Scaring waterfowl as a management tool: how much more do geese forage after disturbance?

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Appendix S2. Method to calculate energy intake rate and expenditure

Energetics

We assume that the birds aim to be in weight balance, meaning that on a daily basis metabolizable energy intake ($MEI$, J d$^{-1}$) is equal to energy expenditure ($DEE$, J d$^{-1}$), or in case an energetic deficit is incurred, it will be counterbalanced by an energetic surplus as soon as the circumstances allow. A 24h day ($T = 86,400$ s d$^{-1}$) is split into time spent resting, foraging ($T_f$, s d$^{-1}$), and flying ($T_v$, s d$^{-1}$, from and to a roost).

The daily intake of metabolizable energy ($MEI$, J d$^{-1}$) is the product of the instantaneous intake rate ($IIR$, g s$^{-1}$), a function of the sward height (see section Intake rate below), after conversion to metabolizable energy ($q.e.IIR$, J s$^{-1}$), and the daily foraging time ($T_f$):

$$MEI = q \cdot e \cdot IIR \cdot T_f$$

(eqn 1)

where $q$ is the assimilation and $e$ (J g$^{-1}$) the energy content of the food. $T_f$ is a function of the energy balance (see below).

The daily energy expenditure ($DEE$, J d$^{-1}$) is:

$$DEE = (T - T_f - T_v)RMR + T_f \cdot FMR + T_v \cdot VMR$$

(eqn 2)

where $RMR$ (J s$^{-1}$) is resting metabolic rate, $FMR$ (J s$^{-1}$) is field metabolic rate, and $VMR$ (J s$^{-1}$) is flying metabolic rate.

Flying is an energy-demanding activity. Flight time ($T_v$, s d$^{-1}$) is $2V/v$ where $V$ is the average distance (m) from the roost to the foraging site and $v$ is the average flight speed (m s$^{-1}$) [11]. The flight costs $VMR$ (J s$^{-1}$) are allometrically scaled to body mass according to empirical data from other bird species [10]. For parameter values see Table S1.

The bird is in balance when the time spent foraging yields a net intake of foraging exactly covering the costs of resting and flying. Equalling $MEI$ to $DEE$, the required time spent foraging amounts to

$$T_f^* = \frac{(T - T_v)RMR + T_v \cdot VMR}{q \cdot e \cdot IIR - (FMR - RMR)}$$

(eqn 3)

However, because the geese only forage during the day, the foraging time is limited by $T_l$, the available time (day length including civil twilight; day length was calculated from geographical location, http://herbert.gandraxa.com/length_of_day.xml, adding 0.5 h to account for the timing of roost flights). Hence, if $T_l < T_f^*$, the bird cannot cover its energy requirements on this day, and it loses weight [12]:

$$\Delta M = k_m (MEI - DEE)/e$$

(eqn 4)

where $k_m$ is the efficiency for utilization of metabolizable energy during maintenance (0.95, [3]) and $e$ is the energy density of the tissue (27.5 kJ/g, [9]). As soon as the circumstances allow, and as long as the current weight is below the starting weight, body weight is gained again.
\[ \Delta M = k_m (MEI - DEE) / e \]  

(eqn 5)

where \( k_m \) is the efficiency for utilization of metabolizable energy during fat synthesis (0.8, [3]).

Within the thermoneutral zone, RMR is \( 1.4 \times BMR \) (basal metabolic rate) and FMR is \( 1.9 \times BMR \) [17]. During cold weather with wind and little radiation from the sun, the costs of maintaining body temperature can be higher than these standards (RMRs and FMRs). Therefore, using the theory on heat exchange, we calculate the metabolic rate HMR needed to keep a bird body at 40 °C, both during the day (HMRd) and during the night (HMRn) [4, 14, 18]. Thus, realized resting metabolic rate \( RMR = \max(RMR_s, HMR_n) \) and, likewise, realized field metabolic rate \( FMR = \max(FMR_s, HMR_d) \). HMR is a function of ambient air temperature \( T_a \) (°C), wind speed \( u_{hc} \) (m s\(^{-1}\)) at \( h_c = 10 \) m, and the global radiation \( R_g \) (W m\(^{-2}\)). The effect of cooling by wind is a function of the sward height. We neglect the heat loss through evaporation [4]. For further details see Thermoregulation costs.

**Intake rate**

On grassland, bite size \( S \) (g; all biomass in dry weight) is a function of sward height \( L \) (m) [6, 19]:

\[ S_{(L)} = \frac{b_1 L}{1 + b_2 L} \]  

(eqn 6)

where \( b_1 \) and \( b_2 \) are regression-coefficients. As these herbivores are foraging on spatially concentrated plants [process 3, 15], total handling time \( T_h \) (s) is:

\[ T_{h(S)} = T_c + \frac{1}{R_{max}} S \]  

(eqn 7)

where \( T_c \) is cropping time (s) and \( R_{max} \) the maximum rate of chewing (in the absence of cropping, g s\(^{-1}\)). The cropping time \( T_c \) is in turn a function of sward height \( L \), presumably because the birds are becoming more selective with increasing sward height [6]:

\[ T_{c(L)} = T_{c0} + cL \]  

(eqn 8; [Box 1, 8])

One should also consider that geese regularly look up during foraging in order to check their surroundings. The ratio alert : feeding varies between 0.22 to 0.03, being lower the larger the group size [16] and the shorter the day length [7]. During alert the heart beat is elevated above resting levels [1, 13], and therefore we modelled alert as part of foraging. The intake rate is calculated over the time span feeding + alert, assuming a minimum proportion alert of 0.05. These processes together result in a type 4 functional response, with an instantaneous intake rate \( IIR \) (g s\(^{-1}\)) as function of sward height \( L \):

\[ IIR_{(L)} = \frac{S_{(L)}}{dT_{h(S)}} = \frac{1}{\alpha} \left[ 1 + \frac{b_2 L}{b_1 L} (T_{c0} + cL) + \frac{1}{R_{max}} \right]^{-1} \]  

(eqn 9)

where \( \alpha \) is the factor with which the feeding time is multiplied to account for the alert time (\( \alpha = 1.05 \)). See Table S1 for parameter values.
## Table S1. Parameter values for white-fronted geese

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
<th>Footnote, [Ref]</th>
</tr>
</thead>
<tbody>
<tr>
<td>body mass $M$ (g)</td>
<td>2094</td>
<td>1,[5]</td>
</tr>
<tr>
<td>functional response $b_1$ (g m$^{-1}$)</td>
<td>0.246</td>
<td>2</td>
</tr>
<tr>
<td>functional response $b_2$ (g m$^{-1}$)</td>
<td>29</td>
<td>3</td>
</tr>
<tr>
<td>functional response $c$ (s m$^{-1}$)</td>
<td>0.5</td>
<td>4</td>
</tr>
<tr>
<td>minimal cropping time $T_{c0}$ (s)</td>
<td>0.59</td>
<td>5</td>
</tr>
<tr>
<td>maximal chewing rate $R_{max}$ (g s$^{-1}$)</td>
<td>0.032</td>
<td>6</td>
</tr>
<tr>
<td>metabolic energy content of grass $q\cdot e$ (J g$^{-1}$)</td>
<td>7300</td>
<td>[2]</td>
</tr>
<tr>
<td>basal metabolic rate $BMR$ (J s$^{-1}$)</td>
<td>7.35</td>
<td>7</td>
</tr>
<tr>
<td>resting metabolic rate $RMR$ (J s$^{-1}$)</td>
<td>1.4$x$BMR</td>
<td>[17]</td>
</tr>
<tr>
<td>foraging metabolic rate $FMR$ (J s$^{-1}$)</td>
<td>1.9$x$BMR</td>
<td>[17]</td>
</tr>
<tr>
<td>flight speed $v$ (m s$^{-1}$)</td>
<td>9.44</td>
<td>8</td>
</tr>
<tr>
<td>flight metabolism $VMR$ (J s$^{-1}$)</td>
<td>114.4</td>
<td>9,[10]</td>
</tr>
<tr>
<td>distance from roost $V_{max}$ (m)</td>
<td>3200</td>
<td>8</td>
</tr>
</tbody>
</table>

1 average of adults in winter  
2 based on allometric relationship: log $b_1 = -0.332 \log M + 0.493$ ($R^2 = 0.66$, $N = 4$)  
3 based on allometric relationship: log $b_2 = -1.49 \log M + 6.40$ ($R^2 = 0.85$, $N = 3$)  
4 interpolation  
5 average of other waterfowl species  
6 based on allometric relationship: log $R_{max} = 0.871 \log M - 4.38$ ($R^2 = 0.84$, $N = 4$)  
7 based on allometric relationship: log $BMR = 0.755 \log M - 1.642$ ($R^2 = 0.97$, $N = 9$); in [2] erroneously listed under pink-footed goose  
8 this study  
9 based on allometric relationship in [10]
Thermoregulation costs

Input variables are the ambient air temperature $T_a$ (°C), windspeed $u_{hc}$ (m s$^{-1}$) at 10 m height and daily sunshine duration $SSD$ (h day$^{-1}$). For daytime we used maximum temperature and windspeed and daily sunshine, and for nighttime minimum temperature and windspeed and no sunshine. Output is $HMR$, the metabolic rate needed to heat the body and keep it at 40 °C.

$$HMR = H \cdot 4\pi \cdot r^2$$  (Note: [18] uses $\pi \cdot r^2$)

where

$r$ (m) is the radius of the bird, calculated from body mass $M$ (g) using an empirical relationship (Birkebak 1966 in [18]):

$$r = \sqrt{(485.6 \times M/1000+592.83)/(4\pi)} / 100$$

and

$H$ (W m$^{-2}$) is the heat flux per surface area, which in turn is calculated as:

$$H = (\rho \cdot cp) \cdot (T_b - T_{es})/(r_p+r_e)$$

where

$\rho$ (g m$^{-3}$) is the density of dry air as a function of $T_a$:

$$\rho = 1292 - (5 \cdot T_a) + (0.01567 \cdot T_a^2) \text{ (Monteith 1973 in [14])}$$

$cp$ is specific heat of air (1.010 J g$^{-1}$ oC$^{-1}$)

$T_b$ is body temperature (40 °C)

$T_{es}$ is standard operative temperature (°C) (see below)

$r_p$ is plumage resistance (867 s m$^{-1}$) [18]

$r_e$ (s m$^{-1}$) is equivalent outer resistance:

$$r_e = (r_r \cdot r_a)/(r_r+r_a)$$  [14]

with:

$r_r$ (s m$^{-1}$) is radiation resistance:

$$r_r = (\rho \cdot cp) / [4 \cdot \varepsilon \cdot \sigma \cdot (T_a+273)^3]$$

where

$\varepsilon$ is emissivity of the surface of the bird (0.98) [4]

$\sigma$ is the Stefan-Boltzmann constant (5.67 $10^8$ W m$^{-2}$ oC$^{-4}$)

$r_a$ (s m$^{-1}$) is convection resistance:

$$r_a = (r_{fr} \cdot r_{fo})/(r_{fr}+r_{fo})$$

with:

$r_{fr}$ (s m$^{-1}$) is free convection resistance:

$$r_{fr} = 820 \cdot 2 \cdot r / (T_s - T_a)^{\frac{1}{4}}$$

and

$r_{fo}$ (s m$^{-1}$) is forced convection resistance:

$$r_{fo} = 307 \cdot \sqrt{(2 \cdot r / u)}$$

where:

$u$ (m s$^{-1}$) is the wind speed experienced by the bird (see below).

Furthermore:

$$T_{es} \equiv T_b - (1 + 0.26 \cdot \sqrt{u}) \cdot (T_b - T_e)$$  (Bakken, 1990 in [4])

where:

$T_e$ (°C) is equivalent temperature:

$$T_e = T_a + (R_{abs} - R_{emi}) \cdot r_e / (\rho \cdot cp)$$  (Campbell, 1977 in [4])
in which:

\[ R_{abs} \text{ (W m}^{-2}\text{)} \] is the **radiation absorbed** by the bird:

\[ R_{abs} = \alpha \cdot A_{ratio} \cdot R_g + \varepsilon_s \cdot \sigma \cdot (T_s + 273)^4 \]  
(Campbell, 1977 in [4])

where:

- \( \alpha \) is **absorptivity to radiation** (0.75) (Calder & King 1974 in [14])
- \( A_{ratio} \) is **relative surface receiving direct radiation** (0.29) [4]
- \( \varepsilon_s \) is **emissivity of the surroundings** (0.94) [4]
- \( R_g \text{ (W m}^{-2}\text{)} = R_a \cdot (Aa + Ba \cdot (SSD / DL)) \)

\[ R_{em} \text{ (W m}^{-2}\text{)} \] is the **radiation emitted** by the bird:

\[ R_{em} = \varepsilon \cdot \sigma \cdot (T_s + 273)^4 \]  
(Campbell, 1977 in [4])

The wind speed \( u \text{ (m s}^{-1}\text{)} \) at the bird level is:

\[ u = u^* / k_v \cdot [\ln ((h_b + z_m - pd_0 \cdot h_v) / z_m)] \]  
(Campbell, 1977 in [4])

where:

- \( u^* \text{ (m s}^{-1}\text{)} \) is **friction velocity**:
  \[ u^* = u_{hc} \cdot k_v / [\ln ((h_c + z_m - pd_0 \cdot h_v) / z_m)] \]  
(Campbell, 1977 in [4])

with:

- \( u_{hc} \text{ is the wind speed measured at height } h_c \text{ (} h_c = 10 \text{ m)} \)
- \( k_v \text{ is the Von Karman proportionality constant} \text{ (0.41) (note: } k_v \text{ cancels out in eqn } u^*\text{)} \)
- \( z_m \text{ is roughness length} \text{ (0.01 m)} \)  
(Wieringa, 1993 in [18])
- \( pd_0 \text{ is relative displacement height} \text{ (0.78 of } h_v\text{)} \)  
(Shuttleworth, 1989 in [18])
- \( h_v \text{ (m)} \text{ is vegetation height} \)
- \( h_b \text{ (m)} \text{ is height of the bird’s centre of gravity above the ground, from } r \text{ (bird radius)} \)
- \( h_b = 1.5 \times r \)

Footnotes: \( ^5 \) [2] incorrectly gives (W) as unit; \( ^\S \) [4] incorrectly gives \( T_b \) instead of \( T_s \)
References


