Appendix S1

Ecosphere

Predicting impacts of food competition, climate and disturbance on a long-distance migratory herbivore

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Table S1. Sources and derivation of parameter values used in the model.

(a) Time and environmental parameters

Parameter	Value(s)	Derivation / source
Time step length (hours)	1	Time during which environmental conditions are assumed to remain constant.
Model length (days)	319	1 Aug to 15 June. Period of usage of the study site by migratory brant and cackling geese (Reed et al. 1989, Dau 1992, and Mason et al. 2006, 2007).
Seasons	Fall = 1 Aug to 15 Dec Winter = 16 Dec to 31 Mar Spring = 1 Apr to 15 Jun	Based on duration of stay of migrant brant and cackling geese in fall, overwintering brant in winter, and migrant brant in spring (Reed et al. 1989, Dau 1992, and Mason et al. 2006, 2007).
Duration of daylight (hours)	8.7 – 19.4	Range of daylight hours (twilight to twilight) from 1 Aug 2016 to 15 June 2017. Derived for Cold Bay from United States Naval Observatory Astronomical Applications Department calculator (http://aa.usno.navy.mil/data/docs/RS_OneYear.php).
Percentage and duration of ice coverage in Izembek Lagoon	0% 25% - 40 days 50% - 40 days 100% - 27 days	Ice coverage varied between patches, with those at higher tidal elevation more likely to freeze, and non-Izembek Lagoon patches less likely to freeze (Petrich et al. 2014, Wilson and Dau 2016). See Data S1 for patch-specific values.
Mid-point of icing conditions	Early - 15 Jan Mid - 14 Feb Late - 15 Mar	Mean observed in winters of varying severity.
Hunting and boating disturbance rate (hour^{-1})	Fall = 0.00, 0.30, 0.60 or 0.42 (x3 original rates) Winter = 0.00 or 0.06 Spring = 0.00	Disturbances per hour caused by hunting from land or boats. Varies between patches, with more disturbance closer to shore with access by road. Recently observed values up to 3x those reported previously (Ward et al. 1994, D. Ward pers. obs.). See Data S1 for patch-specific values.
Natural disturbance rate (hour^{-1})	Fall = 0.13 - 0.32 Winter/Spring = 0.32 all areas	Disturbances per hour caused by eagles and other potential predators. Varied between patches (Ward et al. 1994; D. Ward pers. obs.). See Data S1 for patch-specific values.

(b) Patch and eelgrass parameters

Parameter	Value(s)	Derivation
Patch size (m^2)	1000x1000 = 1000000	Maximum area exploited by an individual in a single hour time step.
Number of patches	308	Total number of discrete 1000x1000 m areas occupied by eelgrass across all sites. See Data S1 for details.
Number of sites	11	Six sub-sites in Izembek Lagoon, and other sites at the end of the Alaska Peninsula. Sites based on brant count sectors performed by U.S. Fish and Wildlife Service. See Data S1 for patch-specific values.
Patch elevation (m MLLW)	-2.43 to 0.87	Derived from digital terrain model. Patch elevation calculated as the mean elevation within patch. See Data S1 for patch-specific values.
Water level (m MLLW)	Varies	Hourly tidal water level data for 1 Aug 2016 to 31 May 2017 from tidal gauges at Grant Point, St. Catherine Cove, Morzhovoi Bay, Peterson Bay, and Cold Bay. Offsets used for each site: Izembek Lagoon (all sub-sites) = Grant Point, Hook Bay = St. Catherine Cove, St. Catherine Cove = St. Catherine Cove, Middle lagoon and Little John Lagoon = Morzhovoi Bay, and Kinzarof Lagoon = Cold Bay with 1hr lag; Big Lagoon = Morzhovoi Bay with 2hr lag.
Eelgrass initial biomass (B) (g DM m^{-2})	Bering Sea sites $B = 169.27 - 120.15H - 8.7932H^2$ Gulf of Alaska sites $B = 198.93 - 94.75H - 72.413H^2$ where H = patch elevation (m MLLW).	Derived from summer surveys of eelgrass biomass across sites. Separate equations used for sites on Bering Sea (Izembek Lagoon (all sites), Hook Bay, St. Catherine Cove) and Gulf of Alaska (Middle and Big lagoons, Little John Lagoon, and Kinzarof Lagoon) due to different growth conditions. See Data S1 for patch-specific values.
Eelgrass initial shoot length (L) (m)	Bering Sea sites $L = 0.56279 - 0.39378H$ Gulf of Alaska sites $L = 0.48837 - 0.25641H$ where H = patch elevation (m MLLW).	Derived from summer surveys of eelgrass biomass across sites. Separate equations used for sites on Bering Sea (Izembek Lagoon (all sites), Hook Bay, St. Catherine Cove) and Gulf of Alaska (Middle and Big lagoons, Little John Lagoon, and Kinzarof Lagoon) due to different growth conditions. See Data S1 for patch-specific values.
Eelgrass seasonal changes in biomass independent of depletion by the geese	End of biomass decline = day 138 Proportional change per time step = 0.9996361223 Start of biomass growth = day 245 Proportional change per time step = 1.0003706031	Determined from repeated monthly sampling within high and low intertidal areas of the Old Boat Launch eelgrass bed in Izembek Lagoon (Ward and Amundson 2019).

Eelgrass seasonal changes in shoot length (L_{rel})	$L_{rel} = \frac{136.23 - 1.1294D + 0.0027L}{136.23}$ where D = Days since 1 August	Determined from repeated monthly sampling within high and low intertidal areas of the Old Boat Launch eelgrass bed in Izembek Lagoon (Ward and Amundson 2019). Relative eelgrass shoot length was calculated as a proportion of the annual maximum of shoot length.
Eelgrass metabolizability (%)	51	Proportion of energy within eelgrass that is assimilated by the geese. Derived for *Zostera marina* leaves; (Mason et al. 2006).
Eelgrass energy content (kJ g-1 DM)	16.8	Amount of energy per g of eelgrass. Derived for *Zostera marina* leaves; (Mason et al. 2006).
Eelgrass floating biomass (% of rooted biomass in patch)	Fall = 5% of rooted biomass Winter / spring = no floating biomass	No floating eelgrass during winter and spring, as major die-back occurs during fall (Daniels 2014). Floating eelgrass biomass during fall following Stillman et al. (2015).

(c) Goose parameters

Name	Value	Derivation
Population size (number passing through sites)	Brant fall = 160,736 (of which 117,526 during fall only and 43089 during fall and winter) Brant winter = 43,210 Brant spring = 52,058 Cackling fall =34,648	Based on mean of annual survey counts across all sites conducted by U.S. Fish and Wildlife Service-Migratory Bird Management (2010-2016). Fall (Wilson 2019), winter (Wilson 2017a), and spring (Wilson 2017c). Spring: Assumes 75% of brant passing through sites in fall also pass through the sites in the spring.
Size of flocks	1000 individuals	Realistic as geese in site form large flocks (Ward and Stehn 1989).
First and last arrival dates	Brant fall = 25 Aug to 8 Oct Brant winter = 25 Aug to 8 Oct Brant spring = 1 Apr to 27 may Cackling fall = 2 Sep to 6 Sep	Uniformly distributed across a range of reported arrival dates, with geese arriving relative to distance travelled from breeding areas to the Izembek Lagoon (Reed et al. 1989, Dau 1992, Mason et al. 2006, 2007, and Baldassarre 2014).
Departure date	Brant fall = 4 Nov Brant winter = 15 May Brant spring = 15 May Cackling fall = 29 Oct	Based on the earliest observed dates when brant leave the study site (Reed et al. 1989, Dau 1992, Mason et al. 2006, 2007, and Baldassarre 2014). Model geese emigrate after these dates if they have gained sufficient weight.
Initial distribution across sites (proportion in each site)	Sites = 60, 61, 62, 63, 64, 65, 67, 68, 80, 81, 85, 100 Brant fall / winter = 0.086, 0.280, 0.081, 0.093, 0.156, 0.215, 0.007, 0.035, 0.022, 0.000, 0.025, 0.000 Brant spring = 0.059, 0.101, 0.087, 0.008, 0.477, 0.161, 0.073, 0.008, 0.026, 0.000, 0.000, 0.000 Cackling fall = 0.383, 0.117, 0.042, 0.009, 0.107, 0.133, 0.007, 0.139, 0.062, 0.00, 0.001, 0.000	Based on observed distribution of geese in relevant season, from the 2016 Fall Izembek Brant Survey (Wilson 2017b).
Body mass on arrival (g)	Brant fall = 1369 Brant winter = 1369 Brant spring = 1522 Cackling fall = 2202	Brant spring and fall arrival body masses taken from empirical data for juveniles and adults (Mason et al. 2007), less mean daily gain (8.9g d^{-1}, Dau 1992) to adjust arrival dates. Cackling goose body masses taken from empirical data (Hupp et al. 2013) and recalculated as the mean of the entire population, assuming 30% of the population was juvenile and 70% adult.
Energy density of fat (kJ g^{-1})	Brant / Cackling = 34.3	Energy content of avian tissue (Kersten and Piersma (1987)

Starvation mass (g)	Brant = 964 Cackling = 1610	Spaans et al. (2007) estimated the lean mass (i.e., with no energy stores) of dark-bellied brent geese *Branta bernicla bernicla* to be 73% of mass on arrival at breeding area. Thus, for brant, 1320g * 0.73 = 964 g Cackling goose value allometrically scaled from brant value.
Target body mass during staging (g)	Brant fall = 1752 Brant winter = 1715 to 1585 Brant spring = 1611 Cackling fall = 2529	Taken from empirical measurements of adult and juvenile brant prior to peak migration at Izembek Lagoon in fall and spring (Mason et al. 2007), and adult and juvenile Cackling geese (assuming 70/30 population split) at Izembek during fall (Hupp et al. 2013). The range for brant in winter refers to the target at the start and end of winter.
Departure body mass (g)	Brant fall = 1752 Brant winter = 1611 Brant spring = 1611 Cackling fall = 2529	Taken from empirical body masses of adults and juveniles prior to peak migration in fall and spring (Mason et al. 2007), and adult and juvenile Cackling geese (assuming 70/30 population split) at Izembek during fall (Hupp et al. 2013). Model geese must attain these weights to emigrate.
Maximum foraging depth (m)	Brant = 0.40 Cackling = 0.52	Taken from Clausen (1994, 2000) for brant. Cackling geese are about 12cm longer than brant from mid-belly to beak tip, so assumed to gain 12cm greater foraging depth.
Rate of consuming eelgrass biomass (g DM hr^{-1}) (C)	Brant: $C = 60\frac{0.419B}{20.2+B}$ Cackling: $C = 60\frac{0.659B}{20.2+B}$ where B = eelgrass biomass (g DM m^{-2}).	Calculated from consumption rates of East Atlantic light-bellied Brent goose (*Branta bernicla hrota*), feeding on eelgrass (*Zostera marina*; Clausen 2013). Consumption rate of cackling geese allometrically scaled from brant rates.
Maximum energy assimilation (KJ day^{-1}) (E_{max})	$E_{max} = 1713M^{0.72}$ where M = body mass Brant fall: M = 1597 Brant winter: M = 1585 Brant spring: M = 1491 Cackling fall: M = 2366	Calculated from body mass using equation derived by Kirkwood (1983). Body masses are season-specific means (Mason et al. 2007).
Energy expenditure while foraging (J s^{-1})	Brant fall = 13.5 Brant winter (ice free) = 15.3 Brant winter (25% ice) = 17.1 Brant winter (50% ice) = 17.1 Brant winter (100% ice) = 19.9 Brant spring = 14.4 Cackling fall = 18.4	See paper for details
Energy expenditure while resting (J s^{-1})	Brant fall = 12.8 Brant winter (ice free) = 15.3 Brant winter (25% ice) = 17.1 Brant winter (50% ice) = 17.1 Brant winter (100% ice) = 19.9 Brant spring = 14.4 Cackling fall = 18.4	See paper for details

Time cost per disturbance event (s) (D_T)	$D_T = p_R d_T$ where p_R = probability of responding to disturbance and d_T = time cost of response Land-based disturbance: p_R = 0.824; d_T =139 Boat disturbance: p_R = 0.931; d_T = 224 Natural disturbance: p_R = 0.980; d_T = 206	Same time costs assumed for brant and cackling geese. Taken from empirical evidence on brant responses to human and natural disturbance during fall at the Izembek Lagoon (Ward et al. 1994).
Energy cost per disturbance event (KJ) (D_E)	$D_E = p_F d_E$ where p_F = probability of flying due to disturbance and d_E = energy cost of response Land-based disturbance: p_F = 0.900; Brant fall: d_E = 10.23 Brant winter: d_E = 10.38 Brant spring: d_E = 10.27 Cackling fall: d_E = 15.50 Boat disturbance: p_F = 0.944; Brant fall: d_E = 17.02 Brant winter: d_E = 17.27 Brant spring: d_E = 17.08 Cackling fall: d_E = 25.78 Natural disturbance: p_F = 0.917; Brant fall: d_E = 10.50 Brant winter: d_E = 10.65 Brant spring: d_E = 10.53 Cackling fall: d_E = 15.90	Same energy costs assumed for brant and cackling geese. Derived from a combination of evidence on brant responses to disturbance at Izembek (Ward et al. 1994) and calculations of the energetic cost of each disturbance event through the seasons (Mason et al. 2006, 2007, Nudds and Bryant 2000, Gudmundsson 1995). Flight costs were calculated by combining 10 seconds of costlier take-off flight (based on video footage of disturbed brant in Izembek Lagoon) with the remaining duration of steady forwards flapping flight. A previous study on passerines (Nudds and Bryant 2000) found that short flights equated to metabolic power (P_{met}) requirements >3 x those predicted by existing aerodynamic models, which only consider the costs of established flight once the bird is fully airborne. However, comparison of passerine and non-passerine costs during established flight showed that passerine costs scale more steeply with body mass, suggesting that application of short flights formula of Nudds and Bryant (2000) would result in excessively high values for geese. Therefore, this approach was compared with data on wingbeat frequency (Gudmunsson 1995) in heavy pre-migratory brent (*Branta bernicla hrota*), a measure which can be related to heartbeat frequency and thus P_{met}. During take-off, brent displayed high wingbeat frequencies, in the region of 6.4 – 7.5 Hz: in contrast to values of c. 5.5 Hz during established flight. Bishop et al. (2015) found that in free-flying Bar-headed geese (*Anser indicus*), a 5% increase in wingbeat frequency from 4.0 to 4.2 Hz caused a 19% increase in heartbeat frequency, leading to a 41% increase in estimated P_{met}. If this scaling is theoretically applied to the brent in Gudmunsson (1995), the 36% increase in wingbeat frequency on take-off from 5.5Hz to 7.5Hz could potentially cause a 295% increase in P_{met} to 232.5 W for the take-off phase. This value is in good agreement with Nudds and Bryant (2000) prediction of an approximately 3x increase in metabolic costs during short flights in passerines.

Table S2. Sources and derivation of observations used to test the model.

Test	Species / season	Value(s)	Derivation / source
Proportion of geese surviving	Fall brant Winter brant Spring brant Fall cackling	0.99 1.00 0.99 ?	Brant: Table 4 of Ward et al. (1997).
Proportion of geese emigrating	Fall brant Winter brant Spring brant Fall cackling	Approx. 1 Approx. 1 Approx. 1 Approx. 1	Ward and Flint (1995).
Proportion of time spent feeding (over 24 hours)	Brant in fall Brant in winter Brant in spring Cackling in fall	0.48 0.73 0.68 ?	Brant in fall: Table 4.6 of Ward and Stehn (1989). Brant in winter and spring: Table 1 of Daniels (2014) and combining foraging and vigilant and locomotion behaviors of foraging.
Mean rate of body mass change (g day^{-1})	Brant in fall Brant in winter Brant in spring Cackling in fall	5.7 -0.82 4.00 9.5	Brant in fall: Table 7.3 of Ward and Stehn (1989). Brant in winter and spring: Mean mass change divided by duration of season (winter) or mean duration of stay (fall, spring; Mason et al. 2007). Cackling geese: Mean lipid mass gain in juvenile and adults (Hupp et al. 2013)
Staging duration (days)	Fall brant Winter brant Spring brant Cackling in fall	46 247.3 17.3 56	Brant in fall: Table 1 of Reed et al. (1989) using mean dates of arrival and departure. Brant in winter and spring based on geese marked with light-archival geolocators, 2012-2014 (winter: n = 19, range 229-271 days; spring: n = 59, range = 5-43 days; Hupp et al. 2018) Cackling geese: Hupp et al. (2013)
Peak mean count (no. geese)	Brant in fall Brant in winter Brant in spring Cackling in fall	175,222 41,728 49,622 41,971	Mean of peak annual counts over a 10-year period of aerial surveys by U.S. Fish and Wildlife Service-Migratory Bird Management, 2010-2016. Fall (Wilson 2017b, 2019), winter (Wilson 2017a), and spring (Wilson 2017c).
Number of bird days	Brant in fall Brant in winter Brant in spring Cackling in fall	7,304,246 4,084,552 858,466 1,920,812	Staging duration / duration of winter multiplied by mean count during each season. Mean of mean annual counts over period of aerial surveys U.S. Fish and Wildlife Service-Migratory Bird Management, 2010-2016. Fall (Wilson 2017b, 2019), winter (Wilson 2017a), and spring (Wilson 2017c).
Diversity of sites occupied	Brant in fall Brant in winter Brant in spring Cackling in fall	5.75 4.33 3.56 4.66	Simpson index ($1/\sum_{i=1}^{S} p_i$; where S = number of sites, i = site number, and p_i = proportion of population in site i), derived from mean proportion of population within each site during ice-free winter. Observation from observed distribution of geese in relevant season, from the 2016 Fall Izembek Brant Survey (Wilson 2017b).

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