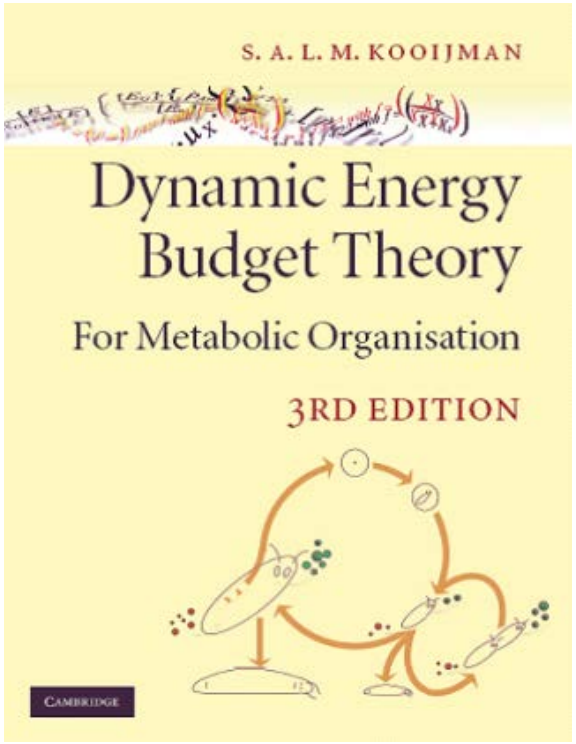
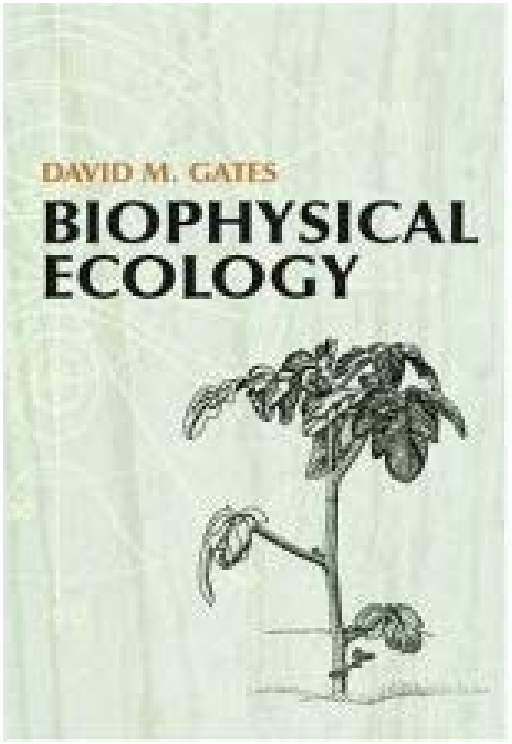
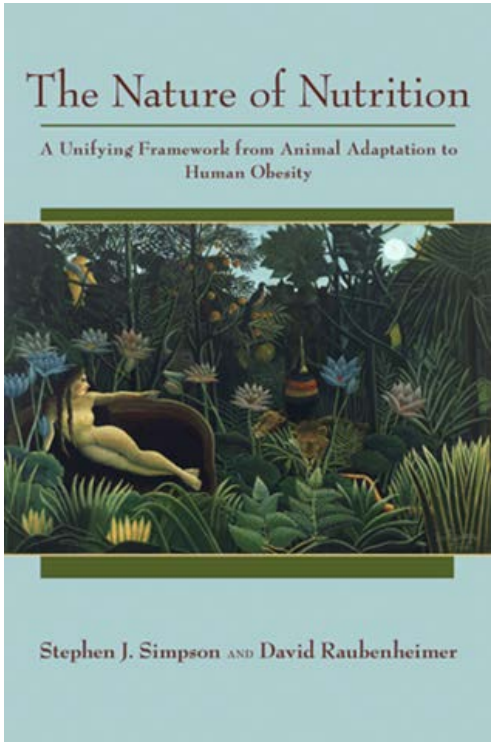
Mechanistic Niche Models







Michael Kearney mrke@unimelb.edu.au
School of BioSciences, The University of Melbourne

Mechanistic Niche Models

Part I

- What is a mechanistic niche model?
- Thermodynamic basis to the niche
- The importance of temperature
- Heat budgets
- Microclimates
- Water budgets

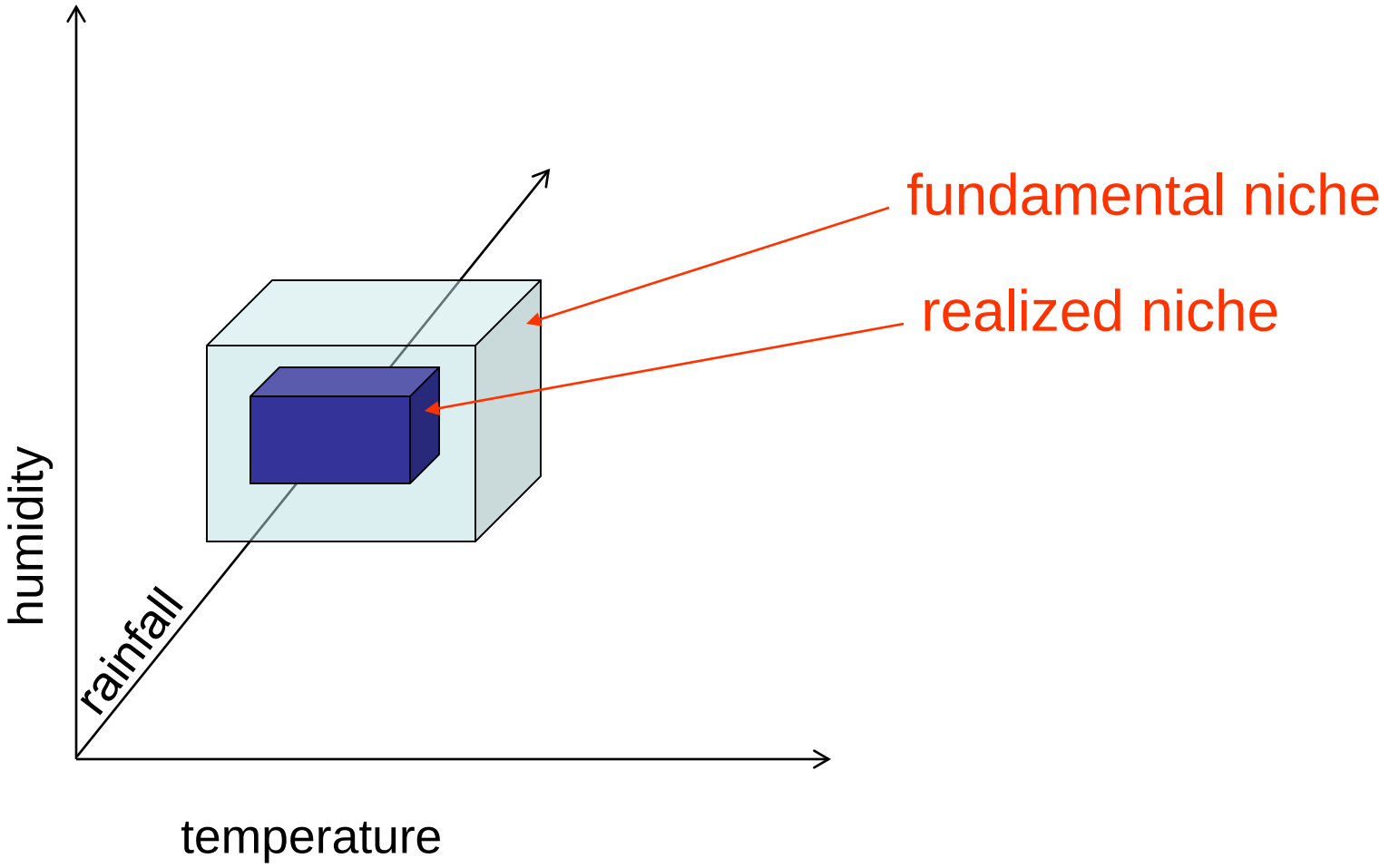
Biophysical Ecology

- Play with NicheMapR

Part II

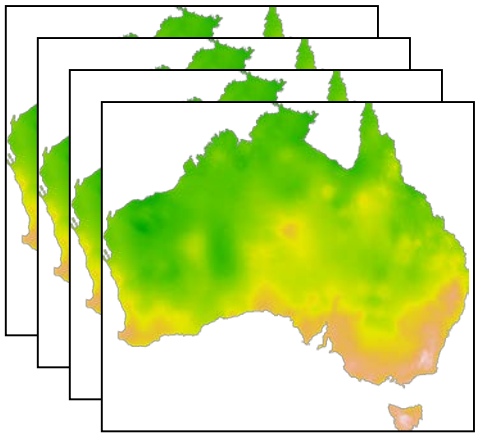
- Connecting to the Dynamic Energy Budget
- Play with NicheMapR
- Inferring climatic constraints
- Nutritional constraints

What is a mechanistic niche model?



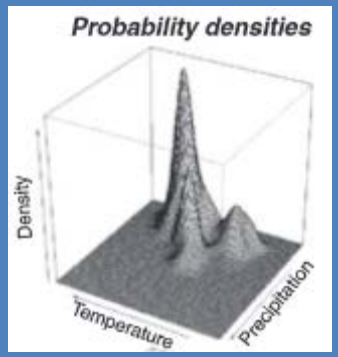
What is a mechanistic niche model?

Environmental Layers

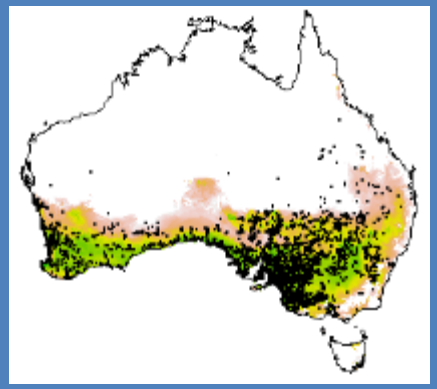


Correlative Model (process implicit)

Maxent model

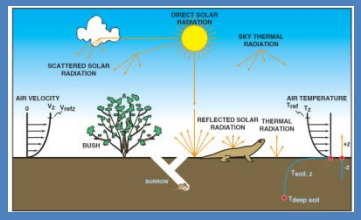


probability of occurrence

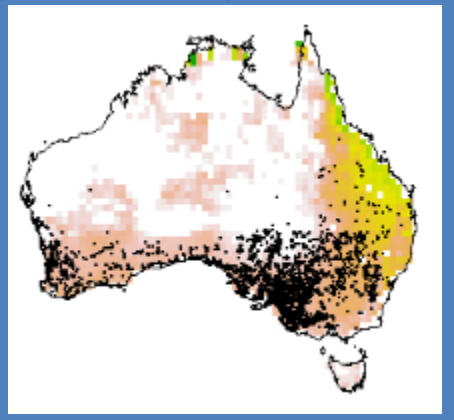


Mechanistic Model (process explicit)

NicheMapR model

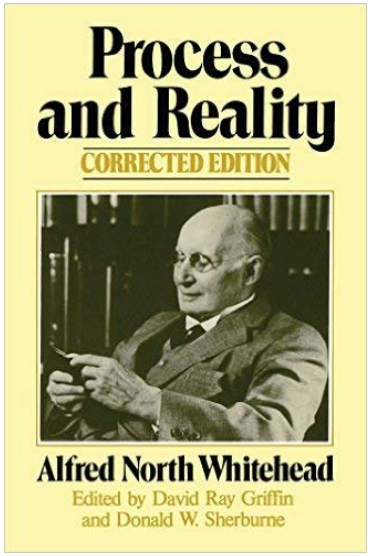


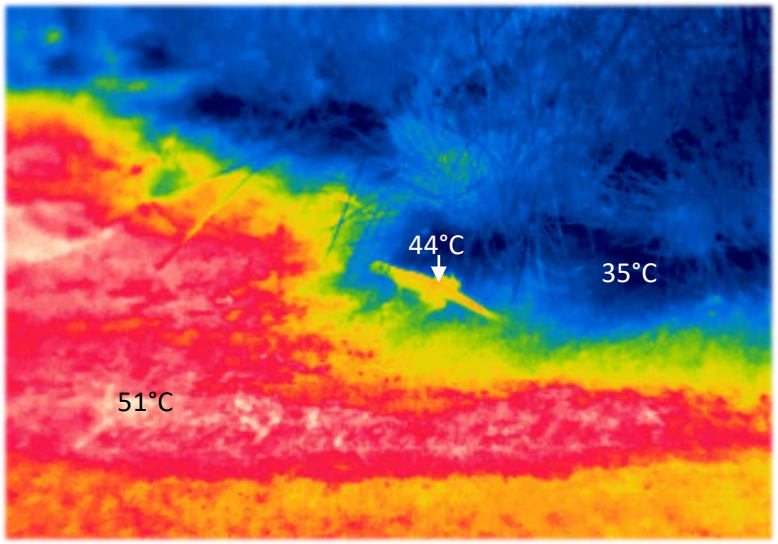
potential reproduction



Thermodynamic basis to the niche

Military Dragon, *Ctenophorus isolepis*





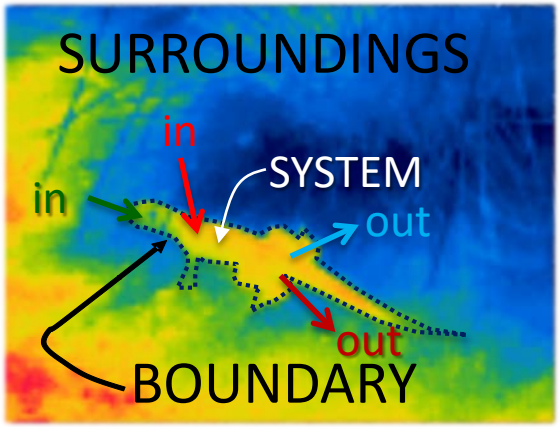
Thermodynamic basis to the niche

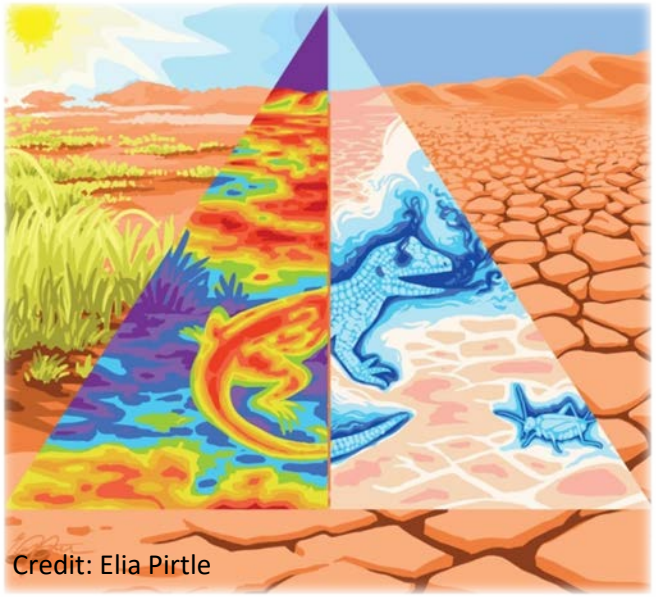
energy in =

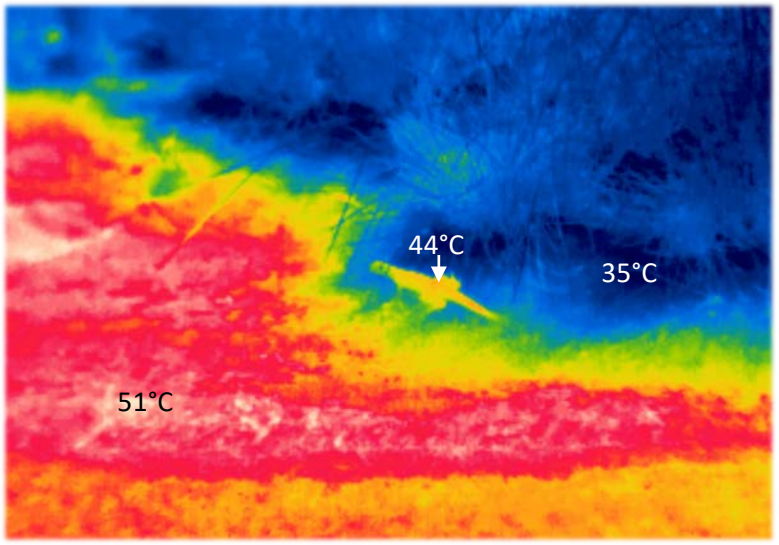
energy out + energy stored

mass in =

mass out + mass stored







Thermodynamic basis to the niche

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J = mass flux
X = food
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I = ingested
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U = urinated
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O_2 = oxygen
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N = nitrogenous waste
MET = 'metabolism'
EVAP = evaporation
SOLAR = solar radiation
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COND = conduction

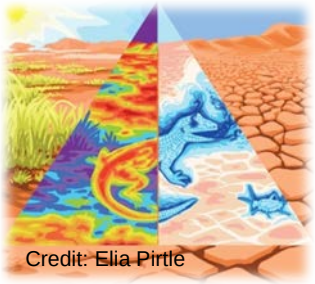
$$p_{SOLAR} + J_{O2,MET} + p_{IR,in} + \left(\frac{p}{J}\right)_{MET} = J_{X,I} = J_{X,G} + J_{X,R} + J_{X,S} + J_{X,P}$$

$$J_{CO2,MET} + p_{IR,out} + J_{N,MET} + p_{CONV} = J_{H,I} + J_{H,MET} = J_{H,U} + J_{H,P} + J_{H,S} + \left(\frac{p}{J}\right)_{EVAP} + p_{COND} + p_S$$

heat

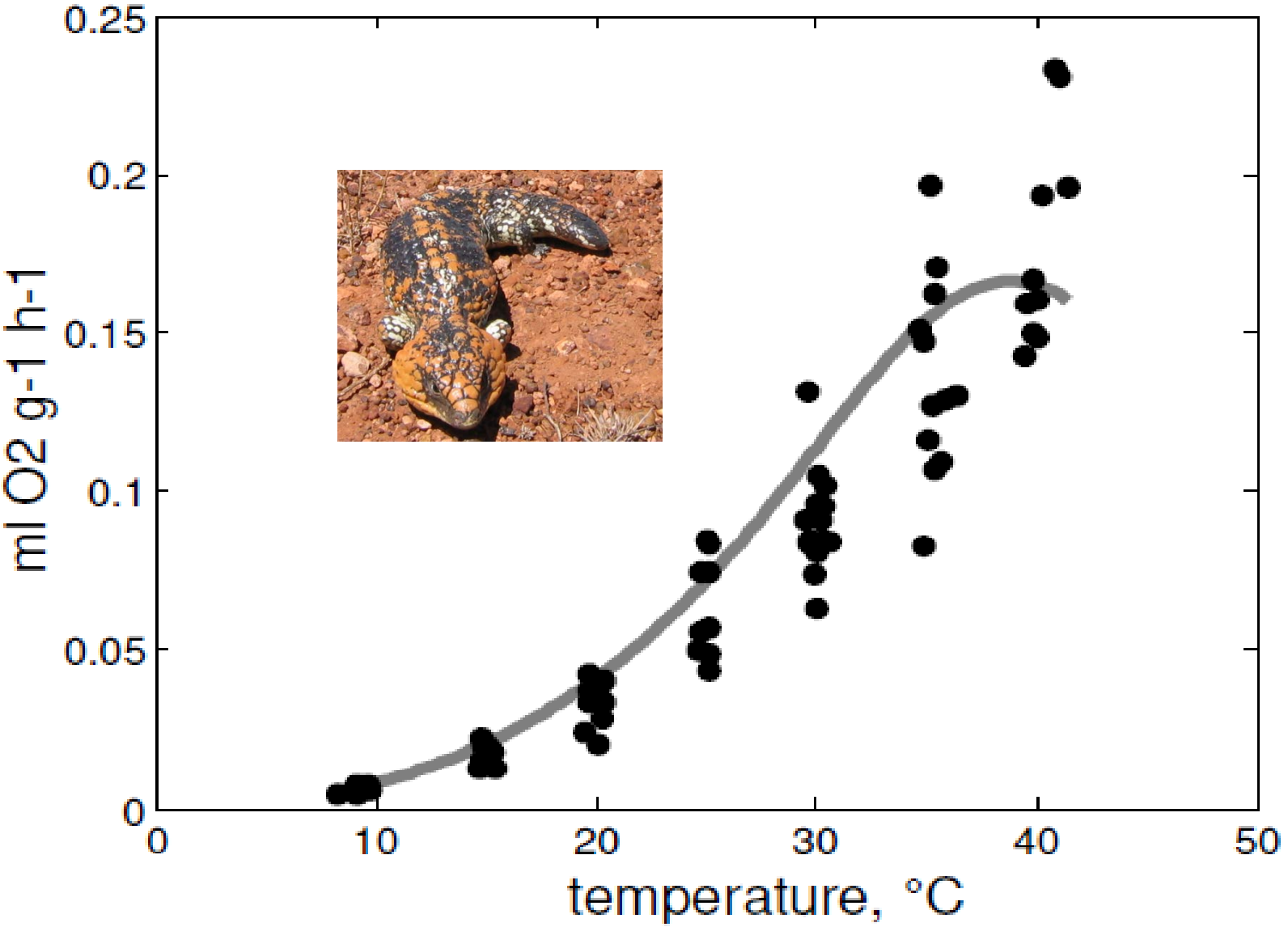
$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

feeding
breathing
temperature
water


Credit: Elia Pirtle

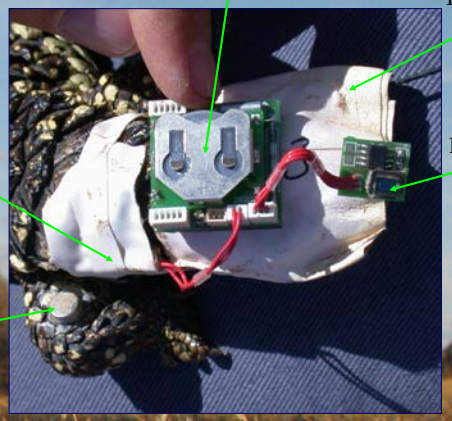
Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

The importance of temperature

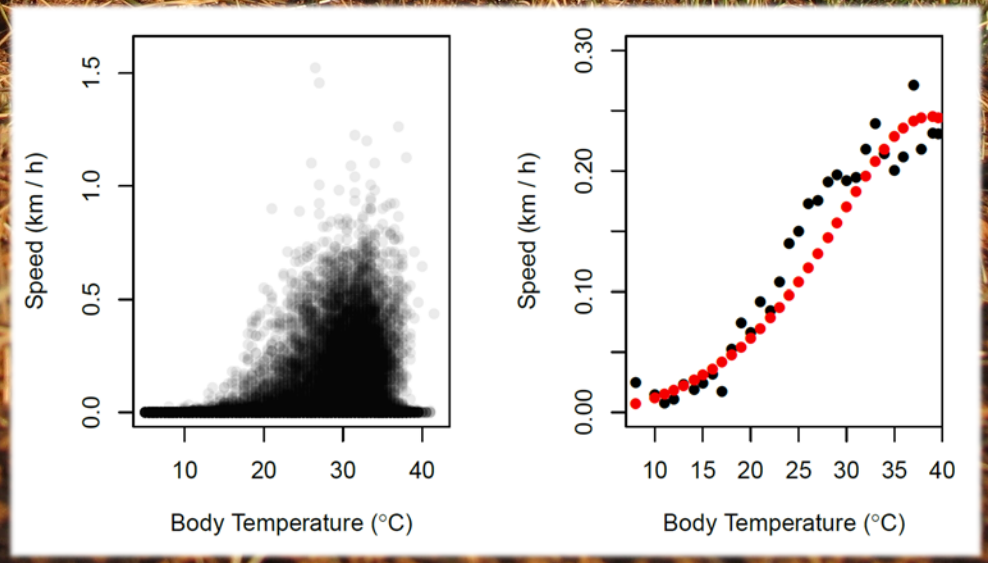


The importance of temperature

The ‘waddleometer’

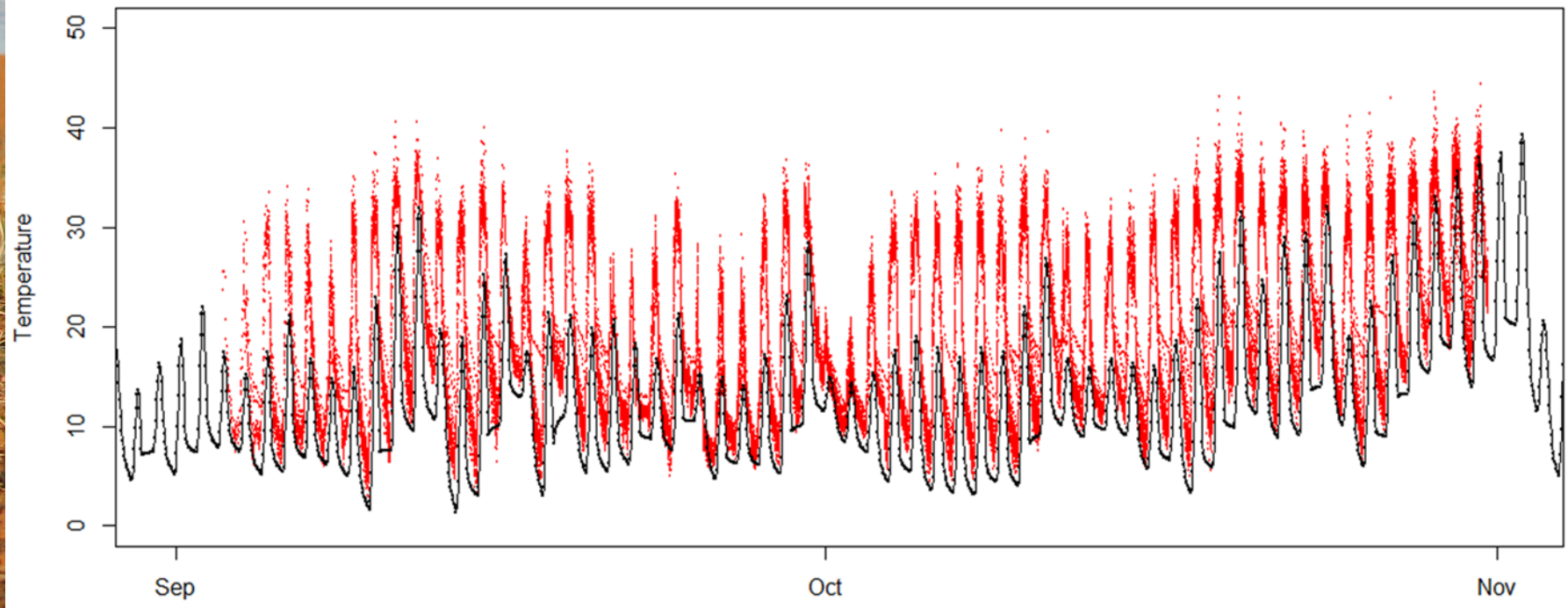


Prof. Mike Bull

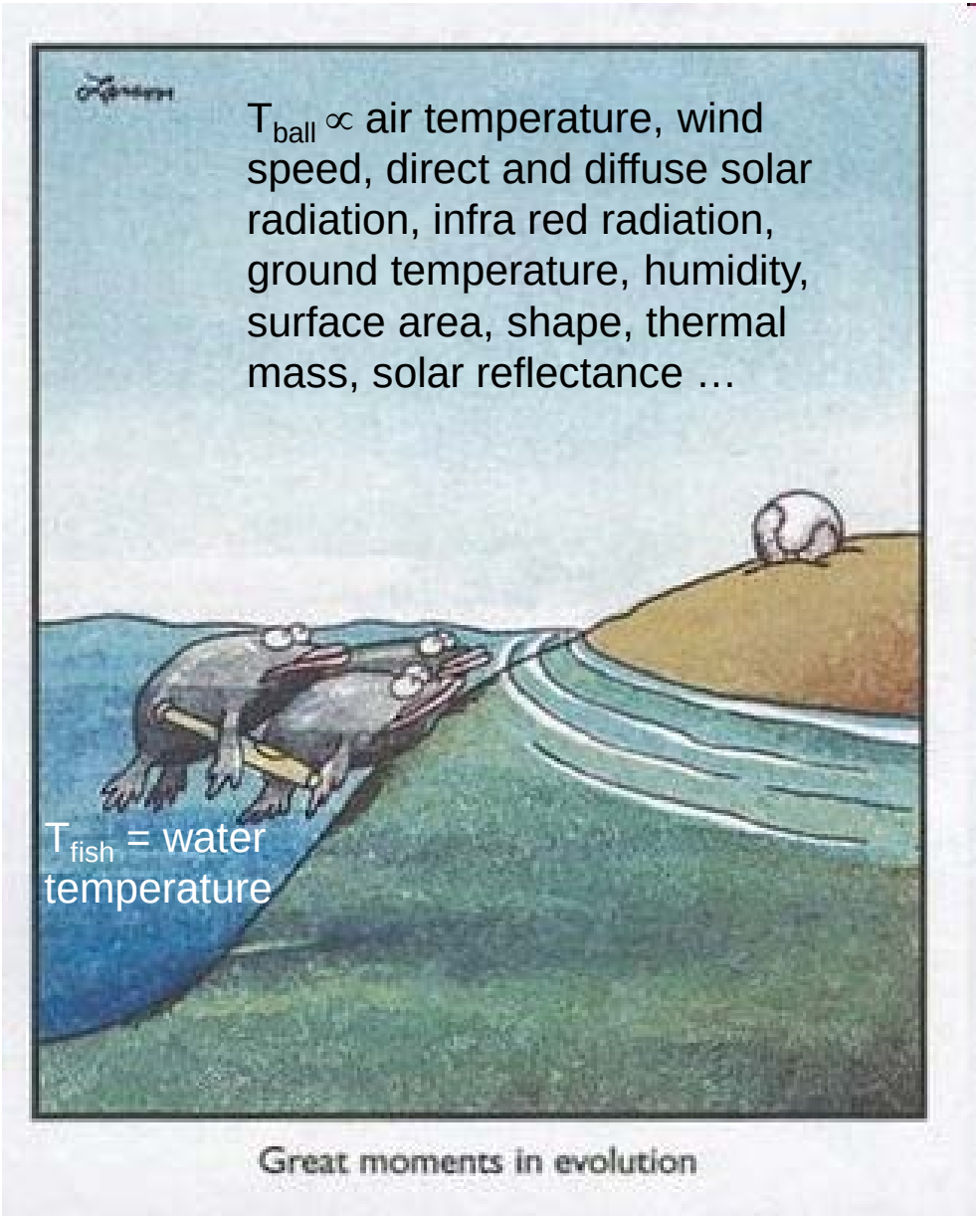


The importance of temperature

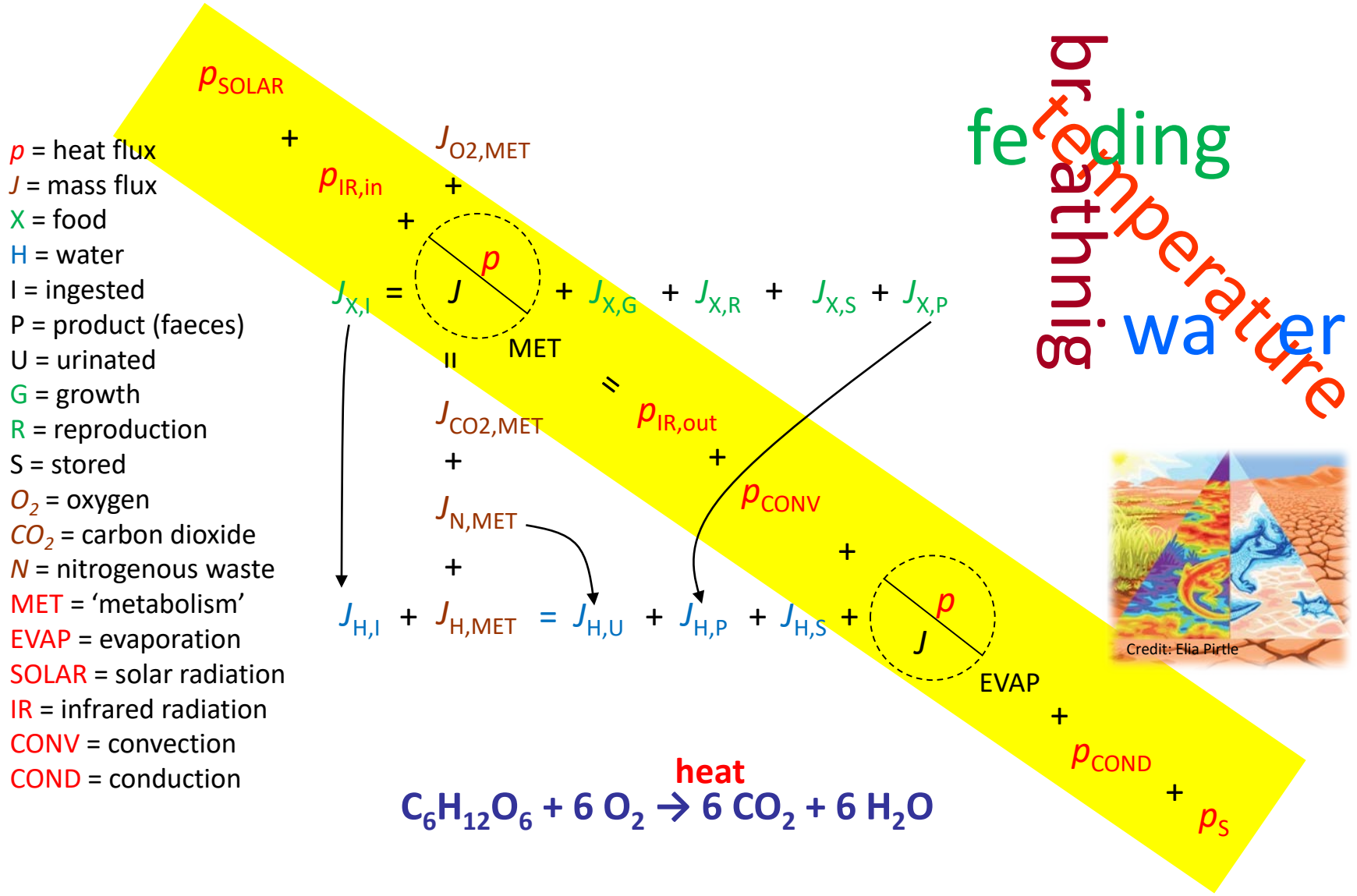
60 Lizards' T_bs in 2009



The importance of temperature



Thermodynamic basis to the niche



Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

Biophysical Ecology

THERMODYNAMIC EQUILIBRIA OF ANIMALS WITH ENVIRONMENT[1]

WARREN P. PORTER[2] AND DAVID M. GATES
Missouri Botanical Garden
2315 Tower Grove Avenue, St. Louis, Missouri 63110
and
Washington University, St. Louis, Missouri 63130

Ecological Monographs **39**(3), 227-244 (1969)

Warren Porter
University of Wisconsin, Madison

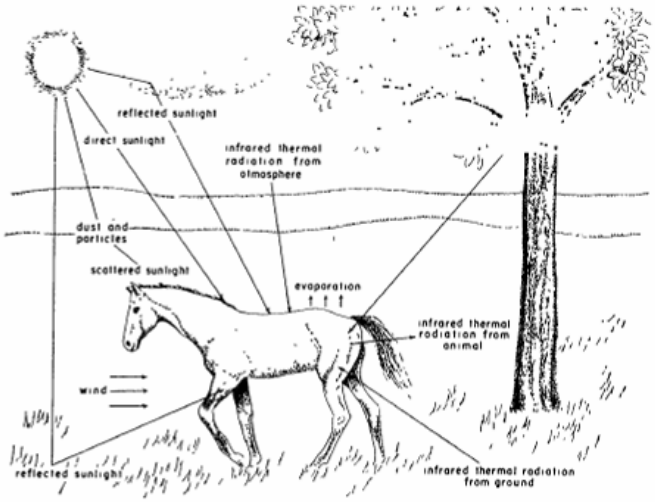
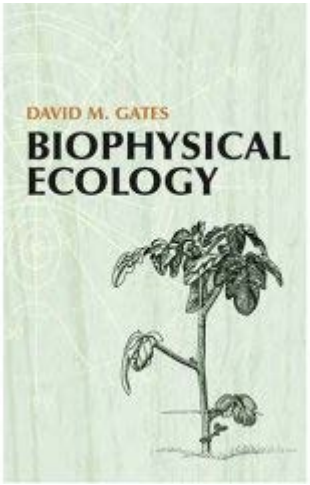


FIG. 1. Streams of energy between an animal and the environment.



Biophysical Ecology – Heat Budgets

(Heat) Energy Balance of a Lizard

Solar (gained) + Infra-red (gained) =

Infra-red (lost) + Convection (gained/lost)

$$Q_a - \sigma[T_b + 273]^4 - h_c[T_b - T_a] = 0$$

- Q_a: infra-red and solar radiation gained
- $\sigma[T_b + 273]^4$: infra-red radiation lost
- $h_c[T_b - T_a]$: convection
  - h_c: wind speed V, organism size D
  - T_b
  - T_a: air temperature

$$h_c = 3.49 \frac{V^{0.5}}{D^{0.5}}$$

Biophysical Ecology – Heat Budgets

What would the body temperature be if …?

Diameter = 0.015 m

Wind speed = 2.0 m/s

Air temperature = 20 ºC

Radiation = 700 W/m2

T_b = 26 ºC

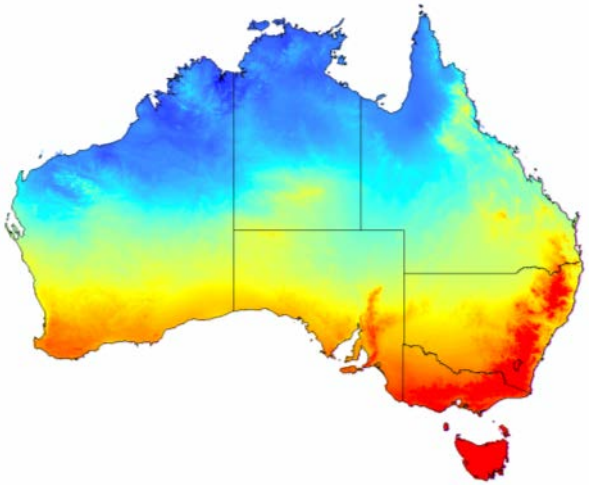
If we know the environmental conditions, we can find the body temperature which satisfies the energy balance equation

$$Q_a - \sigma[T_b + 273]^4 - 3.49\frac{V^{0.5}}{D^{0.5}}[T_b - T_a] = 0$$

$$700 - \sigma[T_b + 273]^4 - 3.49\frac{2.0^{0.5}}{0.015^{0.5}}[T_b - 20] = 0$$

Biophysical Ecology – Microclimates

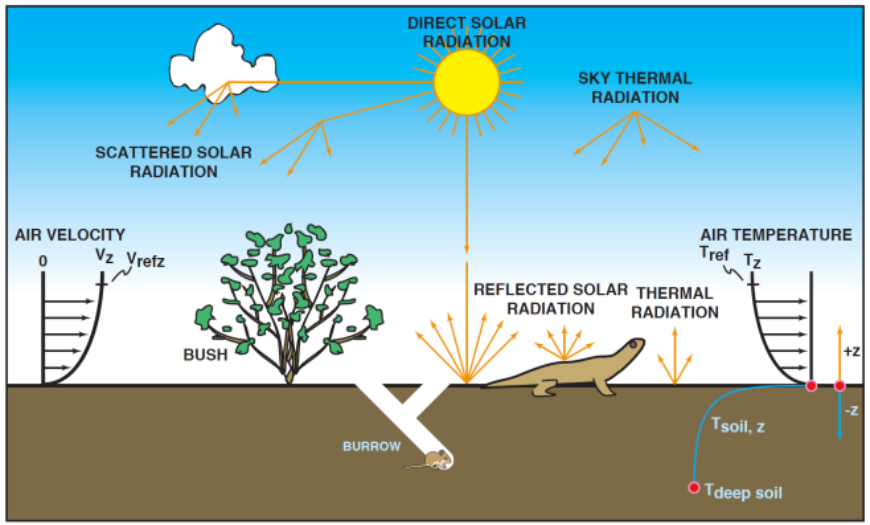
weather station

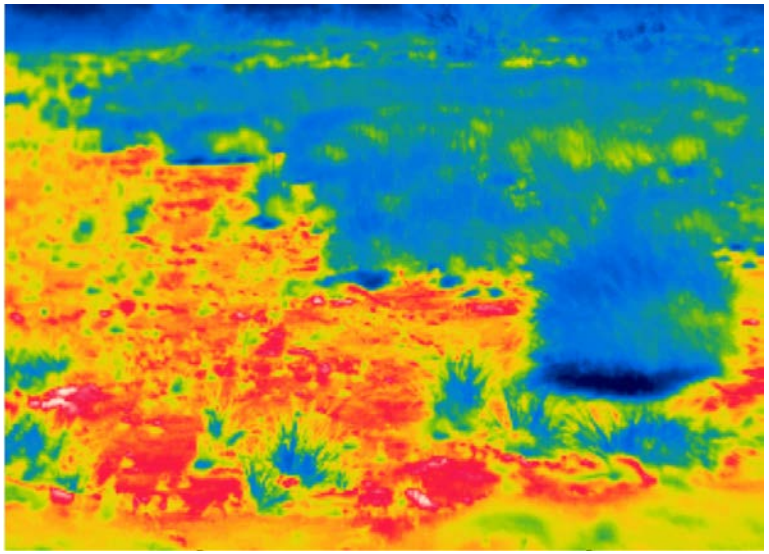


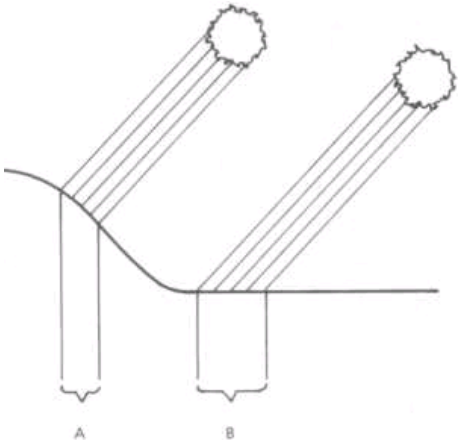
air temperature layer

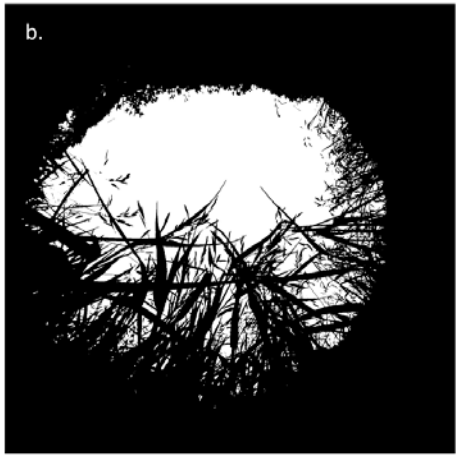
?

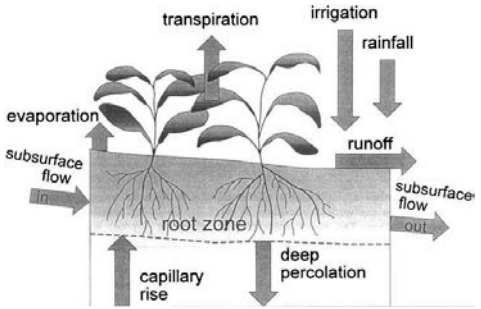
Biophysical Ecology – Microclimates





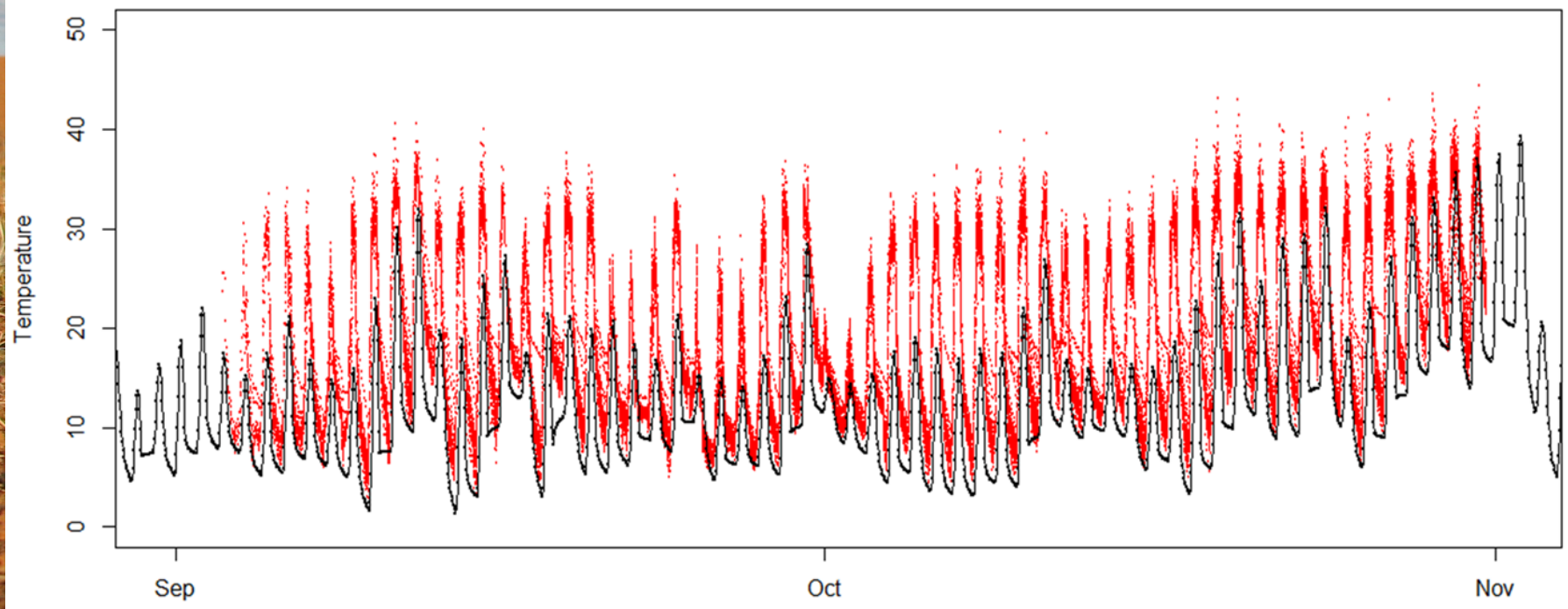






Biophysical Ecology – Heat Budgets

60 Lizards' T_bs in 2009



Biophysical Ecology – Heat Budgets

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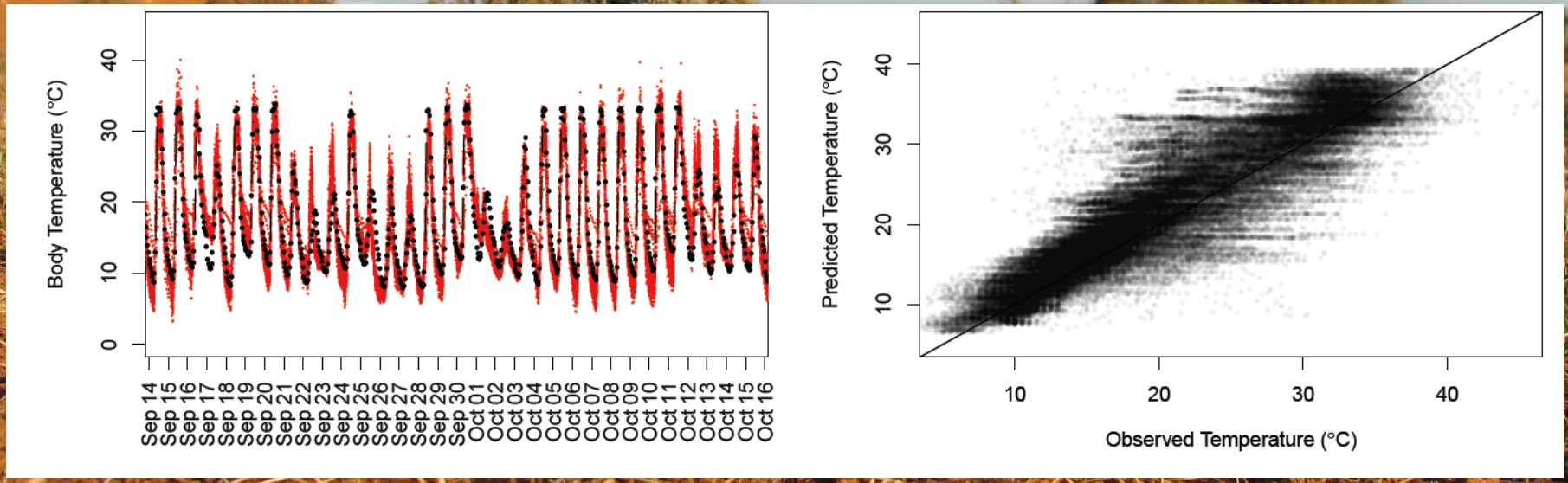
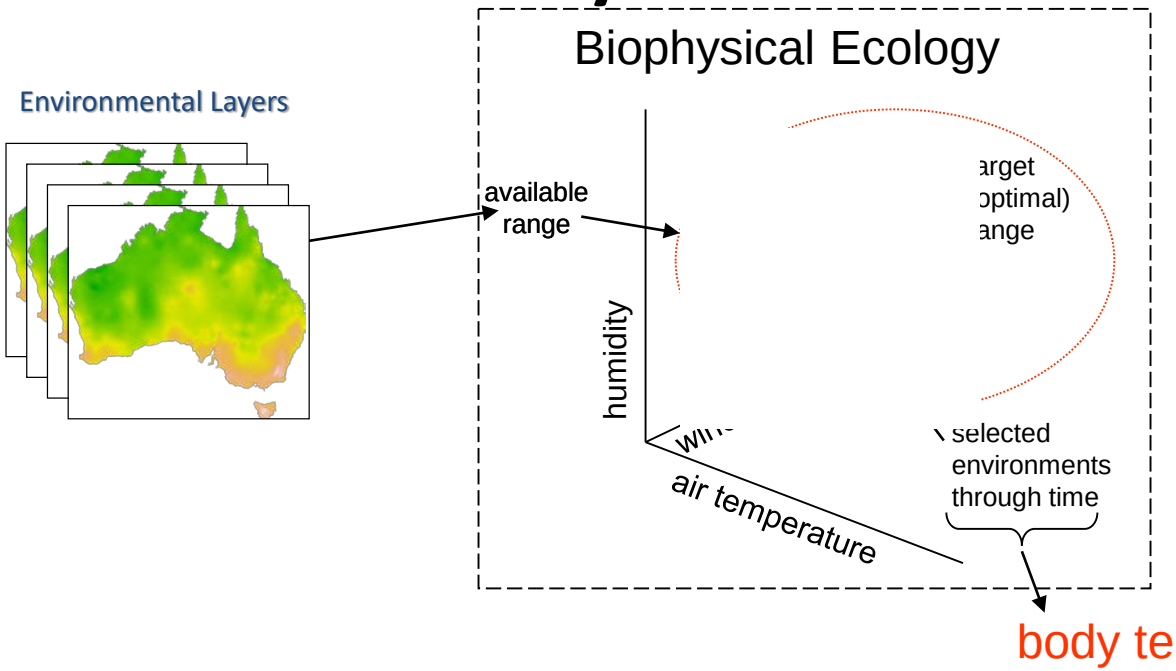


Thermodynamic basis to the niche



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MET = 'metabolism'
EVAP = evaporation
SOLAR = solar radiation
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$$p_{SOLAR} + J_{O2,MET} + p_{IR,in} + \frac{p}{J}_{MET} = J_{X,I} + J_{X,G} + J_{X,R} + J_{X,S} + J_{X,P}$$

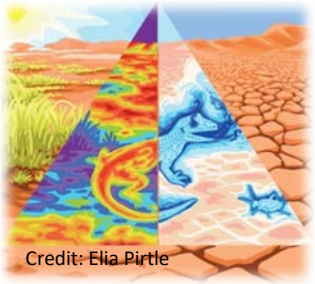
$$= J_{CO2,MET} + p_{IR,out} + J_{N,MET} + p_{CONV}$$

$$J_{H,I} + J_{H,MET} = J_{H,U} + J_{H,P} + J_{H,S} + \frac{p}{J}_{EVAP} + p_{COND} + p_S$$

heat

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

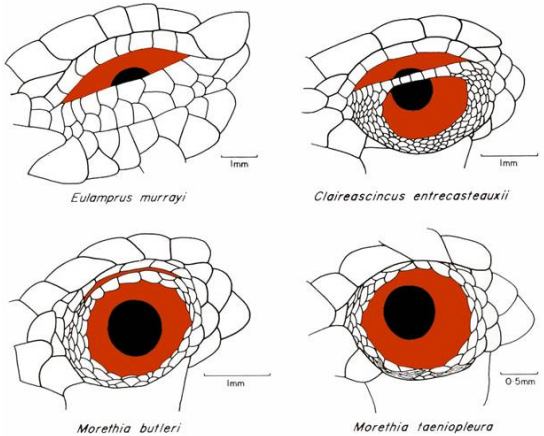
feeding
breathing
temperature
water

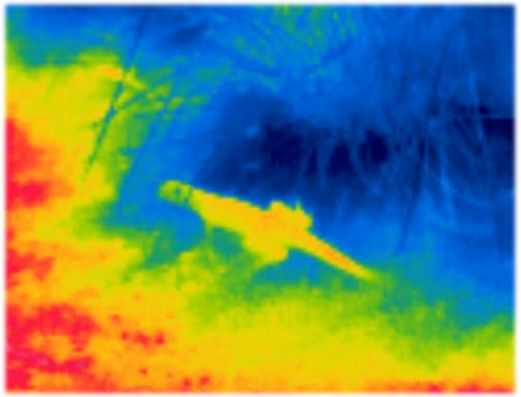

Credit: Elia Pirtle

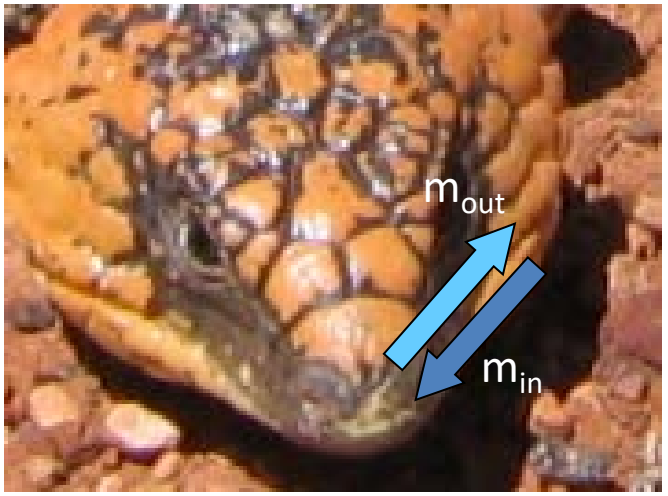
Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

Water budget - evaporation

Greer 1989 Biology and Evolution of Australian Lizards







area wet, m^2

latent heat of vaporisation, λ

$$Q_{evap,cut} = A_{evap} h_d (V_{d,skin} - V_{d,air}) \lambda$$

mass transfer coefficient

vapor density,

$$Q_{evap,resp} = \lambda(m_{out,resp} - m_{in,resp})$$

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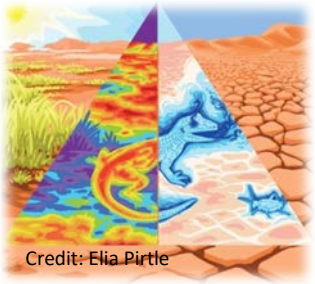
heat

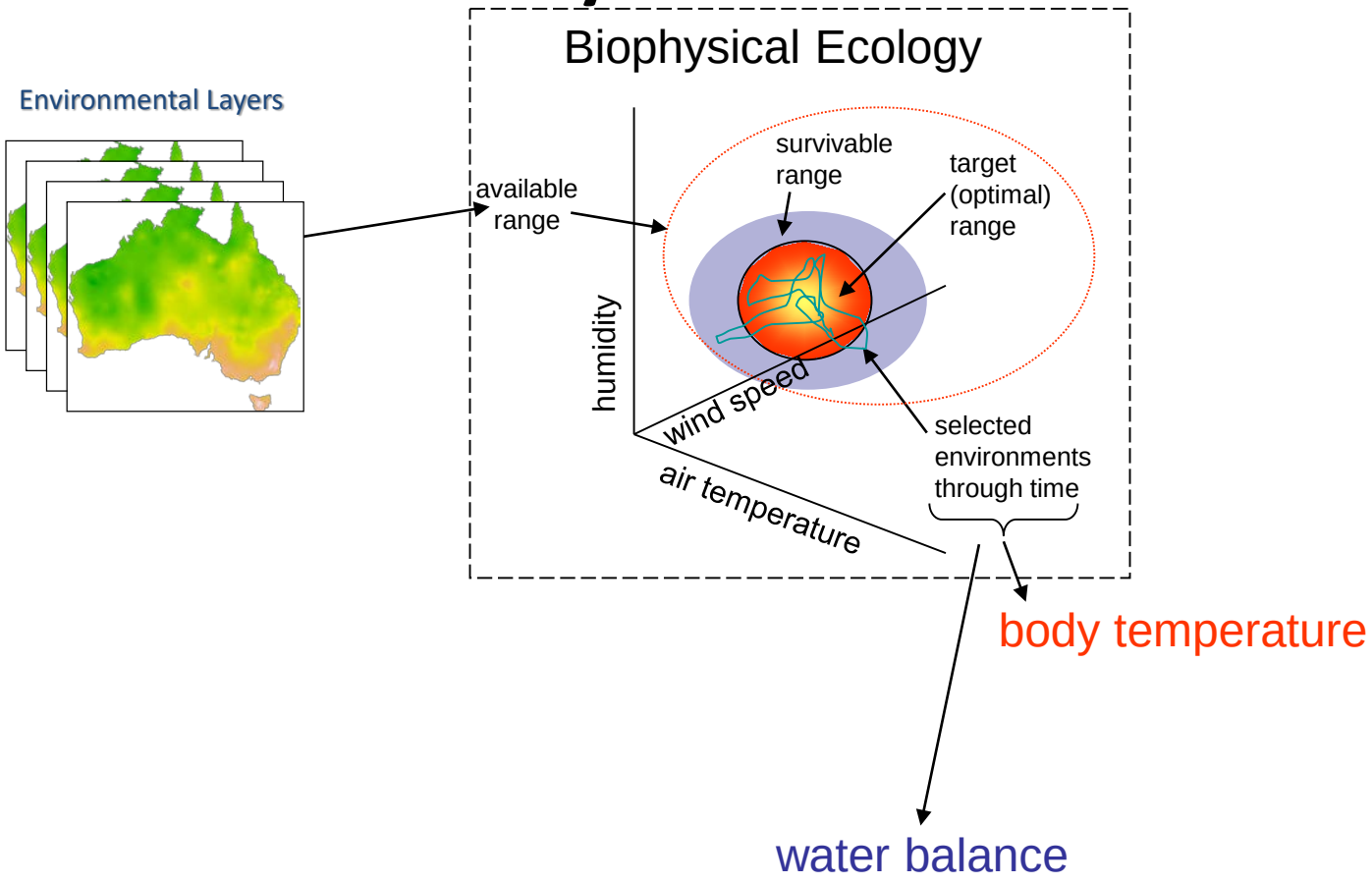
$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6\,H_2O$$

feeding
breathing
temperature
water


Credit: Elia Pirtle

Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

Thermodynamic basis to the niche



Mechanistic Niche Models

Part I

- What is a mechanistic niche model?
- Thermodynamic basis to the niche
- The importance of temperature
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- Microclimates
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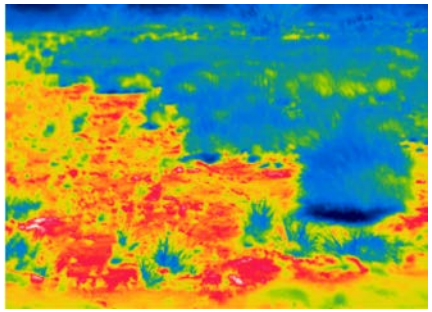
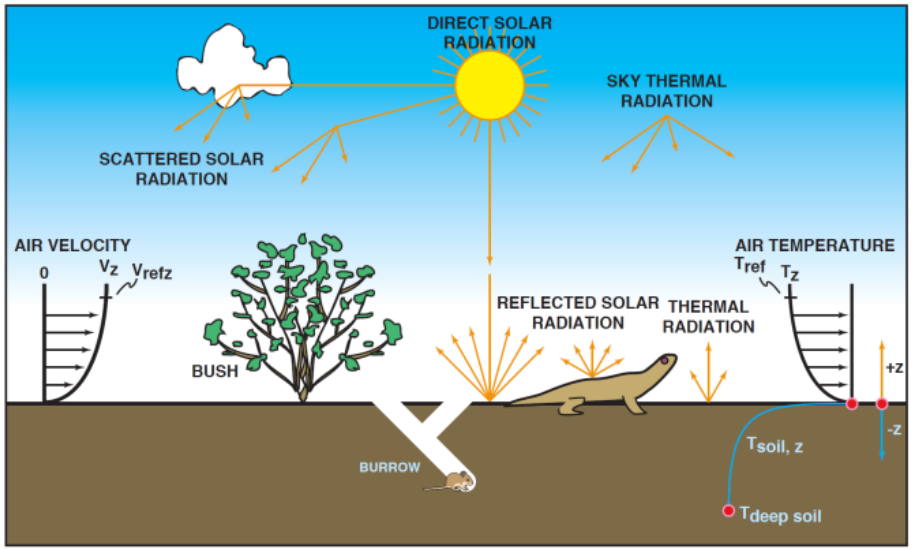
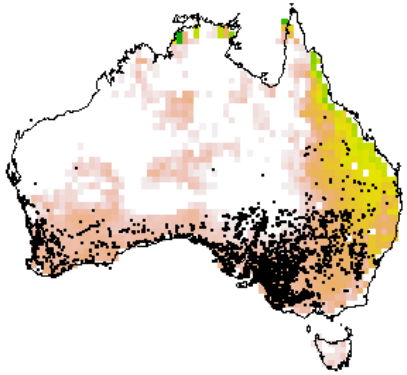
Biophysical Ecology

- Play with NicheMapR

NicheMapR – a general system for mechanistic niche modelling







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Software notes

Ecography 40: 664–674, 2017
doi: 10.1111/ecog.02360

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Subject Editor: Brody Sandel. Editor-in-Chief: Miguel Araújo. Accepted 7 August 2016

NicheMapR – an R package for biophysical modelling: the microclimate model

Michael R. Kearney and Warren P. Porter

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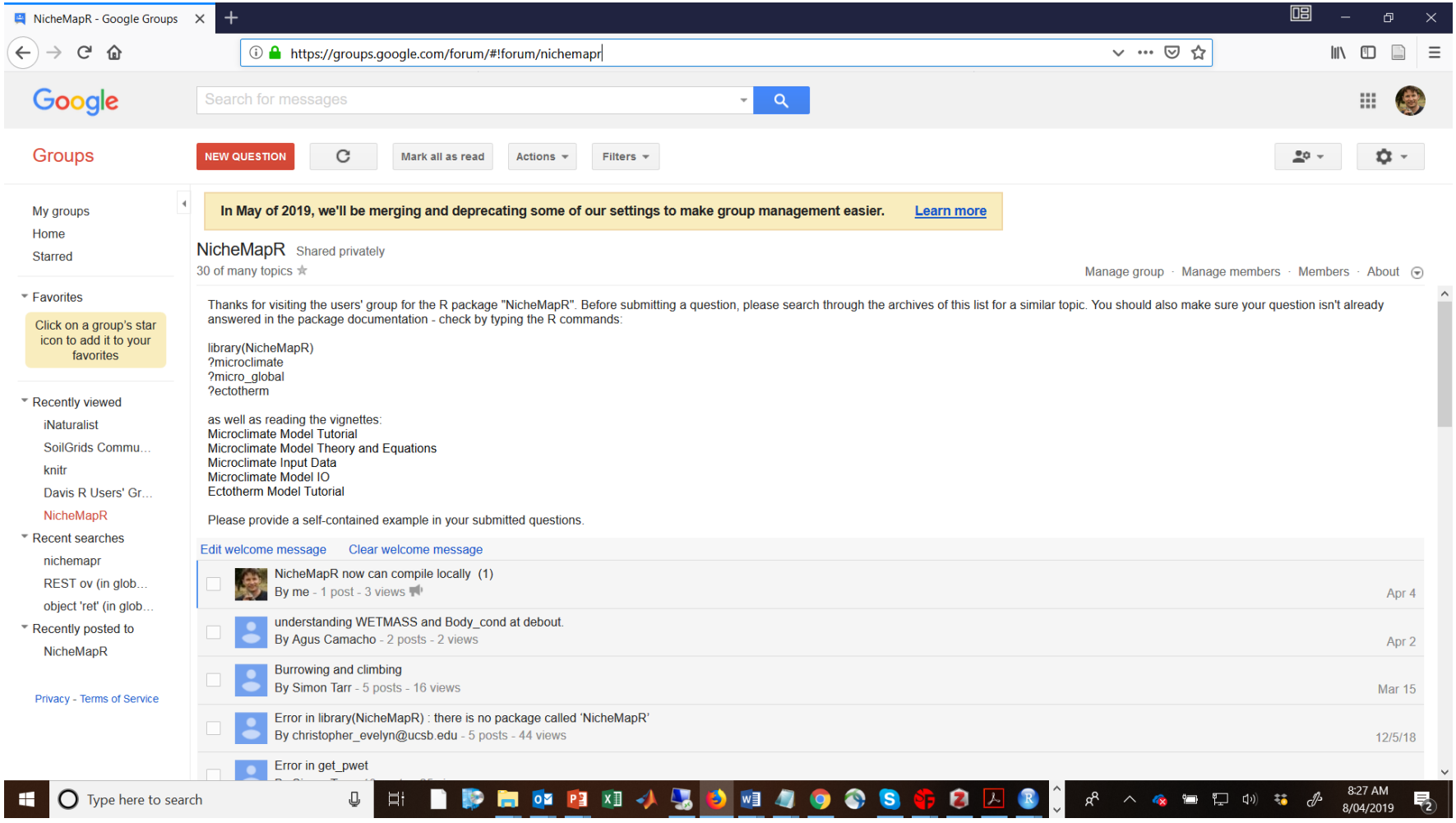
NicheMapR Google Group

@NicheMapR

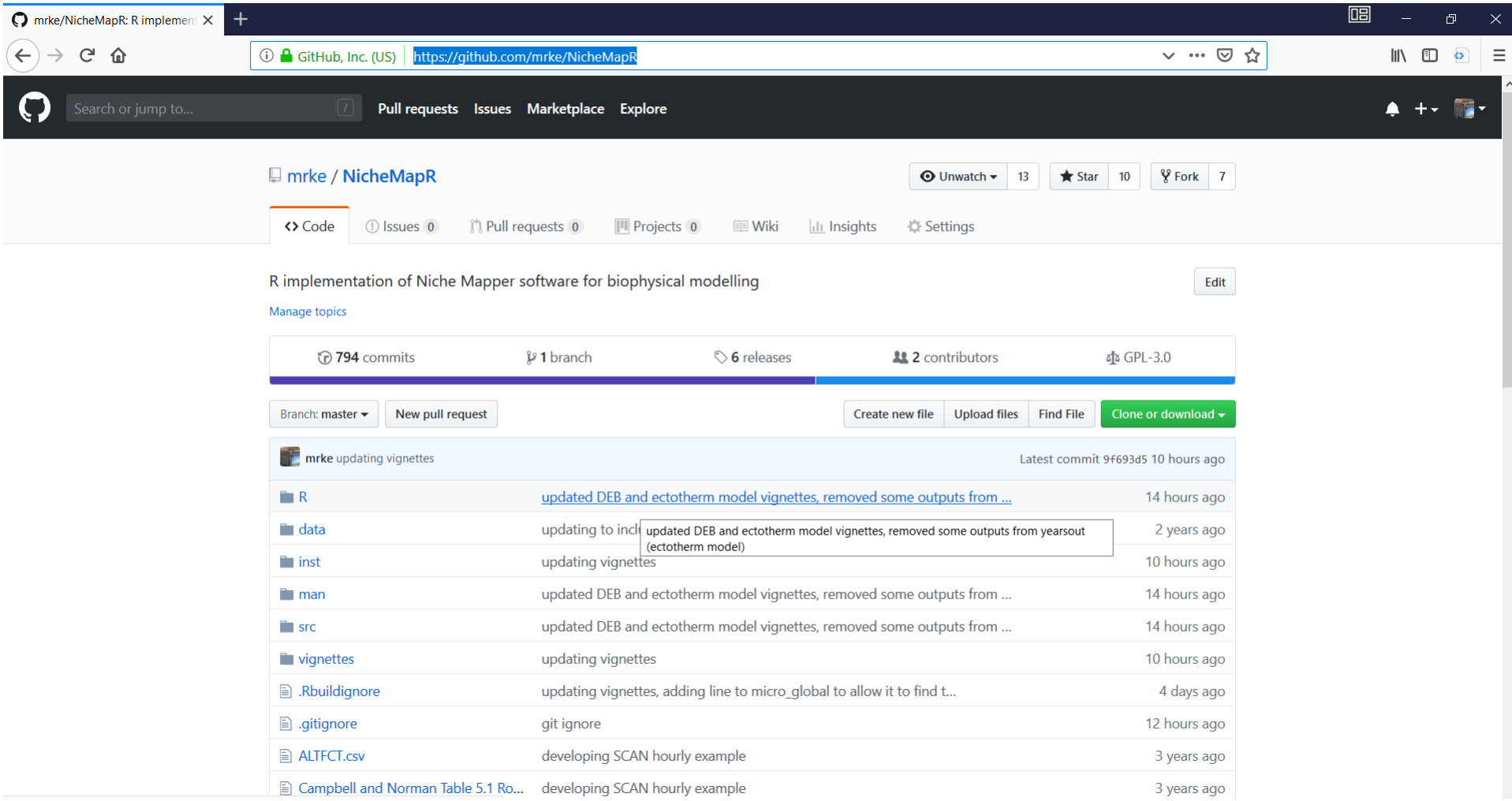
https://groups.google.com/forum/#!forum/nichemapr



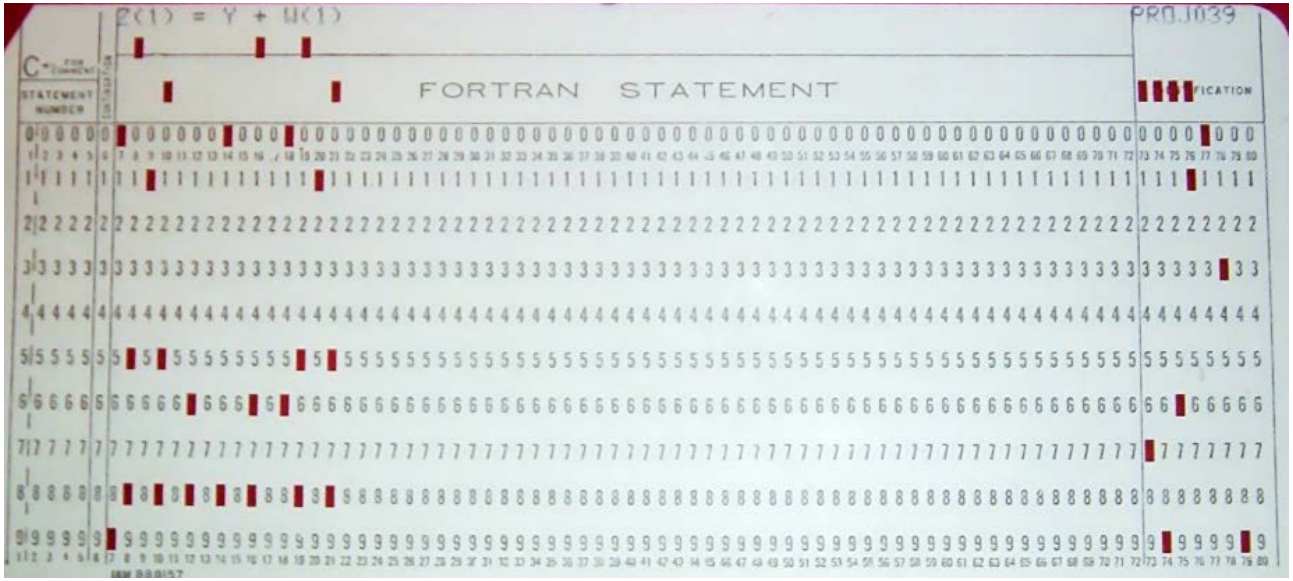
NicheMapR Google Group

@NicheMapR

https://github.com/mrke/NicheMapR



NicheMapR

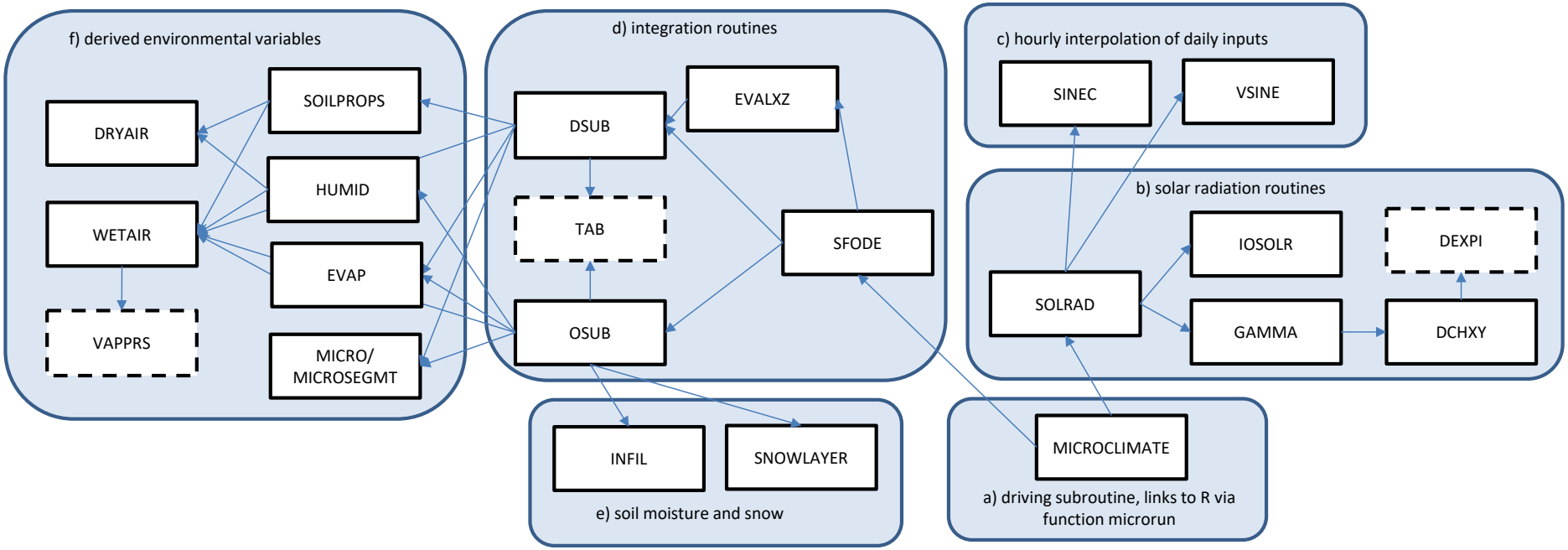


Fortran

Niche Mapper

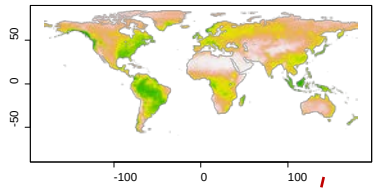
Microclimate Program Structure

Niche Mapper → NicheMapR

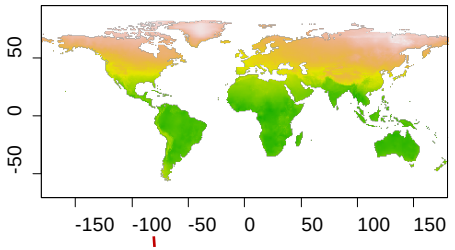


NicheMapR

CPC soil moisture



New et al. 2002



a) Call to Fortran

Fortran microclimate model library

microrun.R

c) User arguments

User Input (location, terrain, shade, soil type, …)

e) Global Aerosol Data Set

rungads

GADS Tables

Fortran GADS library

b) micro_global.R

d) Climate and soil data sets

CampNormTbl9_1

soil.mon.ltm.v2.nc

global_climate.nc

f) output

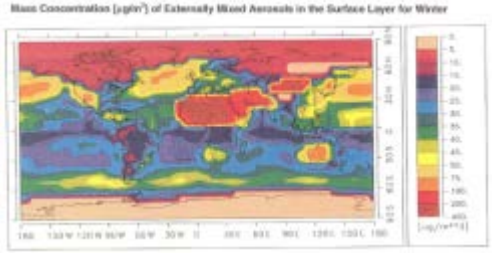
metout

soil

soilmoist

soilpot

humid



Koepke et al 1997

NicheMapR

a) Call to Fortran

Fortran microclimate model library

microrun.R

c) User arguments

User Input (location, terrain, shade, soil type, …)

e) Global Aerosol Data Set

rungads

GADS Tables

Fortran GADS library

b) micro_aust.R

d) Climate, terrain and soil data sets

McVicar wind

GEODATA 9 Second DEM

SLGA bulk dens, sand/silt/clay

AWAP tmax, tmin, solr vpr, rr

f) output

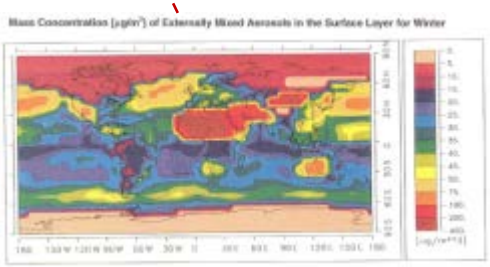
metout

soil

soilmoist

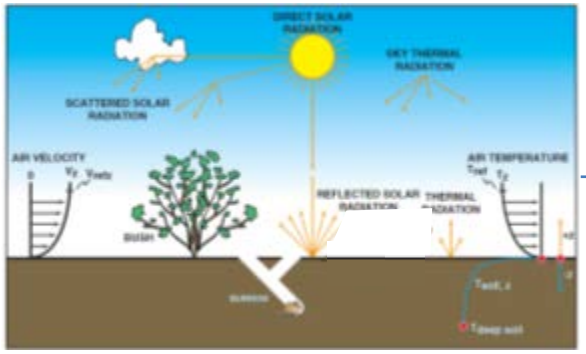
soilpot

humid



Koepke et al 1997

The Heat and Water Budget Model



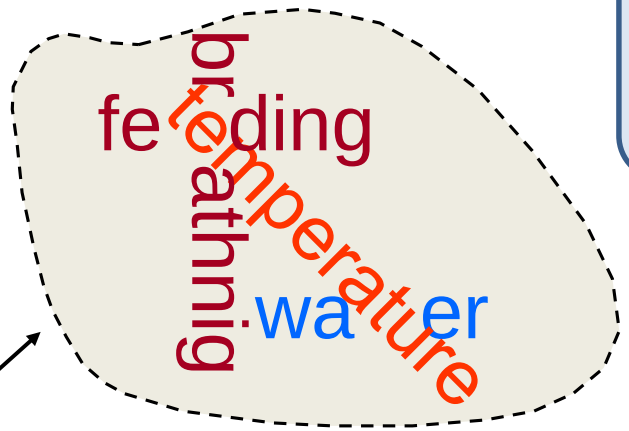
output

- metout
- soil
- soilmoist
- soilpot
- humid

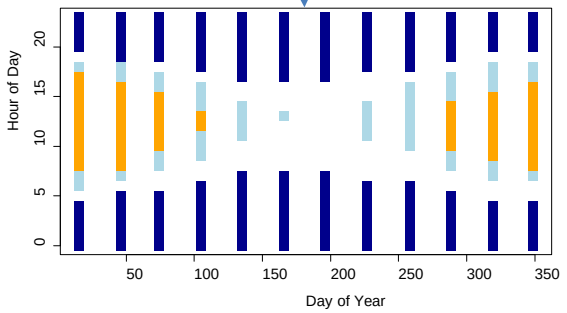
SURROUNDINGS

ectotherm.R

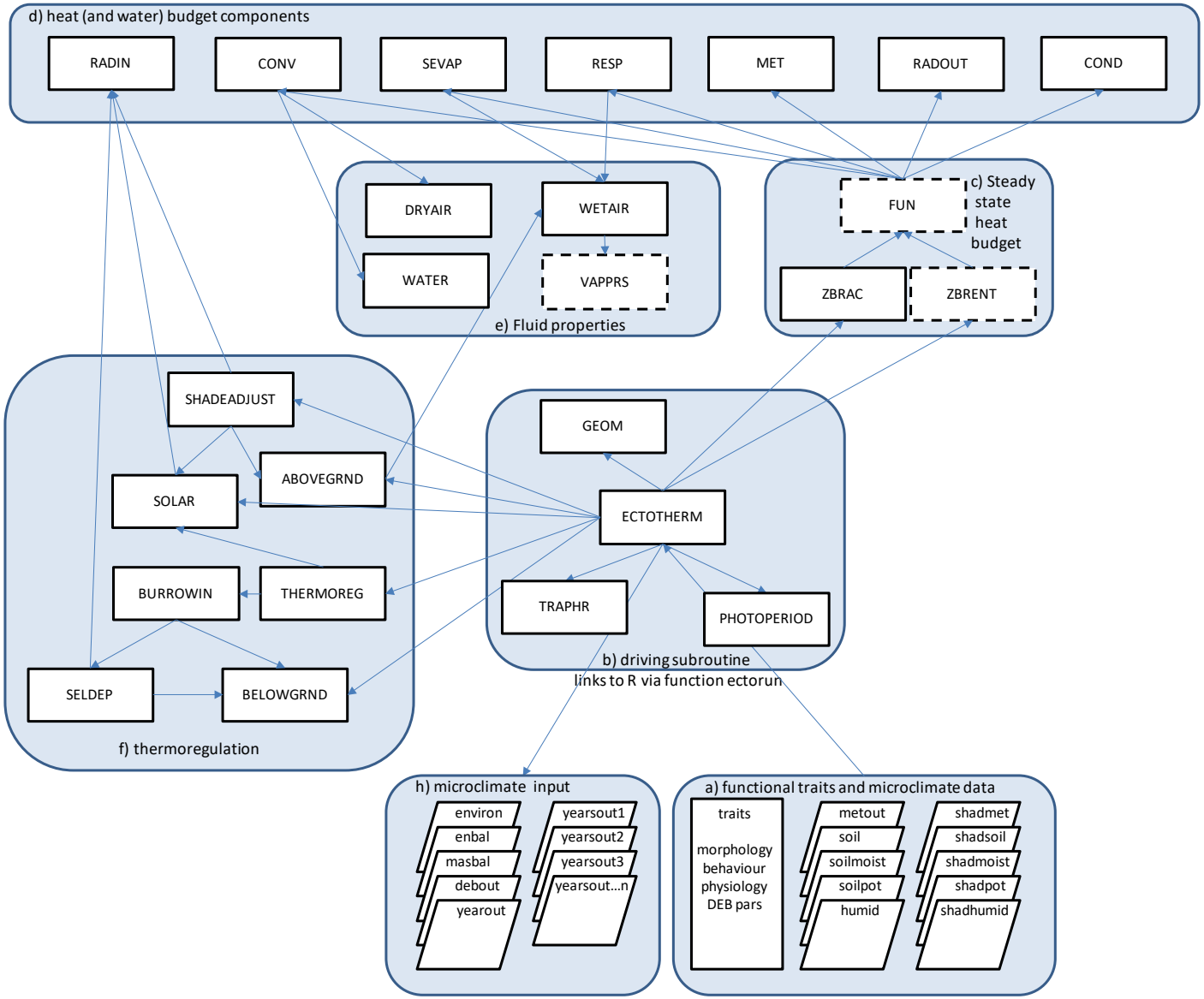
- environ
- enbal
- masbal



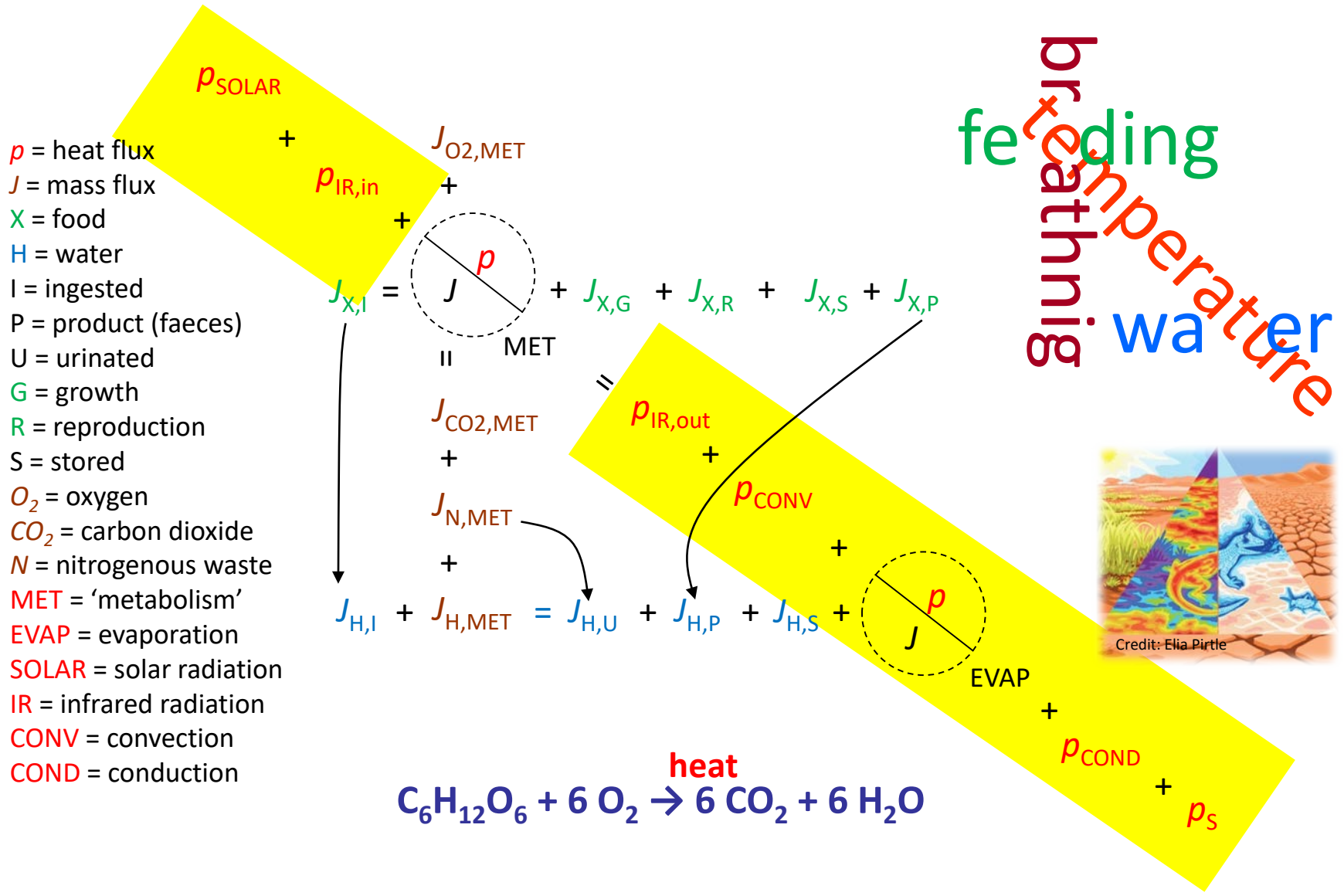
BOUNDARY



The Heat and Water Budget Model

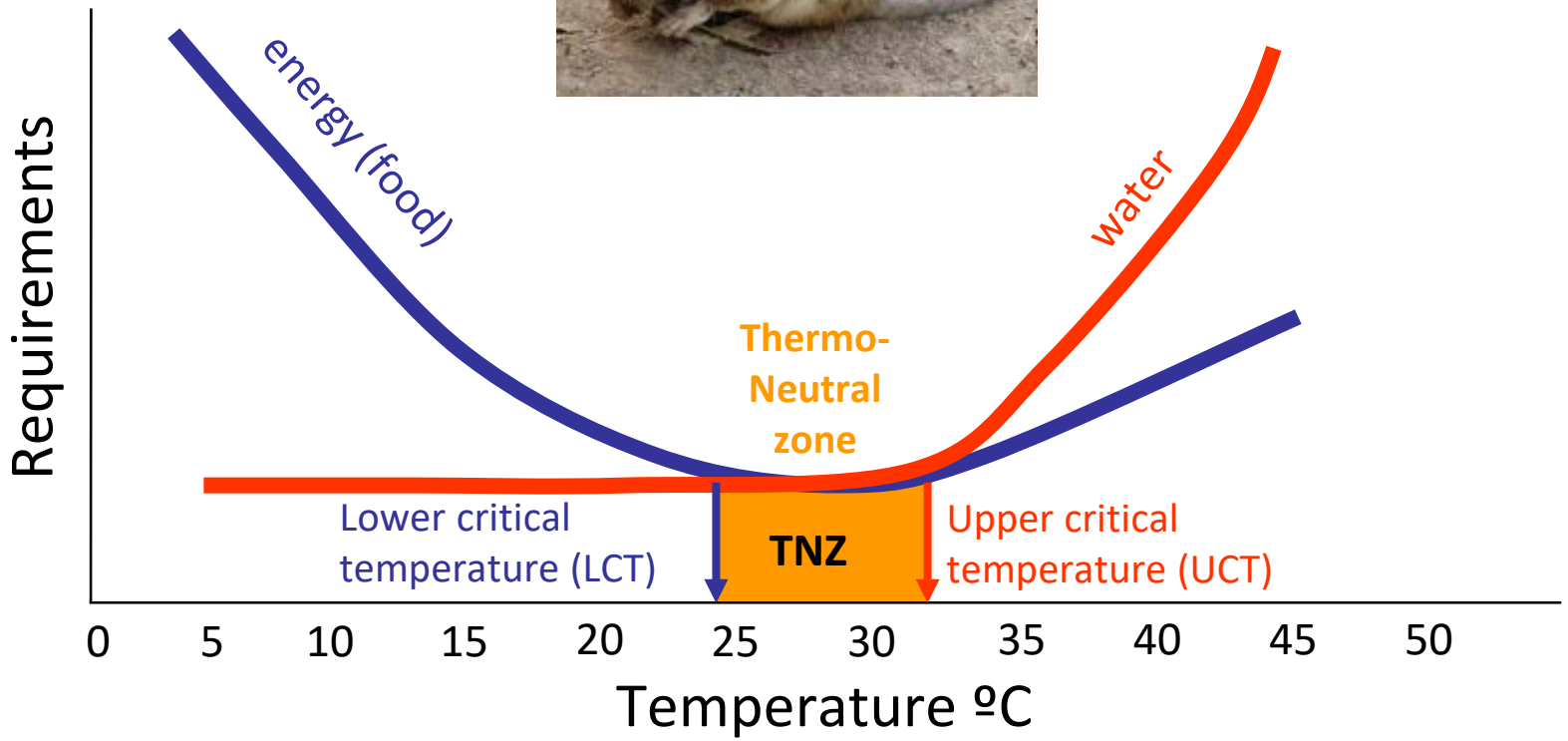


Thermodynamic basis to the niche

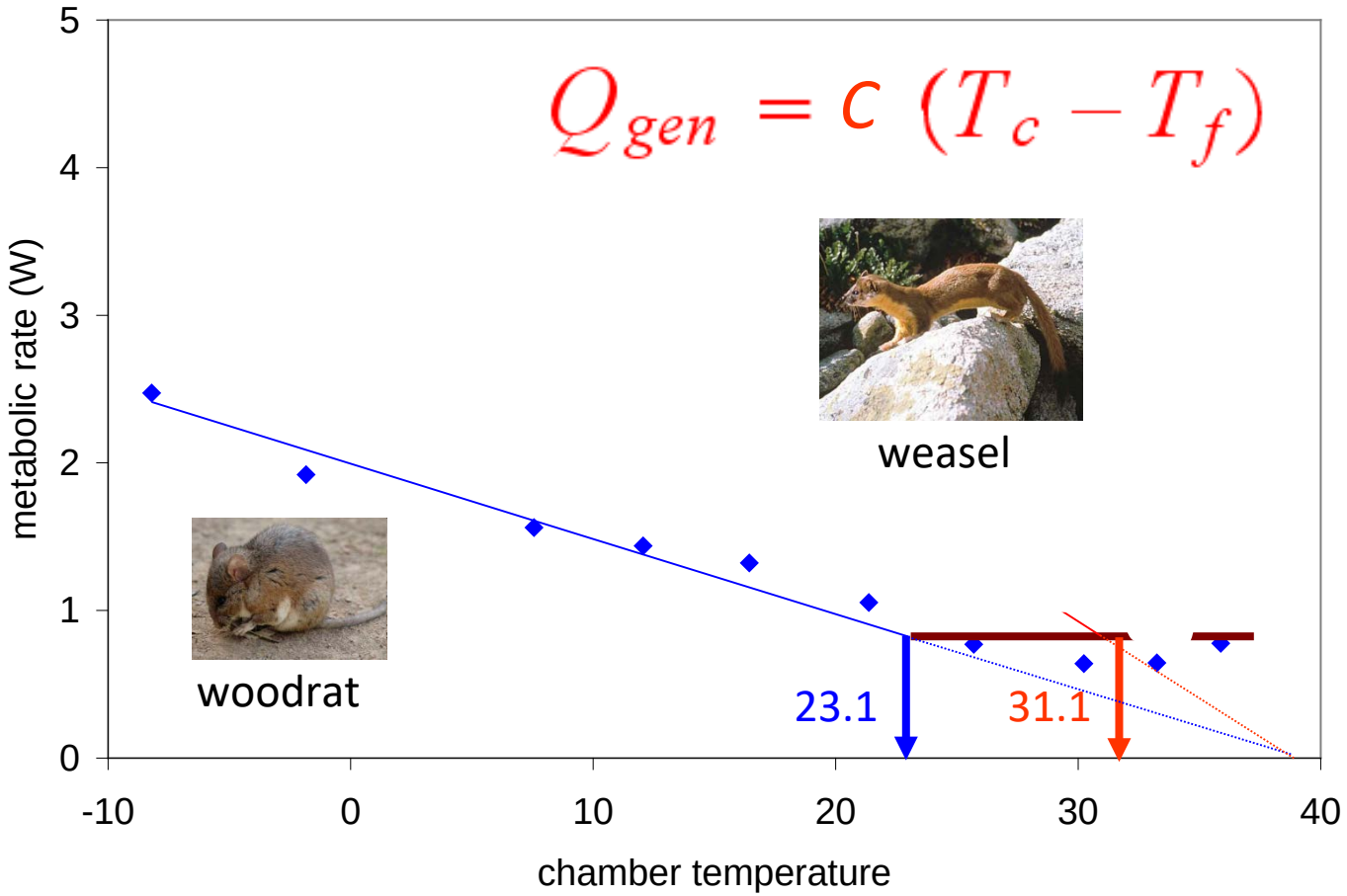


Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

Biophysical Ecology – Heat Budgets



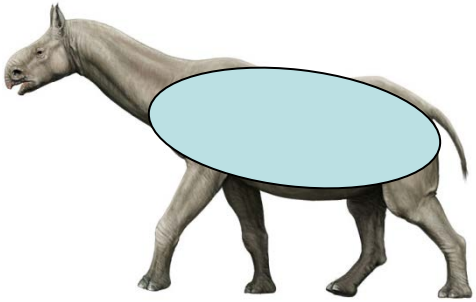
Biophysical Ecology – Heat Budgets

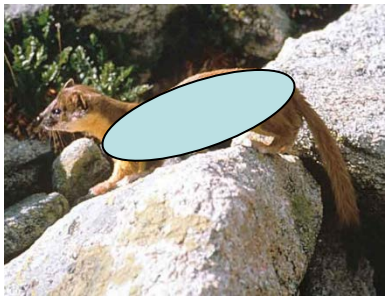


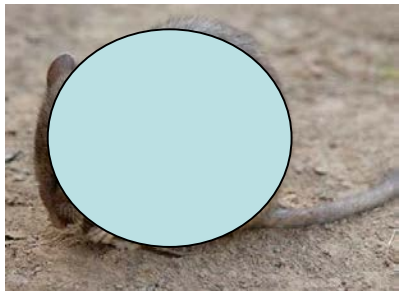
Brown J.H. & Lasiewski R.C. (1972). *Ecology, 53, 939-943.*

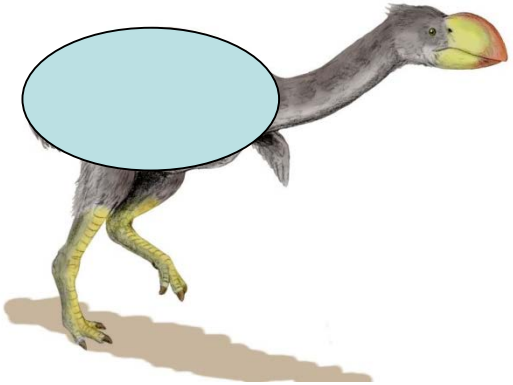
Predicting Endotherm Energy and Water Requirements

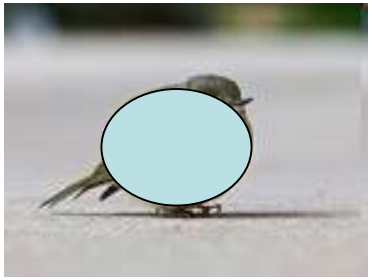
consider an elliptical animal









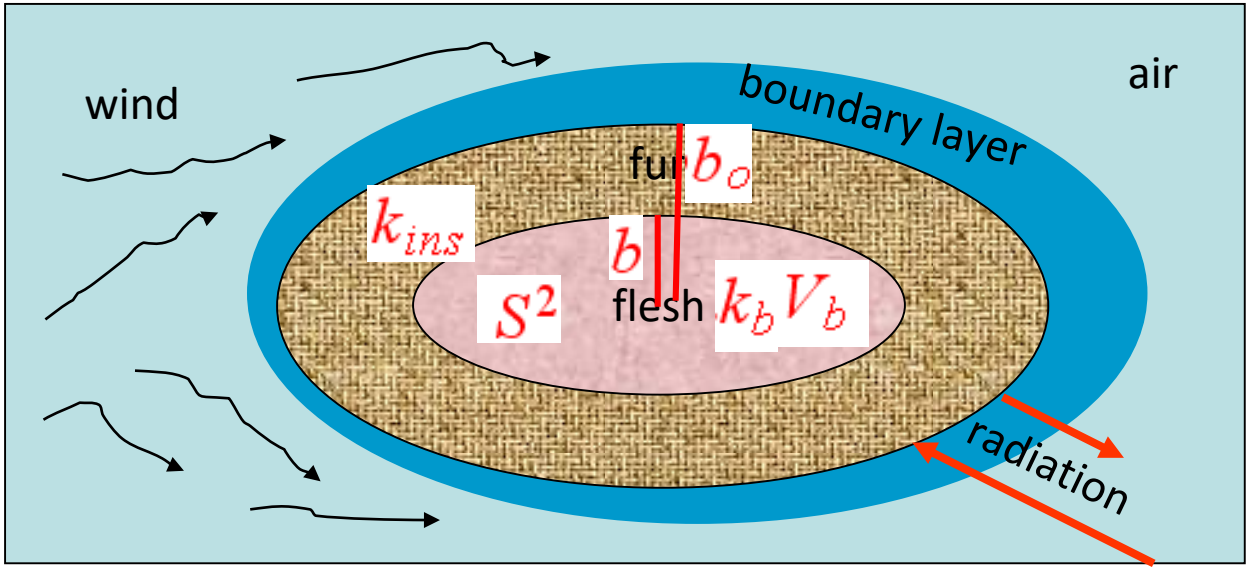


Predicting Endotherm Energy and Water Requirements

heat energy balance of an endotherm

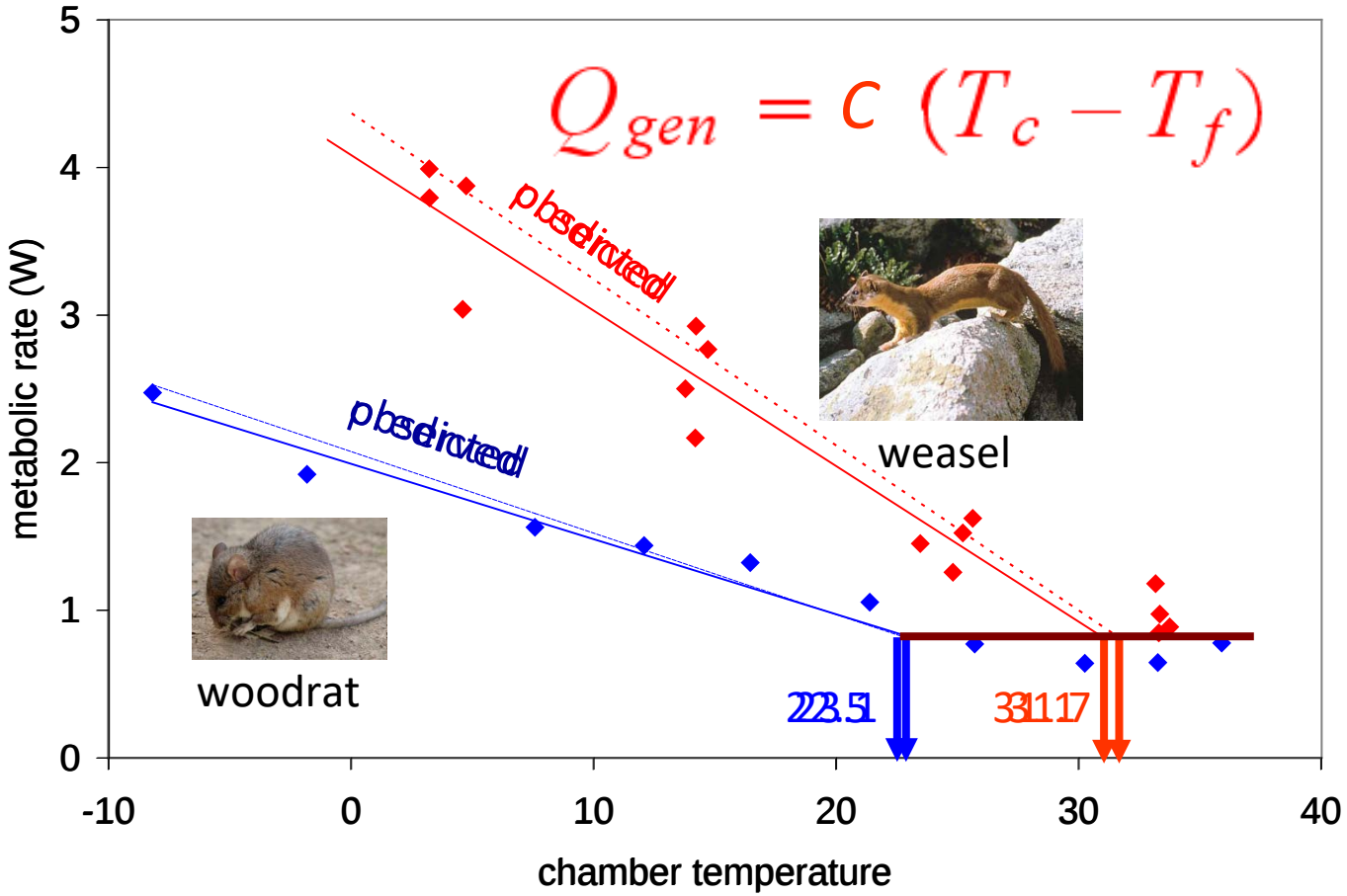
$$Q_{gen} = \left[\frac{Q_{gen} = C\ (T_c - T_f)}{\text{body resistance} + \text{fur resistance} + \text{environmental resistance}} \right]$$

$$Q_{gen} = \left[\frac{Q_{gen} = C\ (T_c - T_f)}{R} \right]$$



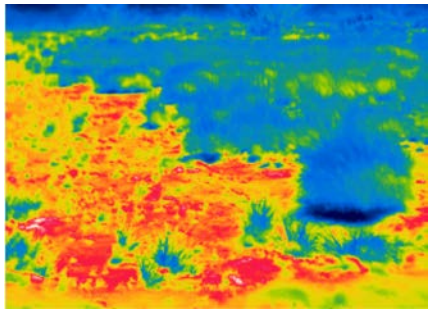
Porter & Kearney (2009) PNAS *106, 19666-19672.*

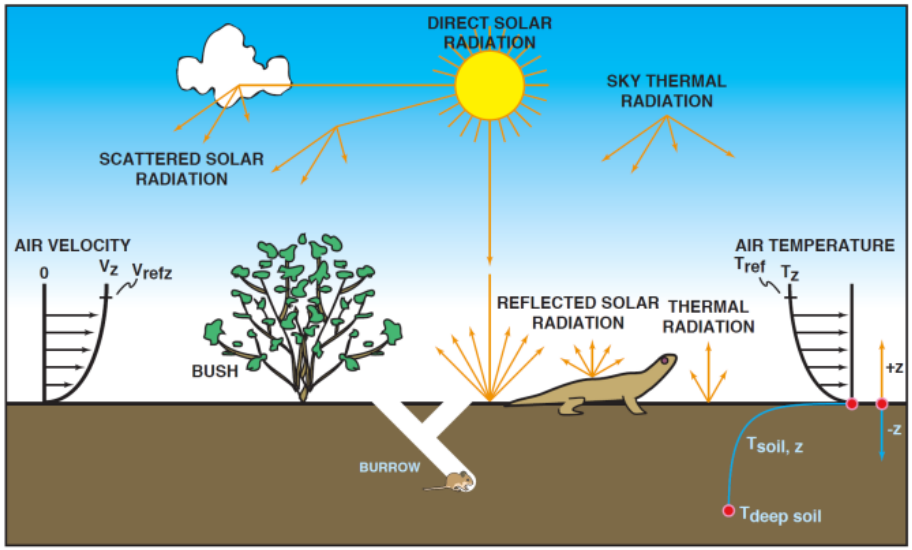
Predicting Endotherm Energy and Water Requirements

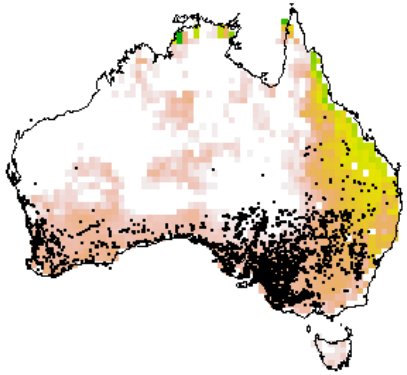


Porter & Kearney (2009) PNAS *106, 19666-19672.*

NicheMapR – a general system for mechanistic niche modelling







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Software notes

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doi: 10.1111/ecog.02360

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Mechanistic Niche Models

Part I

- What is a mechanistic niche model?
- Thermodynamic basis to the niche
- The importance of temperature
- Heat budgets
- Microclimates
- Water budgets

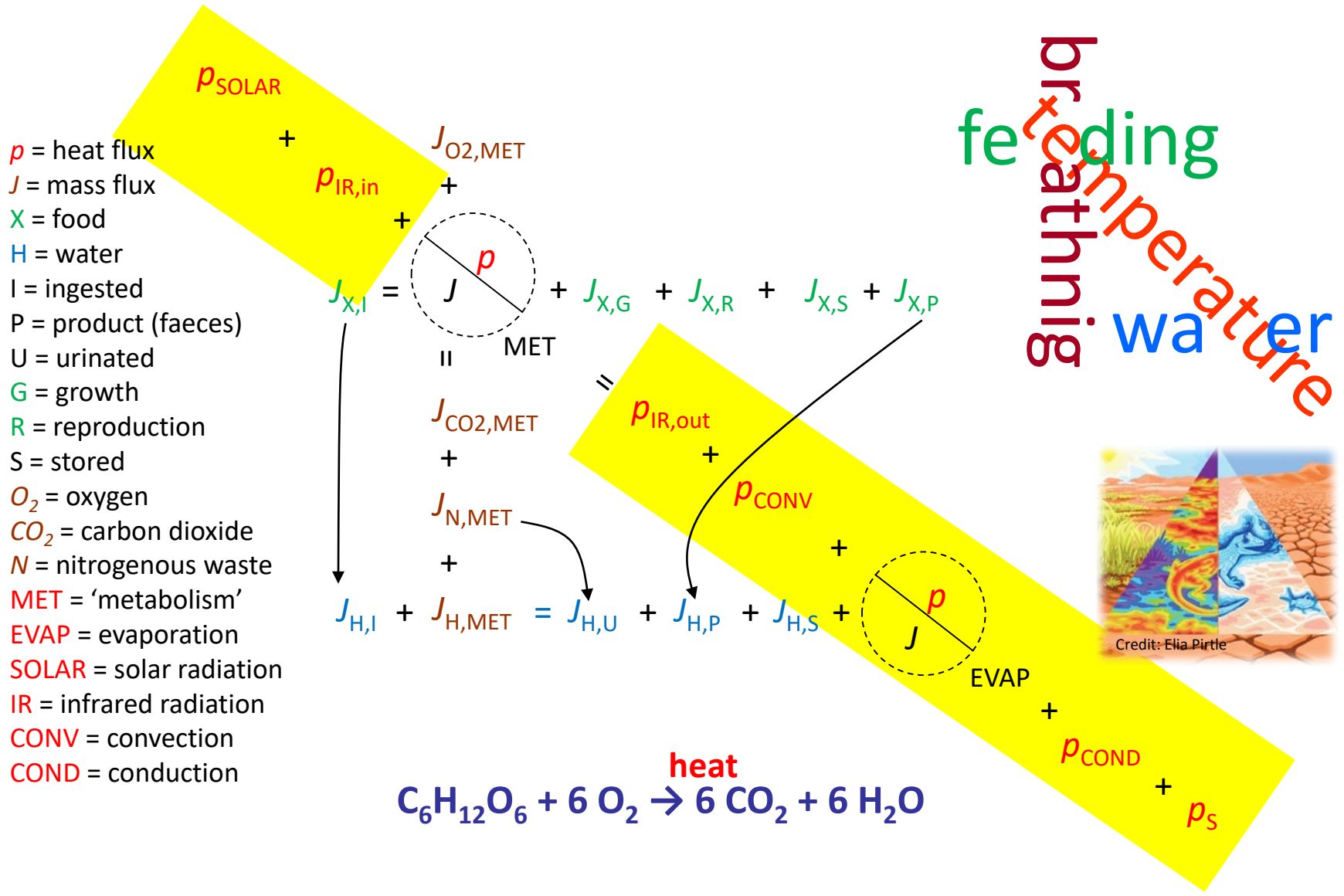
Biophysical Ecology

- Play with NicheMapR

Part II

- Connecting to the Dynamic Energy Budget
- Play with NicheMapR
- Inferring climatic constraints
- Nutritional constraints

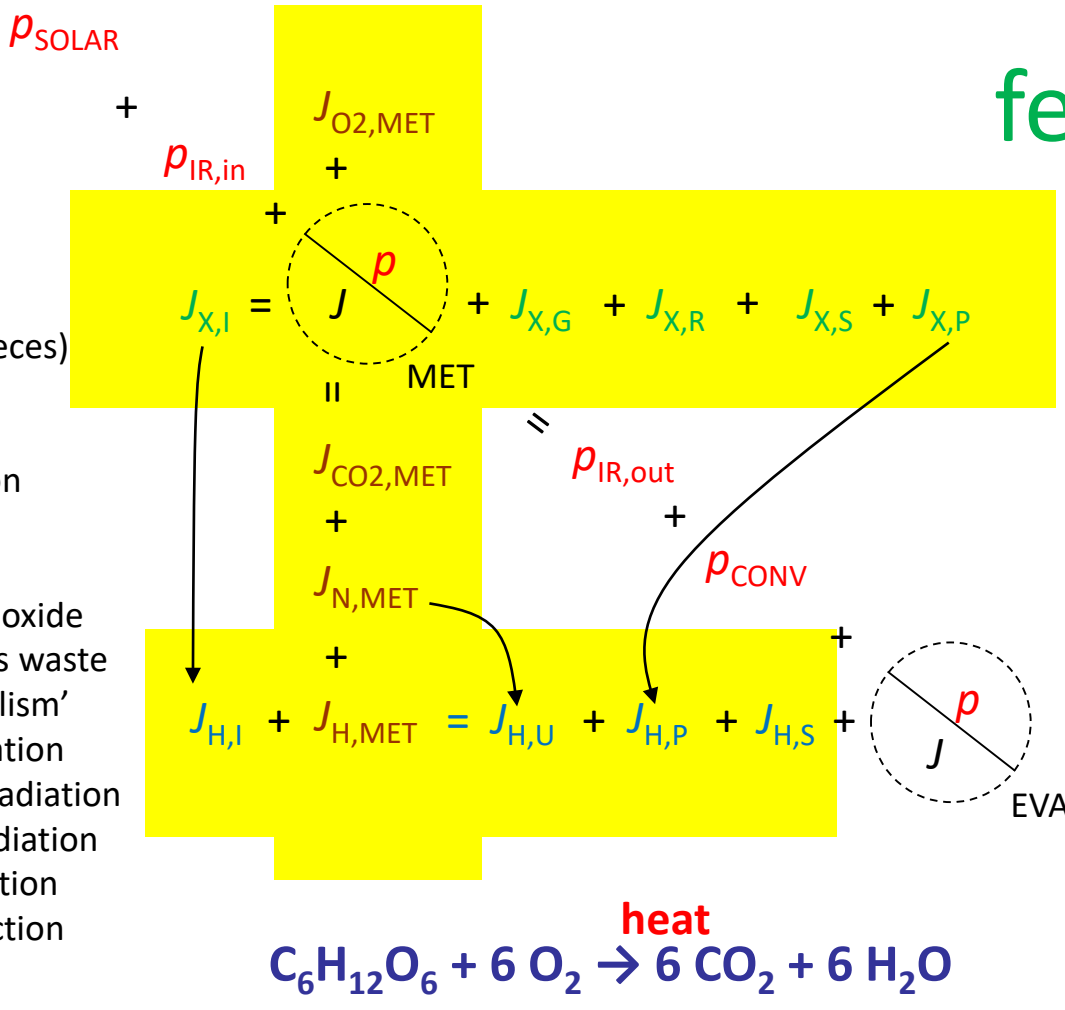
Thermodynamic basis to the niche

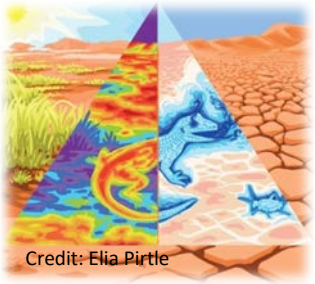


Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

Thermodynamic basis to the niche

p = heat flux
J = mass flux
X = food
H = water
I = ingested
P = product (faeces)
U = urinated
G = growth
R = reproduction
S = stored
O_2 = oxygen
CO_2 = carbon dioxide
N = nitrogenous waste
MET = 'metabolism'
EVAP = evaporation
SOLAR = solar radiation
IR = infrared radiation
CONV = convection
COND = conduction

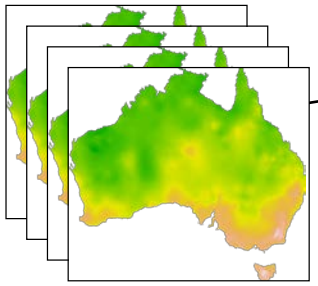




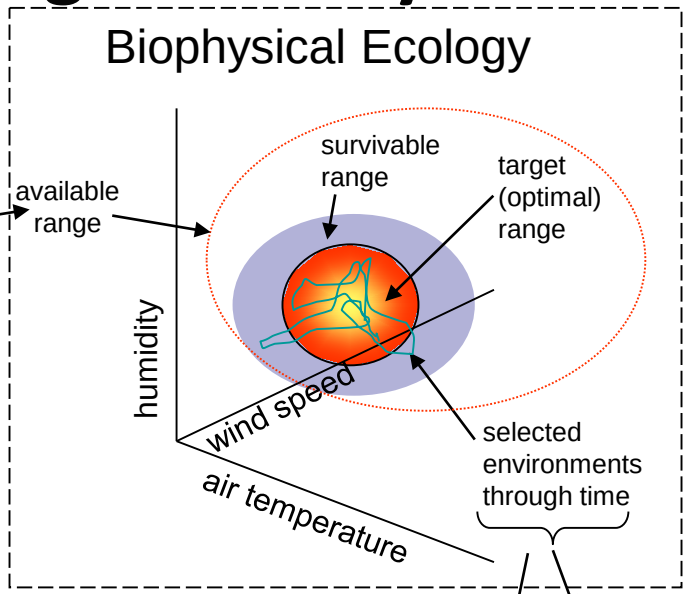
Kearney et al. **Functional Ecology (2013)** after Porter and Tracy (1983)

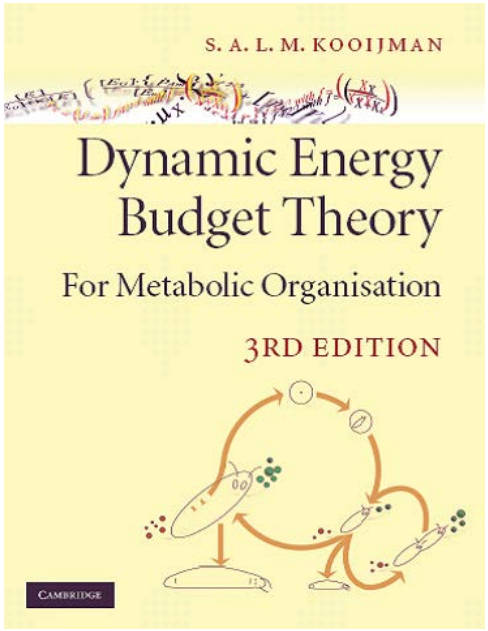
Connecting to the Dynamic Energy Budget

Environmental Layers



Biophysical Ecology



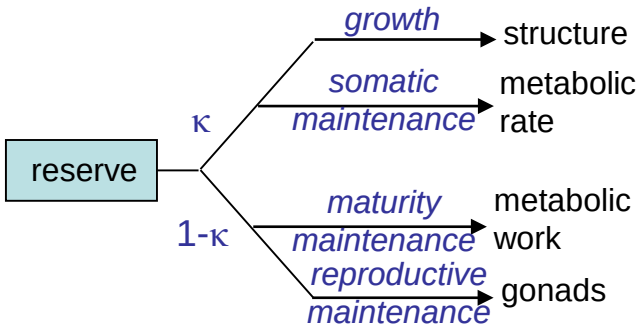


body temp/metabolic rate

physiological rates

water balance

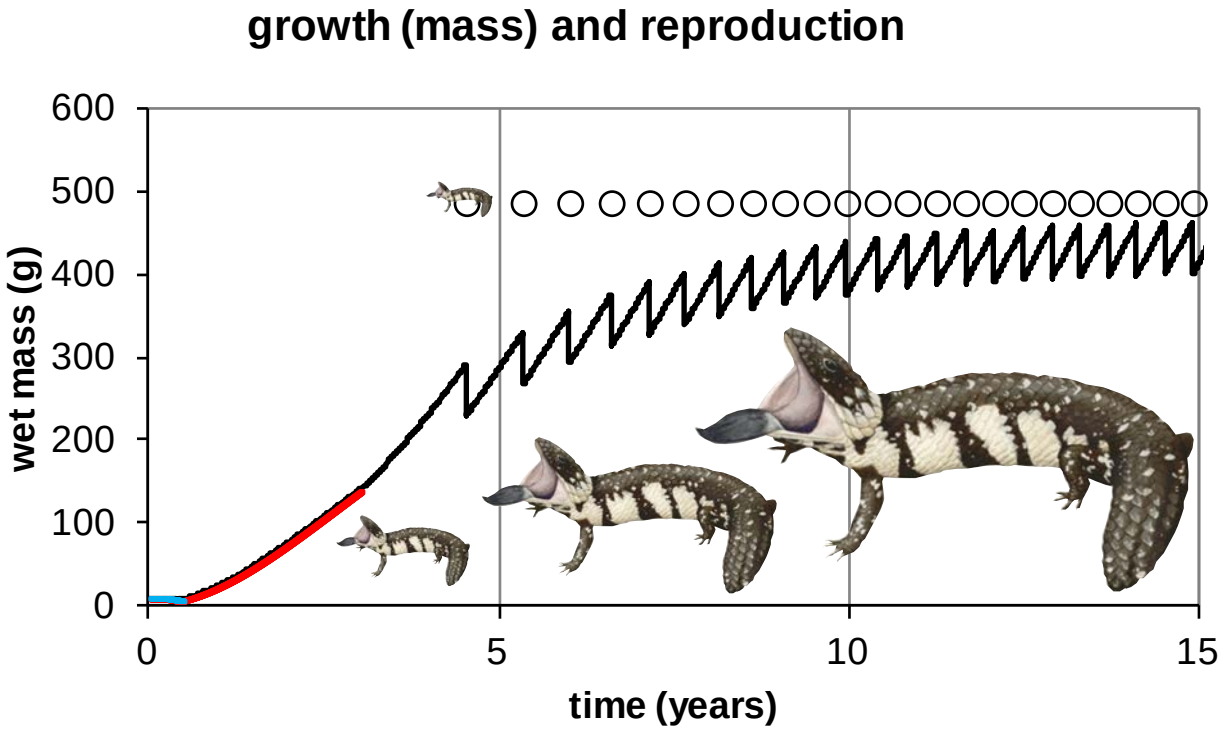
Dynamic Energy/Mass Budget



Connecting to the Dynamic Energy Budget

A year in the life of the Fence Lizard in Utah

Inferring climatic constraints



Food Structure Reserve Faeces

$$\begin{pmatrix} n_{CX} & n_{CV} & n_{CE} & n_{CP} \\ n_{HX} & n_{HV} & n_{HE} & n_{HP} \\ n_{OX} & n_{OV} & n_{OE} & n_{OP} \\ n_{NX} & n_{NV} & n_{NE} & n_{NP} \end{pmatrix} \begin{pmatrix} j_X \\ j_V \\ j_E + j_{E_R} \\ j_P \end{pmatrix}$$

Food
Structure
Reserve
Faeces

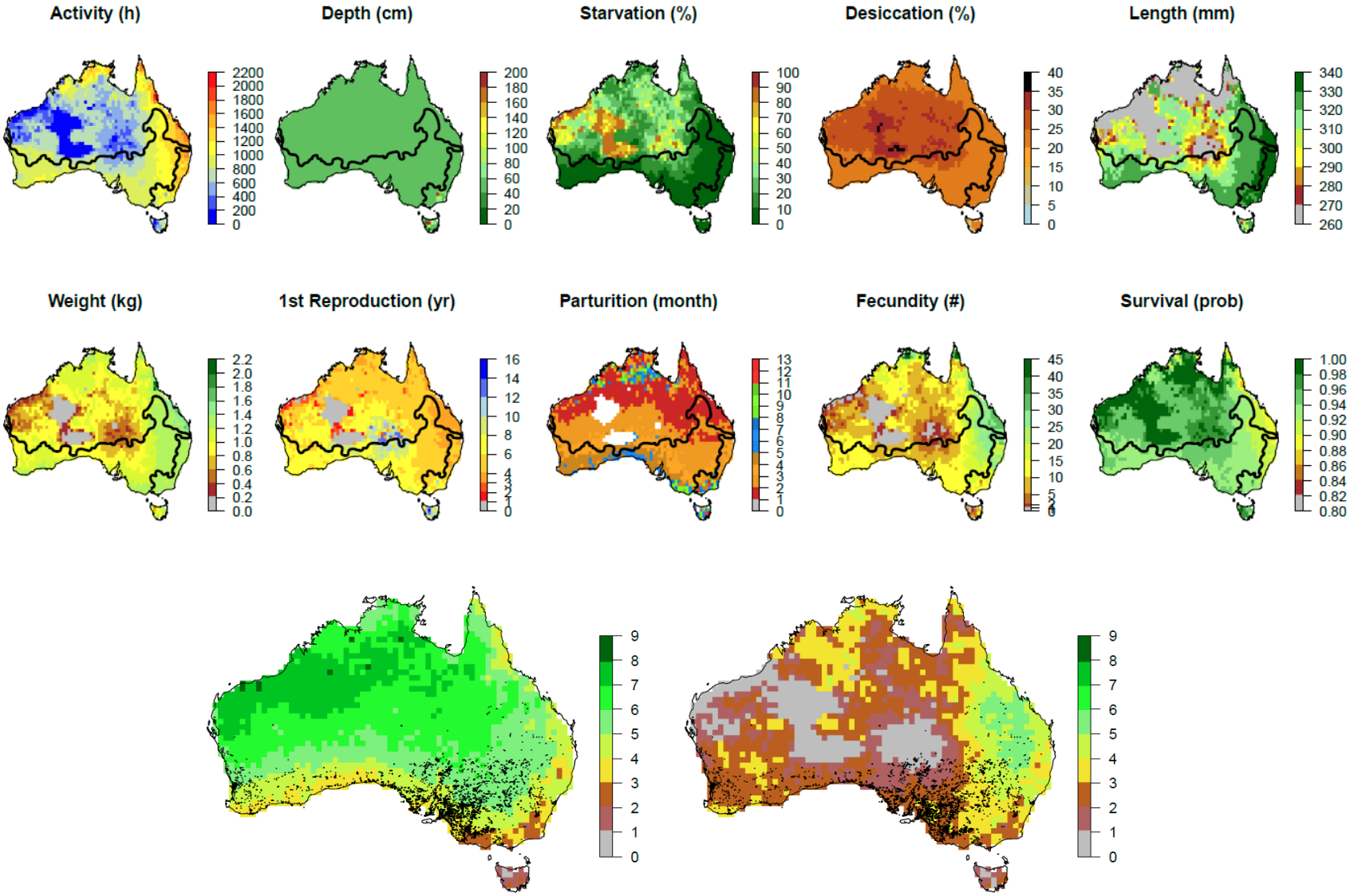
$=$

CO_2 H_2O O_2 N waste

$$\begin{pmatrix} 1 & 0 & 0 & n_{CN} \\ 0 & 2 & 0 & n_{HN} \\ 2 & 1 & 2 & n_{ON} \\ 0 & 0 & 0 & n_{NN} \end{pmatrix} \begin{pmatrix} j_C \\ j_H \\ j_O \\ j_N \end{pmatrix}$$

CO_2
H_2O
O2
N waste

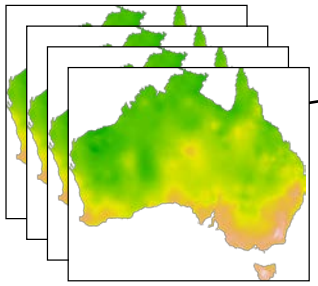
Inferring climatic constraints



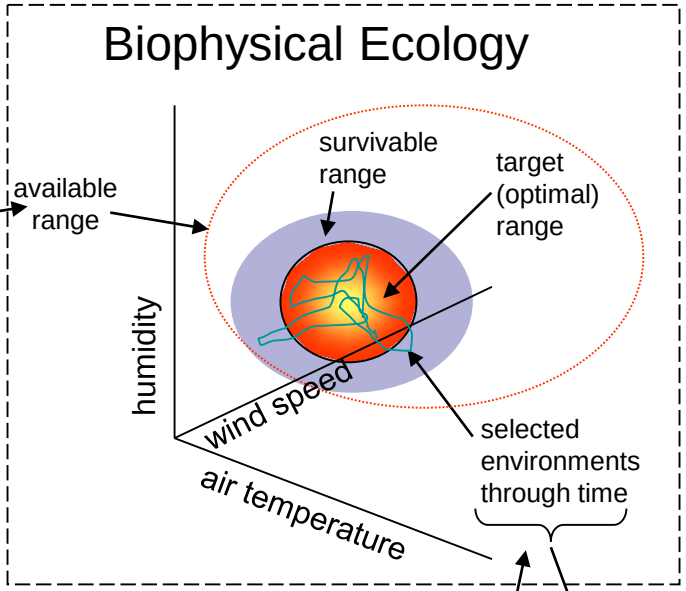
Kearney et al.. 2018. Field tests of a general ectotherm niche model …. Ecological Monographs 88:672–693.

Nutritional constraints

Environmental Layers



Biophysical Ecology



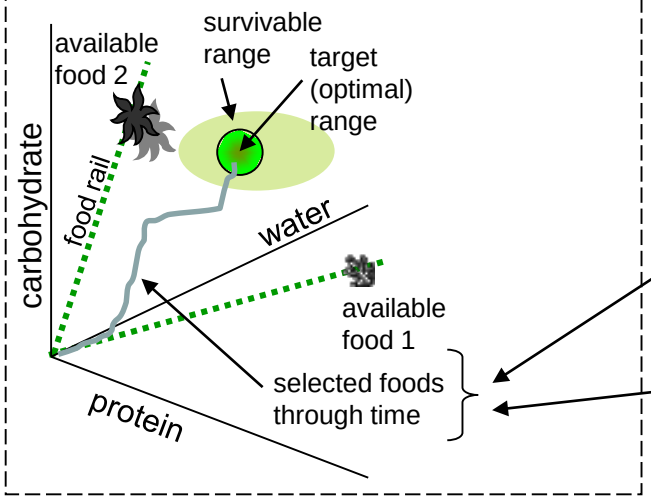
Kearney and Porter TREE 2006

Kearney et al. PTRS 2010

body temp/metabolic rate

physiological rates

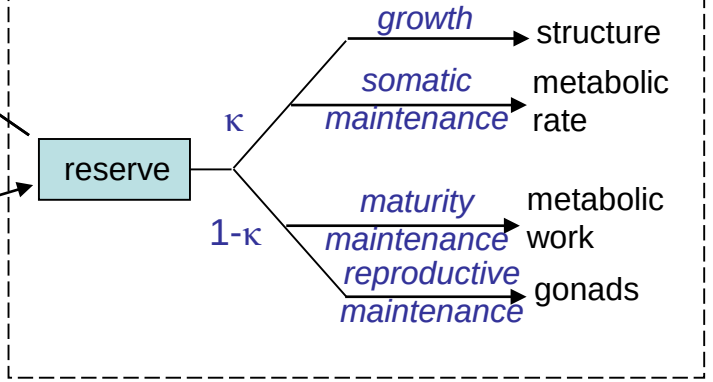
Geometric Framework



water balance

food ingested

Dynamic Energy/Mass Budget



Nutritional constraints

iso221

Food Structure Reserve Faeces

$$\begin{pmatrix} n_{CX} & n_{CV} & n_{CE} & n_{CP} \\ n_{HX} & n_{HV} & n_{HE} & n_{HP} \\ n_{OX} & n_{OV} & n_{OE} & n_{OP} \\ n_{NX} & n_{NV} & n_{NE} & n_{NP} \end{pmatrix} \quad \begin{pmatrix} \dot{J}_X \\ \dot{J}_V \\ \dot{J}_E + \dot{J}_{E_R} \\ \dot{J}_P \end{pmatrix}$$

Food
Structure
Reserve
Faeces

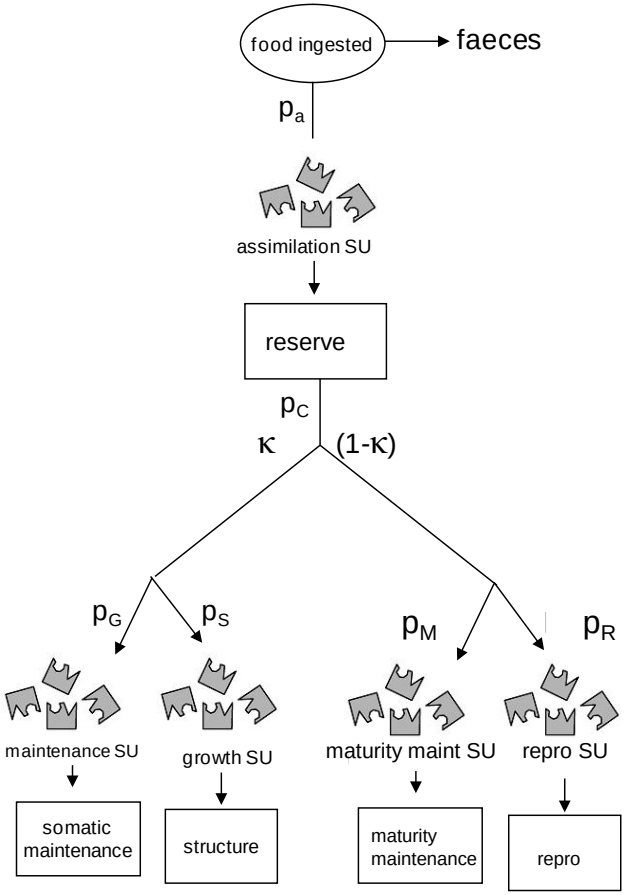
Food 1 Food 2 Structure Protein reserve Non-protein reserve Faeces from food 1 Faeces from food 2

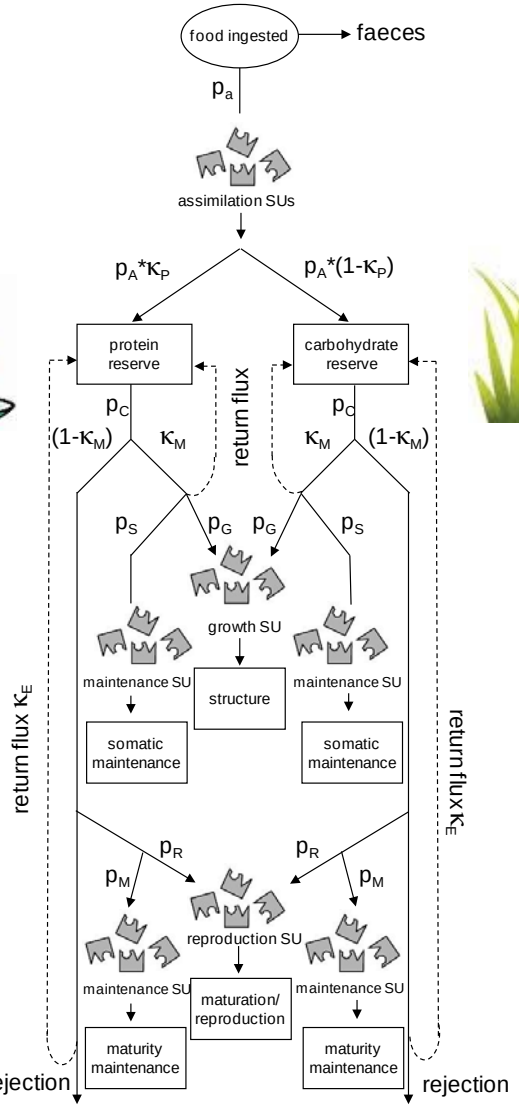
$$\begin{pmatrix} n_{CX} & n_{CY} & n_{CV} & n_{CE_1} & n_{CE_2} & n_{CP_X} & n_{CP_Y} \\ n_{HX} & n_{HY} & n_{HV} & n_{HE_1} & n_{HE_2} & n_{HP_X} & n_{HP_Y} \\ n_{OX} & n_{OY} & n_{OV} & n_{OE_1} & n_{OE_2} & n_{OP_X} & n_{OP_Y} \\ n_{NX} & n_{NY} & n_{NV} & n_{NE_1} & n_{NE_2} & n_{NP_X} & n_{NP_Y} \end{pmatrix} \quad \begin{pmatrix} \dot{J}_X & \dot{J}_Y & \dot{J}_V & \dot{J}_{E_1} + \dot{J}_{E_1R} & \dot{J}_{E_2} + \dot{J}_{E_2R} & \dot{J}_{P_X} & \dot{J}_{P_Y} \end{pmatrix}^T$$

Food 1 Food 2 Structure Protein reserve Non-protein reserve Faeces (food 1) Faeces (food 2)

Nutritional constraints

iso221



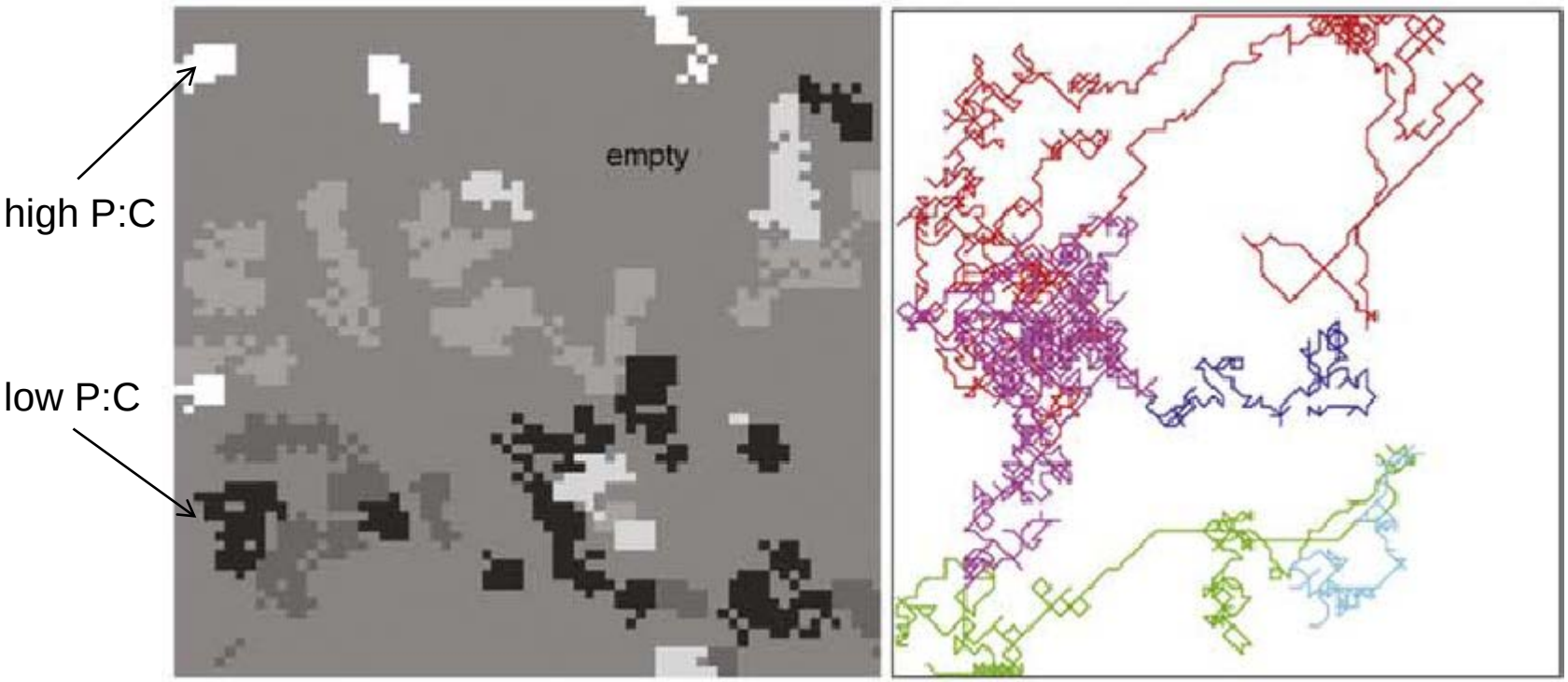


Kearney et al. PTRS 2010

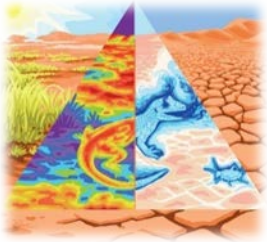
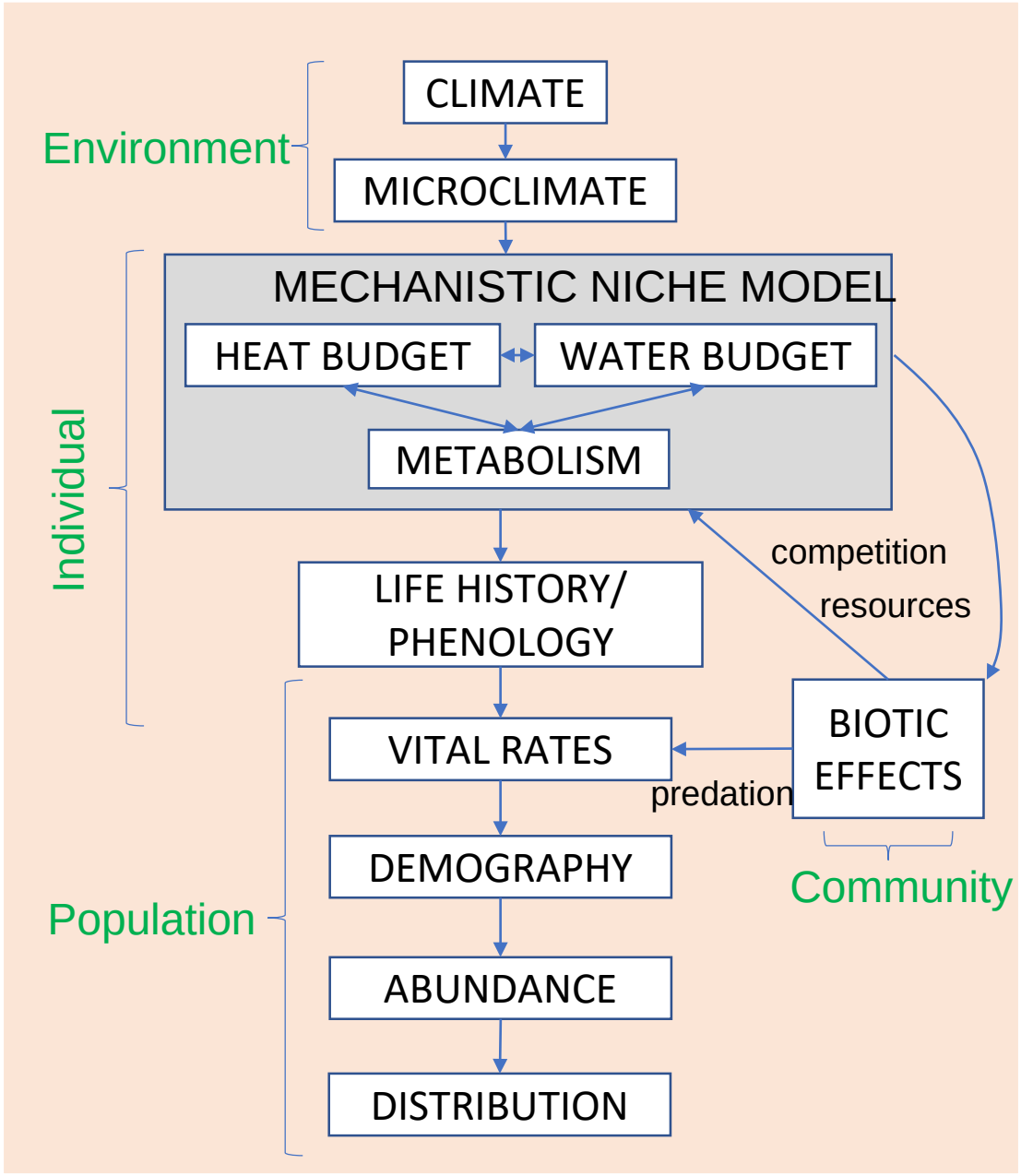
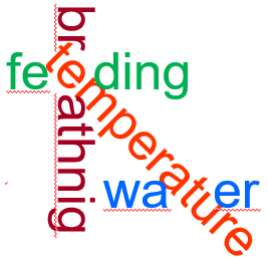
Nutritional constraints

Nutritional Landscape

Agent Behaviour



- Preference behaviour/targets will change with ontogeny

Simpson et al. (2010). ***Trends in Ecology & Evolution, 25, 53-60.***

Mechanistic Niche Models