Effects of a Topographical Gradient on Food Availability, Nest Site Selection, Nest Initiation, and Nest Success for Two Small, Low Arctic Breeding Bird Species

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Abstract

Effects of Elevation on Food Availability, Nest Site Selection, Nest Initiation, and Nest Success for Two Small Subarctic Breeding Bird Species

Sarah M.F. Bonnett

Climate change affects birds' reproductive ecology by altering breeding timing, distribution, and habitat suitability. Snowmelt patterns complicate these changes affecting habitat availability and suitability for birds and their arthropod prey. Snow varies as a function of both large-scale climate patterns and local-scale topography. I used elevational gradients as a proxy for local-scale snow impacts, investigating how elevation affects arthropod abundance, and nest placement, initiation, fate, and habitat for Lapland Longspur (*Calcarius lapponicus*) and Semipalmated Sandpiper (*Calidris pusilla*) north of Baker Lake, Nunavut. I found and monitored nests over multiple breeding seasons and used pitfall traps and conducted vegetation surveys. Results show that elevation significantly affects arthropod biomass and nest placement, but not nest initiation or success. Both species preferentially nested at lower elevations with higher arthropod biomass. Thus, birds in the central Arctic choose nesting sites at lower elevations with better food availability rather than higher elevations with earlier snowmelt.

Keywords: Arctic, Lapland Longspur, Semipalmated Sandpiper, arthropod biomass, nest site selection, nest success

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Introduction

The Canadian Arctic is warming at more than twice the rate of the global average, with more precipitation falling as rain instead of snow in winter, longer growing seasons, earlier snowmelt, more extreme weather events, and melting permafrost (Bintanja & Andry, 2017; Environment and Climate Change Canada, 2024). These changes in climate can have substantial impacts on wildlife by altering the distribution or composition of habitats and prey communities, but also by altering the availability of habitats and prey through changes to snowmelt patterns (Post et al. 2009). Annual increases in Arctic temperatures between 2-10°C are predicted to convert up to half of tundra into shrubland by the end of this century (Myers-Smith et al., 2015). This shrub increase has already been observed in Alaska, U.S.A., with shrub coverage increasing at a rate of 1.2% per decade since 1950, and in Nunavik, Canada, where over 40 years shrub coverage increased by 10% (Chapin et al., 2005; Tremblay et al., 2012). These changes occur within the context of snowmelt which varies not only as a function of climate, but also topography and habitat (Kępski et al., 2017).

Snowmelt patterns represent the underlying topography of the ground due to wind transport during winter (König & Sturm, 1998). In the northern hemisphere, south-facing slopes melt faster than north-facing slopes due to increased sun exposure, and slopes facing prevailing winds clear of snow before slopes facing away from the wind, because of increased snow accumulation from drifts (König & Sturm, 1998). Tops of hills also have less snowpack and can become snow free earlier in the melt season, while valleys and lower elevation areas can hold deeper snow which will melt later in the spring (Weller, 1972).

Vegetation cover type can also influence snow cover, and visa-versa, where increasing snow depth was associated with graminoids and other lowland plant species (Schaefer & Messier, 1995), and with the shortest snow cover duration in the arctic occurring on lichen-herb-heath tundra (Kępski et al., 2017). Snow is also retained the longest on rock, with almost two weeks of melt difference between lichen-herb-heath tundra and rock (Kępski et al., 2017). Open areas tend to have less snow cover, with wind more easily moving that snow from one area to another, while shrubs can hold snowpack and prevent movement via wind, so shrubby areas or areas adjacent to shrubs will become snow-free later (Liston et al., 2002; Sturm et al., 2001). These shrubs that retain snow can result in warmer soil temperatures throughout the winter (Liston et al., 2002; Sturm et al., 2001).

Climate-related changes in snowpack and spatial variation from habitat and topography, have consequences for arthropods in the Arctic, as most species rely on snow cover in the winter to insulate overwintering sites and protect against desiccation and extreme temperatures (Danks, 2004). While many arctic arthropods are freeze-tolerant and are active as soon as temperatures are high enough (some species become active as soon as temperatures are above 0°C), many other species enter diapause, which stops growth and development at specific stages or photoperiods until the following spring to facilitate synchronized emergence of adults (Danks, 2004). Decreased snowpack and increased rainfall in the winter exposes overwintering soil arthropods to greater temperature fluctuations and can result in higher mortality in these species, due to decreased insulation from freeze-thaw cycles (Koltz et al., 2018; Walters, 2023). As a result of decreased insulation, areas with topography that create deeper snowpack (lower elevation, hill slopes facing away from prevailing winds) should have higher arthropod abundances and winter survival when compared to open areas at the tops of hills which have shallower snowpack, early snowmelt, and tend to be drier.

Negative impacts on the abundance of arthropods caused by reduced snowpack and reduced insulation could have severe impacts up the food chain, for example, for the many migratory birds who migrate long distances from South America and the southern United States to nest and take advantage of the flush of abundant food that occurs during short Arctic summers (Baker & Baker, 1973). Shorebirds, as income breeders, rely on these abundant arthropods for females to form eggs and for both sexes to rebuild energy reserves for successful incubation (Klaassen et al., 2001; Morrison & Hobson, 2004). Reduced abundance of arthropod prey could lead to altered bird distributions, or reduced reproductive success (Bolger et al., 2005).

Changes in snow melt patterns can also influence the timing of arthropod emergence, with important consequences for birds. As the tundra warms, arthropods are predicted to respond quickly to increasing temperatures, emerging up 0.2 days/year earlier (Tulp & Schekkerman, 2008), and birds may not be able to adjust to earlier peak arthropod emergences that they rely on for rapid chick growth (Hodkinson et al., 1996; Kwon et al., 2019; Tulp & Schekkerman, 2008, but see Corkery et al., 2019). Increased temperatures can lead to earlier and larger insect emergences in the Family Chironomidae, a family of flies that forms an important component of the diet of many Arctic birds (Hodkinson et al., 1996). While birds may depend on these patterns of insect emergence, these larger emergences can happen all at once with overall biomass of potential prey not maintained throughout the summer (Hodkinson et al., 1996; Kwon et al., 2019). The ability of birds to respond to both ongoing and anticipated changes in snowmelt, precipitation and accompanying changes in the timing of emergence of their invertebrate prey is poorly known.

As snowfall patterns depend on underlying topographic patterns, arthropods may also be affected by variation in topography, or vegetation patterns that result from topographic gradients. For example, compared to higher elevations, wet lowland areas near water have higher invertebrate prey preferred by most shorebird species for chick development (Cunningham et al., 2016; Holmes & Pitelka, 1968; Smith et al., 2007; Tulp & Schekkerman, 2008).

The timing of snowmelt is important for arctic breeding birds, which are mostly ground nesters, as they cannot begin to nest until the ground is snow-free. The date of 50% snow cover has been closely linked with the timing of nest initiation of breeding birds at several sites across the North American Arctic (Liebezeit et al., 2014; Meltofte, Høye, et al., 2007; Meltofte, Piersma, et al., 2007; Smith et al., 2010). The changing climate and unpredictability of snowmelt can lead to uncertainty for the future of these nesting birds, with changing snowmelt timing showing the strongest effects on shorebirds in eastern North America, where earlier timing of snowmelt increases the mismatch between peak food availability and peak food demands by chicks (Kwon et al., 2019).

My thesis uses elevational gradients as proxies for variation in future snow melt, to determine the effects of anticipated climate-change induced impacts on arthropod biomass as food for Lapland Longspur (*Calcarius lapponicus*) and Semipalmated Sandpipers (*Calidris pusilla*). I examine how elevation along small rolling hills affects nest placement, nest initiation, nest success and habitat of these two species. I test four mechanisms for potential impacts of elevation on these factors, by comparing birds that nest across short elevation gradients (77-153m asl), in Nunavut, in the central Canadian Arctic. First, I test the assumption that arthropod biomass varies across elevational gradients in my central Arctic study site. I then determine whether the timing of nest initiation varies across these elevational gradients, anticipating earlier initiation at higher elevations with earlier snow melt, and later initiation at lower areas where snow can linger. Next, I test whether there are associations between elevation and nest success, because birds with greater access to arthropods should reduce foraging bouts and distances (Tremblay et al., 2005), and hence be able to attend nests more consistently, thus decreasing the probability of detection of potential predators (Bulla et al., 2016; Smith et al., 2012). Finally, I test the alternative hypothesis that birds are nesting at different elevations because these are associated with different landcover and vegetation types that birds might prefer.

Study Species

The Lapland Longspur (*Calcarius lapponicus*) is a small passerine (Family: Calcariidae), and one of the most abundant breeding birds on the Arctic Tundra (Hussell & Montgomerie, 2002). They have a Holarctic distribution, breeding across the Low Arctic and sub-arctic in North America, Asia, and Europe. Population estimates of Lapland Longspur are 93 million birds in Canada and up to 140 million worldwide (Environment and Climate Change Canada & Birds Canada, 2024a). Although Lapland Longspur are thought to be increasing according to the IUCN (BirdLife International, 2017), trend estimates from Christmas Bird Counts show a decline in Canada (-1.37% per year 1967-2017), and an increase in the United States (2.21% per year 1967-2017) (BirdLife International, 2017; Meehan et al., 2018; Rosenberg et al., 2019).

In North America, Lapland Longspur are a medium-distance migrant, and, in the winter, they gather in flocks of up to a million in the Great Plains but can be found in the winter across North America, often in mixed flocks with Snow Bunting (*Plectophenax nivalis*) or Horned Lark (*Eremophila alpestris*) (Hussell & Montgomerie, 2002). They return to their arctic breeding grounds in early spring, and initiation of nesting is closely related to snow cover (Liebezeit et al., 2014). Nests are a cup nest on the ground, usually in the side of a hummock, in areas of sedge-dominated tussock tundra (Boelman et al., 2015).

Lapland Longspur lay 2-8 eggs in a clutch, with an average of 4.3 eggs per nest near Baker Lake, Nunavut (Custer & Pitelka, 1977; Hussell, 1972). Chicks are altricial and stay in the nest an average of 7.4 days and begin to fly short distances 8-11 days after hatch (Hussell & Montgomerie, 2002; Maher, 1964). These young birds begin to forage on their own at 12 days old, with peak food demands between 8-12 days after hatch. Young Lapland Longspur become independent of adults by 24 days old (Custer et al., 1986).

Lapland Longspur diets vary seasonally, consisting of mainly seeds in the winter and arthropods in the summer, heavily relying on dipterans and hymenopterans during the breeding season (Custer & Pitelka, 1978). Throughout the breeding season they can shift their diet, from mainly foraging on larval arthropods early in the season, and switching to adult arthropods during peak emergence, and then returning to feeding on larvae (Custer & Pitelka, 1978; Hussell, 1972).

The Semipalmated Sandpiper is a small shorebird (Family: Scolopacidae) which breeds in the low and sub-arctic across North America from northern Labrador to Alaska, and a small area into the eastern tip of Russia (Hicklin & Gratto-Trevor, 2020). Population estimates of

Semipalmated Sandpiper are 10 million individuals breeding in Canada, and up to 12 million individuals globally (Environment and Climate Change Canada & Birds Canada, 2024b). Their population has decreased significantly over the last 50 years, with a decline of -2.83% per year (±1.43), and as a result they are listed as Near Threatened by IUCN Red List (BirdLife International, 2016; Environment and Climate Change Canada & Birds Canada, 2024b). In Canada they are considered Apparently Secure by Wild Species 2020 (North American Bird Conservation Initiative Canada, 2019) and are a 'watch list' species on State of North Americas Birds 2016 (North American Bird Conservation Initiative, 2016). Semipalmated Sandpiper are classified as a 'tipping point species' by the State of the Birds 2022 report, which means that they have declined by more than 50% in the past 50 years. Additionally, tipping point species are at risk of becoming Endangered if no concrete actions are taken to reverse their declines (North American Bird Conservation Initiative, 2022). Approximately 80% of the global population of Semipalmated Sandpiper breed in Canada, and as such, Canada ranks them as a species of high responsibility for the conservation of this species (North American Bird Conservation Initiative Canada, 2019).

Semipalmated Sandpipers are long-distance migrants, travelling yearly from their Arctic breeding grounds to their wintering grounds along the coast of Central and South America, where they use beaches, mudflats, and saltmarshes for foraging (Hicklin & Gratto-Trevor, 2020). They migrate throughout North America, with western breeders typically migrating through the prairies, and central and eastern breeders travelling along the Atlantic Coast (Hicklin & Gratto-Trevor, 2020).

Semipalmated Sandpipers are usually an early-nesting shorebird, as in some locations, they typically initiate nesting before most other species of shorebirds in the same area (Saalfeld & Lanctot, 2015). Earlier snowmelt at several sites in Arctic Alaska has been linked to advancement of nest initiation by 4-7 days over a period of 9 years (Liebezeit et al., 2014).

Semipalmated Sandpipers typically incubate their four eggs for 19-21 days, and chicks are precocial, leaving the nest within 24 hours after hatching (Hicklin & Gratto-Trevor, 2020). Chicks feed on their own almost immediately after hatching; however, at least one parent (almost always the male) broods and guards the chicks for 2 weeks until they can thermoregulate on their own (Ashkenazie & Safriel, 1979; Hicklin & Gratto-Trevor, 2020).

Semipalmated Sandpipers are territorial and space out from conspecifics, with little variability in territory size or nest density in Alaska. They have moderate nest site fidelity, with about 28% of adults returning to the same nest sites in subsequent years (Cunningham et al., 2016; Saalfeld & Lanctot, 2015). Nests are typically found in tundra with a high degree of microrelief, where this species nests in dry areas surrounded by moist areas (Cunningham et al., 2016)

Semipalmated Sandpiper are selective feeders. Composition of their stomach contents show preferential feeding on larval flies (Order: Diptera) including chironomids, tipulids, and dolichopodids on the breeding grounds near Churchill Manitoba (Baker, 1977), as well as small dipteran adults, beetles, and spiders (Holmes & Pitelka, 1968).

Methods

Study Site

I conducted this study ~120km north of Baker Lake, Nunavut Canada (65°24’N, 96°41’W) where I was based out of the AGNICO-Eagle Mines Ltd. Amaruq camp at Whaletail Lake (Figure 1). This area is primarily composed of tundra habitats with rolling hills, rocks, and many scattered lakes, dwarf shrub, and graminoid wetlands (Figure 2). The area is classified as subzone D on the Circumpolar Arctic vegetation map: between 2-10% lake coverage, acidic substrate, with erect dwarf-shrub tundra (Walker et al., 2005). The average elevation for the study area is 119masl, with a topographic relief of 76m (Table 1).

I conducted this research in 34 intensively-searched plots of 6 ha each (200 x 300 m), pre-established in the study area in collaboration with another project (Holmes, 2022). Eighteen plots were chosen, in sets of 3 along Amaruq Road, the main road to the Amaruq camp. An additional 16 irregularly-shaped plots were established around Whaletail Lake in sets of 4 (2 adjacent to the lake, and 2 at slightly higher elevation adjacent to the lake plots). Plots within a set were usually established in similar habitats, in which I grouped adjacent plots into 8 groups (Table 1).

Arthropods

Pitfall traps were deployed to collect arthropods in 2021 (n=21) and collected every 3-7 days during the field season. Deployment occurred as soon as possible after researchers arrived in the field, once snow had melted enough to place traps in the substrate. Pitfall traps consisted of yellow disposable plastic bowls (3cm deep, 8cm diameter across at the bottom and 15cm diameter across the top, Figure 3b) dug into the ground so that the lip was level with the surrounding tundra. Bowls were filled with water and a few drops of liquid dish soap to break the surface tension. Pitfall traps were set up across 5 intensively-searched plot groups, using a transect between the highest point of elevation to the lowest point and every 5m in elevation change (Figure 3a) to provide invertebrate samples across a range of elevations that represented the elevations at which the nests also occurred.

Arthropods were counted and identified to family level where possible, with body length measured with a ruler (to nearest millimeter) under a dissecting microscope (Leica MZ6, 6.3-40x magnification). Body length was measured from the tip of the head to the end of the abdomen, excluding antenna, ovipositors, and extended wings. In the lab I dried arthropods and weighed these individually on a microbalance (Sartorius SE2, ±0.25µg) to determine best-fit equations to calculate dry biomass. Where there was not a large sample or individuals were not preserved well, dry biomass was calculated using published body-length to biomass equations (Appendix Table 6).

After measuring and calculating the dry biomass for all samples, I filtered out arthropod species not listed as food sources in the literature for either Lapland Longspur or Semipalmated Sandpiper (e.g., bumblebees (Hymenoptera: Genus *Bombus*), because of their large size potentially skewing biomass in the traps). I also removed mites (Subclass Acari) from further analysis because I was unable to count them accurately or distinguish some smaller individuals from plant seeds when using the lower powered (20x) dissecting microscope that was used in the field for sorting samples.

Nest Monitoring

I searched and monitored nests from early June to late July in 2018 (6 June – 16 July), 2019 (4 June – 16 July), and 2021 (10 June – 16 July), in the same areas in all years, although nest searching/monitoring effort around Whaletail Lake was limited in 2018. Nests were found through behavioural observations of adults or through walking systematically through the plots and flushing a bird off a nest. Nests found during egg-laying were aged assuming 1 egg laid per day, while nests found with complete clutches were aged through egg-floatation (Liebezeit et al., 2007) or by ageing the largest chick in a brood based on descriptions of Lapland Longspur chicks of different ages (Hussell, 1972; Jongsomjit et al., 2007). All nests were checked every 3-7 days throughout the season and notes were recorded about adult behaviour and nest contents including the number of eggs or nestlings, signs of hatch, age of nestlings, and evidence of predation. Nest locations were marked with a hand-held GPS (±3m).

Lapland Longspur nests were assumed successful when at least one chick fledged the nest at an appropriate age (at least 6-8 days since hatch, averaged 7.4 days (Maher, 1964)), adults were observed carrying food, chicks were seen near the nest, or adults were alarm calling or performing distraction displays. Semipalmated Sandpiper nests were assumed successful based on the presence of chicks in the nest, egg fragments found in the nest (Mabee, 1997; Mabee et al., 2006), or adults observed with chicks or agitated near the nest. Nests were considered unsuccessful if signs of predation were present such as a smell of fox urine, large pieces of eggshell found nearby, or eggs (or chicks) were gone before estimated completion date with no signs of hatching. Nests were assigned unknown fates if they were still active when the crew left at the end of the season, or, because of a low frequency of nest checks.

I banded adult Lapland Longspur and Semipalmated Sandpiper on the nest after chicks hatched by trapping them using a bow net during good weather, with no precipitation, and above 5°C (under Canadian Wildlife Service banding permit 10515AQ). Banding was conducted to allow me to individually identify birds, to account for potential pseudo-replication in subsequent analyses. Only female Lapland Longspurs could be reliably trapped at the nest during incubation, so I also trapped male Lapland Longspurs during the nestling stage while they fed chicks. Adult Lapland Longspur captured were banded with a combination of plastic colour bands and one federal metal individually numbered leg band. I banded all Lapland Longspurs with a pink band over the metal band on the lower left leg, and a combination of 1-2 bands of other colours on the right leg (black, blue, green, light blue, mauve, orange, pink, red, white, or yellow). Adult Semipalmated Sandpipers were banded with a metal band on one leg, and a white leg flag with a 3-letter code engraved in black, following Howe et al. (2016). Individual colour band combinations and flag codes allowed us to resight individual adults within a season and between years without the need for recapturing that adult to confirm identity. When individuals were resighted between years, a GPS coordinate was recorded for the location of the bird, and every effort was made to find a nest.

Landcover Plots

I conducted landcover assessments at each nest (after nests were completed and chicks had fledged the nest), at pitfall traps (while removing them from the plot), and at random points. Random points were selected using ArcMap with random UTM's generated and were at least 7m away from any known nests within the same year of either Lapland Longspur or Semipalmated Sandpiper that occurred. The random points were grouped for both species due to time constraints in the field not allowing for a separate set of landcover points for each species. In 2019, five random points were chosen in each intensively-searched plot, and in 2021 I assigned 20 random points per plot group, but not necessarily within the intensive search plots because many of the nests were found outside the intensively-searched plot boundaries.

I measured habitat characteristics in a 5m x 5m square centred on the nest cup or random site. In the square I classified habitat types into broad categories similar to Smith et al. (2007), including moss carpet, scrub willow (including birch shrub (*Betula* spp.)), dry heath, rock/gravel, mud/exposed substrate, and sedge meadow. I then estimated the proportional cover of each habitat category at this 25m^2 scale.

Elevation

All elevations were determined using the ArcticDEM from the Polar Geospatial Centre. I used the 2m resolution digital elevation model (DEM) which has a vertical and horizontal absolute accuracy of 4m (Porter et al., 2018). Elevation for all waypoints (nests, random sites, pitfall traps) were then extracted from the DEM in ArcMap. This ensured minimal error in the elevation recorded compared to the handheld GPS units and allowed for elevation statistics to be easily generated inside polygons drawn in ArcMap for plots and plot groups.

Statistical Models

Plot Grouping

Intensive plots in each set were grouped for analysis; boundaries were drawn in ArcMap after the field season to include intensively-searched plots and areas where handheld GPS tracks of researchers frequently crossed, indicating areas where we walked/searched for nests and were likely to find nests when active. These areas were also added to the groups of plots. These demarcations resulted in 8 plot groups (4 total around Whaletail Lake, and 4 along Amaruq Road), which were then grouped for analysis based on elevational similarity and nest sample sizes down to 4 intensively searched areas for analysis for Lapland Longspur, and 3 for Semipalmated Sandpiper because Semipalmated Sandpiper occurred in the study area in lower numbers, so two groups were combined (Figure 1, the two northern most sections).

Food Abundance

To test if food availability (measured as the sum of arthropod biomass, excluding the non-diet arthropods as described above) changed with elevation, I used data collected from 2021 along elevational gradients and then I calculated total biomass per day for each trap. First because there was large variation in biomass (mg) per day, I log-transformed ($\ln(x+1)$) biomass, which helped reduce the variance and improved the distribution of residuals. I then checked for a significant effect of sampling date on arthropod biomass using a GLM (family: Gaussian). The final GLMM (lme4) model included biomass per day as the response variable, elevation and season day as fixed effects, and plot group (or trap line) as a random effect (Bates et al., 2015). We ran a candidate model with the quadratic date, as we might expect a peak in arthropod abundance throughout the season, but this model had higher AIC value (ΔAIC=6.11) than the model where season day was untransformed and thus, this term was not used in further analysis.

Nest Elevation

To assess the effect of elevation on nesting locations I used a binomial (used vs available) Generalized Mixed Effects Model (GLMM) in R with the package lme4 (Bates et al., 2015). In both the separate models for Lapland Longspur and Semipalmated Sandpiper, individual bird was included as a random effect as I occasionally had more than one nest per individual within (1 LALO renest in 2019) and across years (7 LALO and 12 SESA nests), and I included plot group as a fixed effect because the model was overfit when this variable was included as a random effect. Including plot group as a fixed effect is suitable because there were elevational changes over the study site (the plots farther north were at higher elevation than those further south; Table 1), and the plots around Whaletail Lake were directly adjacent to a larger body of water. Therefore, I assumed that there might be an effect of plot group on the relationship between elevation and nest presence. I excluded nests from the Whaletail plots in 2018 because these plots were surveyed only twice in that year, and areas of higher elevation adjacent to these plots were not surveyed. In 2019 and 2021 the areas further from the lake and at higher elevations were included in nest searching.

Elevation and Initiation Date

I built a GLMM separately for Lapland Longspur and Semipalmated Sandpiper to assess how nest initiation date was affected by the elevation of the nest. I standardized nest initiation date within each year by calculating the mean initiation date and assigning that date as “0” for each species. Nests were assigned the difference in days since “0” for initiation date so that nests initiated before that date were given negative values (i.e., early nests), and those initiated after that date were given positive values (i.e., late nests). I included the same plot groups as a random effect for each species model as the plot groups used to assess nest elevation.

Elevation and Daily Nest Survival

I used the package RMark version 3.0.0 to calculate daily nest survival rates (DSR) using logit-link functions and included different potential predictors (Laake, 2013). I excluded nests with unknown fates, nests abandoned during nest building (no evidence of eggs being laid), and nests which were found on the fate date (first checked, last checked, and fate date cannot all be the same in RMark), and nests which were outside of the study area (Laake, 2013). I ran 8 candidate models: the null model, models including a categorical effect of year, temporal (linear, quadratic, and cubic) effects of date, and nest age, and elevation of the nest. I used Akaike's Information Criteria (AIC_c) to compare candidate models, and only parameters with 95% confidence intervals not overlapping zero were considered important for explaining variation in daily nest survival rate.

Nest age was a not a good predictor of daily nest survival for either Lapland Longspur or Semipalmated Sandpiper (low on AIC_c list, confidence intervals overlapping zero), so I reran the candidate models without the model for nest age and was then able to include nests with unknown ages (Fromberger, 2020; Weiser, 2021). These nests included more failed nests, which was important for the Semipalmated Sandpiper model where most nests with known dates were successful, and, therefore, the binomial models were not converging.

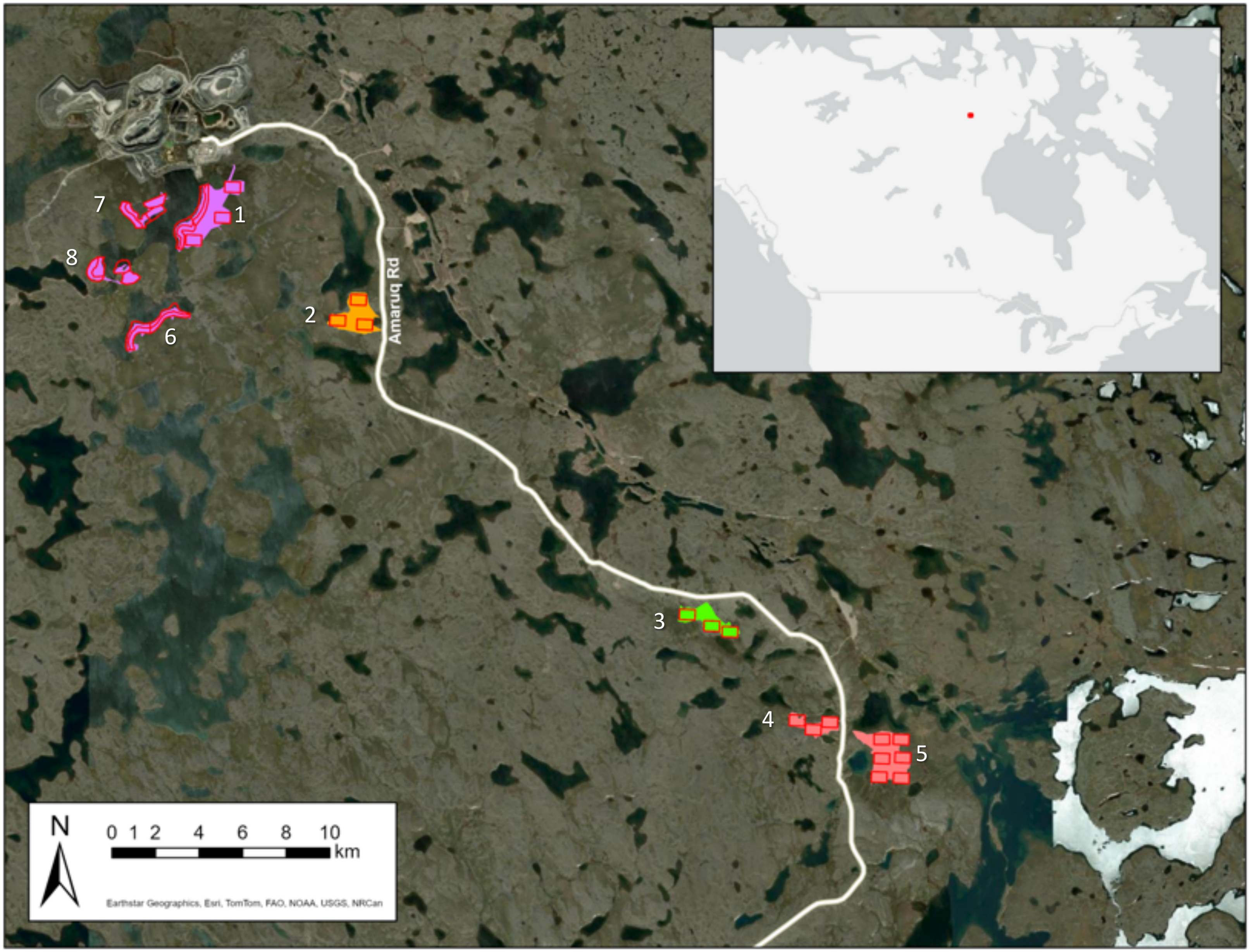
Landcover and Elevation

To investigate the relationship between elevation and the abundance of the five landcover types in the random habitat surveys from 2019 and 2021, I first used zero-inflated beta regression in R with the package glmmTMB (Brooks et al., 2017). I included the same plot groupings used in the Semipalmated Sandpiper models as a random effect in the model as there were differences in landcover composition between some plot groups. The zero-inflated model tests for two things: in the conditional model, the test determines whether the proportion of a given landcover type varies across elevational gradients, and in the zero-inflated model, the test determines if the absence (likelihood of a zero) of a landcover type is affected by elevation.

I then ran a binomial GLMM for both Lapland Longspur and Semipalmated Sandpiper nest (1) vs unpaired random landcover surveys (0), predicted by the landcover variables that had a significant relationship with elevation in the conditional model; these models also included a random effect of plot group (using the same plot group assignment as in the landcover models) to account for differences between areas. This approach was taken rather than combining elevation and habitat into one model to avoid reducing sample sizes as not all nests had landcover surveys completed.

Table 1. Elevation (masl) of the plot groups, including the individual plots included within each group. All elevations calculated using ArcMap and ArcticDEM (Porter et al., 2018).

Plot Group	High Intensity Plots	Mean	Median	Min	Max	Topographic Relief
1	1-3 & WT2	122.3	120.7	113.1	140.8	27.7
2	4-6	126.5	126.7	120.6	131.3	10.8
3	7-9	109.0	107.9	102.5	120.9	18.5
4	10-12	94.6	94.8	87.7	111.0	23.4
5	13-18	89.3	89.3	81.5	96.1	14.6
6	WT1	118.2	117.7	114.5	128.5	14.0
7	WT3	118.8	118.6	114.9	125.4	10.5
8	WT4	117.6	117.3	114.8	122.6	7.8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km
Earthstar Geographics, Esri, TomTom, FAO, NOAA, USGS, NRCan

Figure 1. The study area ~120km north of Baker Lake, Nunavut Canada (65°24’N, 96°41’W, red dot on the inset map of Canada). At the North end is the Amaruq camp of Agnico Eagle Mines Limited, where our crew stayed while in the field. The red outlines are the intensive search plots, the white numbers indicate the groups as described in Table 1, and the coloured polygons represent the plot groups used for analysis, with areas of the same colour being the same plot groups. The purple polygons at the North end all border on Whaletail Lake, which resulted in intensive search plots that were irregularly shaped but of the same area (6ha) as the rectangular 200x300m search plots. The purple and orange plot groups at the North end were combined into one plot group for the analysis of all attributes of Semipalmated Sandpiper nests.

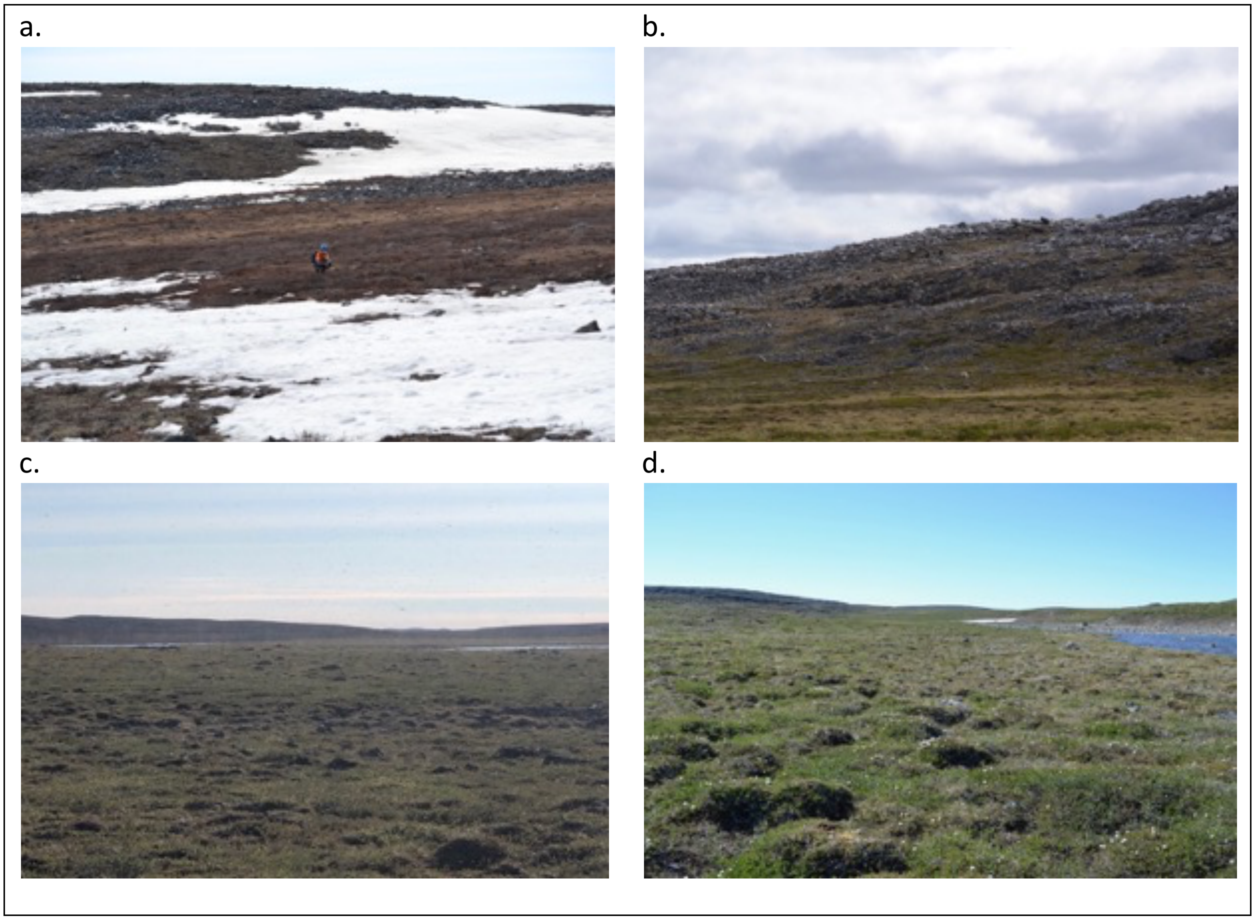

Figure 2. A sample of variation in terrain in the study area, showing rolling hills, hummocks, low lakes, and some rock fields. (a) 13 June 2021 in Plot 11, showing early season snow cover and rolling hills, field crew member, Alice Atikessé, in the middle of the photo for a sense of scale. Snow remains in the lower areas of this hill, with the top of the hill having melted first. This is a South facing photo and some snow remains in drifts on the North side. (b) 10 July 2019, showing the edge of plot 11 and 12. In mid-July the lower areas of this area are sedge meadow hummocks with lots of flowing and still water, and abundant sedges (*Carex* sp.) and grasses (Family: Poaceae). The tops of the hills with the rocks are still drier. (c) 8 July 2021, in the WT4 plots, while it appears very flat here, there is a gradual slope to the lake. The "haze" in this

photo is caused by a cloud of mosquitoes (Culicidae) and other flying insects. (d) 14 July 2018, looking towards the northwest corner of plot 10 and 11, the lower areas of the plot are characterized by wet hummocky tundra with Labrador tea (*Rhododendron tomentosum* ssp. *decumbens*), and dwarf birch (*Betula nana*), intermingled with grasses and sedges. A very small amount of snow remains on a small, south-facing sheltered slope.

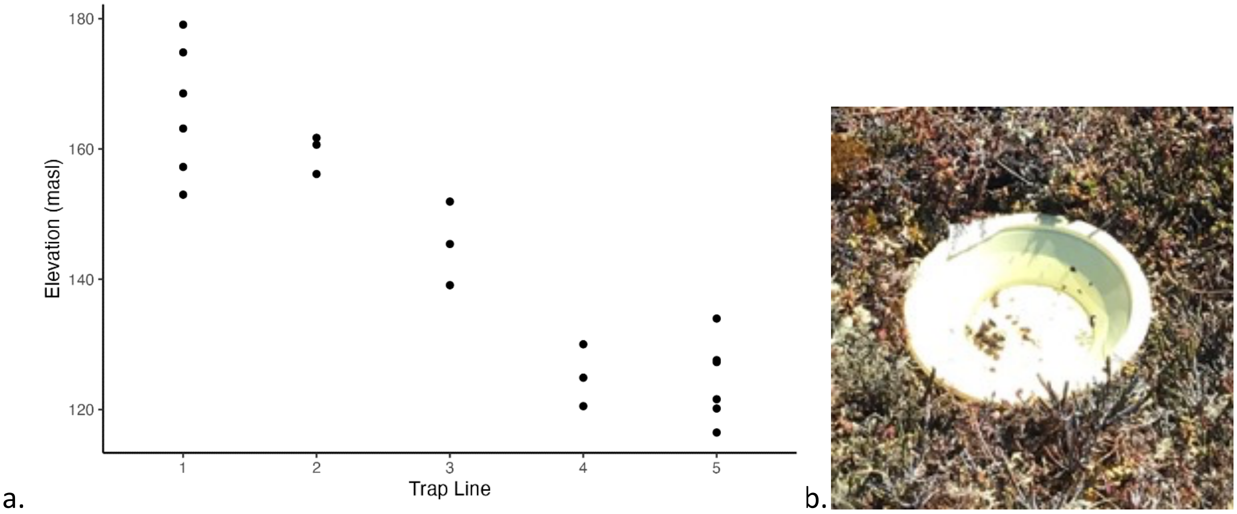

Figure 3. (a) Elevation of pitfall traps in 2021. Pitfall traps were placed approximately every 5m in elevation change from the lowest to the highest point in the plot groups. (b) A photo of a pitfall trap right before collection of samples. Edges of the bowl are level with the surrounding tundra.

Results

I conducted field work for 3 breeding seasons: 2018, 2019, and 2021, with most days spent in the field if weather conditions allowed. Upon arrival in 2018 and 2019 the field sites had 100% snow cover, while in 2021 there was less than 50% snow cover.

Pitfall traps in 2021 were set out for an average of 32 days (range: 26-36 days), and collected weekly, with the first trap deployed on 10 June, and the final one collected on 17 July. I made 96 collections from 21 traps, some of which were excluded because there was evidence that an arctic fox (*Vulpes lagopus*) tampered with traps (scat, urine smell, destroyed traps).

I modeled the biomass of arthropods from 3 Classes: Insecta (9555 individuals, 8270.59mg), Arachnida (548 individuals, 4045.73mg), and Collembola (3618 individuals, 172.53mg). Within Insecta, Diptera was the Order with the largest number of arthropods collected in both individuals (8824) and biomass (4131.67mg). Within Diptera, more Nematocera (midges, including mosquitoes, crane flies, and gnats: 5126 individuals, 634.08mg) were trapped than Brachycera (includes houseflies, scuttle flies, and long-legged flies: 3576 individuals, 3473.34mg). The Family Chironomidae (non-biting midges) had the most individuals collected at 1800 individuals with a biomass of 198.9761mg. The Family with the highest biomass collected was Anthomyiidae (Brachycera), with 780 individuals and 599.62mg (Appendix Figure 11 and Figure 12).

There was a significant effect of sampling date on arthropod biomass, with biomass increasing during the season (GLM, gaussian: β=0.04 ±0.01, $t_{74.23}$=4.39, P<0.001, Adjusted R^2=0.18, Figure 4). Thus, I incorporated season day as a fixed effect into the GLMM for testing the effect of elevation on biomass. There was a significant effect of elevation on biomass per day (log-transformed) with pitfall traps set in lower elevation areas collecting higher arthropod biomass than higher elevations (GLMM, gaussian: β=-0.52 ±0.18, $t_{6.76}$=-2.80, P<0.05, Figure 5).

Avian Nesting Success Results

I found a total of 270 Lapland Longspur nests (77 in 2018, 102 in 2019, and 91 in 2021, Table 2). The mean nest initiation date (±SD days) was 16 June in both 2018 (±3.01) and 2019 (±4.05), and 15 June in 2021 (±3.98, Table *2*). Among these 270 nests, 136 were successful, 83 failed, and 51 had unknown fates. Nests were assigned unknown fates if they were not checked frequently enough or if they were still active when the crew left at the end of the season. Of those nests with known fates, an average of 62% were successful (2018: 47.8%, 2019: 63.0%, and 2021: 69.1%). I found a total of 93 Semipalmated Sandpiper nests (24 in 2018, 34 in 2019, and 35 in 2021, Table 2). Semipalmated Sandpiper nests were initiated with the mean date (±SD days) of the first egg laid on 17 June 2018 (±1.48), 15 June 2019 (±3.39), and 14 June 2021 (±4.08, Table *2*). For nests within areas consistently sampled in all years, this advancement of laying date over time was marginally significant (GLM: β=-0.65 ±0.35, P=0.063). Of these Semipalmated Sandpiper nests, 65 were successful, 13 failed, and 15 had unknown fates. For nests with known fates, an average of 83.3% were successful (2018: 71.4%, 2019: 84.9%, and 2021: 87.1%). I banded a total of 75 Lapland Longspurs (2018: 29; 2019: 24; and 2021: 22) and 49 Semipalmated Sandpipers (2018: 13; 2019: 18; and 2021: 17) at their nests. Of the birds banded, 6 individual Lapland Longspurs were resighted between years, and 1 bird from 2019 whose nest failed by flooding, renested within the same year, for a total of 7 birds with more than one nest recorded (8% total banded, 6 females, 1 male). For these returning individual

Lapland Longspur, nests moved an average of 160.8m horizontally (max: 368.2m, min:44.5m, Appendix Table 7). Elevation of these nests was higher on average, but a one-sample t-test of first and subsequent nests was not significant (t_6=1.93, P=0.10). I resighted 13 (26%) individual Semipalmated Sandpiper between years and of those, only 2 were resighted with no nest found. Ten individuals had nests found in two years (3 of those were seen in all 3 study years but nests were not found in all years), and I found the nest of 1 bird in all 3 study years. Semipalmated Sandpiper nests of resighted birds moved an average of 117.36m horizontally (max: 483.4m, min: 1.3m, Appendix Table 7), with a mean decrease in elevation of 0.9masl (t_{12}=-1.79, P=0.09).

Lapland Longspur

For the analysis of the effect of elevation on Lapland Longspur nest locations, I used 228 Lapland Longspur nests (36 in 2018, 101 in 2019, and 91 in 2021, excluding 25 Whaletail nests from 2018, and 16 nests from other areas of study site outside of search plots) in the GLMM, and included only 5 birds for which I had more than one nest location (2 nests excluded because they were Whaletail Lake nests in 2018). The results of my binomial model of elevation with vs random point showed show no significant effect of elevation on nest placement, but there was a pattern of Lapland Longspurs nesting at lower elevations in each of the plot groups, and a weaker pattern in plot group 1 which included all plots around Whaletail Lake (GLMM: β=-0.71 ±0.39, z=-1.85, P=0.06, Figure 6). The plots varied significantly in elevation, with the northern plots being higher elevation overall compared to the more southern areas.

I used 218 nests to investigate the relationship between elevation and nest initiation date. Nests with no initiation date estimate or far outside of focal study plots were excluded. There was no significant relationship between nest initiation and elevation (GLMM: β=-0.01 ±0.01, $t_{3.29}$= -0.78, P>0.1, Figure 7).

For the DSR analysis I used 196 (excluding 51 nests with unknown fate, 17 nests outside of the intensive plots, 6 nests which were abandoned during egg laying) Lapland Longspur nests with 130 of those nests successfully fledging young, and 66 failed nests. Elevation was not a significant predictor of DSR for Lapland Longspur nests (parameter estimate: β=0.003 ±0.009, Table *3*). The top model for describing DSR was season date + quadratic season date, with an Akaike weight, w_i, of 0.60 (Figure 8). This suggests that time of the season was the most important predictor of daily survival.

Semipalmated Sandpiper

To assess the impact of elevation on nest locations of Semipalmated Sandpiper, I was able to use 80 Semipalmated Sandpiper nests (11 in 2018, 34 in 2019, and 35 in 2021) in the final model, after excluding 10 nests from the area around Whaletail Lake in 2018 due to low sampling effort, and 3 nests which were outside of the focal study areas. Of the 11 individual birds that returned from year to year, only 9 were included in this analysis; 2 were excluded because they were Whaletail Lake nests in 2018, where search effort was low (for the full list of repeat nesters and distances moved, see AppendixTable 7). Our binomial model relating nests vs. random sites to elevation showed that Semipalmated Sandpipers are significantly more likely to nest at lower elevations within the surveyed plots (GLMM: β=-3.00 ±0.89, z=0.89, P<0.001, Figure 9).

I used 77 Semipalmated Sandpiper nests to investigate the relationship between elevation and nest initiation date, after excluding 14 nests with no estimated initiation date and 2 nests outside of the focal study area. There was no significant relationship between nest initiation date and elevation (GLMM: β=-0.02 ±0.07, $t_{3.62}$=-0.32, P>0.05, Figure 10).

To assess the relationship between DSR and elevation, I included 71 Semipalmated Sandpiper nests, 60 of which hatched young, and 11 that failed to hatch. Elevation was included in the top model describing DSR (Akaike weight, w_i = 0.34; Table 4), with DSR increasing slightly at higher elevations. However, this model was only a modest improvement, 0.50 AIC_C units over the null model, and the parameter estimate for elevation overlapped zero (β=0.034 ±0.022, CI95% -0.01, 0.08).

Landcover

I conducted 328 landcover surveys of random points in 2019 (n = 170) and 2021 (n = 158) and included these in the zero-inflated beta regressions to test if elevation affected both the proportion of landcover (count portion) and the probability of each landcover type occurring (zero-inflated portion). Elevation had a significant effect on the proportion of sedge meadow (GLMM: β=-0.335 ±0.069, z=-4.84, P<0.001, Table 5) and rock (β=0.032 ±0,015, z=2.16, P<0.01, Table 5). Sedge meadow occurred at higher proportions at lower elevations within the plot groups while rocky landcover occurred at higher proportions at higher elevations (Table 5).

For the zero-inflated portion of the models there was a significantly higher probability of an absence of dry heath, exposed substrate, moss carpet, and rock at lower elevations (Table 5). The opposite was found for water, where it was more likely to be absent in the landcover surveys at higher elevations (Table 5).

I then used the two landcover types with proportions significantly related to elevation in a binomial model for each Semipalmated Sandpiper and Lapland Longspur to see if these landcover variables were related to selection of landcover for nest sites. Both nests of Semipalmated Sandpiper (GLMM: β=1.74 ±0.69, z=2.51, P<0.05) and Lapland Longspur (GLMM: β=1.51 ±0.62, z=-2.41, P<0.05) were more likely to occur in areas with higher proportions of sedge meadow than random landcover surveys. There were no significant relationships between the proportion of rock in the environment and the proportions of rock near the nests of either species.

Table 2. Summary of nest initiation dates of Lapland Longspur and Semipalmated Sandpiper nests found in 2018, 2019, and 2021. n = total nests with initiation dates estimated. Nests from around Whaletail Lake in 2018 often were not visited multiple times so many did not have estimated nest initiation dates.

Year	Earliest	Mean	Median	Latest	n	Total Nests
Lapland Longspur						
2018	12 June	16 June	17 June	28 June	39	77
2019	8 June	16 June	16 June	3 July[1]	99	102
2021	9 June	15 June	15 June	30 June	86	91
Semipalmated Sandpiper						
2018	15 June	17 June	18 June	20 June	13	24
2019	6 June	15 June	16 June	21 June	34	34
2021	4 June	14 June	14 June	26 June	32	35

[1] = a known renest of a failed nester; female was banded previously at another nest.

Table 3. Six candidate models used for Daily Survival Rate analysis for nests of the Lapland Longspur, including Akaike's information criteria for small samples (AIC_c), Akaike weight (w_i), number of parameters (K), and Deviance.

Model	AIC_c	ΔAIC_c	w_i	K	Deviance
Time + $Time^2$	501.98	0.00	0.60	3	495.97
Time + $Time^2$ + $Time^3$	503.92	1.95	0.23	4	495.91
Time	504.65	2.67	0.16	2	500.65
Null Model	511.02	9.05	0.01	1	509.02
Elevation	512.96	10.99	0.00	2	508.96
Year	514.91	12.94	0.00	3	508.90

Table 4. Six candidate models used for Daily Survival Rate analysis for nests of the Semipalmated Sandpiper, including Akaike's information criteria for small samples (AICc), Akaike weight (wi), number of parameters (K), and Deviance.

Model	AIC_c	ΔAIC_c	w_i	K	Deviance
Elevation	99.22	0.00	0.34	2	95.21
Null Model	99.72	0.50	0.26	1	97.71
Time	100.30	1.08	0.20	2	96.29
Time + I($Time^2$)	101.71	2.50	0.10	3	95.69
Time + $Time^2$ + $Time^3$	102.80	3.58	0.06	4	94.76
Year	103.10	3.89	0.05	3	97.08

Table 5. Summary of the zero-inflated beta-regressions for the effect of elevation on landcover of the random landcover plots. Significant effects of elevation are indicated by bolded text. Negative values for the zero-inflated portions of these models represent lower probability of absence of a landcover category at higher elevations (significant values are bolded).

Model	Conditional				Zero-inflated			
	Estimate	SE	z	P	Estimate	SE	z	P
Dry heath	0.027	0.017	1.591	0.112	**-0.107**	**0.026**	**-4.091**	**<0.001**
Exposed substrate	-0.003	0.020	-0.162	0.872	**-0.078**	**0.036**	**-2.170**	**<0.05**
Moss carpet	-0.003	0.016	-0.199	0.842	**-0.079**	**0.025**	**3.118**	**<0.01**
Rock	**0.032**	**0.015**	**2.168**	**<0.01**	**-0.043**	**0.009**	**-4.622**	**<0.001**
Sedge meadow	**-0.335**	**0.069**	**-4.844**	**<0.001**	0.006	0.008	0.685	0.494
Shrub	0.002	0.004	0.730	0.466	0.01	0.011	1.204	0.229
Water	-0.007	0.009	-0.749	0.454	**0.071**	**0.033**	**2.176**	**<0.05**

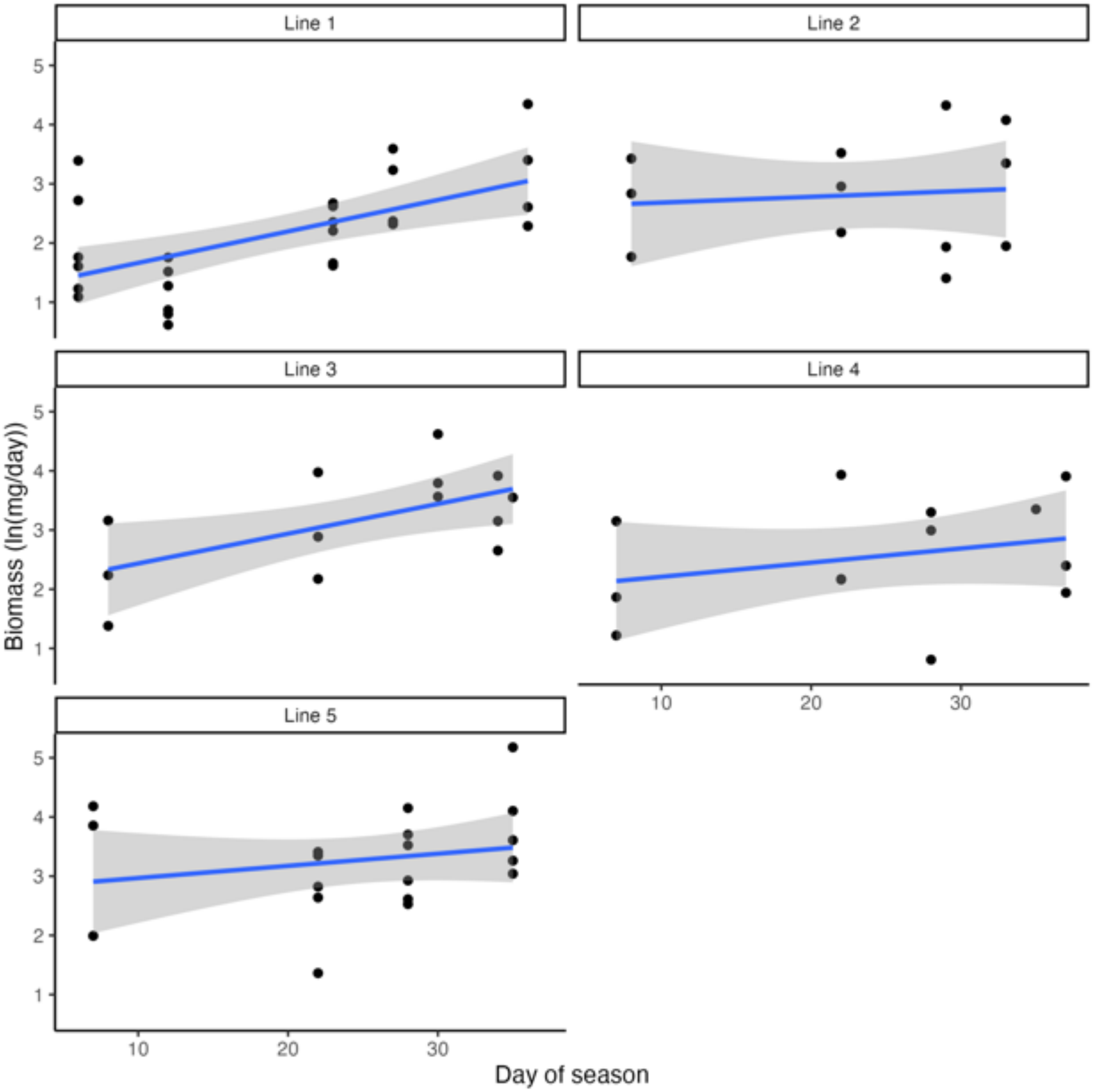

Figure 4. Total trap biomass in 2021 during the nesting season, with day of season starting on the first day a Lapland Longspur nest was found (9 June 2021). There is a significant increase in biomass per day as the season progresses for all pitfall trap lines (slope: 0.04 ±0.009, t=4.39, $P<0.001$, Adjusted $R^2=0.18$).

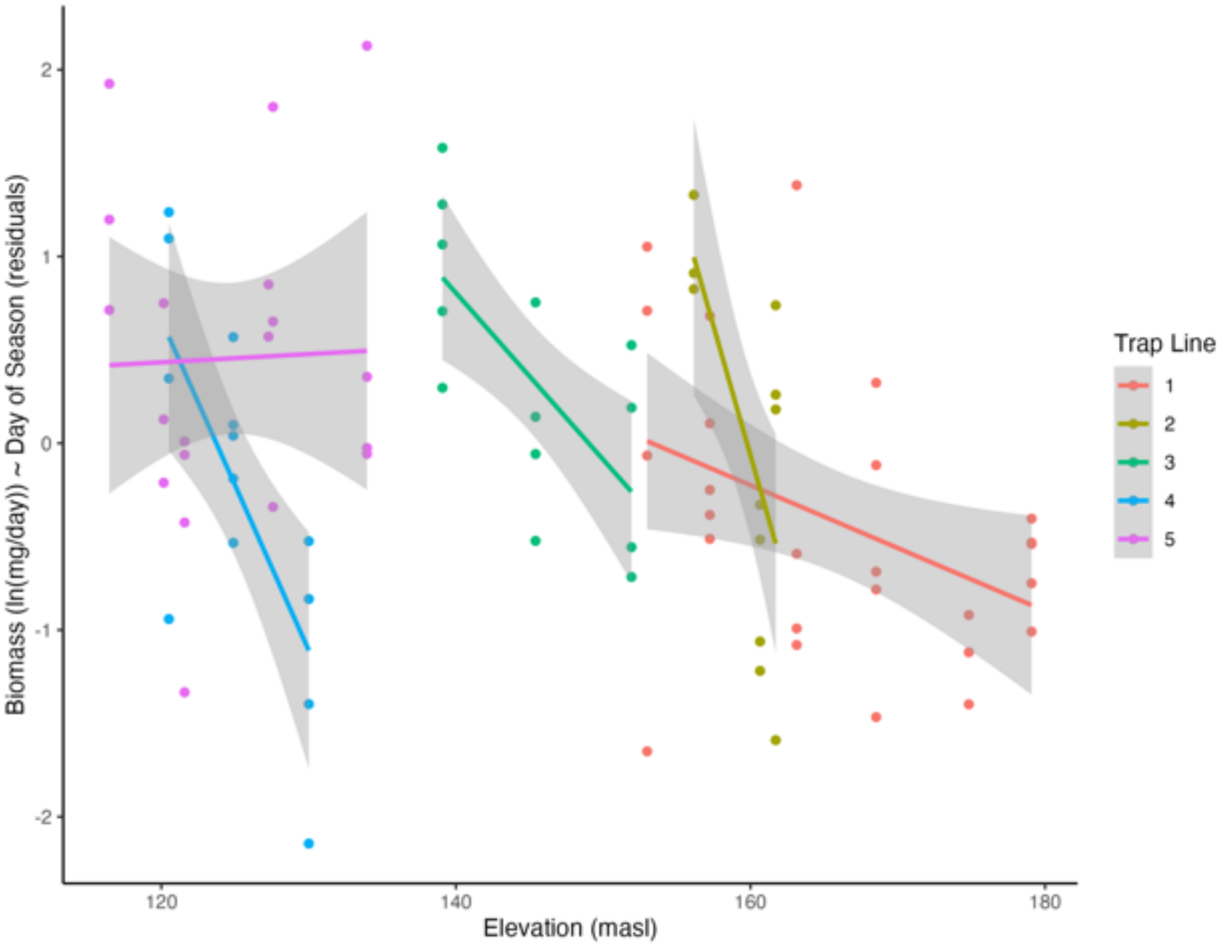

Figure 5. Plots of biomass against elevation at five trap lines north of Baker Lake, Nunavut Canada (65°24'N, 96°41'W), 2021. The residuals of the GLM of biomass (mg/day) vs day of season account for the significant effect of date on biomass. There is significantly higher biomass at lower elevations than higher elevations within the plot groups (GLMM, gaussian: β= -0.52 ±0.18, t=-2.80, P<0.05). In general, biomass decreases with increasing elevation in all traplines except for trapline 5, where there is a slight decline in biomass with an increase in elevation.

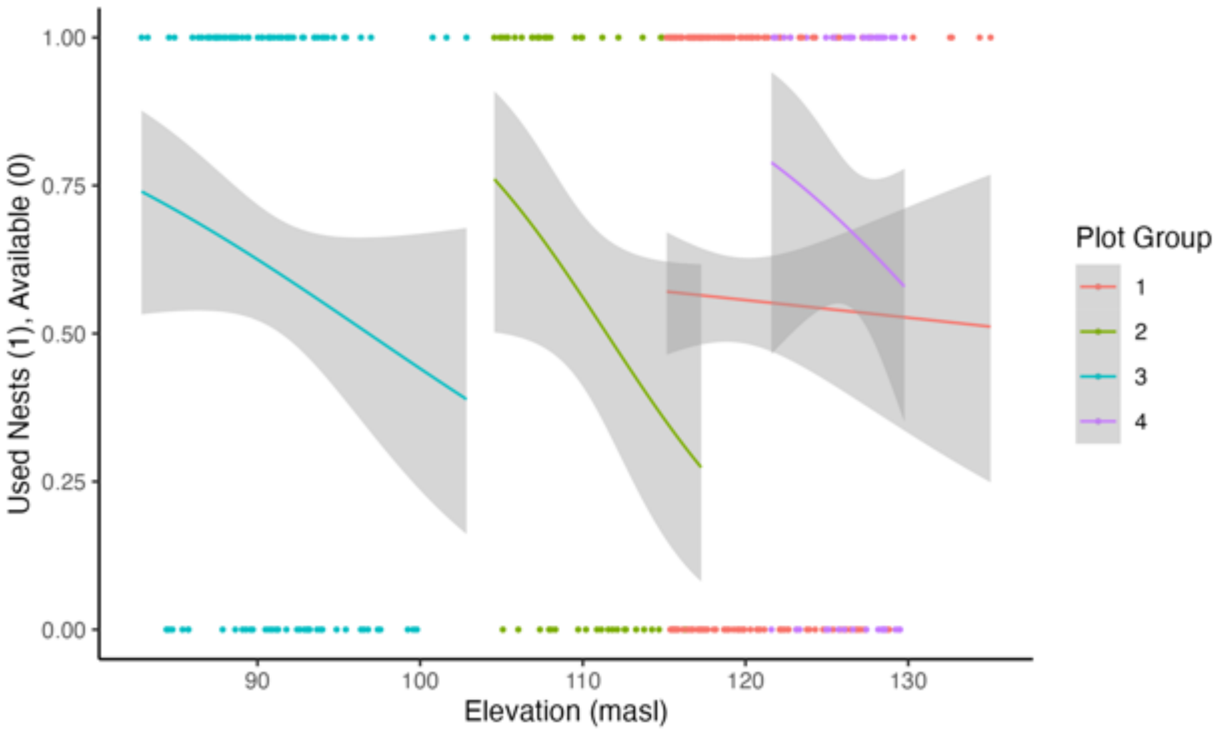

Figure 6. The relationship between elevation at Lapland Longspur nests (used) vs random points (available) (GLMM, binomial: β-0.71 ±0.39, z=-1.85, P=0.06). While not significant, there is a general pattern of Lapland Longspur nesting at lower elevations within the plot areas.

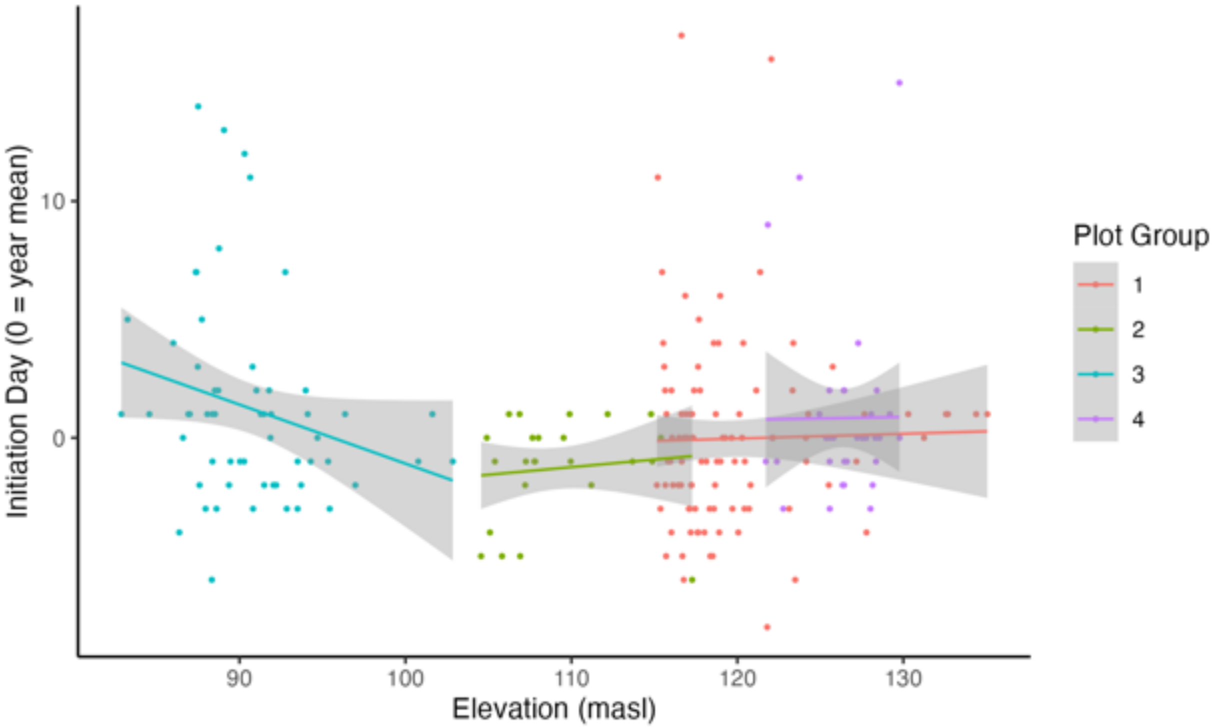

Figure 7. Elevation of Lapland Longspur nests vs standardized initiation day (0 = average nest initiation date within year). There was no significant relationship between nest initiation and elevation of nest (GLMM: β=-0.01 ±0.01, t=-0.78, P>0.1).

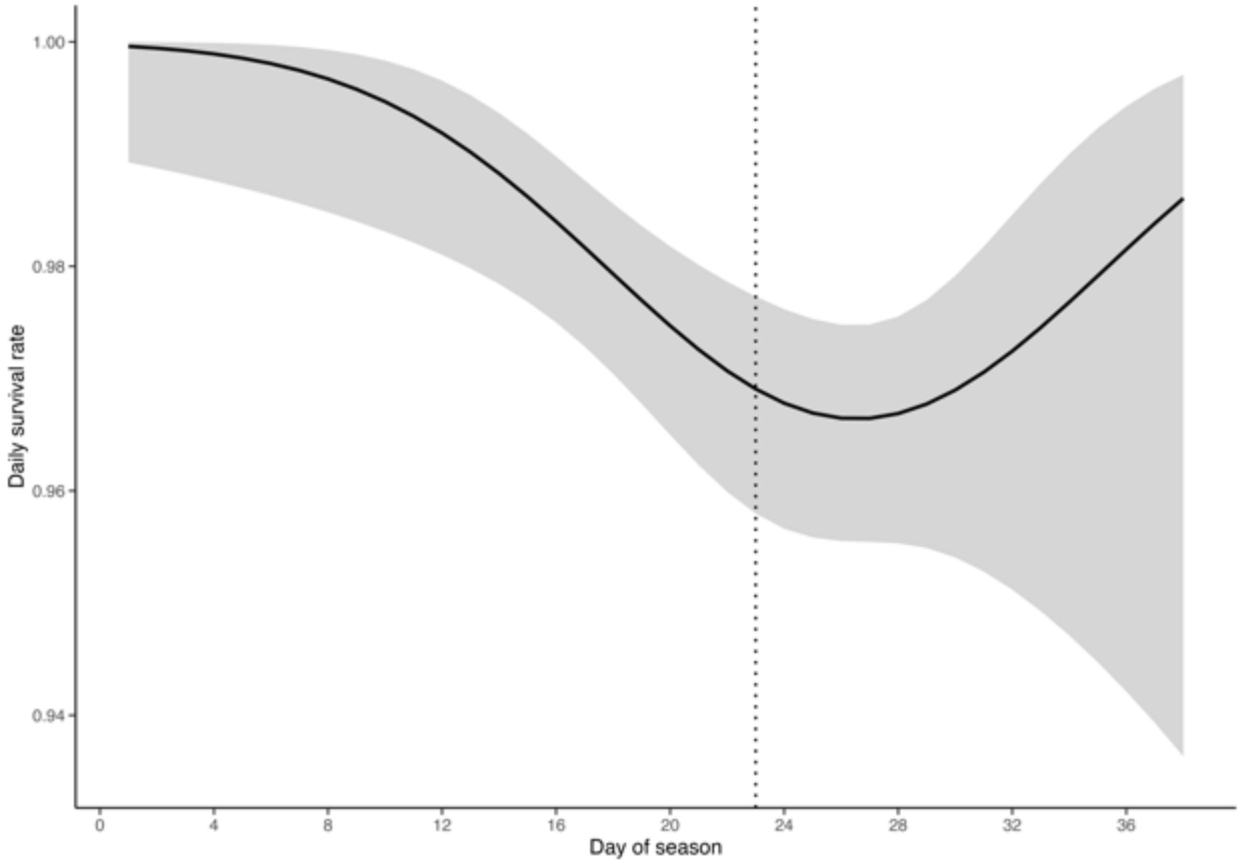

Figure 8. The top model (quadratic time) for predicting daily survival rate of Lapland Longspur nests throughout the field season. The dotted line represents the average hatch date of Lapland Longspur nests.

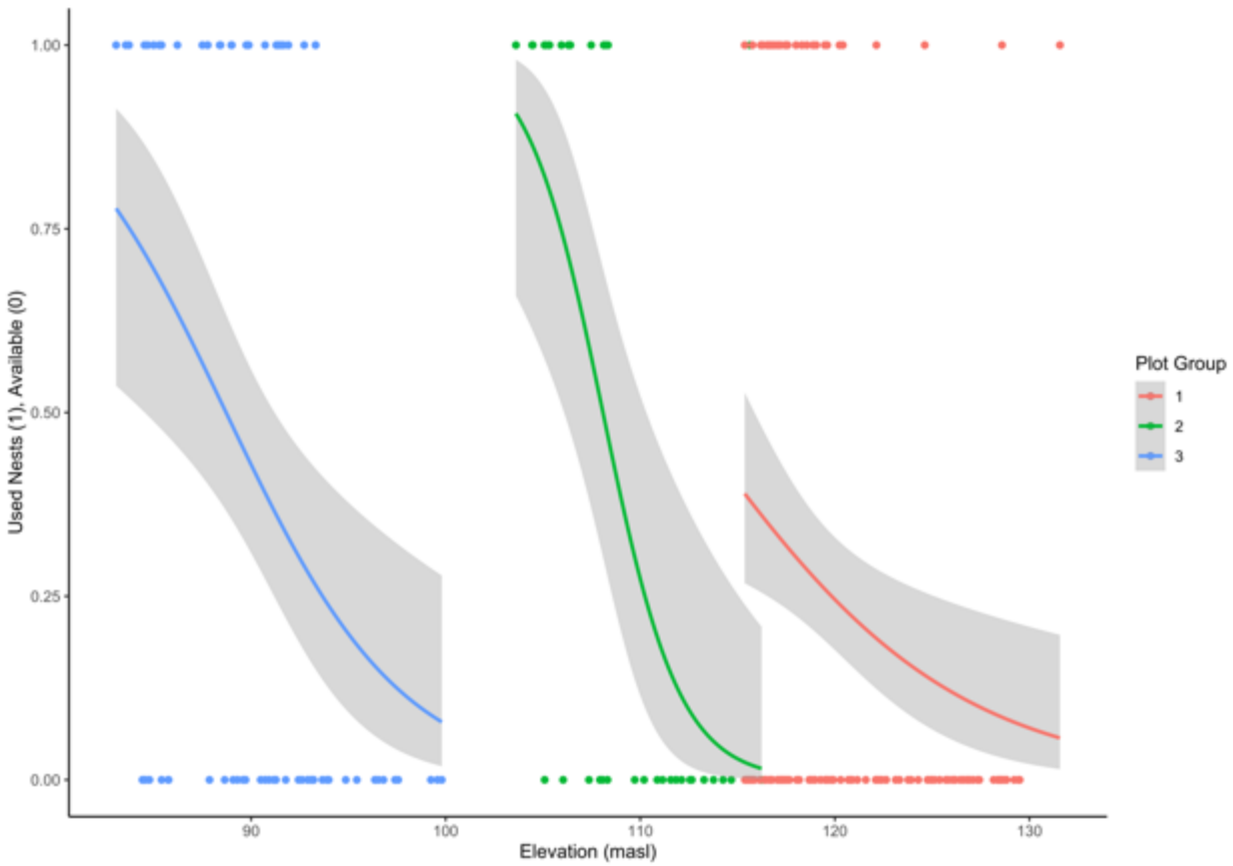

Figure 9. The relationship between elevation and Semipalmated Sandpiper nests (used) vs random points (available) within 3 areas in north of Baker Lake, Nunavut Canada (65°24’N, 96°41’W). Semipalmated Sandpiper are significantly more likely to nest at lower elevations within the plot areas. (GLMM, binomial: β=-3.00 ±0.89, z=0.89, P<0.001).

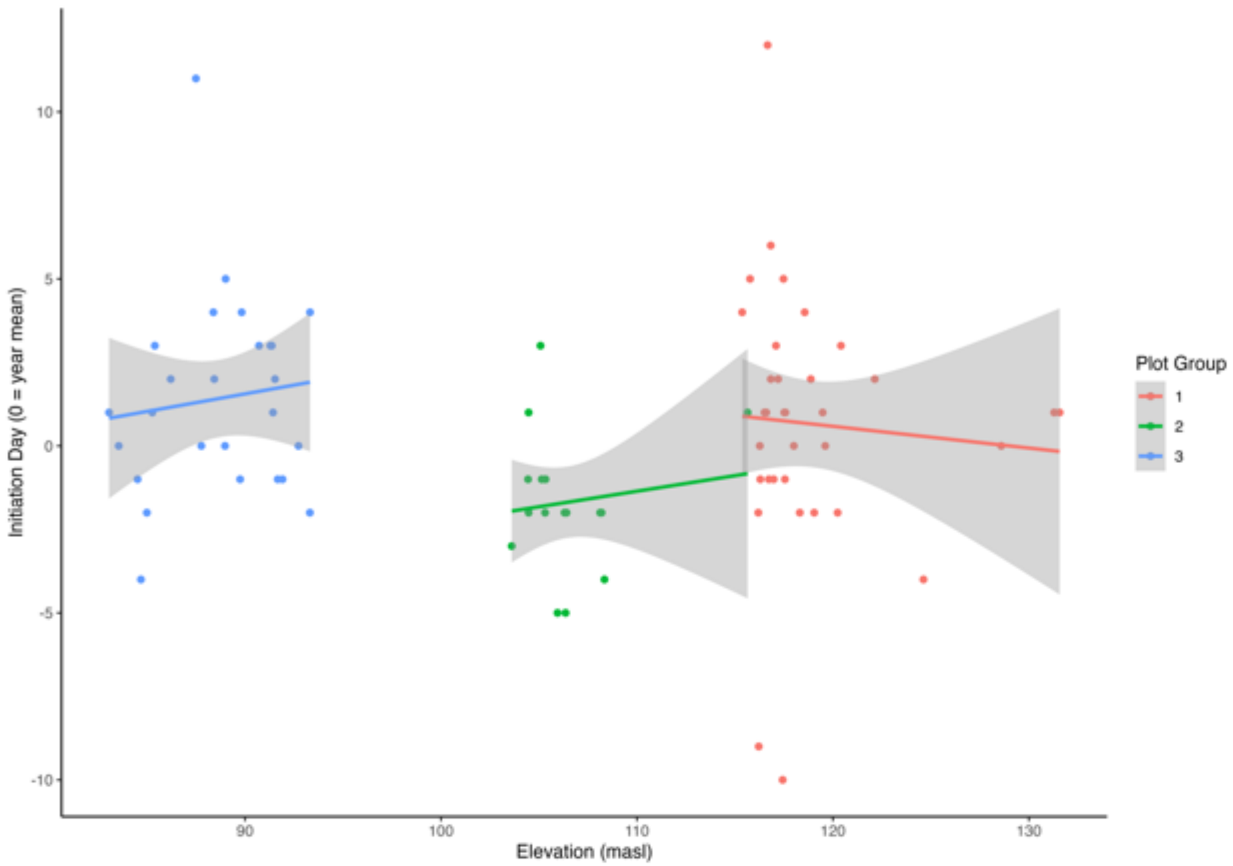

Figure 10. Elevation of Semipalmated Sandpiper nests vs standardized day (0 = average nest initiation date within year). There was no significant relationship between nest initiation and elevation of nest (GLMM: β-0.02 ±0.07, -0.32, P>0.1)

Discussion

In my Low Arctic study site, I found that elevation had a significant effect on food availability, with higher arthropod biomass at lower elevations. There was also a highly significant effect of date on arthropod biomass, with higher biomass later in the season. Both bird species (Lapland Longspur and Semipalmated Sandpiper) were more likely to nest at lower elevations in the rolling hills of the inland low arctic, with this result significant for Semipalmated Sandpiper but not for Lapland Longspur. For neither species was there a significant relationship between elevation and the date of nest initiation, and only a weak relationship was found between Semipalmated Sandpiper daily nest survival and elevation with higher DSR occurring at higher elevations. Nests of both focal species were more likely to be sedge meadow habitat, which was also more abundant at lower elevations.

Previous studies have shown that lower areas with wetlands have higher abundances of the invertebrate species preferred as prey by shorebird chicks, compared to upland areas (Cunningham et al., 2016; Holmes & Pitelka, 1968; Smith et al., 2007; Tulp & Schekkerman, 2008). Similarly, my results showed higher biomass of arthropods at lower elevations, and birds may be selecting these lower elevation nest sites to access these preferred prey items more easily. While I did not look at the relationship between elevation and abundance of specific arthropod families, it could be a logical extension of this research.

My arthropod samples included several families of insects that have been noted in the literature as important prey for Lapland Longspur and Semipalmated Sandpiper chicks and adults on the breeding grounds, including the Dipteran Families Chironomidae and Tipulidae.

Chironomids, which I detected in high frequencies, are an important food source for both Semipalmated Sandpiper and Lapland Longspur early in the season (Custer & Pitelka, 1978; Holmes & Pitelka, 1968). Tipulidae are often thought to be one of the most important food items in Arctic breeding shorebird diets, comprising of up to 50% of Semipalmated Sandpipers diet and more in other species (Flemming et al., 2022). Tipulidae were also detected as over 50% of the diet composition by weight in Lapland Longspurs from late June to early July at a site in Barrow, Alaska (Custer & Pitelka, 1978). However, in previous studies Semipalmated Sandpiper were more reliant on Chironomid larvae and adult Diptera (small, unidentified) during their breeding season than Tipulidae (Holmes & Pitelka, 1968). While I did not detect a high frequency or biomass of Tipulidae, this could be due to trapping design, or a general lack of tipulids in the area, suggesting that birds in these regions can shift their dietary preferences to align with the arthropods that are most abundant. I did not look at individual diet of the birds at my study site to compare to the invertebrates present in the area, but future studies could collect fecal samples from adults or nestlings to look for presence/absence of invertebrate families using DNA metabarcoding to compare actual diet to available food in a minimally invasive method (McClenaghan et al. 2019).

Food demand of Lapland Longspur nestlings peaks between 8-12 days old (around the time nestlings leave the nest), which roughly coincided with Semipalmated Sandpiper hatch dates. Lapland Longspur nests with 5 chicks were found to receive approximately 6000 food items per day (3000 from each parent, or 293 kJ/adult/day) between day 8-12 to meet energetic demands (Custer et al., 1986). At these 5-chick nests, the adult males collected 5-6 prey items/minute for chicks, in addition to the necessary 5-6 prey items/minute to sustain themselves (Custer et al., 1986). This need for frequent access to high quality foraging habitat could explain why nests were preferentially placed at lower elevation sites in my study, where arthropod biomass was significantly higher.

Although Semipalmated Sandpipers don't feed their precocial chicks, the same relationship could be true for them, as food availability has a significant effect on growth rates of chicks in another shorebird species. Eurasian Golden-Plover (*Pluvialis apricaria*) nesting in Sweden in areas with higher arthropod biomass had chicks that experienced faster growth rates (Machín et al., 2018). However, Smith et al. (2007) found that habitats with the greatest food abundance were not preferred for nesting by other shorebirds on Southhampton Island, Nunavut, and other studies have shown that shorebirds can move their broods significant distances to access preferred foraging habitat (Parmelee et al., 1968). Proximity of nests to high quality foraging habitats is only one important factor affecting nest site selection, in addition to predator avoidance, microclimate, and competition (Cunningham et al., 2016).

The timing of nest initiation for Semipalmated Sandpiper and Lapland Longspur in Alaska is closely related to snowmelt timing (Liebezeit et al., 2014). Other studies have also found shorebird nest initiation was closely related to the date of 50% snow cover at breeding sites (Smith et al., 2010). I used elevation as a proxy for snowmelt, with the assumption that lower areas would retain snow longer than upland sites (Schaefer & Messier, 1995; Russell, 2024) but found no significant effect of elevation on nest initiation. Snowmelt timing was variable across the three years (50% cover = 2018: 10 June, 2019: 3 June, and 2021: earlier than 9 June when crew arrived) and followed a general pattern of clearing from the tops of hills before the lower elevation areas (Figure 2a, personal observation). However average nest initiation for both species in my study was highly invariant, and always well after the date of complete snowmelt. I was not able to visit each plot daily for snow cover measurements, so I was unable to obtain useful snow coverage estimates frequently enough for analysis to investigate the loss of snow over time. In future work to investigate the pattern of snowmelt across the study area, researchers could use remote sensing, timelapse cameras, or manual measurements. It could also be that I failed to see an effect of elevation on nest initiation timing because other factors affecting nest timing may have a larger influence at my site such as predator abundance (Smith et al., 2010) or food abundance (Nol & Flynn, 1997) or a time delay upon arrival at the breeding sites. An income breeding strategy suggests birds arriving back to their breeding grounds need time to gain nutrients necessary for egg-laying (Klaassen et al., 2001; Ruthrauff et al., 2021). This time delay may have allowed snow melt to advance enough for lower areas to be available.

I did notice modest advancement of average nest initiation date for Semipalmated Sandpiper across my study years, with average initiation dates that were slightly earlier each year: 2018 (n=11, 17 June), 2019 (n=34, 15 June), and 2021 (n=32, 14 June). Advancement of clutch initiation dates in Semipalmated Sandpiper were also observed in Alaska at a rate of 0.4-0.8 days/year (Liebezeit et al., 2014). Earlier nest initiation could have been due to earlier snowmelt or increasing temperatures in the early nesting season, but was not analyzed at my study site.

Elevation was not a good predictor of nest success for either focal species, although elevation did occur in the top model for Semipalmated Sandpiper, but confidence intervals slightly overlapped zero. This lack of, or weak influence of, elevation on nest success could be due to inability to detect differences caused by high rates of nest success at my sites (apparent survival LALO: 62%, SESA: 83%), with few failed nests incorporated into the models. However, the lack of effect of elevation on nest success could also simply be a result of short elevational gradients in my study area.

Nest success can change throughout the season, and Liebezeit et al. (2011) also had day of season included as one of the terms in their top model, similar to my quadratic effect of date. However, their top model showed that longspur survival increased as the season progressed, and nest age and nest stage (incubation vs nestling) did not have an effect (Liebezeit et al., 2011). They also found higher survival later in the season for biparental shorebird (including Semipalmated Sandpiper) nests, and higher survival with increasing vegetative nest concealment (Liebezeit et al., 2011). I did not test for the effect of nest concealment on nest success but possibly that analysis would also be hampered by the low number of unsuccessful nests. Liebezeit et al. (2011) had a nest success of 57.4% for all species, 31.3% failed nests, and 11.3% with unknown fates. My overall nest success rates for Lapland Longspur were comparable: 50% successful, 31% failed, and for Semipalmated Sandpiper 69% were successful and 16% failed. Liebezeit et al. (2011) did not report the nest success for the nests in the DSR models or for individual species, but for my study species Lapland Longspur in the models had apparent nest success rates of 65.9% (130 nests of 197 nests total in DSR models), and for Semipalmated Sandpiper an apparent nest success rate of 84.5% (60 nests of 71 nests total in the DSR models) which is high compared to that reported from other studies, such as Coat’s Island, Nunavut where nest success rates ranged from 3-36% from 2014-2016 (S. A. Flemming, personal communication, 2024).

Semipalmated Sandpiper in Barrow, Alaska were shown to select nesting sites that were drier than surrounding tundra, had higher degree of microrelief, and were a greater distance from conspecifics than random sites (Cunningham et al., 2016). Both Semipalmated Sandpiper and Lapland Longspur had higher nest densities in wet habitats in Teshekpuk Lake and Prudhoe Bay, Alaska (Liebezeit et al., 2011). In my study, both species were more likely to nest at lower elevations in an area where there was more likely to be higher proportions of sedge meadow and the presence of water (higher elevations had a higher likelihood of no water). Another study in Norway found that Lapland Longspur territories were not heavily influenced by herbaceous plant cover despite having some preferences of early season seed foods (*Potentilla* sp., *Luzula* sp. and *Carex* sp.), suggesting that they may regularly leave their territories to forage (Fjeldheim, 2017). The establishment of Lapland Longspur territories seemed to depend highly on elevation and presence of shrubs in Hardangervidda, Norway, selecting areas with large patches of open tundra and some dwarf shrub (Fjeldheim, 2017). However, that same study found the dry biomass of arthropods was up to 40% of stomach content of Lapland Longspurs, and they speculated that arthropod abundances within territories may be more important than plant communities, suggesting that territories with greater variety of plant communities can support a higher arthropod abundance. This author did not directly test arthropod abundances in territories (Fjeldheim, 2017). Thus, their results could be consistent with my results, where Lapland Longspur nests were more often at lower elevations in an area, which was also where there was greater arthropod biomass.

Both of my study species are declining at the southern edge of their breeding range, and both species used to be found breeding regularly in the Churchill, Manitoba region (Jehl, 2004).

Currently neither species has been found breeding in Churchill for years – the last known Semipalmated Sandpiper nest was found in 2001 (Jehl, 2007), and the last known Lapland Longspur nest was found in 2003 (Jehl, 2004). In addition to these declines on the southern edge of the breeding range, Semipalmated Sandpipers were observed to be increasing in presence in the mid-arctic, suggesting a shift north in the core breeding areas (Anderson et al., 2023). Both species are predicted to lose climatically suitable breeding habitat by 2070: Lapland Longspur is predicted to experience a loss of between 50-70% under a climate warming scenario of 3°C (Boelman et al., 2015) and Semipalmated Sandpiper is predicted to experience a loss of between 6-52% (Wauchope et al., 2017). While my study takes place about 750km north of Churchill Manitoba in an area where these two bird species both remain abundant, these studies suggest that even if these species continue to shift their ranges northwards, the shift may not be enough to keep pace with climate change and declines could be severe for both species.

My findings suggest that arthropod biomass and Semipalmated Sandpiper and Lapland Longspur nest placement are most heavily affected by elevation, but nest initiation and nest success are not. This suggests that birds in my study site in the central Arctic are not taking advantage of earlier snowmelt occurring at the higher elevation sites for nesting, and instead they appear to be selecting nest sites that have higher food abundance, which happen to be at lower elevation. With most snow gone at our sites before birds nested, the birds appeared to be able to take advantage of those site conditions most suitable for arthropod prey. My results might have been different in a year where the snow persists well into the average breeding season, or if the study was carried out at more northerly locations, where snow melt is later.

The impact of snow on the distribution and timing of nests could also change, as climate change alters the amount of snow (Russell, 2024), and the amount of precipitation that falls as rain in winter (Bintanja & Andry, 2017).

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Appendix

Table 6. Arthropod body length to dry biomass equations used to calculate dry biomass (mg) where L = length (mm) and N = number of individuals. Where "N" is not included in the equation, the final output was multiplied by the number of individuals in a trap.

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
Arachnida	Acarina	13	$e^{(0.011+\ln(L)*3.444)}$	0.920	Kassouf et al. in prep.
	Araneae	15	$e^{(0.028+\ln(L)*2.761)}$	0.931	Kassouf et al. in prep.
	Araneidae	90	$e^{(-1.726+\ln(L)*2.746)}$	0.952	Edwards & Gabriel 1998
	Linyphiidae	12	$0.0432e^{0.6846L}$	0.90	This study
	Lycosidae	12	$20.28\ln(L)-33.491$	0.56	This study
	Theridiidae	73	$e^{(-1.746+\ln(L)*2.695)}$	0.958	Edwards & Gabriel 1998
	Thomsidae	52	$e^{(-1.456+\ln(L)*2.839)}$	0.959	Edwards & Gabriel 1998
Coleoptera	Carabidae	36	$2.9037L-10.117$	0.85	This study
	Carabidae LARVA	10	$0.0338*L^{2.162}$	0.898	Hódar 1996

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
	Coccinellidae	12	$0.343*L^{1.5}$	0.91	Sabo 2002
	Coleoptera	104	$e^{(0.045+\ln(L)*2.143)}$	0.663	Kassouf et al. in prep.
	Curculionidae	14	$e^{(0.092+\ln(L)*2.061)}$	0.851	Kassouf et al. in prep.
	Dytiscidae	6	$e^{(0.042+\ln(L)*1.715)}$	0.886	Kassouf et al. in prep.
	Elateridae	12	$e^{(5.248+\ln(L)*-0.45)}$	0.075	Kassouf et al. in prep.
	Latriidae		$0.0664*L^{2.192}$		Morley 2020
	Staphylinidae	13	$e^{(0.006+\ln(L)*2.688)}$	0.983	Kassouf et al. in prep.
	Coleoptera Unidentified adult	16	$0.0664*L^{2.192}$	0.881	Hódar 1996
Collembola[1]	Hypogastruridae		$(2.810L)^3$		Cabellero et al. 2002
	Onychiuridae		$(2.220L)^3$		
	Isotomidae		$(3.060L)^3$		
	Entomobryidae		$(2.460)^3$		
	Sminthuridae		$(3.800)^3$		

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
Diptera	Agromyzidae		$e^{(-3.374)*(L^{2.158})}$		McKinnon 2012, Picotin 2008
	Anthomyiidae	165	$0.0217L^{2.0455}$	0.71	This study
	Calliphoridae	34	$15.525\ln(L)-26.491$	0.28	This study
	Cecidomyiidae	15	$0.0277e^{0.2738L}$	0.23	This study
	Ceratopogonidae	17	$e^{(0.111+\ln(L)*0.191)}$	0.016	Kassouf et al. in prep.
	Chironomidae	6	$0.0277e^{0.2718L}$	0.75	This study
	Culicidae		$0.67*N$		McKinnon 2012, Picotin 2008
	Dolichopodidae	66	$0.1517L-0.2947$	0.75	This study
	Empididae		$0.23*N$		McKinnon 2012, Picotin 2008
	Ephydridae	22	$0.0098e^{0.8192L}$	0.96	This study
	Fannidae	40	$3.9438\ln(L)-4.8388$	0.61	This study
	Muscidae	19	$0.6329L-1.4857$	0.61	This study

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
	Mycetophilidae	12	$0.0169e^{0.3579L}$	0.48	This study
	Phoridae	72	$0.0087e^{1.7561L}$	0.63	This study
	Piophilidae		0.34*N		McKinnon 2012, Picotin 2008
	Psychodidae	14	$e^{(0.022+\ln(L)*2.145)}$	0.973	Kassouf et al. in prep.
	Scathophagidae	56	$0.0137B^{2.53}$	0.74	This study
	Sciaridae	34	$0.0026\ln(L)+0.0018$	0.29	This study
	Sciomyzidae	8	$0.8007\ln(L)-0.7209$	0.18	This study
	Sphaeroceridae		$e^{-3.374}*L^{2.158}$		McKinnon 2012, Picotin 2008
	Tachinidae	18	$0.2278e^{0.2335L}$	0.18	This study
	Tipulidae		$e^{-5.3+2.36(LN(L))}$	0.93	Smock 1980
	Diptera	36	$0.0312*L^{2.392}$	0.872	Hódar 1996
	Diptera larva		$0.0025*L^{2.692}$		Morley 2020, Benke et al 1999

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
	Brachycera	26	$0.0304*L^{2.63}$	0.954	Hódar 1996
	Nematocera	10	$0.021*L^{2.081}$	0.969	Hódar 1996
Hemiptera	Aphididae		$0.0598*L^{1.724}$		McKinnon 2012, Hódar 1996
	Cicadellidae	11	$e^{(-0.112+\ln(L)*0.425)}$	0.071	Kassouf et al. in prep.
	Psyilldae	26	$0.0123*L^{2.995}$	0.752	Morley 2020, Gruner 2003
	Adults averaged		$0.09975*L^{2.49475}$		Morley 2020, Sabo et al. 2002
Heteroptera		21	$0.0341*L^{2.688}$	0.855	Hódar 1996
Hymenoptera	Apidae	13	$e^{(0.961+\ln(L)*0.82)}$	0.875	Kassouf et al. in prep.
	Braconidae	6	$0.0026e^{1.215L}$	0.98	This study
	Eulophidae	10	$-0.066+L*0.08$	0.367	Kassouf et al. in prep.
	Ichneumonidae	10	$0.0058L^{2.8933}$	0.99	This study

Order	Taxonomic Group	N	Dry Mass (mg) Equation	R^2	Reference
	Tenthredinidae	9	$0.1008e^{0.3737L}$	0.51	This study
	Hymenoptera	53	$e^{(0.014+\ln(L)*2.487)}$	0.919	Kassouf et al. in prep.
	Hymenoptera	24	$0.1636*L^{1.9}$	0.874	Hódar 1996
Lepidoptera	LARVA	16	$0.011*L^{2.571}$	0.936	Hódar 1996
	Lepidoptera	14	$e^{(-3.491+\ln(L)*2.46)}$	0.693	Kassouf et al. in prep.
Nematomorpha	Nematomorpha		$0.0009*L^{0.4}$		Morley 2020, Huhta 1975
Plecoptera	Plecoptera		$0.26*L^{1.69}$		Morley 2020, Sabo et al. 2002
Thysanoptera	Thysanoptera	6	$0.0071*L^{2.537}$	0.911	Hódar 1996,
Trichoptera	Trichoptera		$0.01*L^{2.9}$		Morley 2020

1 = I was unable to find a reliable equation for Collembola as a whole, so I used a literature search to ensure that these Families occurred in the Arctic, and then calculated the biomass for all 5 equations and averaged them.

Table 7. Banded birds (Lapland Longspur and Semipalmated Sandpiper) that were resighted between years or had more than one nest recorded for them. Nest names and coordinates (°N & W) included for the year, as well as change in elevation (masl) from earlier to later nests, with "+" to mark nests that moved uphill, and "-" to mark nests that moved down. Distance that the nest moved, from the waypoints taken (error of handheld GPS ±3m). Bolded nests are nests that moved due to flooding of Whaletail Lake, where the first nest was found below the high-water level. Italicized nests are failed nests. "Na" indicates years before the bird was banded, "ns" for years when the bird was not resighted but after the bird was banded, and "nf" for birds that were resighted but the nest was not seen.

Band combination	2018	2019	2021	Elevation (masl)	Distance (m)
Lapland Longspur					
mauve/black	na	*LLGH04*[1] 65.38973, -96.69901	LLTG14 65.38950, -96.70693	+6.77	368
red	**LL087N**[2] 65.385640, -96.68601	ns	LLSB20 65.38408, -96.68258	+11.28	235
red/mauve	na	***LLGH24***[3] 65.39019, -96.69553	LLSB17 65.39071, -96.69400	+0.8	91.67

Band combination	2018	2019	2021	Elevation (masl)	Distance (m)
white	**LL237J**[2] 65.38784, -96.68747	ns	*LLNB03*[4] 65.38769, -96.68437	+4.76	145
white/mauve	na	LLSR04 65.39100, -96.69522	LLSB24 65.39035, -96.69714	-0.98	114
white/red	na	***LLGH20***[5] 65.37622, -96.61230	ns		
		LLGH30[6] 65.37876, -96.71851		+5.63	126
orange/dark blue[7]	LLNP13 65.30028, -96.42231	LLEN01 65.29996, -96.42263	ns	1.82	44
Semipalmated Sandpiper					
CAC	na	SSAW01 65.39121, -96.67649	SSSB02 65.39143, -96.67628	0	25

Band combination	2018	2019	2021	Elevation (masl)	Distance (m)
CAH	na	SSSB01 65.38960, -96.70059	nf	na	Na
CAP	SS238S[2] 65.38006, -96.72178	SSSR06 65.38005, -96.72174	nf	-0.08	1
CAT	na	SSSR05 65.39111, -96.69962	SSSB15[6] 65.39108, -96.69958	-1.07	3
CEK	na	SSGH02[6] 65.38987, -96.67841	SSSB13 65.39404, -96.67533	-1.96	485
CHC	na	SSSR02 65.29365, -96.38690	SSSR02 65.29366, -96.38677	+0.05	6
CKE	SSSB03 65.29339, -96.39085	SSSR03 65.29339, -96.39077	*SSSR01*[1] 65.29266, -96.39506	18-19: 0.14 19-21: -4.67 18-21: -4.52	3 215 212
CKH	SSNP01 65.31751,	SSSR09 65.31749,		-0.35	16

Band combination	2018	2019	2021	Elevation (masl)	Distance (m)
	-96.45935	-96.45969			
CKX	na	SSJH01 65.38760, -96.68048	SSNB01 65,39043, -96.67725	+1.83	348
CME	SS342[2] 65.38981, -96.70488	nf	SSSB07 65.38965, -96.70400	-0.90	44
CMM	SSSB01 65.29603, -96.38993	ns	SSTG03 65.29706, -96.39150	-0.49	135
CMP	na	SSEN04 65.30007, -96.39652	SSSB11[6] 65.29995, -96.39589	+0.13	32
CMY	na	SSSB01 65.38960, -96.70059	nf	na	na

1 = Nest failed due to predation

2 = Nest fate unknown, not monitored

3 = Nest failed due to abandonment

4 = Nest failed due to dud eggs (adult observed incubating but eggs never hatched)

5 = individual that was found to renest within the same year after the first nest attempt failed due to flooding.

6 = Nest fate unknown, still active when crew left or distance between checks to long to confirm

7 = the only LALO male that was resighted between year; all other LALO were females.

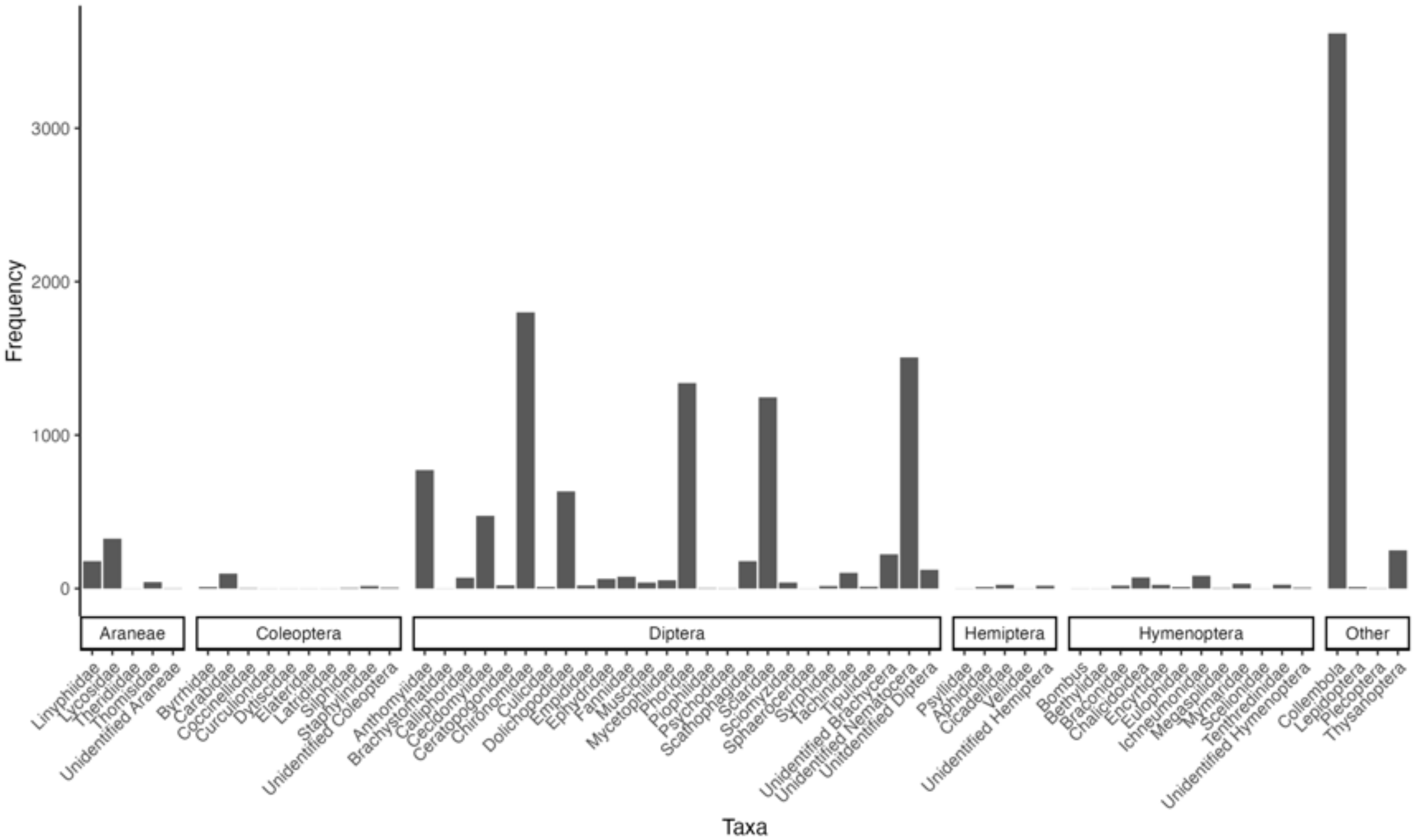

Figure 11. Total number of individual arthropods collected from pitfall traps and included in biomass models. Arthropods captured, but not included in the model are not included in this chart because they are not common shorebird and Lapland Longspur diet items.

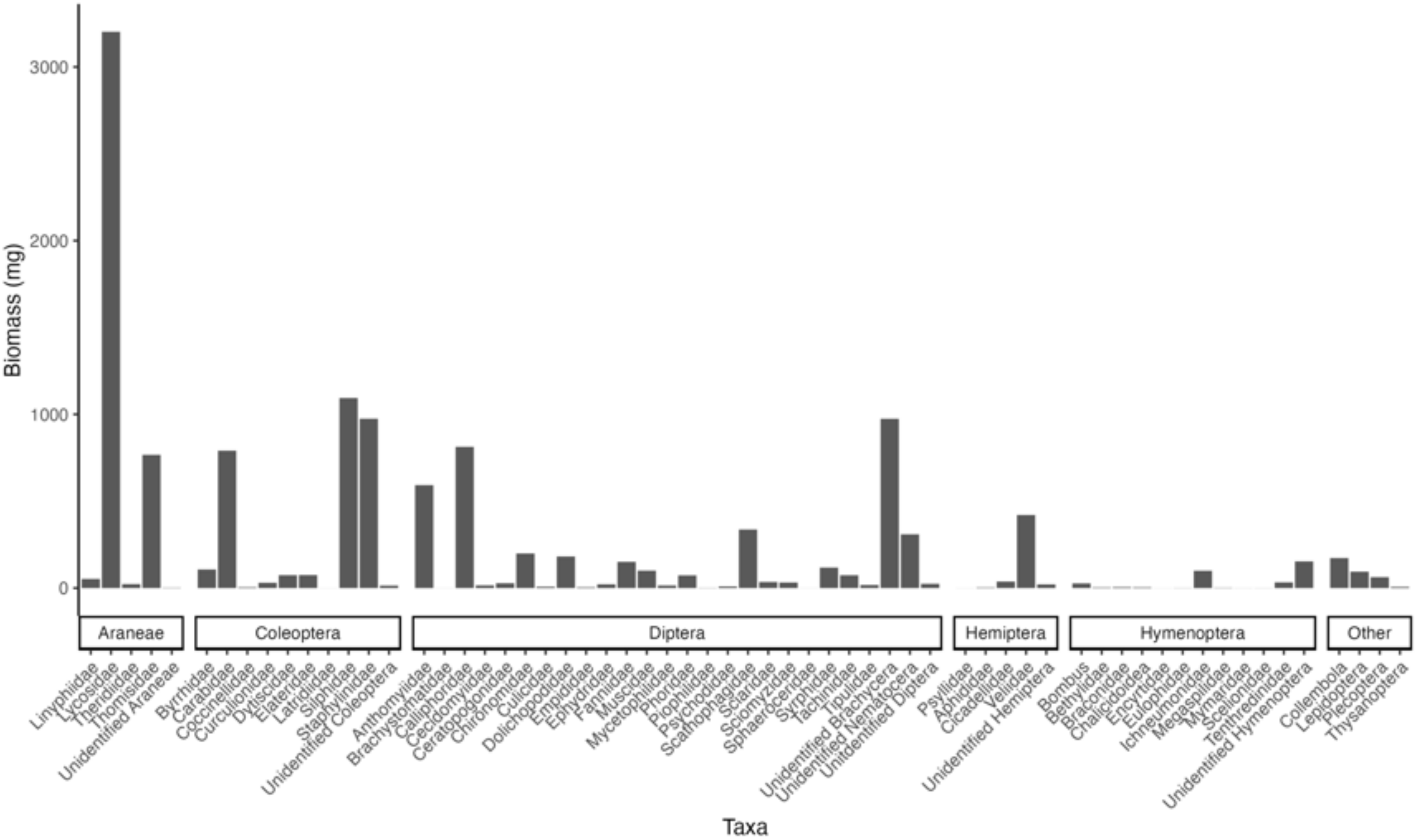

Figure 12. Total dry biomass of arthropods collected and included in biomass models from pitfall traps in 2021, biomass calculated using body length to body mass equations (See Appendix Table 6)