TROPICAL ECOLOGY

Animals' adaptations to desert and arid habitats

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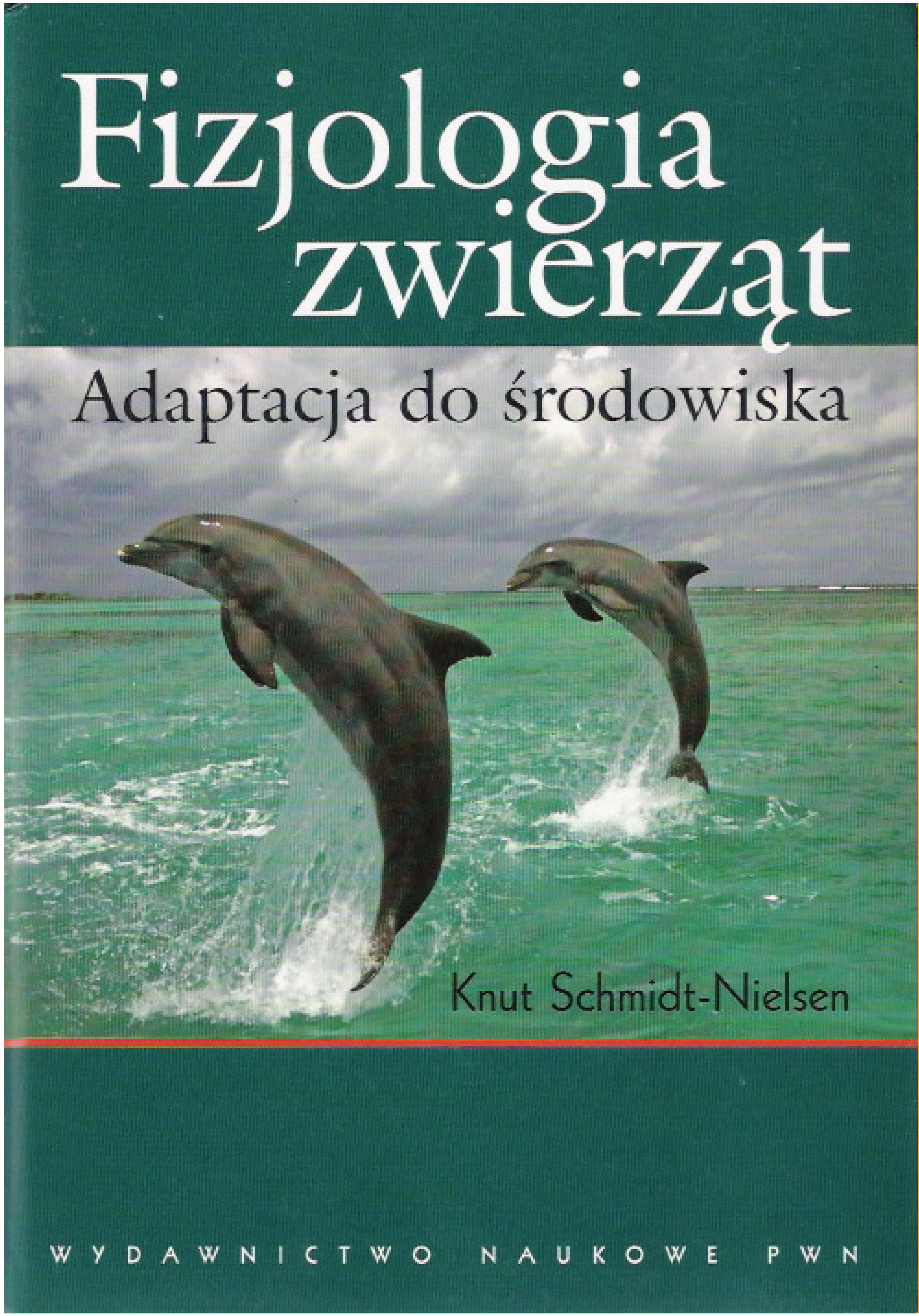
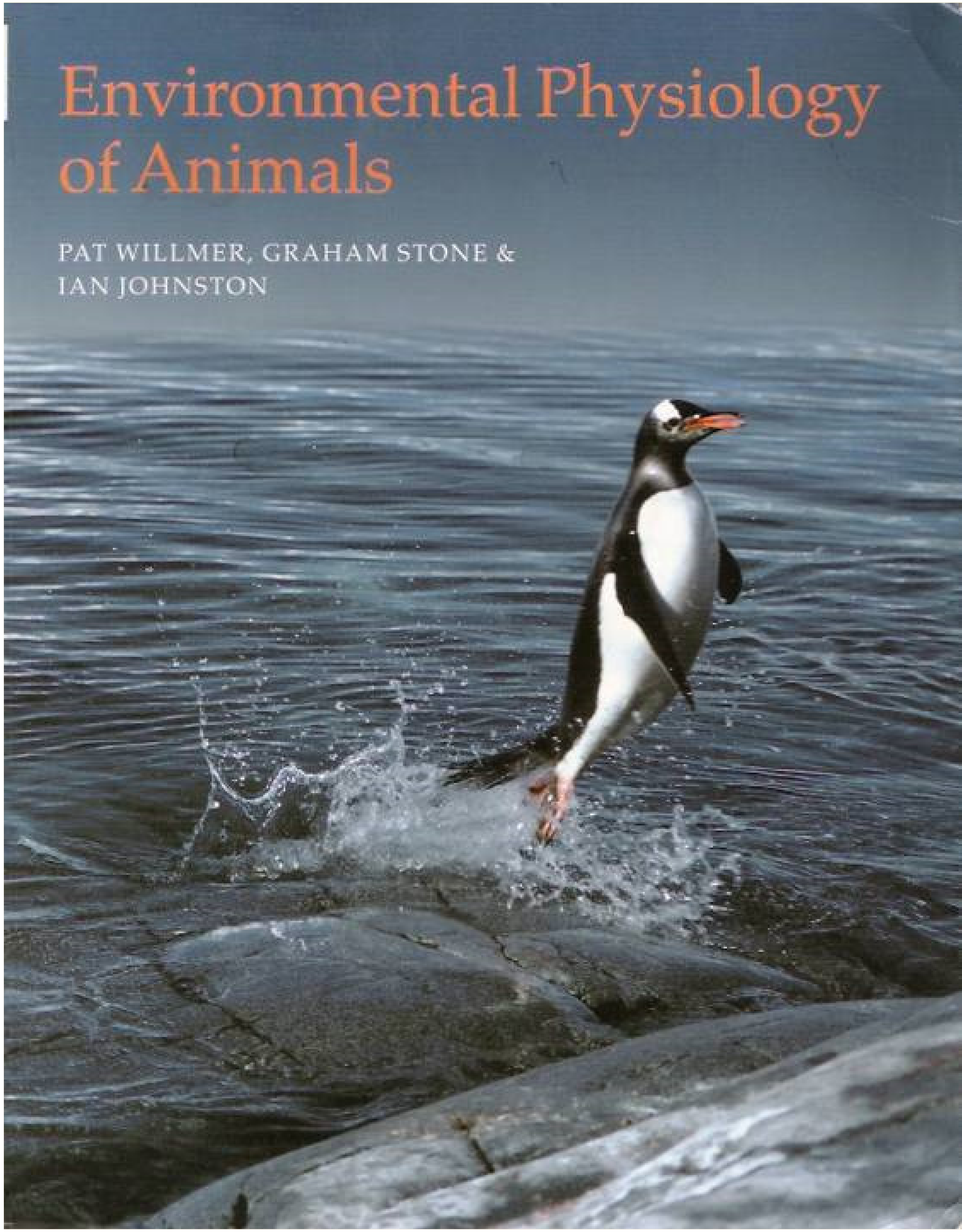


K. Schmidt-Nielsen:

Animal physiology. Adaptation to environment

Polish edition III, PWN 2008 (original Vth edition).



P. Willmer, G. Stone and I. Johnston:
Environmental Physiology of Animals

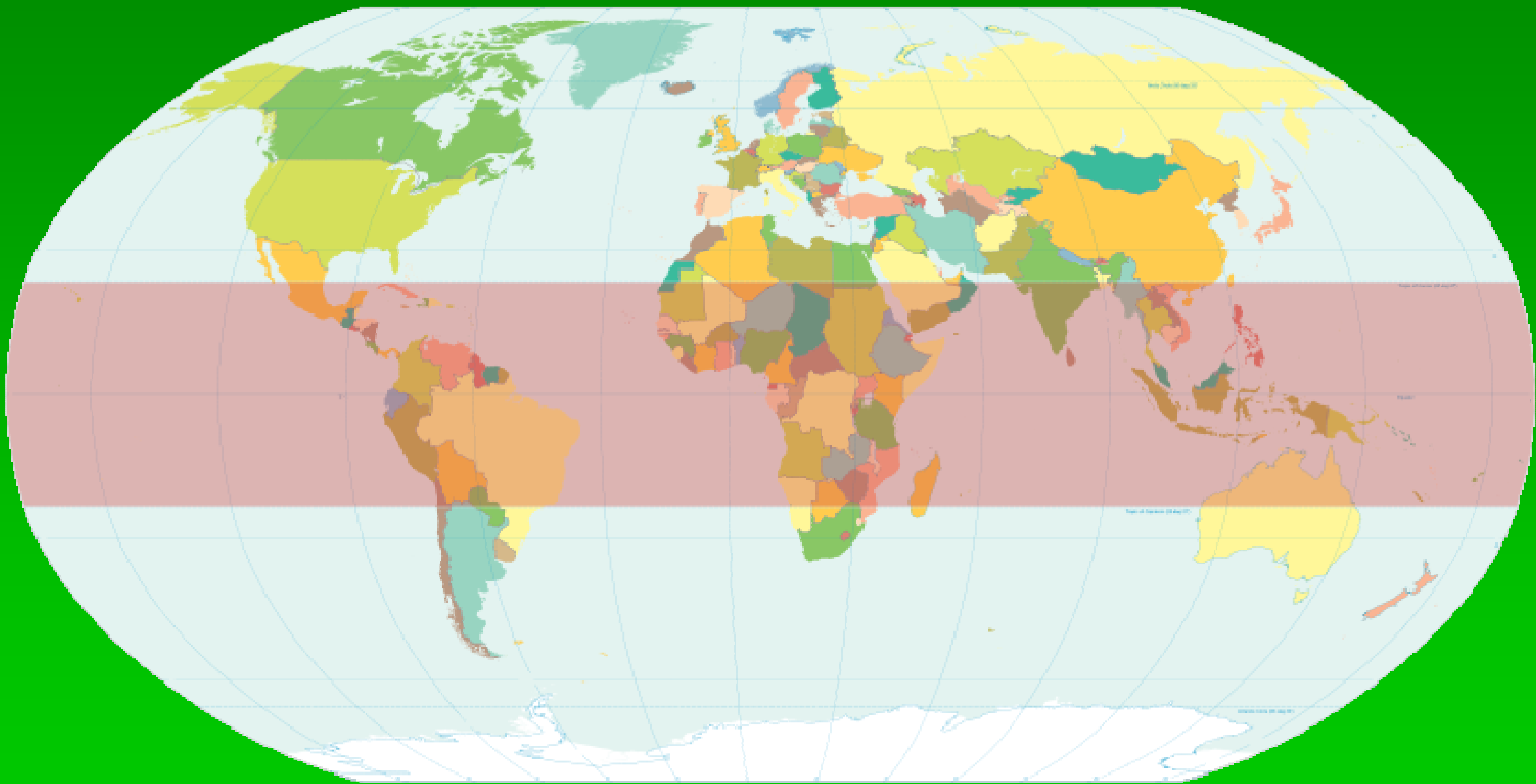
Blackwell Science, 2000

Plan of the lecture

- What are deserts and how do they form?
- Coping with high temperature
- Coping with low water availability
- Coping with low and unpredictable food availability

Where are the tropics?

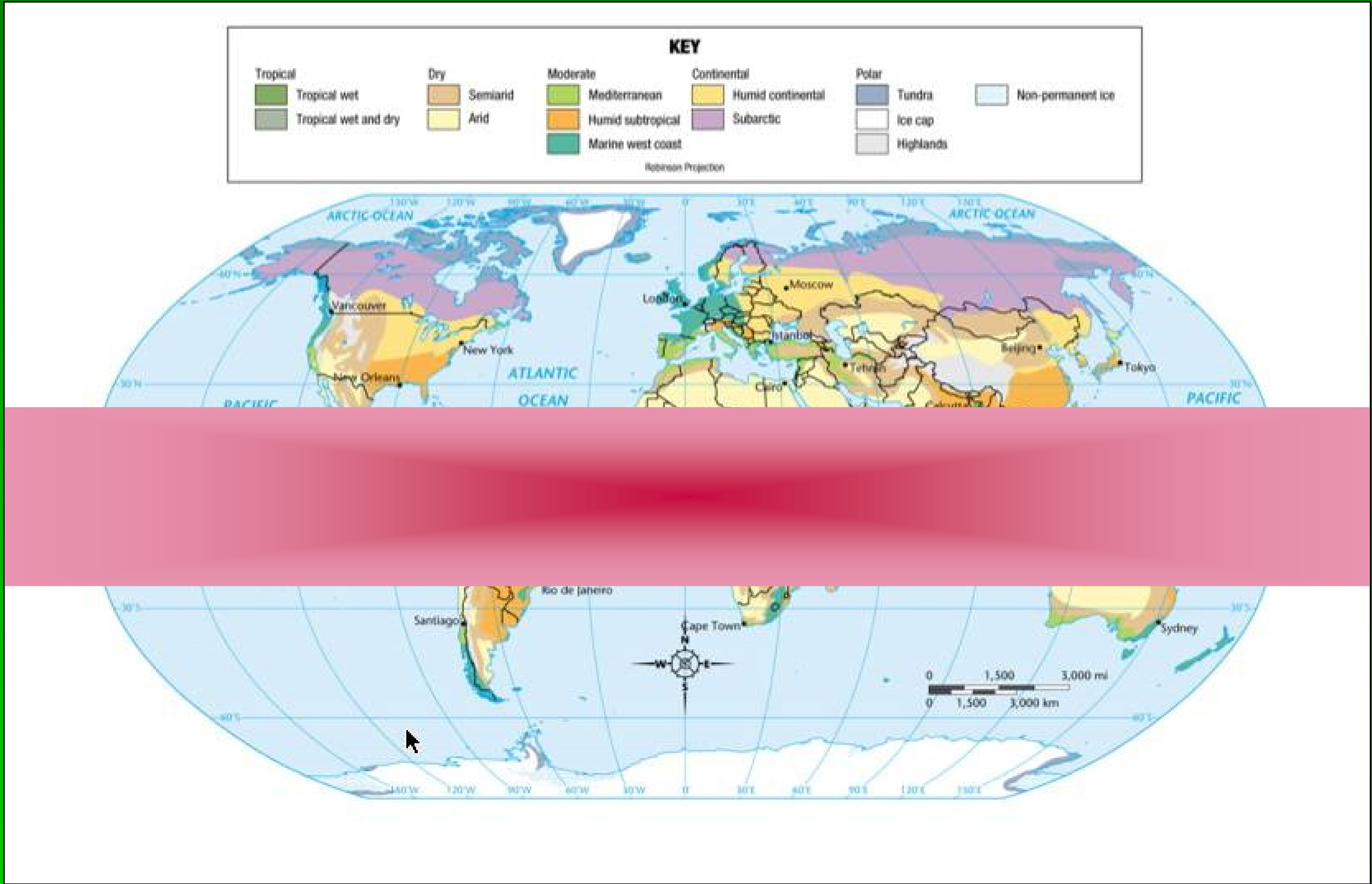
The area between
the Tropic of Cancer and the Tropic of Capricorn



from the lecture of Professor R. Laskowski

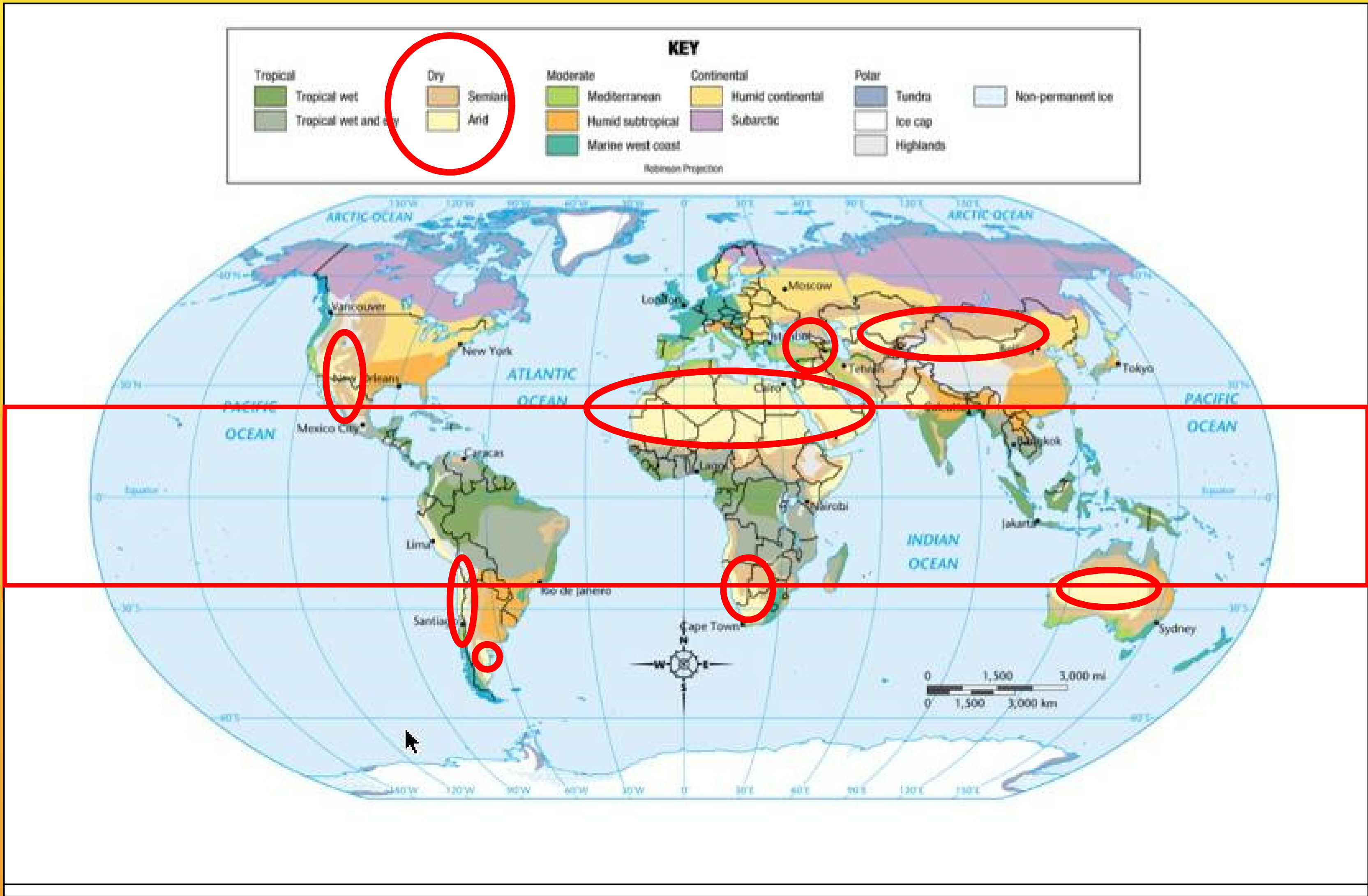
Tropics and types of climate

according to Wladimir Köppen

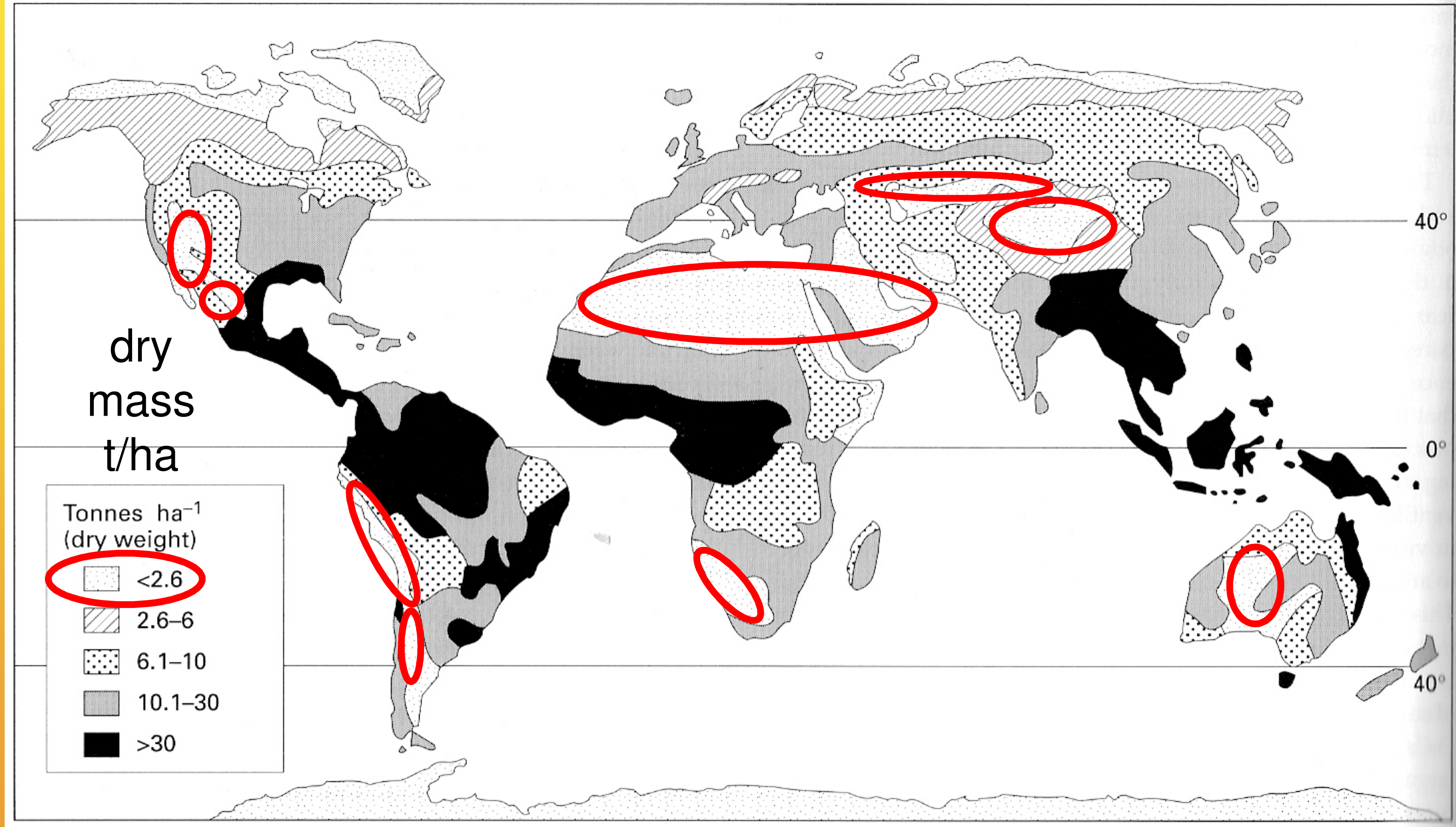


from the lecture of Professor R. Laskowski

Areas of arid and semi-arid climate: deserts, semi-deserts, dry grasslands



"Trophic" deserts:
areas of low primary production



Willmer et al. 2000

"Trophic" deserts:
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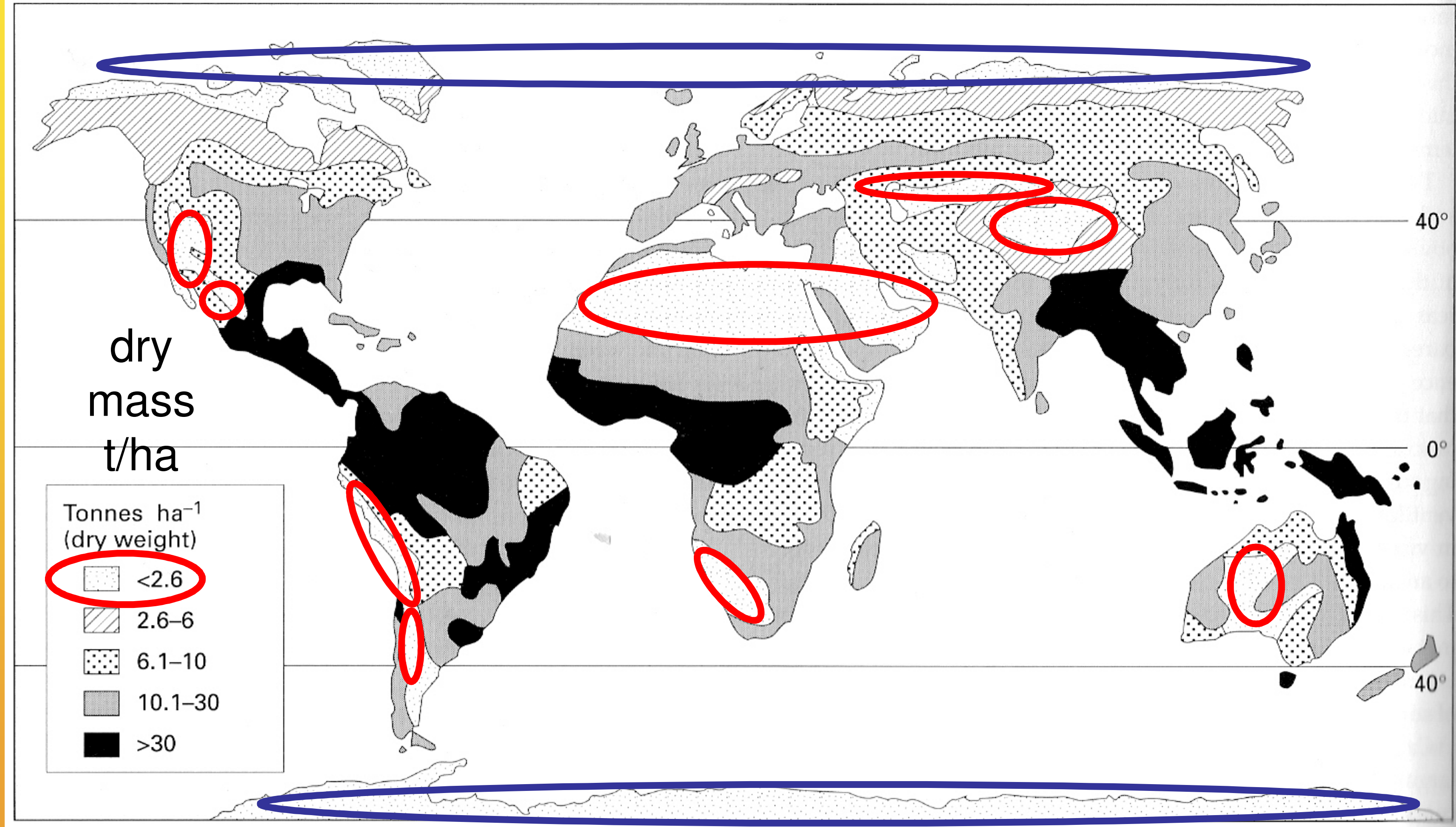

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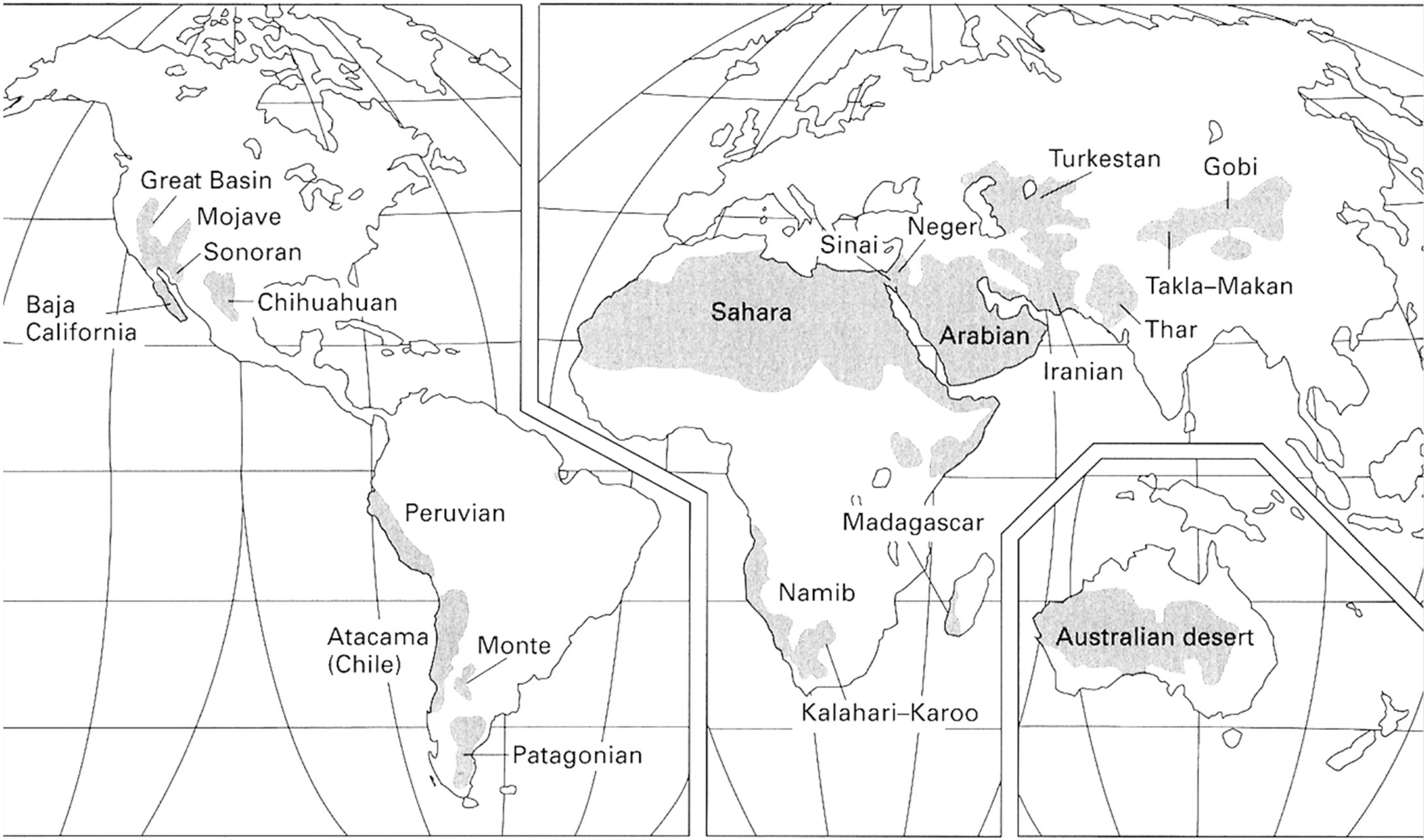
Characteristics of deserts

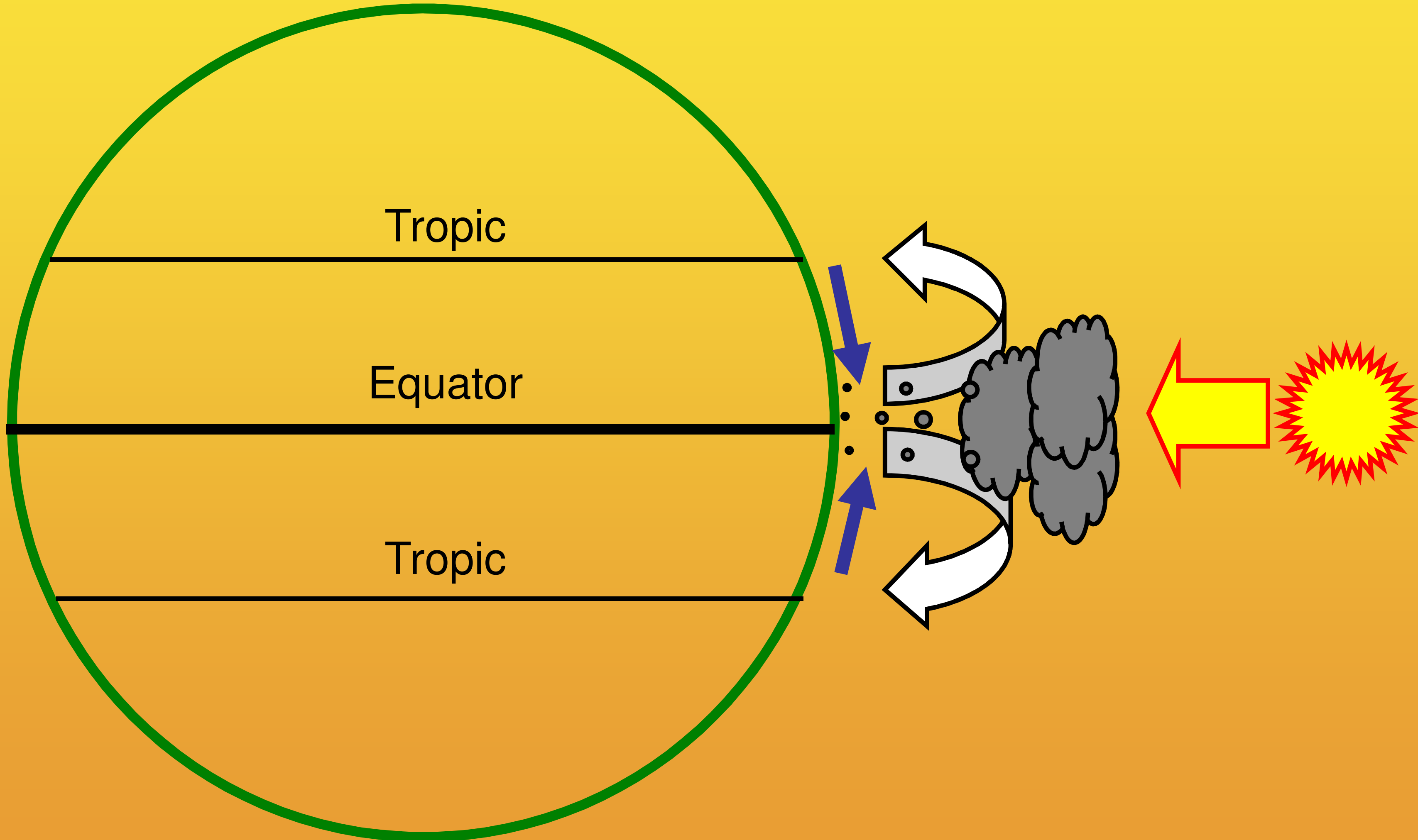
- Low primary production: low food abundance
- Low water availability
- In tropical and subtropical zone: high temperature
- High daily amplitude of temperature
- Unpredictability of resource (food and water) availability

Main deserts

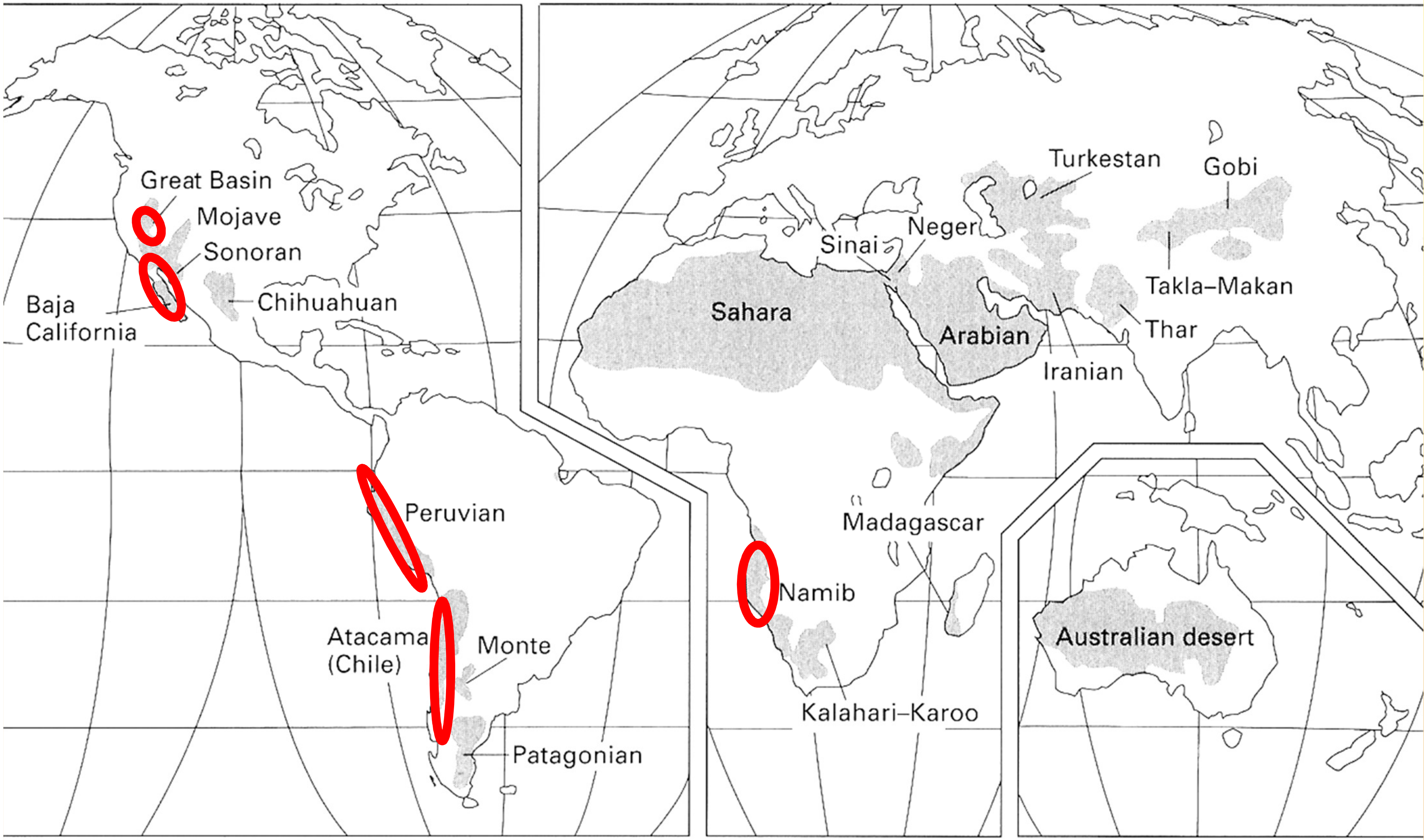


Willmer et al. 2000

Mechanism of formation of a tropical-zone desert

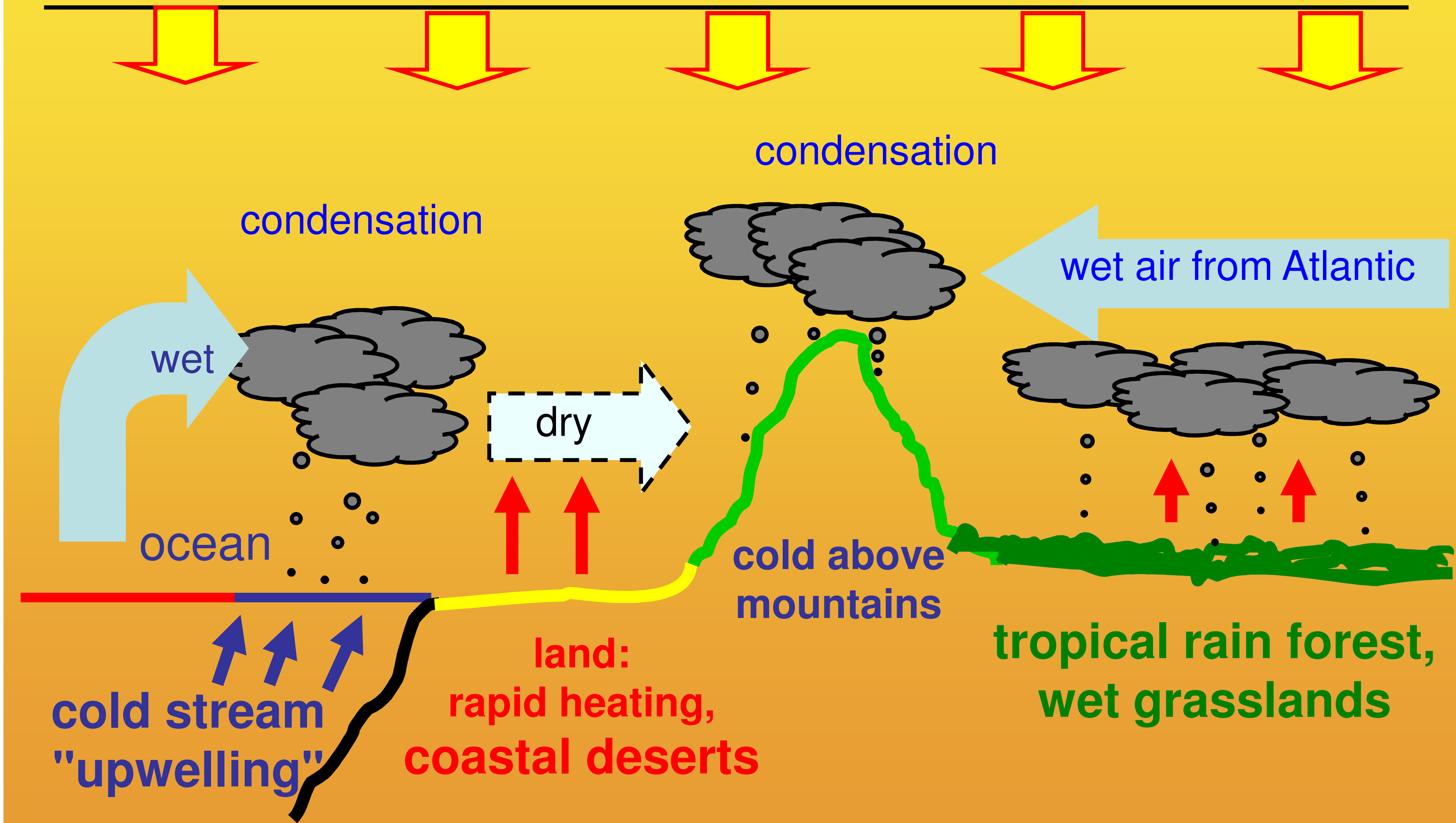


Main deserts

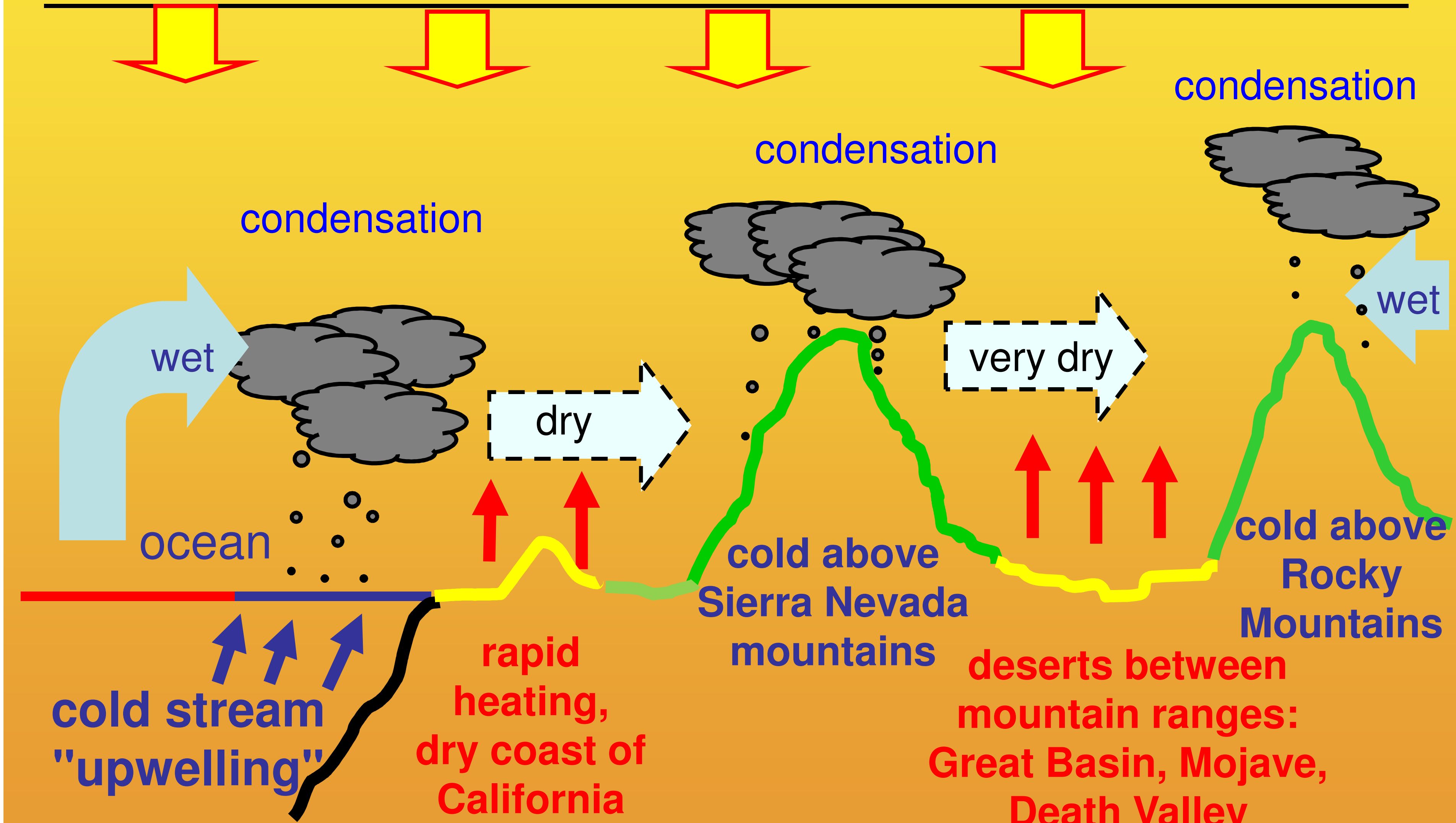


Willmer et al. 2000

Mechanism of formation of a coastal desert: Peruvian, North part of Chilean (Atacama)



Mechanism of formation of a coastal and interior deserts in California and Nevada



Characteristics of deserts: challenges

- Low primary production: low food abundance
- Low water availability
- In tropical and subtropical zone: high temperature
- High daily amplitude of temperature
- Unpredictability of resource (food and water) availability

Coping with high temperature

EFECTS of TEMPERATURE

- Effects of body temperature on the rate of metabolism
- Thermal balance
- Effect of ambient temperature on the rate of metabolism in homeotherms
- Thermal conditions on deserts

Thermodynamics: rate of processes
kinetics of chemical reactions, effects of temperature

- **Arrhenius equation (form 1)**

$$k = k_{max} e^{(-\mu/RT)}$$

k_{max} - maximum reaction constant
(when each collision of molecules results in a reaction)

μ - energy of activation

$e^{(-\mu/RT)}$ - proportion of molecules that have energy exceeding μ

Thermodynamics: rate of processes
kinetics of chemical reactions, effects of temperature

- **Arrhenius equation (form 2)**

$$k_{\mathrm{T2}} = k_{\mathrm{T1}} e^{\frac{\mu}{R(T_2 - T_1)/T_2 T_1}}$$

k_{T1}, k_{T2} - reaction constants at temperatures T_1 and T_2

Thermodynamics: rate of processes
kinetics of chemical reactions, effects of temperature

- **A simplified relation, the rule of van't Hoff:**

A 10C increase of temperature results in a 2-4-fold increase of the rate of a process

$$Q_{10} = V_{(t+10)} / V_t = (V_{t2}/V_{t1})^{10/(t2 - t1)}$$

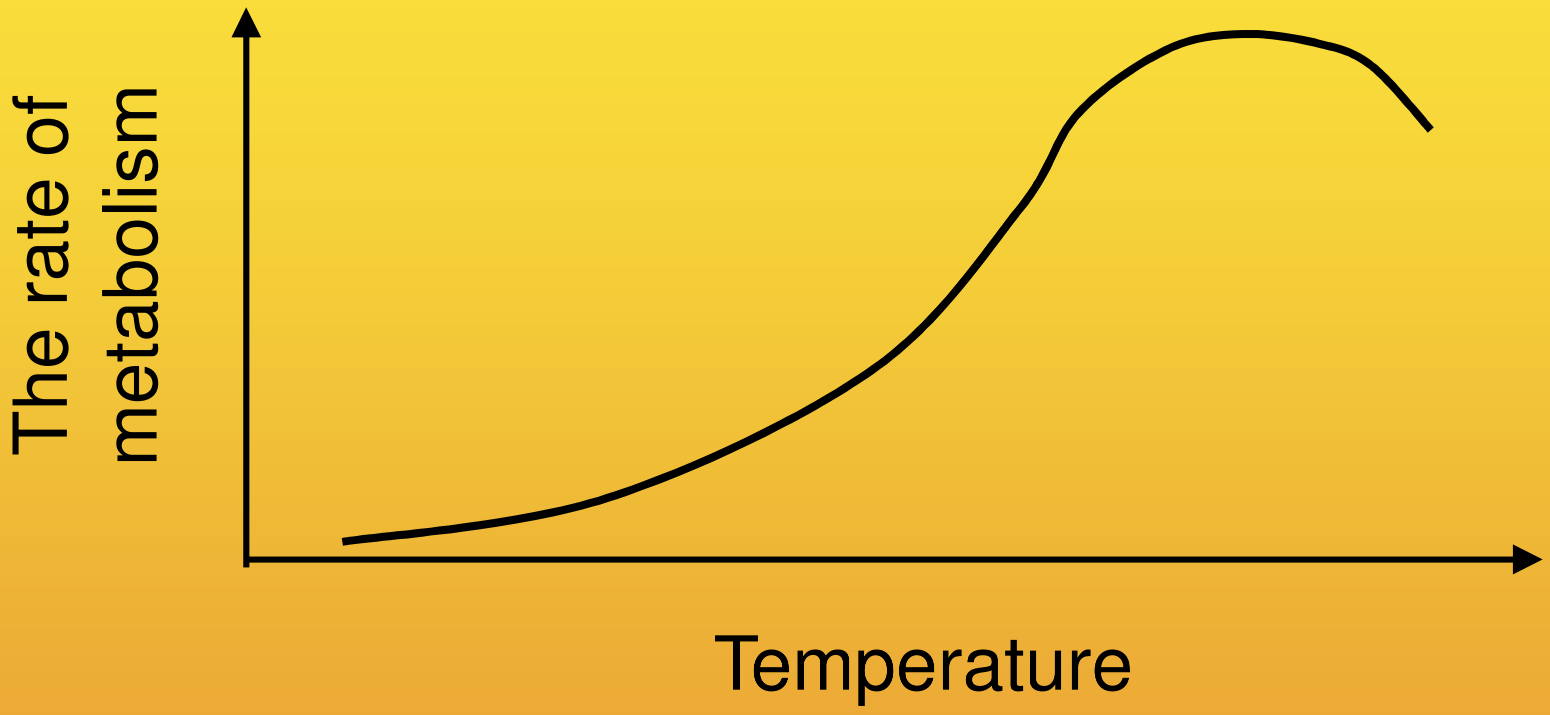
$$V_{t2} = V_{t1} Q_{10}^{(t2-t1)/10}$$

t, t1, t2 - temperature;

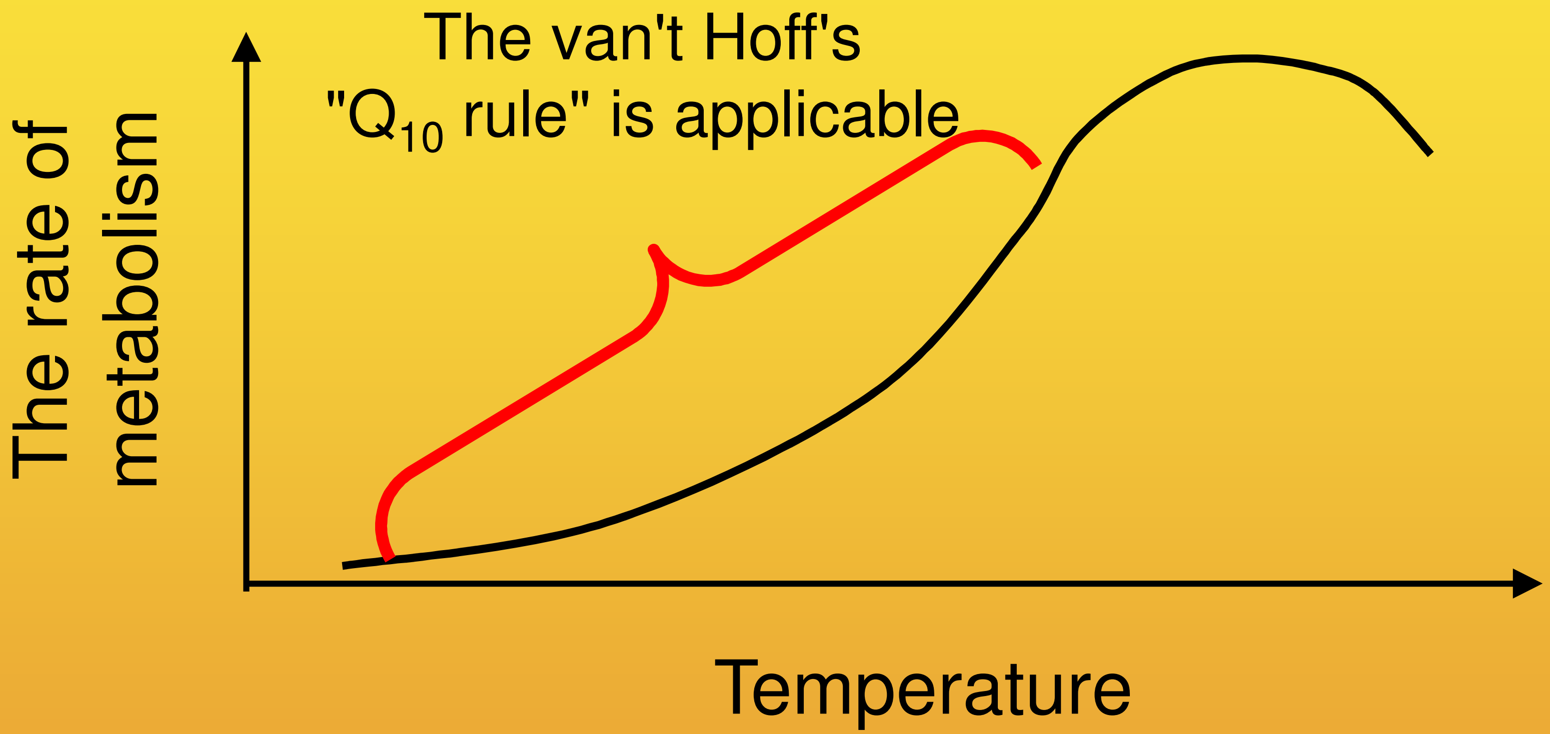
V - rate of a process at temperature *t*

Q_{10} - an empirically determined coefficient (NOT a physical constant)

Rate of biochemical processes:
combined effects of temperature



Rate of biochemical processes:
combined effects of temperature



Rate of biochemical processes:
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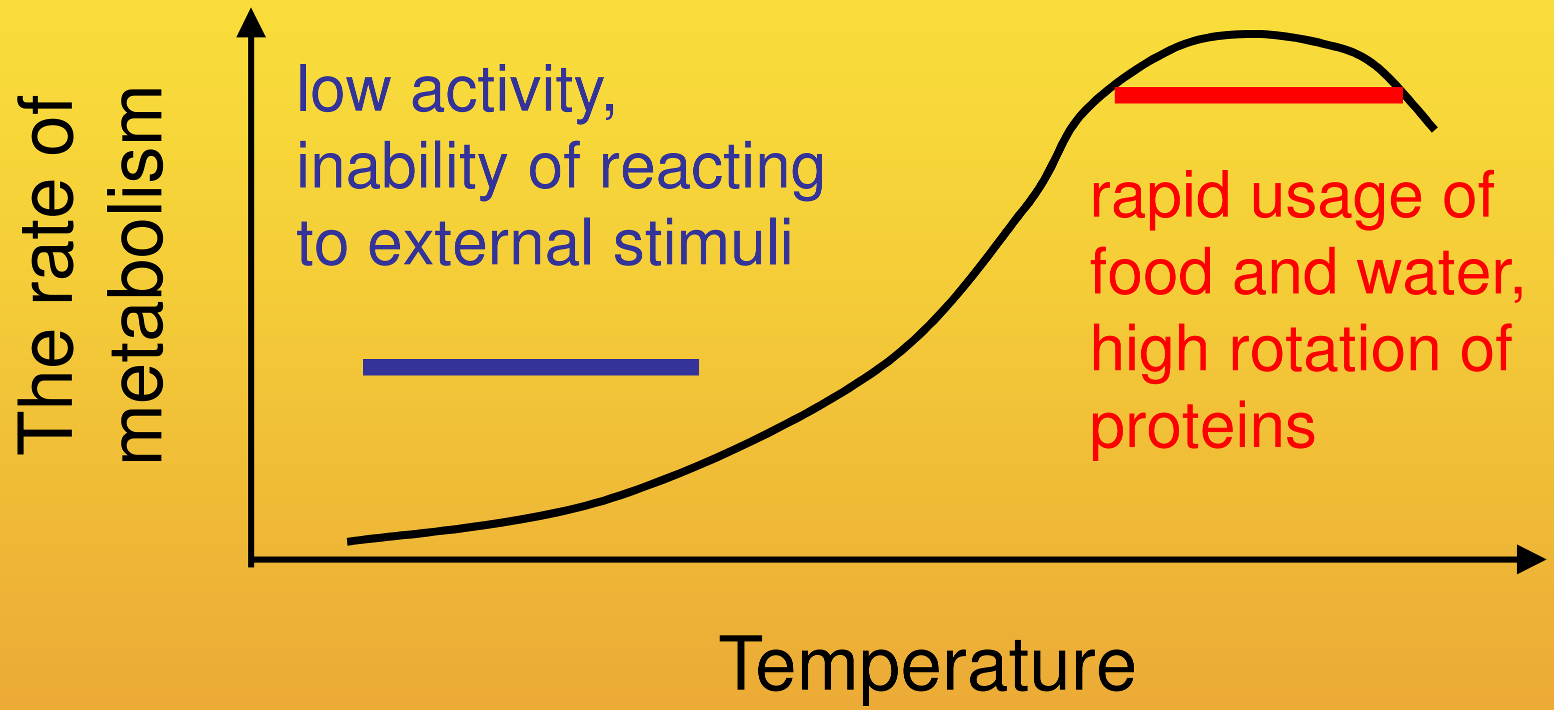
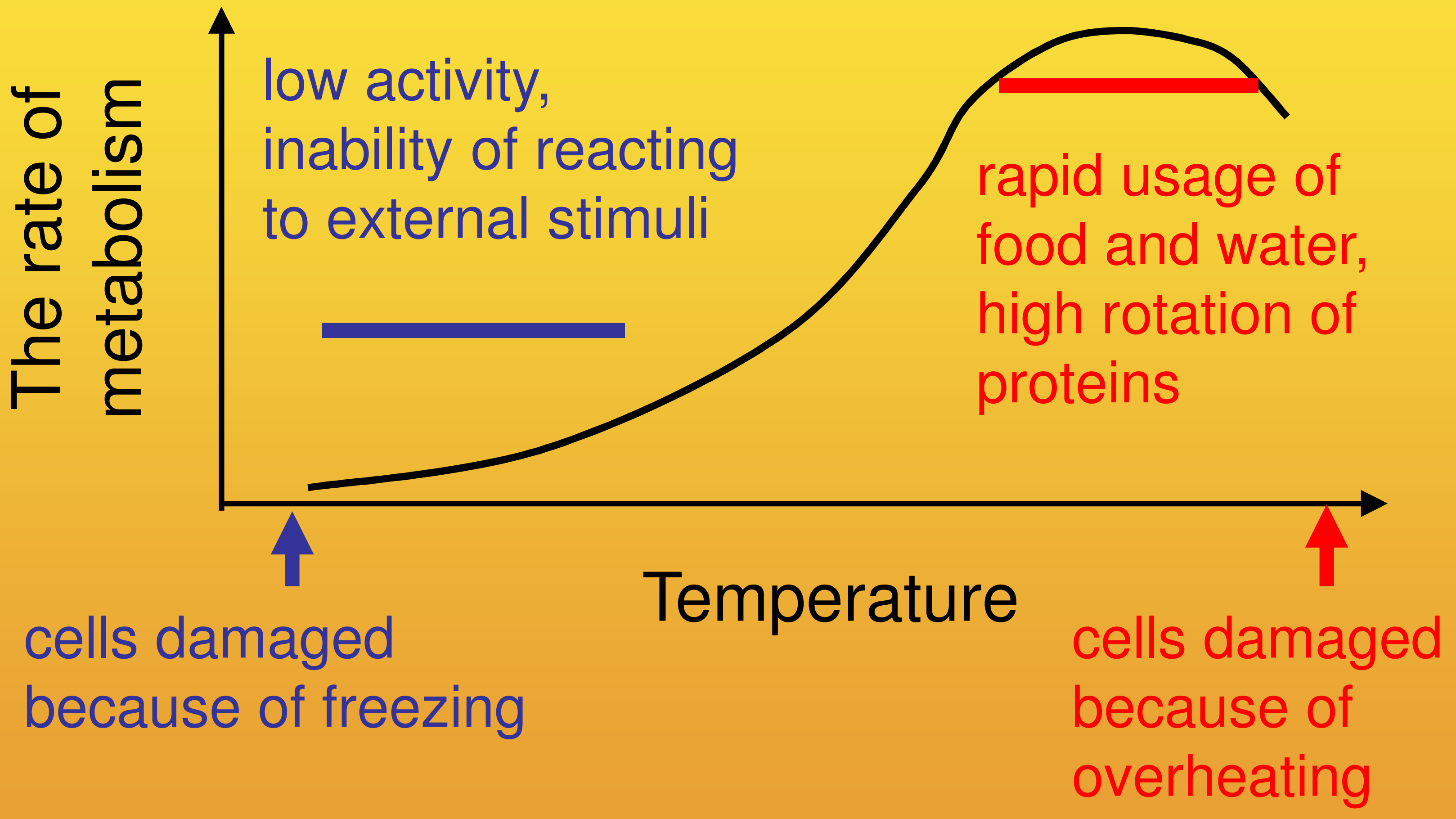
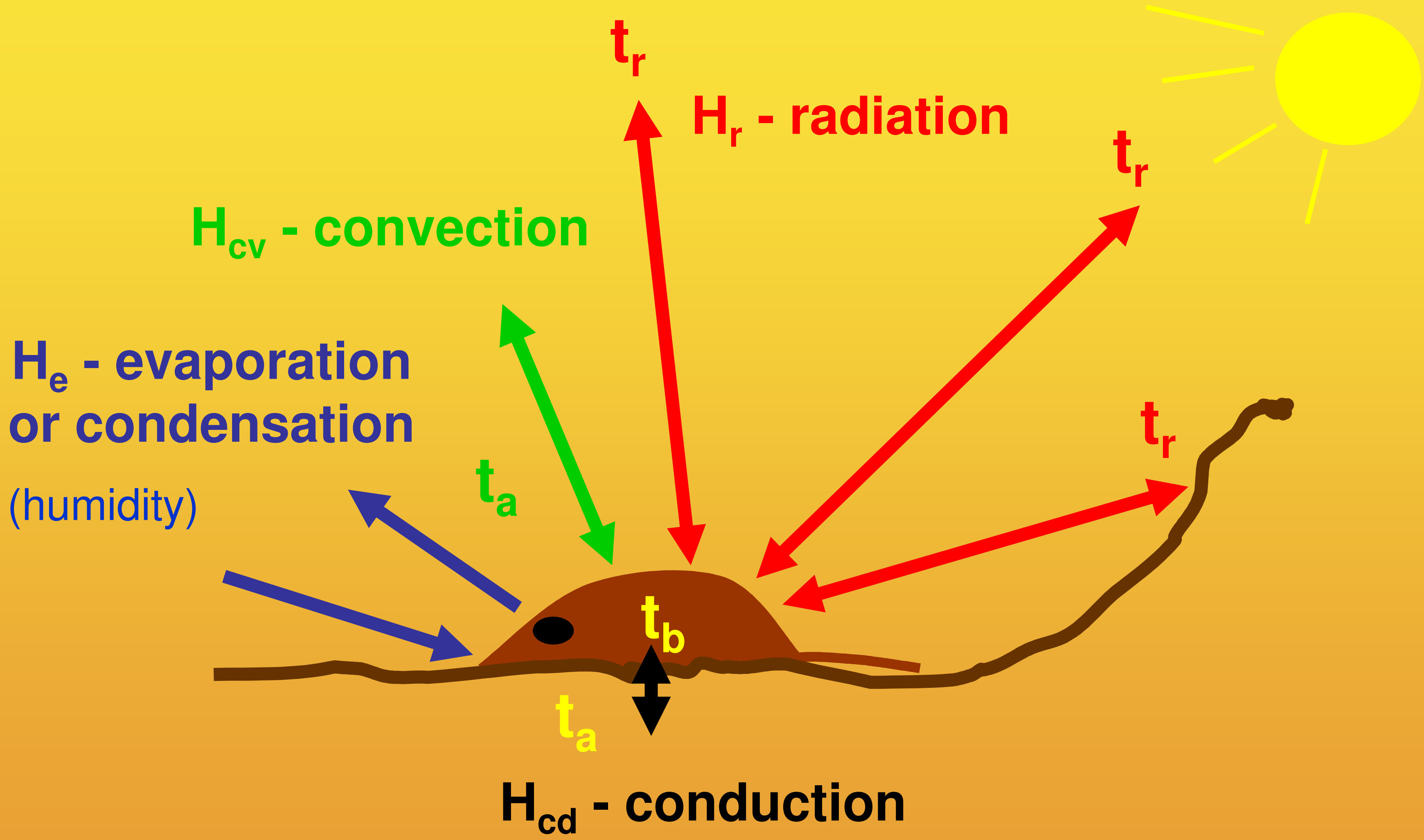


Rate of biochemical processes: combined effects of temperature



Components of heat balance



Components of heat balance

H_{cd} : conduction
H_{cv} : convection
H_r : radiation
H_e : evaporation

$\left.\right\}$ $H \approx c(T_b - T_a)$

$H_e \approx f(T_b, T_a, W\%)$

H_a : accumulation of heat = $\Delta t_b \times M_b \times q$
Q : metabolic heat production

$$H_a = \pm H_{cd} \pm H_{cv} \pm H_r \pm H_e + Q$$

Components of heat balance under a strict homeothermia (Δt_b=0)

H_{cd} : conduction
H_{cv} : convection
H_r : radiation
H_e : evaporation

$\left.\begin{array}{l} H_{cd} \\ H_{cv} \\ H_r \end{array}\right\} H \approx c(T_b - T_a)$

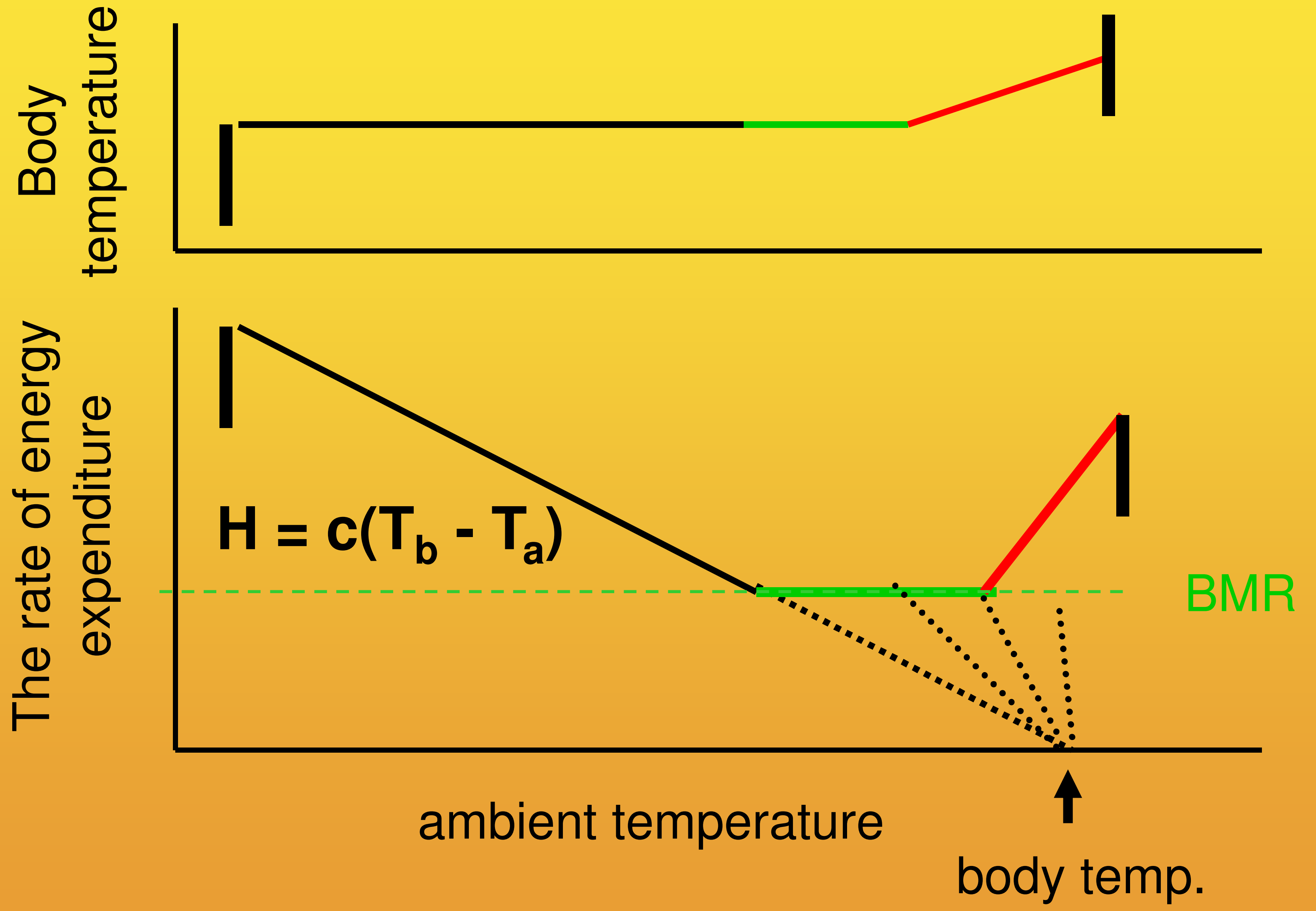
$H_e \approx f(T_b, T_a, W\%)$

H_a : accumulation of heat = $\Delta t_b \times M_b \times q = 0$

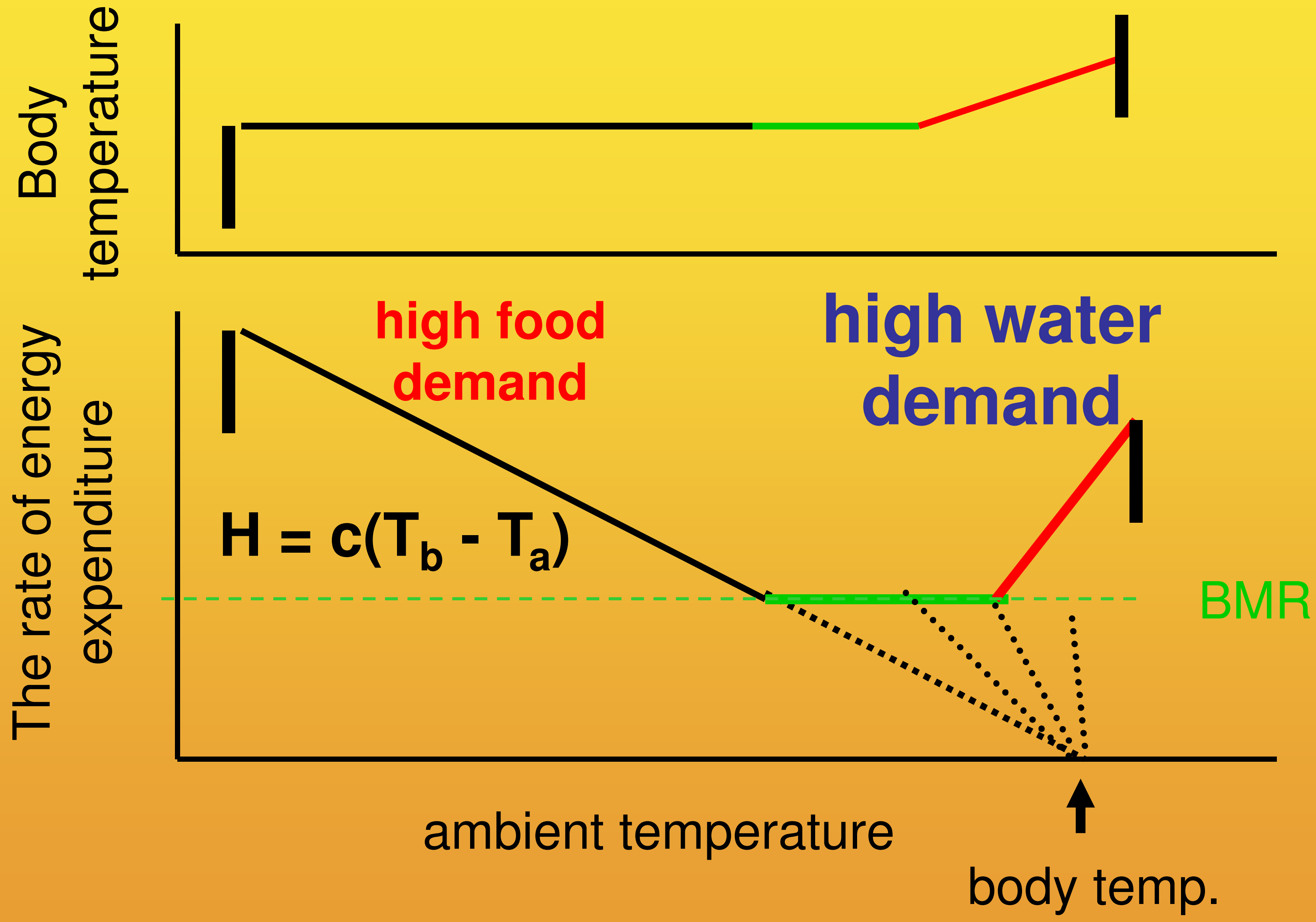
Q : metabolic heat production

$$Q = \pm H_{cd} \pm H_{cv} \pm H_r \pm H_e$$

A simplified model of thermoregulation

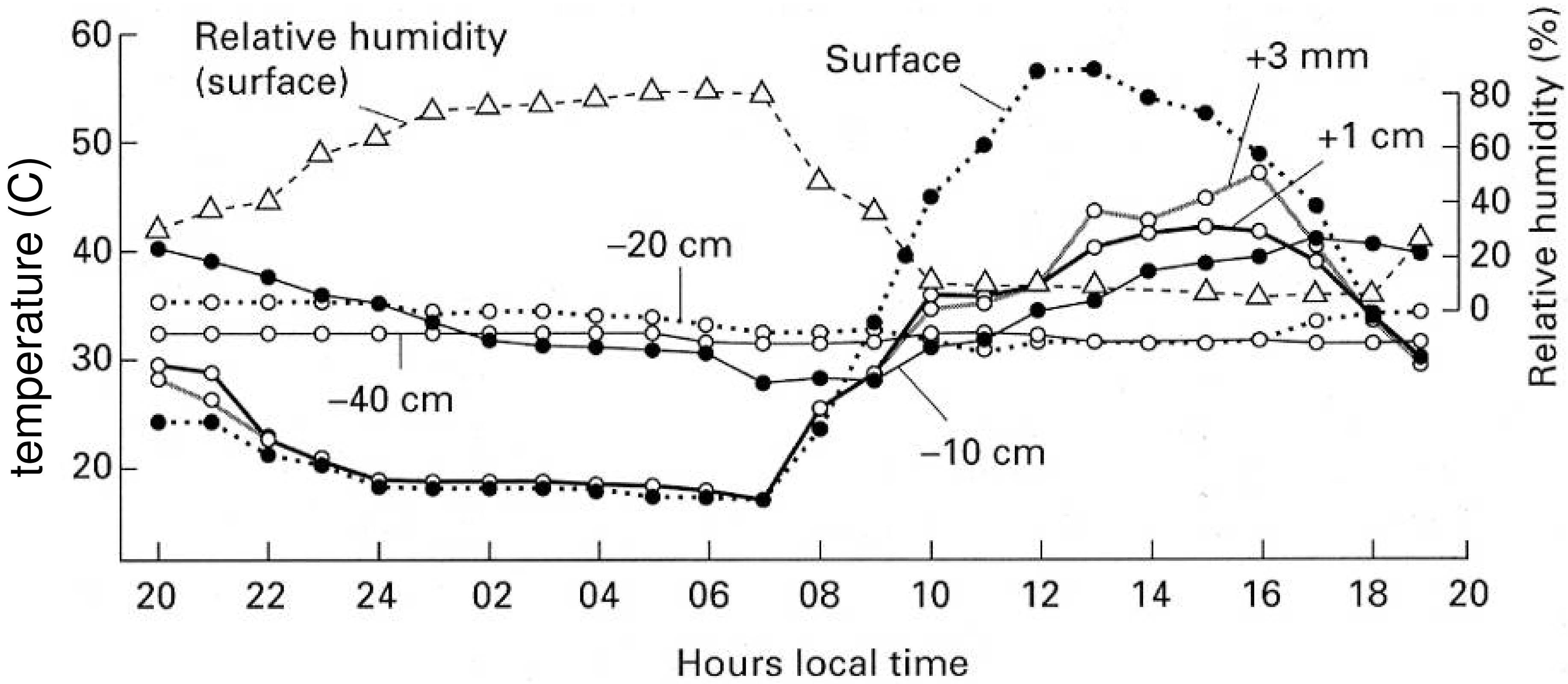


A simplified model of thermoregulation



Thermal conditions on a hot desert

Daily cycle of temperature and humidity



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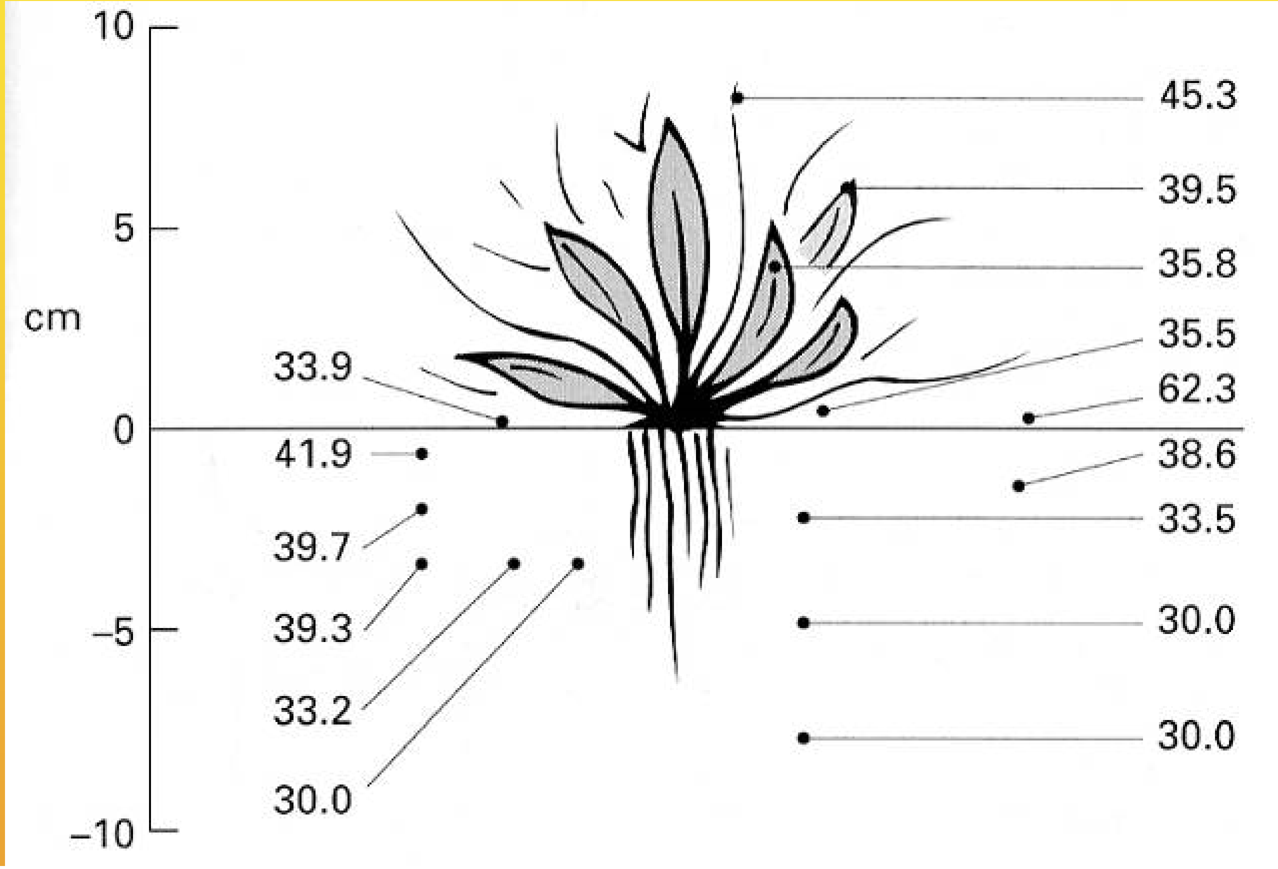
Thermal conditions on a hot desert

Temperature near a clump of a plant



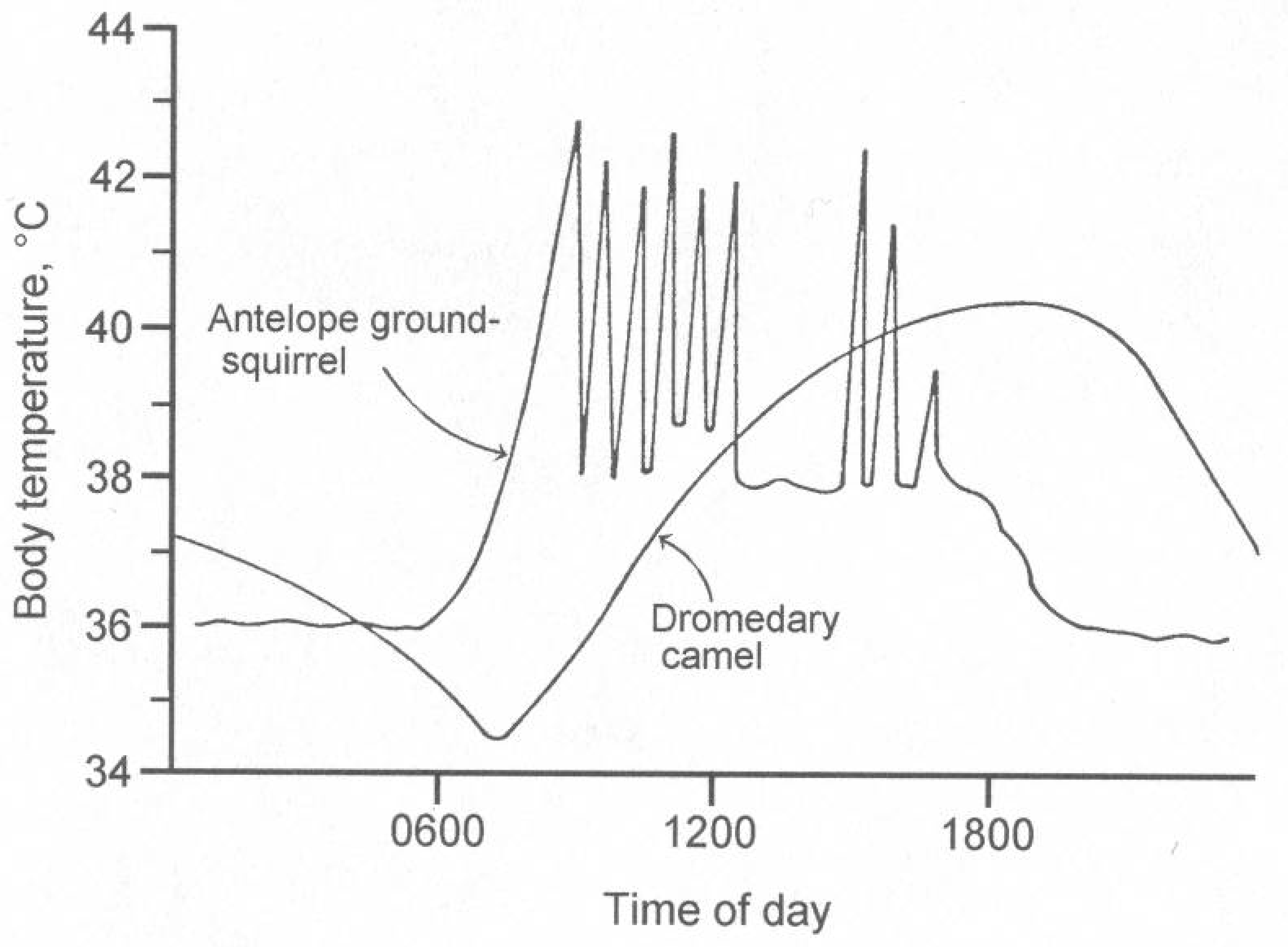
Microclimate experienced by small beetles in, under, and near a desert shrub

Willmer et al. 2000

Main strategies

- **"Endurers"** - large body mass,
  - thermal inertia;
- **"Evaporators"** - intermediate mass,
  - leave on desert edges,
  - daily migrations;
- **"Evaders"** - small body mass
  - escape to suitable microhabitats

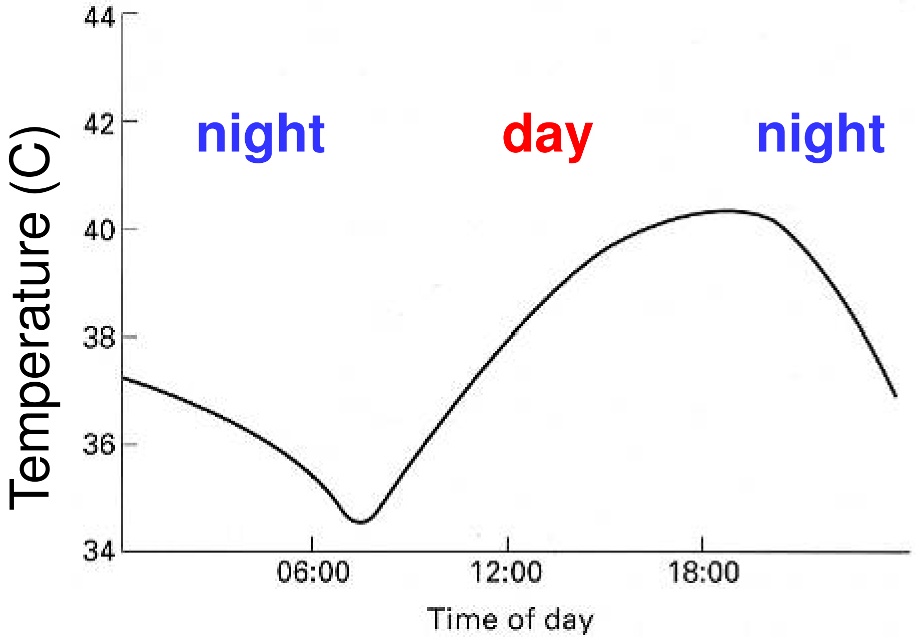
Comparison of distinct strategies



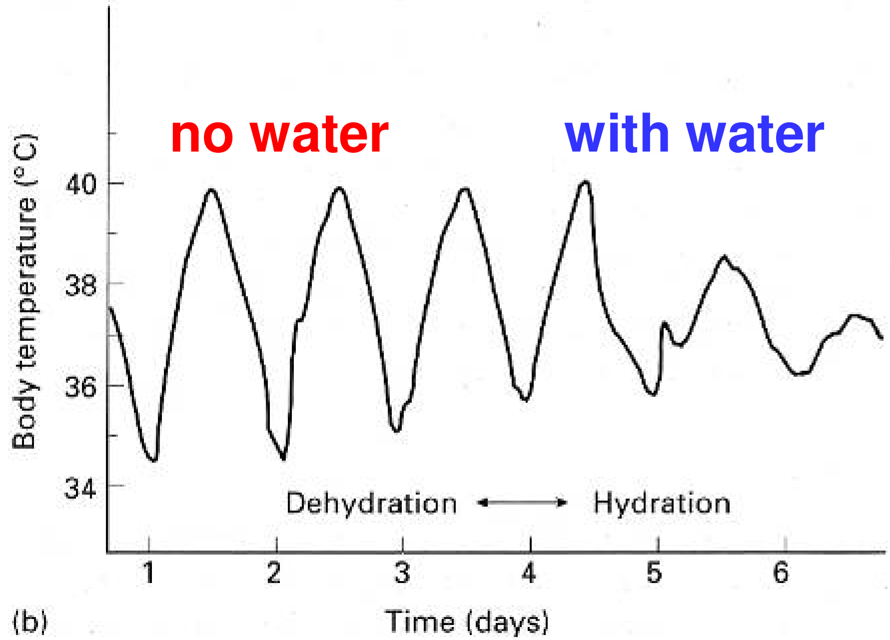
Schmidt-NIelsen, Animal Physiology

The strategy of an "inertial endurer"

Changes of body temperature in a dromedary camel



Time (within one day)



Time (a few subsequent days)

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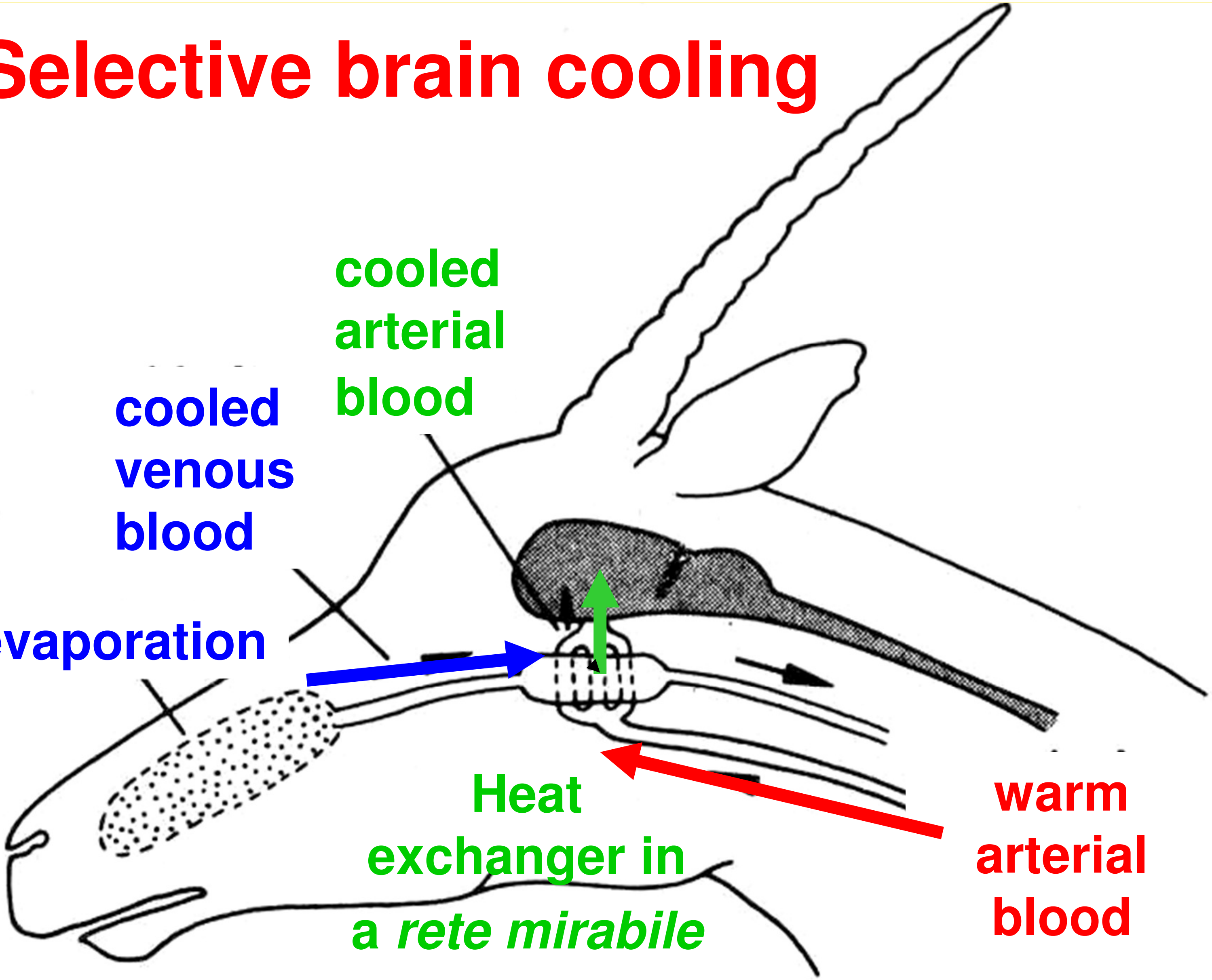
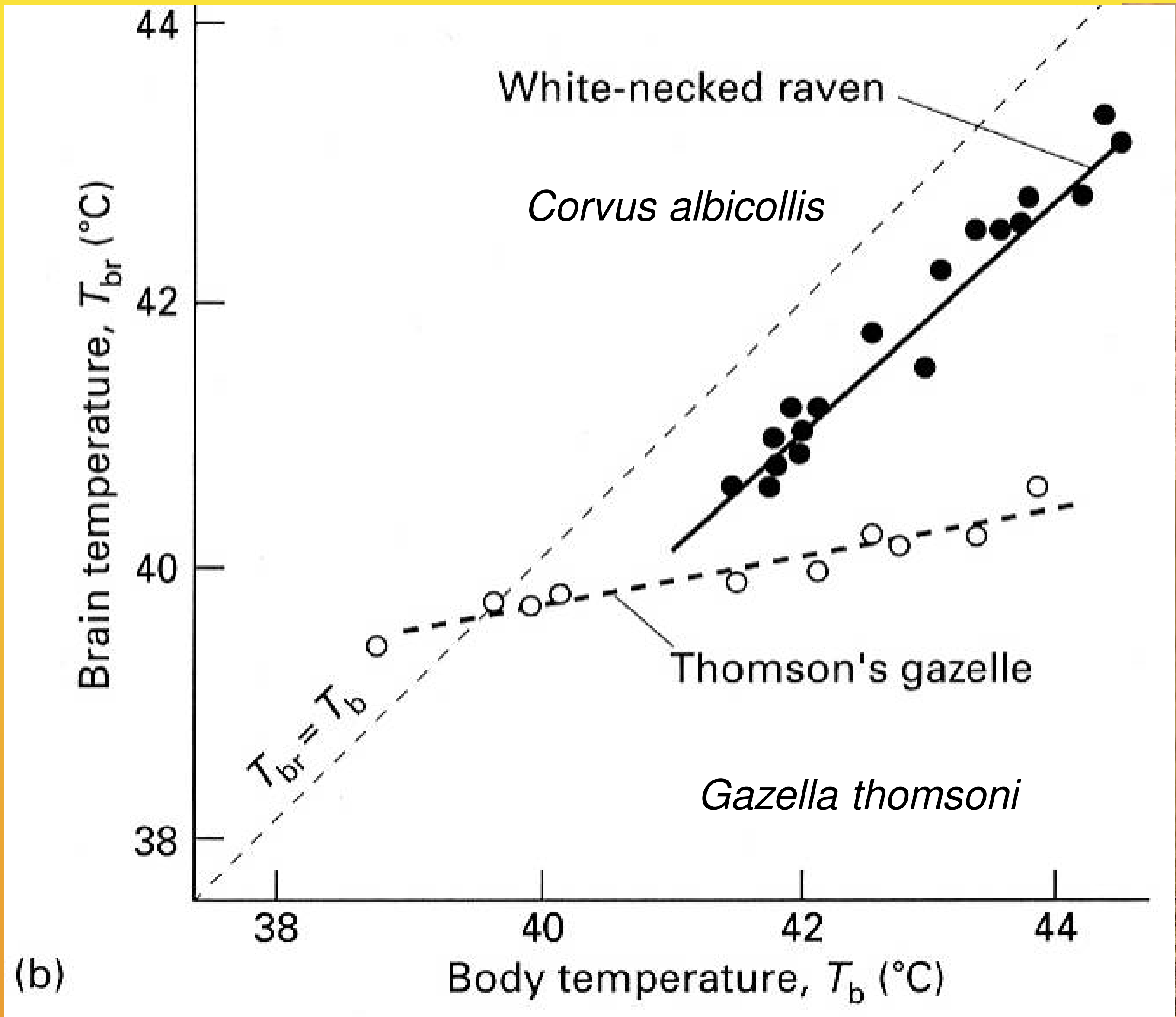
Selective brain cooling



Schmidt-NIelsen 2008 Animal Physiology

Selective brain cooling

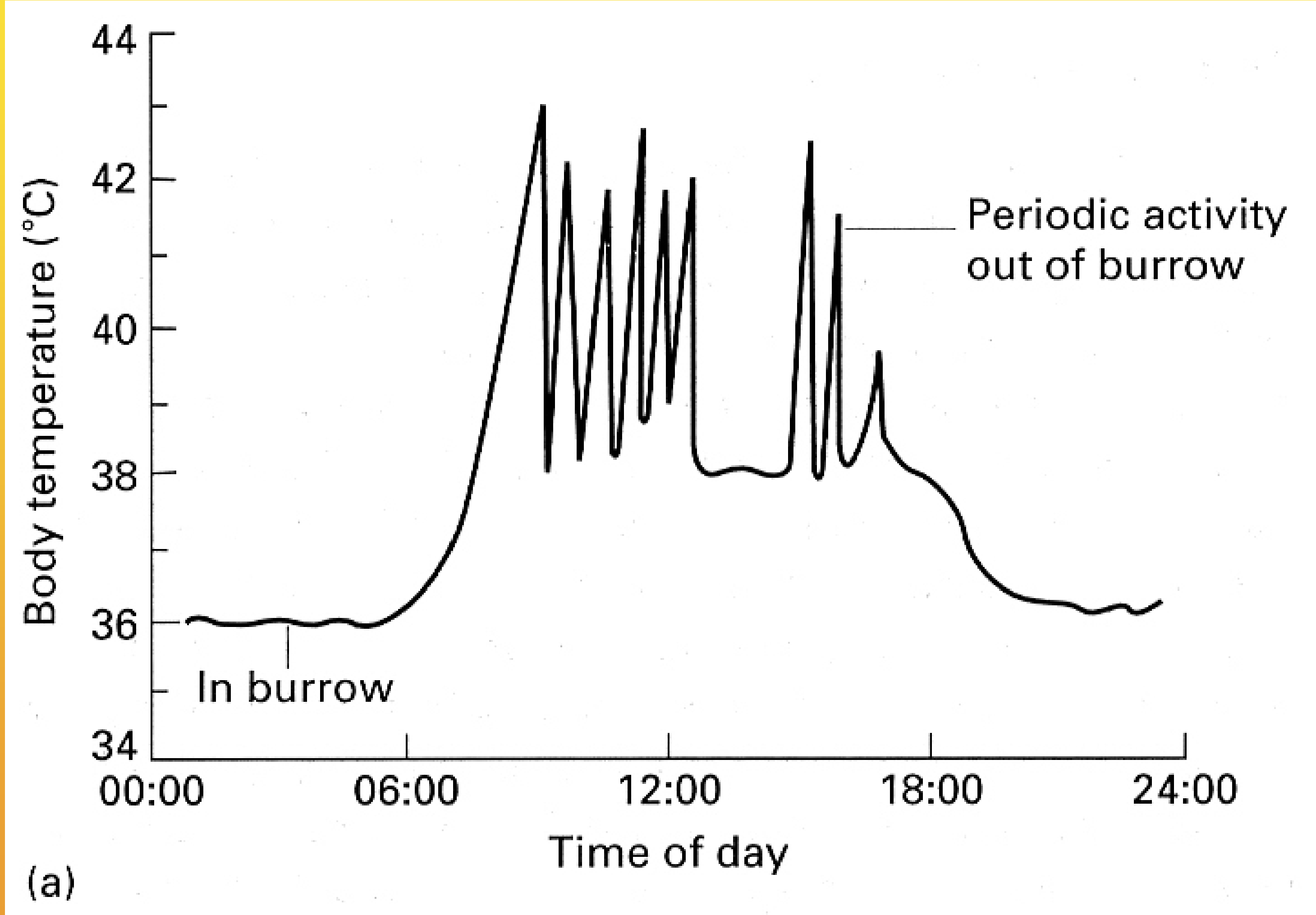


photos: Wikipedia

Willmer et al. 2000

Escape underground...

Body temperature in a rodent: the antelope ground squirrel



Willmer et al. 2000

Escape underground...

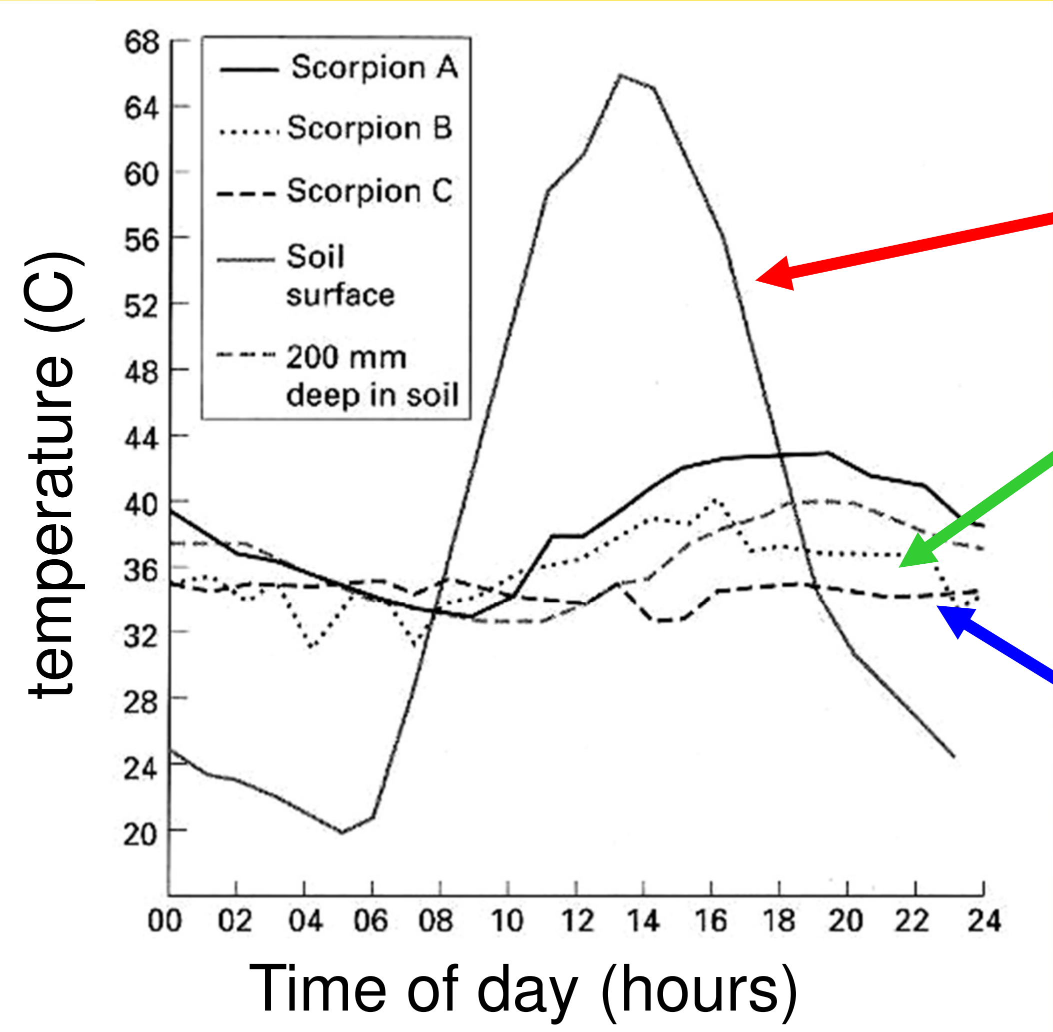


Fig. 14.5 Temperatures in the burrow of the scorpion *Hadrurus*, compared with temperatures at the soil surface and at a depth of 200 mm. (Adapted from Hadley 1970.)

Temperature:

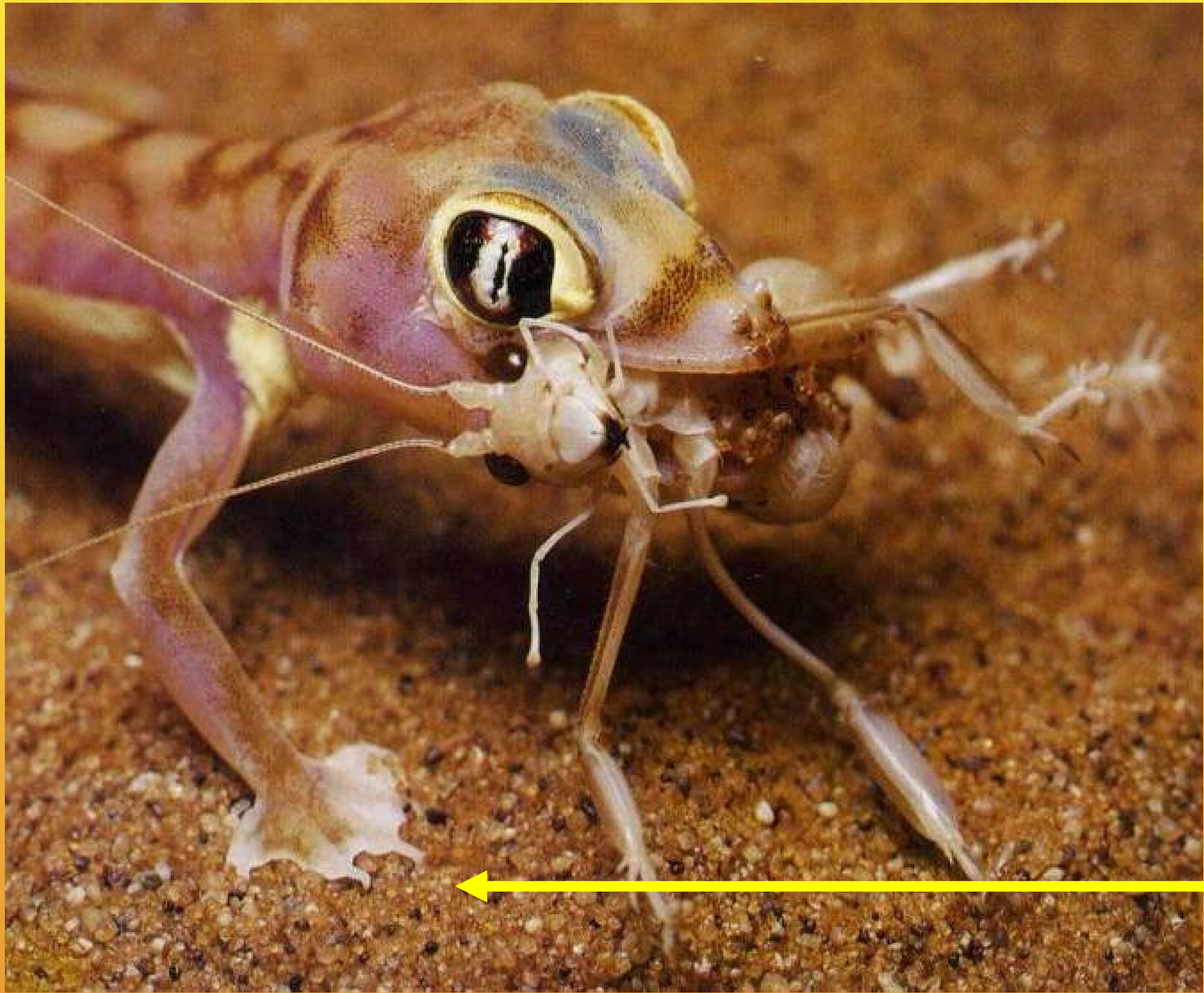
- **soil surface**
- **in burrows of scorpions *Hadrurus sp.* (3 individuals)**
- **20cm deep in soil**

Willmer et al. 2000

Escape underground...

photo: Anthony Bunnister/NHPA; copied from: *Encyklopedia zwierząt gady i płazy*; ELIPSA, Warszawa 1993

Escape underground...



A lizard:
gecko
Palmatogecko rangei

South Africa, Namib Desert

food adapted for digging in sand

photo: Anthony Bunnister/NHPA; copied from: *Encyklopedia zwierząt gady i płazy*; ELIPSA, Warszawa 1993

Escape underground...

photo: Gunter Deichmann/AUSCAPE Internat.; copied from: *Encyklopedia zwierząt gady i plazy*; ELIPSA, Warszawa 1993

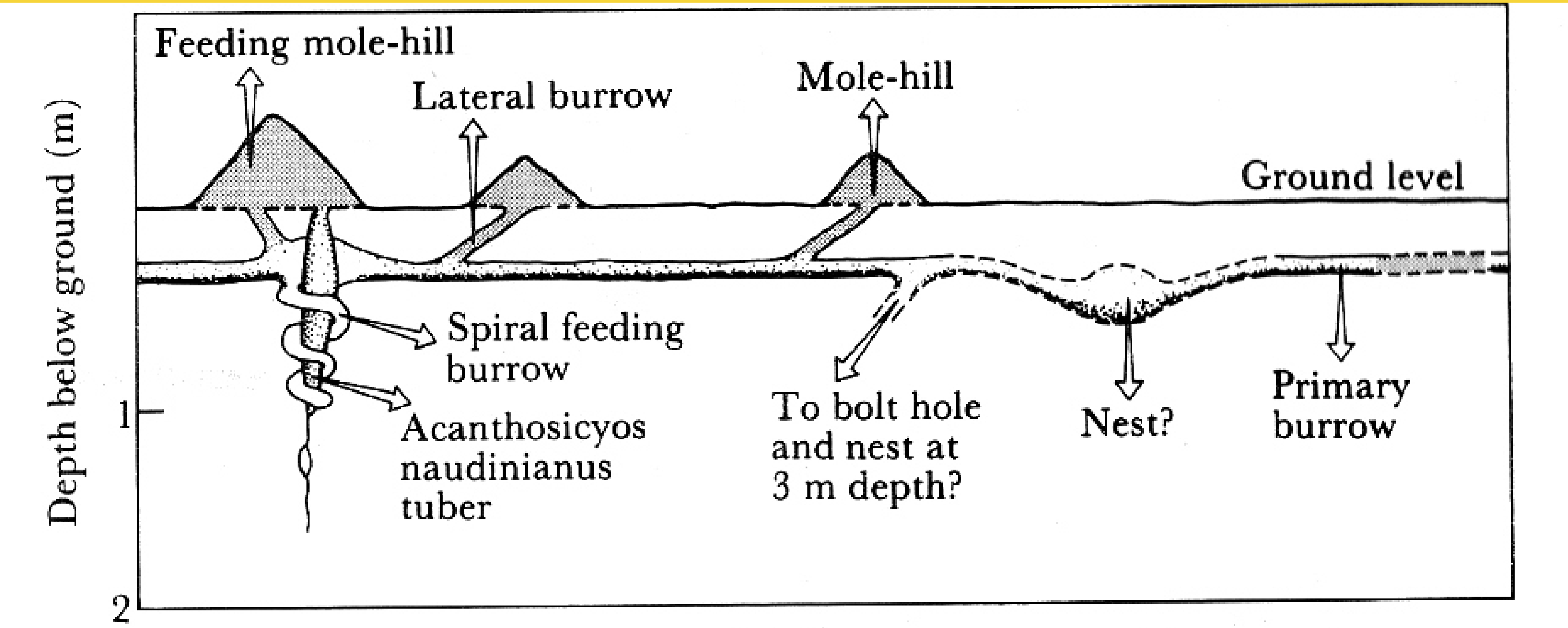
Naked mole rat (in Polish: "golec")

Heterocephalus glaber (Rodentia, Heteromyidae)

Heterocpehalus glaber from www.animalpicturesarchive.com (also on Wikipedia)

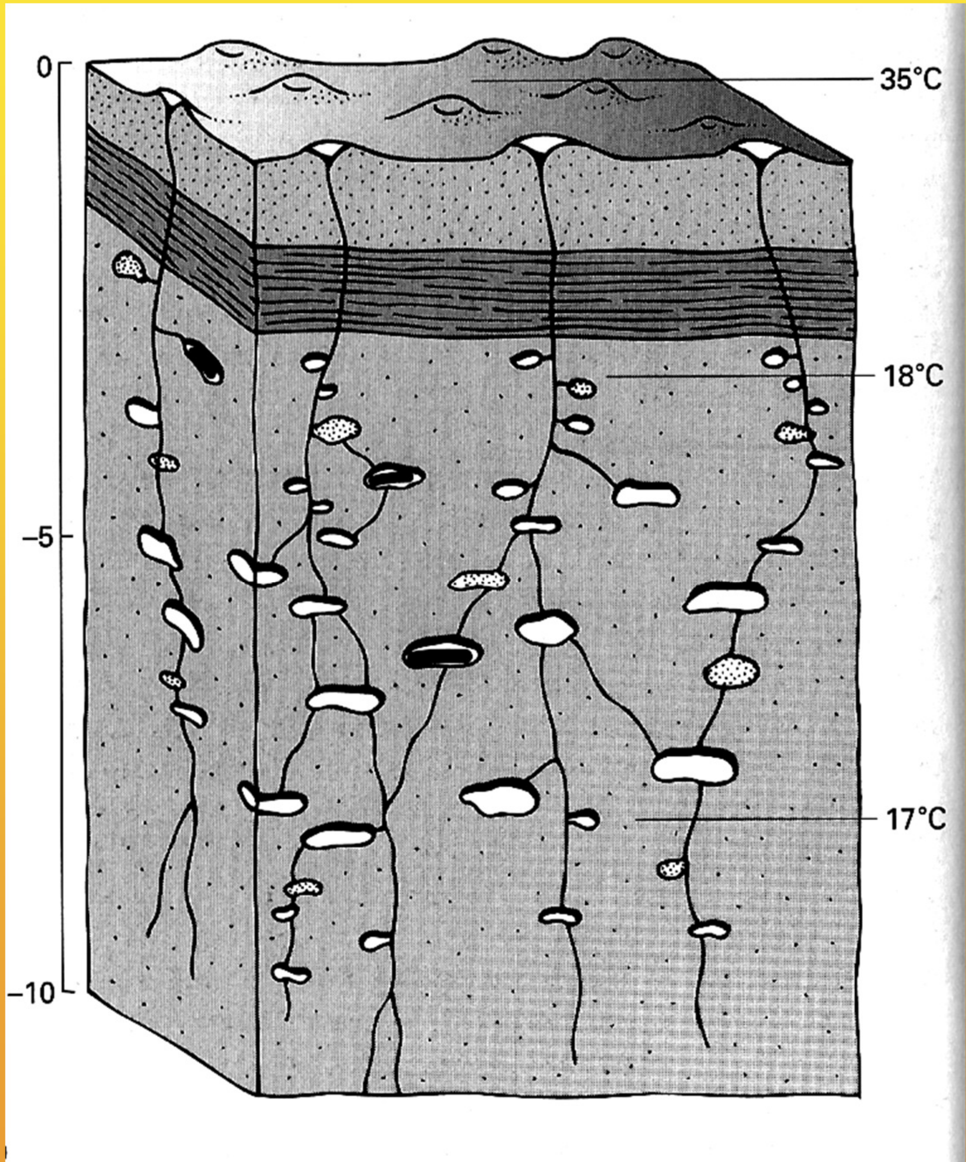
Escape underground...

Burrow system
of the Damaraland mole rat
Cryptomys (=Fucomys) damarensis
South Africa, Namib desert



Louw 1993 Physiological animal ecology

Escape underground...



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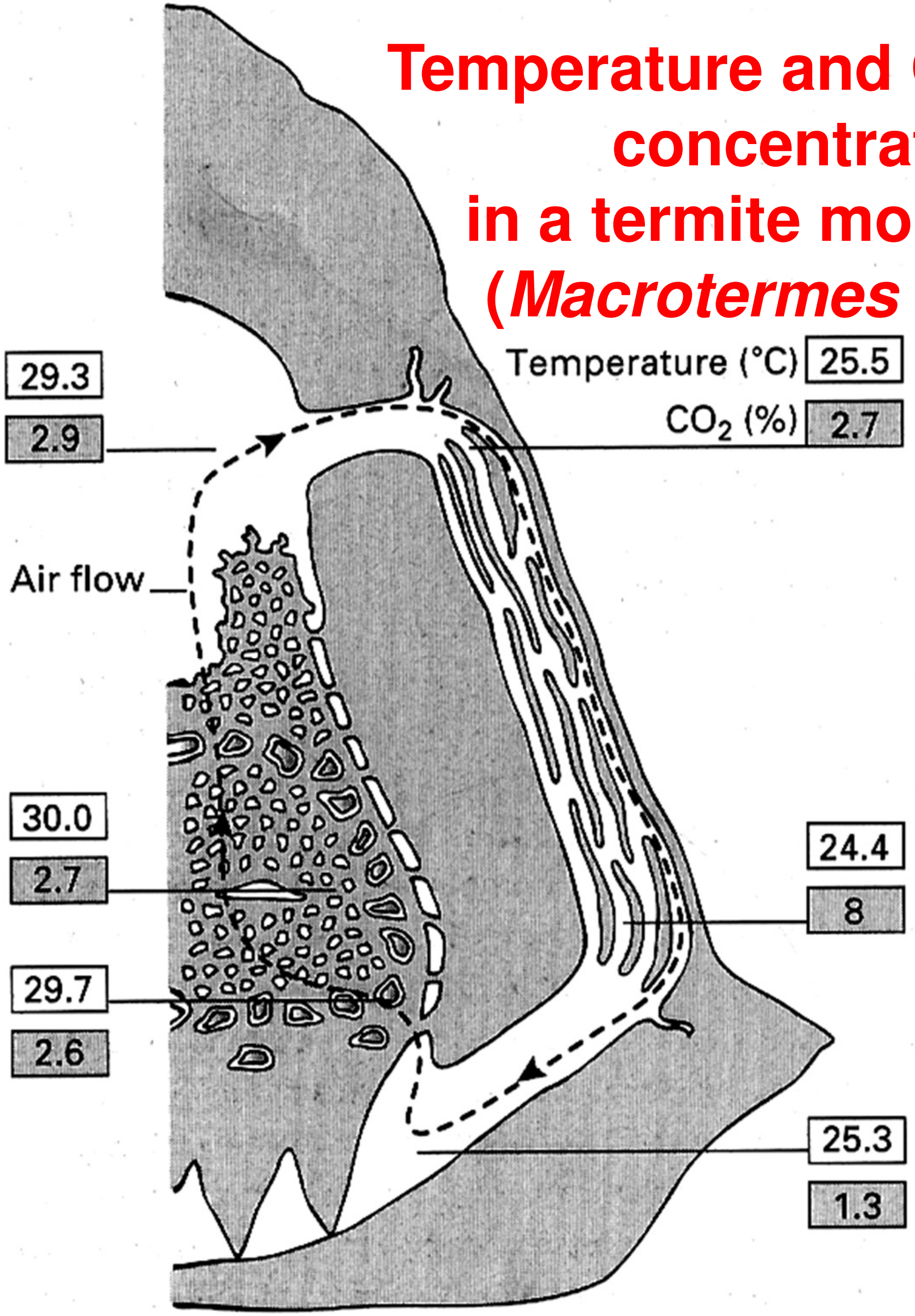
Temperature on and below ground: a nest of leave-cutter ants *Atta sp.*

photo: Wikipedia

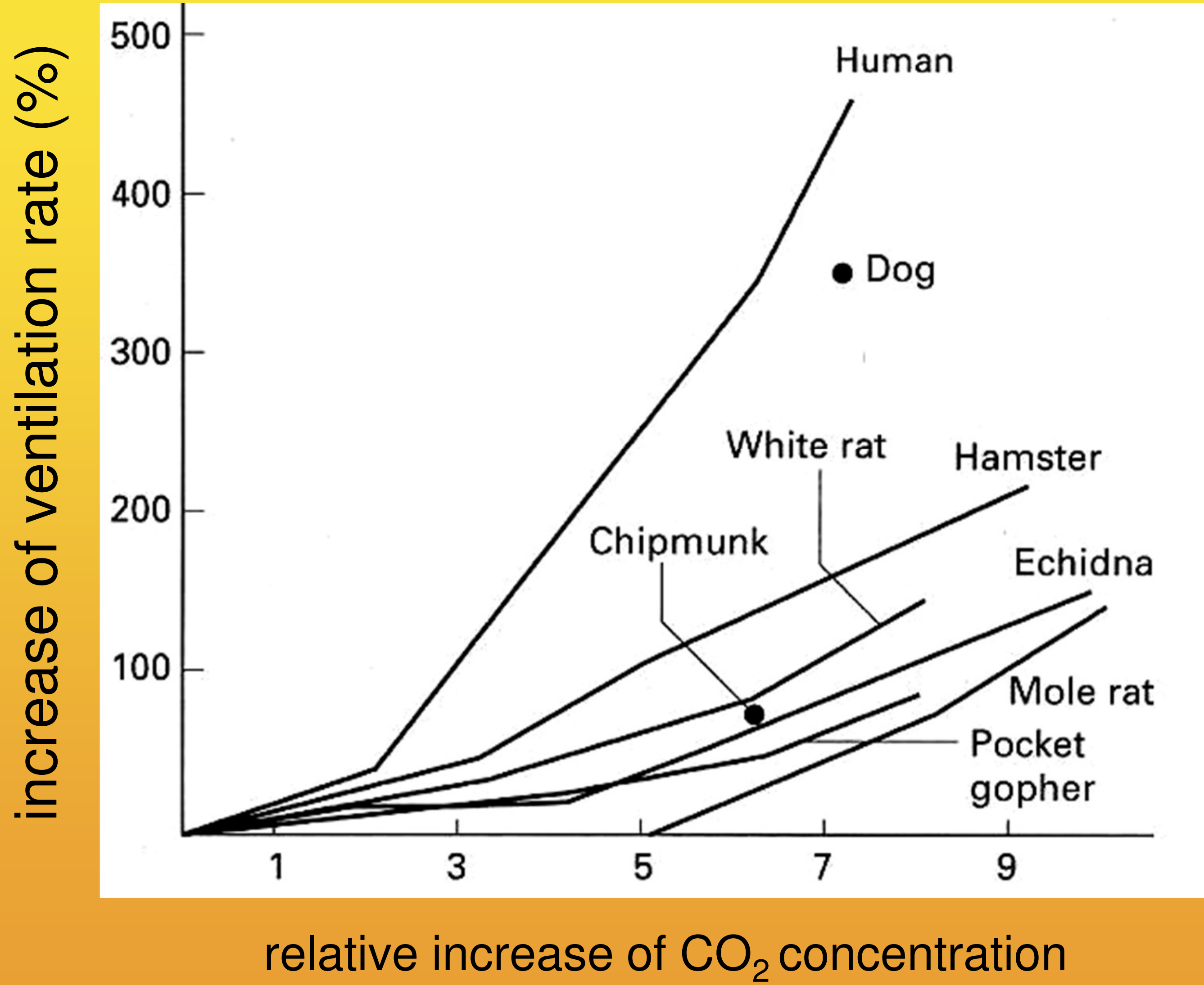
Escape to "buildings"...

Temperature and CO_2 concentration in a termite mound (*Macrotermes sp.*)



Willmer et al. 2000

Life underground...



requires tolerance of a high CO_2 concentration

Willmer et al. 2000

If on the ground surface, than how...?

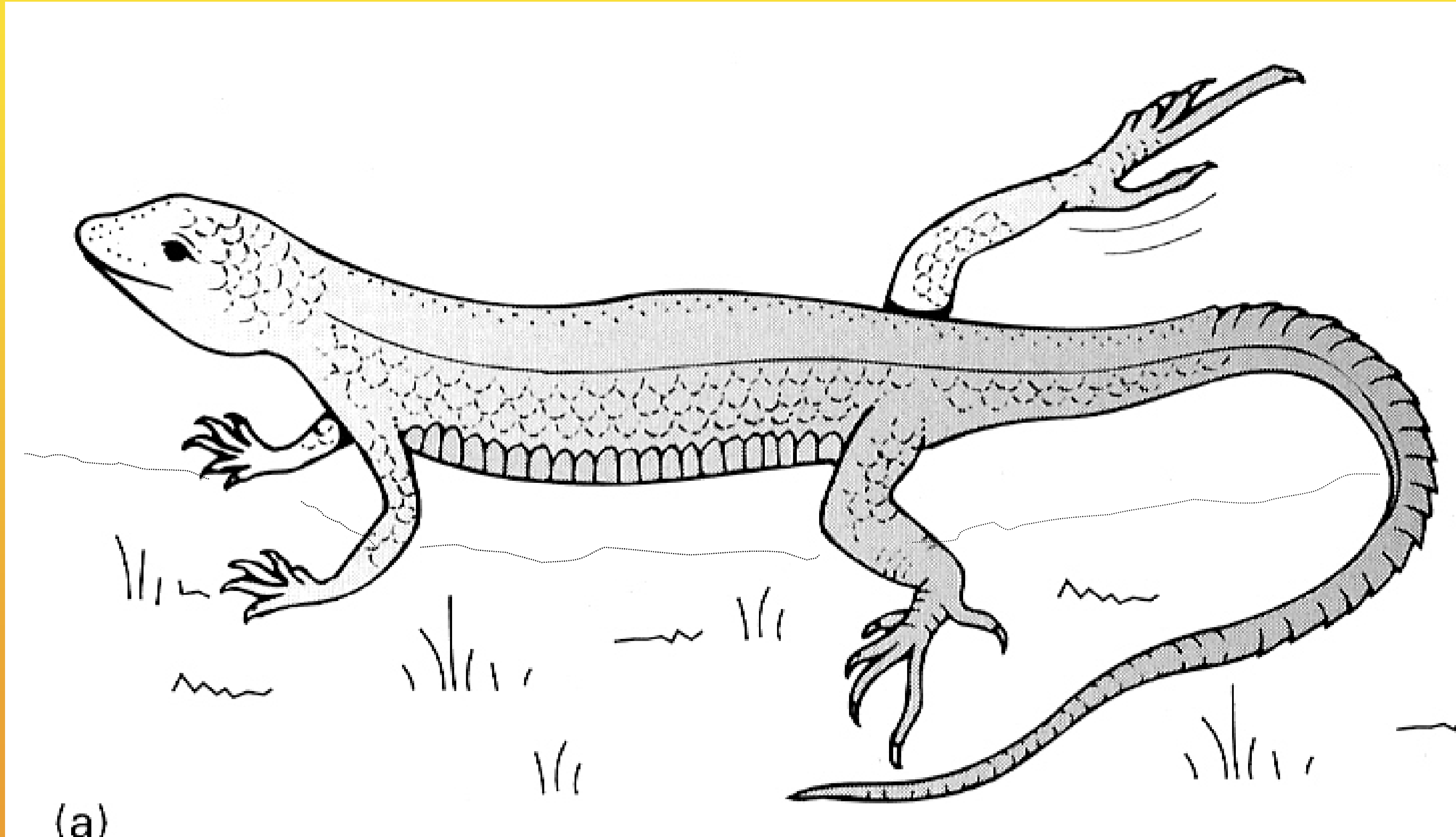
Locomotion on a hot surface: keep your body up!

SOME DESERT ANTS forage (in this case, for a researcher's cheese) at temperatures above 45 degrees Celsius. Photo: Rüdiger Wehner.

Desert ant from: www.animalpicturesarchive.com

If on the ground surface, than how...?

Locomotion on a hot surface: keep your body up!



Willmer et al. 2000

photo: M. i P. Fogden; copiedfrom: *Encyklopedia zwierząt gady i płazy*; ELIPSA, Warszawa 1993

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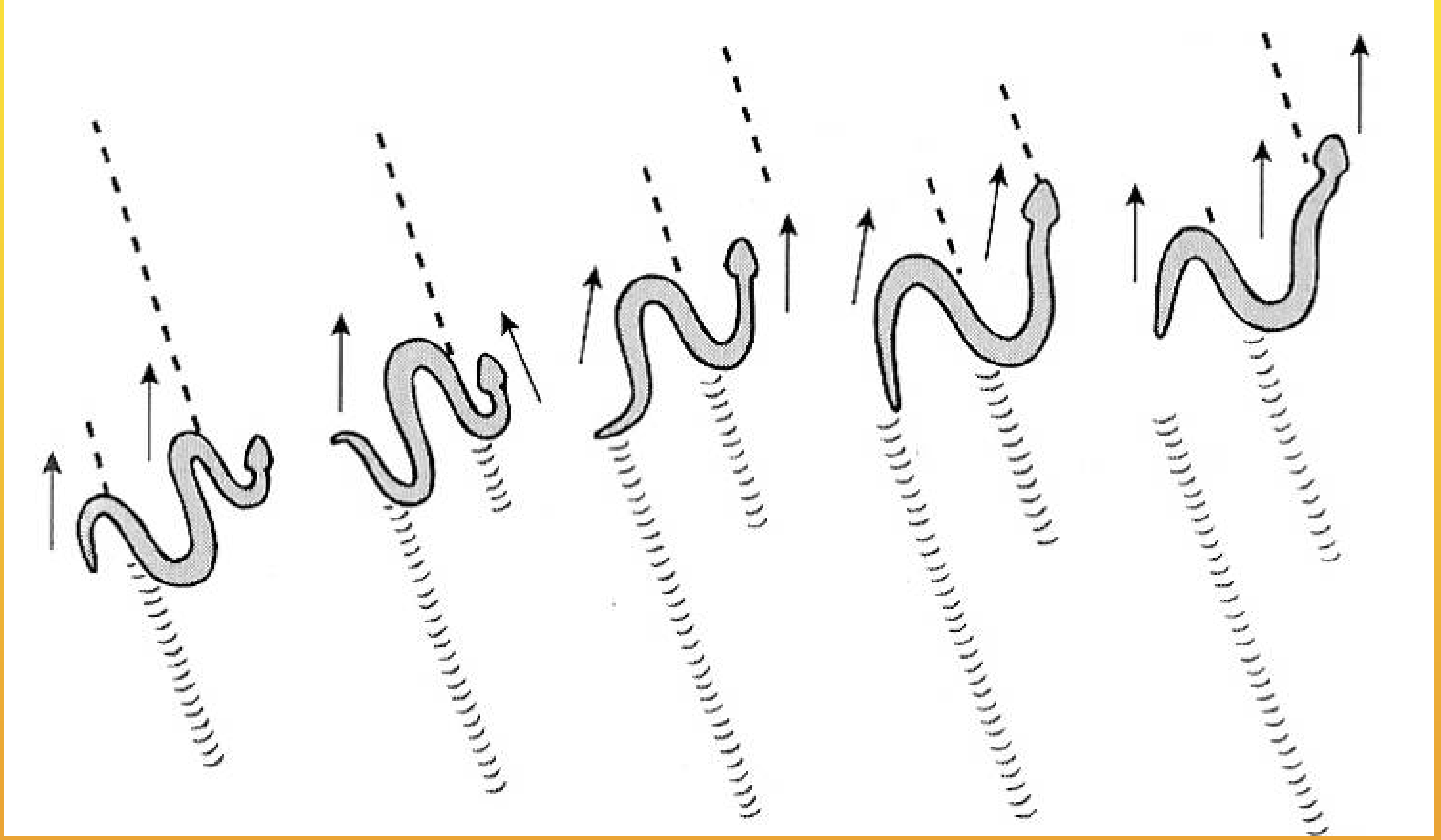


Locomotion of a sidewinding adder

Willmer et al. 2000

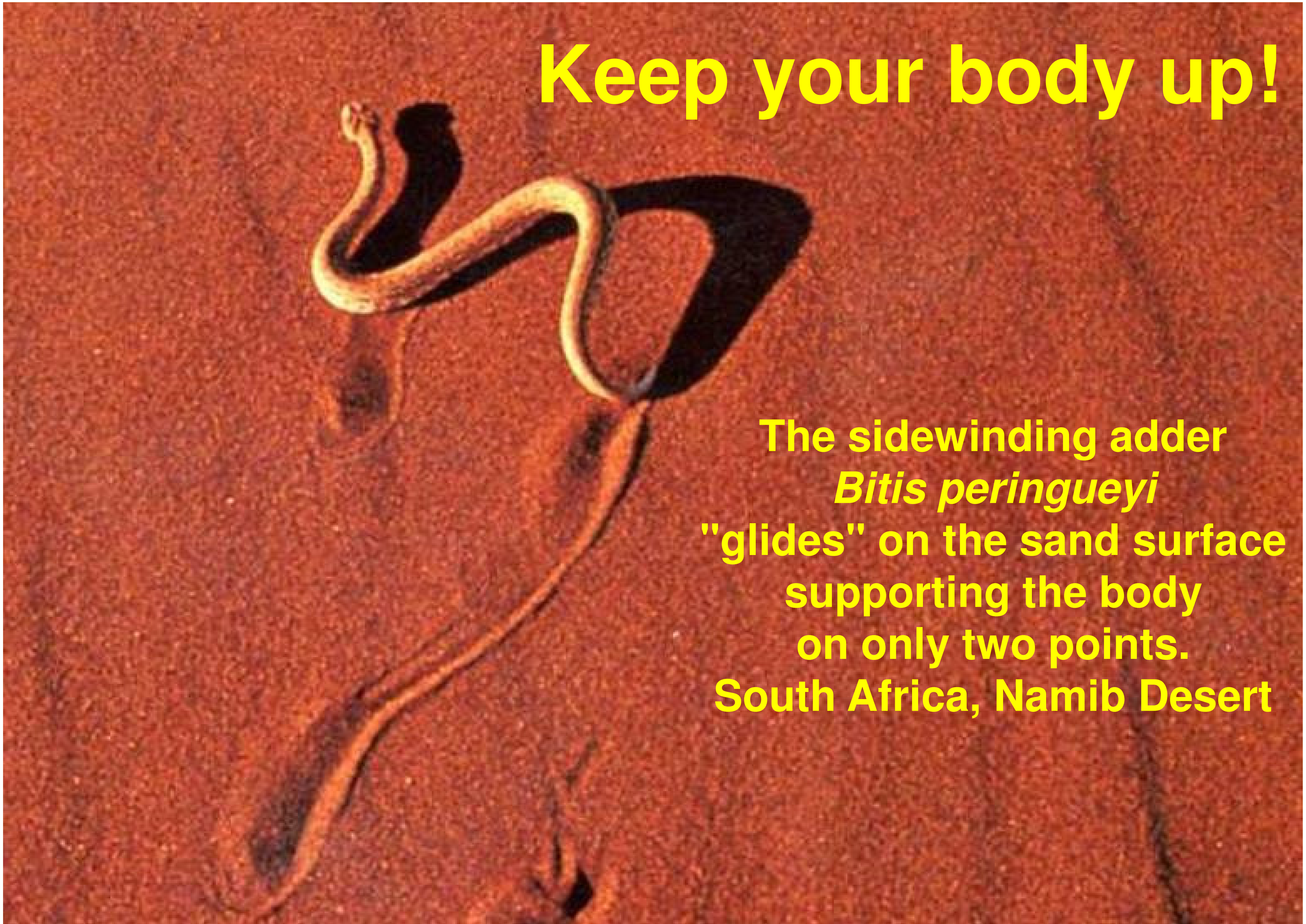


photo: M. i P. Fogden; copied from: *Encyklopedia zwierząt gady i płazy*; ELIPSA, Warszawa 1993

Keep your body up!

The sidewinding adder
Bitis peringueyi
South Africa; Namib Desert

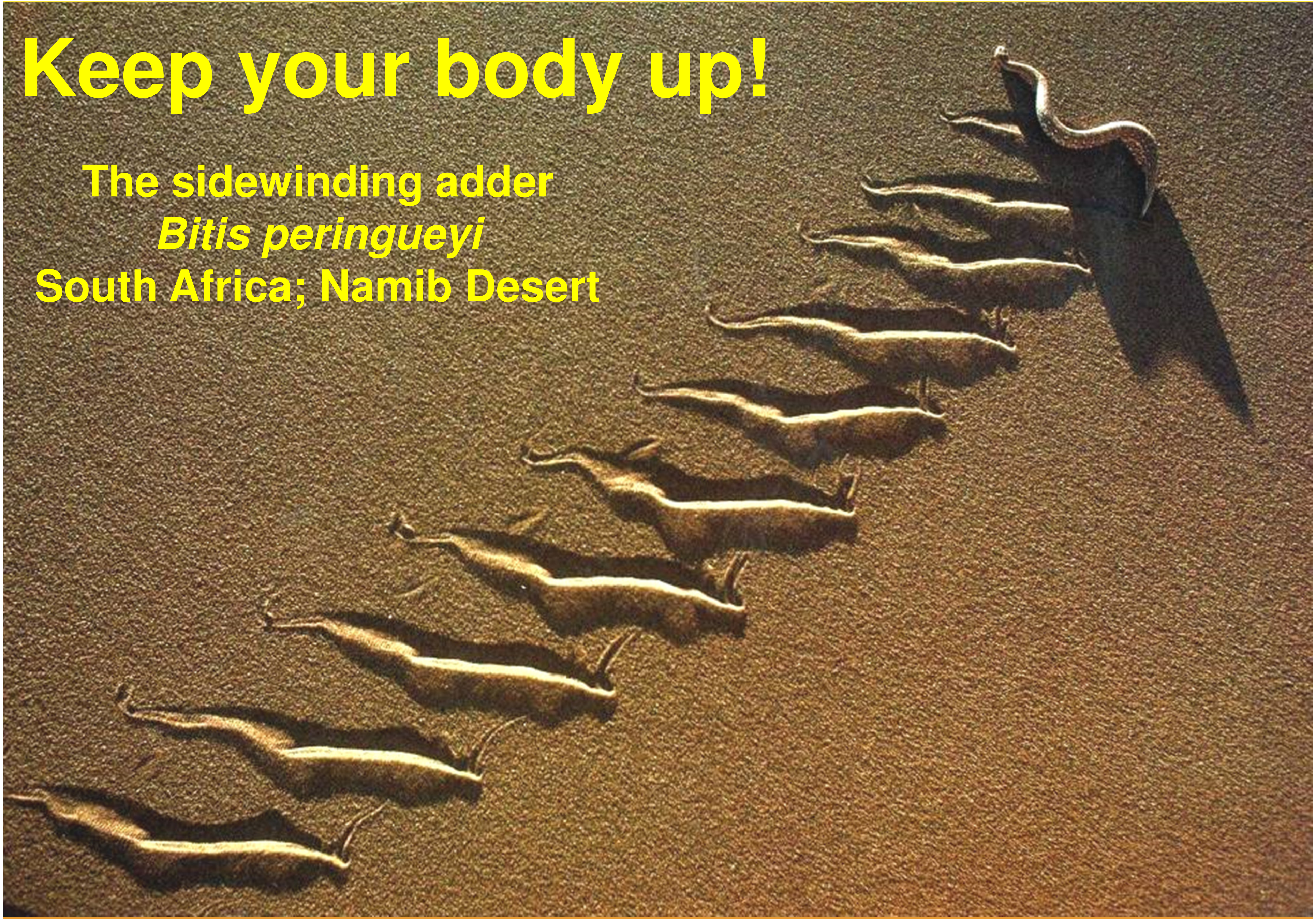
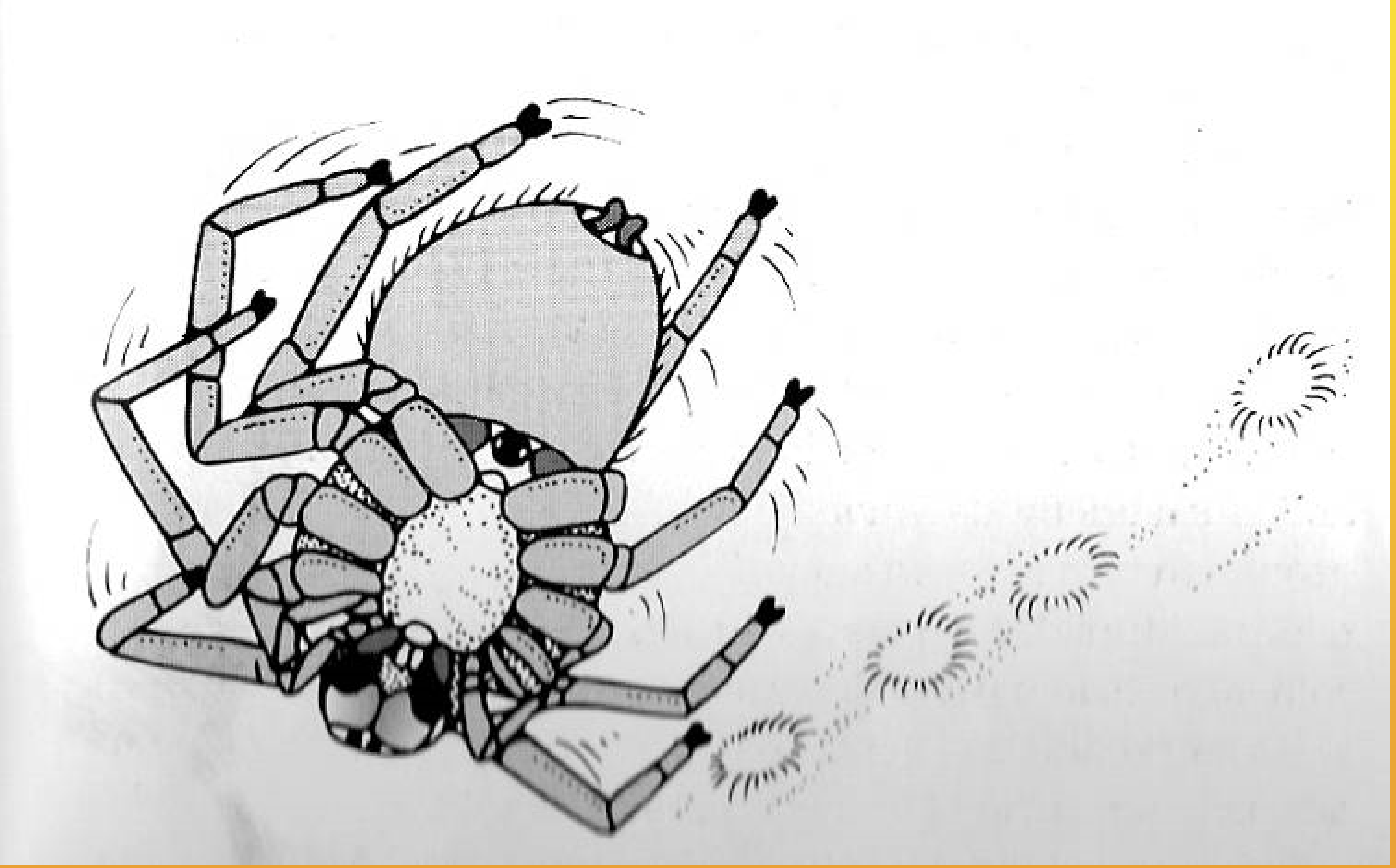


photo: C. i D. Hughes, National Geographic, Polish ed. : wrzesień 1983 (zeszyt specjalny: "100 najlepszych fotografii")

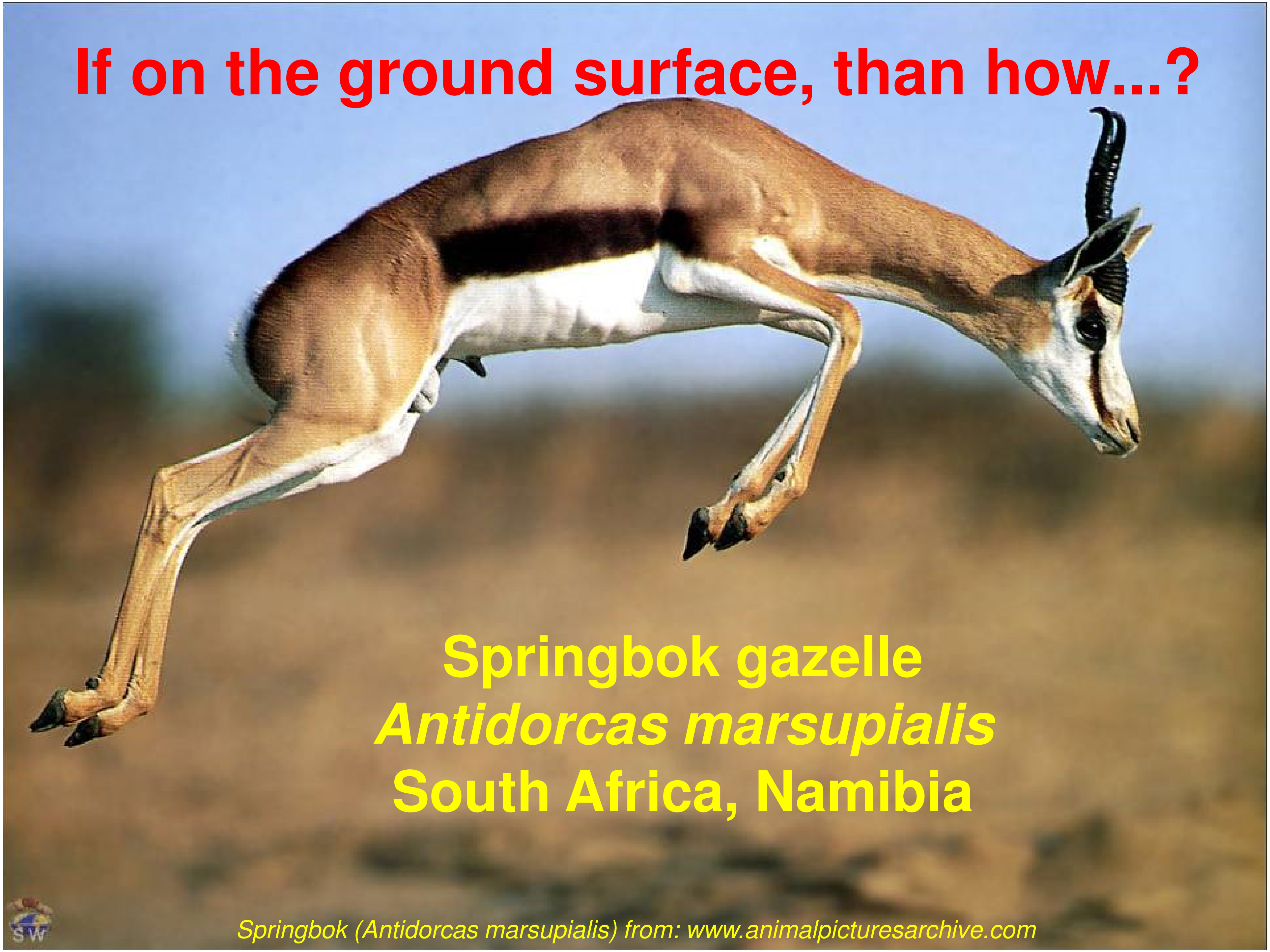
If on the ground surface, than how...?

Locomotion on a hot surface: keep your body up!



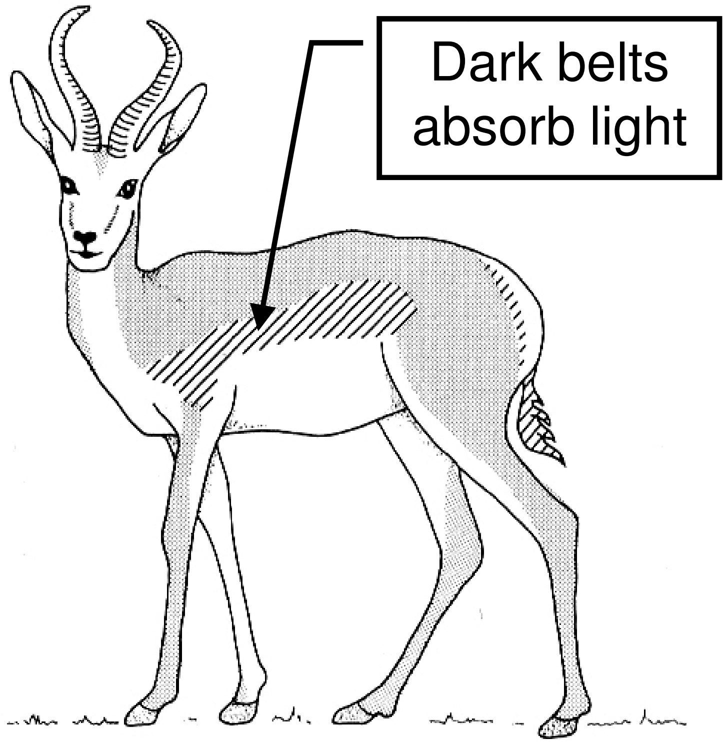
The spider *Carpachne* sp. rolling down a dune

Willmer et al. 2000

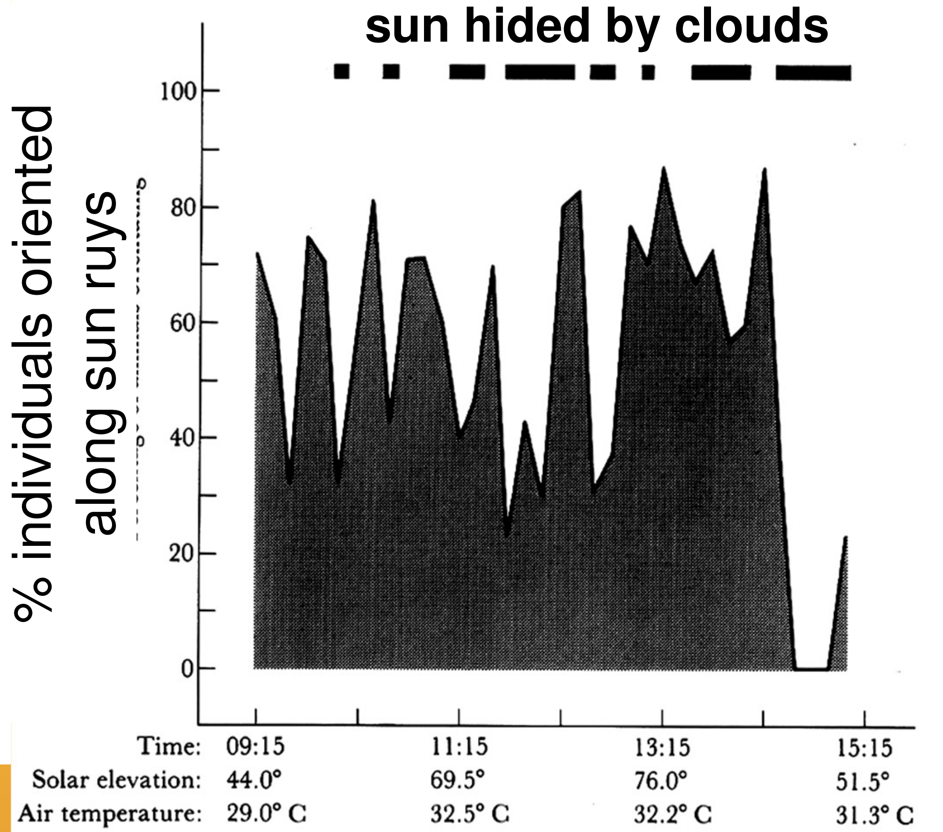

If on the ground surface, than how...?
Springbok gazelle
Antidorcas marsupialis
South Africa, Namibia
Springbok (Antidorcas marsupialis) from: www.animalpicturesarchive.com

If on the ground surface, than how...?

Manipulation with coloration and body orientation



Springbok gazelle
Antidorcas marsupialis



morning, cooler - **noon, hotter**

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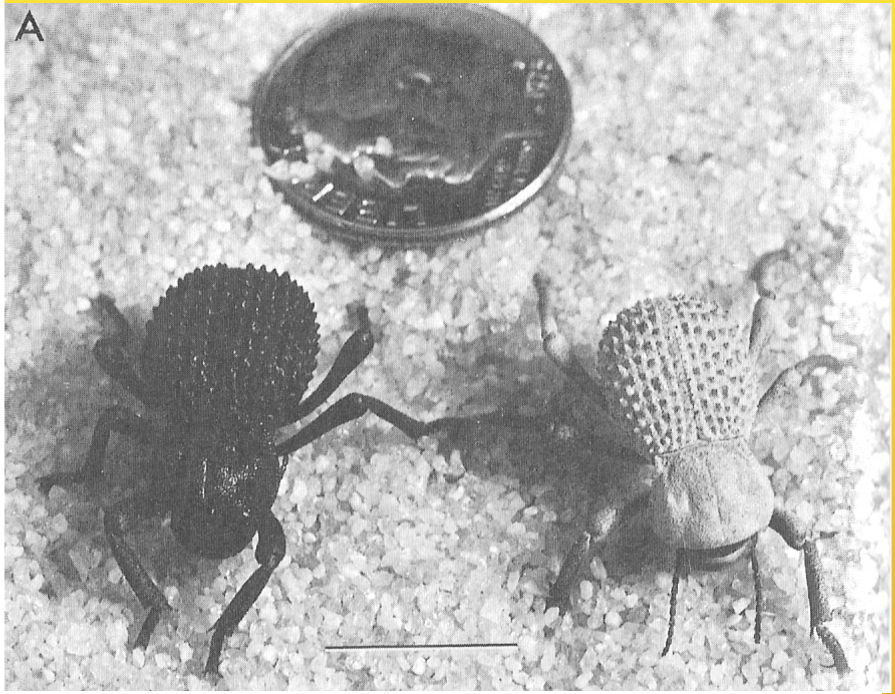
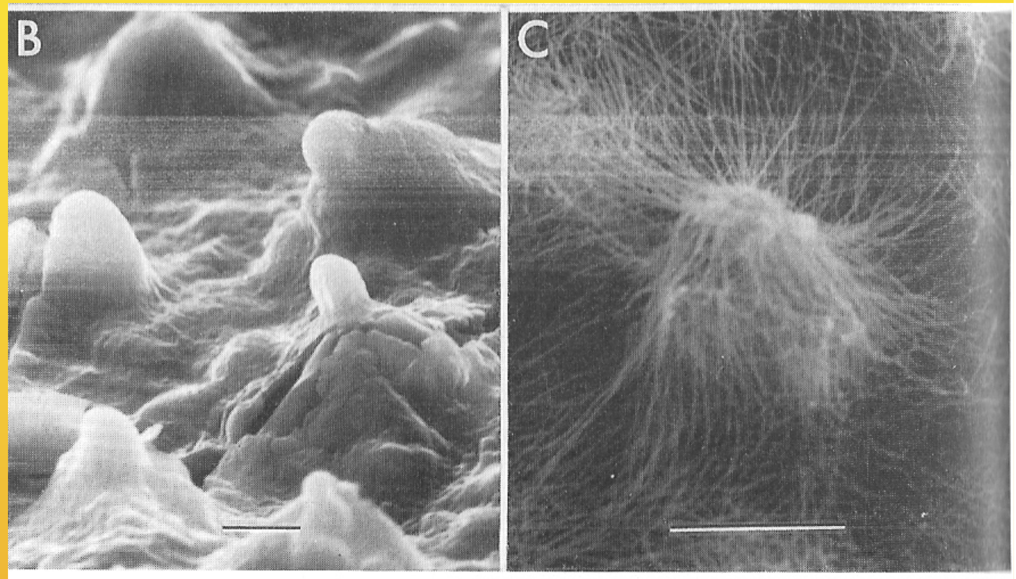
If on the ground surface, than how...?

Manipulation with coloration and permeability



high <- humidity -> low

A tenebrionid beetle
Cryptoglossa verrucosa
North America, Sonoran Desert



Wax filaments produced by tubercles waterproof the surface of elytra and give a light blue color

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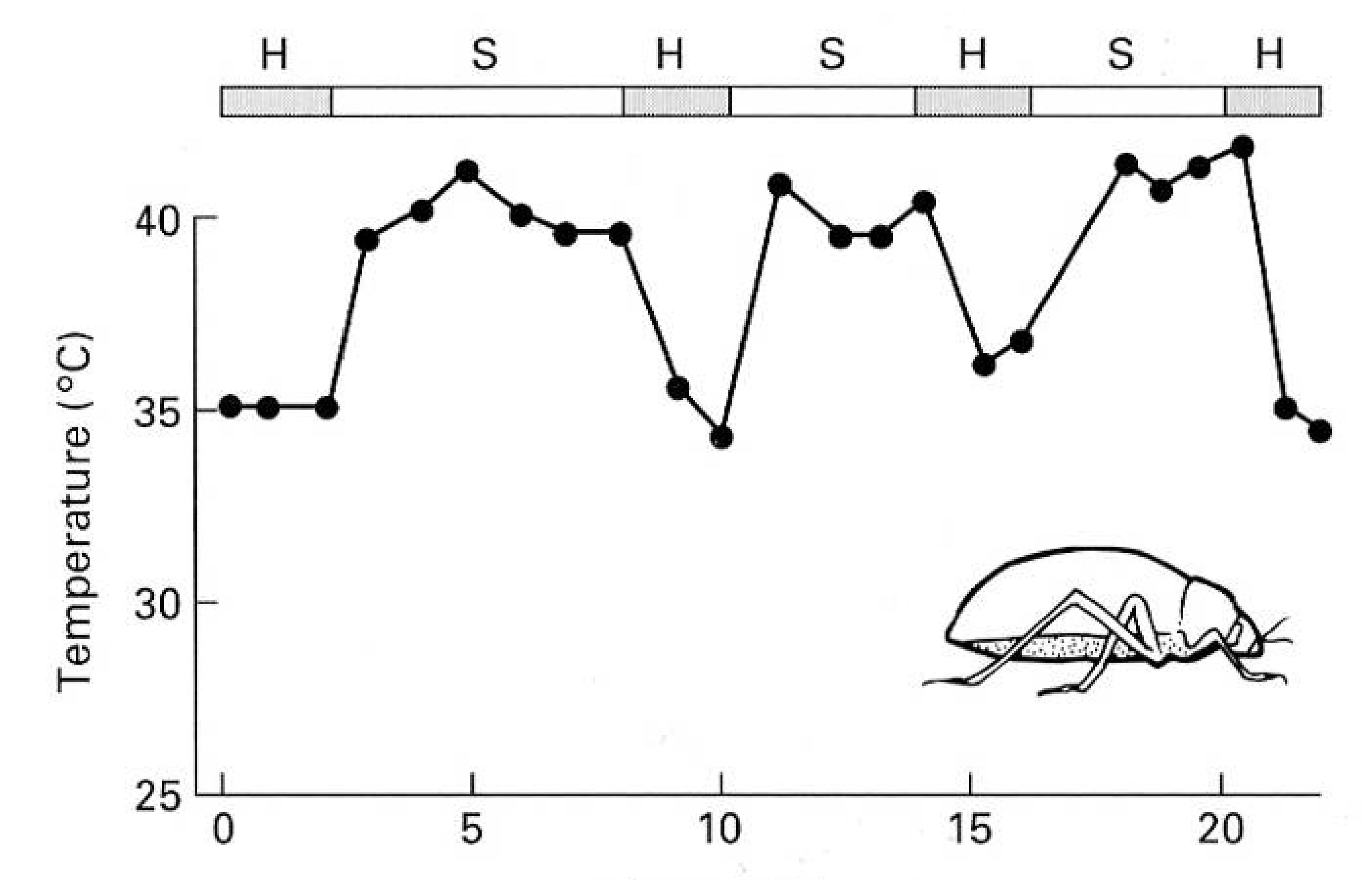
If on the ground surface, than how...?

Manipulation with coloration and body orientation

Orientation: H - head towards sun; S - side towards sun

Thorax temperature in a desert beetle

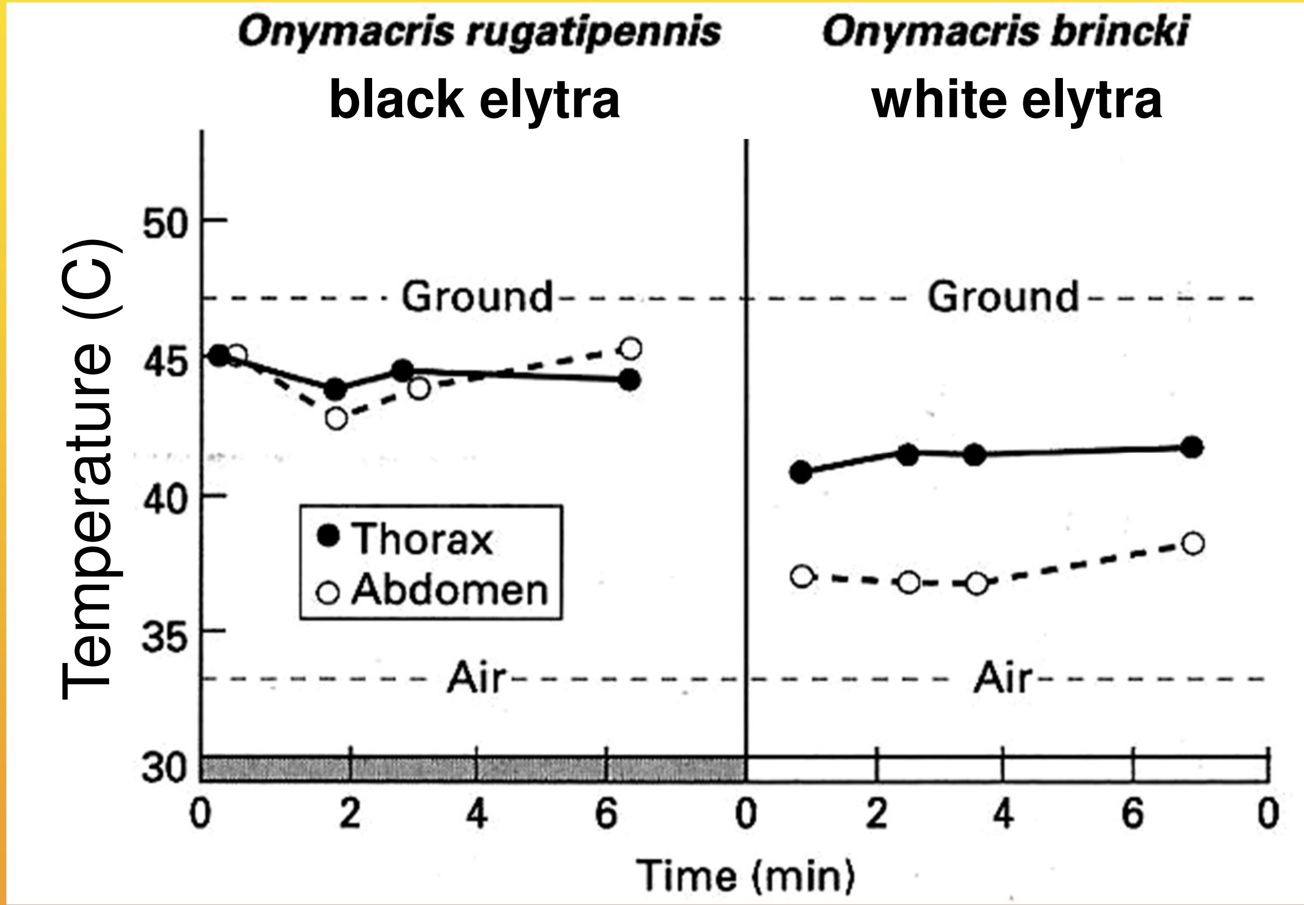


Willmer et al. 2000

If on the ground surface, than how...?

Manipulation with coloration and body orientation

The effect of elytra color on body temperature of desert beetles



Willmer et al. 2000

Coping with low water availability

Evaporation: water lost by breathing

Changes of temperature and humidity of inspired (I) and expired (E) air in the African ostrich: breath-by-breath analysis

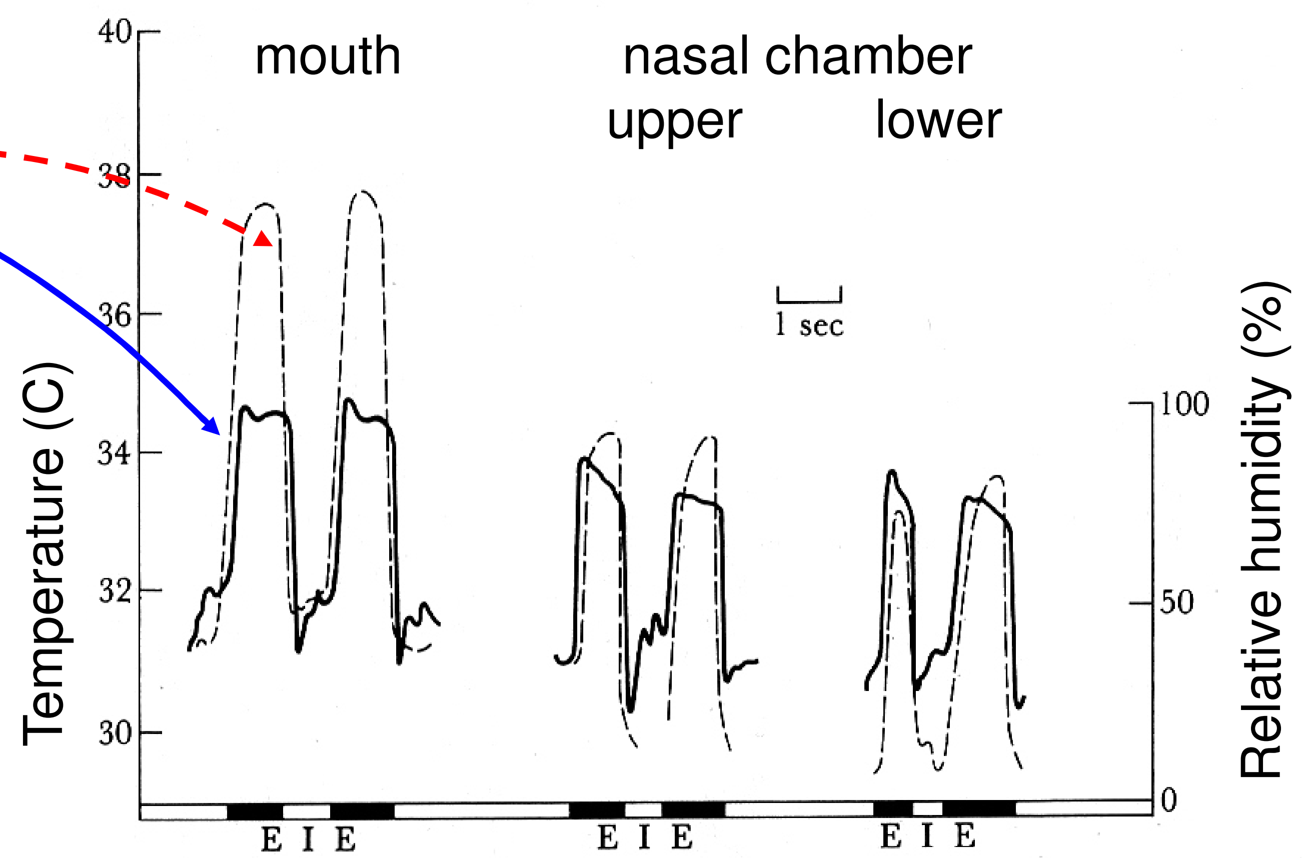


Figure 2.22 Breath-by-breath recorder tracings of relative humidity and temperature of inspired and expired air in the mouth, upper nasal chamber and lower nasal chamber of the ostrich (relative humidity, solid line; temperature, broken line; E, expiration; I, inspiration). From Withers *et al.* (1981).

Willmer et al. 2000

Evaporation: water lost by breathing

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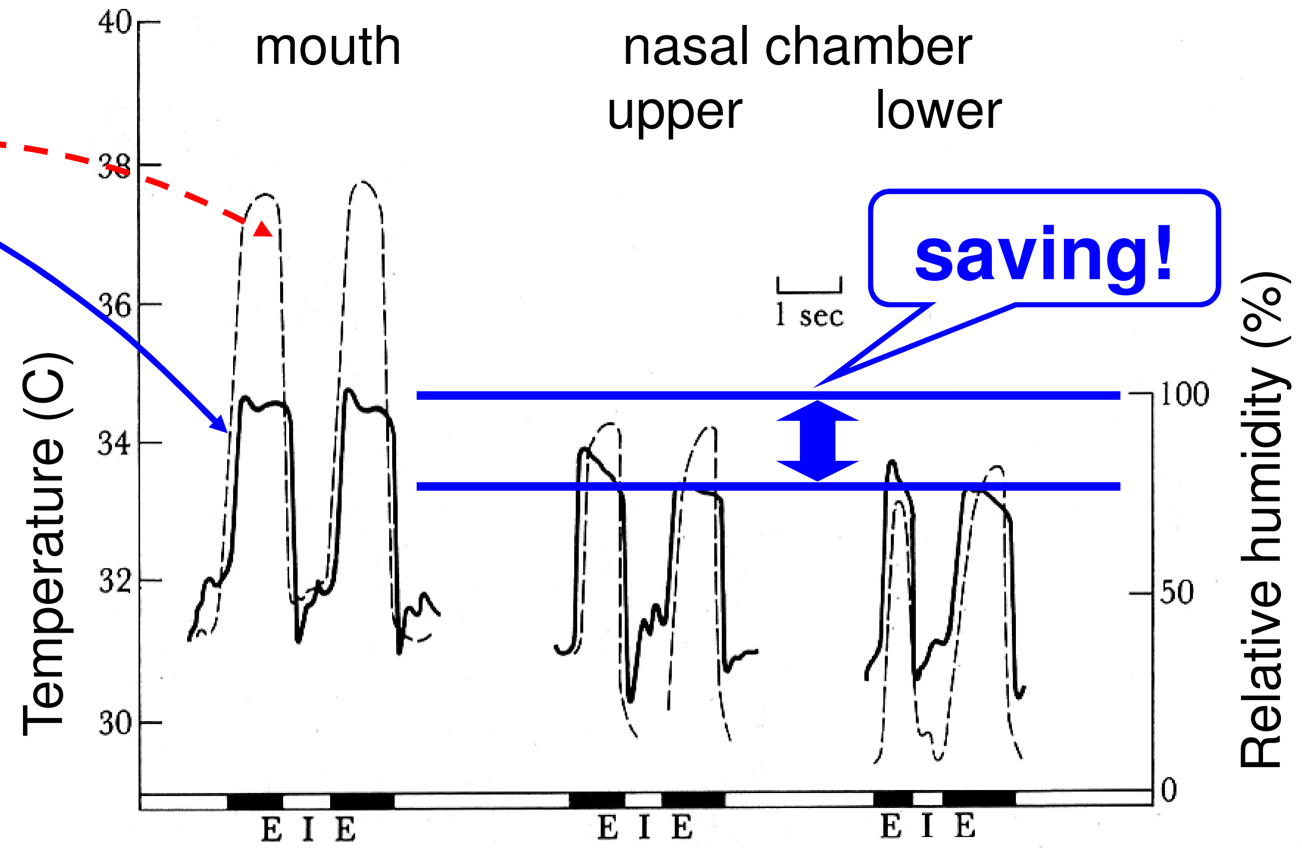

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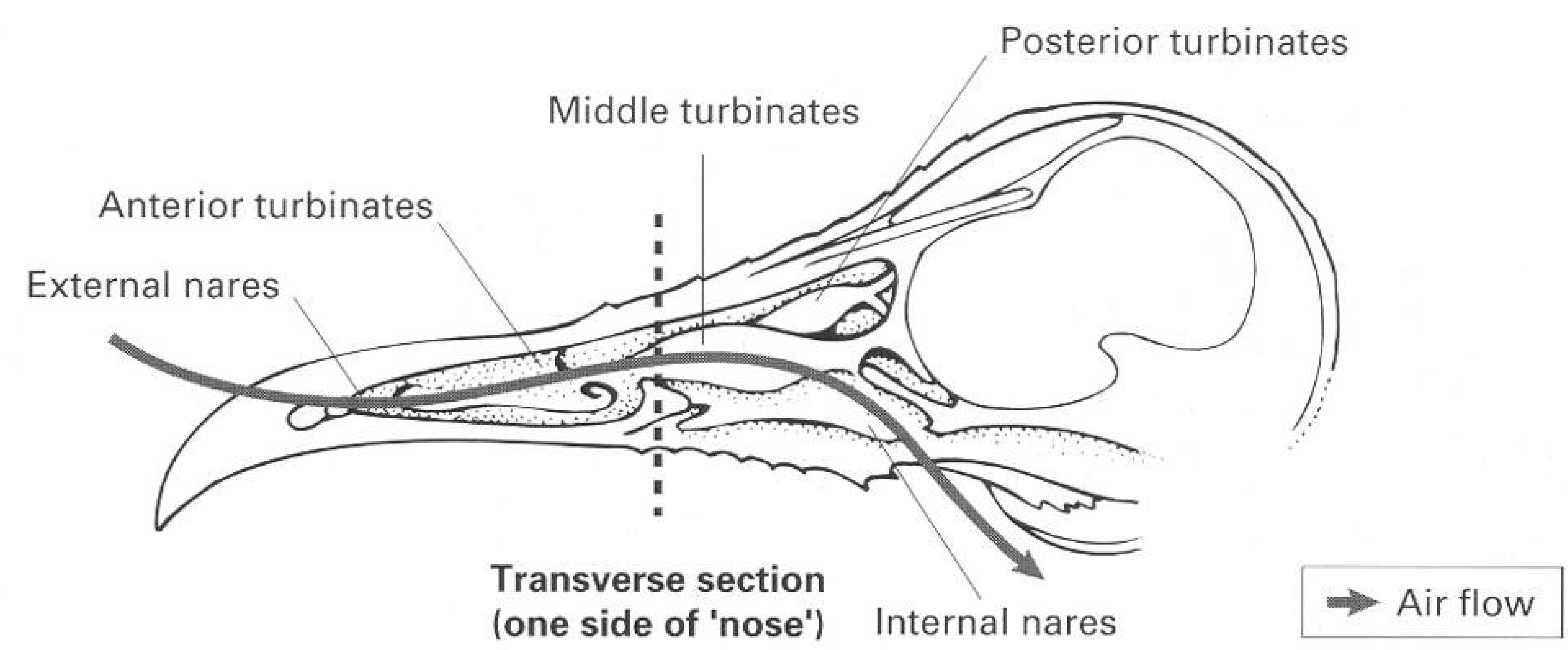
Willmer et al. 2000

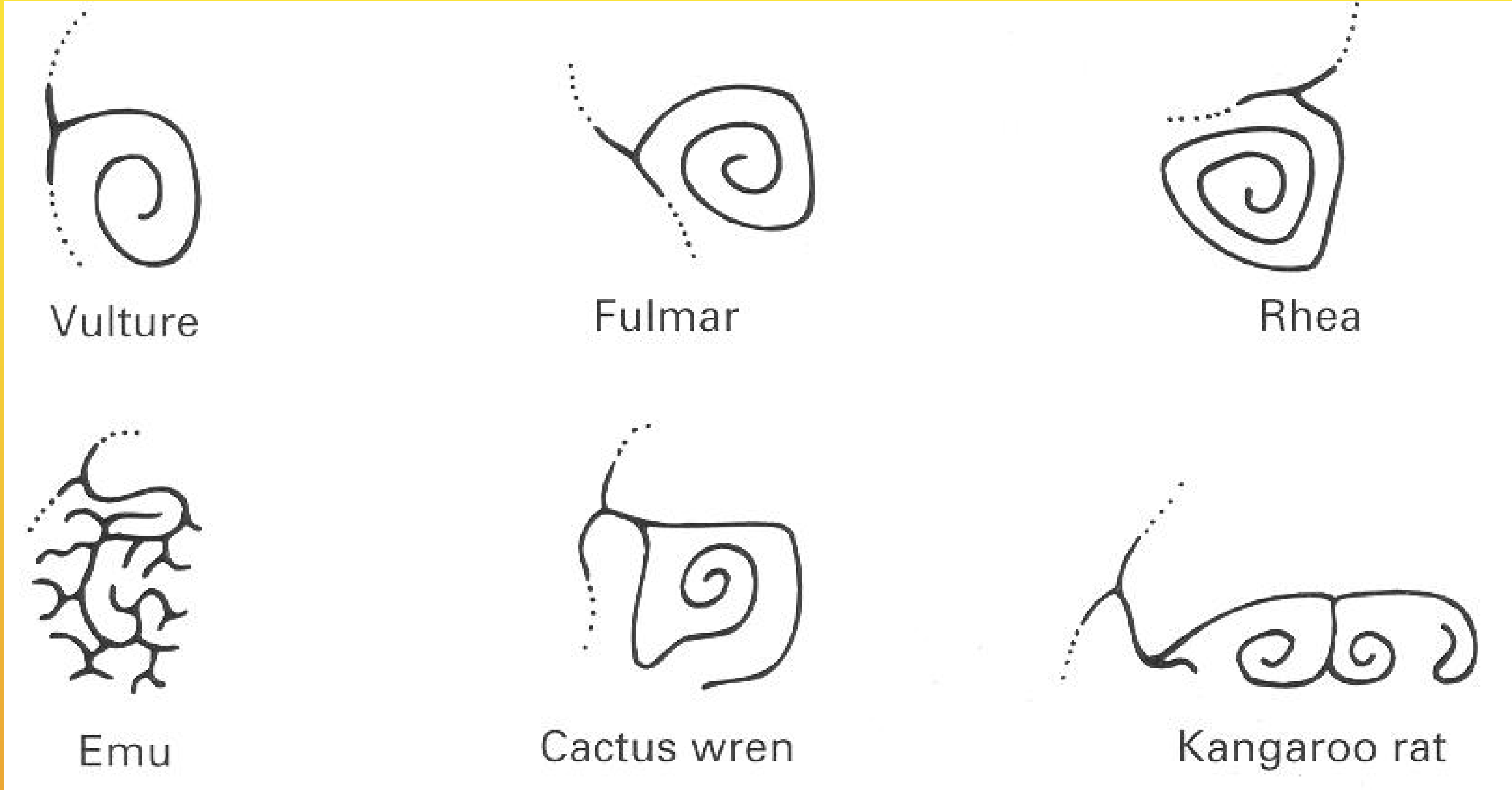
Water-saving mechanism in nasal turbinates (maxilloturbinates)



An increased surface of heat and humidity exchange in nasal channels

Willmer et al. 2000

Cross-sections through nasal turbinates



An increased surface of heat and humidity exchange in nasal channels

Willmer et al. 2000

Cactus Wren

Campylorhynchus brunneicapillus

(pol.: strzyżyk kaktusowy)

North America:
Sonora,
Chihuahuan

Cactus Wren from: www.mangroverde.com.

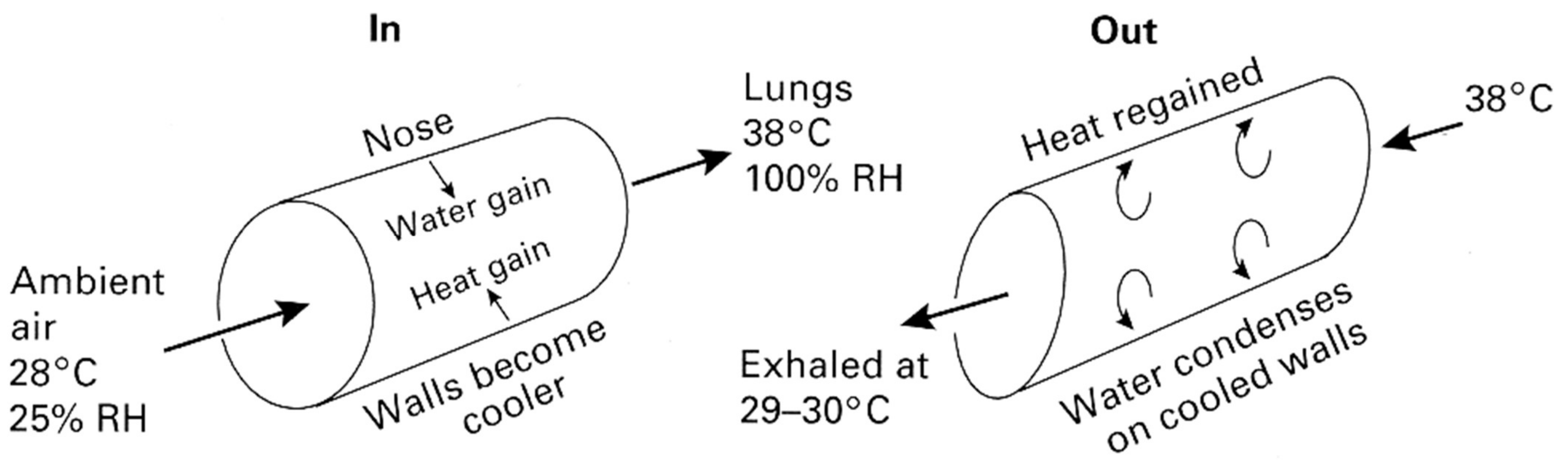
Kangaroo rat (pol.: szczuroskoczek)
Dipodomys sp. (Rodentia, Heteromyidae)

Deserts and arid habitats in North America

Kangaroo rat (Dipodomys ordii) from Wikipedia

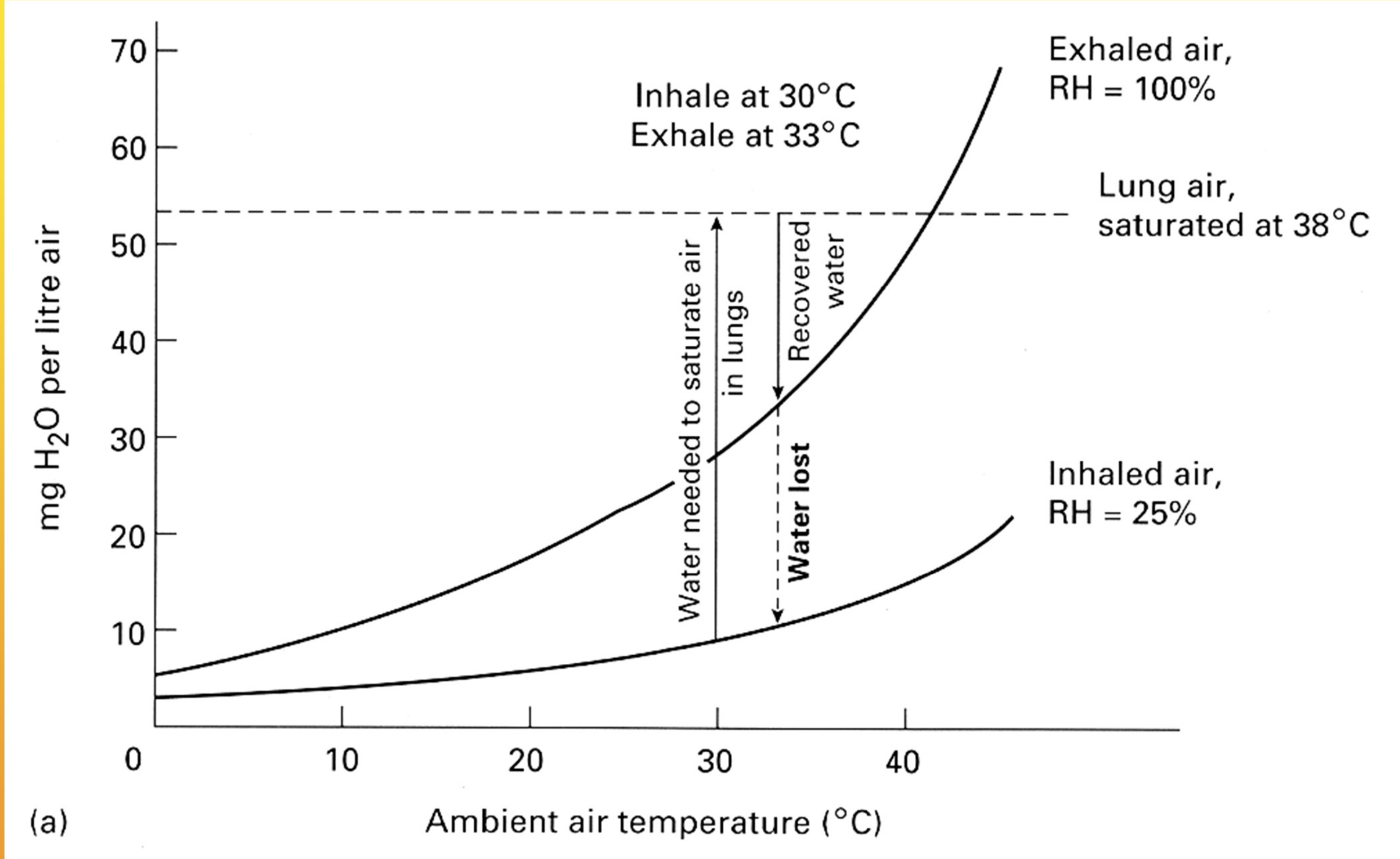
Water-saving mechanism in nasal turbinates

Inhale | Exhale



Willmer et al. 2000

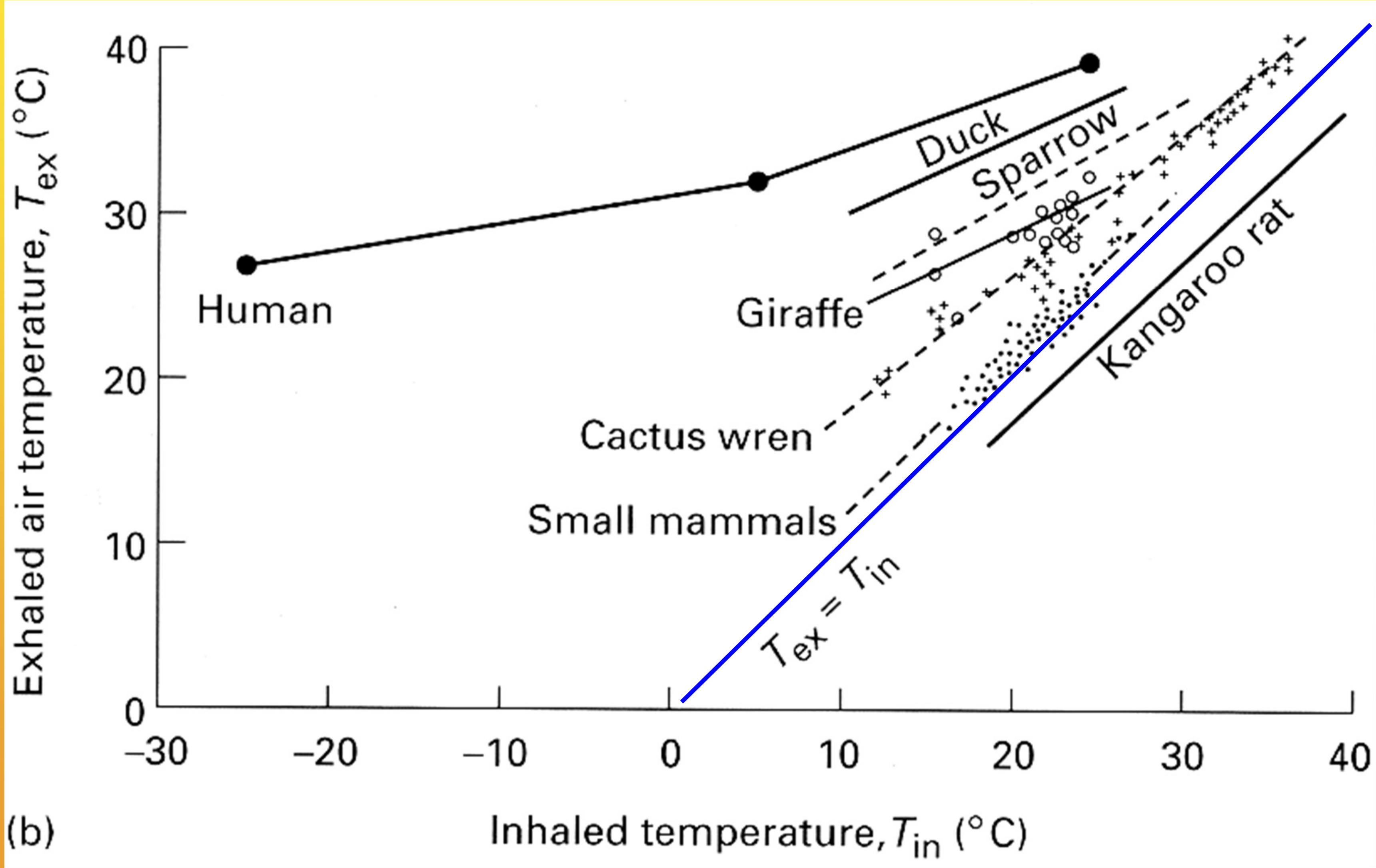
Water-saving mechanism in nasal turbinates



Willmer et al. 2000

Water-saving mechanism in nasal turbinates:

decreased temperature of exhaled air -> decreased water loss



Willmer et al. 2000

Water balance in a kangaroo rat over 1 month

Conditions: Food: 100 g dry barley grain, no drinking water;
Temperature: 25C;
Humidity: 25%

Water gain		Water loss	
Source	ml	Source	ml
Metabolic water (oxidation)	54.0	Evaporation	43.9
Food	6.0	Urine	13.5
		Faeces	2.6
Total	**60.0**	**Total**	**60.0**

Schmidt-Nielsen, Animal Physiology

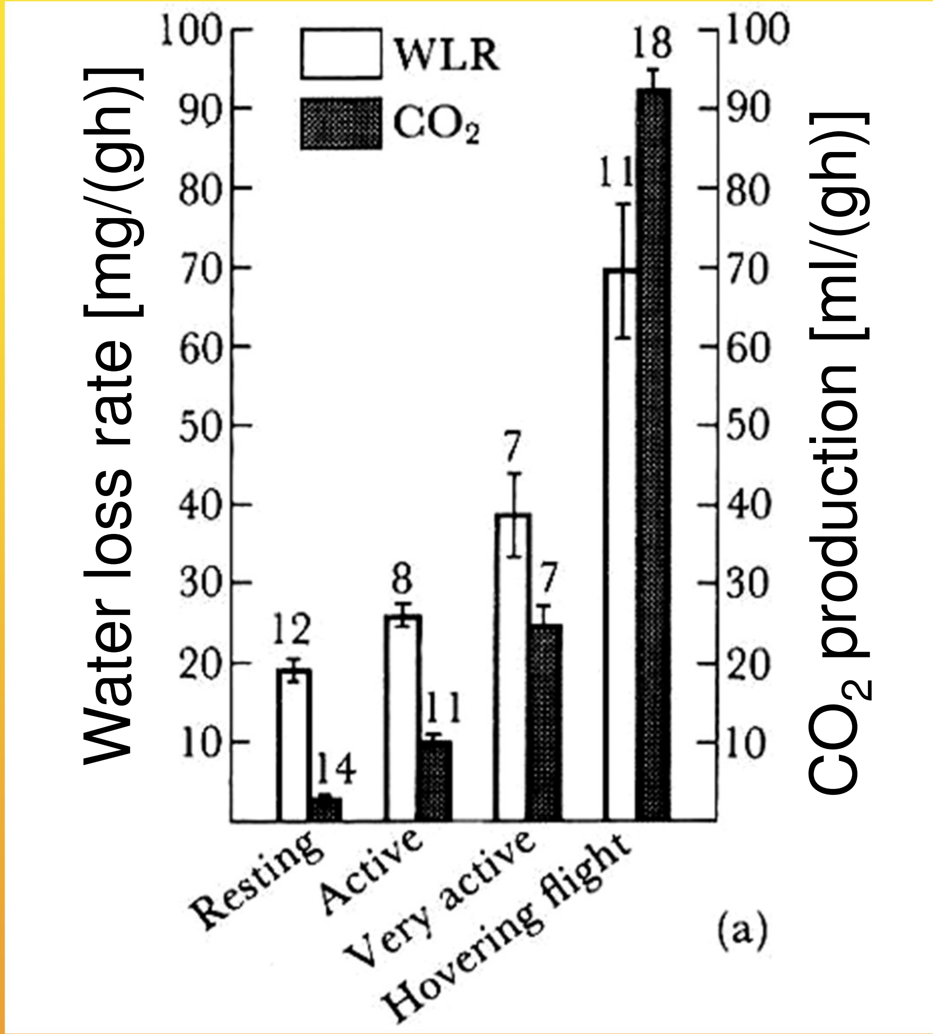
Food substrates as a source of energy... and water

Table 2.4 Relationship between the respiratory quotient (RQ), metabolic water production and energy production when the major nutrients are oxidised. From Prosser (1973) and Schmidt-Nielsen (1983)

Food	RQ	g water g food^{-1}	l O_2 g food^{-1}	l O_2 g water^{-1}	kJ g food^{-1}	g water kJ^{-1}
Carbohydrates	1.0	0.56	0.83	1.49	17.4	0.0320
Fats	0.71	1.07	2.02	1.89	39.7	0.0269
Proteins	0.79	0.40	0.97	2.44	17.4	0.0228

Louw 1993 Physiological animal ecology

Water balance in active insects



Increasing level of activity

In a honey bee:

- A large increase in metabolic rate
- A smaller increase of water loss

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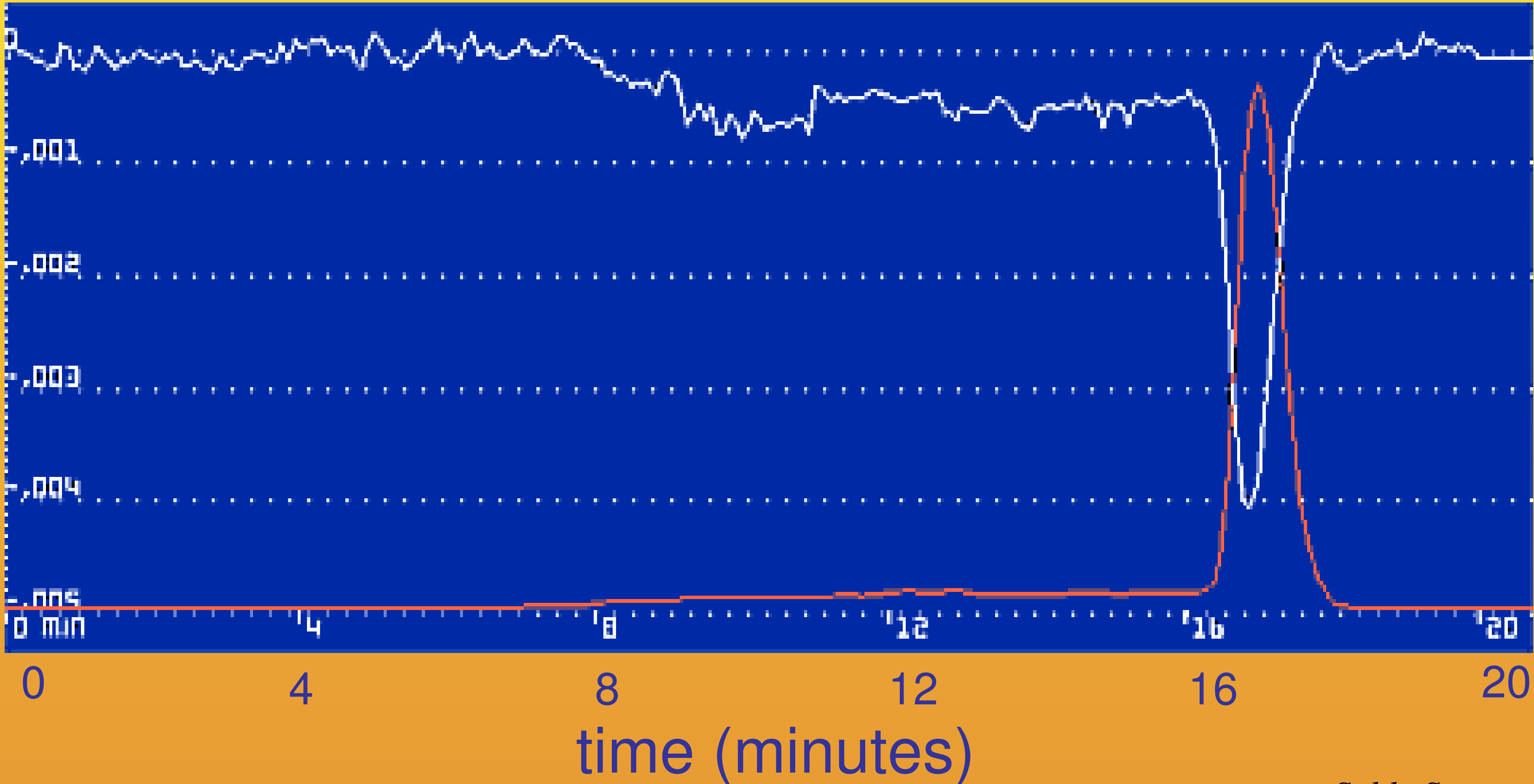
Cycling respiration in an ant

Changes of gas content in the air flowing through a respirometric chamber

- decrease of O_2 content
- increase of CO_2 content

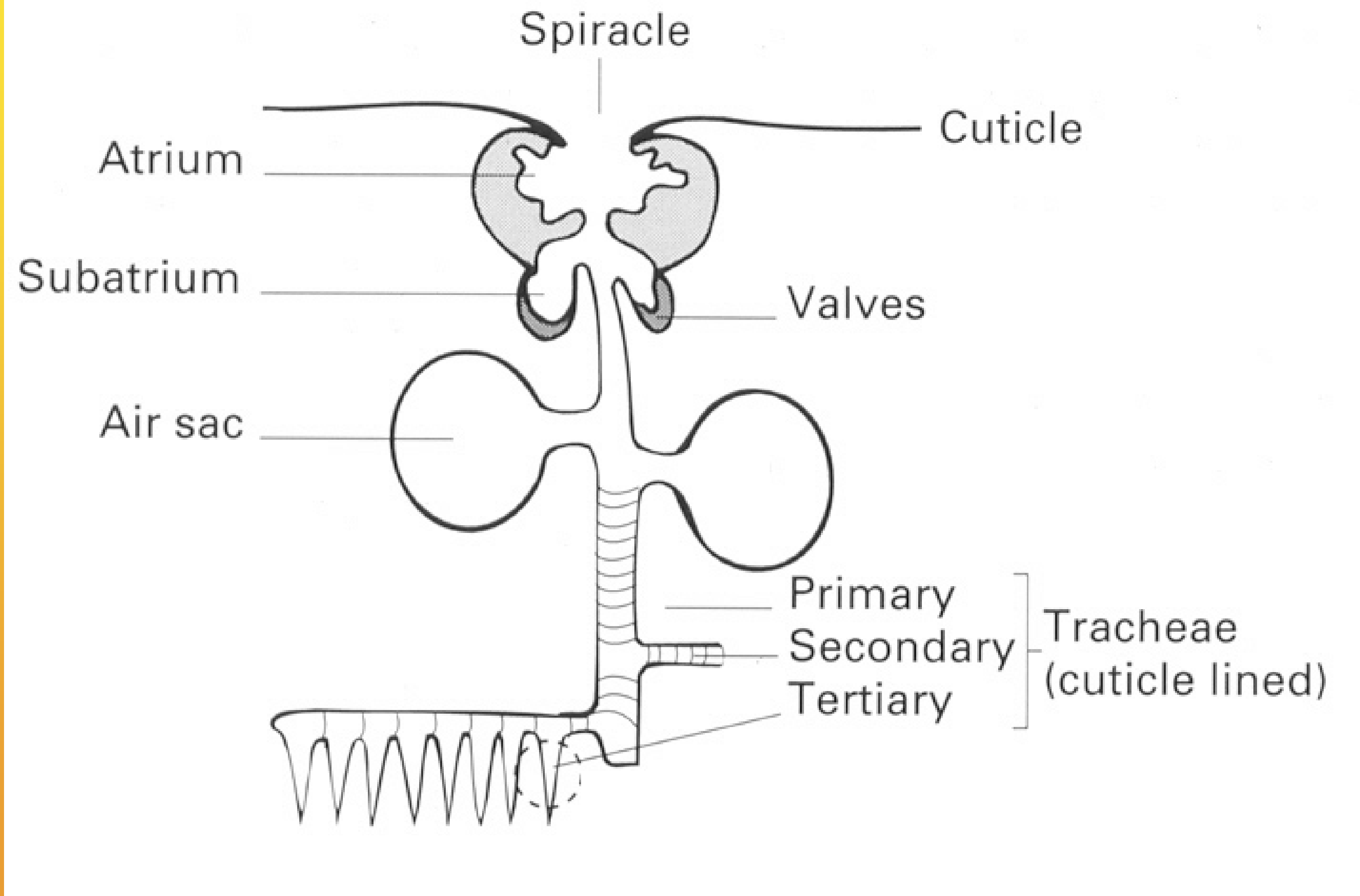


Sable Systems

Cycling respiration in insects

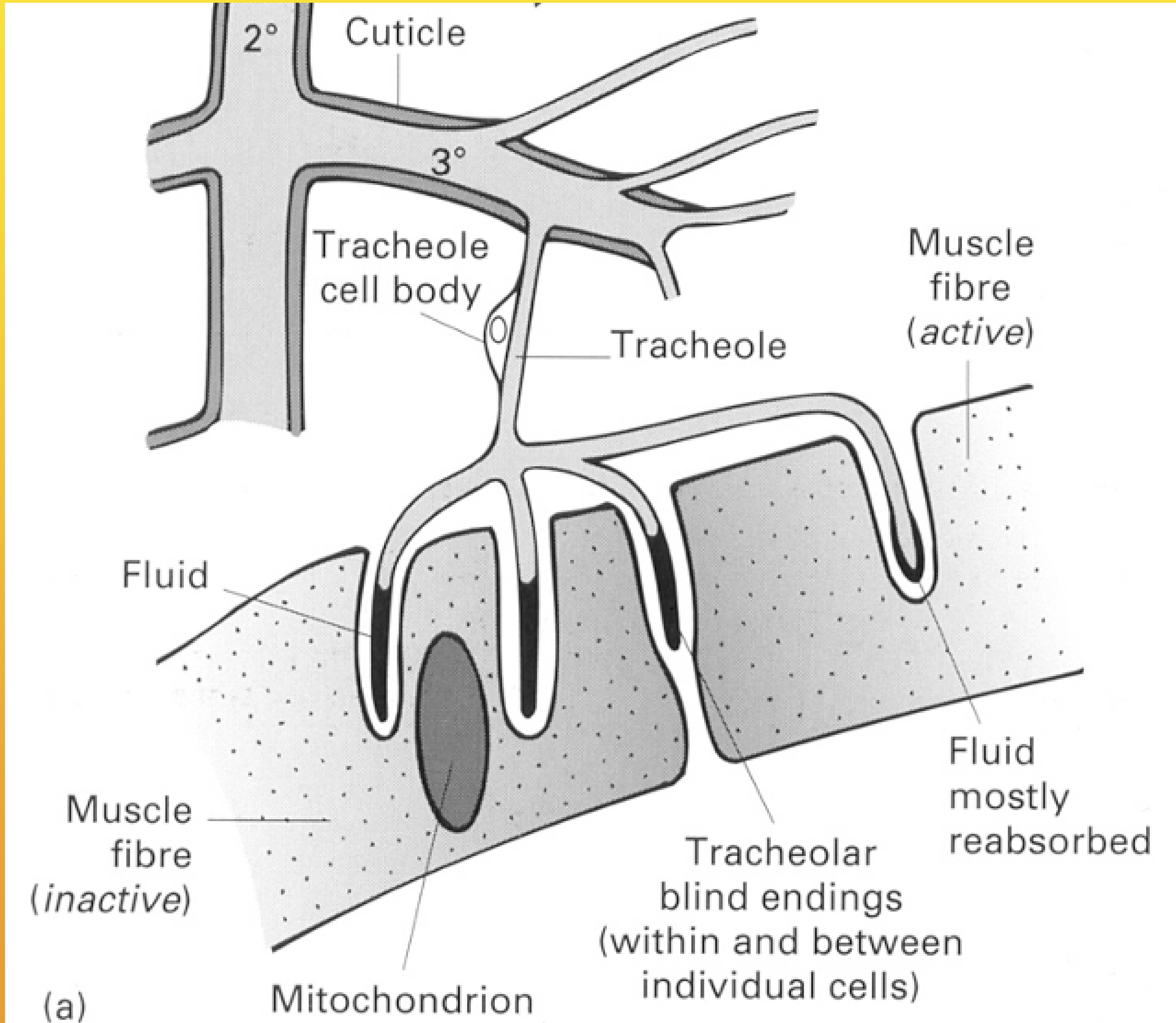
- **Hypotheses:**
- cycling changes of metabolism?
- cycling ventilation?

Respiratory system in insects:
direct oxygen delivery from air to working cells



Willmer et al. 2000

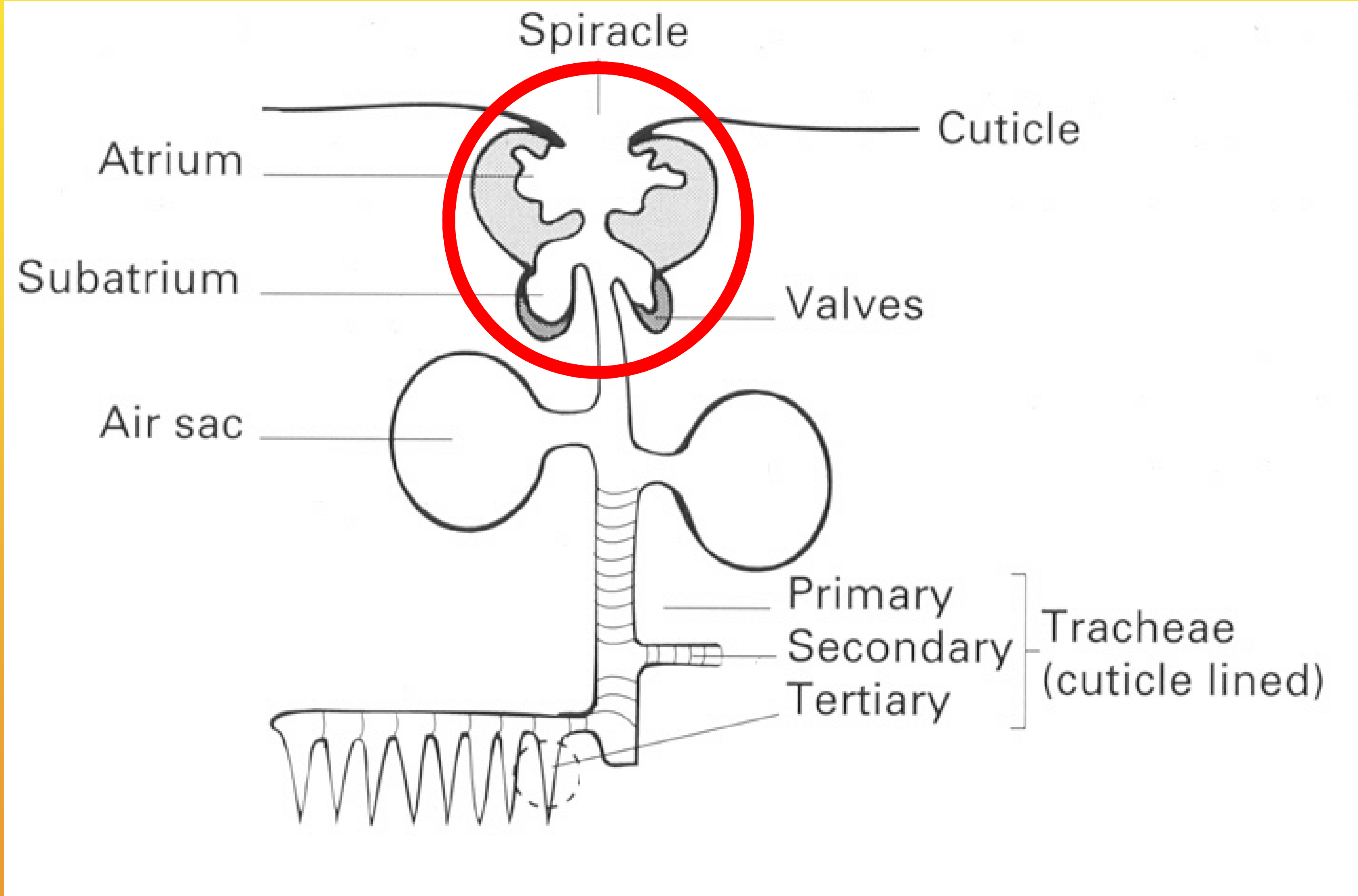
Respiratory system in insects:
direct oxygen delivery from air to working cells



up to 10 mln tracheoli per fiber !

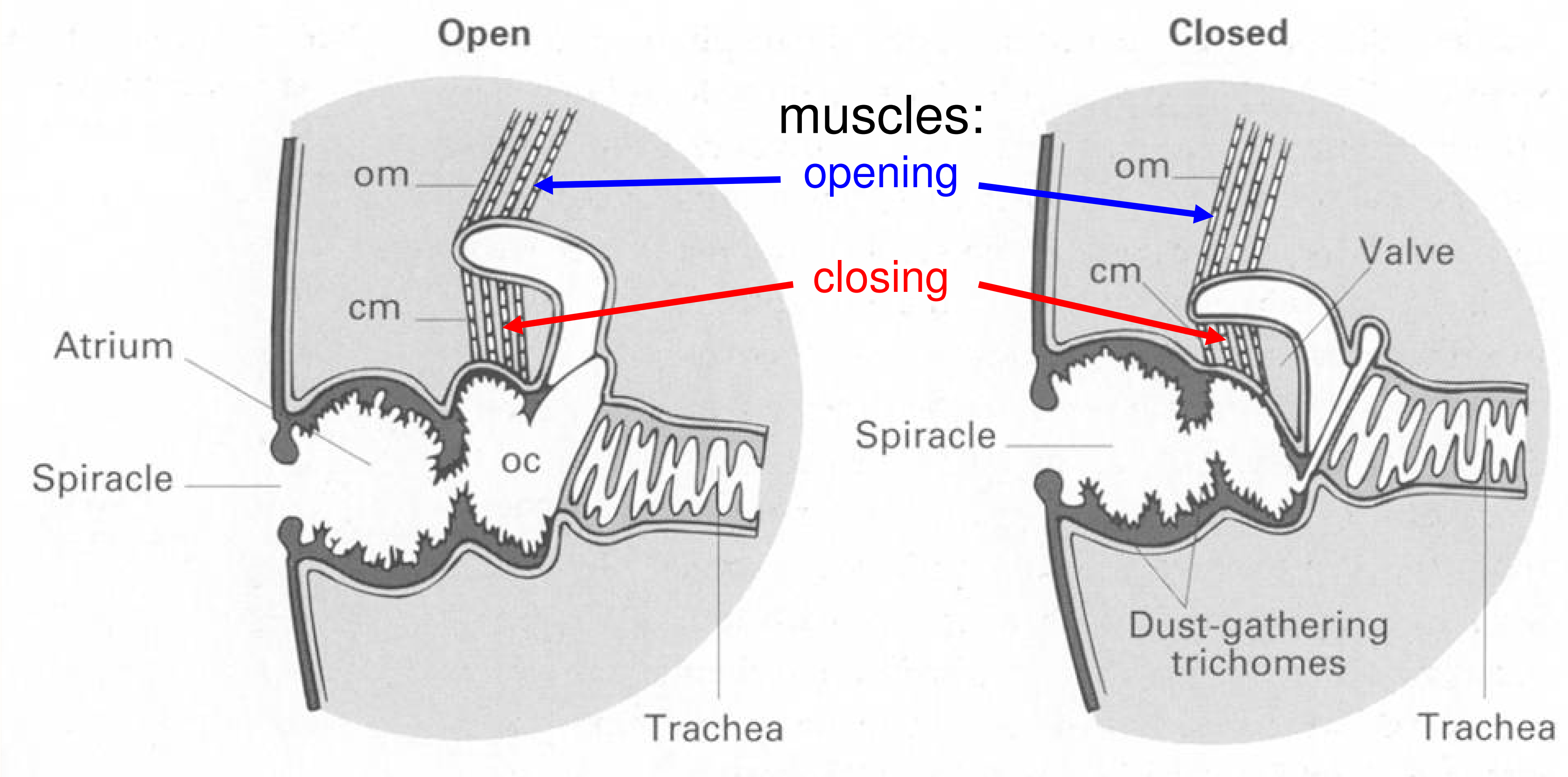
Willmer et al. 2000

Respiratory system in insects:
direct oxygen delivery from air to working cells



Willmer et al. 2000

Respiratory system in insects:
mechanism of ventilation control



opened **closed**

Willmer et al. 2000

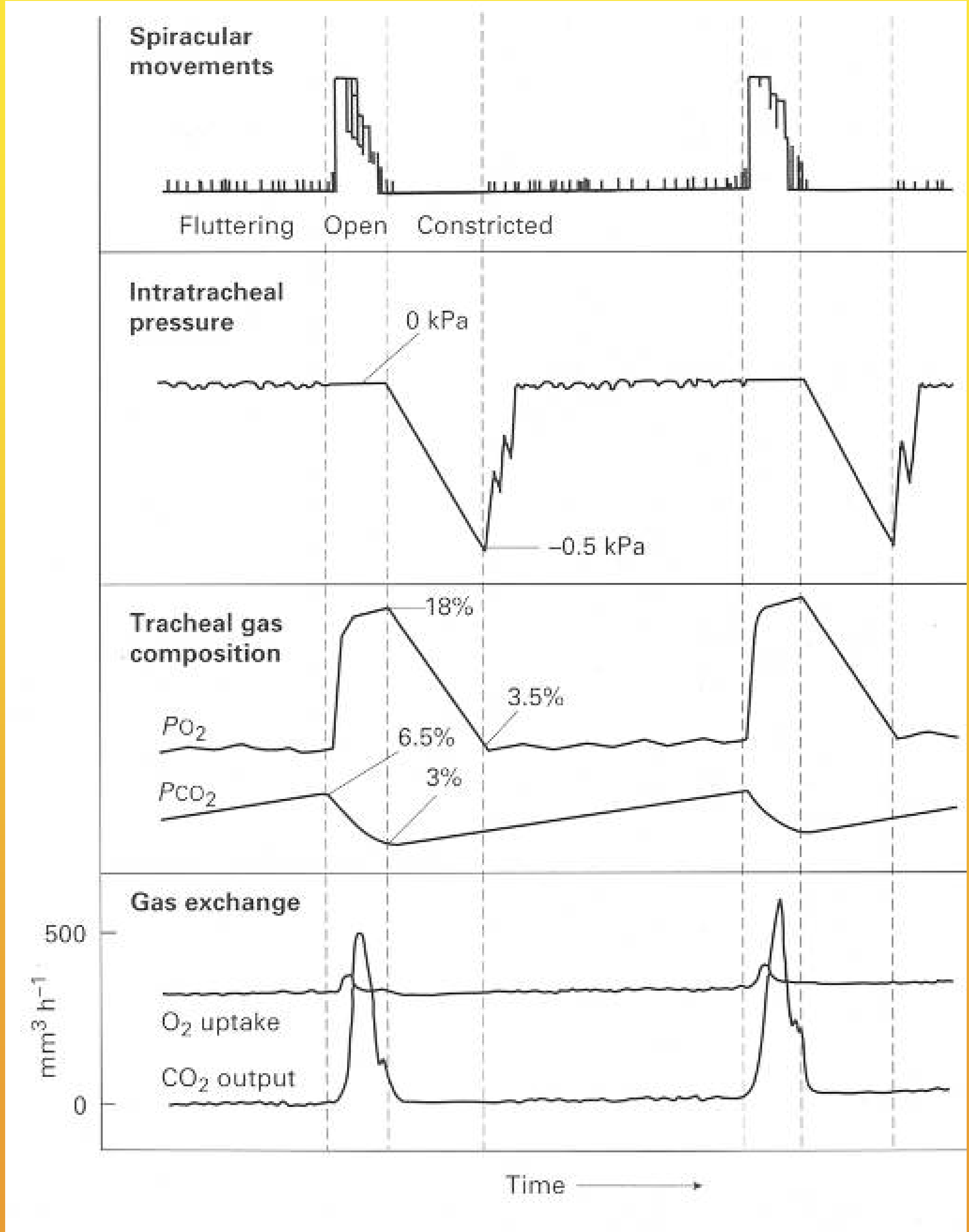
Mechanism of cycling ventilation

spiracle movements:
flattering - open - closed

intratracheal pressure

Tracheal gas composition:
P_{O_2} - oxygen content (%)
P_{CO_2} - CO_2 content (%)

Gas exchange:
Oxygen uptake
CO_2 output

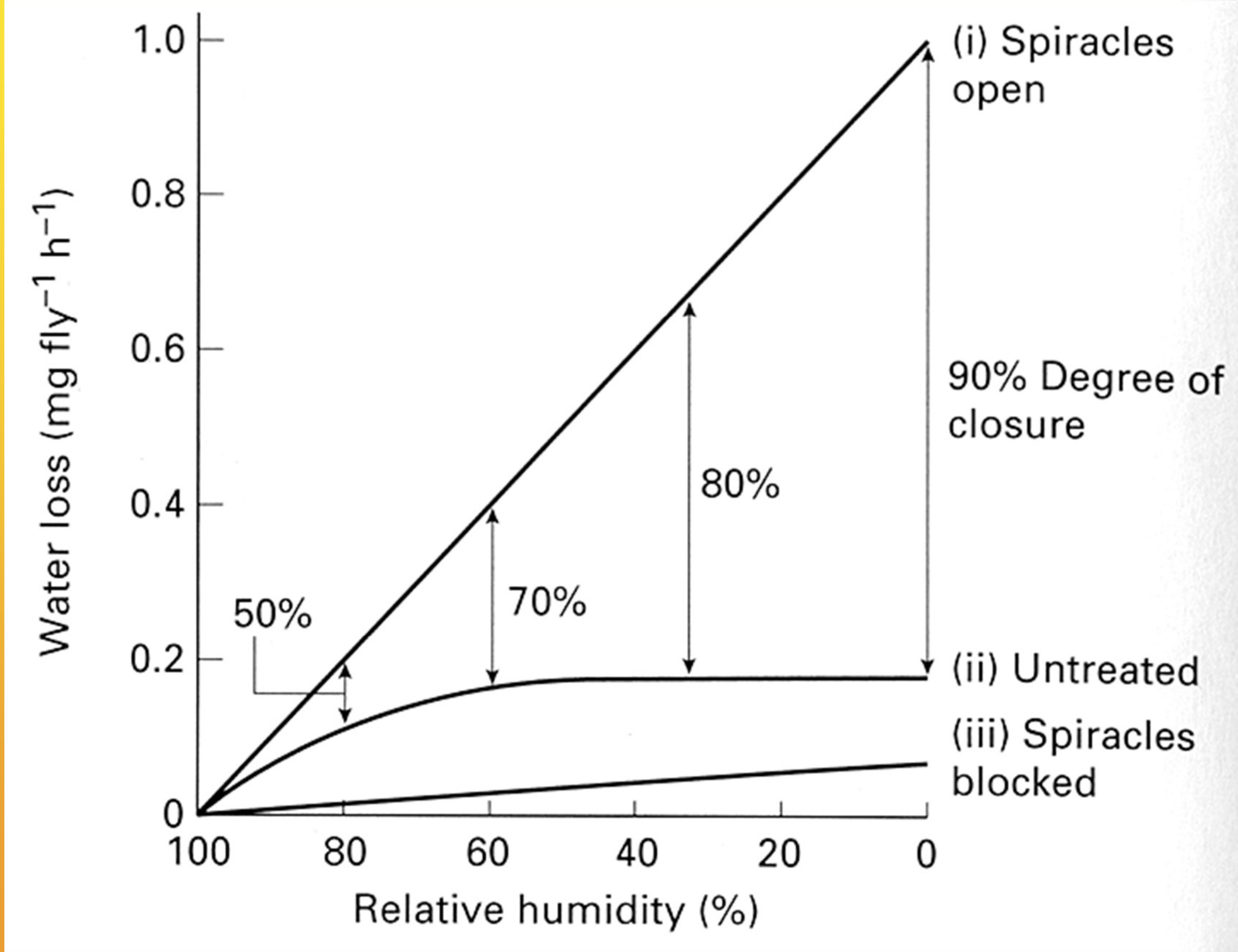


Willmer et al. 2000

Cycling respiration in insects

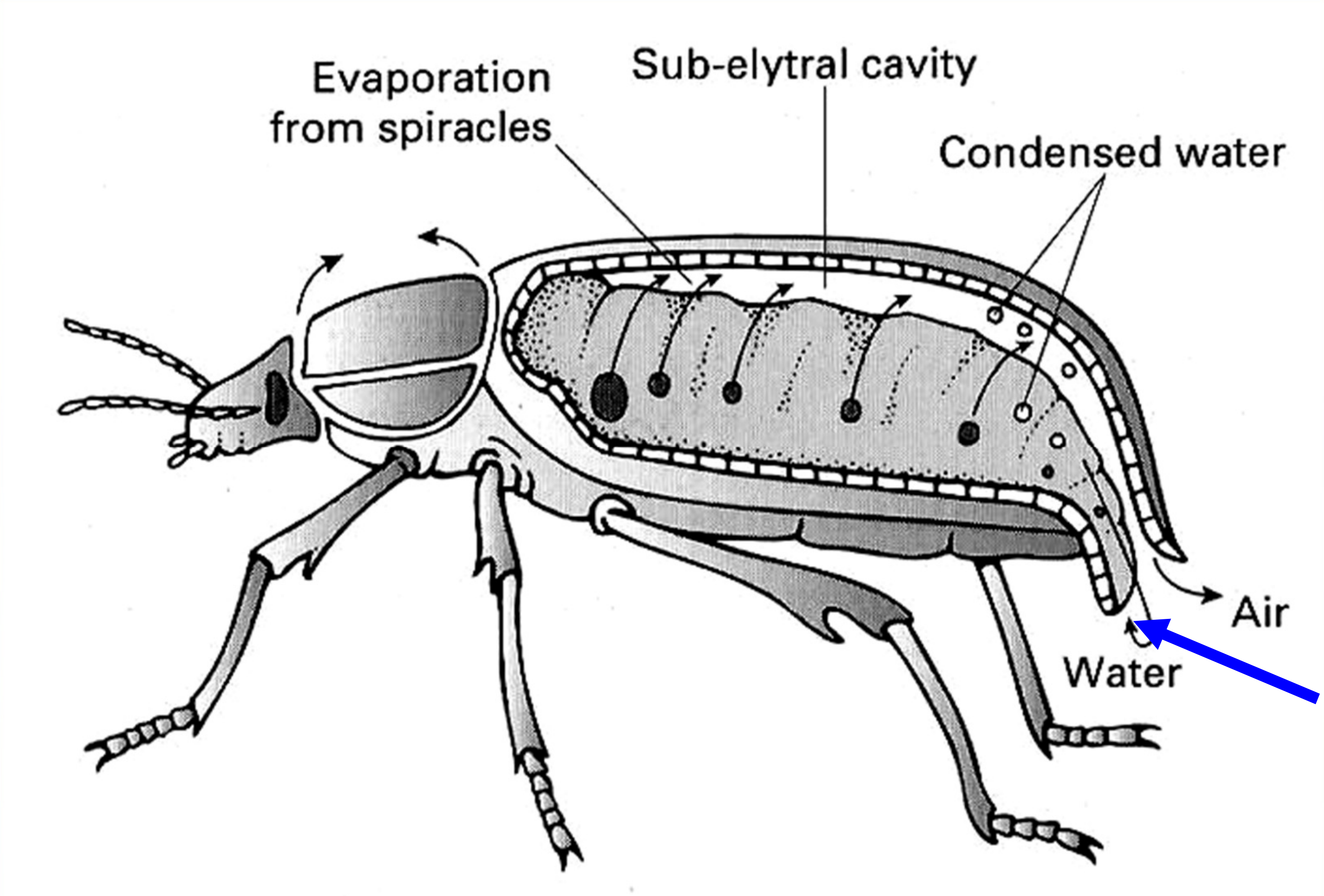
- **Hypotheses:**
- ~~cycling changes of~~ metabolism?
- **cycling ventilation**

Cyclic ventilation: water savings



Willmer et al. 2000

Respiratory water recovery



A tenebrionid beetle

condensed water returned to the body via the anus

Willmer et al. 2000

Water acquisition:
condensing water vapor by tenebrionid beetles

Mechanism:

- elytra covered by hydrophobic layer
- from which ultra-hydrophilic bristles („hair”) are sticking

- water condenses on the hydrophilic bristles
- and flows down along hydrophobic „ditches”

A tenebrionid beetle from the Namib Desert

Stenocara gracilipes

http://www.science-art.com/gallery/24409/24409_8292007213617.jpg

A tenebrionid beetle from the Namib Desert
Onymacris unguicularis

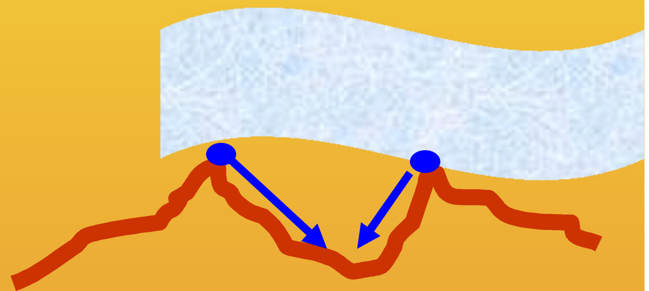
http://www.biomimicryinstitute.org/downloads/Inspiring_Organisms_Library_climate_change.pdf

A tenebrionid beetle from the Namib Desert
Onymacris unguicularis

źródło: Wikipedia

A tenebrionid beetle from the Namib Desert *Lepidochora discoidalis*

- The beetle builds trenches
- Water from mist condenses on the edges of the trenches



http://www.units.muohio.edu/cryolab/education/documents/SandroAdaptationLesson.pdf

Acquisition of water from the vapor without its condensation

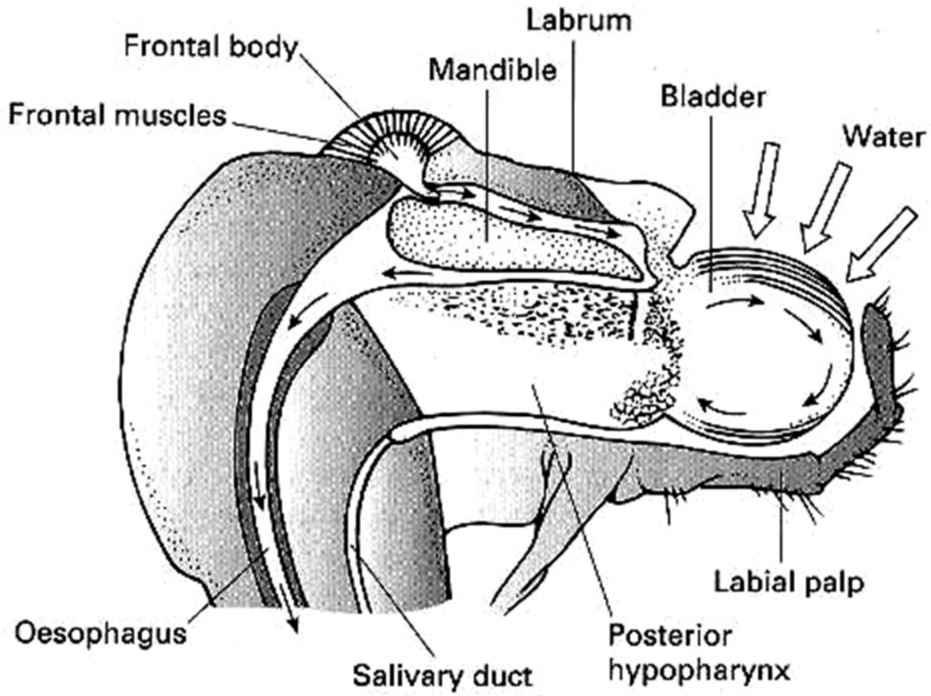
Desert "sand cockroaches" *Arenivaga sp.*

A sand roach from deserts of South-Western USA
(probably *A. investigada*)

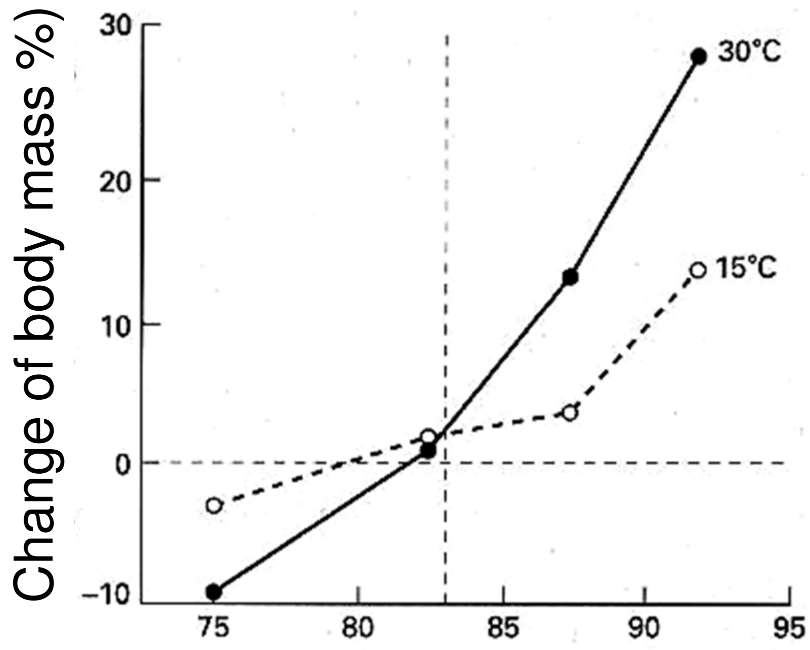
A. floridiensis

Acquisition of water from the vapor without its condensation

The mechanism described in *Arenivaga investigada*



Lateral section through the head



Relative humidity (%)

Willmer et al. 2000

Water: the most potent solvent

Only few processes concern pure water:

- Evaporation associated with respiration
- Absorption of condensed water

Most processes concern solutions:

- thermoregulation by sweating
- drinking liquid water
- excretion
- regulation of osmotic pressure
- regulation of hydrostatic pressure

Water: the most potent solvent

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- Evaporation associated with respiration
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- regulation of osmotic pressure
- regulation of hydrostatic pressure

⇩

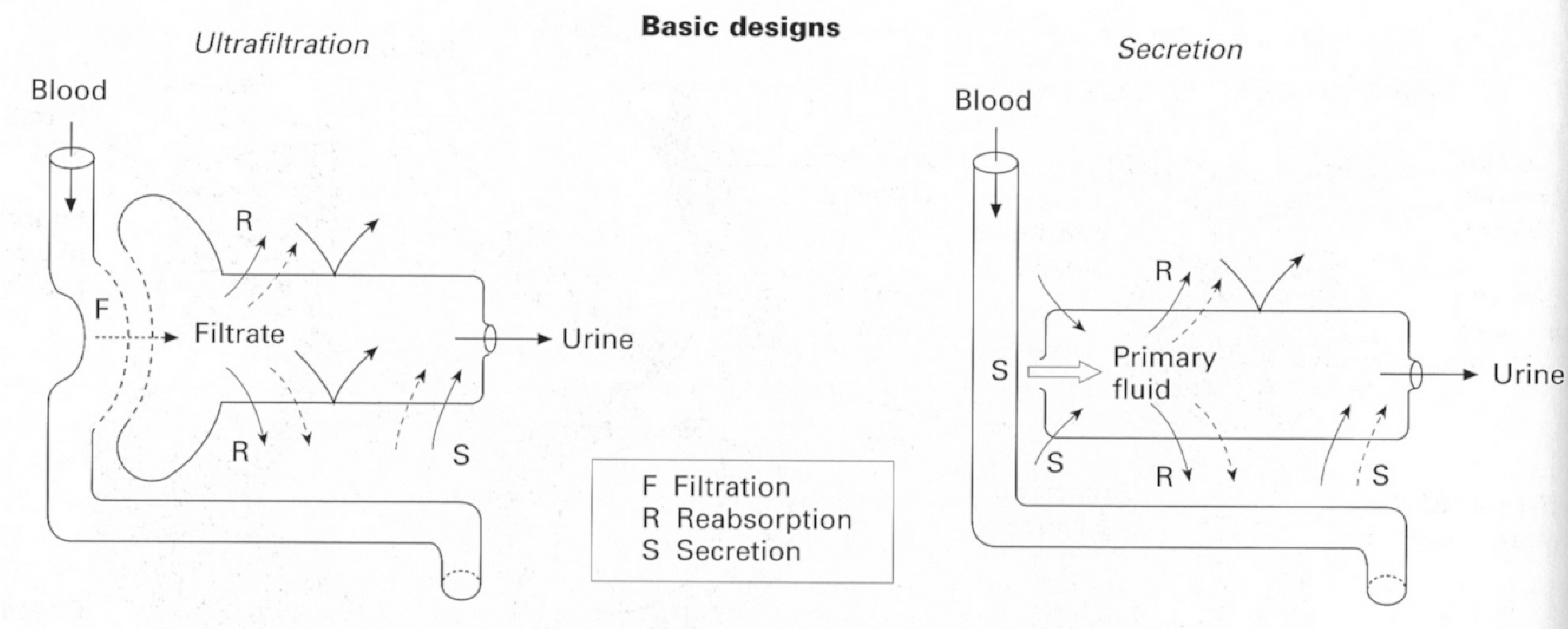
Water-mineral regulation

Key processes in water-mineral regulation

- Osmosis
- Ultrafiltration
- Selective diffusion through plasmatic membrane channels
- Regulation of membrane permeability
- Active transport through membranes
- Co-transport supported by osmotic gradients

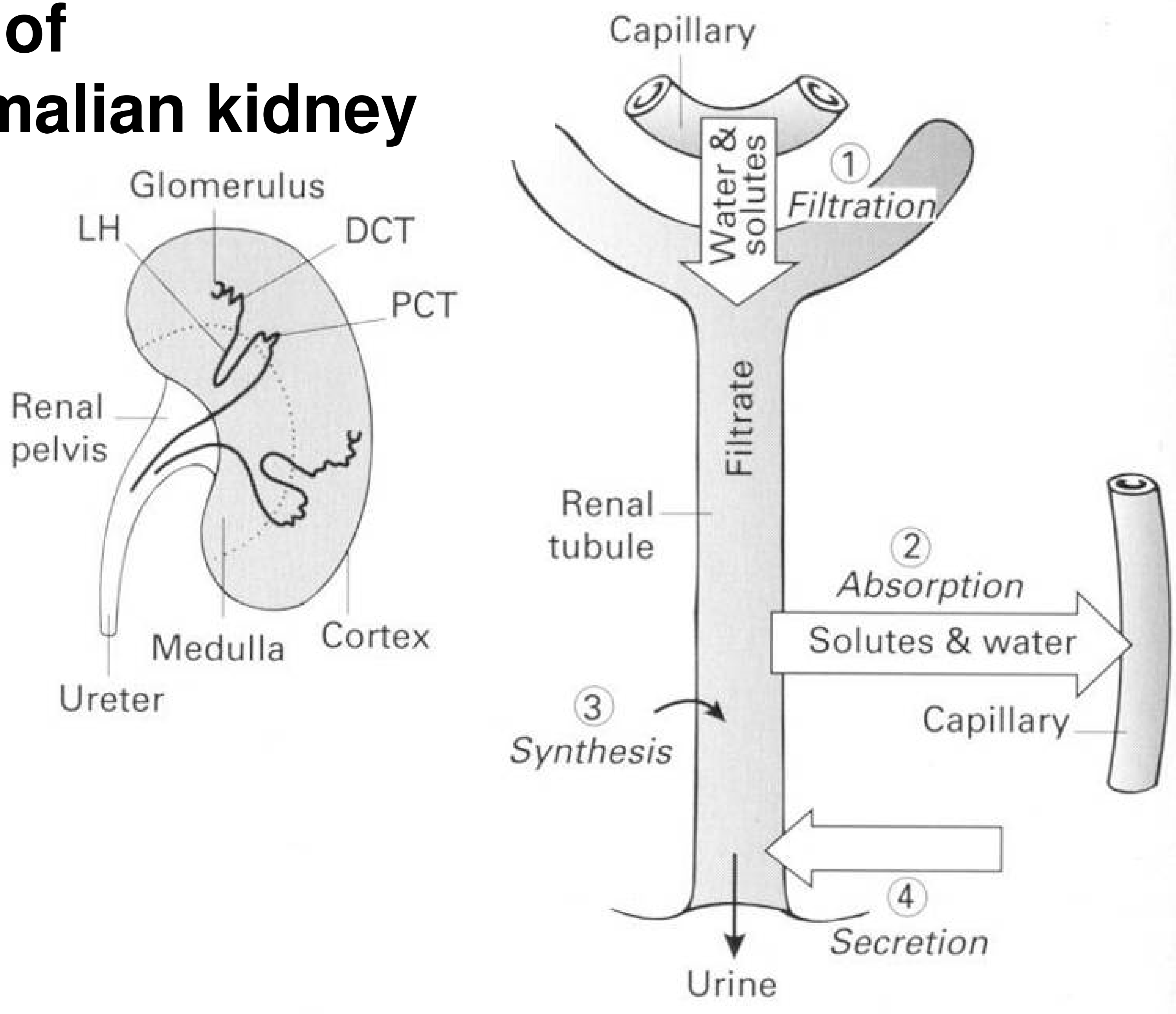
Basic designs of excretory organs

Ultrafiltration Secretion



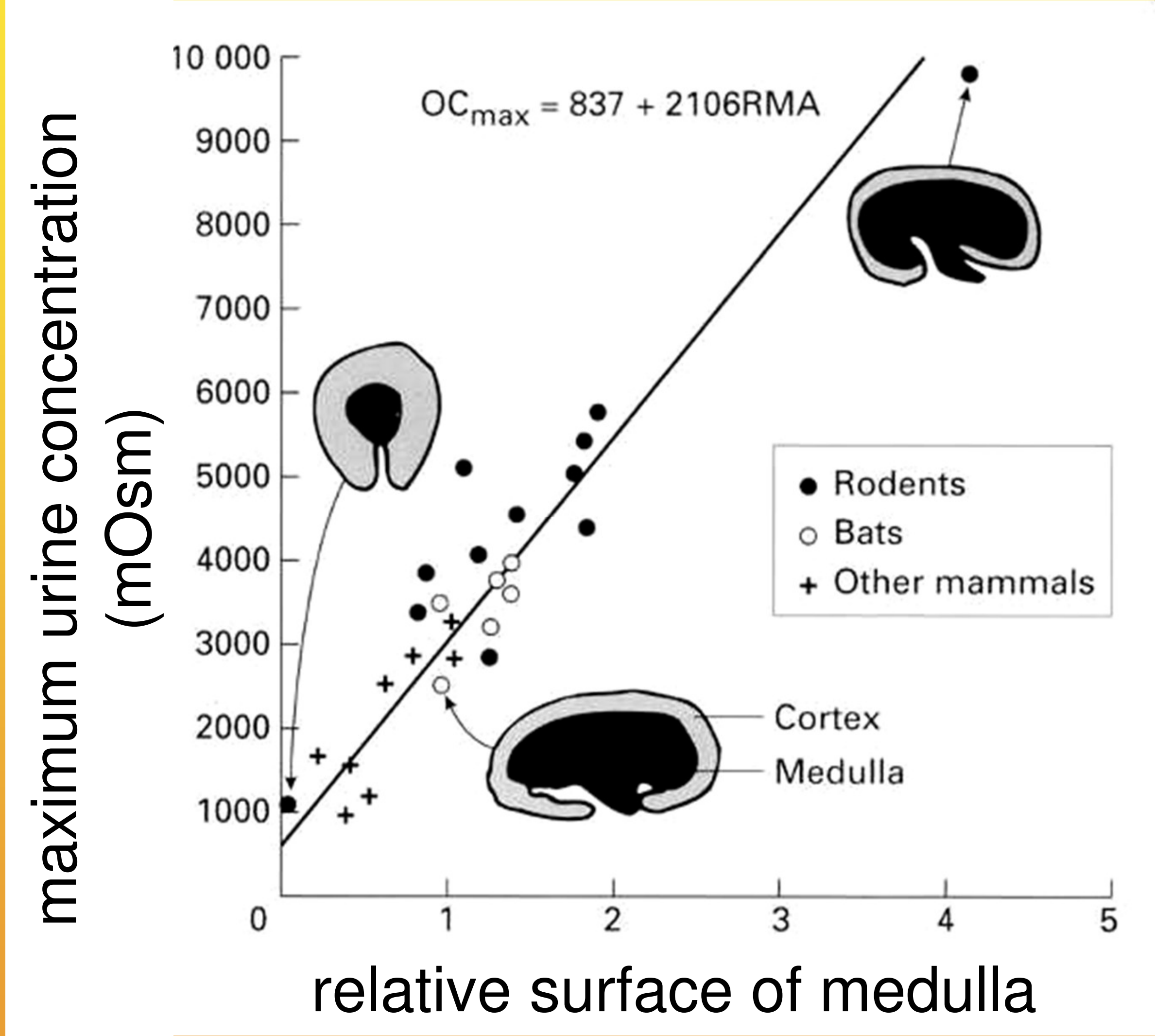
Willmer et al. 2000

Design of a mammalian kidney



Willmer et al. 2000

Relation between kidney morphology and urine concentration in mammals



Willmer et al. 2000

Spiny mouse *Acomys cahirinus*

(Near East, North Africa)

Urine concentration can exceed 9000 mOsm

http://www.tau.ac.il/lifesci/departments/zoology/members/kronfeld/images/

Spiny mouse *Acomys russatus*

(Near East, Negev Desert)

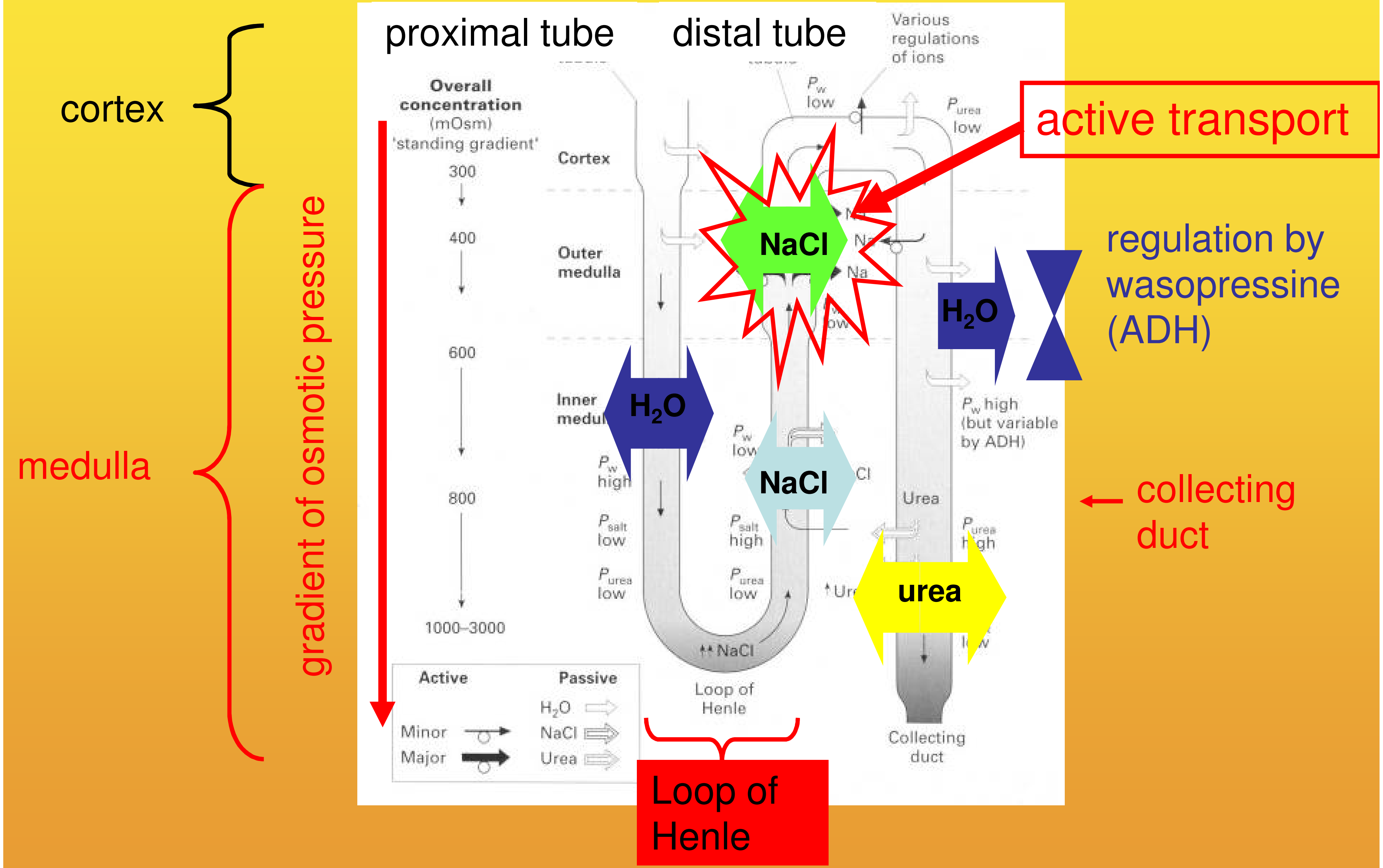
http://animaldiversity.ummz.umich.edu/site/resources/susan_hoffman/acomys.jpg/view.html

Spiny mouse *Acomys nesiotes*

(Cyprus)

http://www.treknature.com/gallery/Middle_East/Cyprus/photo140674.htm

Nephron - a countercurrent "amplifier"



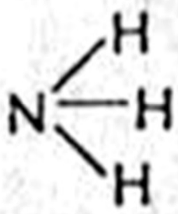
Willmer et al. 2000

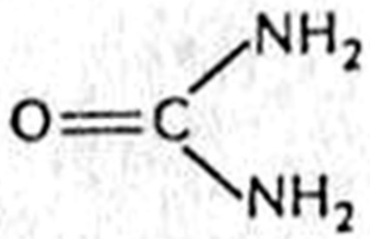
Relation between kidney morphology and urine concentration

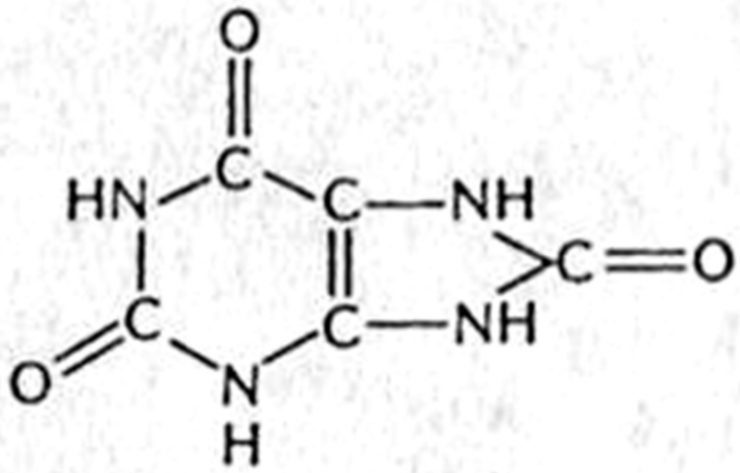
- Reptiles do not have the Henle's loop
- Birds have very short loops
- **How can they dwell in arid habitats?**

The most important forms of nitrogen excretion

Ammonia **Urea** **Uric acid**







The most important forms of nitrogen excretion

Form	Toxicity	Cost	Solubility
ammonia	high	no	high
urea	low	low	high
Uric acid	low	**high**	**low**

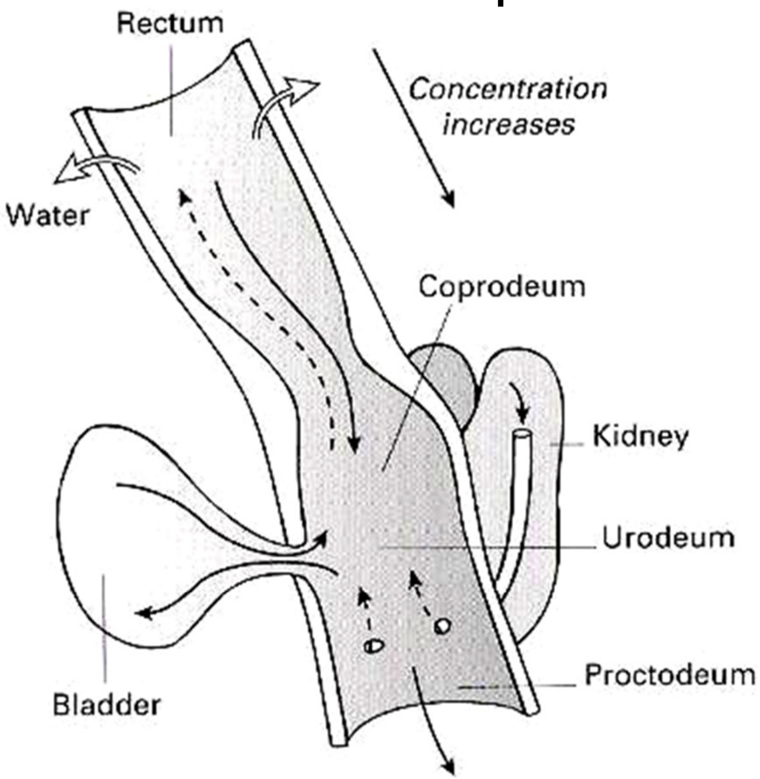
converts to crystal form

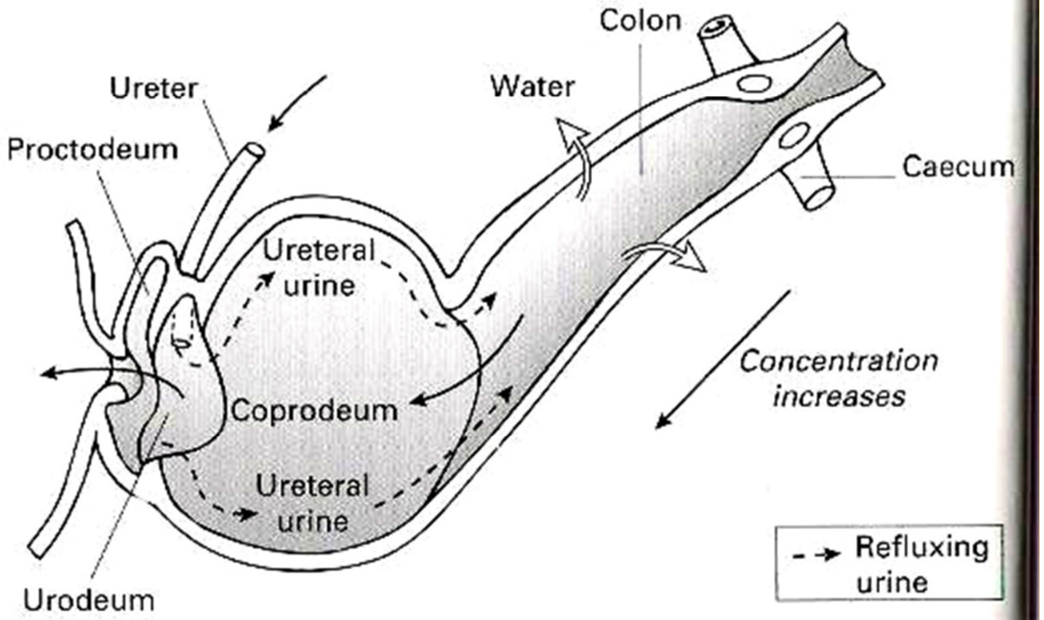
How do birds and reptiles cope with low water availability?

- Urine (not very concentrated) is removed to cloaca
- Water is resorbed in cloaca
- **Uric acid forms crystals: the osmotic pressure is not increased!**
- The „urine” can be almost dry

How do birds and reptiles cope with low water availability?

reptiles | birds



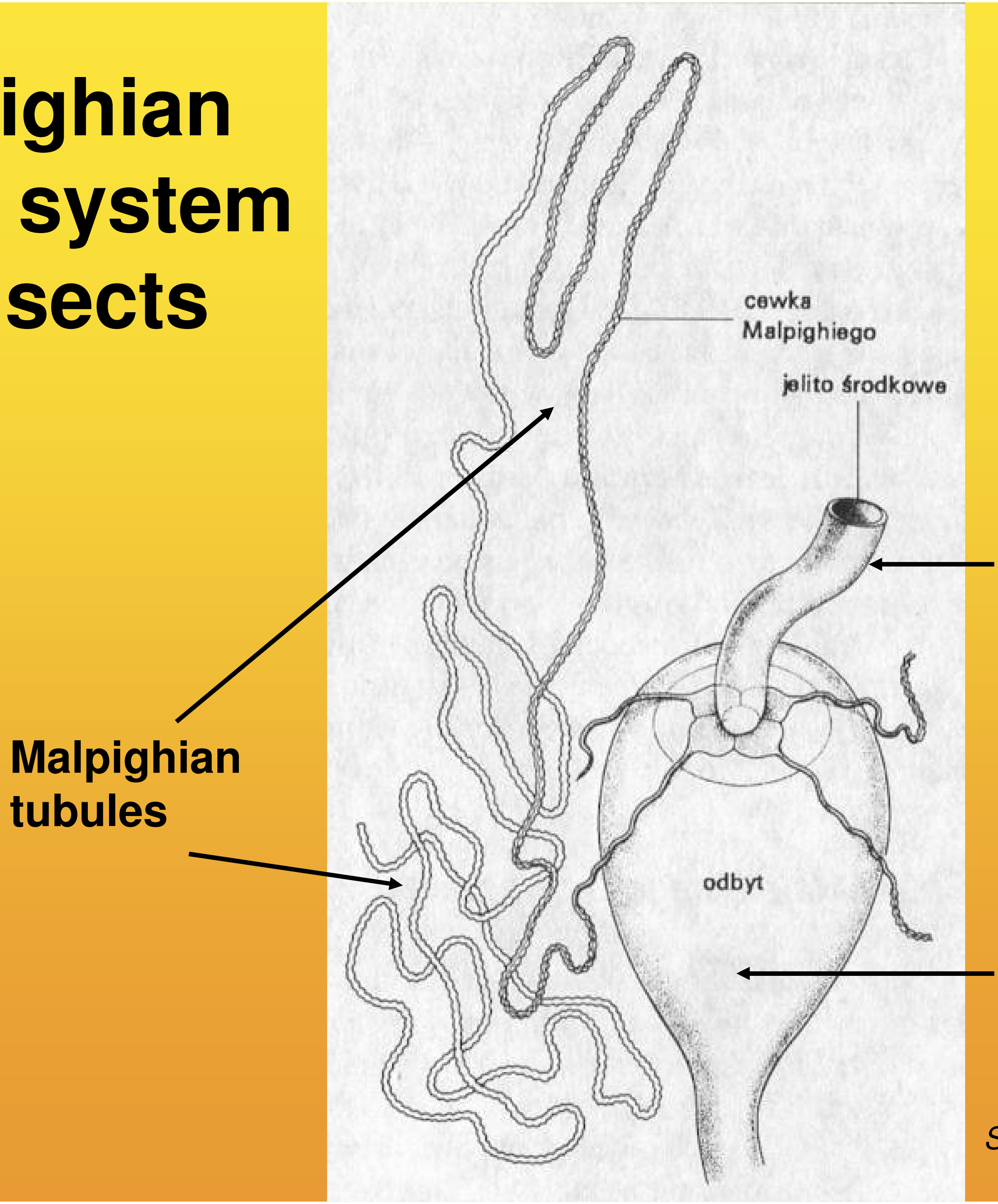


Water retrieval in cloaca

Willmer et al. 2000

Other excretory systems

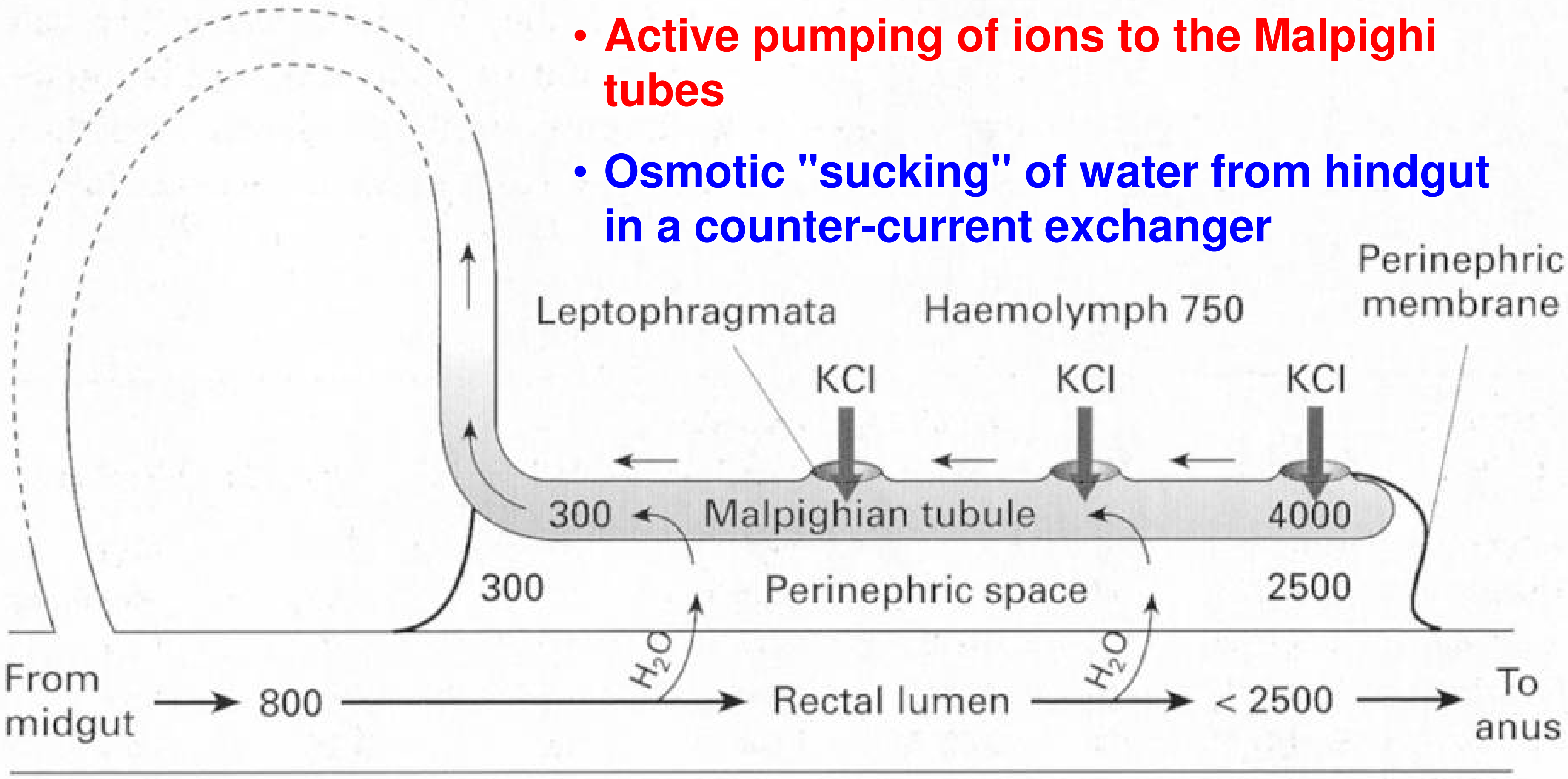
Malpighian tubule system in insects



Schmidt-NIelsen 2008
Animal Physiology

Resorption of water in insects dwelling in arid habitats

- Active pumping of ions to the Malpighi tubes
- Osmotic "sucking" of water from hindgut in a counter-current exchanger

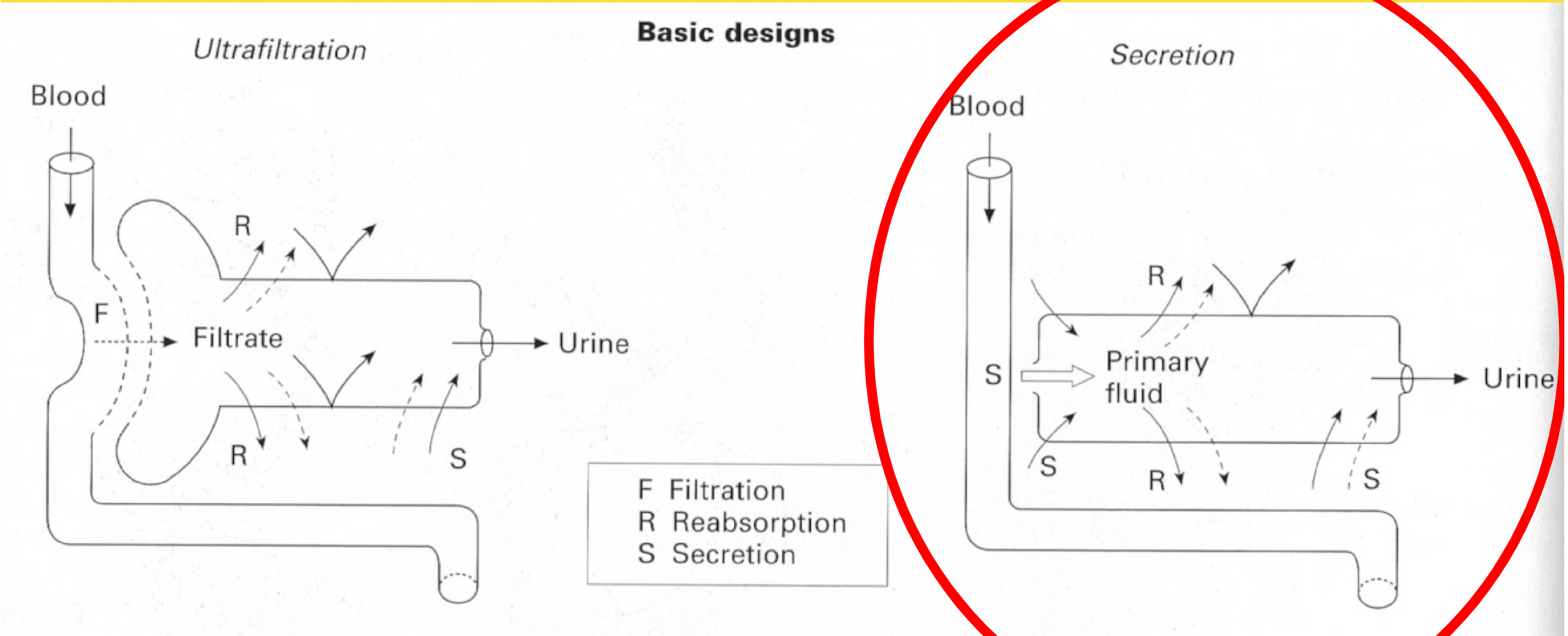


solution concentration (mOsm)

Willmer et al. 2000

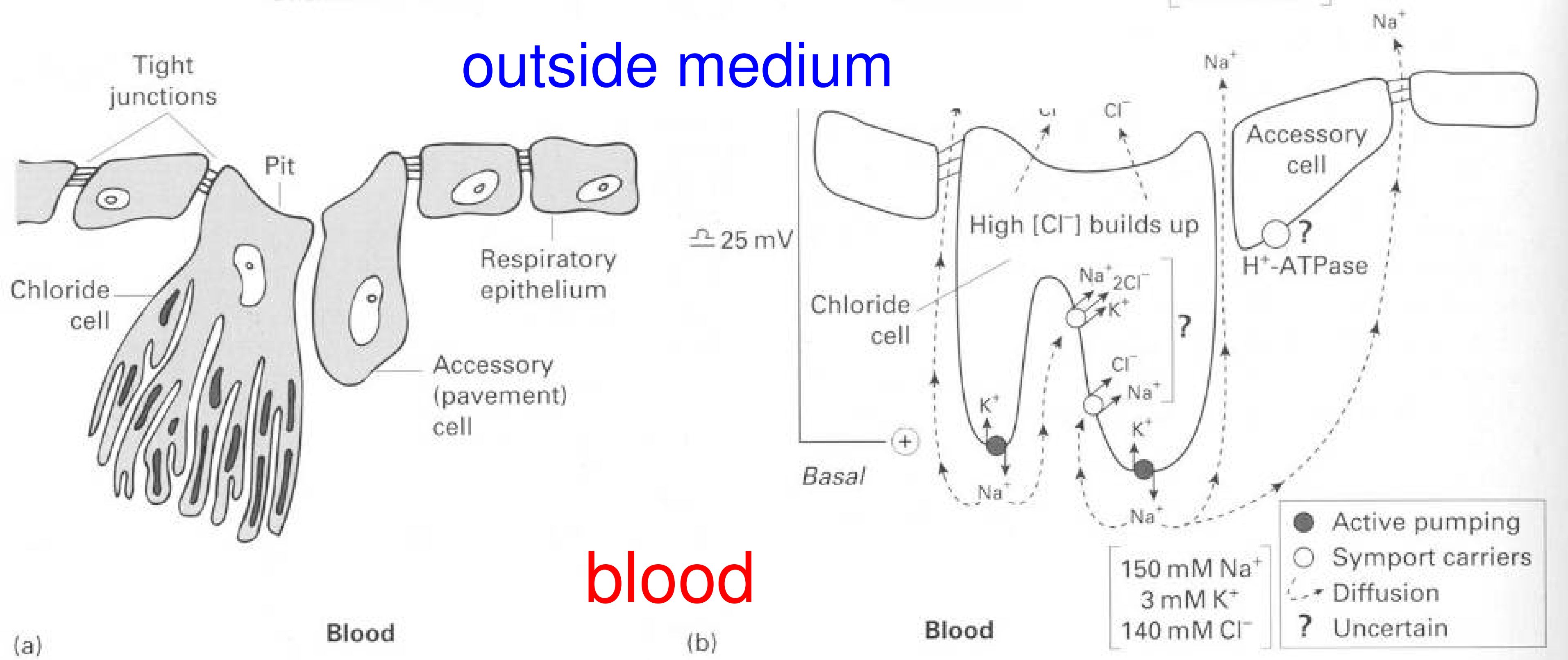
Basic designs of excretory organs

Ultrafiltration
Secretion



Willmer et al. 2000

Salt glands in desert reptiles and birds
(similar to glands in some marine animals)



Active transport of Na^{+}/K^{+} cations into chloride cells works as a pump drifting the transport of chloride anions (Cl^{-})

Willmer et al. 2000

Coping with low food availability

Food availability

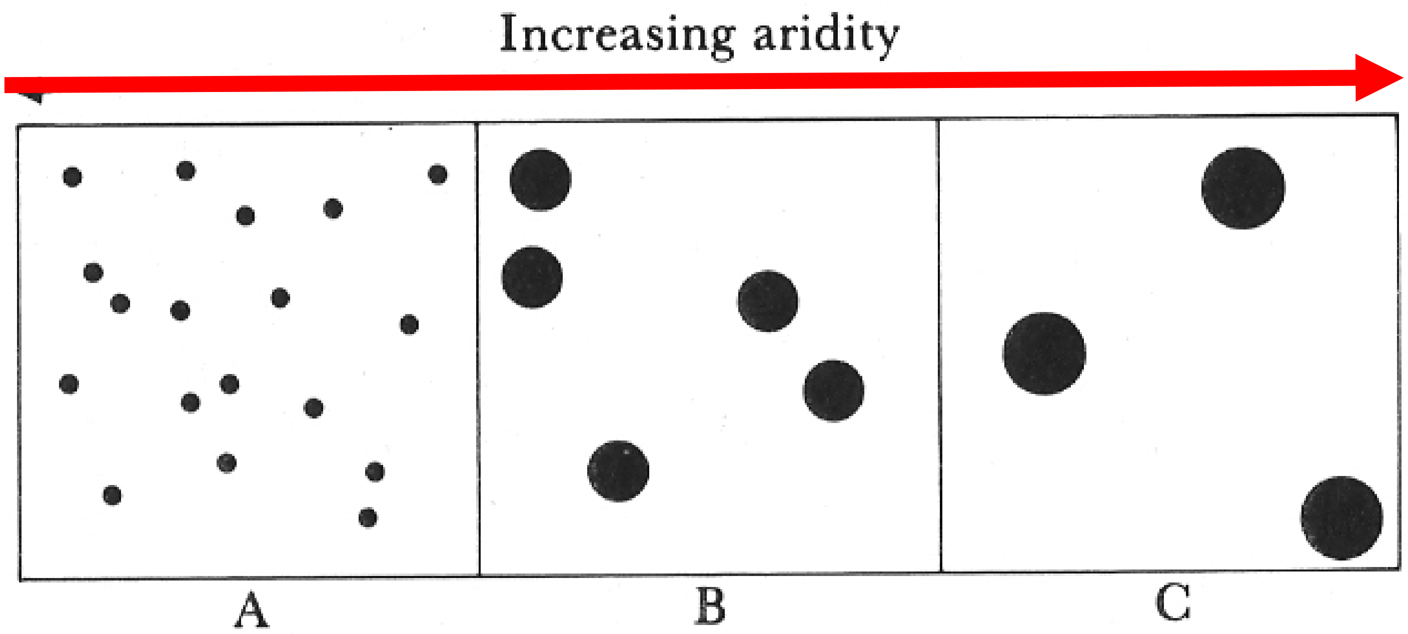
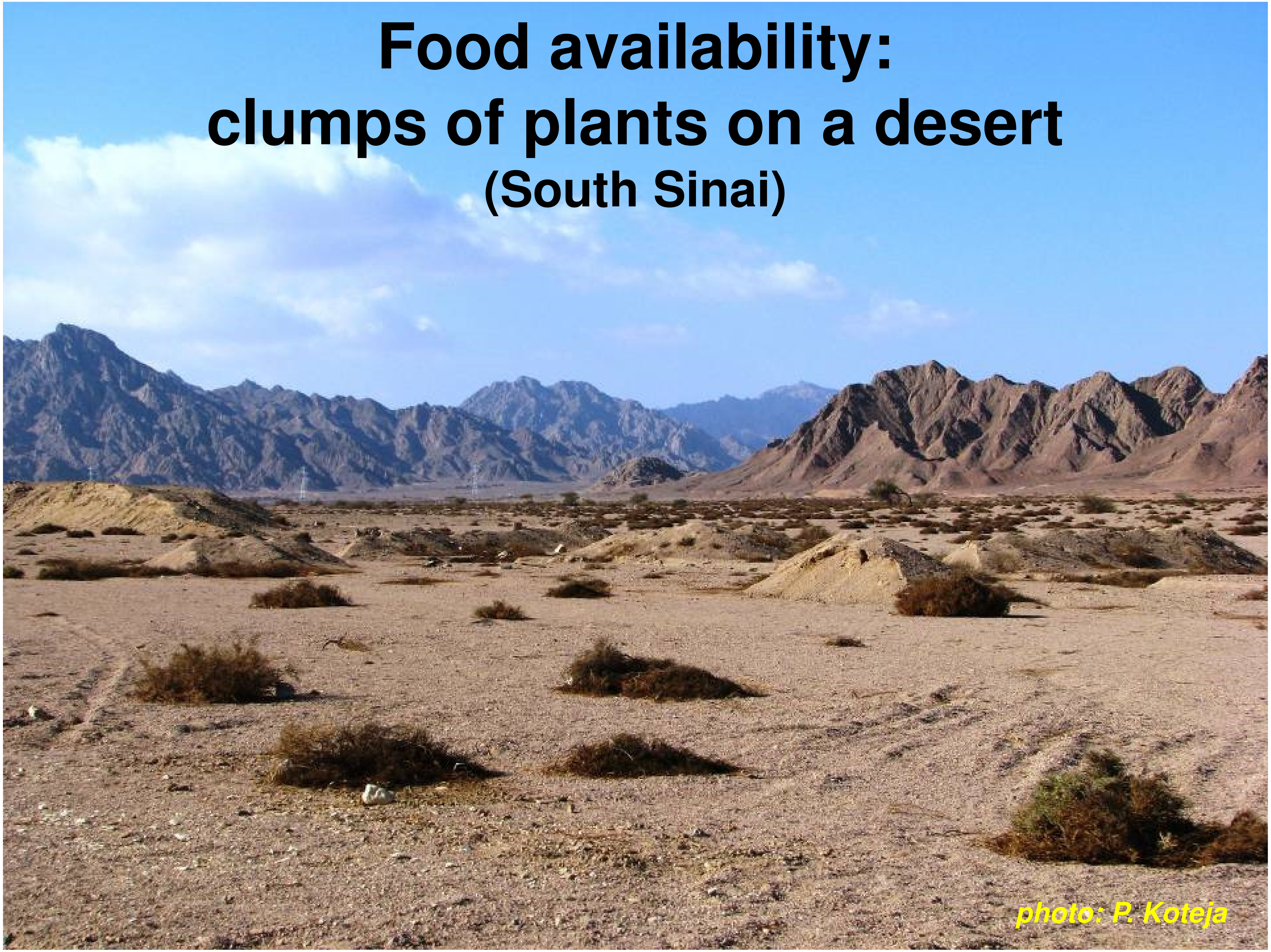


Figure 3.30 Diagrammatical representation of the general trend, with increased aridity, of increased plant tuber size and increased nearest-neighbour distance. Tuber distributions are markedly random for the situation depicted in (B) and (C), but are unknown for the mesic situation depicted in (A). Redrawn from Lovegrove and Wissel (1988).

Louw 1993 Physiological animal ecology

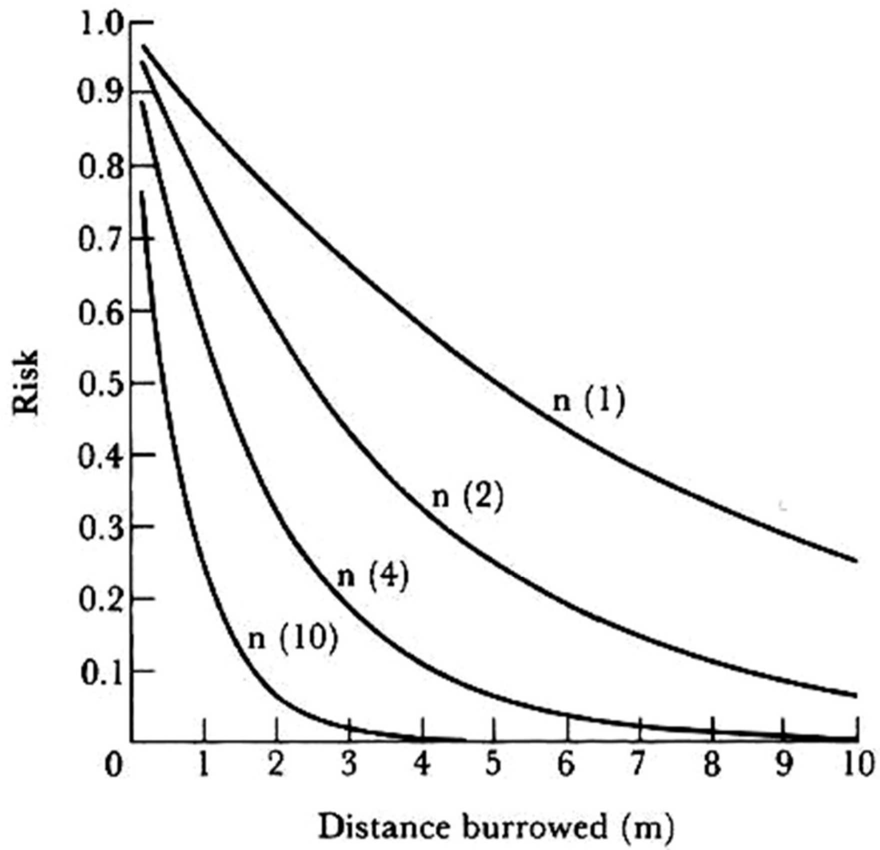
Food availability: clumps of plants on a desert

(South Sinai)



Food availability

Risk of foraging failure is lower during cooperative foraging



32 The decay curves of foraging risk, quantified as the probability of no encounter with a plant tuber, as a function of distance burrowed for different numbers (*n* of cooperatively foraging mole rats). The data show rapid reduction in risk with increasing numbers of cooperatively foraging mole rats. After Lovegrove and Wissel (1988).

Louw 1993 Physiological animal ecology

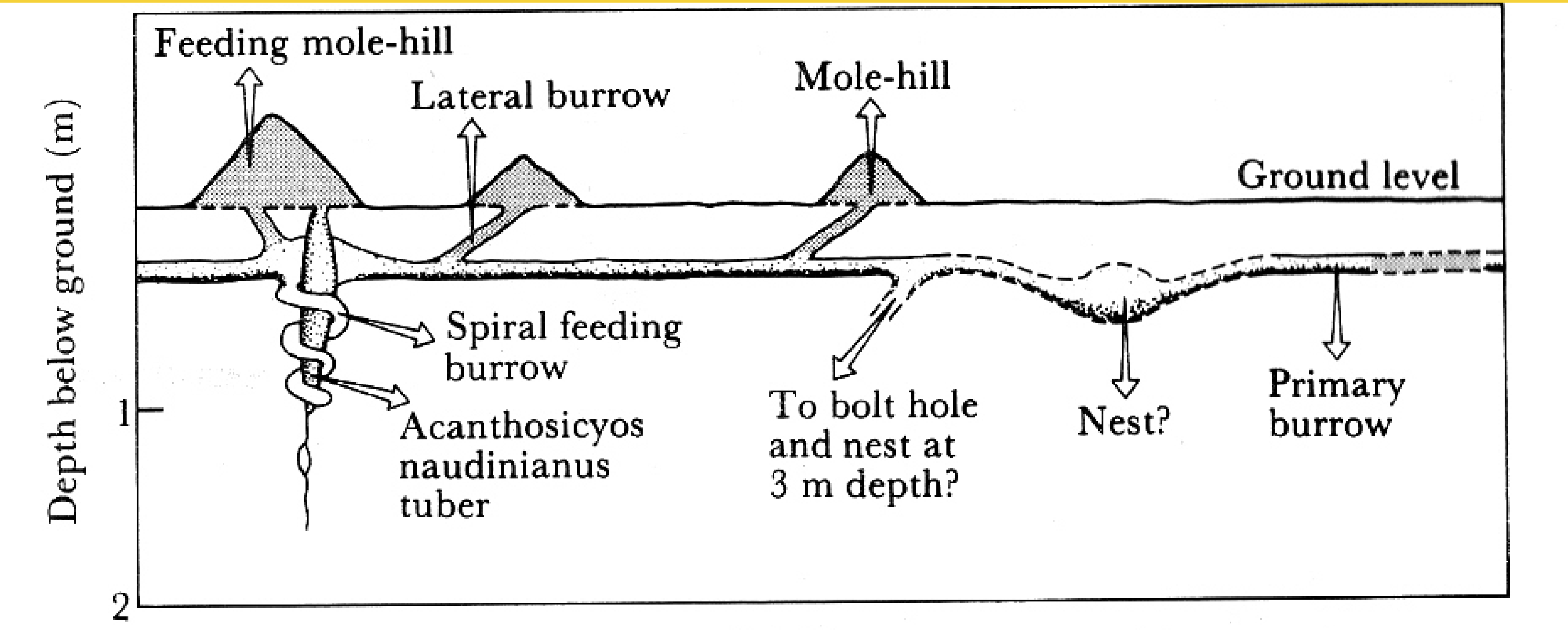
Social life...

Eusocial mammal !

Damaraland mole rat

Cryptomys (=Fucomys) damarensis

South Africa, Namib desert



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Heterocpehalus glaber from www.animalpicturesarchive.com (also on Wikipedia)

Social life...

Meerkat *Suricata suricatta*

Photo: Wikipedia

SUMMARY:
adaptation of animals to desert habitats

- **Minimizing overheating risk: fossorial (underground) microhabitat**
- **Water economy:**
  - minimizing evaporation
  - condensing urine
  - water acquisition from water vapor
- **Low rate of metabolism, extended lifespan (a topic for a separate lecture!)**
- **Life in groups: sociality**