

EnergyBudget

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Using published and unpublished data from Dr. Don Powers' earlier work, we construct here a preliminary energy budget for a North American species, the Broad-billed hummingbird (BBLH; *Cyananthus latirostris*).

1. Basal Metabolic Rate

Basal metabolic rate is the minimum metabolic rate required for survival. It includes basic body upkeep, and does not include thermoregulation, digestive costs, or any activity costs. The basal metabolic rate measurements here are based on a regression of metabolic rates measured under basal metabolic conditions over a range of temperatures (in the dark, fasted, during the sleep phase; measured during summer 2012).

Mean $BMR_{BBLH} = 0.2385 \text{ mL/min}$ (4.8 J/min; 0.0799W; where MR of 1 ml/min = 20.1 Joules/min. 1 Watt is 1 Joule/second)

The assumptions of these measurements are:

- 32°C is the lower critical temperature and represents the lowest temperature for measurement of the basal metabolic rate. A lower critical temperature of 32°C is consistent with measurements for a number of other hummingbirds (Lasiewski 1963 [add more citations]) and data on Costa's Hummingbirds (*Calypte costae*) and broad-tailed hummingbirds (*Selasphorus platycercus*; unpublished, Donald R. Powers).
- Basal metabolism is assumed as a continuous cost for 24 hours except when birds use torpor. If torpor is used then BMR is a continuous cost for 24 hours, excluding the hours spent in torpor. Torpor was used for a maximum of four hours at the Sonoita Creek site where these Broad-billed hummingbirds were studied.

2. Thermoregulation

The thermoneutral zone (TNZ) is the optimum range of ambient temperatures over which there are no regulatory changes in metabolic heat production or evaporative heat loss (Kingma et al. 2012). Thermoregulatory costs are calculated separately below and above the TNZ, as the slopes are different and asymmetric for these two regions, as seen in Figure 1. We thus retain separate equations for the two even though the TNZ of small hummingbirds appears so small that the lower and upper critical temperatures are essentially identical Lasiewski (1963).

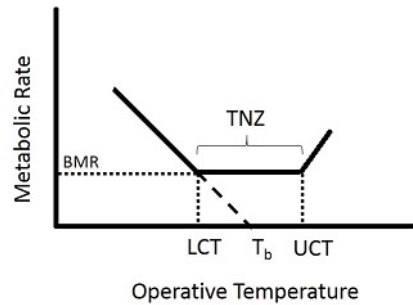


Figure 1: The thermoneutral zone (TNZ). T_b = Body temperature; LCT = Lower critical temperature; UCT = Upper critical temperature; BMR = Basal metabolic rate

A. Below the TNZ (Operative temperature $T_e < 32^\circ\text{C}$)

First, hourly averages for metabolic rate across a range of temperatures below the TNZ were measured, resulting in this relationship: $MR_L \text{ (mL O}_2\text{/min)} = 0.9530 - 0.0223*(T_e)$ **-Equation 1a**

Here, MR_L is metabolic rate when $T_e < 32^\circ\text{C}$, and includes both basal metabolic rate costs and thermoregulatory costs. We can then calculate TRE_L , which is the sum of the hourly averages of MR_L for all hours where mean $T_e < \text{lower critical temperature}$.

$$TRE_L \text{ (kJ)} = \Sigma(MR_L * 60) \quad \text{- Equation 1b}$$

Thus, TRE_L is the total daily energy spent on thermoregulation below the TNZ. Torpor was assumed to be zero because birds rarely entered torpor in Sonoita Creek.

B. Above the TNZ ($T_e > 35^\circ\text{C}$)

Lasiewski's (1963) data suggests that the upper critical temperature for small hummingbirds is $\sim 35\text{--}37^\circ\text{C}$. The only data we know of for metabolic rate above the upper critical temperature in small hummingbirds are Powers' unpublished data on Costa's. These data also show an upper critical temperature of 35°C . The slope of the relationship below was based on unpublished measurements of Costa's Hummingbird (*Calypte costae*), a similarly sized species. The intercept of the equation below was obtained by substituting the Broad-billed hummingbird's BMR and an operative temperature of 35°C into the Costa's regression equation.

$$MR_H \text{ (mL O}_2\text{/min)} = 0.214 (T_e) - 7.2515 \quad \text{- Equation 2a}$$

Where MR_H is metabolic rate above upper critical temperatures. This is calculated by subtracting BMR from the result of equation 2a. Again, for simplicity of calculation the result of equation 2a is the combined cost of BMR and thermoregulation.

$$TRE_H \text{ (kJ)} = \Sigma(MR_H * 60) \quad \text{- Equation 2b}$$

TRE_H is calculated as the sum of hourly averages for all hours where mean $T_e > \text{upper critical temperature}$, again assuming no torpor use.

3. Activity Costs

A. Resting (perching)

Little data are available for how much resting metabolic rate (RMR) is elevated above BMR in hummingbirds. In the late 1980's Powers measured RMR for Costa's ($3.66 \text{ mL O}_2 \text{ g}^{-1}\text{h}^{-1}$; unpublished). Lasiewski (1963) measured BMR for Costa's ($3.025 \text{ mL O}_2 \text{ g}^{-1}\text{h}^{-1}$). Thus,

$$RMR_{\text{Costa}} = 1.21 \times \text{BMR}$$

This is consistent with an Aschoff & Pohl study (1970) which reported data for several bird species suggesting $RMR = 1.25 \times \text{BMR}$. The Aschoff & Pohl correction has often been used to estimate RMR but might underestimate true resting costs because the measurements upon which it is based were typically made on birds resting in the dark. This would eliminate any costs associated with response to light or surrounding events. Further, Aschoff & Pohl fasted birds so the cost of specific dynamic action (i.e. the cost of digestion; SDA) is also not included. Two years ago Powers made RMR measurements on Calliope hummingbirds (*Selasphorus calliope*; $\sim 2.4 \text{ g}$) on a perch in an illuminated chamber. After subtracting thermoregulatory costs $RMR_{\text{Calliope}} = 0.2835 \text{ mL O}_2\text{/min}$. $\text{BMR}_{\text{Calliope}} = 0.1843 \text{ mL O}_2\text{/min}$ (Lasiewski 1963). Thus,

$$RMR_{\text{Calliope}} = 1.54 \times \text{BMR}$$

This is likely to more accurately reflect the metabolic rate of a perching hummingbird in the wild. Thus, we can estimate RMR as:

$$RMR = 1.5 \times \text{BMR} \quad \text{- Equation 3}$$

This is a fair relationship to use for broad-billed hummingbirds, as Calliope and Broad-billed hummingbirds are behaviorally similar and perch in similar environments.

$$\text{Thus, } RMR_{\text{BBLH}} = 1.5 * (0.2385) \text{ ml/min} = 0.3578 \text{ ml/min} \text{ (7.1908J/min; 0.1198W)}$$

B. Hovering

Powers has measured hovering metabolic rate (HMR) in Broad-billed hummingbirds:

HMR = 2.1 mL O₂/min (42.21 J/min; 0.7035W)

This value is 8.8 x BMR, which is reasonable (similar to findings in Fernandez et al. 2011).

C. Forward flight

No measurements have been made on the metabolic cost of forward flight (FLMR) in Broad-billed hummingbirds. If we assume that hummingbirds fly most often at their most efficient speed (6-8 m/s), FLMR can be estimated using data from other hummingbird species. These relationships are well-established from studies on power curves in hummingbirds (Tobalske et al. 2003, 2010).

FLMR_{Calliope} = 0.53 x HMR

FLMR_{Rufous} = 0.49 x HMR

Thus, we can estimate FLMR to be:

FLMR = 0.5 x HMR - **Equation 4**

FLMR = 0.5*2.1 ml/min = 1.05 ml/min (21.11 J/min; 0.3518W)

D. Total activity costs

ACT = ((Time_{RMR} * (RMR - BMR)) + (Time_{HMR} * (HMR - BMR) + (Time_{FLMR} * (FLMR - BMR)) - **Equation 5**

4. Nighttime Metabolic Rate

There is a large amount of individual and daily variation in the frequency and duration of torpor use. For the sake of modeling DEE we assume that either torpor is not used at all, or if torpor is used it is used to the full extent observed. By doing so we can create upper and lower energetic boundaries based on whether or not torpor was used.

A. No torpor

Nighttime metabolic rate (NMR) will be BMR plus the cost of thermoregulation below the lower critical temperatures. Thus, NMR for normothermic hummingbirds can be calculated using equation 1a.

B. Torpor

For birds that used torpor maximally last summer:

Nighttime energy expenditure (NEE) = 2 kJ

Note: This value can change slightly as we refine the calculations. Even so this is such a small component of DEE that small changes to this value will have little impact on model results.

5. DEE Model

DEE = (TRE_L + TRE_H) + ACT + NEE

Where: DEE = Daily energy expenditure

TRE_L = Metabolic rate below lower critical temperature (including thermoregulation and BMR)

TRE_H = Metabolic rate above higher critical temperature (including thermoregulation and BMR)

ACT = Activity costs (from above)

NEE = Nighttime energy expenditure

Note: If no torpor is used then NEE = 0, and NEE is included in TRE_L. If the species had a broader TNZ, BMR for time spent in the TNZ would be included as an additional term (thermoregulatory costs would be 0).

Model Test Using Sonoita Creek *C. latirostris* values

Here, assuming: 1. 70% of the daytime was spent perching and 30% flying. Flying was 50% hovering and 50% forward flight.

2. No torpor (this is realistic for SC).
3. Respiratory quotient (RQ) = 0.85 (for conversion of oxygen consumption to CO₂ production)
4. 14/10 photoperiod.

Results: Mean Measured DEE (DLW) = 51.3 +- 6.6 mL CO₂/h (range 39.5-58.6) Model Estimate = 43.2 mL CO₂/h

The model estimate is 16% lower than the measured value but is within the range of measured values (albeit at the low end). We are very encouraged by this considering that this model is likely biased low since costs of molt and reproduction are not specifically considered.