ARTICLE

Emerging Technologies

Snowmelt progression drives habitat selection and vegetation disturbance by an Arctic avian herbivore

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Abstract

Arctic tundra vegetation is affected by rapid climatic change and fluctuating herbivore population sizes. Broad-billed geese, after their arrival in spring, feed intensively on belowground rhizomes, thereby disturbing soil, mosses, and vascular plant vegetation. Understanding of how springtime snowmelt patterns drive goose behavior is thus key to better predict the state of Arctic tundra ecosystems. Here, we analyzed how snowmelt progression affected springtime habitat selection and vegetation disturbance by pink-footed geese (*Anser brachyrhynchus*) in Svalbard during 2019. Our analysis, based on GPS telemetry data and field observations of geese, plot-based assessments of signs of vegetation disturbance, and drone and satellite images, covered two spatial scales (fine scale: extent 0.3 km^2, resolution 5 cm; valley scale: extent 30 km^2, resolution 10 m). We show that pink-footed goose habitat selection and signs of vegetation disturbance were correlated during the spring pre-breeding period; disturbances were most prevalent in the moss tundra vegetation class and areas free from snow early in the season. The results were consistent across the spatial scales and methods (GPS telemetry and field observations). We estimated that 23.4% of moss tundra and 11.2% of dwarf-shrub heath vegetation in the valley showed signs of disturbance by pink-footed geese during the study period. This study demonstrates that aerial imagery and telemetry can provide data to detect disturbance hotspots caused by pink-footed geese. Our study provides empirical evidence to general notions about implications of climate change and snow season changes that include increased variability in precipitation.

KEYWORDS
Anser brachyrhynchus, drone, grubbing, habitat selection, moss tundra, pink-footed goose, satellite, Sentinel 2, snowmelt, UAV

INTRODUCTION

The Arctic is the region on Earth that is most rapidly changing, due to warmer temperatures, greater levels of precipitation, and increases in variability and unpredictability of weather and seasonality (Bintanja, 2018; Isaksen et al., 2022; Rantanen et al., 2022). Climate change affects herbivores and their habitats through direct and indirect effects, such as changes in plant biomass or predator abundances (Hastings et al., 2007; Ims et al., 2013; Mysterud & Sæther, 2011). Herbivores also impact their biophysical environment, for example, through grazing (Peth & Horn, 2006), trampling (Tuomi et al., 2021), and fertilization (Stark & Grellmann, 2002). To better understand and predict how Arctic tundra ecosystems develop in the future, we need to quantify both the climate-related drivers of landscape change and how these changes affect herbivore behavior and their impact on the landscape (Hastings et al., 2007; Jones et al., 1994; Smit & Putman, 2011; Wilby et al., 2001).

One of the many climate-related variables that are currently changing is snow, which is an important driver of availability and quality of habitat for herbivores (Rixen et al., 2022). It is expected that precipitation in the Arctic will increase by 50%–60% during the 21st century (Bintanja, 2018). Small regional and interannual temperature fluctuations around the freezing point can therefore have large consequences on the duration, physical properties, and distribution of the snow cover (Bokhorst et al., 2016). Long distance migratory herbivores, such as geese, cannot time their departure from spring staging areas in the temperate zone based on environmental conditions at their destination (Fox et al., 2006; Kölzsch et al., 2015). Therefore, annual variations in snow cover in the spring shape habitat availability and the impact these herbivores exert on their habitats (Anderson et al., 2016).

Several species of Arctic-breeding geese have increased in numbers due to favorable overwintering conditions in recent decades (Abraham et al., 2005; Fox & Leafloor, 2018; Heldbjerg et al., 2021). Some of the larger-billed species can impact the state of the vegetation because their beaks are strong enough to remove belowground plant parts when aboveground biomass is not available or is less nutritious (Fox & Bergersen, 2005). This behavior, termed *grubbing*, leads to removal of plants and mosses, which increases soil exposure to erosion and alters soil carbon pools (Petit Bon et al., 2021; Speed, Cooper, et al., 2010; Van der Wal, 2006). For instance, increases in lesser snow goose populations (*Chen caerulescens caerulescens*) have changed the long-term ecological state of salt marsh wetlands by significantly reducing graminoid and shrub cover and caused severe habitat degradation (Abraham et al., 2005;

Jefferies et al., 2003; Peterson et al., 2013). Especially in dry Arctic tundra habitats, goose disturbances can cause long-lasting biomass reductions because vegetation growth and recovery are generally slow (Forbes et al., 2001; Jefferies et al., 2003; Speed et al., 2009; Van der Wal, 2006). Selective feeding for preferred vegetation (Speed et al., 2009) and variations in snow cover will therefore play a role in determining which parts of the tundra will be most exposed to goose disturbances (Anderson et al., 2015). Explicit documentation of snow cover impact on habitat selection and vegetation disturbance are yet limited (but see Anderson et al., 2012).

The Svalbard breeding pink-footed goose population has increased from c. 15,000 in the 1960s (Madsen, 1982) to c. 80,000 in 2015–2019 (Heldbjerg et al., 2021). They utilize pre-breeding sites in Svalbard to feed until their breeding grounds are free from snow (Anderson et al., 2015; Duriez et al., 2009; Fox et al., 2006; Hübner et al., 2010). Upon arrival, geese prefer low-lying moist and wet habitats, but extensive snow cover can prevent access to these areas (Anderson et al., 2016; Pedersen, Speed, et al., 2013). Population increases and late snowmelt may lead to feeding in habitats other than moist or wet moss tundra, such as upslope, exposed drier habitats (Pedersen, Tombre, et al., 2013). Although several studies have discussed the importance of snow in habitat selection and grubbing intensity (Anderson et al., 2016; Pedersen, Tombre, et al., 2013; Speed et al., 2009; Wisz et al., 2008), previous studies have not directly quantified how progression of snowmelt in the spring season influences habitat selection and vegetation disturbance. As habitat availability changes across spatial and temporal scales, it likely generates dynamical patterns of habitat selection (Holbrook et al., 2019; Mysterud & Ims, 1998), it is therefore important to use methods for mapping habitat availability accounting for relevant spatial scales and temporal dynamics.

Recent studies, using drones, to measure Arctic herbivore disturbances show promising results (Barnas et al., 2019; Eischeid et al., 2021; Siewert & Olofsson, 2021), but this methodology relies on differences in optical reflection values between disturbed and undisturbed parts of the vegetation. This method does not capture pink-footed goose grubbing early in the growing season or in dry habitats where disturbances are less visible (Eischeid et al., 2021) but nevertheless occur frequently (Pedersen, Speed, et al., 2013; Pedersen, Tombre, et al., 2013). During spring, pink-footed geese spend a large proportion of the day feeding. It is therefore likely that telemetry positions can be used to not only infer habitat selection (e.g., Schreven et al., 2021) but also where they cause disturbance. Drones can also be used to map characteristics of snow (Masný et al., 2021; Schirmer & Pomeroy, 2020), including snowmelt progression (Niedzielski et al., 2018),

and satellite images can help to upscale results to larger spatial scales (Assmann et al., 2020; Dash et al., 2018; Miranda et al., 2020). Mapping snowmelt progression and goose habitat selection by combining field data with remote sensing at multiple scales will likely provide new insights into the dynamic nature of goose–snow interactions during spring.

In this study, we combined detailed GPS-tracking data and visual observations of pink-footed goose with remote-sensed data from drone and satellite imagery to assess goose habitat selection and signs of vegetation disturbance at two spatial scales during the 2019 spring snowmelt season. We used remote sensing to quantify the availability of two major tundra vegetation classes and to track snowmelt, because we expected both to be drivers of pink-footed goose habitat selection and vegetation disturbance at their pre-breeding site. Specifically, we aimed at (1) estimating how habitat selection is driven by the progression of snowmelt by combining field observations with remotely sensed data at two spatial scales;

(2) building a vegetation disturbance model from field observations of signs of disturbance, vegetation class, and snowmelt progression to produce a fine-scale and valley-wide vegetation disturbance probability map; and (3) assess whether our estimates of habitat selection correspond to estimates of vegetation disturbance rates.

METHODS

Study system

Study area

We conducted our study in the southern side of Adventdalen, one of the largest valleys in Nordenskiöld land in the high-Arctic Svalbard archipelago (Figure 1), in the snowmelt period (10 May–03 June) in 2019. This area is one of the major pre-breeding sites that the Svalbard population of pink-footed geese use as staging

FIGURE 1 Location of the study area for assessment of pink-footed goose habitat selection and vegetation disturbance, May–June 2019, in Adventdalen valley, Svalbard. Upper left panel: map of Northern Europe, showing the location of Svalbard. Lower left panel: map of Svalbard, showing the location of the study area in the central Nordenskiöld Land. Right panel: satellite image (Sentinel 2A, 27 July 2019) of the study area showing the extent of the valley-scale and the fine-scale study sites.

and feeding area before their nesting grounds become free of snow (Anderson et al., 2012; Hübner et al., 2010). The study area (valley scale) covered 30 km^2 (78.19° N, 15.85° E) and was accessible via gravel roads.

Adventdalen is a U-shaped glacial valley with different habitat types along an elevation gradient from the valley bottom to the mountain peaks: a river and wetlands in the bottom of the valley, moist moss tundra in the lower slopes, and drier habitat types with species such as *Dryas octopetala* interspersed with gravel, rushes, and smaller forbs in the upper ranges of the slopes (i.e., dwarf-shrub heath). Rocks and gravel dominate steeper slopes and elevations above (Elvebakk, 1994, 2005). Annual precipitation is around 190 mm (Lawrimore et al., 2021) and the timing of snowmelt varies between years and stretches through the months of May and June (Anderson et al., 2015). In the 2019 study year, snow melted out late, and by the beginning of June still approximately 50% of the study area was snow covered. Svalbard's terrestrial ecosystem is characterized by low vertebrate diversity but is supplemented by large populations of migratory birds, such as pink-footed geese during the summer months (Descamps et al., 2017). The other vertebrate herbivores present in the study area are barnacle geese (*Branta leucopsis*), brent geese (*Branta bernicla hrota*), Svalbard reindeer (*Rangifer tarandus platyrhynchus*), and rock ptarmigan (*Lagopus muta hyperborea*). Neither of these create similar vegetation disturbance signs as the pink-footed geese.

Study species: Pink-footed geese

The pink-footed goose is the most numerous goose species in Svalbard (Fox et al., 2010). They migrate from wintering grounds in Belgium, the Netherlands and Denmark via Norway (and recently also Finland) to breed in Svalbard. The first individuals arrive about the second week of May, and by the fourth week of May, most birds have arrived (Glahder et al., 2006). Geese start egg-laying from late May to early June and incubate for approximately four weeks (Madsen et al., 2007). In dry areas, geese grub by targeting rhizomes directly, leaving distinct holes that can still be visible many years later, whereas in wet areas, geese simultaneously open patches of the moss layer (Van der Wal et al., 2020) (Appendix S1: Figure S1). In the following, we refer to pink-footed geese as "geese" and signs of grubbing activity as "signs of disturbance."

Study design

We applied a multi-method, spatially nested approach to obtain data for the analyses of habitat selection and signs of vegetation disturbance of pink-footed goose in the pre-breeding period (Figure 2). The data were gathered during the spring thaw from 10 May to 03 June in 2019. A "fine-scale" study site (0.3 km^2 extent, 5 cm resolution) was nested within the "valley scale" (30 km^2, 10 m resolution) study area (Figure 1). The two major vegetation classes (i.e., moss tundra and dwarf-shrub heath) were well represented at both scales. We further defined "habitat" by the combination of vegetation class and the date of snowmelt. We applied two methods for obtaining data on goose habitat selection. First, several birds were equipped with GPS collars (see *Goose telemetry*) that provided spatial data with high temporal resolution. Because the number of collared geese present was limited (see *Goose telemetry*), we also conducted field-based observations of goose flocks. These observations yielded a less temporally resolved dataset based on survey counts and positioning of geese but obtained at multiple dates throughout the pre-breeding period. In addition, we generated a vegetation disturbance model from field plots where signs of disturbance were assessed and combined it with the remote sensed explanatory variables (i.e., snowmelt date and vegetation class) to generate vegetation disturbance maps. Finally, we compared the results of the habitat selection assessments and the vegetation disturbance maps.

Data collection and processing

Field plots

We marked 320 field plots (15 × 15 cm) on 18 May 2019 (day of the year [DOY] = 138) covering the two vegetation types in the fine-scale study site (Figures 1 and 2) to assess signs of vegetation disturbance and snowmelt progression. Plots were placed in 20 clusters of 16 plots each. The clusters were placed in moss tundra ($n = 12$), dwarf-shrub heath ($n = 4$), or covering both vegetation classes ($n = 4$). The minimum distance between the centroids of the clusters was 9.2 m (distance: 217 ± 144 m, mean ± SD). To capture differences in snowmelt timing, we placed the clusters in groups along an elevational gradient (high, mid-convex, mid-concave, and low) across the study site, and in each elevation class, at least one cluster in each group was in snow-free terrain ($n = 6$), along the snow edge ($n = 5$) and on ground that was still covered in snow ($n = 9$). Within each cluster, the plots were placed in a perpendicular cross with four plots in each direction. For each of the plots, we registered the vegetation class after the snow had melted (moss tundra, dwarf-shrub or bare ground), and every fourth day, we noted the status of the snow cover in the plot (presence
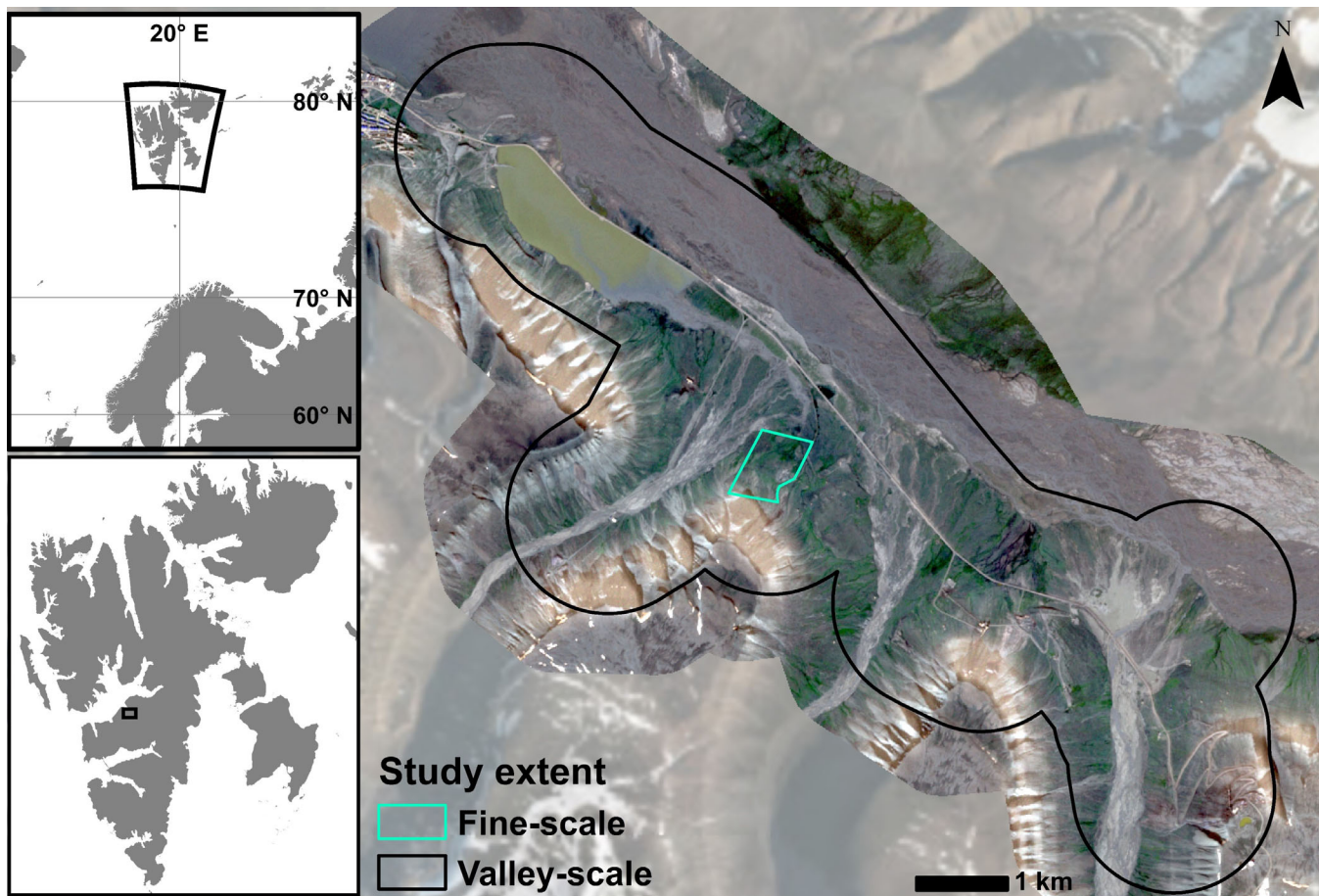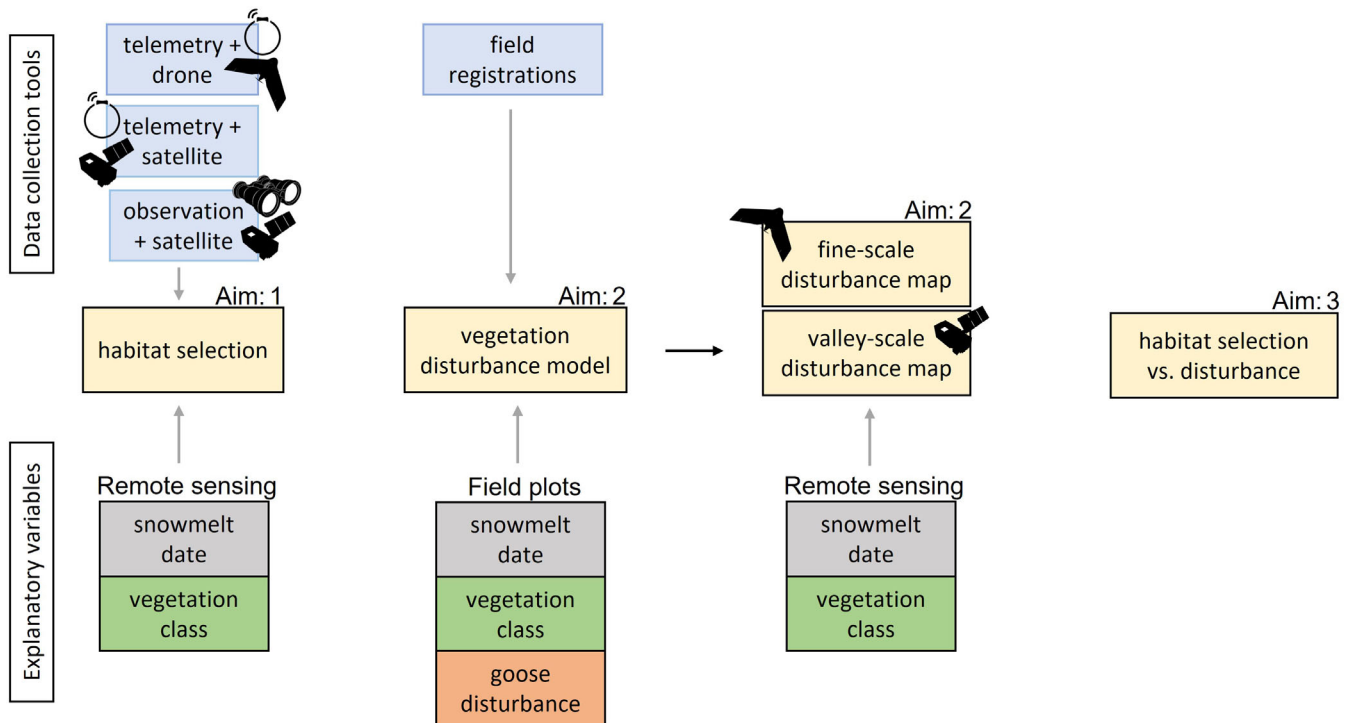
FIGURE 2 Study design for assessment of pink-footed goose habitat selection and vegetation disturbance, May–June 2019, in Adventdalen valley, Svalbard. The study was conducted at two spatial scales: fine scale (5 cm resolution) and valley scale (10 m resolution). Drone and satellite images and field plots were used to obtain explanatory variables on snowmelt date and vegetation class. Aim 1: Habitat selection was assessed using goose GPS telemetry or goose field observations and the remote sensed explanatory variables. Aim 2: A vegetation disturbance model was generated from field plot assessments and combined with the remote-sensed explanatory variables to generate vegetation disturbance maps at the two spatial scales. Aim 3: The results of the habitat selection assessment and the vegetation disturbance maps were compared in the final step.

of snow or snow-free) and presence of signs of disturbance (none or disturbed). Disturbed plots had to have at least one clearly identifiable grubbing hole. Moss tundra and dwarf-shrub heath differed in intensity of signs of disturbance: approximating to the disturbance-level classification of Speed, Woodin, et al. (2010), moss tundra plots appeared with signs of disturbance corresponding to medium intensity (50% of plot had holes) and dwarf-shrub heath corresponding to low intensity level (31%) or lower. We started the field survey on 18 May, but because we had already drone images available for 14 May, we used the images to distinguish which of the plots were already snow-free on 14 May or before. Prior to analysis, we removed the plots that either were placed on bare ground or still covered in snow by the end of the pre-breeding period. This resulted in 285 plots (211 in moss tundra and 74 in dwarf-shrub heath) for analysis.

Goose telemetry

We used goose telemetry data, obtained from a mark–recapture campaign in 2018–2019 aiming at investigating the migration ecology of pink-footed geese, to study habitat selection. Captures took place on a spring staging site in Tyrnävä, Oulu, Finland, in April–May 2018 and 2019, and during molting on brood rearing sites at Daudmannsøyra, western Spitsbergen, and Isdammen in Adventdalen in July–August 2018 (Schreven et al., 2021). A total of 56 adult geese, primarily adult females, were caught and marked with GPS–GSM transmitter neckbands (Ornitela UAB, Lithuania). The collars recorded a GPS position (and speed) every 10 min, with an accuracy of 24% within 5 m, 47% within 10 m, 74% within 20 m, and 96% within 50 m. Of the captured geese, 42 individuals were located in Svalbard during 10 May to 03 June 2019. We removed GPS positions with speeds of over 1 km/h to exclude positions when geese were not feeding. In the fine-scale site, a total of seven tagged individuals (GPS positions $n = 36,934$), and in the valley-scale site, 12 tagged individuals (GPS positions $n = 142,158$) were available for further data processing and analyses. Of these, two bred in Adventdalen and adjacent side valleys, while one bred in Sauriedalen (35 km NNW) and others did not attempt to breed in 2019, as inferred from the movement of GPS-tagged geese

(Schreven et al., 2021). The 2019 season's egg-laying commenced on 01 June on average (range: 29 May–04 June) (Schreven et al., 2021). For more details on handling procedures of geese and the GPS transmitters, see Clausen et al. (2020) and Schreven et al. (2021).

Goose survey counts

We counted goose numbers along the roads in the Adventdalen valley in May 2019. After the first small groups of pink-footed geese were observed on 10 May, we counted them systematically from DOY 131 (11 May) until day 151 (31 May) (daily until 16 May and every 2–3 days thereafter). Counts started at 8 am and were usually finished before noon, with an exception on the days with the maximum number of birds. For each counting day, two observers slowly drove along a predetermined route and stopped every time a goose or a group of geese was observed. We counted geese within a maximum distance of 600 m, as this was the distance where we were confident geese were visible in the terrain. For each observation, we noted (1) the number of geese; (2) their activity according to three categories (feeding, sitting, or walking); (3) snow cover at the observation site of individuals or groups of geese according to three coarse classes (on snow, on snow-free, or at snow-edge); and (4) a GPS position of the observer, a compass course, and measured distance, using distance binoculars (Zeiss Victory 10 × 42) to calculate the positions of each goose (or group of geese). We excluded observations where the geese were walking without feeding or were on a snow-covered area. This resulted in 1300 observations with a total of 6676 geese available for further analysis for the survey approach in the valley-scale analysis.

Developing explanatory spatial layers

Drone imagery

Throughout the snowmelt period (14 May–02 June 2019), we used a fixed-wing drone (eBeeX, Sensefly) to collect aerial images of the fine-scale study site. The drone was rigged with a RGB camera (AeriaX, Sensefly). On one date (02 June), we additionally flew with a pre-calibrated (Cubero-Castan et al., 2018) multispectral camera (Sequoia+, Sensefly) to obtain green, red, near-infrared, and red-edge images. During each flight, we flew perpendicular lines to the main slope of the terrain at altitudes between 50 and 100 m above ground (depending on the camera and date) and speeds between 8 and 15 m/s. Image overlap was 75% or higher for the AeriaX camera, while for the Sequoia+, side overlap was 60% and

horizontal overlap 80%. We flew around noon and only on days with stable light and wind conditions (max 7 m/s). We aimed to fly every fourth day but because of variable weather conditions we flew on 14 May, 18 May, 22 May, and 02 June. We logged the GPS positions with a Leica GS10 (Leica Geosystems) differential GPS base station in vicinity of the study site and used these for kinematic post-processing (PPK) of the drone images. Through the PPK workflow, we obtained an accuracy of 5 cm for the drone images and verified our results using ground control points (GCPs) as checkpoints.

Snow cover maps (drone images, fine scale)

We generated orthomosaics from the drone imagery using structure for motion with Pix4D mapper software (Pix4Dmapper, 2021) to produce snow cover maps at the fine-scale study site. To do so, we generated RGB orthomosaic for all drone flight days, and additional multispectral orthomosaic for 02 June. To classify the images into snow/no snow, we generated a classification training dataset by drawing a minimum of 50 polygons (for snow and no snow) for each date and extracting the values for each RGB and multispectral orthomosaic. Using the R package rminer (Cortez, 2020), we then used the training dataset to train a random forest (RF) classifier to predict the two classes (snow/no snow) for the entire fine-scale study site. This validation method is described in Eischeid et al. (2021) in more detail. We visually inspected the snow classification results and used masks to manually fix some obvious misclassifications (e.g., "dirty snow," GCP targets, and abandoned mining infrastructures and their shadows) and a stitching error on the 22 May that resulted in a thin black stripe. Finally, we resampled each of the snow maps to the same extent, 5 cm resolution.

Vegetation class map (drone images, fine scale)

We used a simplified version of the drone imagery-based ground-cover classification map of Eischeid et al. (2021) that overlapped with our fine-scale study site. We grouped the ground-cover classes into three major vegetation classes: moss tundra, dwarf-shrub heath, and bare ground/water. The moss tundra class included the ground-cover types (as described in Eischeid et al., 2021) moss-graminoid, wet moss tundra, *Carex subspathacea*, brown moss, and moss-equisetum. The dwarf-shrub heath class included the classes dryas, cassiope, heath–graminoid, and heath–moss; the bare ground/water class included areas covered with gravel, rocks, bare ground, biological crust, or water.

Satellite imagery

We created snow cover and vegetation cover maps of the valley-scale site using Google Earth Engine (GEE) and

Sentinel 2A images (Copernicus Sentinel Data, 2019) with the bands red, green, blue, and near-infrared at 10 m resolution. We filtered for cloud free days within the timespan of the study by calculating a cloud probability band (MSK_CLDPRB) and manually checking the quality of the images (e.g., for hazing or shadows).

Snow cover maps (satellite images, valley scale)

To generate snow cover maps from satellite images at the valley scale, we used GEE. For each date, we had a Sentinel 2A image available ($n = 6$); we drew 30 snow/no-snow training polygons to train a classifier. We used the GEE integrated classification and regression trees (CART) classifier (Breiman et al., 1984) to generate the snow cover maps. We had two larger time series data gaps; therefore, we used the images before and after each gap to interpolate estimated snow cover maps for the dates 18 May and 30 May.

Vegetation class map (satellite images, valley scale)

We generated a vegetation class map for the valley using Sentinel 2A image (27 July 2019) and a random forest (RF) classifier based on the red, green, blue, and near-infrared (NIR) bands. In the fine-scale vegetation map, we marked 50 points for each of the three classes (moss tundra, dwarf-shrub heath, and bare ground/water) and extracted the values to use them for training the RF classifier. To test classification robustness, we trained 30 RF with subsets of the dataset and obtained an average macro-$F1$ score of 95% (same method as described in Eischeid et al., 2021). We generated a final RF with 100% of the training data (as variation between the 30 subsets was small) and used the final RF to predict vegetation classes across the valley-scale study area.

Data analysis

Habitat selection

Prior to analysis, we extracted the environmental explanatory variables (vegetation class and date of snowmelt) for each goose GPS location and field observation. GPS locations or observations that occurred in an area before it became snow-free or on bare ground/water were removed from the analysis.

To account for the absence of daily drone or satellite images, and temporally uneven field observations, we included GPS positions of geese that used areas that were detected to be free of snow in images dating up to one day later. For the GPS telemetry dataset, we only included a maximum of one location per hour (always choosing the earliest observation within each hour) to

reduce spatial–temporal autocorrelation (Lombardi et al., 2022). For the fine-scale analysis, we had 609 goose GPS positions available for analysis, while for the valley scale, there were 1981 GPS positions.

To account for the absence of daily satellite images, for goose observations from the census counts, we included observations that could be linked to snow-free areas dating up to two days after the observation. Uncertainties in the estimation of the position of the field-based goose observations and the 10 m resolution of the satellite map resulted in that some observations, noted as snow-free habitat in the field, were assigned to snow-covered areas on the map. In such cases, we assigned the observation to a snow-free patch of the same vegetation class within a 10 m radius of the original location. This resulted in a final dataset of 537 field observations of individual geese or groups of geese (total number of geese = 3130) for analysis of habitat selection at the valley scale.

At each scale, we grouped all GPS locations or goose observations together and treated each combination of vegetation class (moss tundra and dwarf-shrub heath) and snowmelt date as its own habitat class. In the fine-scale analysis, we therefore had a total of 8 habitat classes (four dates × two vegetation classes), and for the valley-scale analyses, we had 16 habitat classes (eight snowmelt dates × two vegetation classes). Although time-specific maps of habitat availability and snowmelt form the basis of the habitat selection analysis, the timing of the goose observations/positions did not enter the analysis directly. We chose this approach of grouping all goose positions because it allowed us to compensate for irregular drone and satellite image availability. It made it also possible to compare habitat selection with the vegetation disturbance probabilities that were calculated for the entire pre-breeding period and not a day-by day basis.

We applied the habitat selection estimation method by Manly et al. (2002) and used the R package adehabitatHS (Calenge, 2006) to calculate habitat selection coefficients and 95% CIs. We calculated habitat selection at (1) the fine scale using GPS locations, (2) the valley scale using GPS locations, and (3) at the valley scale using field observations of geese (Figures 1 and 2). We followed Manly's design 1, where there is no unique identification of animals. but the proportions of available habitat classes are known (Thomas & Taylor, 2006). Thus, we calculated habitat selection by dividing the proportional number of geese per habitat class by the proportional area size of each habitat class. Habitat preference (positive selection) is indicated by values above one and has no maximum limit. Habitat avoidance (negative selection) is indicated by habitat selection ratios between one and zero.

Signs of vegetation disturbance

Vegetation disturbance model

We assessed the impact of vegetation class and snowmelt timing on the presence of signs of vegetation disturbance by geese (i.e., beak holes or moss removal) using the plot data obtained from the field plots ($n = 282$). We applied a regression model with a Bernoulli distribution for the response (0 = not disturbed, 1 = disturbed), starting with 0% disturbance but allowing for the probability asymptote to be less than 1, as not all plots are necessarily disturbed by the end of the pre-breeding period. We treated goose disturbance as the response variable, vegetation class (moss tundra and dwarf-shrub heath) as a categorical explanatory variable, and snow-free date as a continuous explanatory variable. The model was therefore parameterized as $\mathrm{prob(disturbed)} = b_1/(1 + \exp(b_2 + b_3 \, \mathrm{snow}))$, with b_1 as the asymptote, $b_1/(1 + \exp(b_2))$ the intercept (i.e., for snow = 0), b_3 the regression slope, and snow the snow-free date. We fitted models with parameters (b_1 to b_3) either identical or differing between the two vegetation classes and used Leave-One-Out Cross Validation (LOO) criteria to select the best model (Vehtari et al., 2023). All models were fitted using Bayesian methods and the brm() function in the brms library in R (Bürkner, 2017). We used weakly informative priors to facilitate convergence and 10,000 iterations. The slopes for dwarf-shrub heath and moss tundra were similar, and we used a model with a common slope for both vegetation classes. We assessed the predictive power of the model by calculating the correlation between the observed and predicted proportions (Zheng & Agresti, 2000). An evaluation of the model with external ground truthing data collected throughout the 2019 season is presented in Appendix S2: Figures S1 and S2.

Vegetation disturbance probability maps

We used the disturbance probability model, developed with plot-scale signs of disturbance data, to predict grubbing probability across the fine-scale and valley-scale study extents. To do this, we stacked the vegetation and snowmelt maps and reclassified them according to the mean disturbance probabilities of the prediction model using the reclassify function of the R package terra (Hijmans, 2023). We repeated this procedure for the CIs of the disturbance model to map the spatial distribution of the uncertainties (Appendix S2: Figure S3). To estimate the total amount of disturbed areas, we summed the frequencies of each habitat class (each vegetation class and snow-free day combination) and multiplied it with its disturbance probability, that is, area with signs of disturbance = habitat class area × disturbance probability (e.g., 200 m² habitat × 0.8 disturbance probability = 160 m² area with signs of disturbance).

Habitat selection and vegetation disturbance

Finally, we assessed the correspondence between the habitat selection and signs of vegetation disturbance. Because Manly habitat selection ratios are at a different scale above and below one, we first normalized the Manly habitat selection values to a scale between zero and one. We then calculated the Spearman correlation coefficients for each habitat class within all three habitat selection analyses (i.e., fine scale based on GPS data, valley scale based on GPS data, and valley scale based on field observations of geese). Predictions and associated uncertainty from the model were based on the draws from the posterior predictive distributions obtained using the epred_draws() function.

RESULTS

Weather characteristics and spring phenology of geese

In 2019, a late snowmelt year, temperatures were mostly subzero during the study period in May–June with two warm spells at DOY 133–138 and 148–154 (13–18 May and 28 May–03 June) (Figure 3a). During the first days of June, 50% of the valley extent was still covered in snow (Figure 3b). Snowmelt for the two assessed vegetation classes was synchronous throughout May 2019 (Figure 3b). The first geese were counted on day 130 (10 May) and their numbers continued to increase until day 147 (27 May) (Figure 3c). At day 151 (31 May) goose numbers were lower than on day 147, as the geese started leaving the pre-breeding areas. The first GPS collared goose arrived in the study area on day 136 (16 May) (Figure 3c). The maximum number of GPS collared geese ($n = 10$), using the valley-scale study site in one day, was on DOY 142, 143, and 147 (22, 23, and 27 May). The proportions of snow-free area for each date and vegetation class can be found in Appendix S3: Table S1. During the survey counts (morning until noon), approximately 70% of the goose flocks were actively foraging.

Habitat selection

Geese selected the moss tundra vegetation more often than the dwarf-shrub heath vegetation (Figure 4). Habitat selection ratios were generally highest for the areas that became snow-free early in the season (Figure 4) and most profound when measured with goose field observations at valley scale (Figure 4c). These results were broadly consistent across both spatial scales and
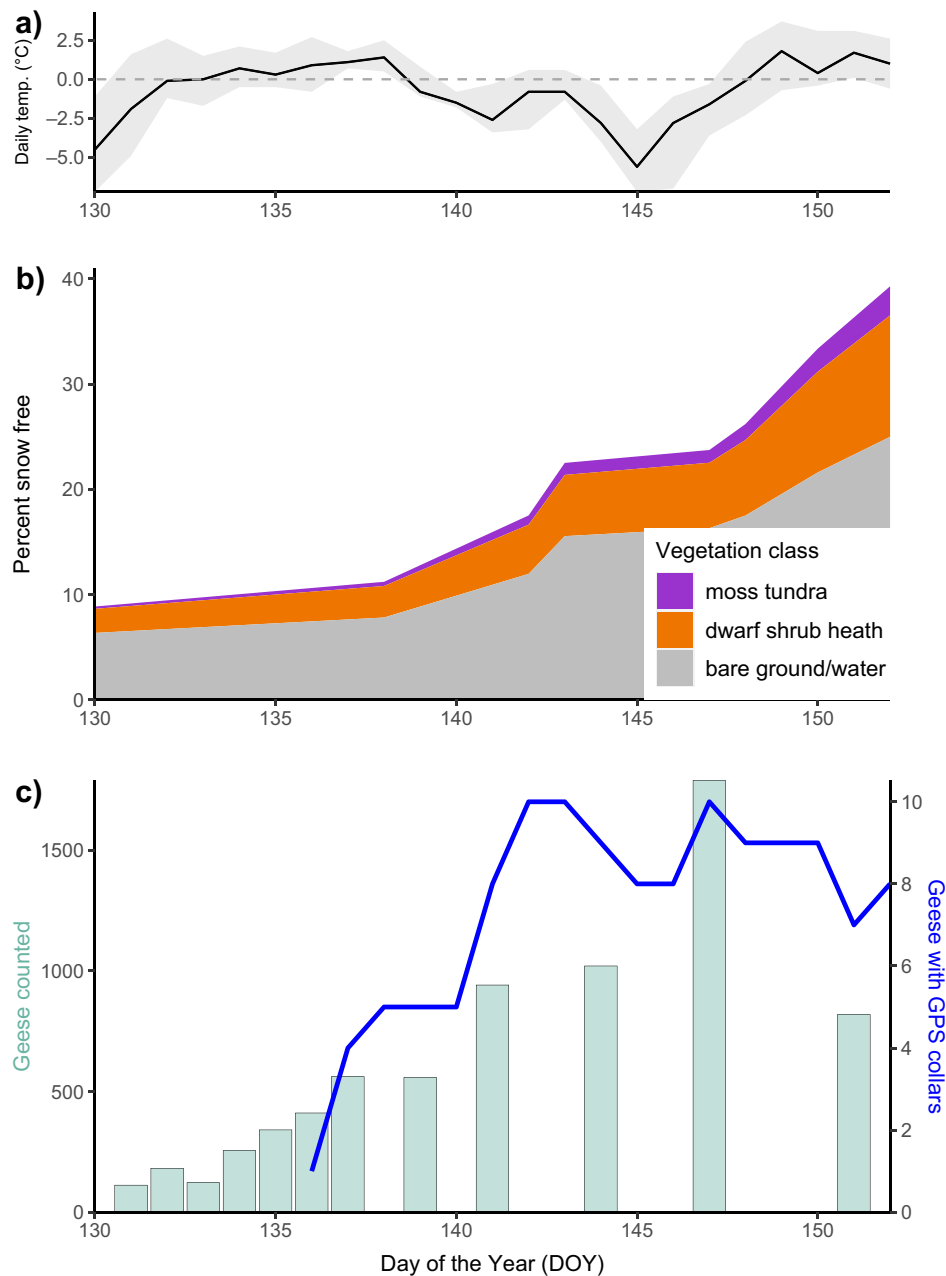
FIGURE 3   Seasonal development in Adventdalen valley, Svalbard (10 May–3 June 2019). (a) Daily mean temperature (black line) at Svalbard airport (~6 km from the study site). The gray field shows the min–max temperature range for each day. (b) The proportion of snow-free area, as measured from satellite imagery, in the valley-scale study area. (c) The arrival of pink-footed geese in Adventdalen valley. The turquoise bars show the number of geese counted during the field survey and the blue dots indicate the daily number of GPS collared geese that were within the spatial extent of the valley-scale study area.

goose observation methods (GPS telemetry or field observation; Figure 4).

Signs of vegetation disturbance

For both vegetation classes, the disturbance probability was lowest for the plots that became snow-free late in the season (Figure 5). Vegetation disturbance was highest

(disturbance probabilities of above 0.8) for moss tundra plots that became snow-free relatively early, that is, DOY 142 (22 May), but dropped steeply after and reached 0.1 for the plots that became snow-free by the end of the study period (DOY 154). For plots in the dwarf-shrub heath, disturbances where highest for plots that became snow-free before DOY 146 (May 26) with disturbance probabilities around 0.5. Disturbance probabilities were consistently above zero for both vegetation classes within
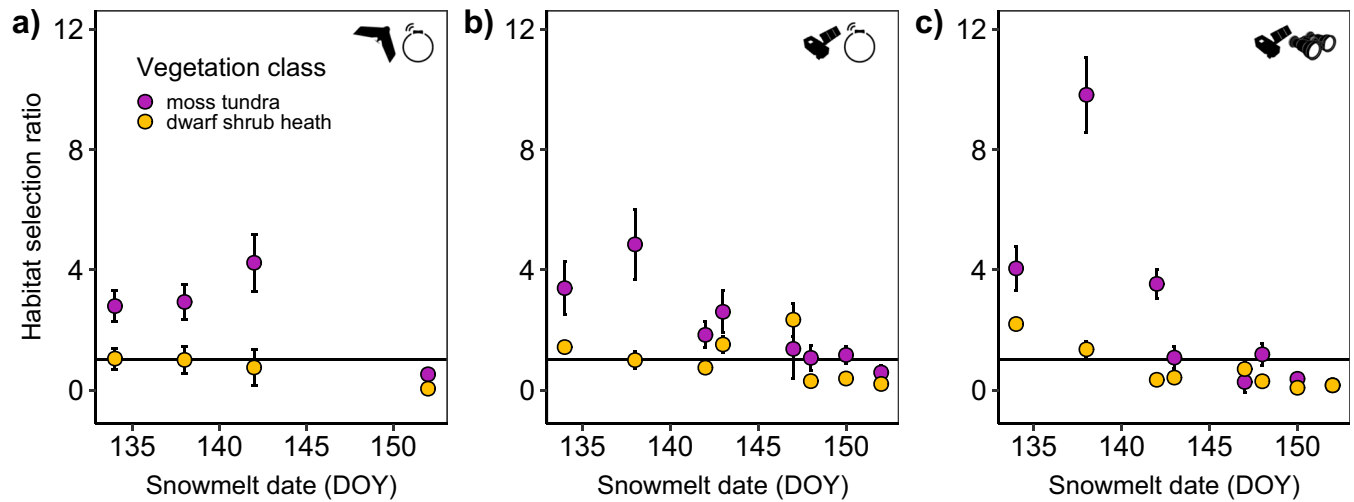
FIGURE 4 Manly's habitat selection ratios (wi) and 95% confidence interval for pink-footed goose in the pre-breeding period (May–June 2019) in Adventdalen valley, Svalbard. Habitats are defined by vegetation class (moss tundra and dwarf-shrub heath) and snowmelt date (day of the year [DOY] days: 134–153). Positive selection (preference) is indicated by wi > 1, and negative selection (avoidance) is indicated by wi < 1. Habitat selection at (a) fine scale (5 cm resolution), based on goose GPS telemetry data and explanatory variables derived from drone images; (b) valley scale (10 m resolution), based on goose GPS telemetry data and explanatory variables derived from satellite images; and (c) valley scale (10 m resolution), based on field observations and explanatory variables derived from satellite images.
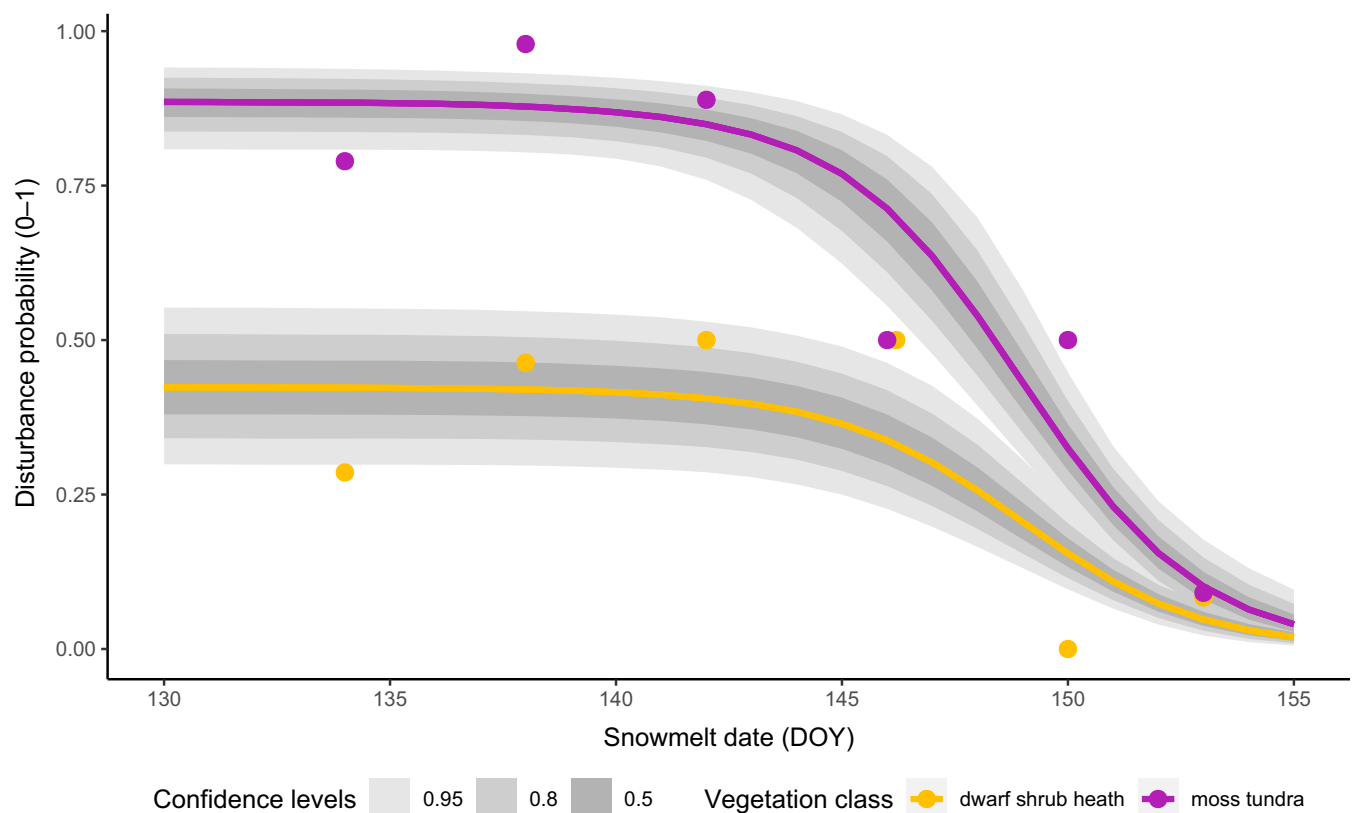

FIGURE 5 Pink-footed goose vegetation disturbance probability predictions based on a logistic regression model of presence/absence of signs of vegetation disturbance, in moss tundra and dwarf-shrub heath vegetation in Adventdalen valley, Svalbard, in relation to snowmelt date of plots (indicated by day of the year [DOY] between 14 May and 03 June 2019). The solid lines indicate the model predictions for the disturbance probability at each day and vegetation class, the confidence intervals are shaded in gray. Datapoints show the proportion of plots disturbed for each vegetation class and assessment day. Disturbance probability is the probability of occurrence of a goose grubbing event in a 15 × 15 cm plot.

the pre-breeding study period. The regression model with vegetation class specific asymptotes was best according to the leave-one-out cross-validation criterion (LOOIC = 268.9, model with identical asymptotes ΔLOOIC = 36.6, and models with different asymptotes as well as different slopes and intercepts, all ΔLOOIC = 36.6 > 1.0) and fitted the data well (correlation between observed and predicted values: $R = 0.91$, Figure 5). The common slope (b_3) was 3.09 (SE = 0.56) and asymptotes (b_1) of 0.43 (with SE = 0.07) for dwarf-shrub heath and 0.89 (SE = 0.03) for moss tundra. The value of date for which the proportion is half the asymptote was 6.1 days for both habitats as only the asymptotes change between the two habitats.

At both study scales, disturbance probabilities were unevenly distributed across the landscape (Figure 6). In the fine-scale study site, 24.8% (32.6% of moss tundra habitat and 13.8% of dwarf-shrub heath) of the vegetated area was predicted to show signs by pink-footed geese disturbance. Further, the highest disturbance probabilities (over 0.8) were predicted to occur in the early snow-free moss tundra areas at low elevations. Within the extent of the valley-scale area, the fine-scale study site was one of the areas with most disturbance. In the valley-scale study area, 5.13% of the total area was predicted to show signs of disturbance, 23.4% of the moss tundra (0.5 km^2) and 11.2% of the dwarf-shrub heath (1.05 km^2). Areas in the vicinity of roads were snow free early in the season and therefore had high predicted disturbance rates for both vegetation classes. At the end of the pre-breeding period, snow-free vegetated areas comprised 52.8% of the fine-scale site and 37.6% of the valley-scale area. Areas that were predicted to have disturbance probability of zero, were either in the class bare ground/water or were still covered in snow by the end of the pre-breeding period.

Habitat selection and signs of vegetation disturbance

Habitat selection was positively correlated with vegetation disturbance at both spatial scales and using both methods (GPS telemetry and field observations) of measuring goose habitat selection (Figure 7; Appendix S3: Table S2). Normalized habitat selection values above 0.1 were generally associated with the highest disturbance rates (Figure 7).

DISCUSSION

We showed that habitat selection of pink-footed goose correlated with vegetation disturbance during the pre-breeding period. This result was consistent across vegetation classes, spatial scales, and methods of assessing habitat selection (GPS telemetry and field observations). Moss tundra was selected over dwarf-shrub heath and more often disturbed by pink-footed geese. Both habitat selection and vegetation disturbance were highest for areas that were free of snow early in the season. Our predictions showed that about 23.4% of moss tundra vegetation showed signs of disturbance by pink-footed geese during a late snowmelt, pre-breeding period in the Adventdalen valley. This indicates that geese may substantially modify tundra vegetation in available habitats.

This study supports previous findings that pink-footed geese prefer moist over dry habitats (Anderson et al., 2012; Pedersen, Speed, et al., 2013; Pedersen, Tombre, et al., 2013; Speed et al., 2009), but gives new knowledge of the role of snowmelt on habitat selection and vegetation disturbance that has not been explicitly addressed earlier. Previous studies on pink-footed goose disturbance have not included snowmelt timing as an explanatory variable (but see Anderson et al., 2016) due to the coarse temporal or spatial scales of snow-related variables (Speed et al., 2009; Wisz et al., 2008) or they had to rely on proxies for snowmelt timing, like air temperature (Fox et al., 2006) or slope aspect (Pedersen, Tombre, et al., 2013). For example, a Svalbard-wide goose disturbance probability model from 2006 and 2007 (Speed et al., 2009) predicted highest disturbance probability in those areas in Adventdalen valley which were never free of snow in the pre-breeding period of 2019, a year with relatively late snowmelt. We found that snow free areas during the first two weeks of the pre-breeding period were used most and therefore had highest vegetation disturbance probabilities. This supports the study of Pedersen, Speed, et al. (2013), which suggests that elevated levels of goose disturbance in south-east-facing slopes were related to early snowmelt. Our study documents the importance of snowmelt and its variability for spring ecology of an avian herbivore and tundra vegetation, providing empirical evidence to general notions about implications of climate change and snow season changes that include increased variability in precipitation (John et al., 2020; Post & Forchhammer, 2002; Rixen et al., 2022).

The vegetation class-specific disturbance predictions from our study provide insights into potential landscape scale variation in ecosystem effects of goose grubbing. Effects of grubbing on vegetation vary considerably, and intensity as well as frequency of the disturbance influence how quickly the habitat recovers or new plant community composition evolves (Jasmin et al., 2008; Kerbes et al., 1990; Van der Wal et al., 2020). Experimental studies have shown that carbon loss due to (simulated) goose disturbance varies greatly between years, habitats, and plant functional group (Petit Bon et al., 2021; Speed, Woodin, et al., 2010). In a simulated goose disturbance
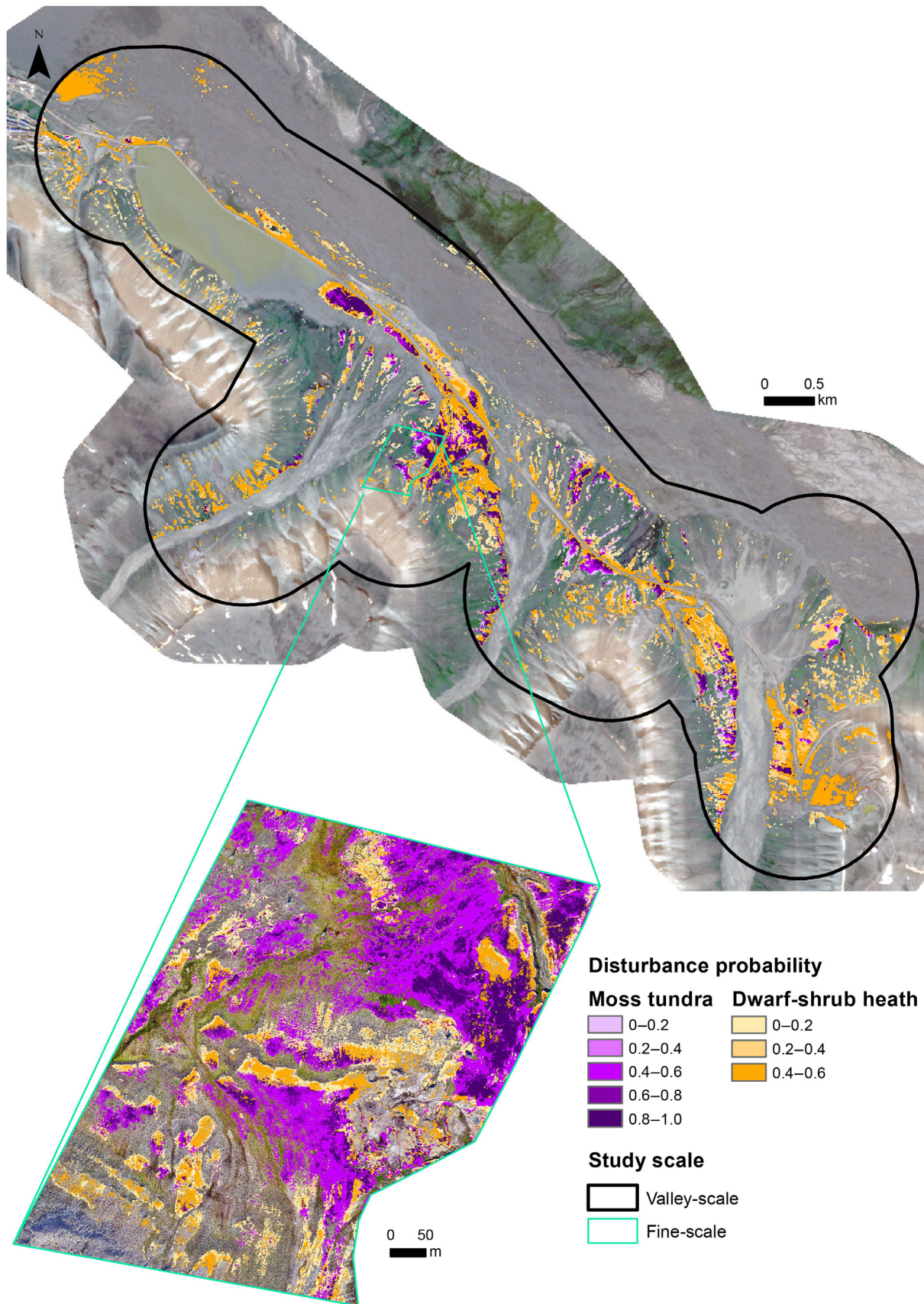
FIGURE 6 Pink-footed goose vegetation disturbance probability predictions, based on a logistic model (see Figure 5) and field surveys of snowmelt date and vegetation disturbance for moss tundra and dwarf-shrub heath vegetation at the fine-scale and valley-scale study areas site in Adventdalen valley, Svalbard, during the pre-breeding period in May–June 2019.
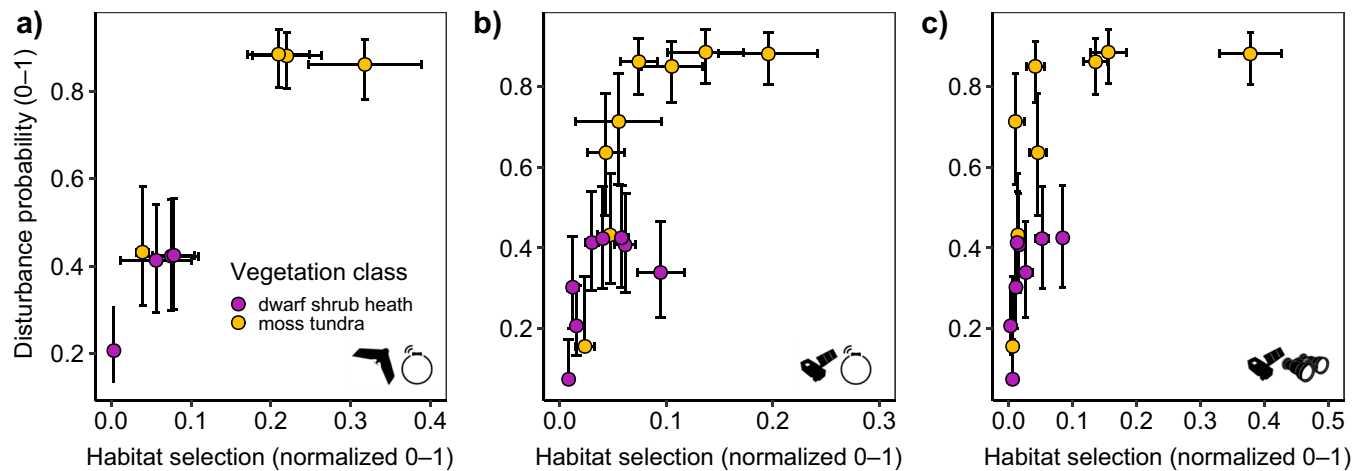
FIGURE 7 Pink-footed goose habitat selection (normalized) and predicted disturbance probability during the pre-breeding period (May–June 2019) in Adventdalen valley, Svalbard. Disturbance probability is the probability of occurrence of a goose grubbing event in a 15 × 15 cm plot. Habitat selection and vegetation disturbance measured at (a) fine scale (5 cm resolution), based on GPS telemetry data and explanatory variables derived from drone images; (b) valley scale (10 m resolution), based on GPS telemetry data and explanatory variables derived from satellite images; and (c) valley scale (10 m resolution), based on field-based observations and explanatory variables derived from satellite images.

experiment, Speed, Woodin, et al. (2010) estimated carbon gain of 343.47 g/m² for dry habitats (low intensity) and carbon loss of 625.46 g/m² in mesic habitats (medium disturbance levels), compared with controls without disturbance. If these numbers were to be extrapolated to our predicted disturbed area in Adventdalen valley, they could result in approximately 300 t carbon lost in wet habitats and equally much gained in the dry habitats. Higher carbon fluxes per square meter in moss tundra would therefore be outweighed by the larger spatial extent of the dwarf-shrub heath. Our study suggests that disturbance estimates via satellite and drone images, given that intensities of experimental disturbances like that of Speed, Woodin, et al. (2010) and the actual disturbance documented in the field are equivalent, thereby could provide a useful data source to approximate carbon fluxes as the result of pink-footed goose disturbance.

The tight linkage between habitat selection and vegetation disturbance during the pre-breeding period that we observed means that GPS telemetry derived estimates of habitat selection can be a good predictor for pink-footed goose disturbance extent and intensity, and can be a complementary alternative for extensive field campaigns. In this study, we focused on snow cover as a predictor for habitat availability, but other factors such as soil and air temperatures can also influence availability. For example, in 2019, a late snowmelt year, habitats were grubbed shortly after they were free from snow. In contrast, during years with shallow snowpack, snowmelt can occur early, but cold soil temperatures (less insulated by snow) can prevent geese from grubbing for large parts of the pre-breeding period (Anderson et al., 2012; Fox et al., 2006).

Alternatively, persistent warm May temperatures and early snowmelt can advance graminoid growth so that grazing can become advantageous over grubbing (Fox et al., 2006). Earlier timing of the switch from grubbing to grazing can thus weaken the link between habitat selection and predicted vegetation disturbances via grubbing. Hence, snowmelt and preferably soil, or air temperatures (as a proxy), need to be considered in future predictions of vegetation disturbance by geese. Similar approaches of linking habitat selection and vegetation disturbance are likely applicable for other broad-billed geese, such as snow geese and swan geese (*Anser cygnoides*) that show seasonally intensive grubbing (Fox et al., 2008; Gauthier et al., 2005) or avian herbivores in general, because they tend to feed during large proportions of the day (van Gils et al., 2007).

Studying vegetation-herbivore interactions in rapidly changing and heterogenous landscapes, demands monitoring methods at appropriate spatial and temporal extent and resolution (Eischeid et al., 2021; Ims et al., 2013; Ims & Yoccoz, 2017; Post et al., 2009; Ravolainen et al., 2020). Only few studies have combined data sources from drone-based aerial images and GPS telemetry to study animal habitat selection (but see Stark et al., 2018) because the target species need to be confined to a rather small area to derive explanatory variables from image captured by short-range drones. Although pink-footed geese at the population level migrate long distance and inhabit areas that span from Western Europe to Svalbard, Iceland, and East Greenland (Madsen et al., 1999), a combination of drones and GPS telemetry was useful as a tool in our fine-scale study site because we studied their behavior over

a restricted spatial extent and time. A similar approach may be valuable for migratory animals that gather and feed intensively in restricted areas along their migration route (e.g., Nolet et al., 2001).

The high-resolution images and the associated derived explanatory variables provided a good data source to capture snowmelt progression in detail that earlier studies in the same region have not been able to (see e.g., Anderson et al., 2016). Drone images are promising data sources in ecology to, for example, derive ecologically relevant habitat explanatory variables to study animal habitat selection (Mangewa et al., 2019) or to improve the interpretation of satellite images for similar purposes (Assmann et al., 2020). The 10-m resolution of the Sentinel 2 image-based snow maps was too coarse to capture smaller snow-free patches, and almost 50% of our field-based observations had to be excluded because we could not assign them to a snow-free patch in vicinity. However, this could be alleviated by using drone images that provided spatial resolutions that allow for more detailed ecological analyses. Pink-footed goose habitat selection and vegetation disturbance estimates were consistent at both spatial scales chosen for this study. Like Stark et al. (2018), we show that drone-based studies can help validate satellite derived-data and thus lift the studies' findings to management relevant scales. Similarly, both methods of locating the birds (telemetry vs. observation) led to the same valley-scale habitat selection estimates. Except for the last week of the study period, when many geese gathered in one location to leave the valley, whereas most of the GPS-tagged individuals stayed spread within study area. This highlights the advantages and limitations of the different methodological approaches. Pending local calibrations with field assessments and drones, using satellite images and telemetry data is a method that requires only minimal presence in the field and can provide a good data source to detect disturbance hotspots caused by herbivores.

There are several methodological considerations that arose from our results that can help future estimation of habitat selection, and prediction of vegetation disturbance based on telemetry data or field observations and remote-sensed data. Using a presence–absence approach of disturbance and extrapolating it to larger areas assumes even disturbance within each plot. We used small plot sizes (0.023 m^2) to reduce within and between plot variation, but disturbance intensities for dwarf-shrub heath were lower than those for moss tundra. Extrapolations therefore represent disturbance intensities typical for each vegetation class. Because goose numbers at the valley scale were not constant throughout the pre-breeding period, the method of grouping all observations to evaluate habitat selection may skew results in favor of habitats that were snow-free when most geese were present. We showed that

our method of mapping at two spatial scales was adequate in a late snowmelt year with small, but highly disturbed, early snow-free areas. In years of early snowmelt, geese may be more spread out in different parts of the landscape (Anderson et al., 2016), and thus signs of their disturbance may be more difficult to capture through drone-based, fine-scaled analyses. Furthermore, cloud cover reduces the availability of optical satellite data. To use these effectively, more work is needed to assess the minimum number of images that would be needed to adequately predict habitat selection and vegetation disturbance in the future. The lack of drone images in the period between 18 May and 02 June may perhaps influence habitat selection values for the period before 18 May. However, by choosing a multi-data approach, which showed consistent results across methods and spatial scales, we were able to minimize the effect of these above-mentioned limitations.

CONCLUSION

Our integration of multiple sources of data documented that timing of snowmelt and vegetation availability were important drivers for pink-footed goose habitat selection and vegetation disturbance. This implies that spring abiotic conditions play a role in how and where biotic factors like herbivores affect tundra ecosystems. We underline the importance of detailed temporal and spatial data on snowmelt patterns. Our study provides empirical evidence to general notions about implications of climate change and snow season changes that include increased variability in precipitation. We further encourage the integration of drone imagery as data source to improve the information that can be gained from using satellite images and GPS telemetry.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.