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 \((\text{MEI}, \text{J d}^{-1})\) is equal to energy expenditure \((\text{DEE}, \text{J d}^{-1})\), 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 \((T = 86,400 \text{ s d}^{-1})\) is split into time spent resting, foraging \(T_f, \text{ s d}^{-1}\), and flying \(T_v, \text{ s d}^{-1}\), from and to a roost.

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

\[
\text{MEI} = q \cdot e \cdot \text{IIR} \cdot T_f
\]

(eqn 1)

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

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

\[
\text{DEE} = (T - T_f - T_v) \cdot \text{RMR} + T_f \cdot \text{FMR} + T_v \cdot \text{VMR}
\]

(eqn 2)

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

Flying is an energy-demanding activity. Flight time \(T_v (\text{ s d}^{-1})\) 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 \(\text{VMR} (\text{J s}^{-1})\) 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 \(\text{MEI}\) to \(\text{DEE}\), the required time spent foraging amounts to

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

(eqn 3)

However, because the geese only forage during the day, the foraging time is limited by \(T_i\), 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 \(T_i < T_f^*\), the bird cannot cover its energy requirements on this day, and it loses weight [12]:

\[
\Delta M = k_m \frac{\text{MEI} - \text{DEE}}{e}
\]

(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:
\[ \Delta M = k_m (MEI - DEE) / e \]  
\text{(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 (\( RMR_s \) and \( FMR_s \)). 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 (\( HMR_d \)) and during the night (\( HMR_n \)) [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]:

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

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

\[ T_{c(L)} = T_{c0} + cL \]  
\text{(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 a function of sward height \( L \):

\[ IIR_{(L)} = \left( \frac{S_{(L)}}{\alpha T_{h(S)}} \right) = \frac{1}{\alpha} \left( \frac{1 + b_2 L}{b_1 L} (T_{c0} + cL) + \frac{1}{R_{max}} \right)^{-1} \]  
\text{(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>
<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>
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<td>3</td>
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<tr>
<td>functional response $c$ (s m$^{-1}$)</td>
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<td>4</td>
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<tr>
<td>minimal cropping time $T_{c0}$ (s)</td>
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<td>5</td>
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<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×$BMR$</td>
<td>[17]</td>
</tr>
<tr>
<td>foraging metabolic rate $FMR$ (J s$^{-1}$)</td>
<td>1.9×$BMR$</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 $T_a$:

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

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

$T_b$ 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:

$$r_e = (r_r \cdot r_o)/(r_r + r_o)$$ [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$^{-2}$ °C$^{-4}$)

$r_a$ (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:

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

and

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

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

where:

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

Furthermore:

$$T_{es} = T_b - (1 + 0.26 \cdot \sqrt{u}) \cdot (T_b - T_e)$$ (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:

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

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

where:

- \( \alpha \) is *absorbtivity to radiation* (0.75) (Calder & King 1974 in [14])
- \( A_{\text{ratio}} \) is *relative surface receiving direct radiation* (0.29) [4]
- \( \varepsilon_s \) is *emissivity of the surroundings* (0.94) [4]

\[ R_g \text{ (W m}^{-2}\text{)} = R_a \cdot (Aa + Ba \cdot (SSD / DL)) \]

where:

- \( R_a \text{ (W m}^{-2}\text{)} \) is the *extra-terrestrial radiation* calculated according to http://www.supit.net
- \( Aa \) and \( Ba \) are Ångström-Prescott constants (calculated with tool on http://www.supit.net)
- \( SSD \text{ (h day}^{-1}\text{)} \) is *daily sunshine duration*
- \( DL \text{ (h day}^{-1}\text{)} \) is *daylength*

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

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

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

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

where:

- \( u^* \text{ (m s}^{-1}\text{)} \) is *friction velocity*:

\[ u^* = u_{hc} \cdot k_v \cdot \left[ \ln \left( (h_c + z_m - pd_0 \cdot h_v) / z_m \right) \right] \]  
(Campbell, 1977 in [4])

with:

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

Footnotes: \( ^{\text{§}} \) [2] incorrectly gives (W) as unit; \( ^{\text{§§}} \) [4] incorrectly gives \( T_b \) instead of \( T_s \)
References


