Paws for thought: Impacts of animal husbandry on tundra greening in High Arctic Svalbard

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Abstract:

Dog sledding in High Arctic Svalbard is a key tourist attraction, and the keeping of animals and livestock has historically been in practice in the settlements of the archipelago. The resulting waste disposal practices - particularly those involving the disposal of animal faeces and fodder - hugely enrich soils with excess nutrients. Here, we explore how animal husbandry affected changes in tundra vegetation greenness from 1985 to 2021 using Landsat satellite observations from 31 sites in Svalbard. In particular, we assessed changes in annual maximum vegetation greenness at contemporary and historical animal husbandry sites using the Normalized Difference Vegetation Index (NDVI) to extract dates of peak-season greenness, green-up, and plant senescence. We found that while peak-season greenness increased across all of our study sites, the greening signal was enhanced at active dog-yards and historic animal husbandry sites. In addition, the greening signal was stronger at all animal husbandry sites compared to reference 'non-disturbed' tundra sites. Across sites, the date of tundra vegetation greening shifted up to 0.81 days earlier, and the date of plant senescence shifted slightly later from 1985 to 2021. Our analysis shows nutrient enrichment from animal husbandry can stimulate long-term increases in tundra vegetation productivity, with a lasting impact of nutrient enrichment at abandoned animal husbandry sites.

Keywords: *remote sensing, polar biology, tundra greening, animal husbandry, tourist impact, ecosystem change*

1. Introduction:

The first permanent settlements in Svalbard were established in the late 1800s in the central Isfjorden region (Arlov 1994), where the main settlements on the archipelago are still found today, including Longyearbyen, Barentsburg and Pyramiden. In this historical period dominated by hunting, trapping and mining, sled dogs (*Canis lupus familiaris*) were an important mode of transportation (Umbreit, 2009). Today, dog sledding is a popular tourist attraction in Svalbard, one that is often packaged as a group activity by tour companies, and largely clustered in the Adventdalen valley with road access to Longyearbyen (Meyer 2016). In addition to dog sledding, animal husbandry in Svalbard also includes pony trekking and historically included the keeping of livestock in the settlements of the archipelago. Historic pig and cattle farms were disbanded during the late 20th century in Longyearbyen, Barentsburg, Pyramiden and Ny-Ålesund, but are known hotspots for both non-native invertebrates and vascular plants due to imported soils, the seed import pathway provided by livestock fodder, intensive human activity and soil disturbance, all of which provide routes for, and facilitate, non-native species establishment (Alsos et al., 2015; Bartlett et al., 2021; Coulson et al., 2013; Liška & Soldán, 2004). Animal husbandry and associated waste disposal practices can hugely enrich soils with excess nutrients such as nitrogen and phosphorus (Steinfeld & Wassenaar, 2007; Xu et al., 2019). As yet, there has been no research into the ecological impact of these activities on the nutrient-poor Arctic tundra ecosystem. Here, we explore impacts of historic and contemporary animal husbandry on tundra vegetation in Svalbard using long-term satellite measurements of vegetation greenness.

Satellite measurements have often been used to track long-term changes in vegetation greenness across high latitude regions (Berner & Goetz, 2022; Bhatt et al., 2013; Forbes et al., 2010; Myers-Smith et al., 2020; Zhu et al., 2016). Vegetation greenness is typically characterised using spectral indices such as the Normalized Difference Vegetation Index (NDVI), with a positive trend in spectral greenness termed "greening" and a negative trend termed "browning". Greening trends often correspond to climate warming and potentially accelerated soil development (Doetterl et al., 2022;

Forbes et al., 2010; Zhu et al., 2016), while browning trends have been associated with extreme local events, such as drought and extreme winter temperatures (Bjerke, 2011; Bjerke et al., 2017; Bokhorst et al., 2008). Satellite-derived greenness indices such as NDVI are useful proxies of plant productivity and aboveground biomass (Berner et al., 2020; Forbes et al., 2010; Myers-Smith et al., 2020; Raynolds et al., 2006), but their applications in High Arctic regions such as Svalbard are often complicated by high cloud cover, long-lasting snow cover, and low solar zenith angles (Karlsen et al., 2021; Macias-Fauria et al., 2017). Previous research indicates that between 1985 - 2015, NDVImax (or annual peak greenness) increased 29% across vegetated parts of Svalbard, a trend that was positively correlated with increased summer temperatures (Vickers et al., 2016). As yet, there has been no research into the correspondence between nutrient enrichment and satellite-derived greening trends in Svalbard, despite bird-cliff vegetation being naturally nutrient-enriched due to high prevalence of bird guano (Odasz, 1994; Solheim et al., 1996; Zwolicki et al., 2013).

Over the last three decades, many tundra plants have exhibited earlier reproductive phenology in response to warmer summer temperatures, and at a rate of change faster than the planet's more temperate regions (Høye et al., 2007; Panchen & Gorelick, 2017; Prevéy et al., 2019; Wookey et al., 1993). Likewise, late-season senescence phenophases have shifted later across many Arctic sites (Collins et al., 2021; Liu et al., 2016; Marchand et al., 2004). In High Arctic regions, such as Svalbard, the transition between vegetation phenophases (e.g. bud burst to flowering, or leaf-out to senescence) often occurs at lower thermal thresholds than observed in low- or sub-Arctic regions (Oberbauer et al., 2013; J. Prevéy et al., 2017). Utilising NDVI data derived from MODIS, Karlsen et al., (2014) found no clear trend in the timing of the onset of plant growth across Svalbard between 2000 and 2013. Furthermore, the detection of early season phenology from satellite-derived imagery corresponds well to *in-situ* observations from timelapse cameras (Karlsen et al., 2021). There is evidence to suggest that nutrient-enriched tundra vegetation exhibits higher - and earlier - peak-season greenness (Andresen et al., 2018), but as yet no research into the plant phenology at animal husbandry sites in the Arctic.

Considering the diversity of animal husbandry practises across the archipelago, and recent development of novel methods to harness and process moderate-resolution Landsat imagery (Berner et al., 2023), we intended to quantify the extent to which tundra greening is being enhanced by human management of dogs and livestock in the High Arctic. The main objective of this study was to **investigate the impact of historical and contemporary animal husbandry associated disturbance on the tundra vegetation in Svalbard**. We examined satellite time series of vegetation greenness immediately surrounding animal husbandry sites, and reference sites across the central and western regions of Svalbard. Our key research questions were **(1) are animal husbandry sites experiencing more tundra greening than non-disturbed tundra vegetation?**, and **(2) is the timing of the growing season different at animal husbandry sites in comparison to non-disturbed tundra vegetation?** We hypothesised that nutrient enrichment at contemporary and historic animal husbandry sites would lead to higher average NDVI and more rapid greening in comparison to areas where no livestock or sled dogs have been kept. We also hypothesised that the growing season would begin earlier and end later at animal husbandry sites in comparison to the non-disturbed sites.

2. **Methods:**

2.1. Study Sites

For this analysis, we selected 31 sites across Svalbard at the location of historical or contemporary dog, pony, pig, or cattle husbandry, in addition to sites with active seabird-cliffs, plus sites of undisturbed vegetation. Sites were classified into five different land use types: historic animal husbandry; active stable; active dog yards; seabird cliff vegetation; and reference sites (Figure 1). We included 12 active dog yards, one Icelandic pony stable that remains active as of 2022, and four historical husbandry sites, including abandoned pig farms, dog yards, and cattle-sheds. To compare vegetation greening trends between animal husbandry sites and in areas without human disturbance, we included six seabird-cliff vegetation sites and eight reference tundra sites. We selected locations for the seabird-cliff vegetation based on the greenest visible points on summer satellite imagery at each site, and selected reference points to cover a range of underlying geological and climatic conditions across the Isfjorden and Kongsfjorden coastlines of Spitsbergen. We used QGIS software (QGIS Team, 2022) to draw polygons around the extent of the animal husbandry locations (yards hereafter), and used the *terra* package in *R* (Hijmans, 2022) to create a 50m radius 'doughnut' around the yard perimeter, with a void space representing the location of the yard to include the surrounding vegetation, but exclude the non-vegetated dog yard. For the seabird-cliff and reference sites, we generated circular polygons using a 50 m buffer radius from each selected location.

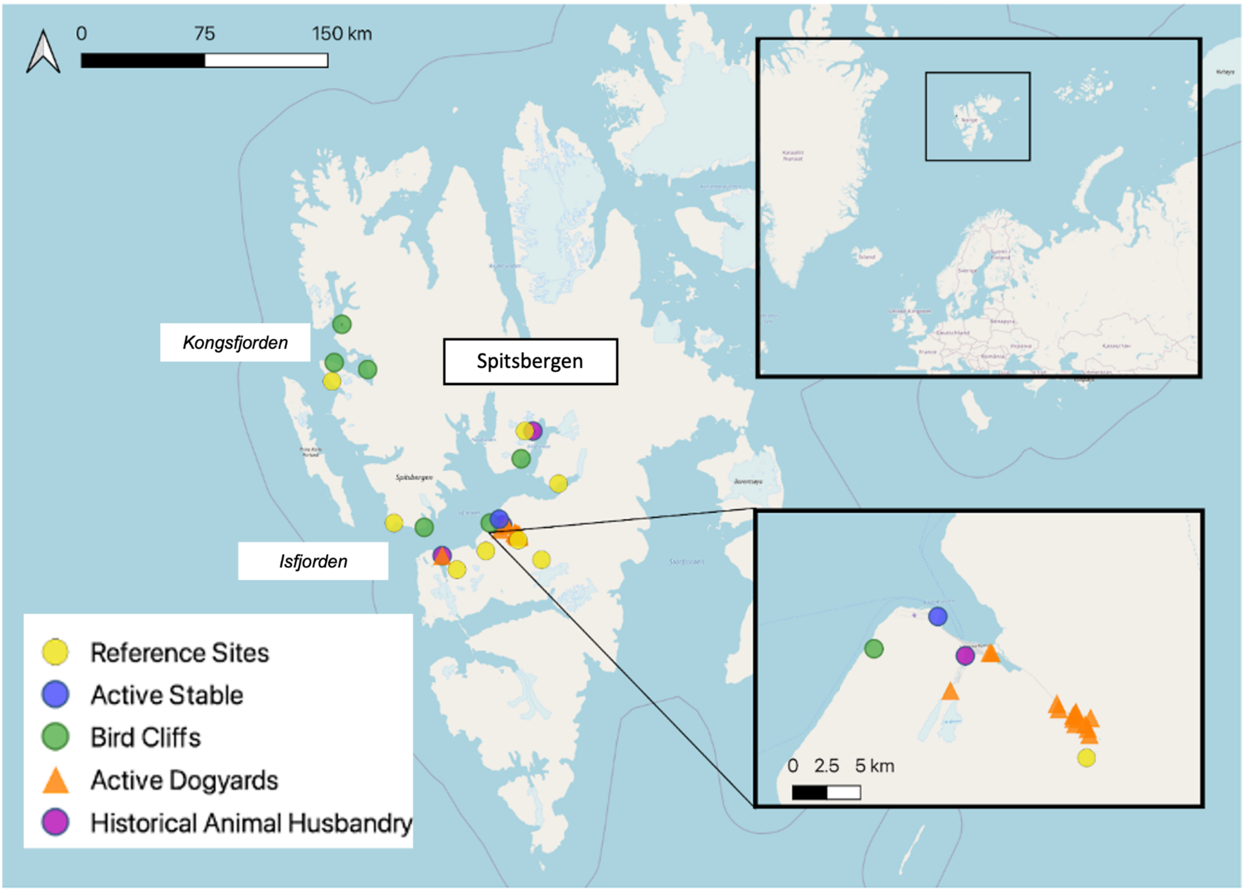


Figure 1: Location of active and historical animal husbandry sites, reference sites and seabird cliffs. Inset 1: Location of Svalbard. Inset 2: Location of sites in the Longyearbyen area.

2.2. Landsat satellite data processing

For each study site, we generated a time series of vegetation greenness from 1985-2021, using surface reflectance measurements from the Landsat satellites. To generate these vegetation greenness time series, we used the newly developed *LandsatTS* software package (Berner et al., 2023) for R (R Core Team 2022). This software package enables users to easily extract Landsat data archived on Google Earth Engine (GEE; Gorelick et al. 2017) and then conduct quality screening, cross-sensor calibration, and phenological modelling. Specifically, we first identified all 30 x 30 m Landsat grid cells that overlapped with each study site polygon and then extracted all Landsat 5, 7, and 8 surface reflectance measurements that were made from May through late September between 1985 and 2021. To ensure the subsequent analysis used high-quality measurements acquired under clear-sky conditions, we filtered out measurements affected by snow, surface water, clouds, or shadows, as well as measurements taken at low solar zenith angles. We derived NDVI using the surface reflectance measurements and because there are systematic differences in NDVI among Landsat sensors (Ju and Masek 2016; Berner et al. 2020), we then further cross-calibrated this metric using random forests that adjusted Landsat 5 and 8 NDVI to match Landsat 7 NDVI based on relationships built from years with overlapping observations. Lastly, we fit phenological models to the NDVI time series at each site, which allowed us to estimate the magnitude and timing of annual maximum NDVI (NDVImax). A prior study showed similar estimates of Landsat NDVImax were positively correlated with field measurements of annual shrub growth, sedge productivity, and ecosystem productivity at sites across the Arctic (Berner et al. 2020).

2.3. Extracting NDVImax values and phenophase dates

Using our daily cross-calibrated NDVI observations generated using the *LandsatTS* package, we extracted key phenophase dates to summarise growing season characteristics across each study site. First, we calculated NDVImax (highest NDVI value for each pixel per year) across the dataset. We then calculated first occurrence of 50% of NDVImax, or ‘green-up’ (amplification in greenness - NDVImax: 100%, NDVImin: 0%), and last occurrence of 50% of NDVImax, or ‘senescence’ (reduction in greenness - NDVImax: 100%, NDVImin: 0%), averaged between pixels for each site and for each year. We did not calculate any earlier or later phenophases (e.g. spring snowmelt or autumn snow return) due to lack of data in these periods due to the filtering out of cloudy data, or data where the solar zenith is too low. Using these data, we evaluated the change over time of key phenophases for each of the animal husbandry and reference sites.

2.4. Statistical Analysis

We used linear mixed effects methods to run three regression models: one to model the change in NDVImax over time across the land use types, one to model the change in green-up date over time across land use types, and one to model the change in senescence date across land use types. For the NDVImax model, we used NDVImax as the response variable, with year (1985-2021) and the classification for land use types (stable, dog yard, historical site, reference site, or bird cliffs) as interacting fixed effects (year*type). This interaction was designed to allow us to compare different greening trends across the land use types included in this study. Similarly, for our phenology models, the timing of either green-up or senescence was used as the response variable, with year and land use type as interacting fixed effects (year*type). For each of our models, we included both "site" and "year" as random effects, because many of the sites are geographically close to one another, and we intended to account for similar conditions across neighbouring sites in the same years. We ran the model using the lme4 package (Bates et al., 2015) in R version 3.6.3 (R Core Team, 2013). All of the code and data used in this research study can be downloaded here**:** **https://github.com/EliseGallois/SvalbardDogHub/tree/main** .

3. Results:

Although NDVImax increased from 1985-2021 across all sites, there were significantly greater changes in NDVImax at the historic and contemporary animal husbandry sites compared to the seabird-cliff and reference sites (Figure 2; Table S1). Over these 36 years, NDVImax significantly ($p < 0.001$) increased 44% ± 0.99% at the dog yards and 39% ± 1.24% at the historical husbandry sites, but only 22% ± 4.96% at the bird cliffs and 26% ± 1.19% at the reference sites, which had higher initial greenness in the 1980s. As such, NDVImax at the dog yards increased 18% more, and the historical sites increased 13% more than the reference sites. In contrast to other animal husbandry sites, the active pony stable has the lowest overall NDVImax (0.22) and the smallest long-term increase in NDVImax (33% ± 1.2%), although there appears to be a jump to higher NDVImax post-2012.

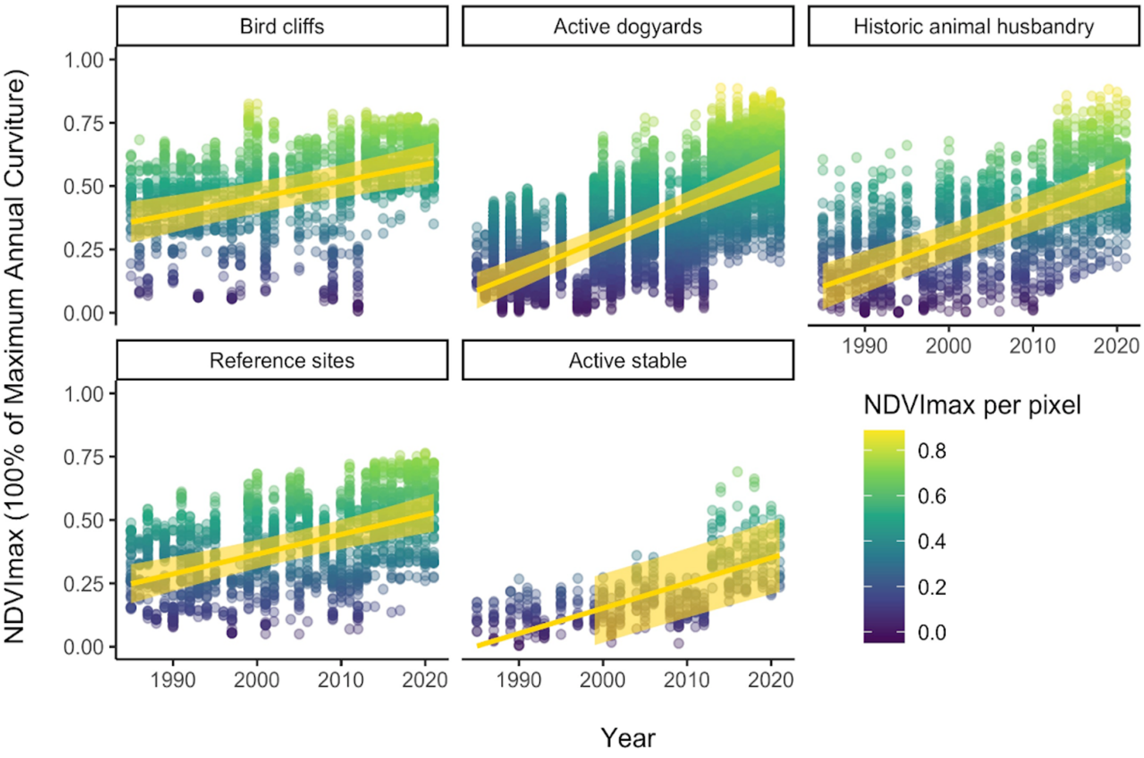


Figure 2: Changes in Landsat NDVImax from 1985 to 2021 for each of the five land use categories. The most pronounced increases occurred at the active dog yards and the historical husbandry sites, which both have much lower intercepts than the bird cliffs and reference sites. Each point represents the annual NDVImax value for each pixel for each year (*n* = 11,919). The yellow ribbon represents 95% confidence intervals. Full outputs can be found in Supplementary materials (Table S1). Marginal $R^2 = 0.407$, conditional $R^2 = 0.714$.

The green-up date (first annual occurrence 50% of NDVImax at each site) shifted earlier at each site - although at different magnitudes (Figure 3, Table S2). Green-up at the active stable site shifted the earliest of all the sites, despite showing relatively limited greening overall (Figure 2; Figure 3) -

green-up here is taking place 0.81 days earlier per year (± 0.09, p = <0.001). Meanwhile, the date of senescence appears to occur slightly later in the growing season across all sites (Table S3). At the active dog yards, the date of senescence has remained fairly static between 1985-2021, only occurring 0.06 days later per year (± 0.12, p = 0.001). Green-up appears to be occurring earlier across all land use types, and senescence appears to be occurring slightly later across all land use types - indicating a gradual lengthening of the growing seasons regardless of animal husbandry practises or seabird activity, though this lengthening is especially pronounced at the low-NDVI active stable site (Figure 3).

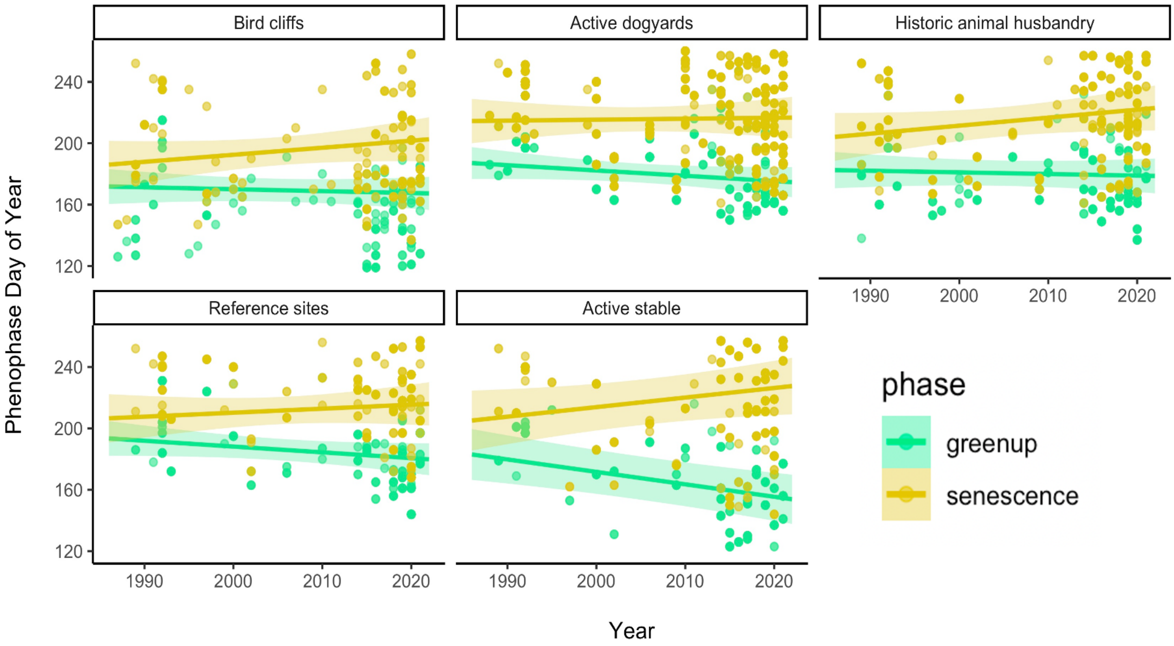


Figure 3: Earlier green-up across all land use types, and slightly delayed senescence over the time period 1985-2021. The active stable is experiencing a lengthening growing season. Each point represents the green-up (green) or senescence (gold) date of occurrence value averaged across pixels for each site for each year (n = 5,217). The gold and green ribbons represent 95% confidence intervals. Full outputs can be found in Supplementary materials (Tables S2 and S3). Greenup Model Marginal R^2 = 0.134, conditional R^2 = 0.596. Senescence Model Marginal R^2 = 0.048, conditional R^2 = 0.464.

4. Discussion:

Nutrient availability is a key limitation on vegetation productivity both globally and within Arctic tundra (Andresen & Lougheed, 2021; Atiyeh et al., 2002; Boelman et al., 2003; Amara & Mourad, 2013; Jónsdóttir et al., 2005), yet nutrient inputs from animal husbandry could alleviate these limitations thereby increasing vegetation productivity. Our analysis revealed that during the past four decades the largest increases in vegetation greenness (i.e. productivity) occurred at the dog yards (+44%) and other animal husbandry (+39%) sites, whereas changes in vegetation greenness were less pronounced at the reference sites (+22%). More rapid increases in vegetation greenness at the animal husbandry sites likely reflects the fact that vegetation has greater access to N and P due to nutrient inputs from faeces, urine, and fodder. Increased access to nutrients could then enable vegetation to grow larger, leafier, and more productively, especially as in many areas, growing seasons have become longer with warming in recent decades (e.g. Zeng et al., 2013). These patterns are broadly consistent with prior research showing that soil nutrient availability mediates the effects of climate warming on vegetation productivity in northern ecosystems (Berner & Goetz, 2022; Gignac et al., 2022; Sullivan et al., 2015). Furthermore, additional nutrient leaching from poor waste management at animal husbandry sites into surrounding tundra are highly likely to be driving enhanced greening.

While the comparison between the active stable, active dog yards, and historic husbandry sites provides an imperfect space-for-time comparison, it must be considered whether the enhanced greening trend at the dog yards may be a result of continual generation of animal waste at the site versus remnant nutrients from previous waste management at the historic husbandry sites. It is also likely that the low-NDVI values and minimal greening trend at the stable site is a result of continual activity including extensive trampling, and refuse dumping at this site, both of which limit direct vegetation growth. In future analyses, it would be beneficial to work with the proprietors of the active yards to compare interannual NDVI variability to site-specific developments such as the expansion of yards and the digging of waste trenches.

Meanwhile, vegetation greenness steadily increased at the seabird cliffs and tundra reference sites during recent decades, but not as rapidly as at the animal husbandry sites. The “baseline” greening trend at the reference sites is consistent with previous research on Svalbard. For example, NDVImax was reported to have increased by 29% across parts of Svalbard from 1985 to 2015 - a trend that was found to be positively correlated with increased mean summer temperatures (Vickers et al., 2016). Meanwhile, seabird cliffs experienced a 22% increase in NDVImax over the study period, but had a higher “baseline” productivity in the 1980s than the other sites. These sea bird cliffs have colonies of little auks (*Alle alle*), guillemots (*Uria lomvia*) and kittiwakes (*Rissa tridactyla*), and the soils below the cliffs contains high levels of nutrients enriched by bird guano (Odasz, 1994; Solheim et al., 1996; Zwolicki et al., 2013). Bird guano has been previously identified as a key nutrient source in the otherwise low-nutrient polar tundra of Svalbard (Solheim et al., 1996). The bird cliff vegetation is classified as ‘Near Threatened’ on the Norwegian Red List for nature (Arnesen et al., 2018) and has been described as “luxuriant communities" and “the only true meadows on Svalbard” (Elvebakk, 1994). A key unknown is whether greening trends will continue or stagnate at the nutrient-rich bird cliffs, animal husbandry sites, and other locations across Svalbard. Future changes in vegetation greenness may depend on the relative influence of enhanced nutrients as a source of fertilisation and the introduction and establishment of non-native plant species versus negative feedbacks such as increased drought stress, rain-on-snow events, changing marine food resources for shore birds, increased bare ground cover due to permafrost thaw, or a non-linear link between climate warming and photosynthesis (Bjerke, 2011; Bjerke et al., 2017; Myers-Smith et al., 2020; Piao et al., 2014). See Fig. 4 for individual case studies across each land-use type.

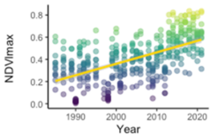
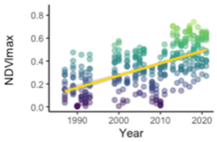
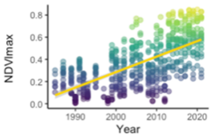
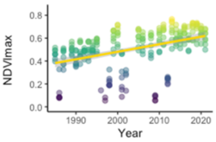
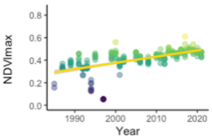
Abandoned Livestock	Abandoned Dog yard	Active Dog yard	Bird Cliff	Natural tundra
				
				
Longyearbyen barn Abandoned 60 years ago Geology: Glacial fluvial deposit	Nybyen dog yard Abandoned ~15 years ago Geology: Glacial fluvial deposit	Adventdalen private dog yard* In use for >10 years Geology: Glacial fluvial deposit **images presented with owners permission*	Alkhornet Bird cliff ~20,000 individuals Geology: Løvliebreen Lithology: psammo-pelitic phyllite, quartzite	Festningen Natural tundra site Geology: Tvillingodden Lithology: shale, siltstone, sandstone

Figure 4: Case studies of individual sites used for each land-use type, each showing an increase in NDVImax over 36 years. Photographs taken by Kristine Bakke Westergaard and Jesamine Bartlett. See Figure S1 for a scatterplot for each site included in the study.

We observed a shift toward earlier green-up across all sites along with a slight shift towards later senescence. Studies using NDVI as a proxy of phenology are common in the Arctic (Assmann et al., 2020; Zeng et al., 2013), but sparse in High Arctic Svalbard, where low solar zenith angles, cloud and snow cover make it difficult to harness adequate spring and autumn data. An analysis of MODIS NDVI found no clear trend in the timing of the onset of plant growth across Svalbard between 2000 and 2013 (Karlsen et al., 2014). Using the much shorter Sentinel time series, Karlsen et al. (2021) found close correspondence between NDVI time series and *in-situ* timelapse camera data - although the results of these two studies are not easily comparable with ours as their threshold for greenup was 70% of NDVImax, whereas we had enough filtered Landsat data to extract 50% greenup, which we believe to be more representative of spring plant phenophases. Growing season ‘greening’ curves of Svalbard reveal varying growing season characteristics dependent on the community composition of the landscape - for example graminoid-dominated plots (similar to many of the sites included in this study) exhibiting a clear and sharp greenness peak (Anderson et al., 2016), which can be seen in many of the dog yard sites (see Fig. S2). Semenchuk et al. (2016) argue that while the timing of the Svalbard growing season onset can be influenced by abiotic factors, the timing between each phenophase among native species may be ‘fixed’, while non-native species may exhibit ‘aperiodicity’, allowing for uncoupled timing of early- and late-season phenophases. This idea merits further analysis. Future vegetation surveys at these sites such as those undertaken focussing on non-native plant species across settlements and selected seabird cliffs in Svalbard by the Norwegian Polar Institute, could characterise the presence and abundance of native versus non-native species to further understand factors that affect changes in growing season length, community composition, and vegetation greenness (see active stable in Fig. 3).

Enhanced greening at animal husbandry sites could lead to cascading ecosystem impacts in the surrounding tundra. Pink-footed geese (*Anser brachyrhynchus*) arrive in Svalbard during spring and preferentially grub at wetter, low-lying, vegetated tundra sites, such as those around Adventdalen (Speed et al., 2009)**.** Geese and other migratory bird species are common in the vicinity of dog yards around Longyearbyen, where many observers speculate that the presence of the sled dogs scare away native predators such as the Arctic fox (*Vulpes lagopus*). Shifting phenologies can also impact animal movements and behaviour in the region. Svalbard reindeer (*Rangifer tarandus platyrhynchus*) preferentially select grazing grounds in areas with high plant biomass (Van der Wal et al., 2000) - for example in the lush meadows as observed in the proximity of animal husbandry sites (personal observations - J. Bartlett and K.B. Westergaard). Plant biomass quantity and seasonal availability may vary due to different nutrient enrichment levels and presence of alien species across the tundra. Across the Arctic, herbivore species richness is positively associated with plant productivity (Barrio et al., 2016). Additionally, plant-pollinator visitations may also be vulnerable to change as a result of phenological mismatches (Gillespie et al., 2016; Hegland et al., 2009; Memmott et al., 2007). Animal husbandry sites act as hotspots for the introduction and establishment of non-native plants (Bartlett et al., 2021) and activities such as importing feed for the animals in addition to increased footfall from increased human activity can promote repeated dispersal events to the tundra surrounding these husbandry sites. For example, *Ranunculus aris* and *Veronica longifolia*, both non-native species, have been observed growing metres away from their original hotspots near animal husbandry sites in Barentsburg (personal observation by K.B. Westergaard). There is scope, therefore, for future analysis on changing conditions at animal husbandry sites, and the various interacting environmental and interspecies processes in the surrounding tundra landscape.

As the number of tourists continues to grow in Svalbard (Meyer, 2016)**,** it is likely that the demand for activities such as dog sledding will remain high. Currently, no regulations or guidance for waste management exist, therefore it may be prudent to consider implementing a waste management policy that reduces, or manages, the level of nutrient run-off from these animal husbandry sites into the surrounding tundra landscape. Our analysis indicates significantly enhanced tundra greening where sled dogs or livestock are actively or were historically kept. Sites with disturbed soil are known hotspots for establishment of non-native plant species in cold regions (Alsos et al., 2015; Bartlett et al., 2021; Lembrechts et al., 2016), therefore our results could be used to inform a future updated action plan on non-native species on Svalbard. For example further raising the profile of public facing biosecurity information schemes / tourist outreach such as 'Stop Arctic Aliens' (https://www.stoparcticaliens.com/) can reduce the introduction of further non-native species, and by assessing the origin, use and disposal of hay and fodder used in animal husbandry on the island a potentially large propagule pressure could be minimised. Further research should incorporate nutrient content and soil chemistry analysis from collected samples across contemporary and historic animal husbandry sites, bird cliffs, and undisturbed tundra sites. Given the potential of animal waste, and in particular that of *Canids*, microbiome pollution and the risk of pathogen exposure to the native mammalian population (especially from the Arctic fox), should also be included when considering the environmental impact of a growing dog population (Elmore et al., 2013; Mandarino-Pereira et al., 2010; Skirnisson et al., 1993; Tamponi et al., 2020). It would also be prudent to examine the influence of local topography and hydrology on nutrient movement at these sites, and quantify the scale and influence of excess nutrient runoff on the surrounding tundra ecosystem. It will be increasingly important to monitor and manage the mounting impacts of tourism and animal husbandry not only in Svalbard, but also more broadly across the rapidly warming Arctic.

5. Conclusion:

We found that peak-season vegetation greenness increased over the past four decades across all of the study sites in Svalbard, yet the rate of greening was much higher at the active dog yards and historic animal husbandry sites. These sites are known hotspots for non-native plants (Bartlett et al., 2021), which can form lush meadows around sites of active and abandoned animal husbandry. Furthermore, the date of green-up has shifted earlier, while the date of senescence has shifted slightly later over this period, with little difference across land use types. We were able to harness moderate resolution Landsat satellite observations to characterise long-term changes in vegetation greenness in an area that has previously been relatively understudied. The *LandsatTS* approach allowed us to strategically analyse time series data for hundreds of individual pixels across Svalbard with relative ease, and can be applied to future analyses of anthropogenic impacts on tundra ecosystems.

Our analysis showed animal husbandry increases surrounding tundra productivity, with lasting impacts even at historic animal husbandry sites. Overall, if the number of sled dogs continues to increase in Svalbard, and both the number of tourists and demand for activities such as dog sledding increase (‘This Is Svalbard 2016. What the Figures Say’, n.d.), then we should expect to see further enhanced greening across the easily-accessible central fjord region of Spitsbergen if waste management and biosecurity strategies are not established to control excess nutrient enrichment or reduce the spread of non-native plants. We recommend further research at these sites to disentangle the interactions between nutrient enrichment, runoff, non-native species, vegetation greening, and faunal interactions.

Reference List

Alsos, I. G., Ware, C., & Elven, R. (2015). Past Arctic aliens have passed away, current ones may stay. *Biological Invasions*, *17*(11), 3113–3123. https://doi.org/10.1007/s10530-015-0937-9

Anderson, H. B., Nilsen, L., Tømmervik, H., Karlsen, S. R., Nagai, S., & Cooper, E. J. (2016). Using Ordinary Digital Cameras in Place of Near-Infrared Sensors to Derive Vegetation Indices for Phenology Studies of High Arctic Vegetation. *Remote Sensing*, *8*(10), Article 10. https://doi.org/10.3390/rs8100847

Andresen, C. G., & Lougheed, V. L. (2021). Arctic aquatic graminoid tundra responses to nutrient availability. *Biogeosciences*, *18*(8), 2649–2662. https://doi.org/10.5194/bg-18-2649-2021

Andresen, C. G., Tweedie, C. E., & Lougheed, V. L. (2018). Climate and nutrient effects on Arctic wetland plant phenology observed from phenocams. *Remote Sensing of Environment*, *205*, 46–55. https://doi.org/10.1016/j.rse.2017.11.013

Arlov, Thor Bjørn. (1994) A short history of Svalbard. 1994. ISBN 82-90307-55-1. Polarhåndbok nr. 4.

Arnesen, G., Hassel, K. and Elven, R. (2018). Fuglefjell meadow, Svalbard. Norwegian red list for nature types 2018. Species data bank, Trondheim. Retrieved (22nd June 2023) from: https://artsdatabanken.no/RLN2018/123

Assmann, J. J., Myers-Smith, I. H., Kerby, J. T., Cunliffe, A. M., & Daskalova, G. N. (2020). Drone data reveal heterogeneity in tundra greenness and phenology not captured by satellites. *Environmental Research Letters*, *15*(12), 125002.

Atiyeh, R. M., Arancon, N. Q., Edwards, C. A., & Metzger, J. D. (2002). The influence of earthworm-processed pig manure on the growth and productivity of marigolds. *Bioresource Technology*, *81*(2), 103–108. https://doi.org/10.1016/S0960-8524(01)00122-5

Barrio, I. C., Bueno, C. G., Gartzia, M., Soininen, E. M., Christie, K. S., Speed, J. D. M., Ravolainen, V. T., Forbes, B. C., Gauthier, G., Horstkotte, T., Hoset, K. S., Høye, T. T., Jónsdóttir, I. S., Lévesque, E., Mörsdorf, M. A., Olofsson, J., Wookey, P. A., & Hik, D. S. (2016). Biotic interactions mediate patterns of herbivore diversity in the Arctic. *Global Ecology and Biogeography*, *25*(9), 1108–1118. https://doi.org/10.1111/geb.12470

Bartlett, J. C., Westergaard, K. B., Paulsen, I. M. G., Wedegärtner, R. E. M., Wilken, F., & Ravolainen, V. (2021). Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments. *Ecological Solutions and Evidence*, *2*(1), e12056. https://doi.org/10.1002/2688-8319.12056

Berner, L. T., Assmann, J. J., Normand, S., & Goetz, S. J. (n.d.). 'LandsatTS': An R package to facilitate retrieval, cleaning, cross-calibration, and phenological modeling of Landsat time series data. *Ecography*, *(2023*), e06768. https://doi.org/10.1111/ecog.06768

Berner, L. T., & Goetz, S. J. (2022). Satellite observations document trends consistent with a boreal forest biome shift. *Global Change Biology*, *28*(10), 3275–3292. https://doi.org/10.1111/gcb.16121

Berner, L. T., Massey, R., Jantz, P., Forbes, B. C., Macias-Fauria, M., Myers-Smith, I., Kumpula, T., Gauthier, G., Andreu-Hayles, L., Gaglioti, B. V., Burns, P., Zetterberg, P., D'Arrigo, R., & Goetz, S. J. (2020). Summer warming explains widespread but not uniform greening in the Arctic tundra biome. *Nature Communications*, *11*(1), Article 1. https://doi.org/10.1038/s41467-020-18479-5

Bhatt, U. S., Walker, D. A., Raynolds, M. K., Bieniek, P. A., Epstein, H. E., Comiso, J. C., Pinzon, J. E., Tucker, C. J., & Polyakov, I. V. (2013). Recent Declines in Warming and Vegetation Greening Trends over Pan-Arctic Tundra. *Remote Sensing*, *5*(9), Article 9. https://doi.org/10.3390/rs5094229

Bjerke, J. W. (2011). Winter climate change: Ice encapsulation at mild subfreezing temperatures kills freeze-tolerant lichens. *Environmental and Experimental Botany*, *72*(3), 404–408. https://doi.org/10.1016/j.envexpbot.2010.05.014

Bjerke, J. W., Treharne, R., Vikhamar-Schuler, D., Karlsen, S. R., Ravolainen, V., Bokhorst, S., Phoenix, G. K., Bochenek, Z., & Tømmervik, H. (2017). Understanding the drivers of extensive plant damage in boreal and Arctic ecosystems: Insights from field surveys in the aftermath of damage. *Science of the Total Environment*, *599–600*, 1965–1976. https://doi.org/10.1016/j.scitotenv.2017.05.050

Boelman, N. T., Stieglitz, M., Rueth, H. M., Sommerkorn, M., Griffin, K. L., Shaver, G. R., & Gamon, J. A. (2003). Response of NDVI, biomass, and ecosystem gas exchange to long-term warming and fertilization in wet sedge tundra. *Oecologia*, *135*(3), 414–421. https://doi.org/10.1007/s00442-003-1198-3

Bokhorst, S., Bjerke, J. W., Bowles, F. W., Melillo, J., Callaghan, T. V., & Phoenix, G. K. (2008). Impacts of extreme winter warming in the sub-Arctic: Growing season responses of dwarf shrub heathland. *Global Change Biology*, *14*(11), 2603–2612. https://doi.org/10.1111/j.1365-2486.2008.01689.x

Collins, C. G., Elmendorf, S. C., Hollister, R. D., Henry, G. H. R., Clark, K., Bjorkman, A. D., Myers-Smith, I. H., Prevéy, J. S., Ashton, I. W., Assmann, J. J., Alatalo, J. M., Carbognani, M., Chisholm, C., Cooper, E. J., Forrester, C., Jónsdóttir, I. S., Klanderud, K., Kopp, C. W., Livensperger, C., … Suding, K. N. (2021). Experimental warming differentially affects vegetative and reproductive phenology of tundra plants. *Nature Communications*, *12*(1), Article 1. https://doi.org/10.1038/s41467-021-23841-2

Coulson, S. J., Fjellberg, A., Gwiazdowicz, D. J., Lebedeva, N. V., Melekhina, E. N., Solhøy, T., Erséus, C., Maraldo, K., Miko, L., Schatz, H., Schmelz, R. M., Søli, G., & Stur, E. (2013). Introduction of invertebrates into the High Arctic via imported soils: The case of Barentsburg in the Svalbard. *Biological Invasions*, *15*(1), 1–5. https://doi.org/10.1007/s10530-012-0277-y

Doetterl, S., Alexander, J., Fior, S., Frossard, A., Magnabosco, C., van de Broek, M., & Westergaard, K. B. (2022). Will accelerated soil development be a driver of Arctic Greening in the late 21st century?#. *Journal of Plant Nutrition and Soil Science*, *185*(1), 19–23. https://doi.org/10.1002/jpln.202100334

Elmore, S. A., Lalonde, L. F., Samelius, G., Alisauskas, R. T., Gajadhar, A. A., & Jenkins, E. J. (2013). Endoparasites in the feces of arctic foxes in a terrestrial ecosystem in Canada. *International Journal for Parasitology: Parasites and Wildlife*, *2*, 90–96. https://doi.org/10.1016/j.ijppaw.2013.02.005

Elvebakk, A. (1994). A survey of plant associations and alliances from Svalbard. *Journal of Vegetation Science*, *5*(6), 791–802. https://doi.org/10.2307/3236194

Forbes, B. C., Fauria, M. M., & Zetterberg, P. (2010). Russian Arctic warming and 'greening' are closely tracked by tundra shrub willows. *Global Change Biology*, *16*(5), 1542–1554. https://doi.org/10.1111/j.1365-2486.2009.02047.x

Ghemam Amara, D., & mohammed mourad, S. (2013). Influence of organic manure on the vegetative growth and tuber production of potato(solanumtuberosum L varspunta) in a Sahara desert region. *International Journal of Agriculture and Crop Sciences*, *5*, 2724–2731.

Gignac, C., Rochefort, L., Gauthier, G., Lévesque, E., Maire, V., Deschamps, L., Pouliot, R., & Marchand-Roy, M. (2022). N/P Addition Is More Likely Than N Addition Alone to Promote a Transition from Moss-Dominated to Graminoid-Dominated Tundra in the High-Arctic. *Atmosphere*, *13*(5), Article 5. https://doi.org/10.3390/atmos13050676

Gillespie, M. A. K., Baggesen, N., & Cooper, E. J. (2016). High Arctic flowering phenology and plant–pollinator interactions in response to delayed snow melt and simulated warming. *Environmental Research Letters*, *11*(11), 115006. https://doi.org/10.1088/1748-9326/11/11/115006

Hegland, S. J., Nielsen, A., Lázaro, A., Bjerknes, A.-L., & Totland, Ø. (2009). How does climate warming affect plant-pollinator interactions? *Ecology Letters*, *12*(2), 184–195. https://doi.org/10.1111/j.1461-0248.2008.01269.x

Hijmans, R.J. (2022). terra: Spatial Data Analysis. R package version 1.5-21. https://CRAN.R-project.org/package=terra

Høye, T. T., Post, E., Meltofte, H., Schmidt, N. M., & Forchhammer, M. C. (2007). Rapid advancement of spring in the High Arctic. *Current Biology*, *17*(12), R449–R451. https://doi.org/10.1016/j.cub.2007.04.047

Jónsdóttir, I. S., Khitun, O., & Stenström, A. (2005). Biomass and nutrient responses of a clonal tundra sedge to climate warming. *Canadian Journal of Botany*, *83*(12), 1608–1621. https://doi.org/10.1139/b05-129

Karlsen, S. R., Elvebakk, A., Høgda, K. A., & Grydeland, T. (2014). Spatial and Temporal Variability in the Onset of the Growing Season on Svalbard, Arctic Norway—Measured by MODIS-NDVI Satellite Data. *Remote Sensing*, *6*(9), Article 9. https://doi.org/10.3390/rs6098088

Karlsen, S. R., Stendardi, L., Tømmervik, H., Nilsen, L., Arntzen, I., & Cooper, E. J. (2021). Time-Series of Cloud-Free Sentinel-2 NDVI Data Used in Mapping the Onset of Growth of Central Spitsbergen, Svalbard. *Remote Sensing*, *13*(15), Article 15. https://doi.org/10.3390/rs13153031

Lembrechts, J. J., Pauchard, A., Lenoir, J., Nuñez, M. A., Geron, C., Ven, A., Bravo-Monasterio, P., Teneb, E., Nijs, I., & Milbau, A. (2016). Disturbance is the key to plant invasions in cold environments. *Proceedings of the National Academy of Sciences*, *113*(49), 14061–14066. https://doi.org/10.1073/pnas.1608980113

Liška, J., & Soldán, Z. (2004). Alien vascular plants recorded from the Barentsburg and Pyramiden settlements, Svalbard. *Preslia*, *76*(3), 279–290.

Liu, Q., Fu, Y. H., Zhu, Z., Liu, Y., Liu, Z., Huang, M., Janssens, I. A., & Piao, S. (2016). Delayed autumn phenology in the Northern Hemisphere is related to change in both climate and spring phenology. *Global Change Biology*, *22*(11), 3702–3711. https://doi.org/10.1111/gcb.13311

Macias-Fauria, M., Karlsen, S. R., & Forbes, B. C. (2017). Disentangling the coupling between sea ice and tundra productivity in Svalbard. *Scientific Reports*, *7*(1), Article 1. https://doi.org/10.1038/s41598-017-06218-8

Mandarino-Pereira, A., de Souza, F. S., Lopes, C. W. G., & Pereira, M. J. S. (2010). Prevalence of parasites in soil and dog feces according to diagnostic tests. *Veterinary Parasitology*, *170*(1), 176–181. https://doi.org/10.1016/j.vetpar.2010.02.007

Marchand, F. L., Nijs, I., Heuer, M., Mertens, S., Kockelbergh, F., Pontailler, J.-Y., Impens, I., & Beyens, L. (2004). Climate Warming Postpones Senescence in High Arctic Tundra. *Arctic, Antarctic, and Alpine Research*, *36*(4), 390–394. https://doi.org/10.1657/1523-0430(2004)036[0390:CWPSIH]2.0.CO;2

Memmott, J., Craze, P. G., Waser, N. M., & Price, M. V. (2007). Global warming and the disruption of plant–pollinator interactions. *Ecology Letters*, *10*(8), 710–717. https://doi.org/10.1111/j.1461-0248.2007.01061.x

Myers-Smith, I. H., Kerby, J. T., Phoenix, G. K., Bjerke, J. W., Epstein, H. E., Assmann, J. J., John, C., Andreu-Hayles, L., Angers-Blondin, S., Beck, P. S. A., Berner, L. T., Bhatt, U. S., Bjorkman, A. D., Blok, D., Bryn, A., Christiansen, C. T., Cornelissen, J. H. C., Cunliffe, A. M., Elmendorf, S. C., … Wipf, S. (2020). Complexity revealed in the greening of the Arctic. *Nature Climate Change*, *10*(2), Article 2. https://doi.org/10.1038/s41558-019-0688-1

Oberbauer, S. F., Elmendorf, S. C., Troxler, T. G., Hollister, R. D., Rocha, A. V., Bret-Harte, M. S., Dawes, M. A., Fosaa, A. M., Henry, G. H. R., Høye, T. T., Jarrad, F. C., Jónsdóttir, I. S., Klanderud, K., Klein, J. A., Molau, U., Rixen, C., Schmidt, N. M., Shaver, G. R., Slider, R. T., … Welker, J. M. (2013). Phenological response of tundra plants to background climate variation tested using the International Tundra Experiment. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *368*(1624), 20120481. https://doi.org/10.1098/rstb.2012.0481

Odasz, A. M. (1994). Nitrate reductase activity in vegetation below an arctic bird cliff, Svalbard, Norway. *Journal of Vegetation Science*, *5*(6), 913–920. https://doi.org/10.2307/3236203

Panchen, Z. A., & Gorelick, R. (2017). Prediction of Arctic plant phenological sensitivity to climate change from historical records. *Ecology and Evolution*, *7*(5), 1325–1338. https://doi.org/10.1002/ece3.2702

Piao, S., Nan, H., Huntingford, C., Ciais, P., Friedlingstein, P., Sitch, S., Peng, S., Ahlström, A., Canadell, J. G., Cong, N., Levis, S., Levy, P. E., Liu, L., Lomas, M. R., Mao, J., Myneni, R. B., Peylin, P., Poulter, B., Shi, X., … Chen, A. (2014). Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. *Nature Communications*, *5*(1), Article 1. https://doi.org/10.1038/ncomms6018

Prevéy, J. S., Rixen, C., Rüger, N., Høye, T. T., Bjorkman, A. D., Myers-Smith, I. H., Elmendorf, S. C., Ashton, I. W., Cannone, N., Chisholm, C. L., Clark, K., Cooper, E. J., Elberling, B., Fosaa, A. M., Henry, G. H. R., Hollister, R. D., Jónsdóttir, I. S., Klanderud, K., Kopp, C. W., … Wipf, S. (2019). Warming shortens flowering seasons of tundra plant communities. *Nature Ecology & Evolution*, *3*(1), Article 1. https://doi.org/10.1038/s41559-018-0745-6

Prevéy, J., Vellend, M., Rüger, N., Hollister, R. D., Bjorkman, A. D., Myers-Smith, I. H., Elmendorf, S. C., Clark, K., Cooper, E. J., Elberling, B., Fosaa, A. M., Henry, G. H. R., Høye, T. T., Jónsdóttir, I. S., Klanderud, K., Lévesque, E., Mauritz, M., Molau, U., Natali, S. M., … Rixen, C. (2017). Greater temperature sensitivity of plant phenology at colder sites: Implications for convergence across northern latitudes. *Global Change Biology*, *23*(7), 2660–2671. https://doi.org/10.1111/gcb.13619

QGIS.org, 2022. QGIS Geographic Information System. QGIS Association. http://www.qgis.org

Raynolds, M. K., Walker, D. A., & Maier, H. A. (2006). NDVI patterns and phytomass distribution in the circumpolar Arctic. *Remote Sensing of Environment*, *102*(3), 271–281. https://doi.org/10.1016/j.rse.2006.02.016

Semenchuk, P. R., Gillespie, M. A. K., Rumpf, S. B., Baggesen, N., Elberling, B., & Cooper, E. J. (2016). High Arctic plant phenology is determined by snowmelt patterns but duration of phenological periods is fixed: An example of periodicity. *Environmental Research Letters*, *11*(12), 125006. https://doi.org/10.1088/1748-9326/11/12/125006

Skirnisson, K., Eydal, M., Gunnarsson, E., & Hersteinsson, P. (1993). PARASITES OF THE ARCTIC FOX (ALOPEX LAGOPUS) IN ICELAND. *Journal of Wildlife Diseases*, *29*(3), 440–446. https://doi.org/10.7589/0090-3558-29.3.440

Solheim, B., Endal, A., & Vigstad, H. (1996). Nitrogen fixation in Arctic vegetation and soils from Svalbard, Norway. *Polar Biology*, *16*(1), 35–40. https://doi.org/10.1007/BF01876827

Speed, J. D. M., Woodin, S. J., Tømmervik, H., Tamstorf, M. P., & van der Wal, R. (2009). Predicting Habitat Utilization and Extent of Ecosystem Disturbance by an Increasing Herbivore Population. *Ecosystems*, *12*(3), 349–359. https://doi.org/10.1007/s10021-009-9227-7

Steinfeld, H., & Wassenaar, T. (2007). The Role of Livestock Production in Carbon and Nitrogen Cycles. *Annual Review of Environment and Resources*, *32*(1), 271–294. https://doi.org/10.1146/annurev.energy.32.041806.143508

Sullivan, P. F., Ellison, S. B. Z., McNown, R. W., Brownlee, A. H., & Sveinbjörnsson, B. (2015). Evidence of soil nutrient availability as the proximate constraint on growth of treeline trees in northwest Alaska. *Ecology*, *96*(3), 716–727. https://doi.org/10.1890/14-0626.1

Tamponi, C., Knoll, S., Tosciri, G., Salis, F., Dessì, G., Cappai, M. G., Varcasia, A., & Scala, A. (2020). Environmental Contamination by Dog Feces in Touristic Areas of Italy: Parasitological Aspects and Zoonotic Hazards. *The American Journal of Tropical Medicine and Hygiene*, *103*(3), 1143–1149. https://doi.org/10.4269/ajtmh.20-0169

Team, R. C. (2013). *R: A language and environment for statistical computing.*

This is Svalbard 2016. What the figures say. (n.d.). *La Recherche*, 28.

Umbreit, A. (2009). *Spitsbergen*. Bradt Travel Guides.

Van der Wal, R., Madan, N., van Lieshout, S., Dormann, C., Langvatn, R., & Albon, S. D. (2000). Trading forage quality for quantity? Plant phenology and patch choice by Svalbard reindeer. *Oecologia*, *123*(1), 108–115. https://doi.org/10.1007/s004420050995

Vickers, H., Høgda, K. A., Solbø, S., Karlsen, S. R., Tømmervik, H., Aanes, R., & Hansen, B. B. (2016). Changes in greening in the high Arctic: Insights from a 30 year AVHRR max NDVI dataset for Svalbard. *Environmental Research Letters*, *11*(10), 105004. https://doi.org/10.1088/1748-9326/11/10/105004

Wookey, P. A., Parsons, A. N., Welker, J. M., Potter, J. A., Callaghan, T. V., Lee, J. A., & Press, M. C. (1993). Comparative Responses of Phenology and Reproductive Development to Simulated Environmental Change in Sub-Arctic and High Arctic Plants. *Oikos*, *67*(3), 490–502. https://doi.org/10.2307/3545361

Xu, R., Tian, H., Pan, S., Dangal, S. R. S., Chen, J., Chang, J., Lu, Y., Skiba, U. M., Tubiello, F.

N., & Zhang, B. (2019). Increased nitrogen enrichment and shifted patterns in the world's grassland: 1860–2016. *Earth System Science Data*, *11*(1), 175–187. https://doi.org/10.5194/essd-11-175-2019

Zeng, H., Jia, G., & Forbes, B. C. (2013). Shifts in Arctic phenology in response to climate and anthropogenic factors as detected from multiple satellite time series. *Environmental Research Letters*, *8*(3), 035036. https://doi.org/10.1088/1748-9326/8/3/035036

Zhu, Z., Piao, S., Myneni, R. B., Huang, M., Zeng, Z., Canadell, J. G., Ciais, P., Sitch, S., Friedlingstein, P., Arneth, A., Cao, C., Cheng, L., Kato, E., Koven, C., Li, Y., Lian, X., Liu, Y., Liu, R., Mao, J., … Zeng, N. (2016). Greening of the Earth and its drivers. *Nature Climate Change*, *6*(8), Article 8. https://doi.org/10.1038/nclimate3004

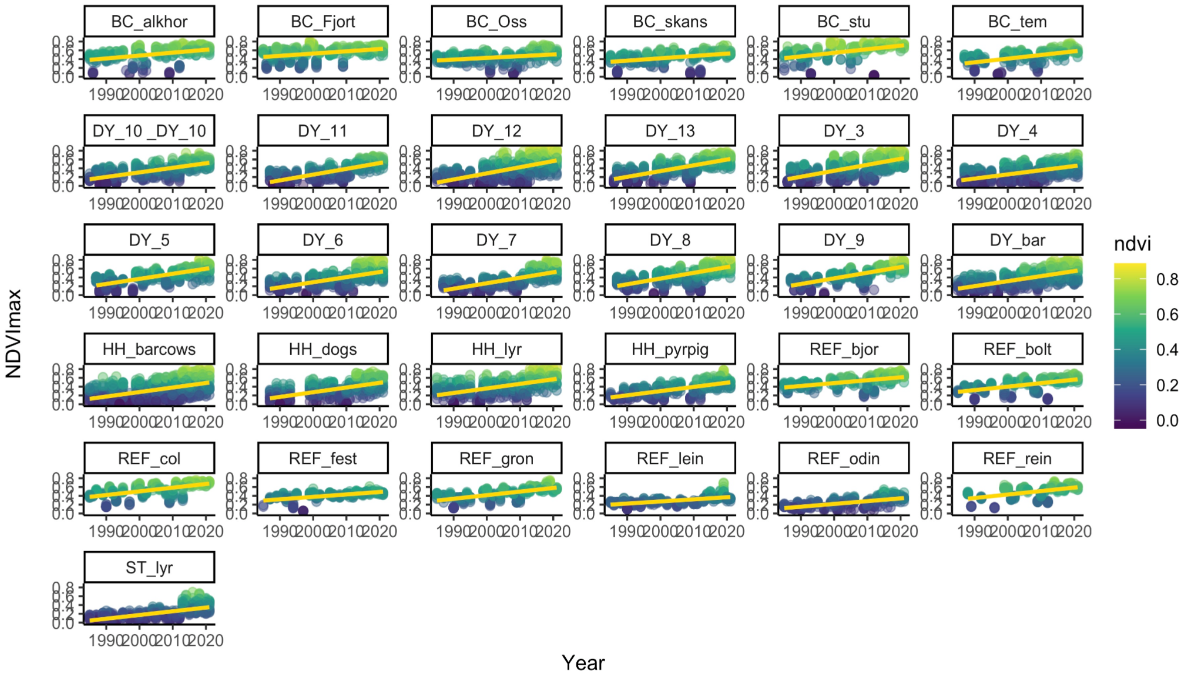
Zwolicki, A., Zmudczyńska-Skarbek, K. M., Iliszko, L., & Stempniewicz, L. (2013). Guano deposition and nutrient enrichment in the vicinity of planktivorous and piscivorous seabird colonies in Spitsbergen. *Polar Biology*, *36*(3), 363–372. https://doi.org/10.1007/s00300-012-1265-5

Supplementary Materials

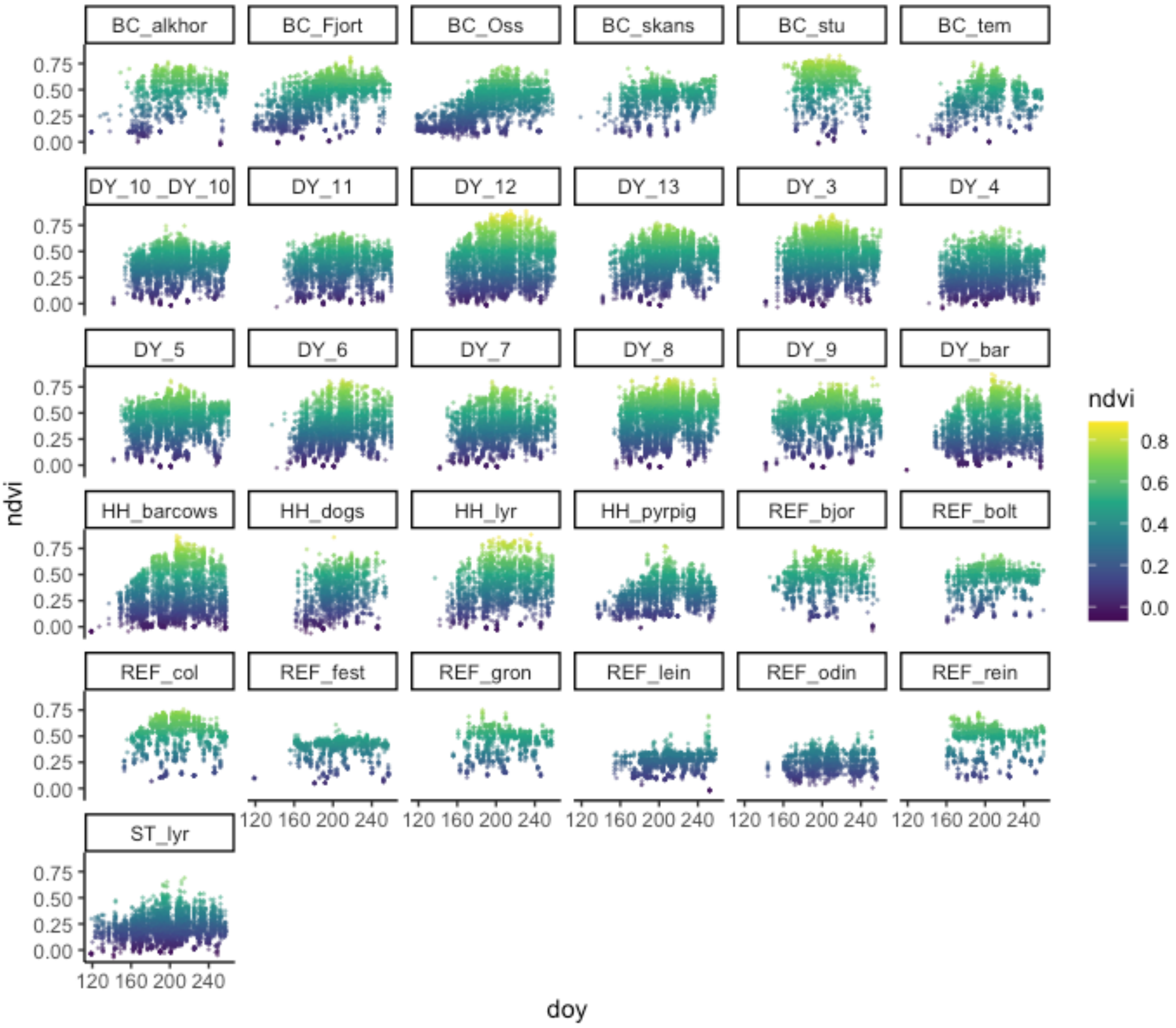
Supplementary Table 1: Statistical results for the hierarchical linear mixed models quantifying NDVImax trends across time across land use types across Svalbard. To account for variance within sites and within years, these models included 'Site' and 'Year' as a random effect. We included an interactive term between land use type and year to account for varying trends between land use types.

Predictors	*Estimates*	*95% Confidence Intervals*	*p-value*
year scaled (1 unit change = 1 year = 0.0924746)	0.064891	0.035684 – 0.094097	**<0.001**
type [Bird Cliffs]	0.487597	0.426219 – 0.548975	**<0.001**
type [Dog Yard]	0.358316	0.310325 – 0.406307	**<0.001**
type [Historical Husbandry]	0.336175	0.263978 – 0.408371	**<0.001**
type [Reference Site]	0.403992	0.348848 – 0.459135	**<0.001**
type [Active Stable]	0.201522	0.066297 – 0.336748	**0.003**
year scaled * type [Dog Yards]	0.070355	0.064493 – 0.076217	**<0.001**
year scaled * type [Historical Husbandry]	0.051280	0.044005 – 0.058554	**<0.001**
year scaled * type [Reference Site]	0.013073	0.006051 – 0.020095	**<0.001**
year scaled * type [Active Stable]	0.034627	0.023318 – 0.045936	**<0.001**
Random Effects			
σ^2	0.01		

$\tau_{00\ \text{yearfactor}}$	0.01
$\tau_{00\ \text{site}}$	0.00
ICC	0.52
N_{site}	31
$N_{\text{yearfactor}}$	36
Observations	11919
Marginal R^2 / Conditional R^2	0.407 / 0.714



Supplementary Figure 1: NDVImax trends over time for each of the individual animal husbandry, bird cliff and reference sites (1985-2021). Yellow lines represent linear model trends across time.



Supplementary Figure 2: ‘Greening curves’ showing NDVI values per day per pixel for each site between 1985-2021.

Supplementary Table 2: Statistical results for the hierarchical linear mixed models quantifying green-up (first annual occurrence of 50% NDVI) trends across time across land use types across Svalbard. To account for variance within sites and within years, these models included 'Site' and 'Year' as a random effect. We included an interactive term between land use type and year to account for varying trends between land use types.

	50% Green-up Day of Year		
Predictors	*Estimates*	*95% Confidence Intervals*	*p-value*
year	-0.12	-0.58 – 0.33	0.590
type [Bird Cliffs]	172.01	159.97 – 184.05	**<0.001**
type [Dog Yards]	187.75	176.64 – 198.86	**<0.001**
type [Historical Husbandry]	182.68	170.22 – 195.14	**<0.001**
type [Reference Site]	194.21	182.20 – 206.22	**<0.001**
type [Active Stable]	184.64	167.58 – 201.69	**<0.001**
year * type [Dog Yards]	-0.22	-0.37 – -0.07	**0.003**
year * type [Historical Husbandry]	0.02	-0.14 – 0.18	0.816
year * type [Reference Site]	-0.25	-0.44 – -0.07	0.007
year * type [Active Stable]	-0.69	-0.86 – -0.51	**<0.001**
Random Effects			
σ^2	183.72		

$\tau_{00\ \mathrm{site}}$	45.36
$\tau_{00\ \mathrm{yearfactor}}$	164.17
ICC	0.53
N_{site}	31
$N_{\mathrm{yearfactor}}$	30
Observations	5217
Marginal R^2 / Conditional R^2	0.134 / 0.596

Supplementary Table 3: Statistical results for the hierarchical linear mixed models quantifying senescence (last annual occurrence of 50% NDVI) trends across time across land use types across Svalbard. To account for variance within sites and within years, these models included 'Site' and 'Year' as a random effect. We included an interactive term between land use type and year to account for varying trends between land use types.

50% Senescence Day of Year			
Predictors	*Estimates*	*95% Confidence Interval*	*p-value*
year	0.46	-0.19 – 1.11	0.168
type [Bird Cliffs]	185.12	168.59 – 201.65	**<0.001**
type [Dog Yards]	214.33	198.80 – 229.86	**<0.001**
type [Historical Husbandry]	203.07	186.44 – 219.69	**<0.001**
type [Reference Site]	206.06	189.25 – 222.88	**<0.001**
type [Active Stables]	203.89	183.50 – 224.27	**<0.001**
year * type [Dog Yards]	-0.40	-0.63 – -0.16	**0.001**
year * type [Historical Husbandry]	0.06	-0.19 – 0.32	0.626
year * type [Reference Site]	-0.20	-0.50 – 0.10	0.192
year * type [Active Stables]	0.16	-0.11 – 0.44	0.248
Random Effects			

σ^2	483.70
$\tau_{00\ \text{site}}$	43.79
$\tau_{00\ \text{yearfactor}}$	332.35
ICC	0.44
N_{site}	31
$N_{\text{yearfactor}}$	30
Observations	5217
Marginal R^2 / Conditional R^2	0.048 / 0.464

Supplementary List 1: List of each of the sites included in this study, and their geographical coordinates, including their designated land use type category (reference site, sea bird cliff, active stable, active dog yard, and historical husbandry site).

Site ID	Longitude	Latitude	Land Use Type
SE_pyr	16.33809271	78.65861545	Reference Site
SE_bar	14.2072914	78.06545415	Reference Site
SE_lyr	15.64337532	78.21747757	Reference Site
SE_nya	11.93143419	78.92367236	Reference Site
BC_skans	16.05061449	78.5258734	Sea Bird Cliff
BC_bjorn	15.32445865	78.22608728	Sea Bird Cliff
BC_calk	13.78241852	78.2056042	Sea Bird Cliff
BC_coss	12.45798379	78.92939156	Sea Bird Cliff
BC_stu	11.67673827	78.96031893	Sea Bird Cliff
BC_fjort	11.85716114	79.12837728	Sea Bird Cliff
ST_lyr	15.52843196	78.2424	Active stable
DY_1	15.69634743	78.21836971	Active Dog Yard
DY_2	15.70280232	78.2178983	Active Dog Yard
DY_3	15.90621984	78.17850048	Active Dog Yard
DY_4	15.95978545	78.17572034	Active Dog Yard
DY_5	15.96003272	78.17482093	Active Dog Yard
DY_6	15.95069815	78.17162812	Active Dog Yard
DY_7	15.95097373	78.17363025	Active Dog Yard
DY_8	15.95589884	78.16810729	Active Dog Yard
DY_9	15.99475465	78.16436267	Active Dog Yard
DY_10	16.00623253	78.17115013	Active Dog Yard
DY_11	15.98770585	78.16724173	Active Dog Yard
DY_12	15.99865591	78.1602709	Active Dog Yard
DY_13	15.90074366	78.18198852	Active Dog Yard
DY_bar	14.20289478	78.07163141	Active Dog Yard
HH_lyr	15.61673116	78.21734448	Historical Husbandry
HH_barcows	14.20228343	78.07089356	Historical Husbandry
HH_pyrpigs	16.32663414	78.65267579	Historical Husbandry

HH_dogs	15.56085995	78.19546309	Historical Husbandry