The thermal dependence of biological traits

Anthony I. Dell[a,b,c*], Samraat Pawar[a,d], and Van M. Savage[a,e,f]

[a] Department of Biomathematics, UCLA, Los Angeles, CA 90024 , USA
[b] School of Marine and Tropical Biology, James Cook University, Townsville, QLD 4811, Australia
[c] Systemic Conservation Biology, Department of Biology, University of Göttingen, Göttingen 37073, Germany
[d] Department of Ecology & Evolution, University of Chicago, Chicago, IL 60637 USA
[e] Department of Ecology and Evolutionary Biology, UCLA, Los Angeles, CA 90024, USA
[f] Santa Fe Institute, Santa Fe, NM 87501, USA

[*] Corresponding author: adell@gwdg.de

Abstract

Environmental temperature has strong and systematic effects on biological processes at all levels of organization, ranging from cells to ecosystems. The large temporal and spatial variation in earth's temperature creates a complex thermal landscape within which life evolves and operates. Here, we present a dataset on how diverse biological rates and times respond to temperature, which we hope will aid in the search for general mechanisms of thermal dependence. For nearly a century, intraspecific studies (within single species' populations) of thermal responses have been conducted on a wide range of organismal traits. Comparative studies of these data are essential for elucidating mechanisms underlying thermal response curves. However, such comparative intraspecific studies have been limited because of a lack of a comprehensive database that organizes these data with consistent units and trait definitions. Here, we present a database of 2,352 thermal responses for 220 traits for microbes, plants, and animals compiled from 270 published sources. This represents the most diverse and comprehensive thermal response dataset ever compiled. The traits in this database span levels of biological organization from internal physiology to species interactions, and were measured in marine, freshwater, and terrestrial habitats for 411 species. Although we include some physiological rates, most data are for ecological traits, which we define here to mean any organismal trait that directly determines interactions between individuals within or between species. We hope that publication of our dataset will encourage others to compile complementary datasets, especially on individual physiology and life history traits. Intraspecific and interspecific (across species' populations) analyses of our dataset should provide new insights into generalities and deviations in the thermal dependence of biological traits, and thus how biological systems, from cells to ecosystems, respond to temperature change. Such insights are essential for understanding how natural biological systems function, and for how life is responding to Earth's complex and rapidly changing thermal landscape.

Key words

Temperature, database, ecoinformatics, trait, environmental driver, thermal response, species, intraspecific, interspecific, ecology, evolution

Metadata

INTRODUCTION

Because environmental temperature has pervasive effects across cells, individuals, populations, and ecosystems, elucidating mechanisms by which biological systems respond to temperature is essential for understanding how these systems operate in nature. Given rapid changes to Earth's thermal environment (IPCC 2007), understanding species' thermal responses and their consequences for biodiversity and ecosystem functioning is especially critical (Petchey et al. 2010, Rall et al. 2010, Dell et al. in print).

Body temperature, a major driver of individual physiology from cellular respiration to whole organismal respiration, is strongly affected by environmental temperature in ectotherms (Johnson et al. 1974, Cossins and Bowler 1987, Huey and Kingsolver 1989, Somero , Gillooly et al. 2001, Brown et al. 2004, Angilletta 2009, Dell et al. 2011). These individual-level effects cascade up to affect populations, species interactions, and ecosystems. An understanding of how these effects translate across levels of biological organization requires analysis of a broad suite of functional traits spanning from cells to communities (Angilletta 2009, Dell et al. 2011). For nearly a century, intraspecific studies, which measure a trait within a single species' population across a range of temperatures, have been conducted on a variety of biological traits (e.g., Bennett 1980, Hertz et al. 1982, Cossins and Bowler 1987, Gillooly et al. 2002, Savage et al. 2004, Ratkowsky et al. 2005, Frazier et al. 2006, Angilletta 2009, Irlich et al. 2009b). However, comparative studies of these intraspecific data have tended to focus on small subsets of available data (e.g., Huey and Bennett 1987, Huey and Kingsolver 1989, Bauwens et al. 1995, Huey and Berrigan 2001, Irlich et al. 2009b), probably for two central reasons. First, there is clearly a general lack of empirical data on the thermal response of ecological traits required to address particular ecological and evolutionary questions. This issue must be addressed by a renewed effort by empirical biologists to collect more thermal response data on traits relevant to species interactions. Second, there is a lack of a comprehensive database that compiles existing data, which is required to compare methodologically and taxonomically diverse thermal response data.

In this paper we address the second issue by constructing from published sources a dataset that contains 2,352 intraspecific temperature responses. This dataset is the most comprehensive ever compiled for the thermal responses of physiological and ecological traits. We emphasize that this database focuses mainly on "ecological traits", which we define here to mean any organismal trait that directly determines or measures interactions between individuals within or between species. Our effort was motivated by the fact that understanding effects of global warming on species interactions is one of the major challenges in contemporary ecology (Harrington et al. 1999, Walther et al. 2002, Helmuth et al. 2005, Vasseur and McCann 2005, Woodward et al. 2010, Dell et al. in print). The resulting global database contains intraspecific thermal responses for 220 traits and 411 species of plants, microbes, and animals that span 16 orders of magnitude in body size. This is also the first compilation of organismal thermal responses wherein all traits have been converted to consistent units and standardized trait definitions.

Analysis of this dataset should reveal how biological systems respond to temperature (Irlich et al. 2009a, Dell et al. 2011, Englund et al. 2011, Nilsson-Örtman et al. 2012). These intraspecific data can also be used to investigate interspecific thermal response curves, which are constructed from trait measurements for multiple species at their optimal temperature and plotted together to construct a single curve (Brown et al. 2004, Angilletta 2009, Dell et al. 2011). Patterns of interspecific thermal response curves are important because they represent underlying constraints on thermal adaptation (Gillooly et al. 2001, Gillooly et al. 2002, Izem 2005, Frazier et al. 2006, Knies et al. 2009, Angilletta et al. 2010, Corkrey et al. 2012). This dataset should also be useful in testing assumptions and predictions of mechanistic models, such as the metabolic theory of ecology (Gillooly et al. 2001, Gillooly et al. 2002, Brown et al. 2004). Ultimately, we hope analysis of this comprehensive dataset will illuminate previously unrecognized generalities and deviations in how biological systems respond to temperature (Dell et al. 2011), and help elucidate the mechanisms by which life responds to Earth's complex and rapidly changing thermal landscape.

CLASS I. DATASET DESCRIPTORS

A. Dataset identity

Compilation of published intraspecific thermal response curves for physiological and ecological traits.

B. Dataset identification code

TempTrait_001.txt

C. Dataset description

Summary: Dataset has 19,921 records from 2,352 intraspecific temperature response curves that measure the thermal dependence of physiological and ecological traits from 411 taxa and various marine, terrestrial and freshwater habitats. Each record has 65 fields that detail the trait, taxa, and experimental conditions of each thermal response.

Principal Investigators: *Anthony I. Dell*, Systemic Conservation Biology, Department of Biology, Georg-August University Göttingen, Göttingen 37073, Germany; *Samraat Pawar*, Department of Ecology & Evolution, University of Chicago, Chicago, IL 60637, USA; *Van M. Savage*, Department of Biomathematics, UCLA School of Medicine, Los Angeles, CA 90024, USA. Queries regarding the dataset should be directed to A.I. Dell (adell@gwdg.de).

Abstract: Environmental temperature has strong and systematic effects on biological processes at all levels of organization, ranging from cells to ecosystems. The large temporal and spatial variation in earth's temperature creates a complex thermal landscape within which life evolves and operates. Here, we present a dataset on how diverse biological rates and times respond to temperature, which we hope will aid in the search for general mechanisms of thermal dependence. For nearly a century, intraspecific studies (within single species' populations) of thermal responses have been conducted on a wide range of organismal traits. Comparative studies of these data are essential for elucidating mechanisms underlying thermal response curves. However, such comparative intraspecific studies have been limited because of a lack of a comprehensive database that organizes these data with consistent units and trait definitions. Here, we present a database of 2,352 thermal responses for 220 traits for microbes, plants, and animals compiled from 270 published sources. This represents the most diverse and comprehensive thermal response dataset ever compiled. The traits in this database span levels of biological organization from internal physiology to species interactions, and were measured in marine, freshwater, and terrestrial habitats for 411 species. Although we include some physiological rates, most data are for ecological traits, which we define here to mean any organismal trait that directly determines interactions between individuals within or between species. We hope that publication of our dataset will encourage others to compile complementary datasets, especially on individual physiology and life history traits. Intraspecific and interspecific (across species' populations) analyses of our dataset should provide new insights into generalities and deviations in the thermal dependence of biological traits, and thus how biological systems, from cells to ecosystems, respond to temperature change. Such insights are essential for understanding how natural biological systems function, and for how life is responding to Earth's complex and rapidly changing thermal landscape.

D. Key words:

Temperature, database, ecoinformatics, trait, environmental driver, thermal response, species, intraspecific, interspecific, ecology, evolution

CLASS II. RESEARCH ORIGIN DESCRIPTORS

A. Overall project description

Identity: The thermal dependence of biological traits.

Originators: Anthony I. Dell, Samraat Pawar, and Van M. Savage.

Period of study: Dates of publications from which data were obtained currently range from 1923 to 2009.

Objectives: The objective of this project was to construct a comprehensive and consistent dataset of measurements of the thermal dependence of a wide range of physiological and ecological traits from diverse taxa and habitats. Such a single, extensive dataset for multiple traits with consistent measurement units and trait definitions should facilitate novel comparative analyses and hypothesis testing, yielding new insights into generalities and important deviations in thermal responses of biological systems. Eventually, these data should help reveal general mechanisms by which life responds to changing thermal landscapes worldwide.

Abstract: As above.

Sources of funding: University of California Los Angeles (Biomathematics); National Science Foundation Division of Environmental Biology (1021010); James Cook University (Tropical Biology), Australian Research Council.

B. Specific subproject description

Data Acquisition. We searched the published literature for intraspecific thermal response curves on biological traits, with a primary focus on traits central to species interactions. The temperature response of traits can be strongly influenced by organismal behavior (e.g., Schieffelin and Dequeiroz 1991, Cooper 2000, Shine et al. 2000, Herrel et al. 2007). Therefore, we focused on rates and times of the execution of biological processes (e.g., attack body velocity, handling rate) and not on decisions about whether to execute them (e.g., attack probability, defense behavior probability). In total, we found 270 data sources that described intraspecific thermal responses, including journal articles, published reports, and books. We attempted to contact authors directly to obtain raw data, but if this was not possible we extracted data directly from tables and text or from figures using DataThief (Tummers 2006). Our use of DataThief made it impossible to know the true precision of the original data. Also, because we sometimes obtained raw data from the authors, in some cases our dataset will not exactly match that described within the original publication (e.g., replicate thermal responses are not combined). This procedure yielded 2,352 intraspecific temperature responses and 19,921 data points. We primarily selected studies where environmental conditions, such as precipitation, light, and prey density were either controlled or standardized. Consequently, most responses were measured in the laboratory, where ectotherm body temperatures were known to be close to ambient (based on direct measurements and extended acclimation times at test temperatures). The 270 sources from which data were described and analysed in this paper are listed in the `Citations` field of the data file. Because the number of studies on thermal responses of ecological traits is increasing rapidly, we are currently adding to the dataset, which will be updated periodically.

Unit Conversions. Definitions and measures of many traits are inconsistent throughout the literature, so we identified equivalent traits and converted them to comparable definitions and SI units. Where possible, probabilistic trait data were converted to rates or times.

Taxonomy and systematics. Taxonomic designations were used as stated in the source publication, unless there was clear evidence of a name change in which case the new name was used. Each species' taxonomic hierarchy was determined by using Species 2000 (http://www.sp2000.org), the Encyclopedia of Life (http://eol.org), and Animal Diversity Web (http://animaldiversity.ummz.umich.edu).

Body Size. When available, wet mass of each organism was obtained from the original data source. For studies in which body mass was not provided, we developed an algorithm that assigned a wet mass estimate to species in each data row. This algorithm was based on taxonomic relatedness to published size estimates and length-mass regressions, and allowed us to rapidly obtain estimates of wet body mass that well matched published measurements. Details of the algorithm and its implementation are given in Dell et al. (2011).

Permit history: NA.

Legal/organizational requirements: None.

Project personnel: Anthony I. Dell, Samraat Pawar, and Van M. Savage.

CLASS III. DATASET STATUS AND ACCESSIBILITY

A. Status

Latest update: August 2012. Data compilation is ongoing and will be added as collected and verified.

Latest Archive date: August 2012.

Metadata status: Metadata are complete and up to date.

Data verification: A.I. Dell, with assistance from S. Pawar, entered records directly from original sources into MS Access. All values were at minimum triple checked at various stages of data complication and analysis. Plots of each thermal response were automatically produced in MS Access and compared to figures in the original source. In addition, outliers in numeric variables were sorted to examine extreme values. For body size estimates (Class II, Section B) we constructed box plots by taxonomy (Family and Order) and observed outliers for errors. It is important to note that in cases where we obtained raw data directly from authors (see above) our data will not exactly match that described within the original publication, because our data will be more detailed (e.g., replicates are not averaged).

B. Accessibility

Storage location and medium: The dataset is available from the Ecological Society of America's data archives. A digital version of the dataset in MS Excel format is held by A.I. Dell, and a beta mySQL version (searchable by trait, taxa and citation) is now available online at www.biotraits.ucla.edu.

Contact person: Anthony I. Dell, Systemic Conservation Biology, Department of Biology, Georg-August University Göttingen, Göttingen 37073, Germany (adell@gwdg.de).

Copyright restrictions: None.

Proprietary restrictions: None, except this data paper, NSF Division of Environmental Biology Award 1021010, and the website (www.biotraits.ucla.edu) should be cited when the data are used for a publication. In addition, we would appreciate hearing which research questions or teaching exercises the data are being used for.

Costs: None.

CLASS IV. DATA STRUCTURAL DESCRIPTORS

A. Dataset file

Identity: TempTrait_001.txt

Size: 19,921 records (including header) and 65 fields. Total file size is 17.8 mb.

Format and storage media: Uncompressed UTF-16 text, tab delimited.

Header information: The first row of the file contains variable names (see below).

Row information: Each row represents trait performance at a single ambient or body temperature for a single species, or combination of two species when the trait involves interactions between species (e.g., encounter or consumption rate).

Alphanumeric attributes: Mixed. Note that degree of precision (i.e., number of decimal places) in number fields does not always match the original source for two reasons. First, our data is often more detailed than in the original source because where possible we obtained raw data from the authors (e.g., replicate thermal responses are not combined). Second, our use of DataThief (Class II, Section B) made it impossible to know the true precision of the original data. For consistency all SI number fields were converted to scientific notation floating point (Table 1).

Special characters/fields: Missing data denoted as `NA`.

Authentication procedures: Only data from published literature were obtained, although in a few cases we included other associated data offered by authors that we contacted about their published data. Field sums for all numeric fields are listed in the `Authen` field (Table 1) and should be used to authenticate the accuracy of the data.

B. Variable information

Variables and their details are provided in Table 1. Further details about variables are given in Dell et al. (2011).

TABLE 1. Summary of variable information. "Authen" represents the sum of that numeric field (i.e., all rows) rounded to closest integer, and should be used to authenticate the contents of the data file.

Variable	Variable definition	Type	Variable codes	Authen
DataSeriesID	Unique identifier code for each intraspecific thermal response curve	Integer	NA	634618613
Trait	Trait name	Character	NA	NA
TraitDef	Trait definition	Character	NA	NA
TraitOrg	Level of biological organization of the trait	Character	internal = processes internal to the organism; individual = processes at the level of individual organisms that include mechanical interactions with the external environment; population = processes for a group of conspecific individuals; interaction = processes involving interaction between two or more species	NA
AmbientTemp	Temperature (°C) of ambient environment (i.e., field or experimental arena).	Floating point	If null (NA) then see ConTemp or ResTemp	404934
TraitValueSI	Value of trait performance in SI units	Floating point	NA	523272551
TraitUnitSI	Units for trait performance in SI units	Character	NA	NA
ErrorPosSI	Positive value of error in SI units (see ErrorUnitSI)	Floating point	NA	26230188
ErrorNegSI	Negative value of error in SI units (see ErrorUnitSI)	Floating point	NA	25702176
ErrorUnitSI	Unit of error	Character	SD = standard deviation; SE = standard error; 95% CI = 95% confidence interval; interquartile range; range	NA
Replicates	Number of replicates for each record	Integer	NA	145002
Habitat	Habitat where trait performance was measured	Character	terrestrial; freshwater; marine	NA

Variable	Variable definition	Type	Variable codes	Authen
LabField	Whether trait performance was measured in the laboratory or field	Character	laboratory; field	NA
ArenaValueSI	SI value of size of arena where trait performance was measured	Floating point	NA	165367
ArenaUnitSI	SI unit of size of arena where trait performance was measured	Character	cubic meter; square meter; meter = when only length of arena was stated	NA
ObsTimeValueSI	SI value of total observation time (i.e., time over which experiment was run for measurement of trait performance)	Floating point	NA	4251168740
ObsTimeUnitSI	SI unit of total observation time (i.e., time over which experiment was run for measurement of trait performance)	Character	second; prey caught = time taken for ObsTimeValueSI number of prey caught	NA
ObsTimeNotes	Notes for total observation time (i.e., time over which experiment was run for measurement of trait performance)	Character	NA	NA
ResRepValueSI	SI value for how often resources were replaced over observation time	Floating point	NA	810257360400
ResRepUnitSI	SI value for how often resources were replaced over observation time	Character	not replaced; second; to satiation = resources replaced sufficiently frequently so that consumer always had access to resources	NA
Location	Location (generally town, state, country) of where organisms were collected, or when measurements were taken at a different location then both are listed	Character	NA	NA
Latitude	Approximate latitude of middle of location where animals were collected (e.g., filed station, town, state, country), or when not available then where measurements were taken.	Numeric (3 decimal places)	NA	616917
Longitude	Approximate longitude of middle of location where animals were collected (e.g., filed station, town, state, country), or when not available then where measurements were taken.	Numeric (3 decimal places)	NA	-809413
TaxaPresent	Whether one or two taxa are part of the trait measurement and definition. If only a single organism is involved (e.g., metabolic rate, heart rate), it is always listed as a trait for a consumer.	Character	consumer = trait involves a single organism; consumer-resource = trait involves two organisms	NA

Variable	Variable definition	Type	Variable codes	Authen
ConType	Type of consumer	Character	alive = organism alive when trait performance measured; dead = organism dead when trait performance measured; artificial = 'organism' simulated by a physical stimulus (e.g., predator model, prodding, gravity)	NA
Con	Binomial name of consumer or lowest taxonomic identity, or other appropriate name for artificial taxa (see ConType)	Character	NA	NA
ConCommon	Common name of consumer	Character	NA	NA
ConStage	Life stage of consumer, and sex in parenthesis when available	Character	NA	NA
ConIDLevel	Taxonomic level to which the consumer was identified	Character	kingdom, phylum, class, order, family, genus, species	NA
ConKingdom	Taxonomic name of Kingdom of consumer	Character	NA	NA
ConPhylum	Taxonomic name of Phylum of consumer	Character	NA	NA
ConClass	Taxonomic name of Class of consumer	Character	NA	NA
ConOrder	Taxonomic name of Order of consumer	Character	NA	NA
ConFamily	Taxonomic name of Kingdom of consumer	Character	NA	NA
ConTrophic	Broad trophic group of consumer, as determined by published literature and expert opinion	Character	carnivore; detritivore; herbivore; omnivore, producer, artificial (see ConType); self = energy self-supplied (e.g., pupae, egg); dead (see ConType)	NA
ConThermy	Thermy of consumer	Character	ectotherm; endotherm	NA
ConTemp	Body temperature (°C) of consumer	Floating point	NA	482173
ConTempMethod	Method of determining body temperature of consumer	Character	direct = measured directly from within or on the organism; inferred (ambient) = estimated from known ambient temperature and generally within arena where organism not able to thermoregulate; inferred (endotherm) = body temperature relatively constant and estimated from published literature; inferred (consumer) = estimated from known consumer body temperature (relevant for ResTempMethod, see below)	NA
ConMassValueSI	Mass of consumer as obtained from original source or estimated from other published literature (see Dell et al. (2011) for further details)	Floating point	NA	196296
ConMassUnitSI	SI unit of consumer mass	Character	kilogram (wet body mass) = wet mass of entire body of consumer; kilogram (wet tissue mass) = wet mass of tissue of consumer (e.g., excluding shell for gastropods)	NA

Variable	Variable definition	Type	Variable codes	Authen
ConDenValueSI	Value of consumer density standardized to SI units	Floating point	NA	2471839374
ConDenTypeSI	Type of units of consumer density	Character	individual; kilogram (dry body mass); kilogram (wet body mass); liter; to satiation = resource density above what consumer could fully consume (relevant for ResDenTypeSI, see below)	NA
ConDenUnitSI	SI units of consumer density	Character	arena; square meter; cubic meter	NA
ResType	*Same as for ConType (see above), but for resource*			NA
Res	*Same as for Con (see above), but for resource*			NA
ResCommon	*Same as for ConCommon (see above), but for resource*			NA
ResStage	*Same as for ConStage (see above), but for resource*			NA
ResIDLevel	*Same as for ConIDLevel (see above), but for resource*			NA
ResKingdom	*Same as for ConKingdom (see above), but for resource*			NA
ResPhylum	*Same as for ConPhylum (see above), but for resource*			NA
ResClass	*Same as for ConClass (see above), but for resource*			NA
ResOrder	*Same as for ConOrder (see above), but for resource*			NA
ResFamily	*Same as for ConFamily (see above), but for resource*			NA
ResTrophic	*Same as for ConTrophic (see above), but for resource*			NA
ResThermy	*Same as for ConThermy (see above), but for resource*			NA
ResTemp	*Same as for ConTemp (see above), but for resource*			312208
ResTempMethod	*Same as for ConTempMethod (see above), but for resource*			NA
ResMassValueSI	*Same as for ConMassValueSI (see above), but for resource*			554
ResMassUnitSI	*Same as for ConMassUnitSI (see above), but for resource*			NA
ResDenValueSI	*Same as for ConDenValueSI (see above), but for resource*			423196940674347
ResDenTypeSI	*Same as for ConDenTypeSI (see above), but for resource*			NA
ResDenUnitSI	*Same as for ConDenUnitSI (see above), but for resource*			NA
CitationID	Unique identification number for citation	Integer	NA	7026820
Citation	Citation from which data was obtained	Character	NA	NA
FigureTable	Figure or table from which data was obtained within original citation	Character	NA	NA

CLASS V. SUPPLEMENTAL DESCRIPTORS

<u>A. Data acquisition</u>

Potential data sources were identified using three methods:

1. Using literature search engines (e.g., Web of Science, JSTOR) to find published literature using keyword combinations that included: ‘ecological’, ‘ecology’, ‘interaction’, ‘physiological’, ‘physiology’, ‘response’, ‘temperature’, ‘thermal’, and ‘trait’. In many cases, the authors of these studies were contacted directly to obtain raw data.
2. Contacting known researchers in the field of thermal biology and directly requesting data.
3. Looking through citations in the publications found by method 1.

Once identified, data were obtained by contacting authors and asking for raw data, otherwise directly from the main text and tables of published literature, and from figures using DataThief (Tummers 2006) that allows digitization of data points from a graph.

B. Quality assurance/quality control procedures

See comments on data verification (Class III, Section A).

C. Related material:

NA.

D. Computer programs and data processing algorithms:

Data from figures in published literature were obtained with DataThief (Tummers 2006) (see Class V, Section A). Data were entered into a form within MS Access, where unit conversions to SI units were also undertaken. Body size estimates were made using an algorithm we constructed and implemented using MS Access (Class II, Section B) (Dell et al., 2011).

E. Archiving:

Data files and metadata will be updated periodically at Ecological Archives, and are available in beta version at www.biotraits.ucla.edu.

F. Literature cited:

Publications from which data were obtained are stated in the `Citation` field of the data file.

G. Publications using the dataset:

Dell, A. I., S. Pawar, and V. M. Savage. (2011). Systematic variation in the temperature dependence of physiological and ecological traits. *Proceedings of the National Academy of Sciences of the United States of America* **108**:10591-10596.

Dell, A. I., S. Pawar, and V. M. Savage. (In press). A framework for the temperature dependence of trophic interactions and the consequences of asymmetries in consumer and resource responses. *Journal of Animal Ecology*.

Pawar, S., A. I. Dell, and V. M. Savage. 2012. Dimensionality of consumer search space drives trophic interaction strengths. *Nature* **486**:485-489.

G. History of dataset usage

Data request history: NA

Dataset update history: NA.

Review history: NA.

Questions and comments from secondary users: NA.

ACKNOWLEDGMENTS

We sincerely thank the many authors who graciously donated their time and data. Without their careful work, the compilation of this dataset would have been either impossible or meaningless. In addition, we would like to thank the many organizations that helped fund each of these projects. We thank Kina Winoto for help in porting the original dataset to mySQL and, together with William King, for helping develop the website where this dataset is currently being made available (www.biotraits.ucla.edu). We thank Mike Angilletta, William King and one anonymous reviewer for their detailed and insightful comments. Support for compiling this dataset was provided by James Cook University, the University of California Los Angeles, and the National Science Foundation Division of Environmental Biology Award (1021010).

LITERATURE CITED

Angilletta, M. J. 2009. Thermal adaptation: a theoretical and empirical synthesis. Oxford University Press, Oxford ; New York.

Angilletta, M. J., R. B. Huey, and M. R. Frazier. 2010. Thermodynamic effects on organismal performance: Is hotter better? Physiological and Biochemical Zoology **83**:197-206.

Bauwens, D., T. Garland, A. M. Castilla, and R. Vandamme. 1995. Evolution of sprint speed in lacertid lizards - morphological, physiological, and behavioural covariation. Evolution **49**:848-863.

Bennett, A. F. 1980. The thermal-dependence of lizard behaviour. Animal Behaviour **28**:752-762.

Brown, J. H., J. F. Gillooly, A. P. Allen, V. M. Savage, and G. B. West. 2004. Toward a metabolic theory of ecology. Ecology **85**:1771-1789.

Cooper, W. E. 2000. Effect of temperature on escape behaviour by an ectothermic vertebrate, the keeled earless lizard (Holbrookia propinqua). Behaviour **137**:1299-1315.

Corkrey, R., J. Olley, D. Ratkowsky, T. McMeekin, and T. Ross. 2012. Universality of Thermodynamic Constants Governing Biological Growth Rates. PLoS ONE **7**:e32003.

Cossins, A. R. and K. Bowler. 1987. Temperature biology of animals. Temperature biology of animals.:i-x, 1-339.

Dell, A. I., S. Pawar, and V. M. Savage. 2011. Systematic variation in the temperature dependence of physiological and ecological traits. Proceedings of the National Academy of Sciences of the United States of America **108**:10591-10596.

Dell, A. I., S. Pawar, and V. M. Savage. in print. Temperature dependence of trophic interactions driven by asymmety of species responses and foraging strategy. Journal of Animal Ecology.

Englund, G., G. Ohlund, C. Hein, and S. Diehl. 2011. Temperature dependence of the functional response. Ecology Letters **14**:914-921.

Frazier, M. R., R. B. Huey, and D. Berrigan. 2006. Thermodynamics constrains the evolution of insect population growth rates: "Warmer is better". American Naturalist **168**:512-520.

Gillooly, J. F., J. H. Brown, G. B. West, V. M. Savage, and E. L. Charnov. 2001. Effects of size and temperature on metabolic rate. Science **293**:2248-2251.

Gillooly, J. F., E. L. Charnov, G. B. West, V. M. Savage, and J. H. Brown. 2002. Effects of size and temperature on developmental time. Nature **417**:70-73.

Harrington, R., I. Woiwod, and T. Sparks. 1999. Climate change and trophic interactions. Trends in Ecology & Evolution **14**:146-150.

Helmuth, B., J. G. Kingsolver, and E. Carrington. 2005. Biophysics, physiological ecology, and climate change: does mechanism matter? Annual Review of Physiology **67**:177–201.

Herrel, A., R. S. James, and R. Van Damme. 2007. Fight versus flight: physiological basis for temperature-dependent behavioral shifts in lizards. Journal of Experimental Biology **210**:1762-1767.

Hertz, P. E., R. B. Huey, and E. Nevo. 1982. Fight versus flight - body-temperature infuences defensive responses of lizards. Animal Behaviour **30**:676-&.

Huey, R. B. and A. F. Bennett. 1987. Phylogenetic studies of coadaptation - preferred temperatures versus optimal preformance temperatures of lizards. Evolution **41**:1098-1115.

Huey, R. B. and D. Berrigan. 2001. Temperature, demography, and ectotherm fitness. American Naturalist **158**:204-210.

Huey, R. B. and J. G. Kingsolver. 1989. Evolution of thermal sensitivity of ectotherm performance. Trends in Ecology & Evolution **4**:131-135.

IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.

Irlich, U., J. Terblanche, T. Blackburn, and S. Chown. 2009a. Insect rate-temperature relationships: environmental variation and the metabolic theory of ecology. The American Naturalist **174**:819-835.

Irlich, U. M., J. S. Terblanche, T. M. Blackburn, and S. L. Chown. 2009b. Insect rate-temperature relationships: environmental variation and the metabolic theory of ecology. The American Naturalist **174**:819-835.

Izem, R. a. K., J. G. . 2005. Variation in continuous reaction norms: quantifying directions of biological interest. American Naturalist:277-289.

Johnson, F. H., H. Eyring, and B. J. Stover. 1974. The theory of rate processes in biology and medicine. Wiley, New York,.

Knies, Jennifer L., Joel G. Kingsolver, and Christina L. Burch. 2009. Hotter Is better and broader: thermal sensitivity of fitness in a population of bacteriophages. The American Naturalist **173**:419-430.

Nilsson-Örtman, V., R. Stoks, M. De Block, H. Johansson, F. Johansson, and B. Enquist. 2012. Latitudinally structured variation in the temperature dependence of damselfly growth rates. Ecology Letters.

Petchey, O. L., U. Brose, and B. C. Rall. 2010. Predicting the effects of temperature on food web connectance. Philosophical Transactions of the Royal Society B-Biological Sciences **365**:2081-2091.

Rall, B. C., O. Vucic-Pestic, R. B. Ehnes, M. Emmerson, and U. Brose. 2010. Temperature, predator–prey interaction strength and population stability. Global Change Biology **16**:2145-2157.

Ratkowsky, D. A., J. Olley, and T. Ross. 2005. Unifying temperature effects on the growth rate of bacteria and the stability of globular proteins. Journal of Theoretical Biology **233**:351-362.

Savage, V. M., J. F. Gillooly, J. H. Brown, G. B. West, and E. L. Charnov. 2004. Effects of body size and temperature on population growth. American Naturalist **163**:429-441.

Schieffelin, C. D. and A. Dequeiroz. 1991. Temperature and defense in the common garter snake - warm snakes are more aggressive than cold snakes. Herpetologica **47**:230-237.

Shine, R., M. M. Olsson, M. P. Lemaster, I. T. Moore, and R. T. Mason. 2000. Effects of sex, body size, temperature, and location on the antipredator tactics of free-ranging gartersnakes (Thamnophis sirtalis, Colubridae). Behavioral Ecology **11**:239-245.

Somero, G. S. 1997. Handbook of physiology. Oxford University Press, New York.

Tummers, B. 2006. DataThief.

Vasseur, D. A. and K. S. McCann. 2005. A mechanistic approach for modeling temperature-dependent consumer-resource dynamics. American Naturalist **166**:184-198.

Walther, G. R., E. Post, P. Convey, A. Menzel, C. Parmesan, T. J. C. Beebee, J. M. Fromentin, O. Hoegh-Guldberg, and F. Bairlein. 2002. Ecological responses to recent climate change. Nature **416**:389-395.

Woodward, G., J. P. Benstead, O. S. Beveridge, J. Blanchard, T. Brey, L. E. Brown, W. F. Cross, N. Friberg, T. C. Ings, U. Jacob, S. Jennings, M. E. Ledger, A. M. Milner, J. M. Montoya, E. J. O'Gorman, J. M. Olesen, O. L. Petchey, D. E. Pichler, D. C. Reuman, M. S. A. Thompson, F. J. F. Van Veen, and G. Yvon-Durocher. 2010. Ecological Networks in a Changing Climate. Pages 71-138 *in* G. Woodward, editor. Advances in Ecological Research: Ecological Networks, Vol 42.