Science of the Total Environment 793 (2021) 148619

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Springtime grazing by Arctic-breeding geese reduces first- and second-harvest yields on sub-Arctic agricultural grasslands

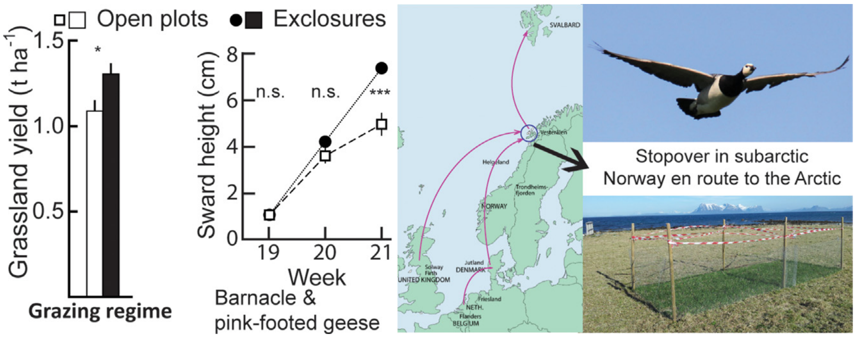
Jarle W. Bjerke [a,*], Ingunn M. Tombre [a], Marvell Hanssen [b,c], Anne Kari Bergjord Olsen [d]

[a] Norwegian Institute for Nature Research (NINA), Fram – High North research Centre for Climate and the Environment, P.O. Box 6606, Langnes N-9296, Norway
[b] Norsk landbruksrådgivning, Kleiva, N-8404 Sortland, Norway
[c] Lilandvegen 42, N-8407 Sortland, Norway
[d] Norwegian Institute of Bioeconomy Research (NIBIO), P.O. Box 115, N-1431 Ås, Norway

HIGHLIGHTS

- Subarctic agricultural grasslands are attractive stopover habitats for the Arctic-breeding pink-footed and barnacle geese.
- A warmer climate has contributed to increasing goose populations, with economic consequences for subarctic farmers.
- A field experiment excluding geese from grassland plots was run over three consecutive years.
- First and second harvest yields across fields and years were 19-20% higher in exclosures than in plots open for grazing.
- Cool spring weather led to slow sward development and little or no effects on harvest yields.
- It is unlikely that the current subsidy scheme is sufficient to cover the farmers' economic loss.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 5 January 2021
Received in revised form 11 June 2021
Accepted 19 June 2021
Available online 22 June 2021

Editor: Charlotte Poschenrieder

Keywords:
Agricultural conflict
Crop damage
Grazing intensity
Interannual variability

ABSTRACT

Large population increases of Arctic-breeding waterfowls over recent decades have intensified the conflict with agricultural interests in both Eurasia and North America. In the spring-staging region Vesterålen in sub-Arctic Norway, sheep, dairy and meat farmers have reported reduced agricultural grassland yields due to pink-footed geese *Anser brachyrhynchus* and barnacle geese *Branta leucopsis* that rest and forage in the region for 3–4 weeks in spring on their way to their breeding grounds on Svalbard. Here, we report from an experimental exclosure design where goose access to plots at three grassland fields in Vesterålen was prevented. The experiment was conducted over 3 years between 2012 and 2014. Goose abundance varied greatly between fields and years as a function of variable spring weather and forage quantity, facilitating evaluation of longer-term impacts under contrasting grazing intensities. First and second harvest yields across fields and years were 20% and 19% higher in exclosures than in plots open for grazing, while total yields (sum of first and second harvests) were on average 27% higher. Within-year effects on harvest yields varied substantially, primarily due to highly contrasting sward development during the spring-staging periods. Cool weather (2012) led to slow sward

---

[*] Corresponding author.
E-mail address: jarle.bjerke@nina.no (J.W. Bjerke).

https://doi.org/10.1016/j.scitotenv.2021.148619

Wildfowl
Wildlife management

development and little or no effects on harvest yields, warmer weather (2013) resulted in generally large effects, while variable weather (2014) led to treatment effects varying across fields, with one field experiencing 61% higher yields in exclosures while there were no significant impacts on first-harvest yields at the two other fields. Goose grazing did not increase dry weight-based proportions of weeds. Overall, the farmers' reports on yield-loss due to goose grazing were confirmed, although impacts varied substantially between years. A novel finding is that second-harvest yields were also reduced. For the most affected farmers, it is unlikely that the current subsidy scheme is sufficient to cover all the their losses.

1. Introduction

Agriculture at high northern latitudes is constrained by low temperature. However, due to a warmer than average climate for its latitudes, the coastal regions of north-westernmost Europe have large land areas allocated to agriculture (Höglind et al., 2010). Climate warming may stimulate increased agricultural yields in this region (Uleberg et al., 2014), but also brings other changes to these northern regions such as increasing goose populations. Over recent decades, large population increases of Arctic-breeding goose species have intensified the conflict with agricultural interests in both Eurasia and North America (Fox and Madsen, 2017; Lefebvre et al., 2017; Cuker, 2020).

For decades, there have been geese grazing in the coastal landscape of sub-Arctic Norway (Tombre et al., 2010, 2013, 2019). The most widely distributed species, greylag goose (*Anser anser* L.) which migrates in small flocks and breeds in the region has become an increasing challenge for many farmers due to a steadily increasing population size (Shimmings and Heggøy, 2017; Powolny et al., 2017). Moreover, Arctic-breeding goose species that migrate in groups of several thousands of individuals are causing severe conflicts and challenges for sustainable farming at their stopover sites in spring, grazing intensively over a limited time-period on vulnerable agricultural grasslands (Bjerke et al., 2014a; Fox et al., 2017; Olsen et al., 2017). The Svalbard-breeding populations of pink-footed goose (*Anser brachyrhynchus* Baillon) and barnacle goose (*Branta leucopsis* Bechstein) have stopover sites during the early growing season in the Vesterålen archipelago of sub-Arctic Norway (Fig. 1) where they feed on newly snow-free agricultural grasslands (Tombre et al., 2005). Vesterålen is located 200–300 km north of the Arctic Circle and the number of geese using this region in spring has increased in parallel with the general increase in the goose populations over the last 25 years (Fox et al., 2010, 2017; Tombre et al., 2019). A policy of intensified agricultural practice in most of Europe, combined

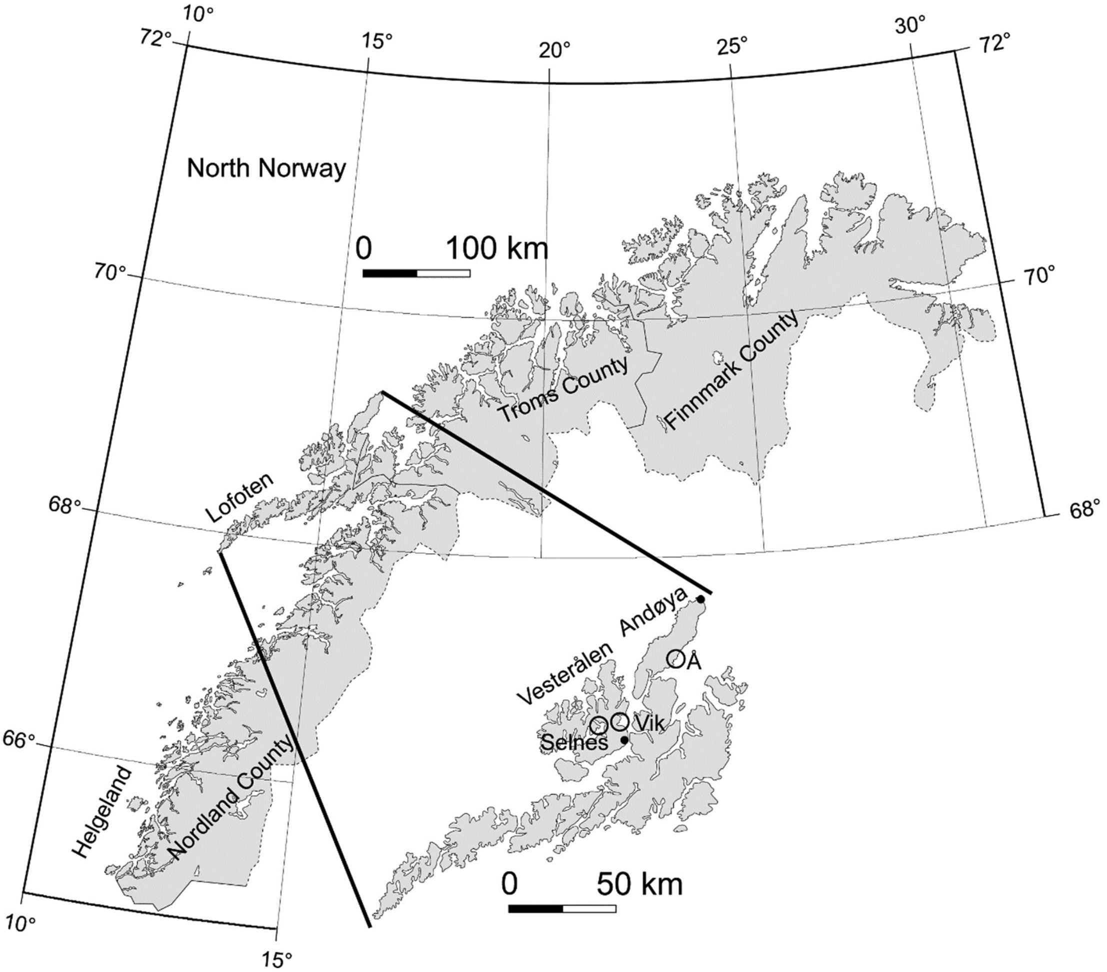


Fig. 1. Map of North Norway. The inset shows the region Vesterålen including the locations of the three study fields Å, Selnes and Vik (open circles). Dots: the weather stations Andøya (upper dot) and Sortland (lower dot).

with improved climatic conditions has increased the food availability and winter survival rates of the geese (Fox et al., 2017). Moreover, reduced snow cover at nest initiation may boost the populations as more pairs find snow-free nest sites within the narrow time window for breeding in the high-Arctic (Madsen et al., 2007; Jensen et al., 2014).

In Vesterålen, both species spend most grazing time on coastal managed grasslands on the limited agricultural land available between infrastructure (primarily roads and buildings) and the seashore and may feed up to 18 h per day due to the long period of daylight at these northern latitudes in spring (Madsen, 1998; Drent et al., 2003). Above this narrow coastal strip of agricultural land, the landscape is steeper and is covered by forest, mires and alpine heaths and provide hardly any forage resources for geese in spring. Farmers in the area report reduced grassland harvests (reduced round bale silage production) due to the increasing goose grazing intensity, and the conflicts between geese and farmers have increased (Eythórsson, 2004; Eythórsson et al., 2017; Tombre et al., 2005, 2013). A public subsidy scheme has been established to alleviate the pressure on affected farmers (Ministry of Agriculture and Food, 2006; Eythórsson and Tombre, 2013; Eythórsson et al., 2017) which has reduced the conflict level to a certain degree (Tombre et al., 2013).

For subsidy schemes to work well, a clear relationship between goose grazing pressure and agricultural yield loss should form the basis for the distribution of subsidies (Groot Bruinderink, 1989; Eythórsson and Tombre, 2013). In order to establish such relationships, detailed analyses are needed, preferably from experimental field designs. Such impacts have been experimentally tested in several countries by excluding geese from patches of grassland by fenced plots and comparing yields in these plots against yields in plots open for grazing. Such experiments have, however, primarily been undertaken at overwintering sites in temperate regions and mostly for single years only, as reviewed in Fox et al. (2017). The results from these studies are highly contrasting, thus making it challenging to draw overarching conclusions on the impacts of goose grazing and the agricultural grassland yields that would be available to sheep and cattle. Knowledge regarding goose grazing impacts on spring-staging sites in more northerly (boreal to sub-Arctic) agricultural regions is limited. In these northern regions, grass is harvested for round-bale silage that provides fodder for livestock during winter and spring. One of the very few studies of goose impacts on northern agricultural grasslands was a multiannual experiment undertaken in mid-Norway, which elucidated that grazing impacts of pink-footed geese were strongly related to grazing intensity, but also to weather variability (Bjerke et al., 2014a; Olsen et al., 2017). Hence, in respect to the subsidy scheme for farmers in the area, the variable impact of multiple drivers challenge a fair distribution of subsidies to affected farmers.

Vesterålen is a region where economically sustainable farming is taxing, partly due to climatic constraints. Goose grazing may, for some farmers, be the additional external pressure for tipping the production from sustainable to unsustainable (Eythórsson, 2004; Eythórsson and Tombre, 2013). The continuing increase in goose numbers, their steadily increasing impacts on agricultural grasslands, the lack of possibilities for population regulation (spring hunt and derogation shooting are illegal), as well as the limited budgets of the subsidy scheme have all raised the question of the size of yield reductions caused by goose grazing. It is unknown whether the available resources in the subsidy scheme actually match the value of the yield loss, as the subsidy is a result of an annual political negotiation process between the agricultural authorities and farmers' representatives and not a compensation scheme reflecting real damage (Eythórsson et al., 2017).

There are several reasons why the knowledge from existing experimental data cannot be applied directly to the Vesterålen archipelago. While farmers in mid-Norway generally harvest two or three times per growing season (Olsen et al., 2017) and allow their cattle to graze for a long time on the grasslands after the last harvest of the season, farmers in Vesterålen harvest twice, and occasionally only once per season, and with little time for sheep and cattle to graze on the grasslands after the last harvest of the season (Norsk landbruksrådgivning, 2018). The comparatively shorter growing season also implies that the grazed grassland has less time to recover after the geese leave and before harvesting begins. Finally, one of the most important differences from the situation in mid-Norway, where only pink-footed geese stage, is that a large proportion of the managed grasslands in Vesterålen are grazed by both pink-footed and barnacle geese (Madsen et al., 2014). The number of barnacle geese has increased significantly over the last decades, and as they have a higher pecking rate and cut the grass closer to the base of the leaf, hence removing more of the green parts than pink-footed geese, the conflicts and frustrations among local farmers have escalated correspondingly (Madsen and Tombre, 2011, *unpublished data*). Based on this, the negative impacts per goose day of barnacle goose grazing may presumably be larger than the earlier studied impact of pink-footed geese in mid-Norway.

We conducted an experimental study in Vesterålen where we sought to determine the multi-annual effects of goose grazing on agricultural grass-for-silage productivity of this region. Fenced plots (exclosures) were established in order to compare the yield production in plots protected against grazing with plots open for grazing. The experiment was repeated for three years at the same plots in order to obtain multi-year data on grassland productivity, which would allow for analyses of variation between years caused by variable grazing impacts and for changes over time in productivity and species composition. We used goose dropping densities as proxies for goose grazing intensities (Ydenberg and Prins, 1981; Simonsen et al., 2016; Olsen et al., 2017). Using systematic goose counts, we also determined the goose species (pink-footed geese or barnacle geese) that were feeding on the study fields (mixed flocks are rare, *unpublished data*) and the daily averages of goose presence in the areas. The experiment was designed such that we could test the following hypotheses: (I) preventing goose access to grassland plots would lead to increased first-harvest yields in exclosure plots compared to plots open for grazing (i.e. control plots); (II) treatment effects size, i.e. the relative difference between exclosures and controls, would differ between fields with contrasting goose abundance; (III) first-harvest yields in controls would be inversely correlated with grazing intensity; (IV) second-harvest yields would not be affected since the geese do not graze on the grasslands between the first and second harvests; and (V) preventing goose access over 3 years would affect plant species composition by reducing the establishment rate of non-preferred weeds.

2. Materials and methods

2.1. Study area and experimental design

The agricultural land areas in the Vesterålen archipelago mainly consists of cultivated grassland where sheep and new-born lambs forage in early spring, and for round bale silage production. In late summer and autumn, after the final harvest for silage production of the season, sheep and cattle are allowed onto the grassland to feed on the remaining sward. The geese arrive in the region in late April and prefer grazing on agricultural grasslands, foraging for c. 18 h per day due to favourable light conditions in spring at these northern latitudes (24 h daylight from early May). Meteorological data used to evaluate weather conditions during the project period were retrieved from the Norwegian Centre for Climate Services (2021). Deviation from temperature normals (1991–2020) for April and May at the two coastal weather stations Sortland and Andøya (Fig. 1) were used for comparisons between study years.

Four exclosures of 5 m × 2 m were established at three different grassland fields; Selnes and Vik in Sortland municipality, and Å in Andøy municipality (Fig. 1), following established design for goose grazing exclosures (Groot Bruinderink, 1989; Bjerke et al., 2014a; Olsen et al., 2017). Selnes and Vik are located 14 and 10 km northwest of Sortland weather station, respectively, whereas Å is ca. 29 km south of Andøya weather station and 45 km north-east of Sortland weather station. Nearby the exclosures, four open plots (5 m × 2 m) were established, marked with small poles in the corners. Only the top three centimeters of the poles were visible and these areas were left open for grazing by geese. Exclosures and open plots were grouped in pairs (blocks), meaning that paired plots were established close to each other (ca. eight metres distance). The pairs were distributed along the vertical axis of the fields and with a minimum 30 m between each pair. Altitudinal differences between lowermost and uppermost pairs varied between fields. Maximum altitudinal difference was ca. 10 m. The plot pairs were numbered from one to four, where one was close to the seashore, while number four was furthest away from the seashore, and closer to farm buildings, roads and other infrastructure.

The frames of the exclosures were constructed by placing wooden poles in the corners as well as at the middle on each long side. In the first year, we nailed white Poly ropes (5 mm diameter with an inner 0.4 mm wide core of stainless steel) to the poles and wrapped them along the sides at 5, 15, 25 and 40 cm from the ground and, also, in a crisscross arrangement between the tops of the poles. In later years, the ropes were supplemented with wire netting. The exclosures and the open plots at each of the three fields were monitored during 3 years, from 2012 to 2014.

As the fields have been subject to substantial goose grazing impacts for several decades (Tombre et al., 2010, 2013), the farmers rarely reseed. Hence, upon the start of this experiment, only one of the fields (Selnes) consisted of newly sown grassland. At the two other fields, according to farmers' information, the grasslands were three years old upon the start of the experiment. The fields were originally seeded with seed mixtures dominated by timothy (*Phleum pratense* L.; 50–80%), and this was the dominating species when exclosures were established. Other sown species varied between fields and included meadow fescue (*Festuca pratensis* Huds.; <20%), smooth meadowgrass (*Poa pratensis* L.; <15%), and clovers (*Trifolium repens* L. and *T. pratense* L.; <15%). Fields were conventionally fertilized with manure both before the study was initiated and during the experimental years.

Exclosures were established every spring during the study period (2012, 2013 and 2014) as soon as conditions allowed, meaning when the snow had at least partly melted and the ground was sufficiently thawed to allow for securing the corner piles of the exclosures into the ground. During this period, before the sward has started to grow, the geese primarily use the grassland fields as resting places while they feed on plant remains from the previous season that grow along the nearby grassy seashores and on the few snow-free patches on the grassland fields. Removal of withered leaves from the previous growing season is assumed not to have any negative effect on the farmers' harvest yields. All goose droppings found during establishment of experimental plots were counted and then removed, making the initial nutrient conditions as equal as possible for all study plots every spring.

2.2. Data collection during and after the goose-staging period

Goose censuses were conducted as a part of the annual goose monitoring in the region (Tombre et al., 2019). Goose areas, which cover more or less all the cultivated fields in the municipalities in the Vesterålen archipelago, were systematically registered at a distance, once per day, from cars and vantage points in the terrain using telescopes and binoculars, and numbers of each goose species were registered. The three fields with exclosures are geographically separated in a way that goose counts per area were independent. The total number of geese per day was summarised for each area (which also include fields adjacent to the experimental fields; each area representing ca. 2 km^2) and averaged by the number of observation days ($n = 20$, 6 and 6 days for the years 2012, 2013 and 2014, respectively) between 1 and 20 May (the core staging period for geese in the region). These averages provide a comparable spatial and temporal measure between the fields. Counts are presented for 2012–2014, except for the Å-location in 2013, as no systematic goose counts were conducted that year.

The plots were surveyed once a week from ca 1 May each year to the departure of the last geese approximately 3 weeks later. Grazing intensity was quantified by counting goose droppings (faeces) in all the plots within an area of 3.14 m^2 (a circle of 2 m diam.) at each visit. Droppings were removed between each visit. The amount of standing plant biomass was also quantified at each visit as compressed sward height (CSH), which is measured by the use of a rising plate meter consisting of a polyethylene plate of 30 cm diameter, weighing 0.15 kg, that freely moves along a vertical central pin with a centimetre scale. This method provides good non-destructive estimates of sward development before harvesting (Mould, 1992; Bakken et al., 2009).

The harvests of experimental plots were performed at the same time as the farmers harvested the rest of the agricultural grassland fields, which was undertaken after the geese had departed for their breeding grounds on Svalbard. Generally, grassland fields in this regions are harvested twice per season, first in early July and then in the last part of August. In 2012, farmers harvested only once due to an unusually cool growing season (Table 1). Hence, yield data from the second harvests are only available for 2013 and 2014. In 2013, no data are available for the second harvest at Å. Hence, second-harvest yield data from 2013 are from two fields, whereas data from 2014 are from all three fields. The fresh weight per hectare was measured in the field. One fresh sample (randomly selected) of ca. 2 kg from each plot was transported to the laboratory and dried at 60 °C for 48 h to establish a relationship between fresh and dry weights.

From the first harvest at each field, another fresh sample of ca. 2 kg was extracted from each plot and transported to the laboratory, semidried and frozen. These samples were later thawed and sorted according to species, assuming the sample was representative for the species composition of the experimental field. After species identification, samples of each plant species were placed in separate paper bags and dried at 80 °C for 48 h and weighed to nearest milligram. These dry weights were then used to test for differences in vegetation composition between treatments, focusing on any changes in the fraction of sown species. All plants not sown were termed as weeds, and these were also identified to species. We used the species data to test for any goose impacts on fraction of preferred (sown) species and on the diversity of weeds; the latter test arising from the observation that geese can bring in viable seeds of troublesome weeds through their digestive tracts and as seeds attached to their plumage or feet (Ayers et al. 2010; Farmer et al., 2017). Species diversity was calculated thereafter using the Shannon diversity index (Magurran, 1988), an index which in this context provides a value for sown species and weeds. Samples collected in 2014 suffered from freezer failure and could not be analyzed. Hence, for the evaluation of goose grazing effects over time on the remaining fraction of sown species, only a comparison between the first 2 years of the experiment, 2012 and 2013, was possible.

2.3. Statistical analyses

The designed block experiment was dispersed over three geographically distant fields, with $n = 4$ per treatments per field. Univariate and repeated-measures analyses of variance (ANOVA) within the general linear model procedure in SPSS Statistics 27 (IBM Corp., NY, USA)

Table 1
Air temperature (2 m above ground) at meteorological stations close to the three fields during the goose-staging period in 2012, 2013 and 2014. Temperature in the months April and May in are shown as deviations from the monthly averages for the period 1991–2020.

Field	Average April	Average May	April 2012	May 2012	April 2013	May 2013	April 2014	May 2014
Å (Andøy)	2.0	5.9	−1.4	−1.2	−1.1	2.5	0.5	−1.0
Selnes & Vik (Sortland)	2.7	6.6	−1.8	−1.5	−0.9	3.1	0.1	−0.7

were applied. First we tested whether there was any goose-grazing variation within fields. Within-field grazing intensity (i.e. between blocks) in open plots did not differ at any of the fields ($F_{1,3} = 0.050$, $P = 0.984$; data not shown), meaning that geese grazing was evenly distributed within fields. Therefore, blocks were not included as a variable in the ANOVAs. In repeated-measures ANOVA, agricultural grassland yields and vegetation composition from two or 3 years were included as within-subjects variables, and treatments and sites as between-subject factors. In cases with analyses of data from a single year, univariate ANOVA was applied with treatments as fixed factors and site as random factor. Normality was checked with normal and detrended Q-Q plots supplied with the Shapiro-Wilks and Kolmogorov-Smirnov tests. Homogeneity of variance was evaluated using Levene's test. In cases of non-normality and/or heterogeneity, transformation of the response variable was applied. One dataset (total yield in 2014), did not meet the criteria for normality and homogeneity even after transformations, and treatment effects for this parameter were therefore tested using non-parametric tests. Relationships between predictor variables and response variables were evaluated using linear Pearson correlation coefficients and were fitted with 95% confidence intervals in XLfit ver. 5.3.1.3 (ID Business Solutions Ltd., Guildford, UK).

3. Results

3.1. Goose registrations

Goose counts from the three locations show that barnacle goose dominate over pink-footed goose at Å and Vik, with smaller differences in numbers between the species at Selnes (Fig. 2). Pink-footed geese dominated at Selnes in 2012, but in 2014, barnacle geese had become the dominant species.

3.2. Grazing intensity

Exclosures had a significant impact on grazing intensity (Fig. 3). In 2012, there were intrusions of geese into the exclosures at all fields. The number of droppings recorded in 2012 in exclosures were 9.3% (Selnes), 32.2% (Vik) and 27.2% (Å) of the numbers in open plots. In 2013 and 2014, there were no intrusions after the improved exclusion system was used (see Materials and methods).

At Selnes, the grazing intensity was much lower than at the two other locations (repeated-measures ANOVA, Tukey HSD, $p < 0.001$), in open plots amounting only to 18.7% of mean grazing intensity for the two other fields (Fig. 3). These results are consistent with the corresponding goose registrations showing that the total number of geese were lower at Selnes than at Vik and Å in all the 3 years of the study (Fig. 2). The grazing intensities at Å and Vik were, for the whole study period, similar (Tukey HSD, $p = 0.504$).

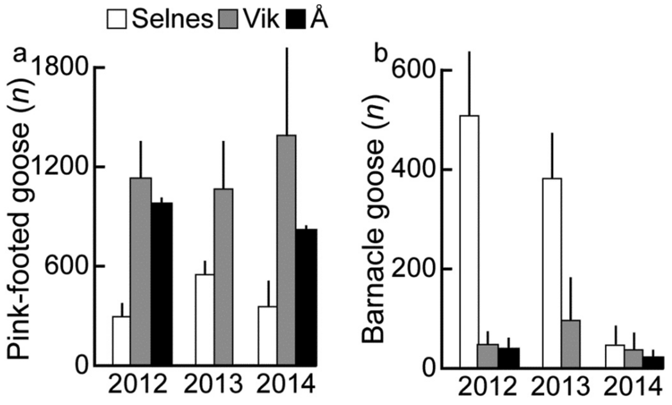


Fig. 2. Daily mean number of spring-staging pink-footed goose (a) and barnacle goose (b) at three locations in Vesterålen, northern Norway, 1–20 May in 2012–2014 (note the different scales of the vertical axes). Averages are based on 22, 6 and 6 observation days in 2012, 2013 and 2014, respectively. No registrations were performed at Å in 2013. Error bars represent ±1 S.E.

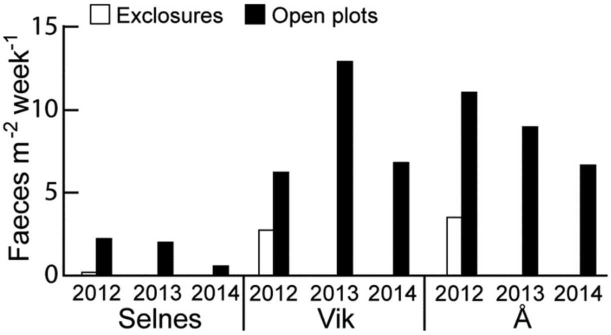


Fig. 3. Grazing intensities, in terms of number of goose droppings (faeces m^{-2}) per week, in open plots and exclosures after establishment of exclosures in spring. Intensities are field averages of the weekly surveys undertaken during the goose-staging periods.

3.3. Sward development during contrasting spring weather

April and May 2012 were 1.2–1.8 °C cooler than the monthly average between 1991 and 2020 (Table 1). The cool temperature this spring led to delayed sward development in all plots. Growth was initiated during the last week of the goose-staging period, and at the last survey compressed sward height (CSH) was significantly higher in exclosures than in open plots at Selnes and Å (Fig. 4a-c).

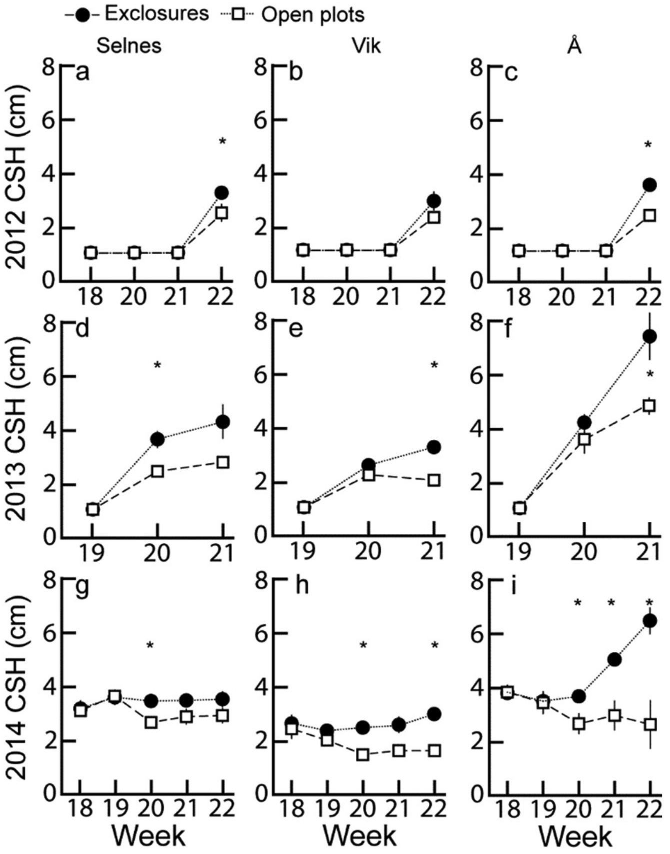


Fig. 4. Compressed sward height (CSH) development during the goose-staging period in 2012, 2013 and 2014 in open plots (open squares) and exclosures (closed circles) at Selnes (a, d, g), Vik (b, e, h) and Å (c, f, i). Significant differences between open plots and exclosures are indicated by asterisks (*: P ∈ [0.01, 0.05]). Vertical lines indicate ±1 SE.

April 2013 was 0.9–1.1 °C cooler than normal, while May 2013 was 2.5–3.1 °C warmer than normal (Table 1). Correspondingly, the swards started to grow in the middle of the goose-staging period, between 8 and 15 May 2013, i.e. from week 19 to week 20 (Fig. 4d-f). At the end of the 2013 goose-staging period, the differences in CSH between exclosures and open plots were not significant at Selnes (Fig. 4d), but 1.3 and 1.7 times higher in exclosures at Vik and Å, respectively (Fig. 4e-f).

April 2014 was 0.1 to 0.5 °C warmer than normal, while May 2014 was 0.7–1.0 °C cooler than normal (Table 1). This year, the tree fields showed contrasting sward development. At Selnes (Fig. 4g) and Vik (Fig. 4h), CSH in exclosures varied little during the entire goose-staging period, while CSH in open plots showed a slight decrease. At the end of the goose-staging period, CSH at Vik was 1.8 times higher in exclosures than in open plots (Fig. 4h), while there was no significant difference at Selnes (Fig. 4g). At Å, CSH in exclosures grew well from week 20 to week 22, while CSH in open plots was constant during the goose-staging period (repeated-measures ANOVA, time: $F_{1,4} = 4.298$ $p = 0.337$), resulting in 2.5 times higher CSH in exclosures at the end of the goose-staging period (Fig. 4i).

3.4. First-harvest yields

Overall first-harvest yields, i.e. all fields and years included, were on average 20.2% higher in exclosures than in open plots ($F_{1,21} = 21.487$, $P < 0.001$) (Fig. 5a). However, effects varied with year. In 2012, there was no treatment effect on yield level ($F_{1,20} = 1.212$, $P = 0.386$), while in 2013 yields were 26.7% higher in exclosures ($F_{1,17} = 13.978$, $P = 0.002$; ANOVA performed on data normalized and homogenized with reciprocal square root transformation). In 2014, there was a mean difference of 29.4% between yields in exclosures and open plots (Fig. 5b), but due to large variation between fields, the difference was not significant ($F_{1,20} = 3.456$, $P = 0.204$). For the three-year study period, exclosures resulted in an overall 31.0% increase ($F_{1,5} = 11.723$, $p = 0.014$) in yields at Vik, a near-significant difference of 16.5% ($F_{1,5} = 4.363$, $p = 0.082$) in yields at Selnes, and a near-significant difference of 14.0% ($F_{1,5} = 5.551$, $p = 0.057$) in yields at Å (Fig. 5c).

The treatment effect on first-harvest yields varied greatly both between years and fields. There was no treatment effect in any of the years at Selnes; at Vik, yields were 61.2% higher in exclosures in 2014, 36.5% higher in 2013 and were not statistically significantly different between treatments in 2012; while at Å, there was a 23.4% difference in 2013, a 16.1% difference in 2014, and no statistically significantly difference in 2012 (Fig. S1).

Ranking of the plots by first-harvest yields for each year (Fig. S2a) provides a visual inspection of the year-to-year variation in relative yields (i.e. plot yield as function of overall yield mean). Between-year plot lines indicate large changes in ranking between years. In 2012, when grazing pressure was low (Fig. 2), five of the 11 plots with highest yields were open control plots. However, in 2013 and 2014, when grazing pressure was higher than in 2012, only two and three control plots were among the top 11 plots. Some plots show extreme interannual variation in ranking and this may be explained in part by a likely effect of grazing, for example the drop from 2nd rank in 2012 to 23rd rank in 2013 for control plot 2 at Vik ("VC2"). However, grazing cannot explain the large year-to-year variation in the ranking of several plots. Exclosure plot three at Selnes ("SE3") is one such example. It falls from 10th place in 2012 via 19th place in 2013 to last place in 2014. Another example is exclosure plot two at Vik ("VE2"), which had the highest yield in 2012 but only the 17th highest in 2013. As expected, ANOVA on ranked first-harvest yields (Fig. S2b) elucidated the same treatment effects as true values (Fig. 5b).

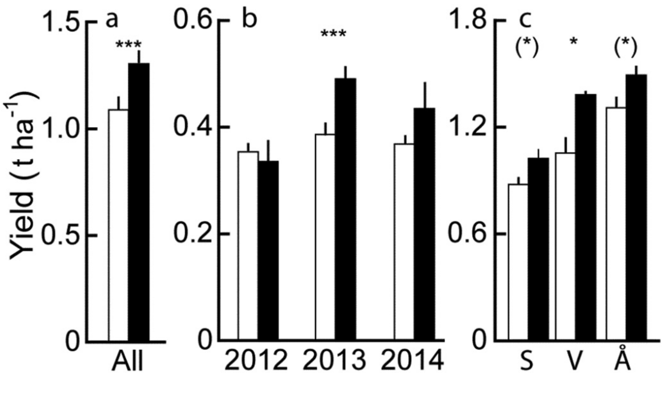


Fig. 5. First-harvest dry matter yields (t ha^{-1}) in exclosures (black bars) and plots open for goose grazing (white bars) from the three study fields in Vesterålen between 2012 and 2014. a) Mean of the sum of the first-harvest yields. b) Mean first-harvest yields; c) Sum of first-harvest yields (S = Selnes, V = Vik, Å = Å). Asterisks denote statistically significant treatment differences. ***: $P < 0.001$; *: $P \in [0.01, 0.05]$; (*): $P \in [0.05, 0.10]$, i.e. near-significant. Vertical lines indicate ±1 SEM.

3.5. First-harvest yields VS. goose and dropping counts

Goose abundance for the years 2012 and 2014 (i.e. the 2 years with goose counts from all three study fields; Fig. 2) is positively correlated with sum of first-harvest yields in open plots of the same 2 years ($r = 0.622$, $P = 0.031$; Fig. 6a). The 3-year sum of first-harvest yields in open plots is also significantly correlated with 3-year sum of faeces ($r = 0.659$, $P = 0.020$) (Fig. 6b). However, the difference in yield between pairs of exclosures and open plots was not correlated with

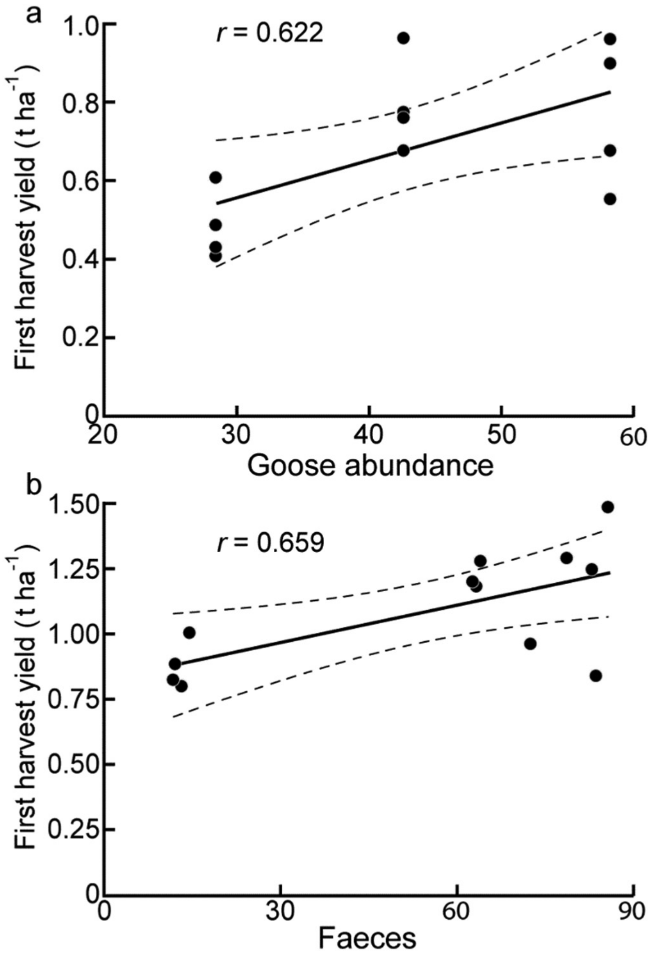


Fig. 6. First-harvest yields in open plots as a function of goose abundance. a) Relationship between field-level goose counts and first-harvest yields (sum of 2012 and 2014). b) Relationship between the 3-year sum of plot-level grazing intensity during the goose-staging periods (faeces m^{-2}) and the 3-year sum of first-harvest yields.

grazing intensity in any of the years, nor for the sum of the 3-year period ($R^2 < 0.171$, $P > 0.181$; data not shown).

3.6. Second-harvest yields

Second-harvest yields in 2013 from the two fields Selnes and Vik were 22.7% higher ($F_{1,11} = 52.187$, $P < 0.001$) in exclosures than in open plots (Fig. 7a). In 2014, when a second harvest was performed at all three study fields, there was no overall treatment effect ($F_{1,17} = 6.905$, $P = 0.119$; Fig. 7a). However, there were differences between fields; at Å yields in exclosures were 36.6% higher than in control plots ($F_{1,7} = 12.502$, $P = 0.012$), while there was no treatment effect at the two other fields (Fig. S3a). The sum of second-harvest yields for the years 2013–2014 at the fields Selnes and Vik was 19.3% higher in exclosures than in open plots ($F_{1,12} = 5.472$, $P = 0.037$; Fig. 7b). First- and second-harvest yields from 2014 were strongly correlated ($r = 0.644$, $P < 0.001$; Fig. S3b).

3.7. Total harvest yields

The year 2014 is the only experimental year with both first and second-harvest yields from all three fields. Total yields, i.e. the sum of first and second-harvest yields, were 27.3% higher in exclosures than in open plots ($F_{1,17} = 14.457$, $P = 0.001$) (Fig. S3a). This analysis was performed on the untransformed dataset, as no transformations improved normality. The non-parametric Mann-Whitney *U* test, excluding field and block variation, confirms the treatment effect ($U_{1,24} = 2.136$, $P = 0.033$). First and second-harvest yields from 2014 were correlated ($r = 0.644$, $P < 0.001$; Fig. S3b).

3.8. Sown species and establishment of weeds

Exclosures did not affect the weight-based proportion of sown species as compared to control (Fig. S4a). However, there was an overall decline in weight in both treatments of 4.3% between 2012 and 2013 ($F_{1,20} = 5.843$, $P = 0.025$). Weed biodiversity, as described by the Shannon index, was unaffected by treatment ($F_{1,17} = 0.177$, $P = 0.679$), but differed considerably between fields ($F_{2,17} = 27.046$, $P < 0.001$). The more recently sown field at Selnes had a much lower Shannon index value than the two other fields, while Å had an intermediate value, and Vik had the highest Shannon index value (Fig. S4b).

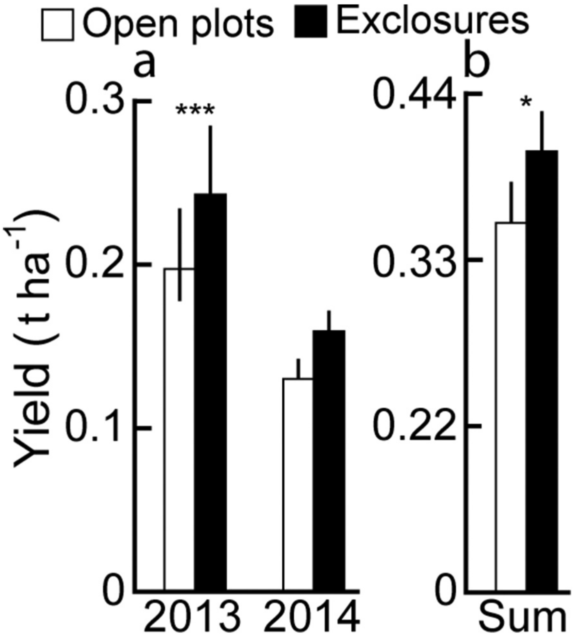


Fig. 7. Second harvest dry matter yields (t ha^{-1}) in exclosures and plots open for goose grazing. a) Mean of the sum of the yields in the years 2013 (two fields) and 2014 (three fields). b) Sum of yields for 2013 and 2014 for the fields Selnes and Vik. *: $P \in [0.01, 0.05]$. Vertical lines indicate ±1 SEM.

4. Discussion

4.1. Impacts on FIRST-harvest yields

By means of exclosures, we were able to evaluate and to a certain degree quantify to what extent goose grazing affected the grassland yields. Our first hypothesis that excluding geese' access to grassland plots would increase first-harvest yields was confirmed. Over the 3-year study period, exclosures resulted in a 20.2% increase in first-harvest yields, as compared to open controls.

The three study years varied greatly in spring weather, which had large impacts on sward growth rates during the goose-staging periods. As the sward barely developed during the goose-staging period in 2012, there was hardly any fresh agricultural grass for the geese to feed on. The geese probably had to rely on alternative resources, for example plant rhizomes, roots and tubers in nearby seashore or wetland vegetation, which is a common food source when they arrive at their breeding grounds on Svalbard (Fox and Bergersen, 2005; Fox et al., 2006, 2007). There was some development of the sward after the goose departure, and first-harvest yields in 2012 primarily reflected sward development after the geese had left. Hence, there was no treatment effect in 2012. The cool weather in the early growing season of 2012 also continued into the peak growing season (Bjerke et al., 2014b). In the study area, July month was 1 °C cooler than normal and with 1.50–1.75 times more rain than normal (Gangstø et al., 2012). Thus, the low yield levels at the studied fields in 2012 (as compared to 2013 and 2014 in Fig. 5) were symptomatic for the entire region (Bjerke et al., 2014b), demonstrating that in certain years, climatic constraints can mask the effects of high goose densities on agricultural grassland productivity.

The counting of geese and faeces showed that goose abundance varied greatly both between fields and between years, but not within fields. Selnes had a much lower density of faeces than the two other fields. This may explain why there was no statistically significant treatment effect on first-harvest yields in any of the years at this field, only a statistically near-significant difference between open plots and exclosures in sum of first-harvest yields over 3 years. However, the goose grazing did have a statistically significant impact on sward development in all the three study years. The two other fields both had a much higher faecal density than Selnes, but a statistically significant overall (3-year) effect of exclosures on first-harvest yields was only found at Vik, which had 31% higher first-harvest yields in exclosures than in open plots. The field Å had statistically significantly 23% higher first-harvest yields in exclosures than in open plots in 2013, and a statistically near-significant difference in 2014, but the overall difference between exclosures and open plots was only statistically near-significant. Overall, these results support the second hypothesis, which stated that the effect of exclosures varies with grazing intensity in open plots. This implies that with minor grazing intensity, the exclusion of geese from the fields will not have any effect on harvestable yields. To define this limit for when the goose grazing intensity is low enough to have no impact may, however, be challenging, as it could differ both between years with different weather and growing conditions, and between fields, and may even vary within the same field. In this study, we set up four blocks per field, in agreement with the farmers who did not want more of their fields being occupied by experimental plots. This is a rather low *n*, and it is reasonable to assume that a higher number of replicates per field would have provided more precise information on the threshold where goose impacts become significant. Overall, the presented data are sufficient to conclude that even the rather minor grazing intensity at Selnes was above the limit for when grazing has no impact. The significant impacts on sward development at Selnes, despite low goose density, may also be partly related to the fact that barnacle goose was the dominant grazer there, as this species cut the grass closer to the basis than the pink-footed goose does (see Introduction).

The third hypothesis stated that first-harvest yields in open plots would be inversely correlated with grazing intensity. The rationale for this hypothesis is that the geese would remove so much green material that sward development would be severely reduced. This would be in line with previous studies (Fox et al., 2017; Olsen et al., 2017). However, for the open plots at the three agricultural fields in our study, there is a clear positive relationship between grazing pressure and first-harvest yields. This may sound counterintuitive. In this case, the positive relationship is largely driven by the plots at Selnes. This was the field with the lowest first-harvest yields and with the lowest grazing pressure. Our goose counts showed that there were around 1000 geese flying around in the Selnes area in 2012 and 2013 (but much less in 2014). However, this high number of geese was not reflected in our dropping counts. It has been shown that the geese easily distinguish between profitable and less profitable fields and therefore congregate at fields providing the highest energy intake rate (reviewed in Fox et al., 2017). Having a green-sensitive vision similar to optical sensors measuring vegetation greenness from satellites, geese are probably highly adapted to search for green fields in the landscape while flying (Kelber, 2019; Teodore and Teodore and Nilsson, 2019; Baden et al., 2020). Thus, geese are likely to assess at a long distance whether it is worthwhile to land on a particular grassland field or not, which may explain why so few of the geese in the Selnes area in 2012 and 2013 decided to land on the particular grassland field where our experiment was set up. Hence, despite having a higher grazing pressure than Selnes, the swards at Vik and Å were able to produce higher yields, presumably due to better growing conditions. If the study had included a fourth site with higher grazing impacts than at Vik and Å, a curved relationship between grazing intensity and first-harvest yields would have been a more likely result, with the top of the curve around 90 faeces m^{-2} y^{-1}; as is the maximum value in Fig. 6b.

These results further imply that there were differences between the fields in the quality of the soil and the condition of the sward. Yield production differences between adjacent agricultural fields may, among other things, be related to soil fertility (Geypens et al., 1999) and soil compaction (Douglas and Douglas and Crawford, 1998). The large decline in relative productivity of some plots from all fields, as shown by the year-to-year ranking of first-harvest yields, suggest that factors outside of our control affected some plots negatively during the study period. A general challenge to sub-Arctic agriculture is damage occurring during the non-growing season, especially due to ice encasement which can affect parts of a field, especially flat or slightly concave parts (Bjerke et al., 2015, Olsen et al. 2017). Productivity at such microsites is also vulnerable to water-logging during rainy periods in the growing season. At Selnes, first-harvest yields in both exclosures and open plots fell remarkably from 2013 to 2014 (Figs. S1, S2a), but not at the two other fields. This may be due to topographically related extreme negative impacts during the cold season at this field. To conclude, our third hypothesis was not supported by the results.

4.2. Impacts on second-harvest yields

Based on the results from a similar study undertaken in mid-Norway, where goose grazing had no significant effect on second-harvest yields (Bjerke et al., 2014a; Olsen et al., 2017), we hypothesized that second-harvest yields would not differ between open plots and exclosures (hypothesis IV). In 2013, when data were collected from two fields only, second-harvest yields were 23% higher in exclosures than in open plots, while in 2014, when a second harvest was performed at all the three fields, the overall yield did not differ significantly between exclosures and open plots. Only at one of the three fields, at Å was there a significant difference in second-harvest yield level between exclosures and open plots in 2014. For the two fields with data from both 2013 and 2014, there was an overall 19% higher yield in exclosures than in open plots. Thus, our second-harvest results rendered only minor support to our fourth hypothesis. The relatively short period between first and second harvests, ca. 45 days, may explain why exclosures in many cases also had positive effects on second-harvest yields. In the study by Olsen et al. (2017), the between-harvest period was ca. 70 days. The shorter time span between the two harvests render less time for positive photosynthetic rates and hence less carbon gain. In addition, the cooler summer climate in sub-Arctic Norway, as compared to mid-Norway, slows down growth rates, further reducing the capacity of swards in open plots to compensate for the biomass lost during the goose-staging period.

4.3. Plant composition

Lastly, we hypothesized that the proportion of weeds would be higher in open plots than in exclosures. This hypothesis was based on the fact that geese may remove seeded plants while bringing in seeds of weeds in their faeces and on their feet and plumage (Ayers et al. 2010; Bjerke et al. 2014a; Farmer et al., 2017; Fox et al., 2017). Our results did not provide any evidence that geese contributed to establishment of weeds at our experimental fields. Instead, the proportion of weeds increased with time both in exclosures and in open plots, indicating that non-experimental pressures (as described above) caused the decline in sown species at all fields. The lower proportion of weeds at the more recently reseeded field Selnes suggests that weeds were not the reason why this field was less frequented by geese.

4.4. Wider implications of the results for geese and farmers

The limited food availability reported from the spring-staging fields in Vesterålen in 2012 contributed to reduced goose reproductive success the same year. A registration of young geese at the wintering grounds in autumn 2012 showed that for pink-footed geese, the reproductive success had been lower than normal that year (Madsen et al., 2017). Also for barnacle geese, the percentage of goslings in the winter population was low (5.5%) in 2012/2013 as compared to other years (an average of 8.3% over the years 2003–2019; Wildfowl and Wetlands Trust, 2019).

Previous studies have demonstrated the importance of body reserves built up at the spring stopover sites for reproductive success (Black et al., 1991; Ebbinge and Spaans, 1995; Madsen, 1995), and as capital breeders these reserves become vital especially when the green-up at the breeding ground is later than normal. The 2012 May and early June temperature at the breeding grounds on Svalbard was one of the coolest observed after the turn of the millennium (Iden et al., 2012a, 2012b; Overland et al., 2012). This resulted in belated snow and ground ice melt (Vickers et al., 2020), and hence delayed onset of spring also at the breeding grounds. This illustrates how severe spring weather can have direct effects on agricultural productivity and goose reproductive success, potentially with lagged opposite impacts on agricultural yields (i.e. higher yields) as fewer recruited goslings in the goose population can lead to reduced grazing intensity during the forthcoming year's spring stopover.

Our study demonstrates that goose grazing leads to yield reductions only after a certain level of grazing intensity. Most fields visited by numerous geese in spring receive financial support by the existing subsidy scheme in the region, whereas less affected fields are not supported (County Governor of Nordland, *unpublished data*). Such patterns are also found elsewhere where subsidies or compensation are available for goose-affected farmers. One example is from Belgium, where farmers only apply for a compensation for reduced harvests when goose numbers are above a threshold level (Verhaeghe, 2020; Floris Verhaeghe (Agency for Nature and Forest), *pers. comm*). A similar pattern has also been reported from Sweden (Montràs-Janer et al., 2019). A common question in goose management is whether population control can be justified as an agricultural damage prevention tool, if there is first evidence of a direct causal relationship between goose numbers in an area and agriculture harvest reductions in the same area (McKenzie and Shaw, 2017). The significantly lower first- and second-harvest yields in plots open for grazing suggests that such a relationship is present for this study area. However, geese are not evenly distributed in the landscape, but commonly find profitable fields where they forage and rest (Madsen et al., 2014). Hence, in order to quantify yield-loss for farmers, assessment of damages ought to be done at the field scale and not at larger scales (e.g. numerous farms over several km distance).

Regardless of scale, overall we have shown that while only the first harvest yield is affected by goose grazing in spring in mid-Norway (Olsen et al., 2017), farmers further north in Norway, within the sub-Arctic region, experience the negative effects of intensive goose grazing on both their harvests. Thus, sub-Arctic farmers tend to lose a higher proportion per unit area of the annual yield to goose grazing than affected farmers at more southern latitudes. For many sub-Arctic farmers, it is unlikely that the subsidy scheme is sufficient to cover all their economic loss. The results of our study should stimulate authorities to revise the subsidy scheme so that it better reflects the farmers' true economic loss.

CRediT authorship contribution statement

Jarle W. Bjerke: Conceptualization, Resources, Data curation, Formal analysis, Writing – original draft, Validation, Writing – review & editing. **Ingunn M. Tombre:** Conceptualization, Resources, Visualization, Validation, Writing – review & editing. **Marvell Hanssen:** Resources, Data curation, Formal analysis, Validation, Writing – review & editing. **Anne Kari Bergjord Olsen:** Conceptualization, Validation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study would not have been possible without the good cooperation, support and positive engagement from the three farmers in Vesterålen allowing experiments on their fields; Knut-Johnny Enoksen (Å), Kjell Jensen (Vik, deceased) and Arne Hansen (Selnes). We are grateful to all. We are also grateful for fruitful cooperation and guidance from the rest of the MIGRAPOP team members Jesper Madsen, Bart A. Nolet, Johannes M. Baveco, Einar Eythórsson, Caroline E. Simonsen and Magda E. Chudzińska. Marte S. Hoholm and Johnny Bakken are acknowledged for field assistance (managing exclosures and conducting goose registrations), Kristian Laustsen for sorting of dried vegetation samples, Jennifer Stien for linguistic editing assistance and biostatistical advice and Floris Verhaeghe for relevant information. We thank anonymous reviewers for constructive comments to previous drafts of this paper.

Funding statement

The study was conducted as a part of the “MIGRAPOP” project funded by the Research Council of Norway (project no. 204342), the Norwegian Environmental Agency, the County Governor of Nordland, Fram – High North Research Centre for Climate and the Environment (‘Terrestrial Flagship’), Sortland Municipality and the Norwegian Institute for Nature Research.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2021.148619.

References

Ayers, C.R., Deperno, C.S., Moorman, C.E., Yelverton, F.H., 2010. Canada goose weed dispersal and nutrient loading in turfgrass systems. Appl. Turfgrass Sci. https://doi.org/10.1094/ATS-2010-0212-02-RS.

Baden, T., Euler, T., Berens, P., 2020. Understanding the retinal basis of vision across species. Nat. Rev. Neurosci. 21, 5–20. https://doi.org/10.1038/s41583-019-0242-1.

Bakken, A.K., Lunnan, T., Höglind, M., et al., 2009. Mer og bedre grovfôr som basis for norsk kjøtt- og mjølkeproduksjon. Resultater fra flerårige høstetidsforsøk i blandingseng med timotei, engsvingel og rødkløver. Bioforsk Rapport. 4:38. Norwegian Institute for Agricultural and Environmental Research (Bioforsk), Ås (95 pp. (In Norwegian)).

Bjerke, J.W., Bergjord, A.K., Tombre, I.M., Madsen, J., 2014a. Reduced dairy grassland yields in mid-Norway after a single springtime grazing event by pink-footed geese. Grass Forage Sci. 69, 129–139. https://doi.org/10.1111/gfs.12045.

Bjerke, J.W., Karlsen, S.R., Høgda, K.A., et al., 2014b. Record-low primary productivity and high plant damage in the Nordic Arctic Region in 2012 caused by multiple weather events and pest outbreaks. Environ. Res. Lett. 9, 084006. https://doi.org/10.1088/1748-9326/9/8/084006.

Bjerke, J.W., Tømmervik, H., Zielke, M., Jørgensen, M., 2015. Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of subarctic Norway. Environ. Res. Lett. 10, 095007. https://doi.org/10.1088/1748-9326/10/9/095007.

Black, J.M., Deerenberg, C., Owen, M., 1991. Foraging behaviour and site selection of barnacle geese *Branta leucoptis* in a traditional and newly colonised spring staging habitat. Ardea 79, 349–358.

Cuker, B.E., 2020. Passenger pigeon and waterfowl: Flights to extinction and not. In: Cuker, B. (Ed.), Diet for a Sustainable Ecosystem. Estuaries of the World. Springer, Cham, pp. 155–174.

Douglas, J.T., Crawford, C.E., 1998. Soil compaction effects on utilization of nitrogen from livestock slurry applied to grassland. Grass Forage Sci. 53, 31–40.

Drent, R., Both, C., Green, M., et al., 2003. Pay-offs and penalties of competing migratory schedules. Oikos 103, 274–292. https://doi.org/10.1034/j.1600-0706.2003.12274.x.

Ebbinge, B.S., Spaans, B., 1995. The importance of body reserves accumulated in spring staging areas in the temperate zone for breeding in dark-bellied brent geese *Branta bernicla* in the high Arctic. J. Avian Biol. 26, 105–113. https://doi.org/10.2307/3677058.

Eythórsson, E., 2004. Gjess til besvær. Utfordringer i forvaltningen av ville gåsebestander med utgangspunkt i beitekonflikten i Vesterålen. Report 2004. vol. 2. Norut NIBR Finnmark, Alta 48 pp. (In Norwegian).

Eythórsson, E., Tombre, I.M., 2013. Tilskudd til tilrettelegging av beitearealer for trekkende hvitkinngås og kortnebbgås. Erfaringer fra Nord-Trøndelag og Vesterålen. NIKU Rapport. 69. Norwegian Institute for Cultural Heritage Research, Oslo (47 pp. (In Norwegian)).

Eythórsson, E., Tombre, I.M., Madsen, J., 2017. Goose management schemes to resolve conflicts with agriculture: theory, practice and effects. Ambio 46, S231–S240. https://doi.org/10.1007/s13280-016-0884-4.

Farmer, J.A., Webb, E.B., Pierce, R.A., Bradley, K.W., 2017. Evaluating the potential for weed seed dispersal based on waterfowl consumption and seed viability. Pest Manag. Sci. 73, 2592–2603. https://doi.org/10.1002/ps.4710.

Fox, A.D., Bergersen, E., 2005. Lack of competition between barnacle geese *Branta leucopsis* and pink-footed geese *Anser brachyrhynchus* during the pre-breeding period in Svalbard. J. Avian Biol. 36, 173–178. https://doi.org/10.1111/j.0908-8857.2005.03540.x.

Fox, A.D., Madsen, J., 2017. Threatened species to super-abundance: the unexpected international implications of successful goose conservation. Ambio 46, S179–S187. https://doi.org/10.1007/s13280-016-0878-2.

Fox, A.D., Francis, I.S., Bergersen, E., 2006. Diet and habitat use of Svalbard pink-footed geese *Anser brachyrhynchus* during arrival and pre-breeding periods in Adventdalen. Ardea 94, 691–699.

Fox, A.D., Bergersen, E., Tombre, I.M., Madsen, J., 2007. Minimal intra-seasonal dietary overlap of barnacle and pink-footed geese on their breeding grounds in Svalbard. Polar Biol. 30, 759–768. https://doi.org/10.1007/s00300-006-0235-1.

Fox, A.D., Ebbinge, B.S., Mitchell, C., et al., 2010. Current estimates of goose population sizes in western Europe, a gap analysis and an assessment of trends. Ornis Svecica 20, 115–127. https://doi.org/10.34080/os.v20.19922.

Fox, A.D., Elmberg, J., Tombre, I.M., Hessel, R., 2017. Agriculture and herbivorous waterfowl: a review of the scientific basis for improved management. Biol. Rev. 92, 854–877. https://doi.org/10.1111/brv.12258.

Gangstø, R., Iden, K., Kristiansen, S., et al., 2012. Været i Norge, klimatisk månedsoversikt juli 2012. Met.no Info 07/2012. Norwegian Meteorological Institute, Oslo (25 pp. (In Norwegian)).

Geypens, M., Vanongeval, L., Vogels, N., Meykens, J., 1999. Spatial variability of agricultural soil fertility parameters in a gleyic podzol of Belgium. Precision Agric. 1, 319–326. https://doi.org/10.1023/A:1009977109430.

Groot Bruinderink, W.T.A., 1989. The impact of wild geese visiting improved grasslands in the Netherlands. J. Appl. Ecol. 26, 131–146.

Höglind, M., Bakken, A.K., Jørgensen, M., Østrem, L., 2010. Tolerance to frost and ice encasement in cultivars of timothy and perennial ryegrass during winter. Grass Forage Sci. 65, 431–445. https://doi.org/10.1111/j.1365-2494.2010.00762.x.

Iden, K., Kristiansen, S., Mamen, J., et al., 2012a. Været i Norge, klimatisk månedsoversikt mai 2012. Met.no Info 05/2012. Norwegian Meteorological Institute, Oslo (35 pp. (In Norwegian).

Iden, K., Kristiansen, S., Mamen, J., et al., 2012b. Været i Norge, klimatisk månedsoversikt juni 2012. Met.no Info 06/2012. Norwegian Meteorological Institute, Oslo (25 pp. (In Norwegian).

Jensen, G.H., Madsen, J., Johnson, F., Tamstorf, M.P., 2014. Snow conditions as an estimator of the breeding output in high-Arctic pink-footed geese *Anser brachyrhynchus*. Polar Biol. 37, 1–14. https://doi.org/10.1007/s00300-013-1404-7.

Kelber, A., 2019. Bird colour vision – from cones to perception. Curr. Opin. Behav. Sci. 30, 34–40. https://doi.org/10.1016/j.cobeha.2019.05.003.

Lefebvre, J., Gauthier, G., Giroux, J.-F., et al., 2017. The greater snow goose *Anser caerulescens atlanticus*: managing an overabundant population. Ambio 46, S262–S274.

Madsen, J., 1995. Impacts of disturbance on migratory waterfowl. Ibis 137, 65–79. https://doi.org/10.1111/j.1474-919X.1995.tb08459.x.

Madsen, J., 1998. Changing trade-offs between predation risk and food-intake: gaining access to feeding patches during spring fattening in pink-footed geese *Anser brachyrhynchus*. Norsk Polarinst. Skr. 299, 303–311.

Madsen, J., Tombre, I.M., 2011. Interactions between spring-staging goose species: a case study from Vesterålen, northern Norway. Presentation at the International Conference on the Waterfowl of Northern Eurasia, Waterfowl of Northern Eurasia: Geography, Dynamics and Population Management, 24–29 March 2011. Elista, Kalmykia, Russia.

Madsen, J., Tamstorf, M., Klaassen, M., et al., 2007. Effects of snow cover on the timing and success of reproduction in high-Arctic pink-footed geese *Anser brachyrhynchus*. Polar Biol. 30, 1363–1372. https://doi.org/10.1007/s00300-007-0296-9.

Madsen, J., Bjerrum, M., Tombre, I.M., 2014. Regional management of farmland feeding geese using an ecological prioritization tool. Ambio 43, 801–809. https://doi.org/10.1007/s13280-014-0515-x.

Madsen, J., Jensen, G.H., Cottaar, F., et al., 2017. Svalbard Pink-Footed Goose - Population Status Report 2016–2017. Aarhus University and Danish Centre for Environment and Energy, Aarhus 14 pp.

Magurran, A.E., 1988. Ecological Diversity and its Measurements. Croom Helm, London.

McKenzie, R., Shaw, J.M., 2017. Reconciling competing values placed upon goose populations: the evolution of and experiences from the Islay Sustainable Goose Management Strategy. Ambio 46, S195–S209. https://doi.org/10.1007/s13280-016-0880-8.

Ministry of Agriculture and Food, 2006. Forskrift om tilskudd til tiltak for å tilrettelegge beitearealer for trekkende hvitkinngås og kortnebbgås. https://www.regjeringen.no/no/dokumenter/forskrift-om-tilskudd-til-tiltak-for-a-t/id92638/ (accessed 19.2.2018) (In Norwegian).

Montràs-Janer, T., Knape, J., et al., 2019. Relating national levels of crop damage to the abundance of large grazing birds: implications for management. J. Appl. Ecol. 56, 2286–2297. https://doi.org/10.1111/1365-2664.13457.

Mould, F.L., 1992. Use of a modified rising-plate meter to assess changes in sward height and structure. Norw. J. Agric. Sci 6, 375–382.

Norsk landbruksrådgivning, 2018. Grovfôrskolen. https://nordland.nlr.no/publikasjoner/grovforskolen/ (accessed 19.2.2018) (In Norwegian).

Norwegian Centre for Climate Services, 2021. Observations and weather statistics. https://seklima.met.no/ (accessed 1.6.2021).

Olsen, A.K.B., Bjerke, J.W., Tombre, I., 2017. Yield reductions in agricultural grasslands in Norway after springtime grazing by pink-footed geese. J. Appl. Ecol. 54, 1836–1846. https://doi.org/10.1111/1365-2664.12914.

Overland, J.E., Key, J., Kim, B.-M., Jeffries, M.O., Richter-Menge, J.A., et al., 2012. Air temperature, atmospheric circulation and clouds. In: Overland, J.E. (Ed.), Arctic Report Card 2012, National Oceanic and Atmospheric Administration, U.S.A., pp. 13–21 ArcticReportCard_full_report2012.pdf (noaa.gov) accessed 4.1.2021)

Powolny, T., Czajkowski, A., Madsen, J., et al., 2017. Biological overview; Greylag goose NW/SW European population. Presentation at AEWA International Management Planning Workshop for the Greylag Goose (NW/SW European Population), 4–6 October 2017, Paris, France.

Shimmings, P., Heggøy, O., 2017. Grågås i Nordland - et estimat på hekkebestand i 2017. NOF-Rapport 3–2017. Norwegian Ornthological Society, Trondheim (29 pp. (In Norwegian). gragas-i-nordland–nof-rapport-2017-3.pdf (fylkesmannen.no) (accessed 4.1.2021)).

Simonsen, C.E., Madsen, J., Tombre, I.M., Nabe-Nielsen, J., 2016. Is it worthwhile scaring geese to alleviate damage to crops? – an experimental study. J. Appl. Ecol. 53, 916–924. https://doi.org/10.1111/1365-2664.12604.

Teodore, C., Nilsson, D.-E., 2019. Avian UV vision enhances leaf surface contrasts in forest environments. Nature Comm 10, 238. https://doi.org/10.1038/s41467-018-08142-5.

Tombre, I.M., Madsen, J., Tømmervik, H., et al., 2005. Influence of organized scaring on distribution and habitat choice of geese on pastures in Northern Norway. Agric. Ecosyst. Environ. 111, 311–320. https://doi.org/10.1016/j.agee.2005.06.007.

Tombre, I.M., Tømmervik, H., Gullestad, Madsen, J., 2010. Spring staging in the Svalbard-breeding pink-footed goose *Anser brachyrhynchus* population: site-use changes caused by declining agricultural management? Wildfowl 60, 3–19.

Tombre, I.M., Eythórsson, E., Madsen, J., 2013. Towards a solution to the goose-agriculture conflict in north Norway, 1988–2012: the interplay between policy, stakeholder influences and goose population dynamics. PLoS One 8, e71912. https://doi.org/10.1371/journal.pone.0071912.

Tombre, I.M., Oudman, T., Shimmings, P., et al., 2019. Northward range expansion in spring-staging barnacle geese is a response to climate change and population growth, mediated by individual experience. Glob. Chang. Biol. 25, 3680–3693. https://doi.org/10.1111/gcb.14793.

Uleberg, E., Hanssen-Bauer, I., van Oort, B., Dalmannsdottir, S., 2014. Impact of climate change on agriculture in northern Norway and potential strategies for adaptation. Clim. Chang. 122, 27–39. https://doi.org/10.1007/s10584-013-0983-1.

Verhaeghe, F., 2020. National Report 2020, Belgium. European Goose Management Platform, Agreement on the Conservation of African-Eurasian Migratory waterbirds. UNEP, Bonn https://egmp.aewa.info/sites/default/files/meeting_files/national_reports/EGMP%20National%20Reporting%202020%20Belgium.pdf (accessed 2.9.2020).

Vickers, H., Karlsen, S.R., Malnes, E., 2020. A 20-year MODIS-based snow cover dataset for Svalbard and its link to phenological timing and sea ice variability. Remote Sens. 12, 1123. https://doi.org/10.3390/rs12071123.

Wildfowl and Wetlands Trust, 2019. Waterbird Monitoring; The Svalbard Barnacle Goose. https://monitoring.wwt.org.uk/our-work/goose-swan-monitoring-programme/species-accounts/svalbard-barnacle-goose/ (accessed 2.9.2020).

Ydenberg, R.C., Prins, H.H.T., 1981. Spring grazing and the manipulation of food quality by barnacle geese. J. Appl. Ecol. 18, 443–453. https://doi.org/10.2307/2402405.