of 4.0 (complete dominance by vascular plants). It should provide sensitivity in both very young and old cairns. In our case, the highest score was 2.8, still not close to the theoretical maximum.

Similarly, the successional score, which was derived from NMS of community data, should have sensitivity throughout the range of cairn ages. It does not, however, have a fixed minimum value. Furthermore, it does not provide numbers that would be comparable across data sets from different areas of the world.

Combining methods

Lichenometry applied to cairns provides absolute age estimates, but with considerable error because we violated key assumptions. Despite this error, lichenometric estimates qualitatively agreed with other methods that the cairns were prehistoric. Yet the discrepancy between lichenometric ages and successional metrics left us with no confidence in the relative ages assigned by lichenometry. Radiocarbon dating also provided absolute age estimates, but with considerable uncertainty and a partially destructive methodology. Successional metrics provided relative ages, probably with more precision than traditional lichenometry (as exemplified by the results for undisturbed versus disturbed cairn H), but not absolute ages.

Combining all methods thus provided more information than any method alone. We conclude that the cairns were built over a range of times, probably over centuries, most likely 500–1500 years B.P.

Although dating old cairns in a moist alpine environment is a difficult challenge, we believe that reasonable estimates can be made for cairns several hundred or more years old. Our methods could be improved with more time and expense: by a larger sample size (in particular more young cairns for comparison with old cairns), more radiocarbon dates, and having the data needed to construct local lichenometric calibration curves.

In our experience, land managers and others responsible for protecting cultural artifacts are typically less concerned with the exact age of structures and most concerned with establishing whether cairns or other rock structures are prehistoric in age. Given this modest objective, all three classes of methods used here, including lichenometry, can be useful.

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Appendix A

Table A1. Taxa recorded on cairns in the Cross Peak study area.

Taxon	Higher taxon	Successional class	Acronym
Andreaea nivalis	Bryophyte	2	And
Andreaea rupestris	Bryophyte	2	And
Antitrichia curtipendula	Bryophyte	3	Antcur
Bucklandiella heterosticha	Bryophyte	2	Buchet
Codriophorus fascicularis	Bryophyte	2	Codfas
Cynodontium jenneri	Bryophyte	2	Dic-sma
Dicranum elongatum	Bryophyte	3	Dic
Dicranum spadiceum	Bryophyte	3	Dic
Grimmia donniana	Bryophyte	2	Gri
Gymnomitrion concinnatum	Bryophyte	2	Gym
Gymnomitrion pacificum	Bryophyte	2	Gym
Kiaeria blyttii	Bryophyte	2	Dic-sma
Pleurozium schreberi	Bryophyte	3	Plesch
Polytrichastrum alpinum var. *septentrionale*	Bryophyte	3	Polalp
Racomitrium lanuginosum	Bryophyte	3	Raclan
Sanionia uncinata	Bryophyte	2	Sanunc
Scapania curta	Bryophyte	2	Sca
Scapania subalpina	Bryophyte	2	Sca
Tetralophozia setiformis	Bryophyte	2	Tetset
Amygdalaria panaeola	Lichen	1	Amy
Amygdalaria pelobotryon	Lichen	1	Amy
Amygdalaria subdissentiens	Lichen	1	Amy
Calvitimela aglaea	Lichen	1	Lec-gra
Calvitimela armeniaca	Lichen	1	Rhi-yel
Cetraria aculeata	Lichen	3	Cetacu
Cetraria ericetorum ssp. *reticulata*	Lichen	3	Cet
Cetraria islandica	Lichen	3	Cet
Cetraria subalpina	Lichen	3	Cet
Cladonia arbuscula	Lichen	3	Cla-usn
Cladonia bellidiflora	Lichen	3	Clabel
Cladonia borealis	Lichen	3	Clabor
Cladonia gracilis	Lichen	3	Clagra
Cladonia phyllophora	Lichen	3	Claphy
Cladonia pleurota	Lichen	3	Claple
Cladonia squamosa	Lichen	3	Clasqu
Cladonia squamules	Lichen	3	Cla-squ
Cladonia stygia	Lichen	3	Cla-nus
Cladonia uncialis	Lichen	3	Claunc
Cladonia verticillata	Lichen	3	Claver
Cladonia wainioi	Lichen	3	Cla-nus

Table A1. (*concluded*).

Taxon	Higher taxon	Successional class	Acronym
Euopsis granatina	Lichen	2	Euo
Euopsis pulvinata	Lichen	2	Euo
Fuscidea intercincta	Lichen	1	Fusint
Gowardia nigricans	Lichen	3	Gownig
Hypogymnia vittata	Lichen	3	Hypvit
Lecanora intricata	Lichen	1	Lecint
Lecanora polytropa	Lichen	1	Lecpol
Lecidea lactea	Lichen	1	Lec-gra
Lecidea lapicida	Lichen	1	Lec-gra
Lecidea lapicida	Lichen	1	Leclap
Lecidea praenubila	Lichen	1	Lec-bro
Lecidea promiscens	Lichen	1	Lecpro
Lepraria neglecta	Lichen	3	Lepneg
Melanelia hepatizon	Lichen	2	Melhep
Miriquidica garovaglii	Lichen	1	Lec-bro
Ochrolechia frigida	Lichen	3	Ochfri
Ochrolechia subplicans subsp. *hultenii*	Lichen	2	Ochsub
Ochrolechia subplicans subsp. *subplicans*	Lichen	2	Ochsub
Parmelia saxatilis	Lichen	2	Parsax
Pertusaria dactylina	Lichen	2	Per
Pertusaria panyrga	Lichen	2	Per
Phylliscum demangeonii	Lichen	2	Phydem
Pilophorus nigricaulis	Lichen	1	Pilnig
Placopsis sp.	Lichen	1	Pla
Porpidia contraponenda	Lichen	1	Lec-gra
Porpidia flavocaerulescens	Lichen	1	Porfla
Porpidia thomsonii	Lichen	1	Lec-gra
Pseudephebe minuscula	Lichen	3	Pse
Pseudephebe pubescens	Lichen	3	Pse
Pyrenopsis furfurea	Lichen	2	Pyr
Pyrenopsis sp.	Lichen	2	Pyr
Rhizocarpon eupetraeoides	Lichen	1	Rhi-yel
Rhizocarpon geographicum	Lichen	1	Rhi-yel
Rhizocarpon hensseniae	Lichen	1	Amy
Rhizocarpon lavatum	Lichen	1	Lec-gra
Rhizocarpon subpostumum	Lichen	1	Lec-gra
Rhizocarpon superficiale	Lichen	1	Rhi-yel
Schaereria cinereorufa	Lichen	1	Schcin
Schaereria fuscocinerea	Lichen	1	Lec-gra
Sphaerophorus fragilis	Lichen	3	Sphfra
Sphaerophorus globosus	Lichen	3	Sphglo
Stereocaulon alpinum	Lichen	3	Ste
Stereocaulon dactylophyllum	Lichen	3	Ste
Stereocaulon spathuliferum	Lichen	3	Ste
Stereocaulon vesuvianum	Lichen	3	Ste
Thamnolia subuliformis	Lichen	3	Thasub
Tremolecia atrata	Lichen	1	Lec-bro
Tremolecia atrata	Lichen	1	Treatr
Umbilicaria cylindrica	Lichen	3	Umbcyl
Umbilicaria proboscidea	Lichen	3	Umbpro
Umbilicaria torrefacta	Lichen	3	Umbtor
Unknown sterile crust	Lichen	1	Unk-wcr
Empetrum nigrum	Vascular	4	Empnig
Salix arctica	Vascular	4	Salarc
Vaccinium uliginosum	Vascular	4	Vaculi

Note: Acronyms indicate lumping that was necessary for field identification, prior to studying samples in the laboratory.