



# Teeth and the gastrointestinal tract in mammals: when $1 + 1 = 3$



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SEB Montpellier 2022*



**University of  
Zurich**<sup>UZH</sup>



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GEORG-AUGUST-UNIVERSITÄT  
GÖTTINGEN

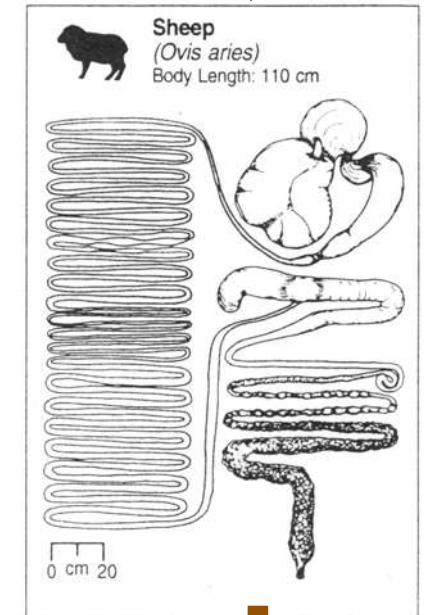
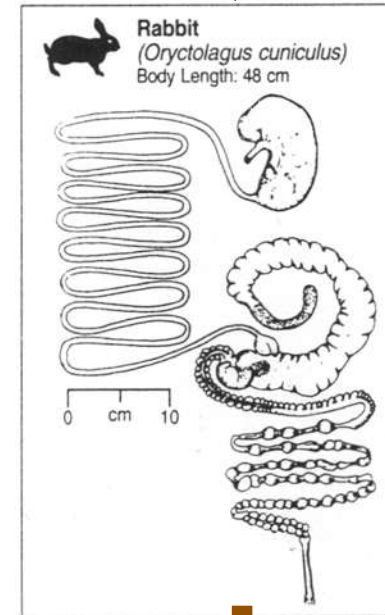
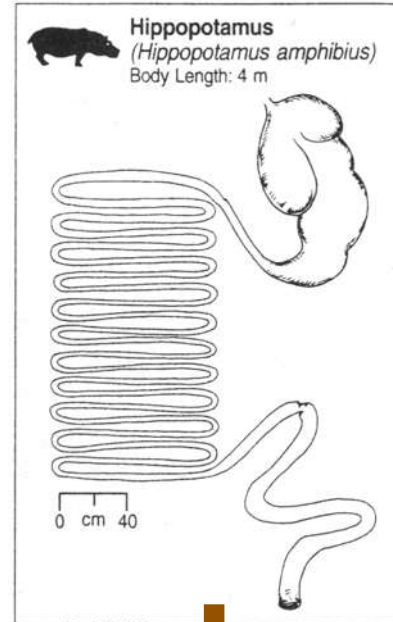
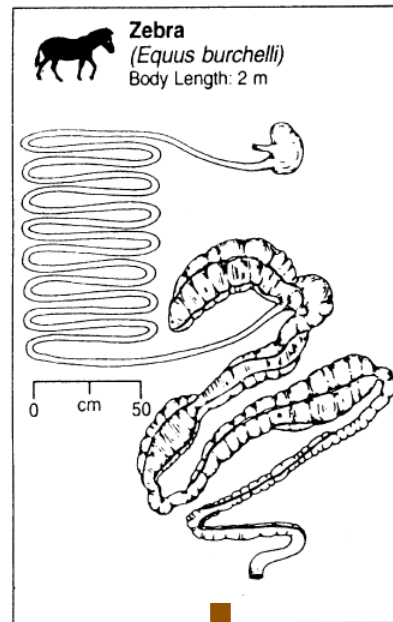
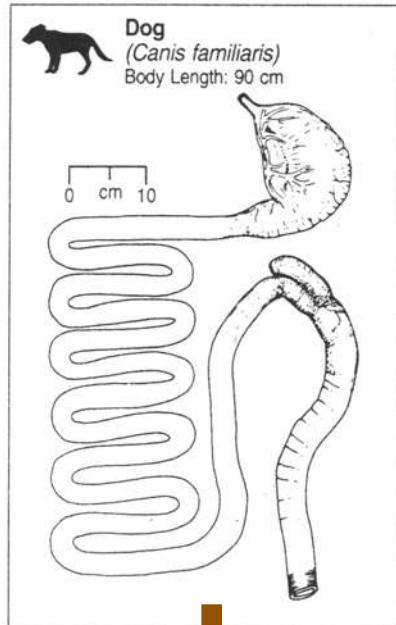
**AgroVet  
Strickhof**



# Sequential processing

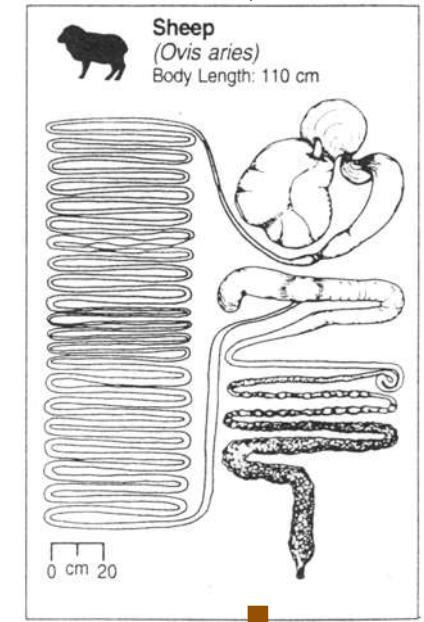
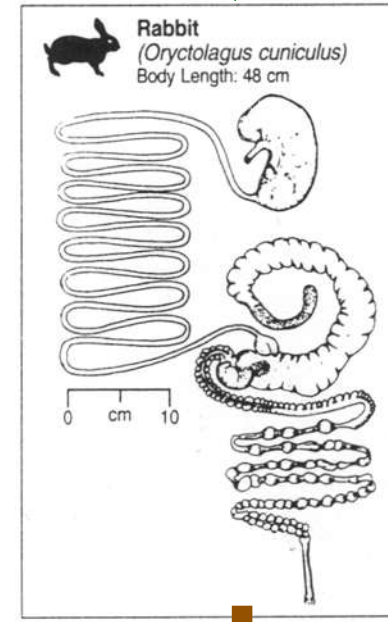
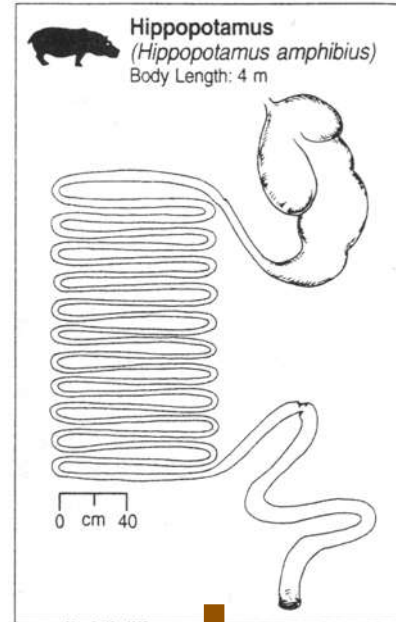
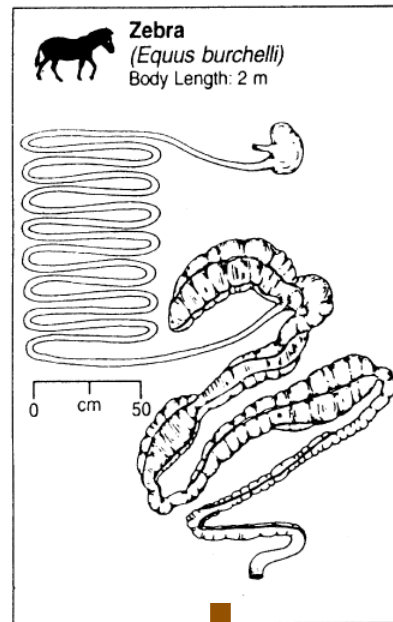
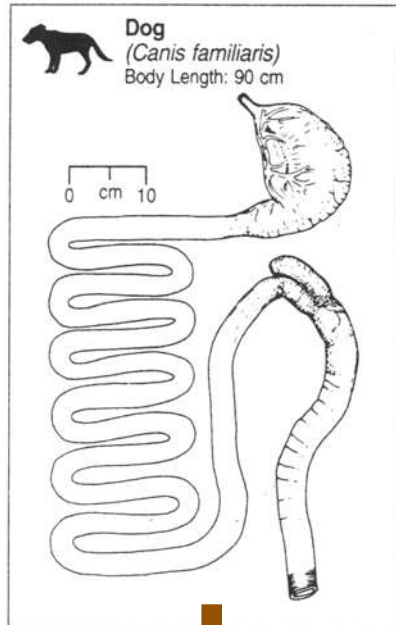


# A one-way process





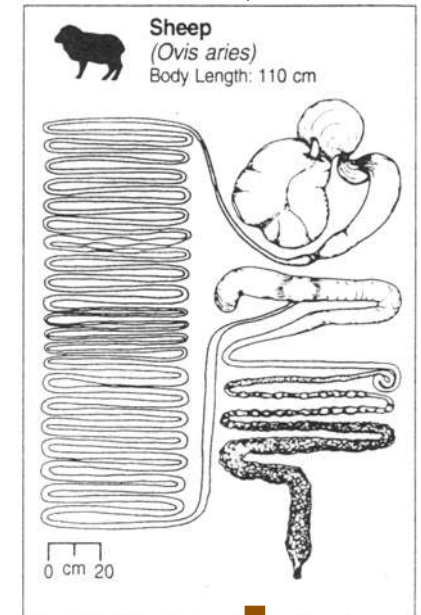
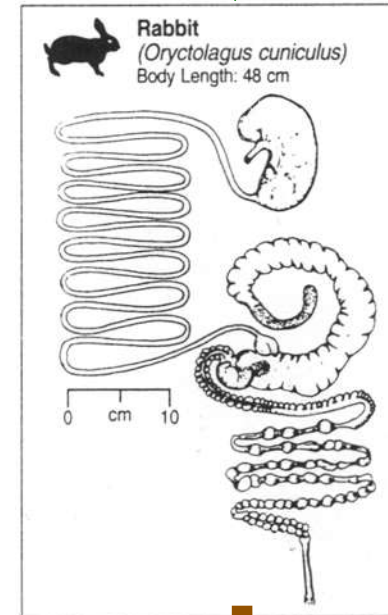
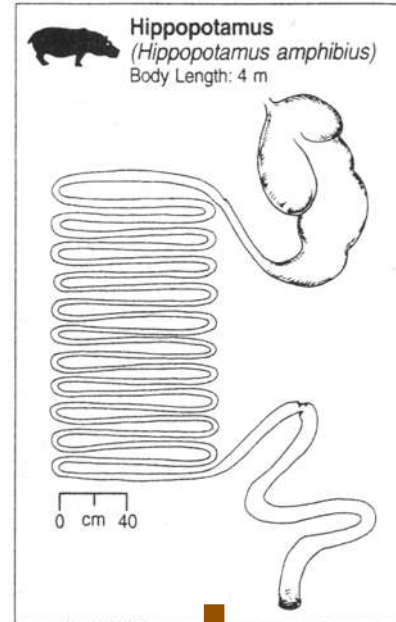
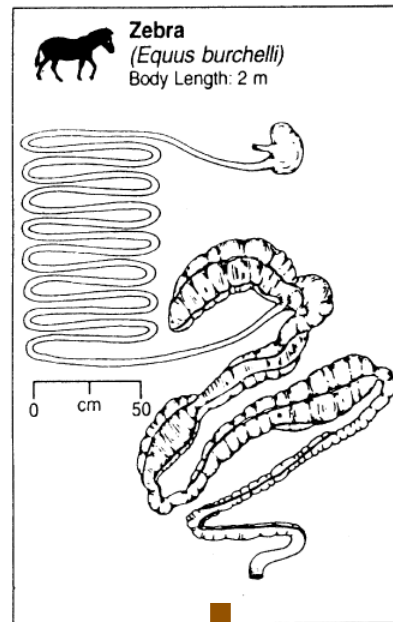
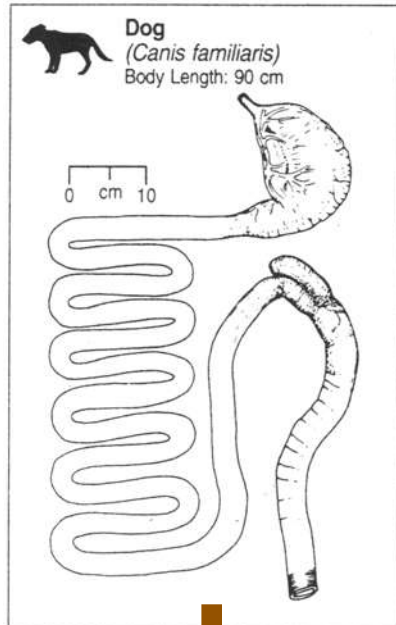
# Teeth and gut do their own thing





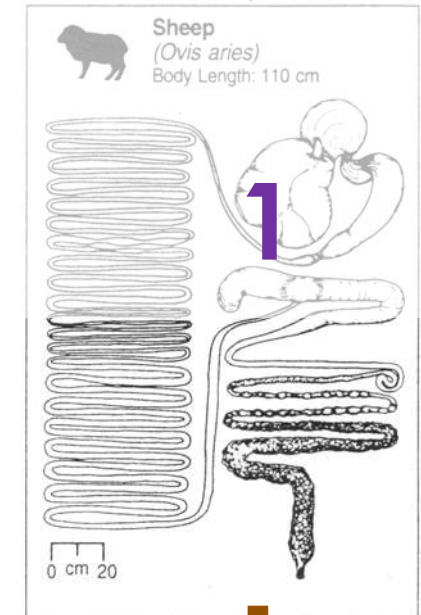
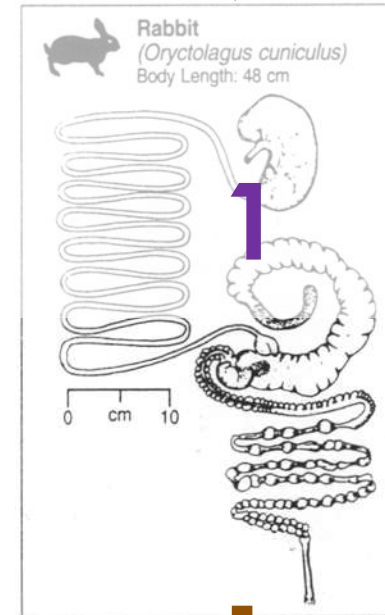
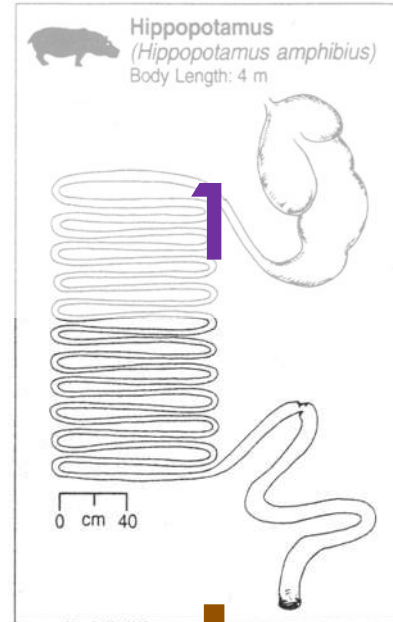
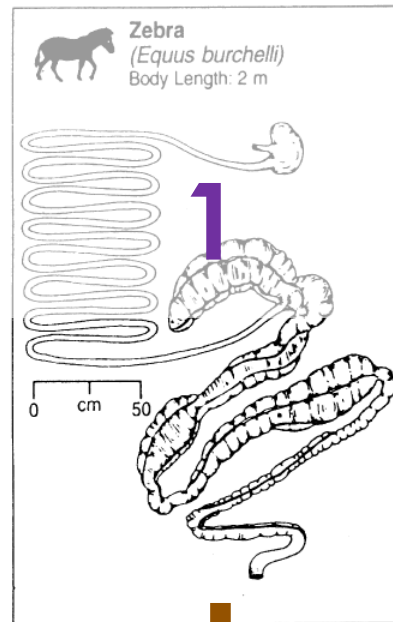
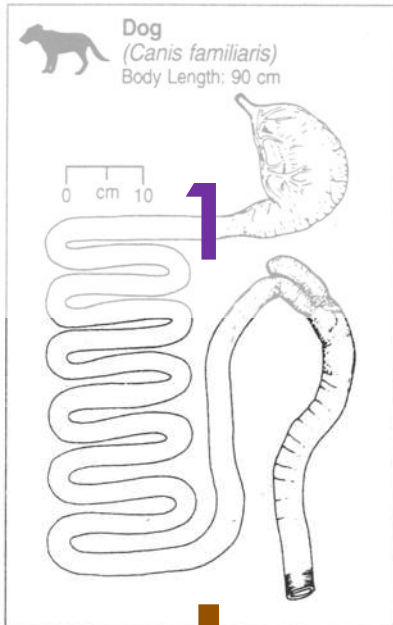


# Teeth and gut do their own thing



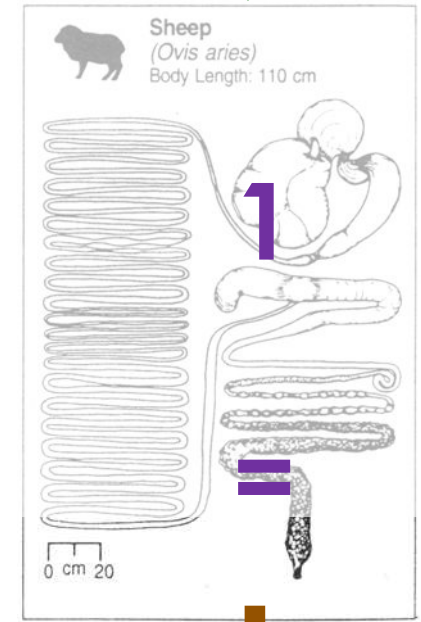
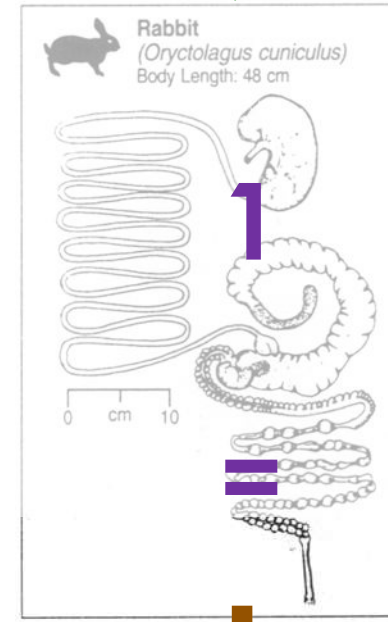
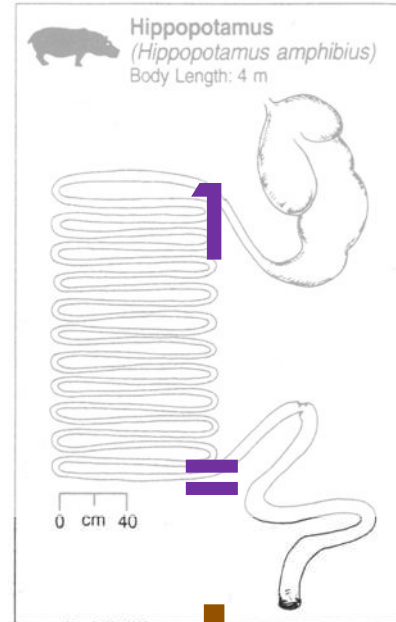
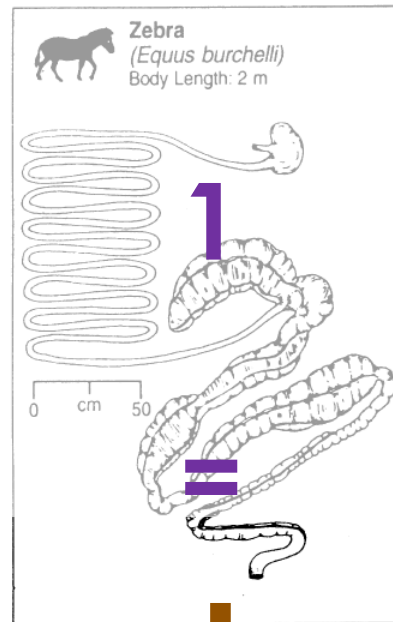
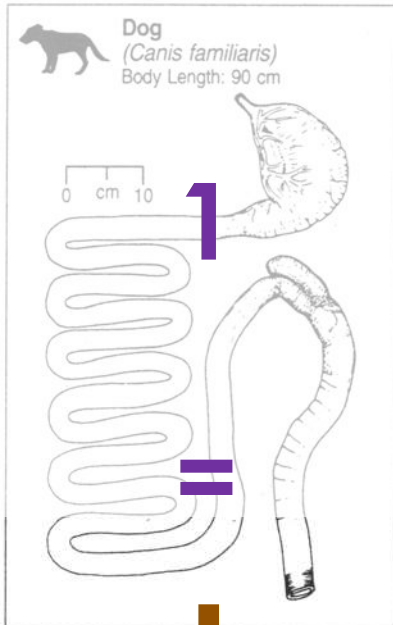


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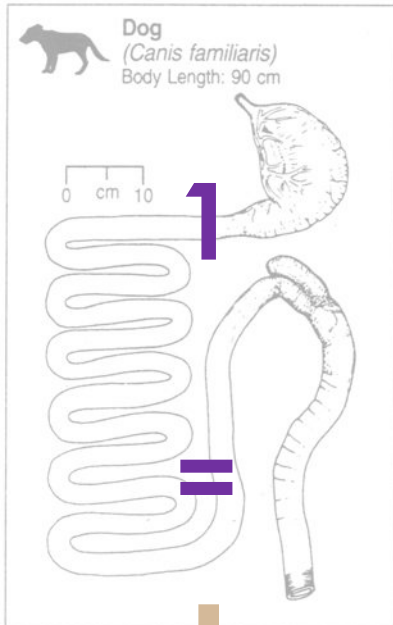


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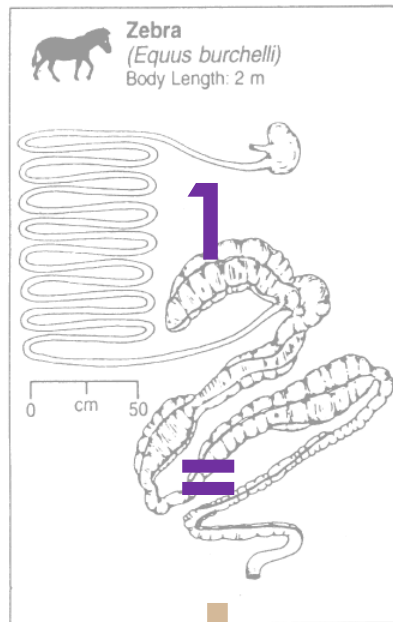




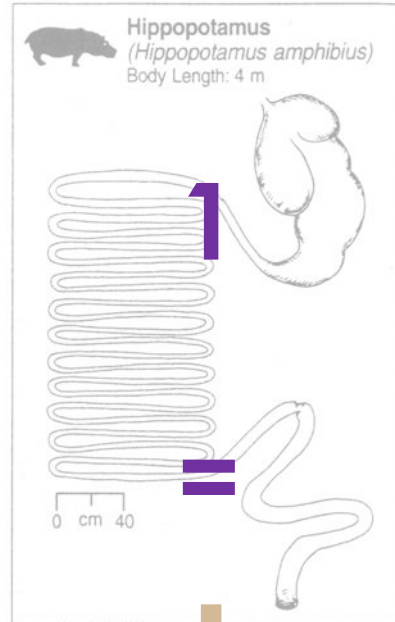
# Teeth and gut do their own thing



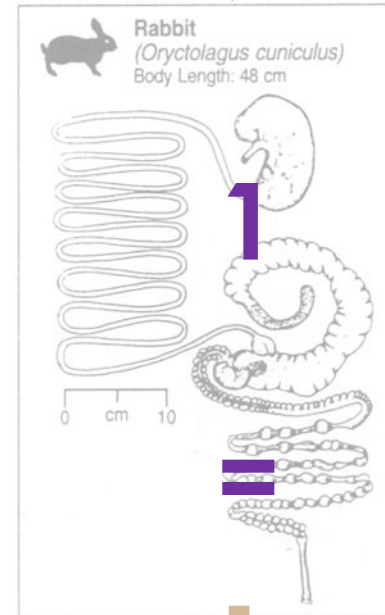
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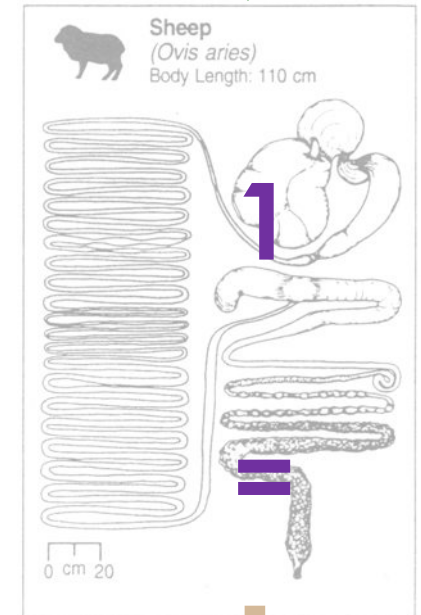
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2



2





The sequence of chewing and digestion:  
teeth are essential for endothermy



# Digestion needs ... time ?

Animal cell

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Plant cell

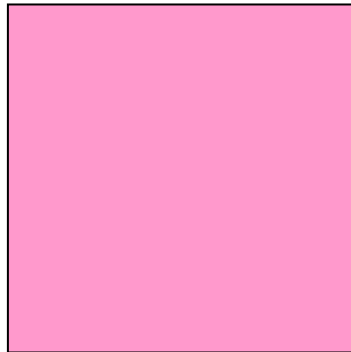


# Digestion needs ... time ?

Animal cell

-----

Plant cell



**Cell membrane**

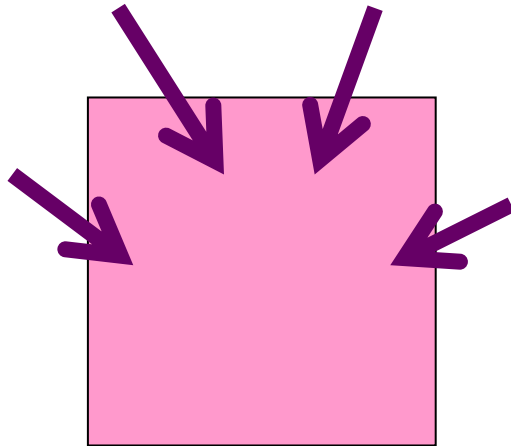


# Digestion needs ... time ?

Animal cell

-----

Plant cell



**Cell membrane**



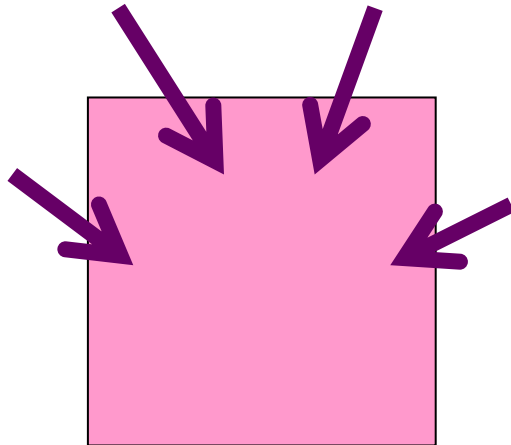


# Digestion needs ... time ?

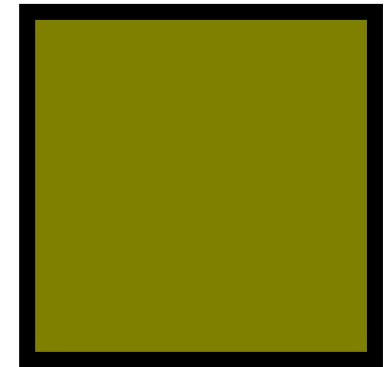
Animal cell

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Plant cell



**Cell membrane**

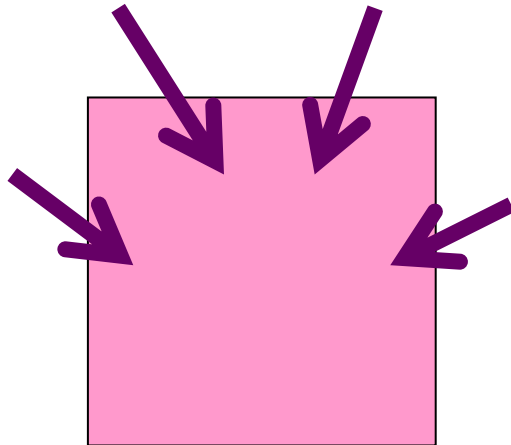


**Cell wall**



# Digestion needs ... time ?

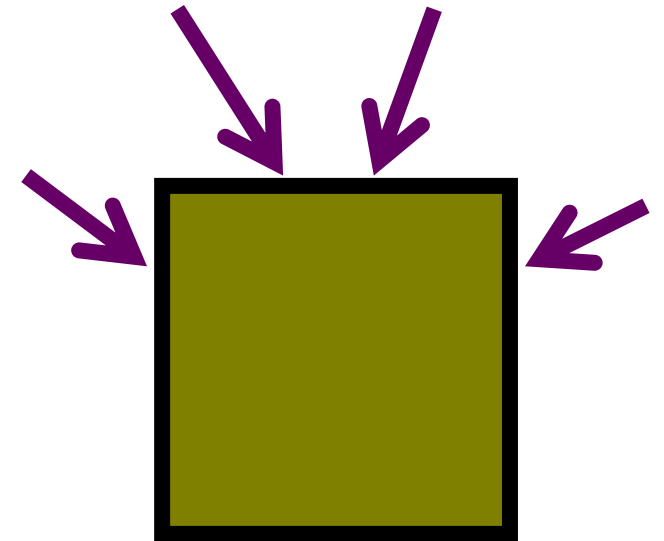
Animal cell



**Cell membrane**

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Plant cell

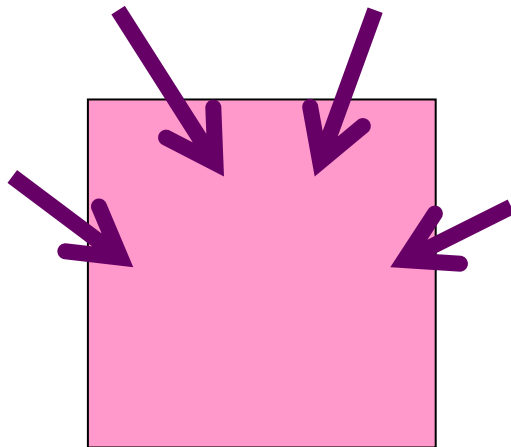


**Cell wall**



# Digestion needs ... time ?

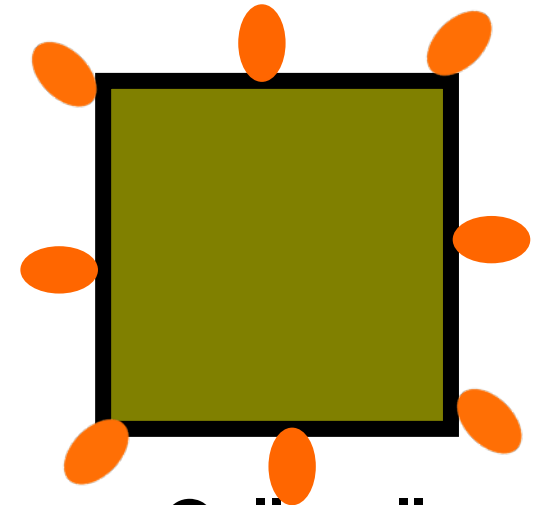
Animal cell



**Cell membrane**

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Plant cell

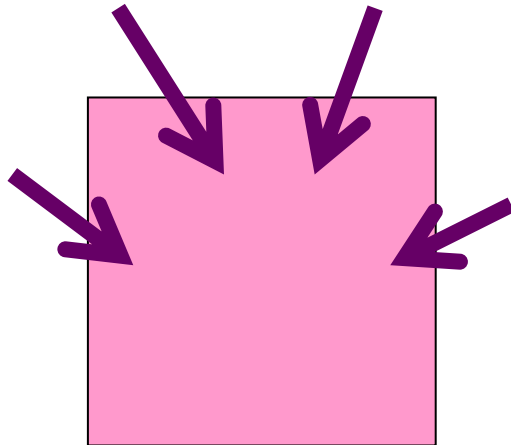


**Cell wall**



# Digestion needs ... time ?

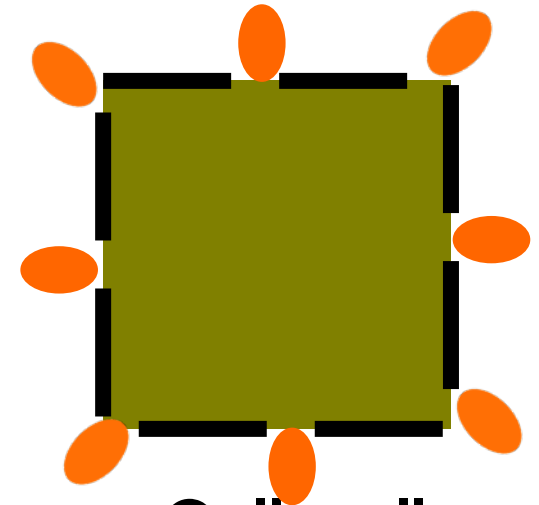
Animal cell



**Cell membrane**

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Plant cell



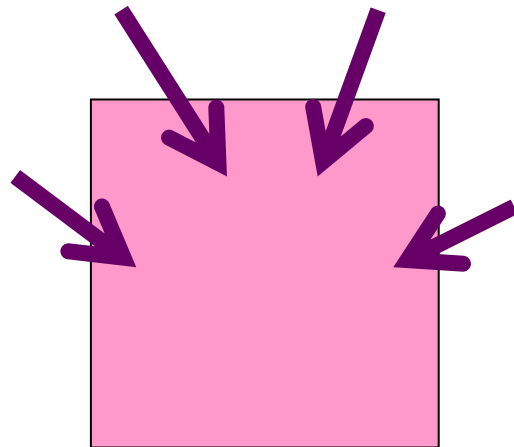
**Cell wall**





# Digestion needs ... time ?

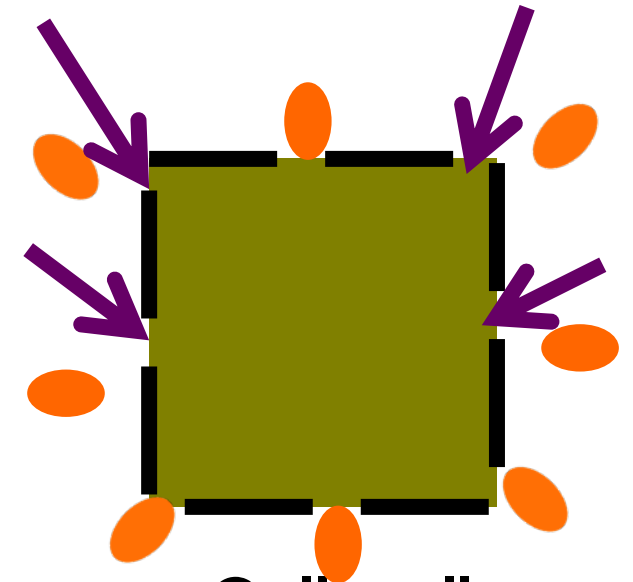
Animal cell



Cell membrane

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Plant cell



Cell wall

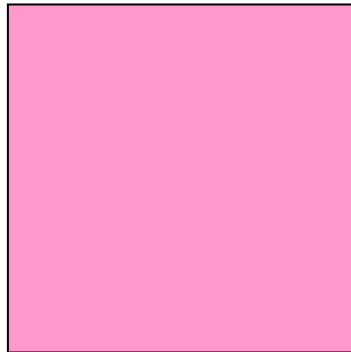


# Digestion needs ... time ?

Animal cell

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Plant cell



**Cell membrane**

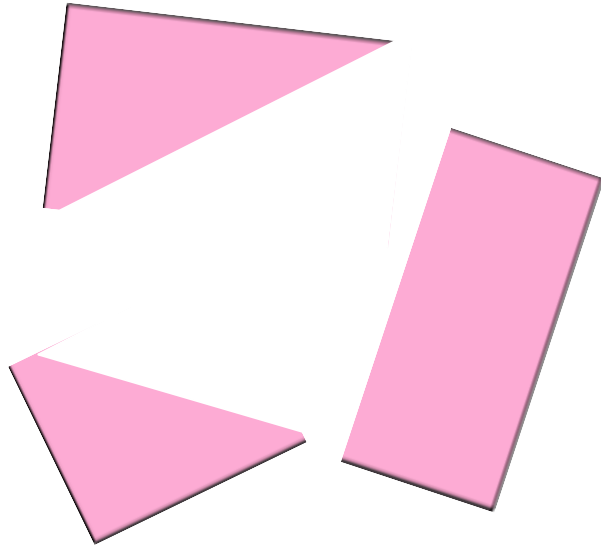


**Cell wall**



# Digestion needs ... time ?

Animal cell



**Cell membrane**

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Plant cell

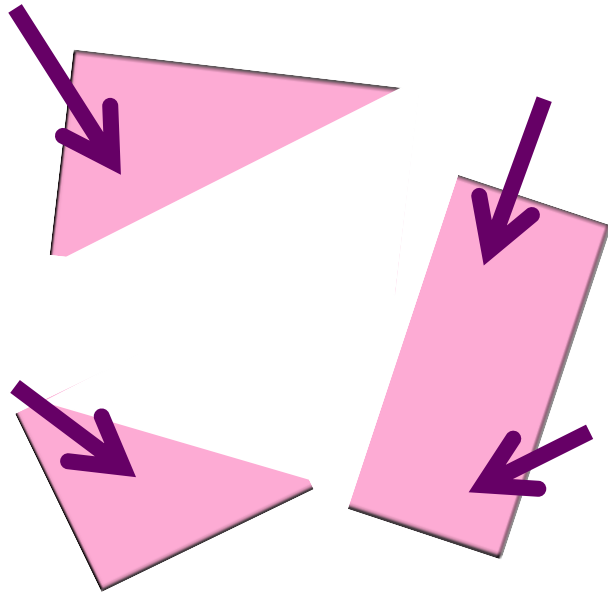


**Cell wall**



# Digestion needs ... time ?

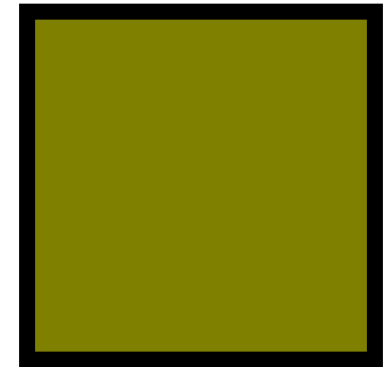
Animal cell



Cell membrane

-----

Plant cell

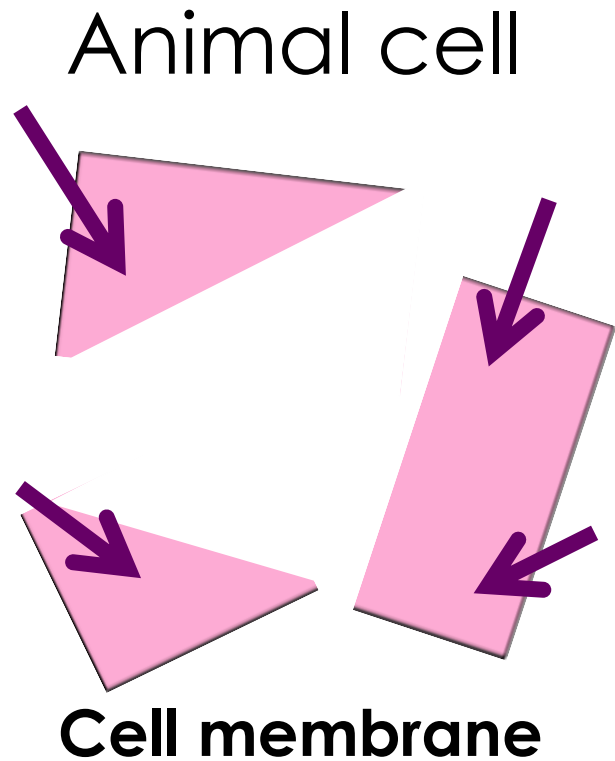


Cell wall

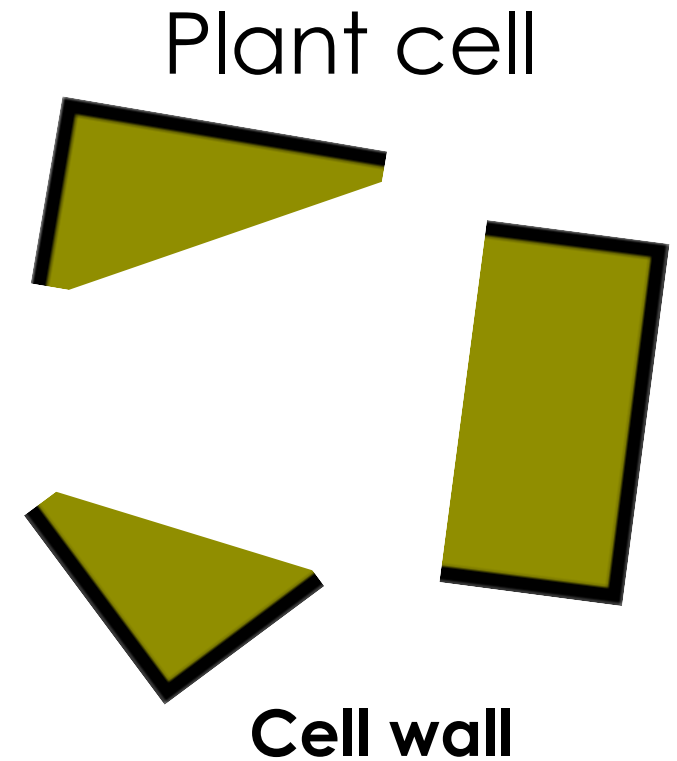




# Digestion needs ... time ?

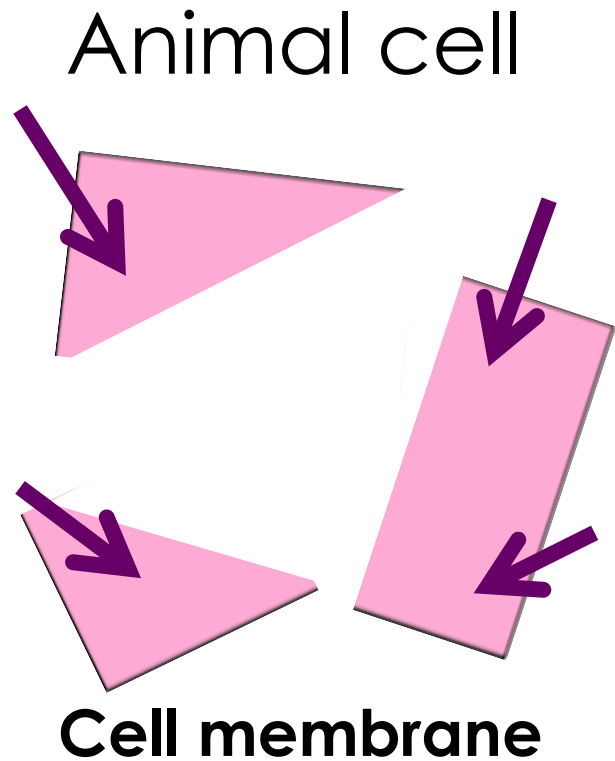


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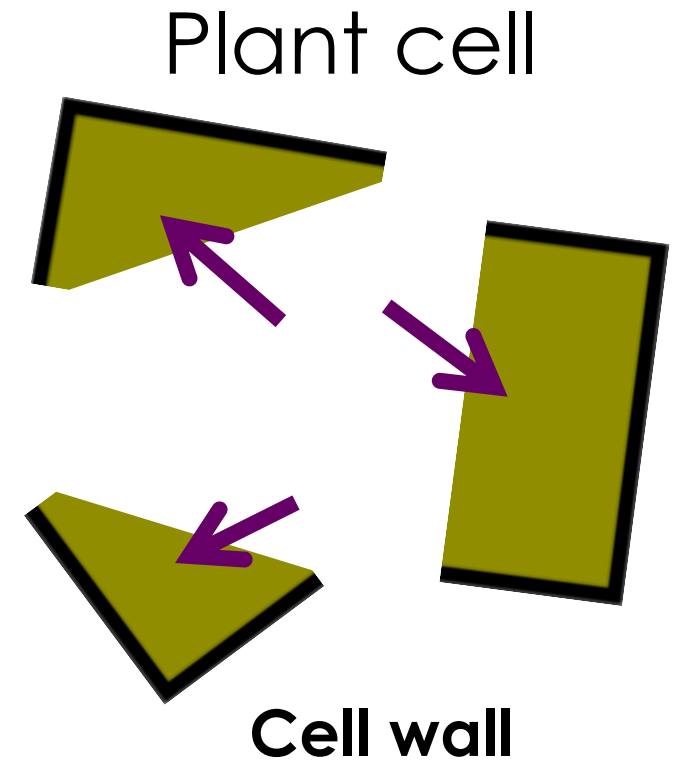




# Digestion needs ... time ?

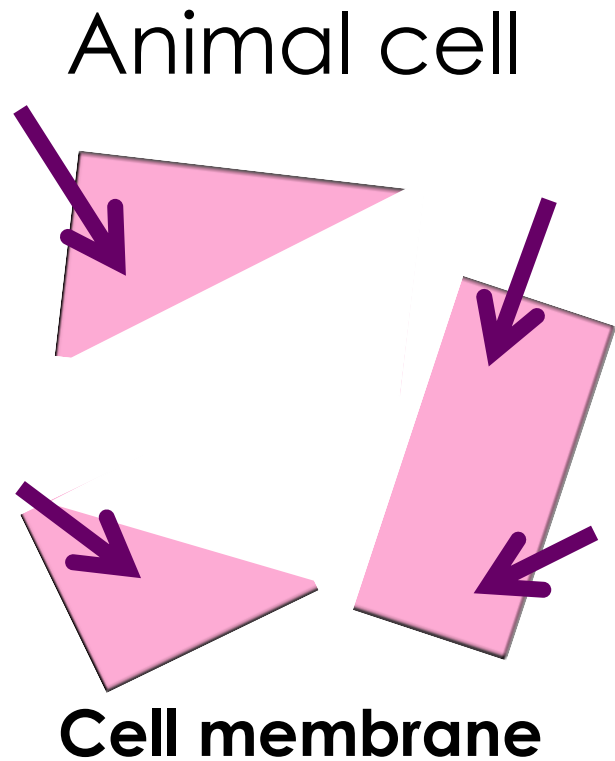


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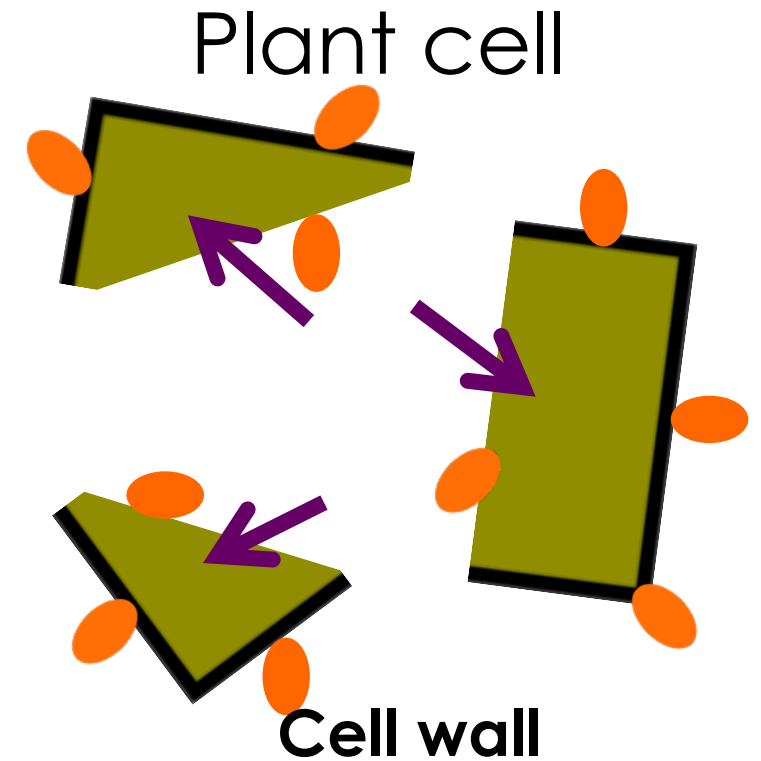




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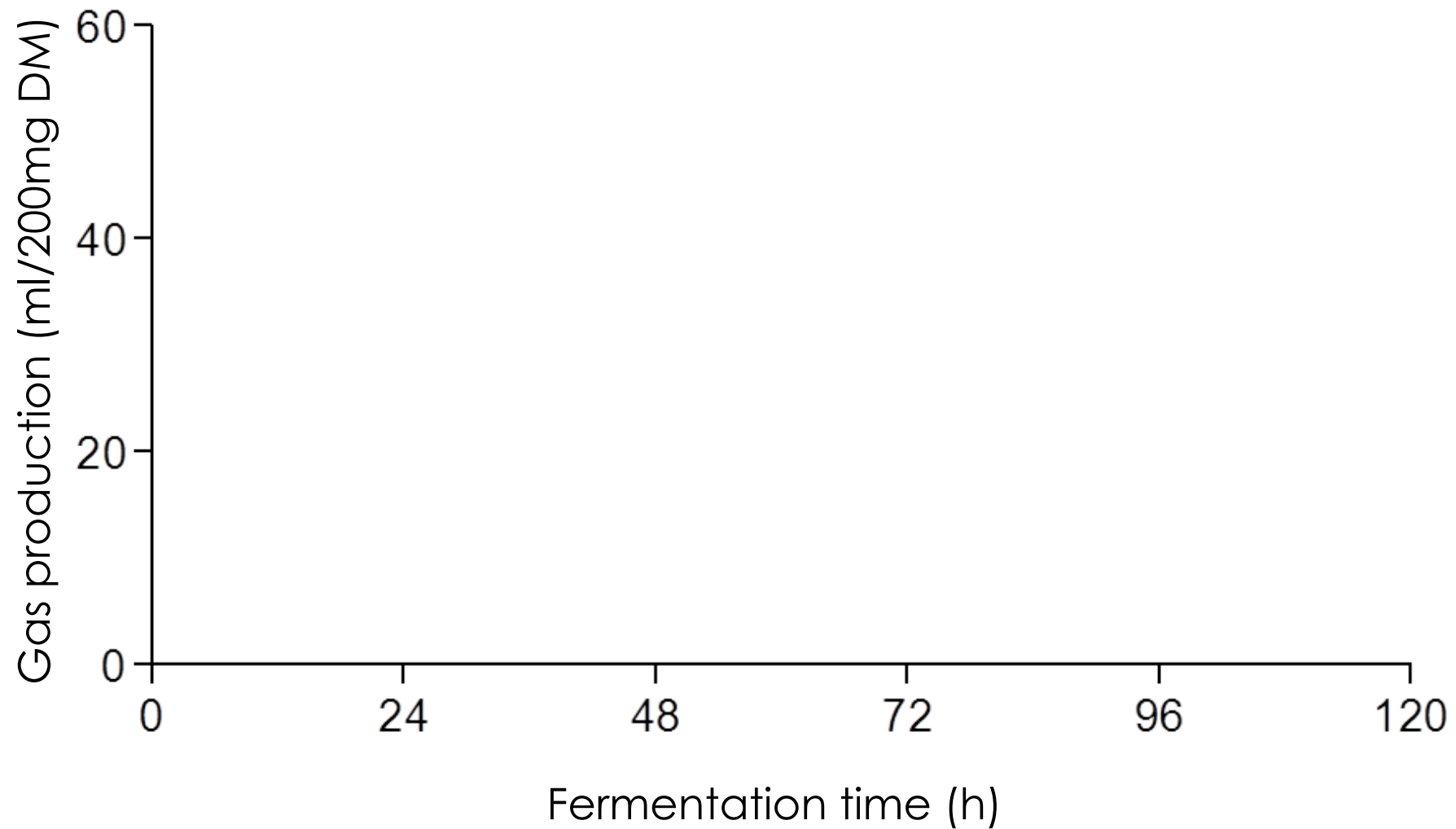


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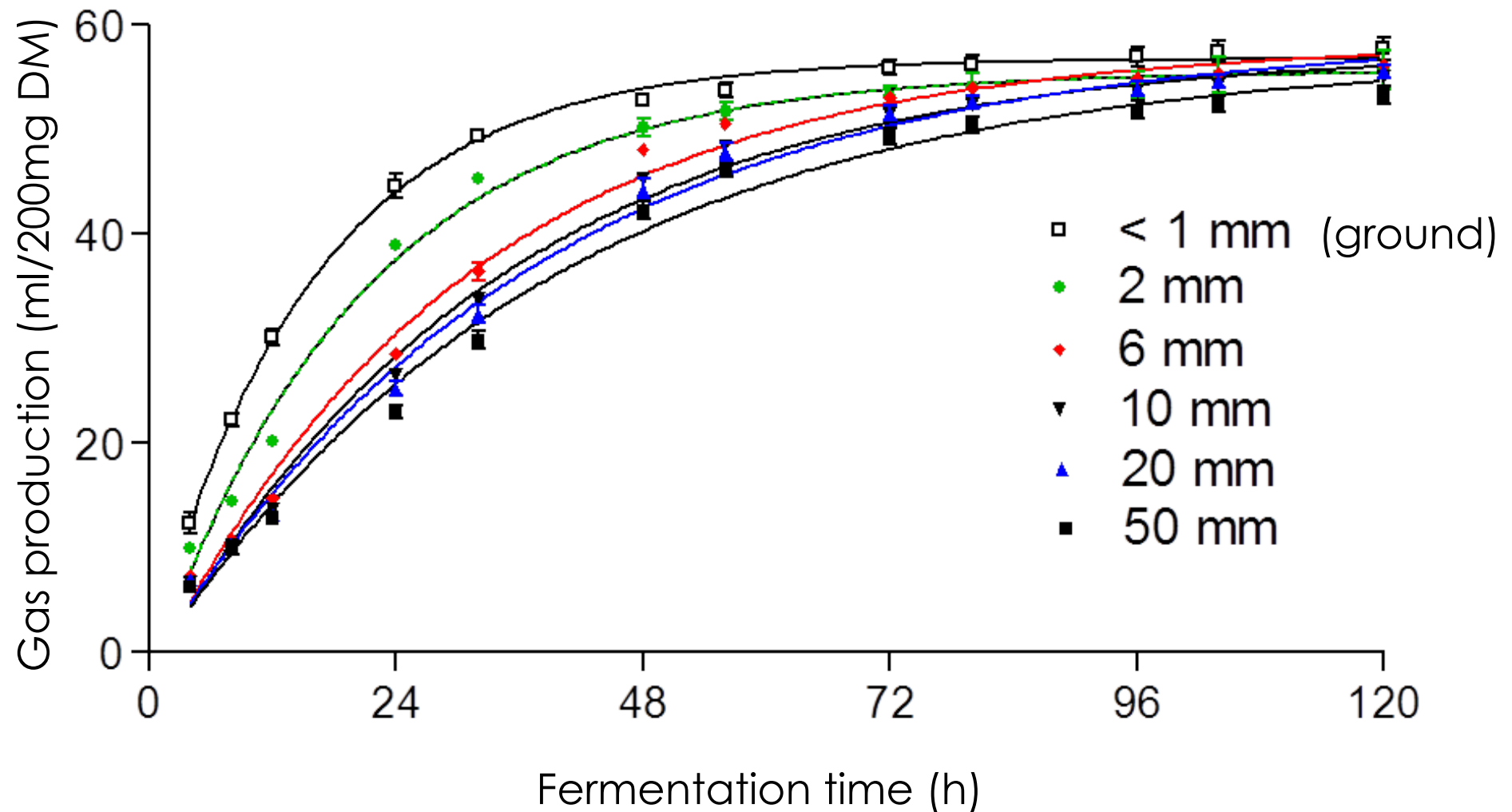
## *in vitro* fermentation and particle size





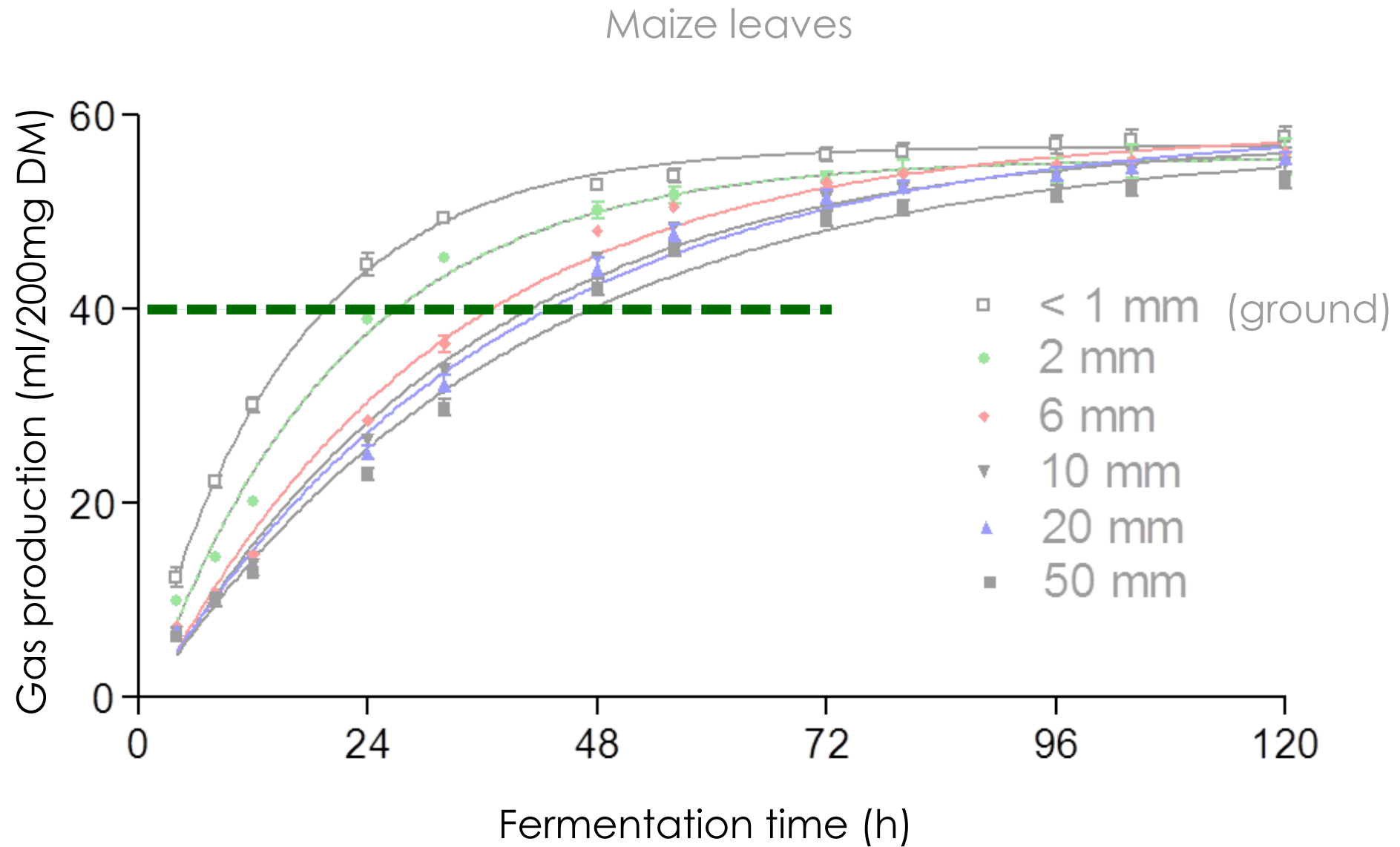
# *in vitro* fermentation and particle size

Maize leaves



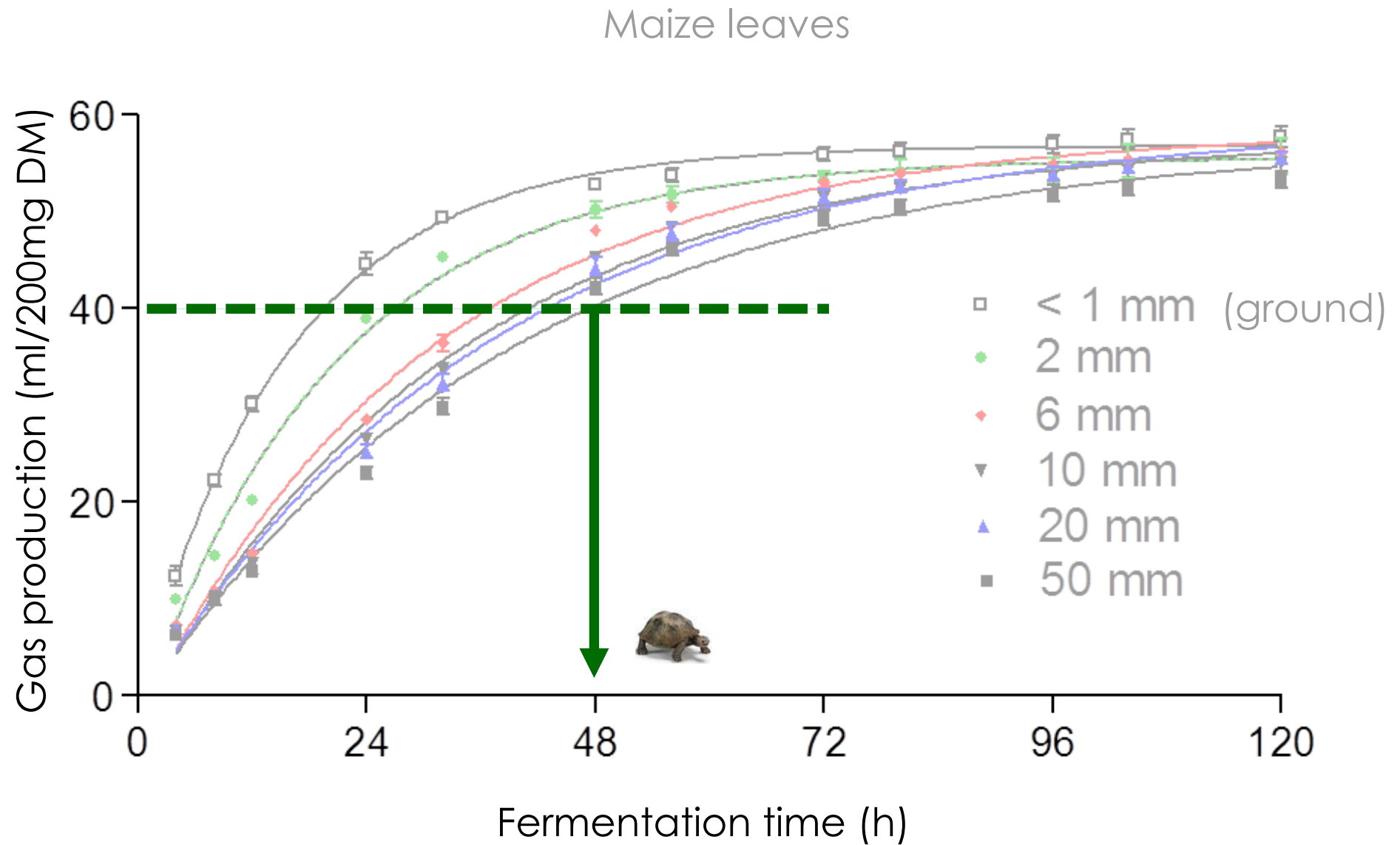


# *in vitro* fermentation and particle size



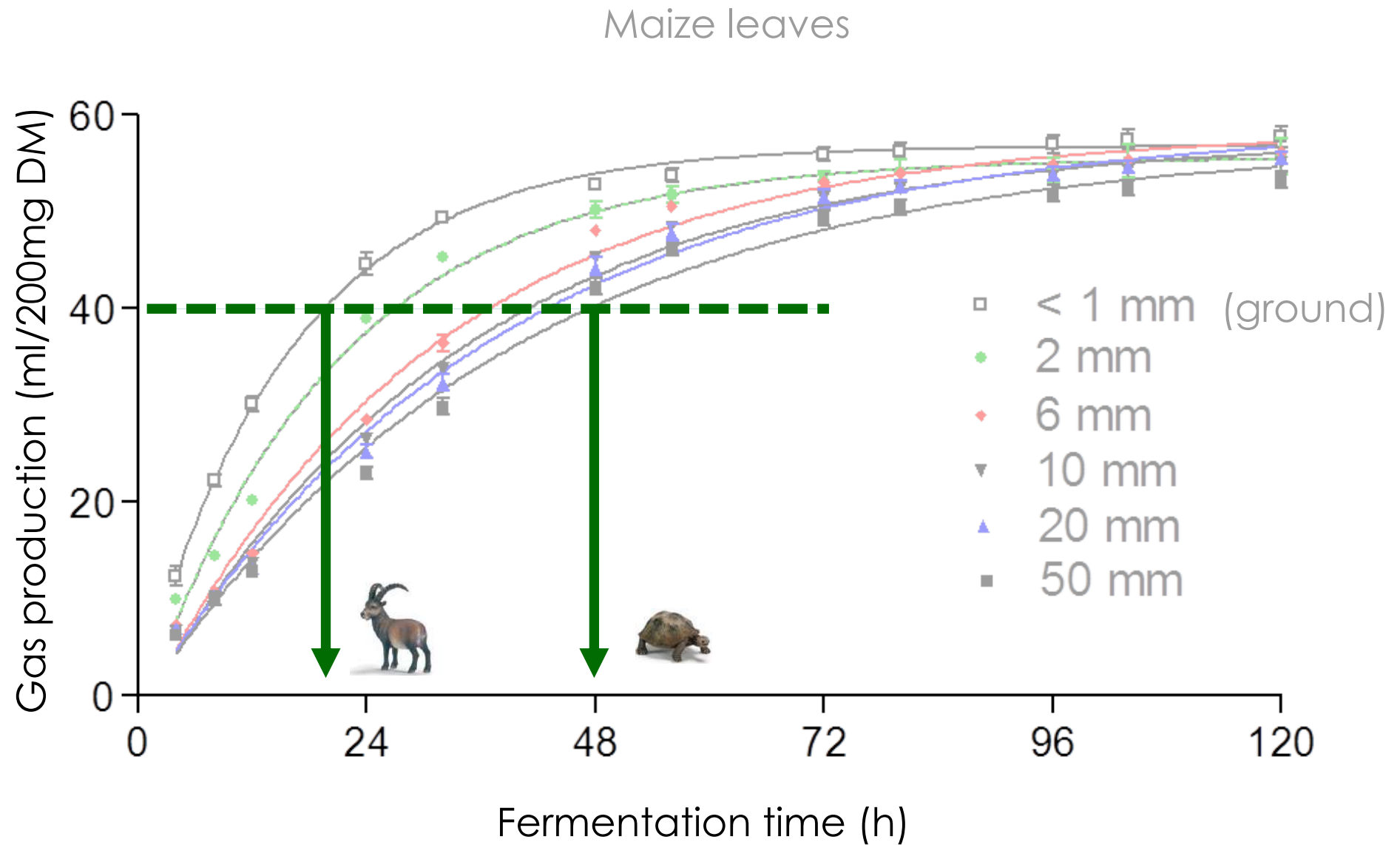


# *in vitro* fermentation and particle size





# *in vitro* fermentation and particle size







# *Particle size reduction in terrestrial vertebrates*



# Comparative chewing efficiency in mammalian herbivores

Julia Fritz, Jürgen Hummel, Ellen Kienzle, Christian Arnold, Charles Nunn and Marcus Clauss

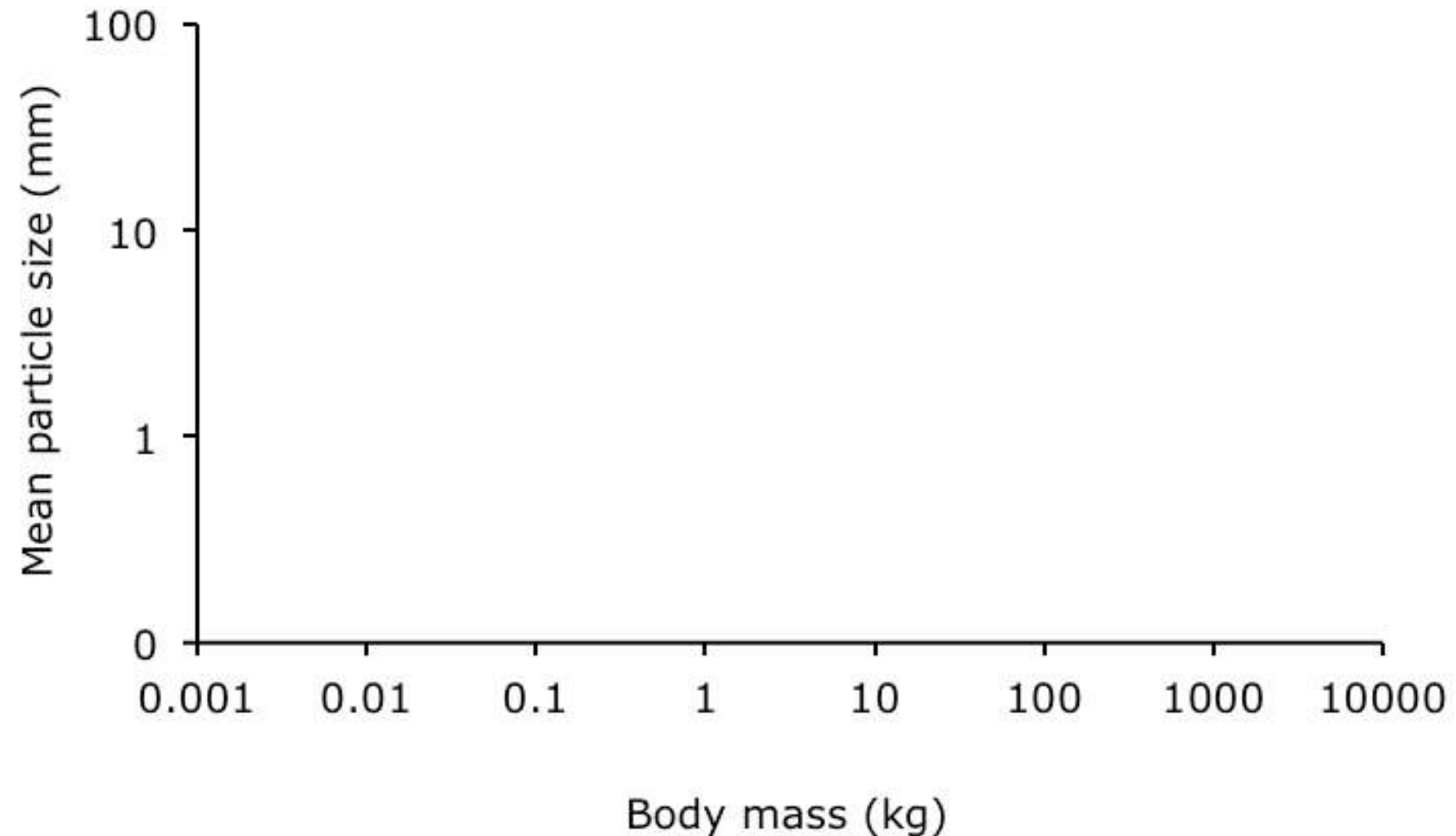
Oikos 118: 1623–1632, 2009



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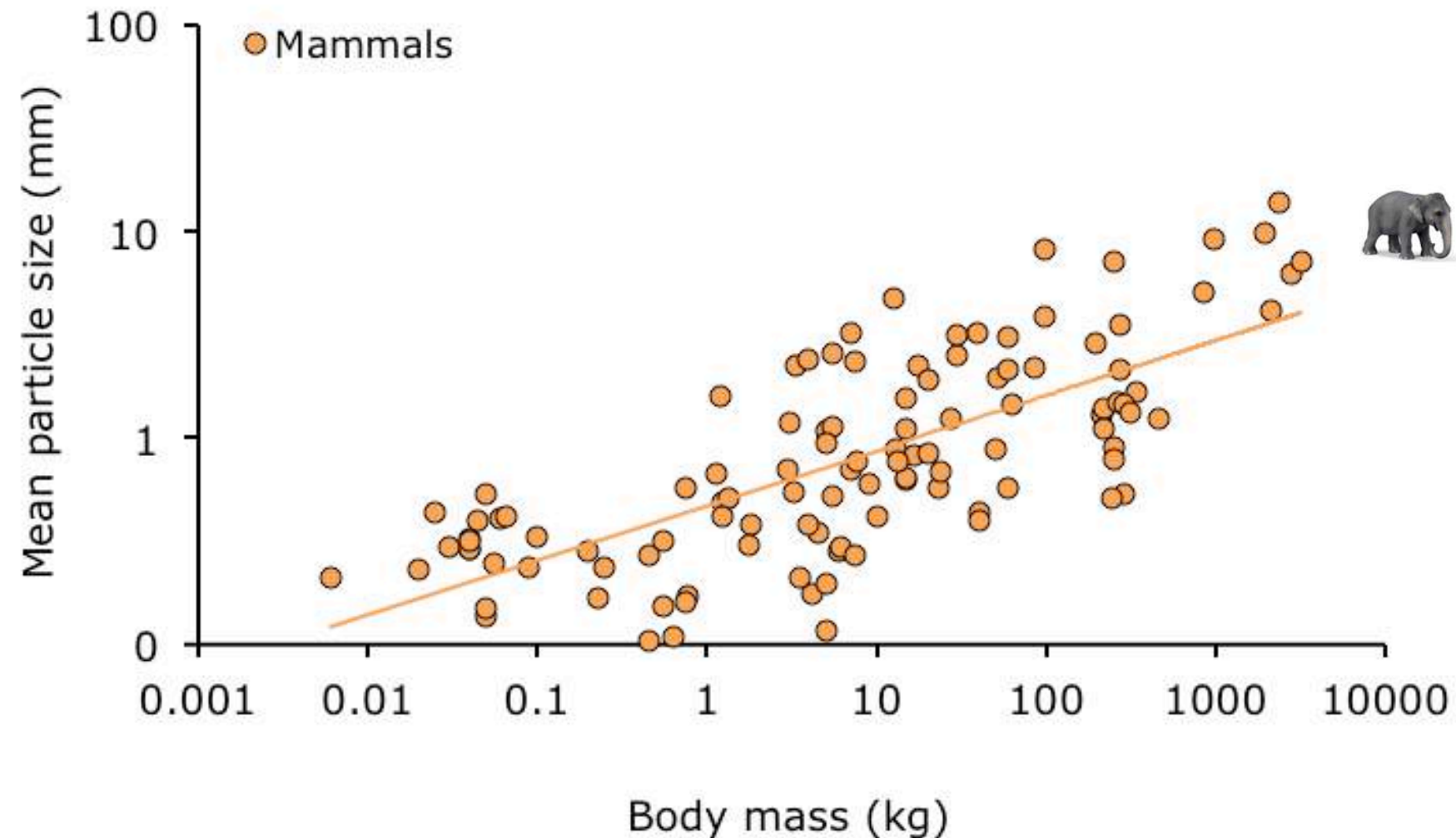




# Comparative chewing efficiency in mammalian herbivores

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# To Chew





# To Chew or Not to Chew





# To Chew or Not to Chew: Fecal Particle Size in Herbivorous Reptiles and Mammals

JULIA FRITZ<sup>1\*</sup>, JÜRGEN HUMMEL<sup>2</sup>, ELLEN KIENZLE<sup>1</sup>,  
W. JÜRGEN STREICH<sup>3</sup>, AND MARCUS CLAUSS<sup>4</sup>

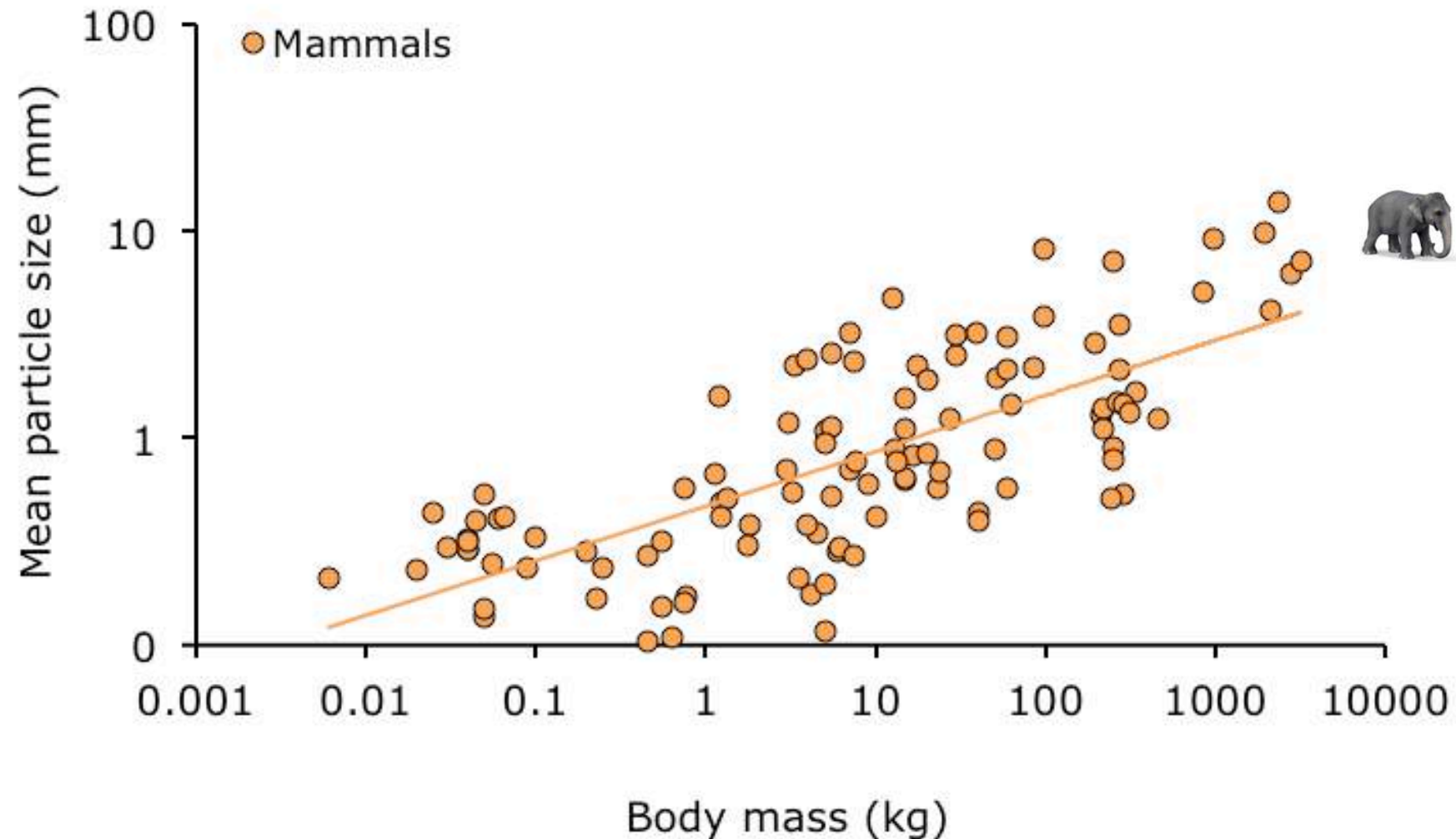
*J. Exp. Zool.*  
313A:579–586,  
2010



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*J. Exp. Zool.*  
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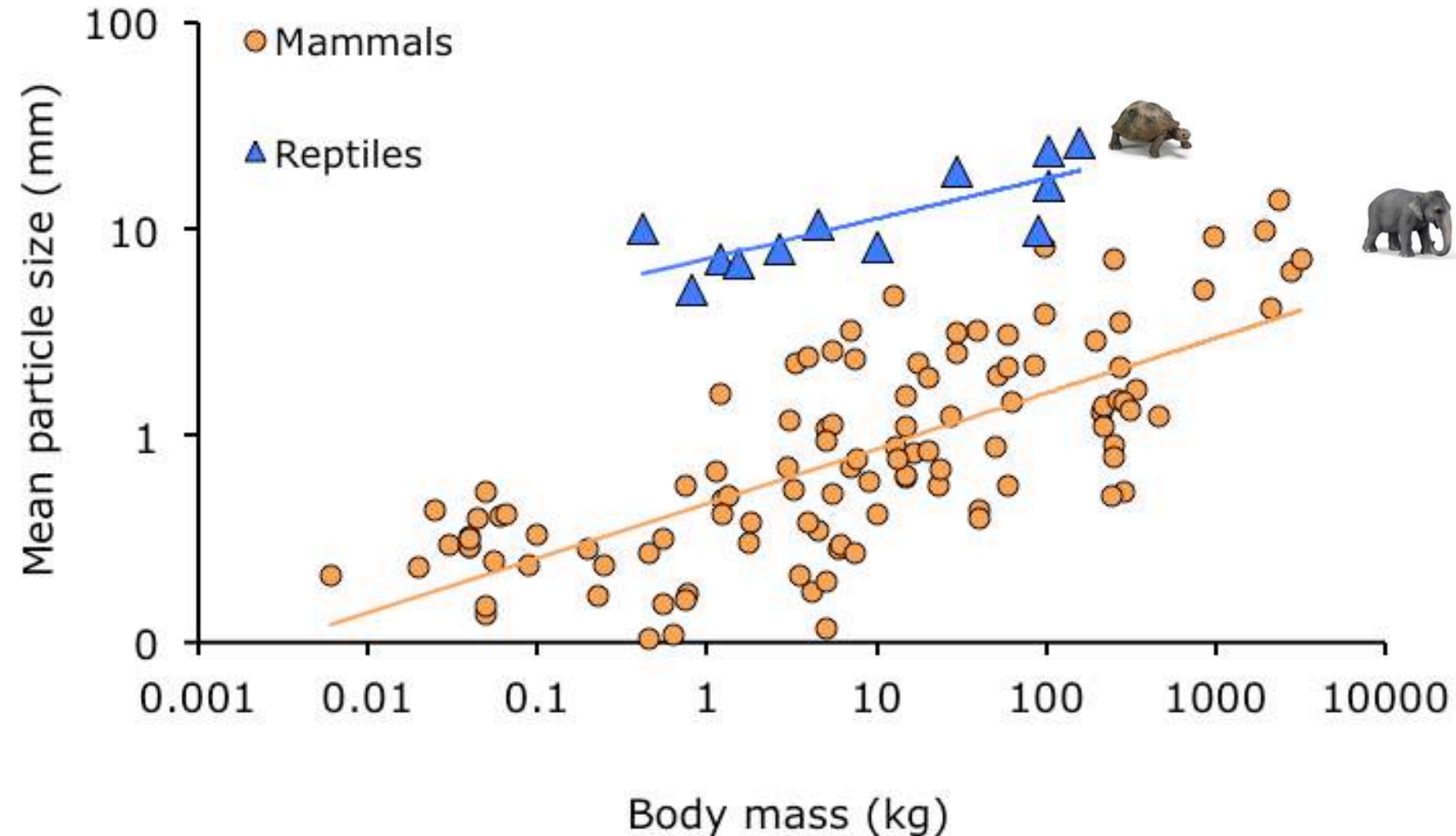




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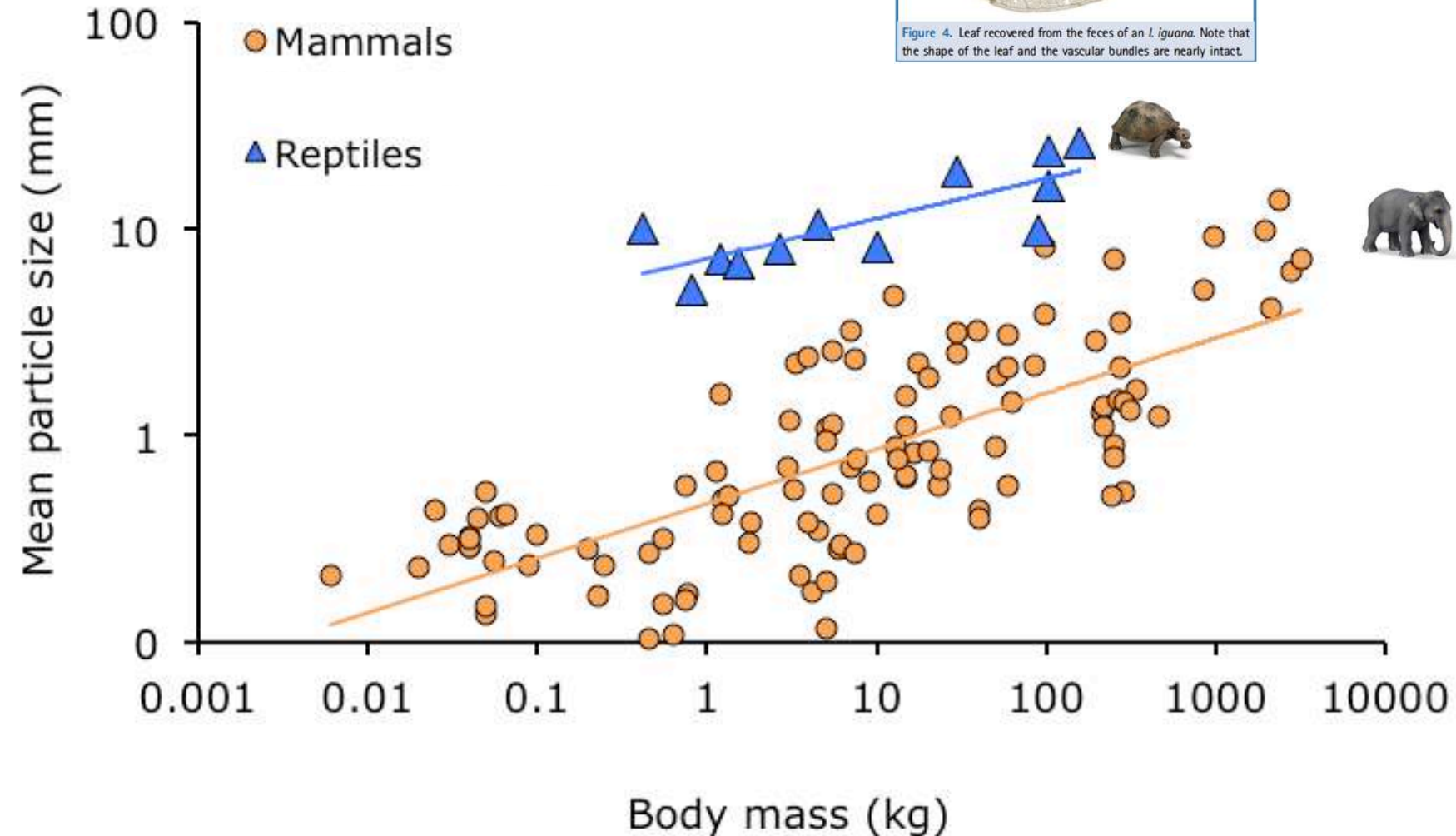
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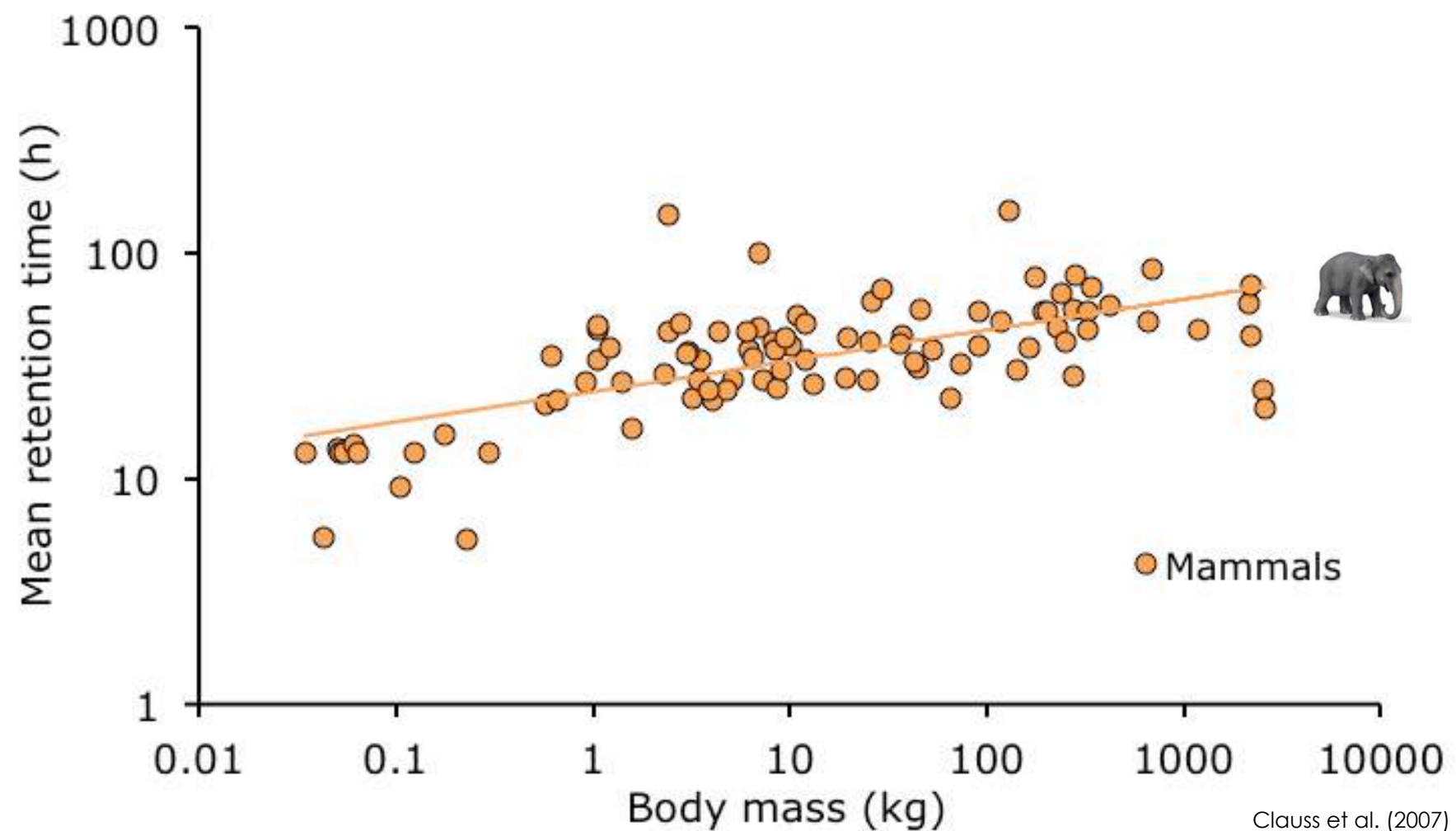


Figure 4. Leaf recovered from the feces of an *I. iguana*. Note that the shape of the leaf and the vascular bundles are nearly intact.



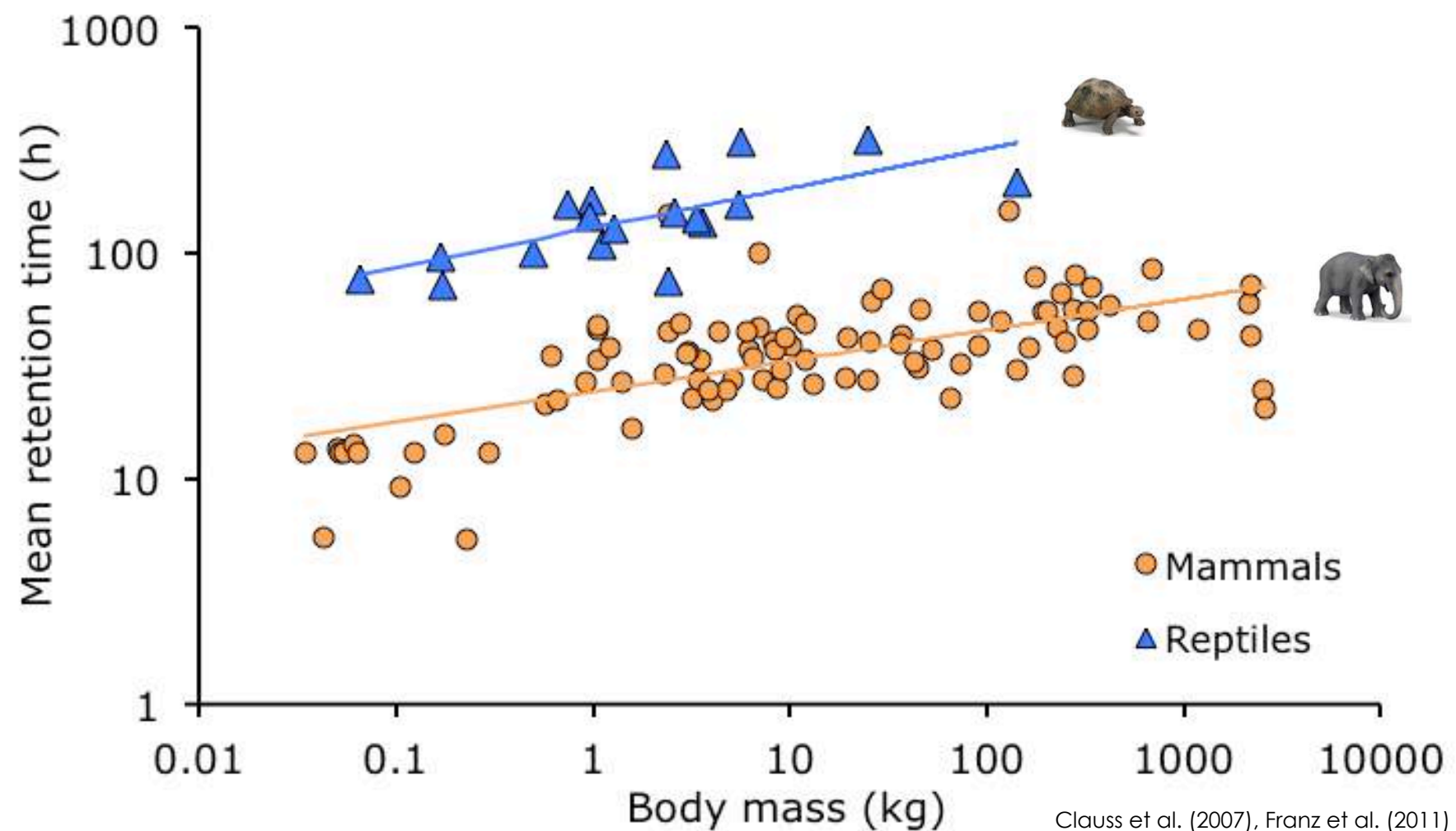


# Retention time in the digestive tract





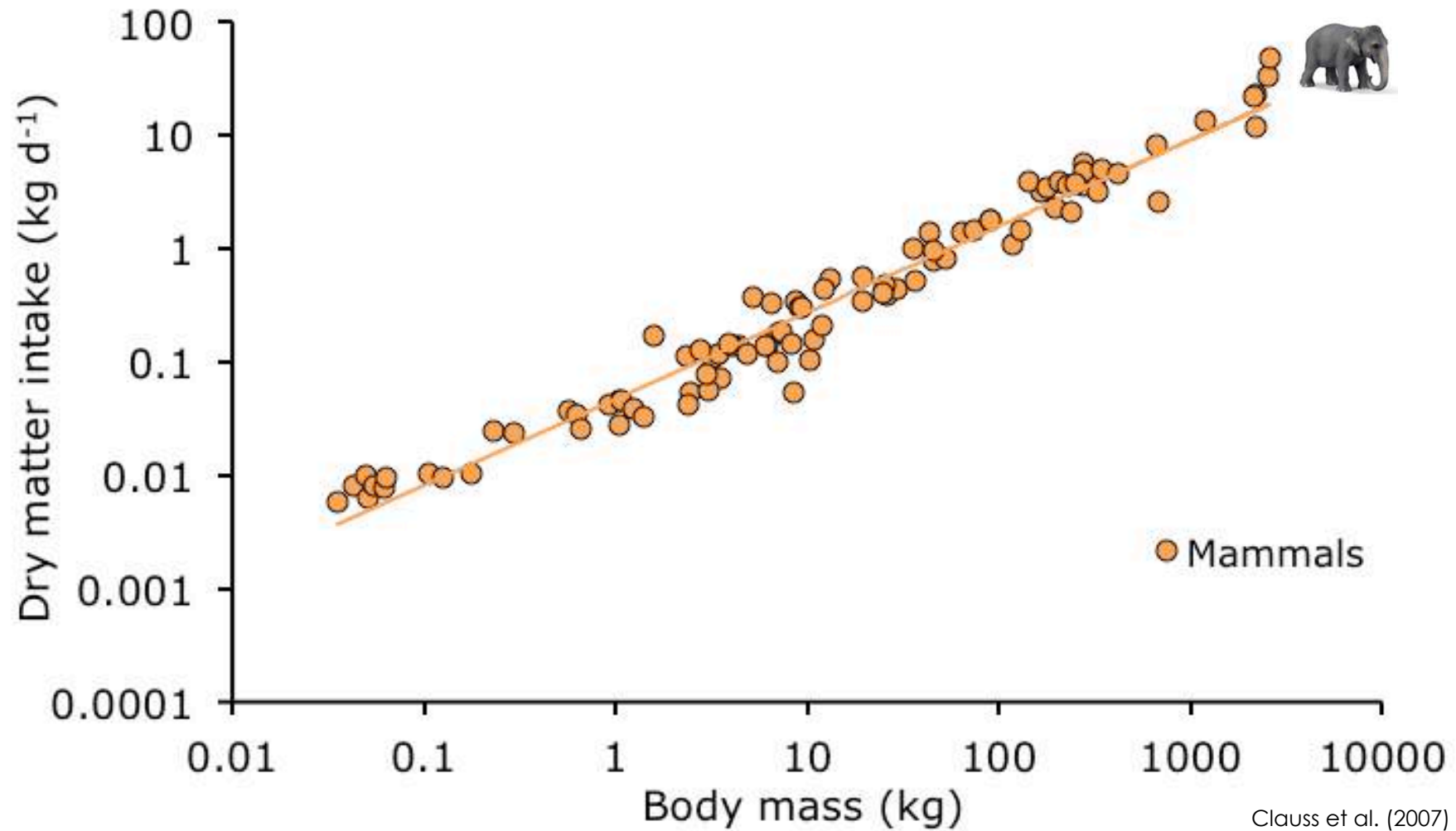
# Retention time in the digestive tract



Clauss et al. (2007), Franz et al. (2011)



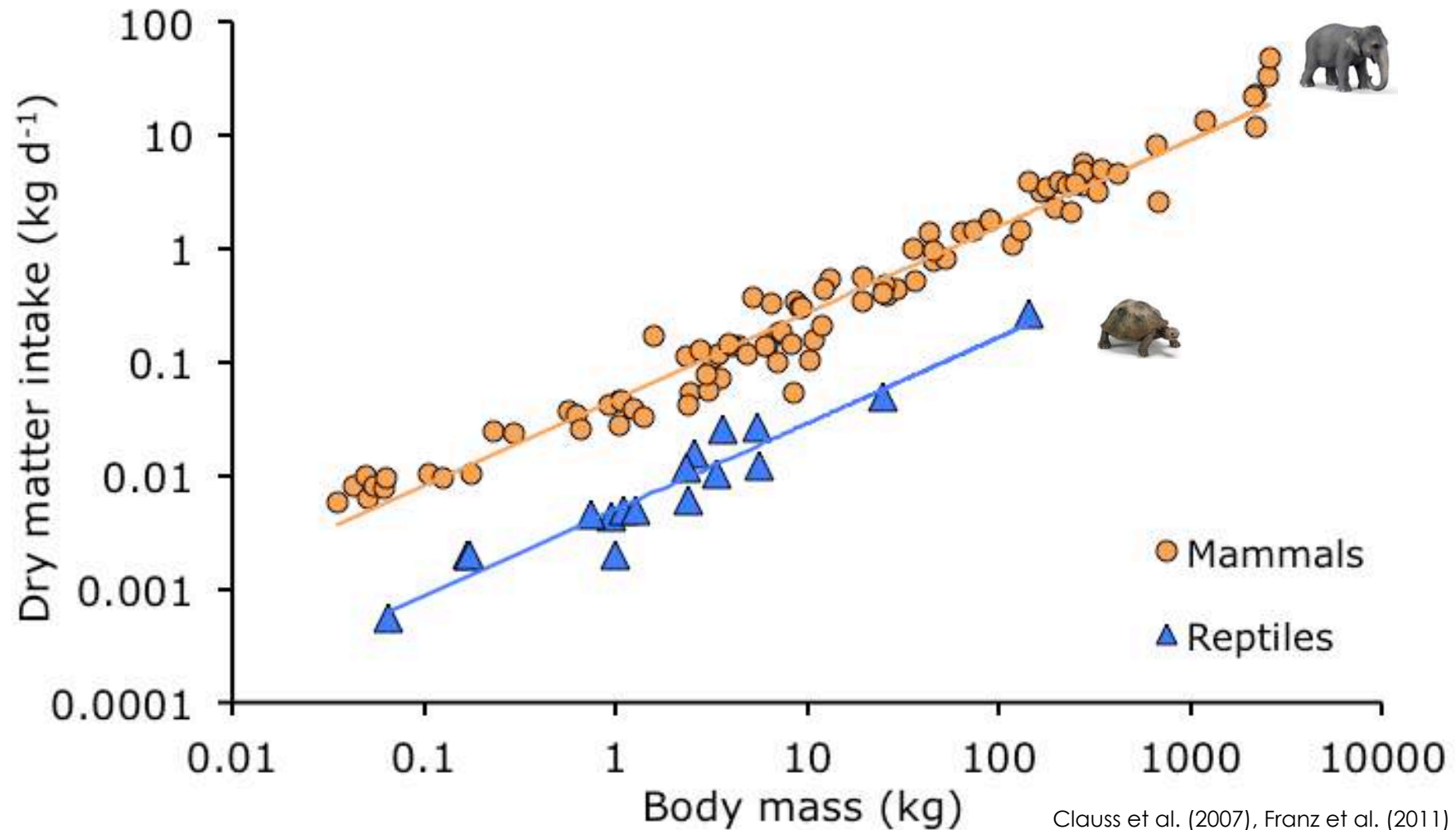
# Food intake





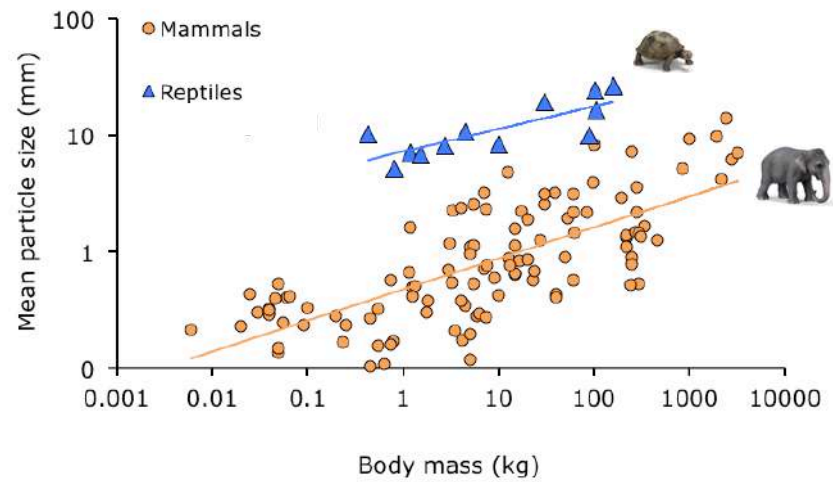


# Food intake



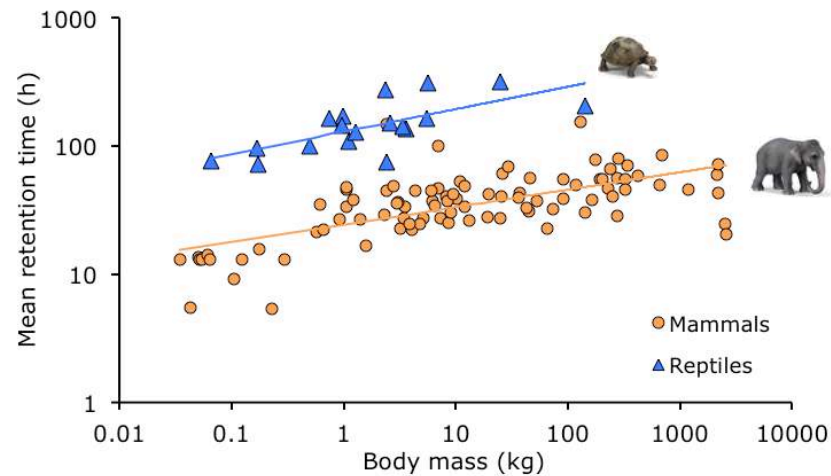
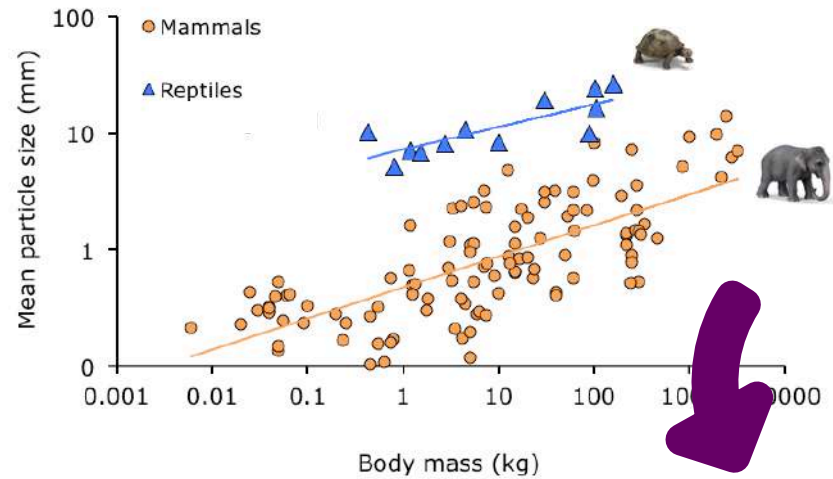


# Chewing ...





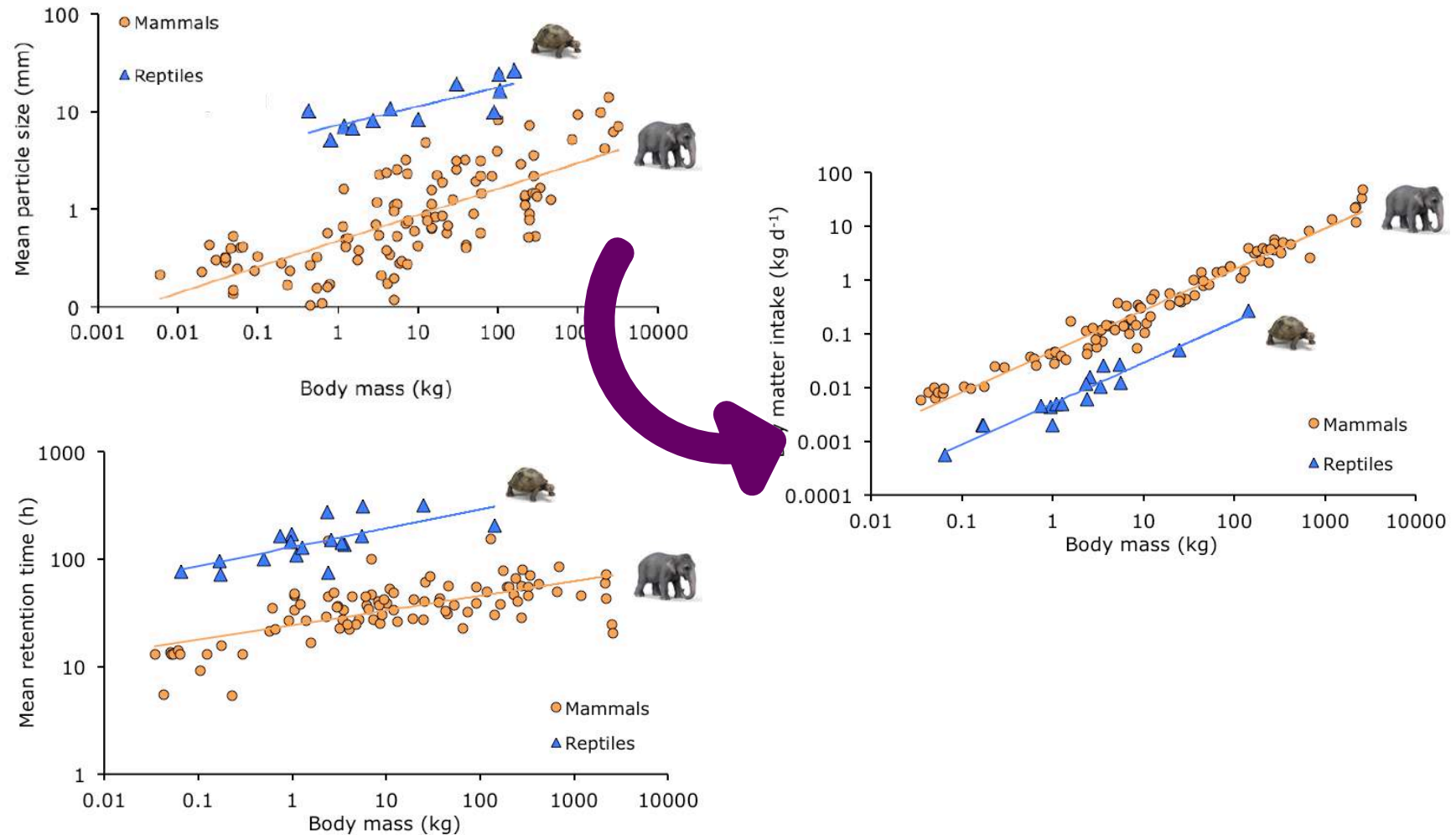
# Chewing ... facilitates shorter retention times







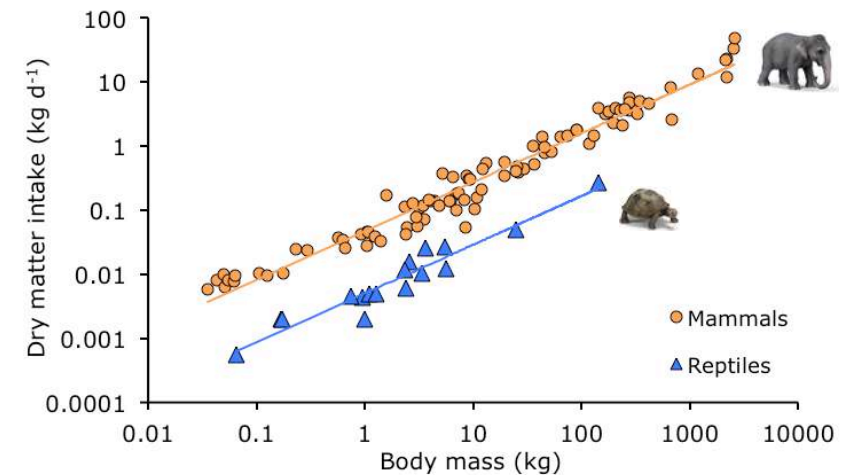
# Chewing ... facilitates higher intakes





# Chewing ... facilitates higher intakes

**for herbivores particle  
size reduction is a  
precondition for  
endothermy !**





*Teeth evolve for ...*



# Evolution and development of the mammalian multicuspid teeth

Atsushi Yamanaka

*Journal of Oral Biosciences* 64 (2022) 165–175



unicuspid teeth  
in reptiles

**Evolution**



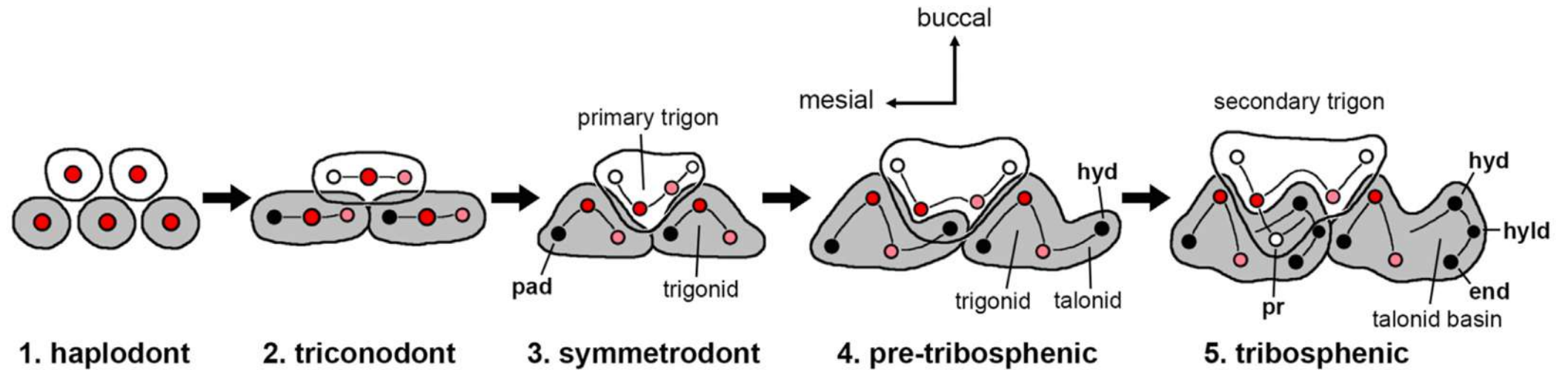
multicuspid molars  
in mammals



# Evolution and development of the mammalian multicuspid teeth

Atsushi Yamanaka

Journal of Oral Biosciences 64 (2022) 165–175

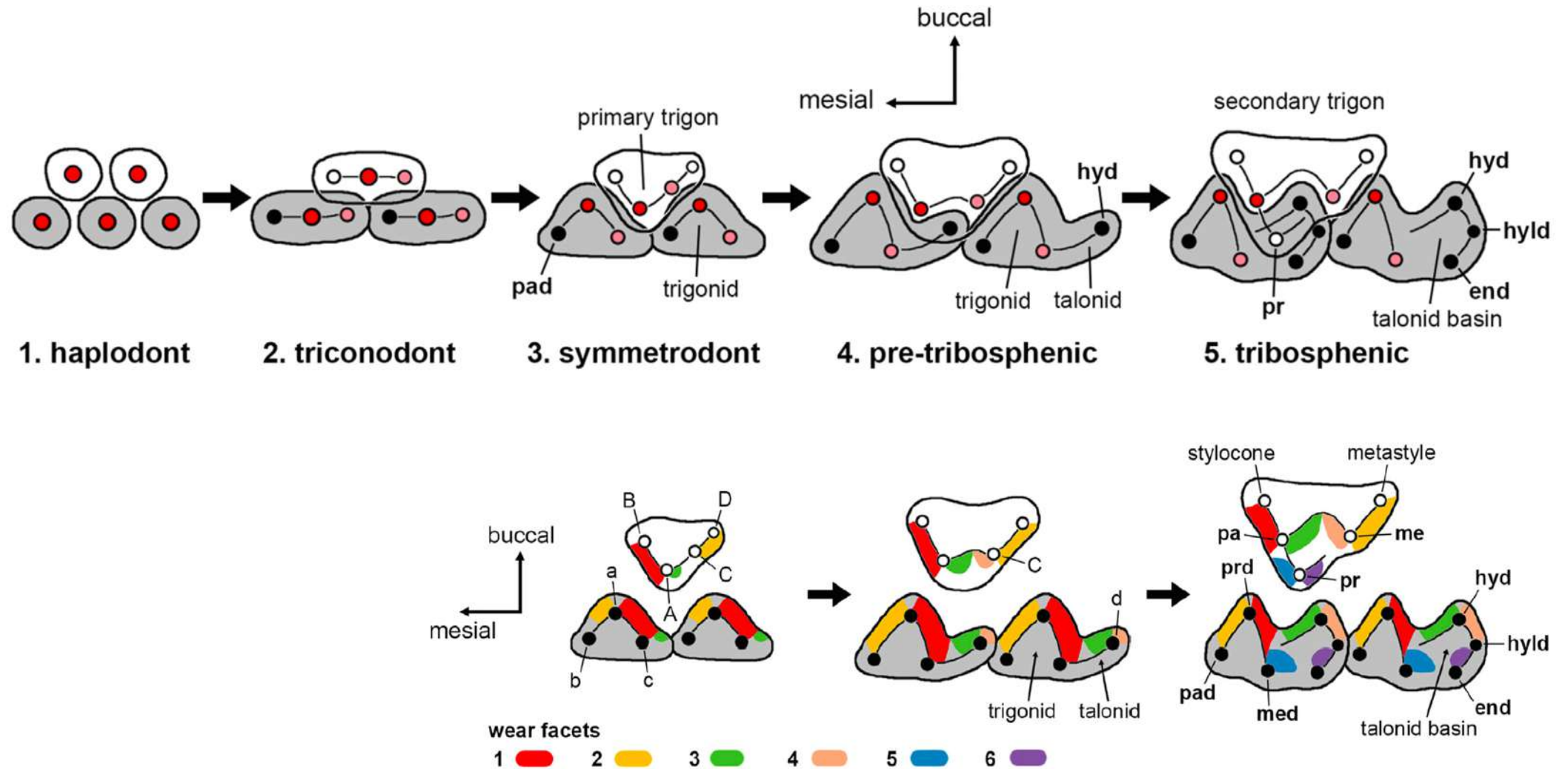




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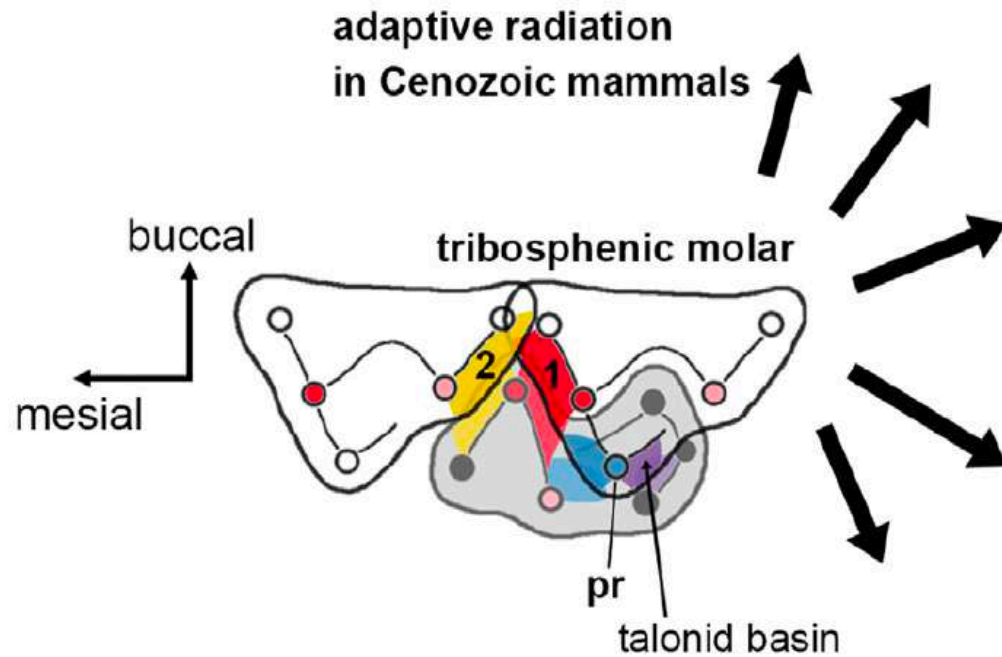




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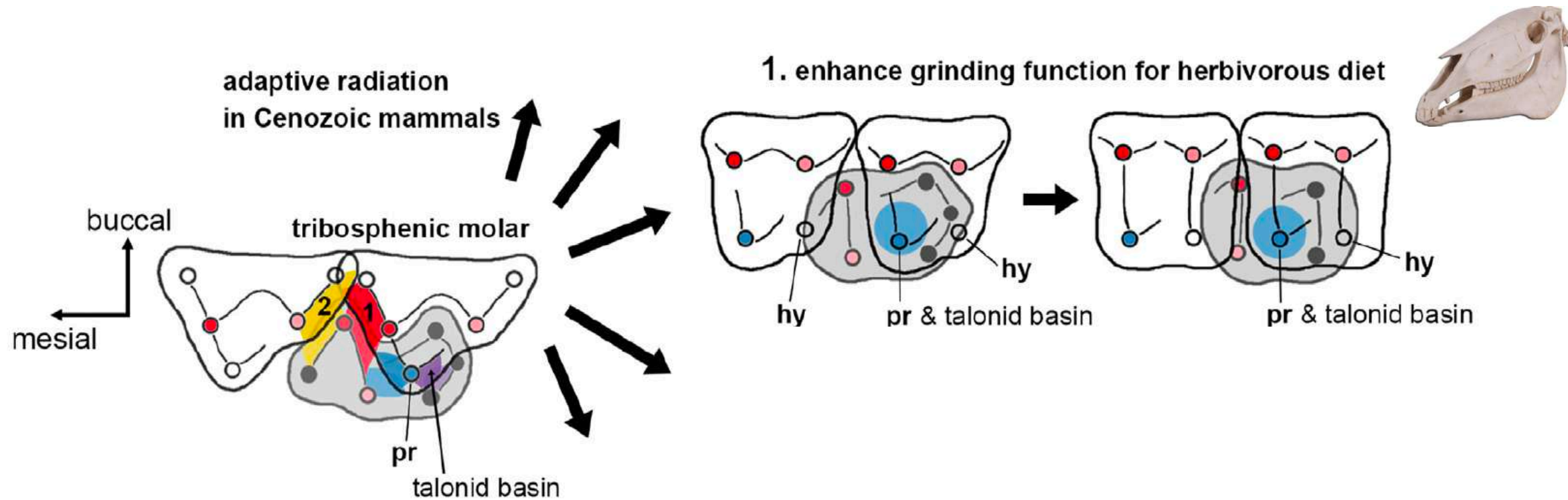




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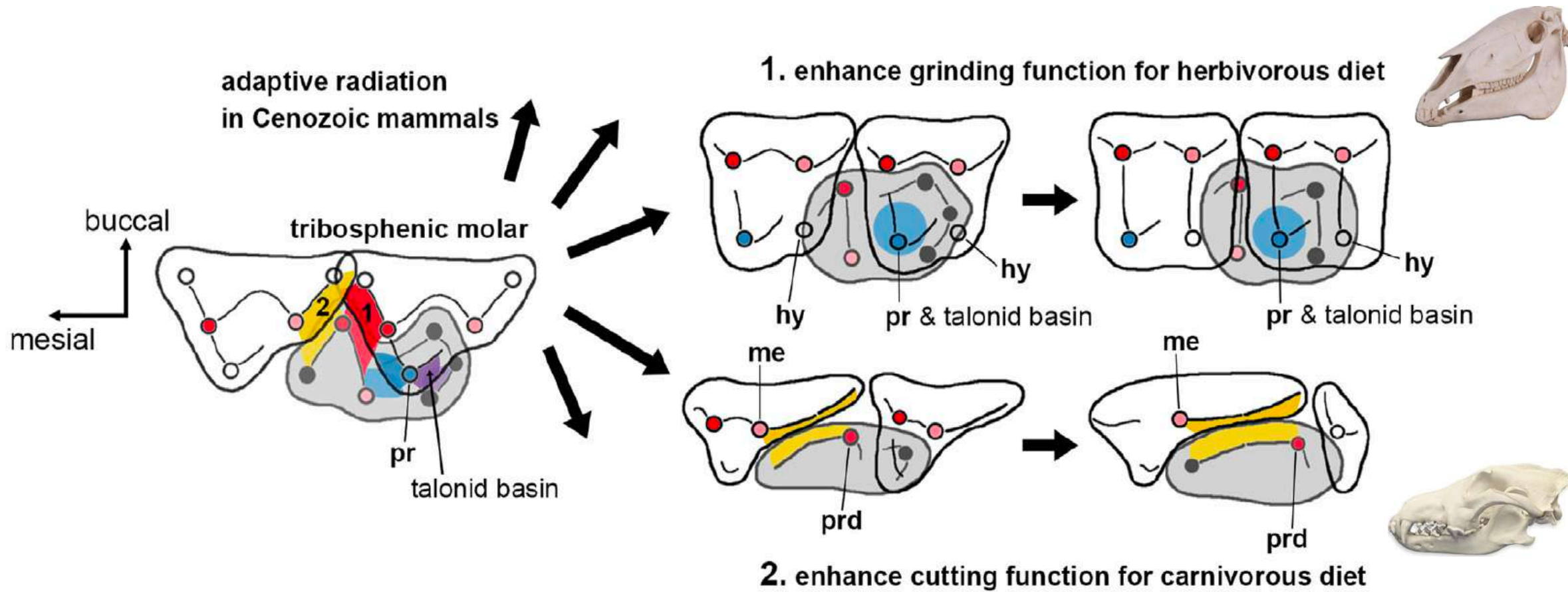


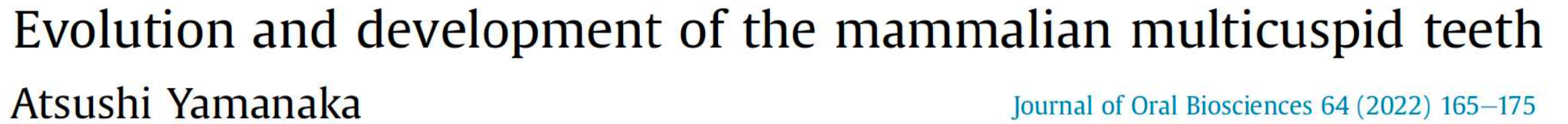


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Journal of Oral Biosciences 64 (2022) 165–175





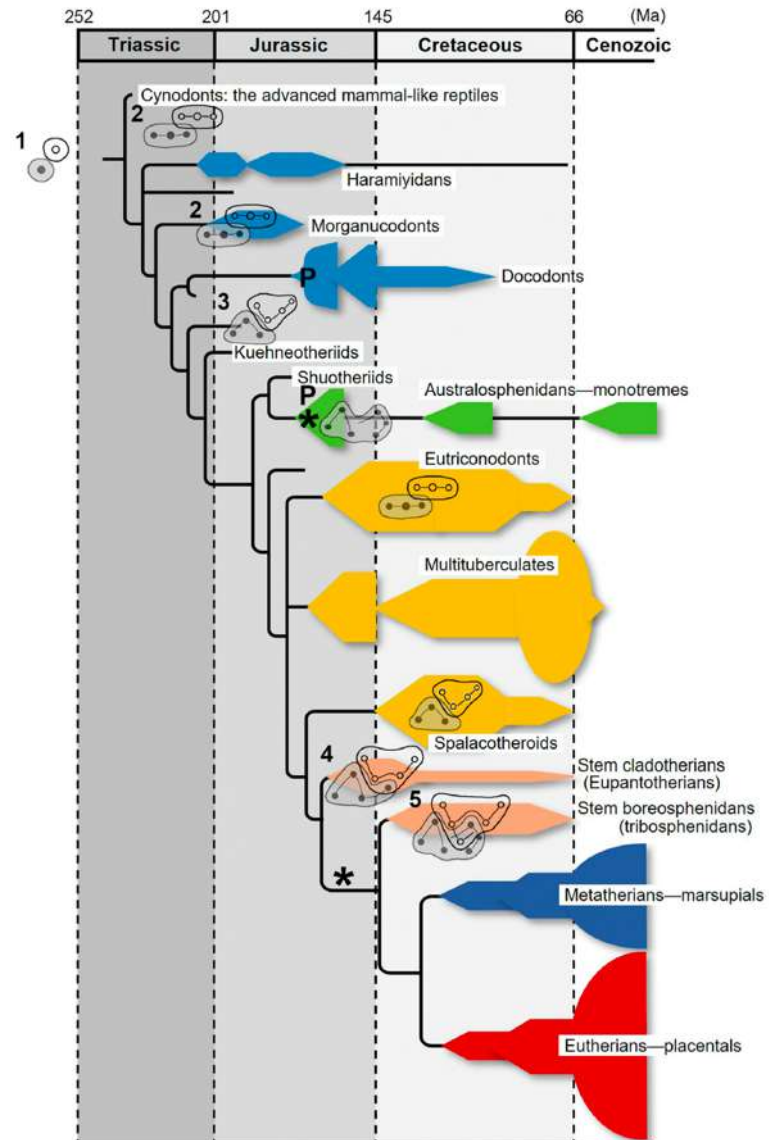
Phylogenetic tree of mammals showing evolutionary relationships from the Triassic to the Cenozoic. The tree is rooted at 252 Ma and branches through the Jurassic, Cretaceous, and Cenozoic eras. Key groups include Cynodonts, Haramiyids, Morganucodonts, Docodonts, Kuehneotheriids, Shuotheriids, Australospheniids (monotremes), Eutriconodonts, Multituberculates, Spalacotherioids, Stem cladotherians (Eupantotherians), Stem boreospheniids (tribospheniids), Metatherians (marsupials), and Eutherians (placentals). The tree is color-coded by group: blue for early cynodonts, green for monotremes, yellow for multituberculates, orange for stem groups, and blue/red for marsupials/placentals. Morphological changes are indicated by icons (1-5) and a 'P' for placental development. A scale bar at the top shows time in millions of years (Ma) from 252 to 66.



# Evolution and development of the mammalian multicuspid teeth

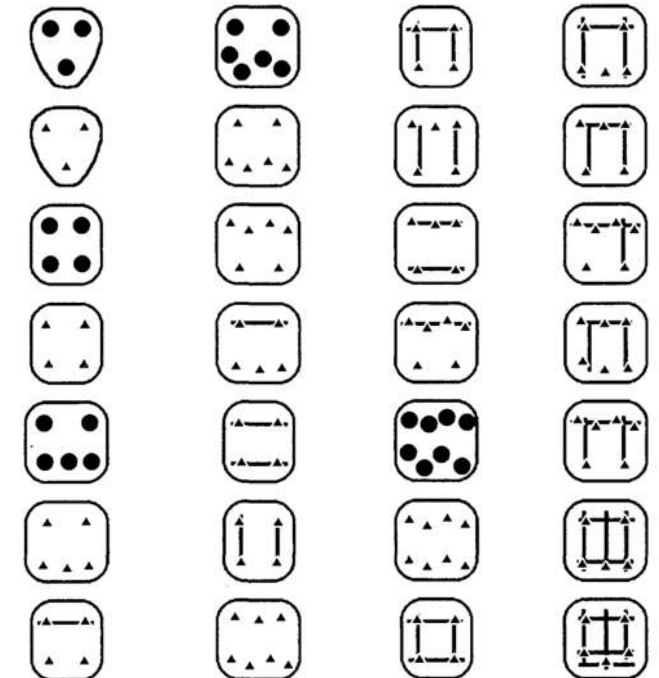
Atsushi Yamanaka

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## Molar Tooth Diversity, Disparity, and Ecology in Cenozoic Ungulate Radiations

Jukka Jernvall, John P. Hunter,\* Mikael Fortelius†



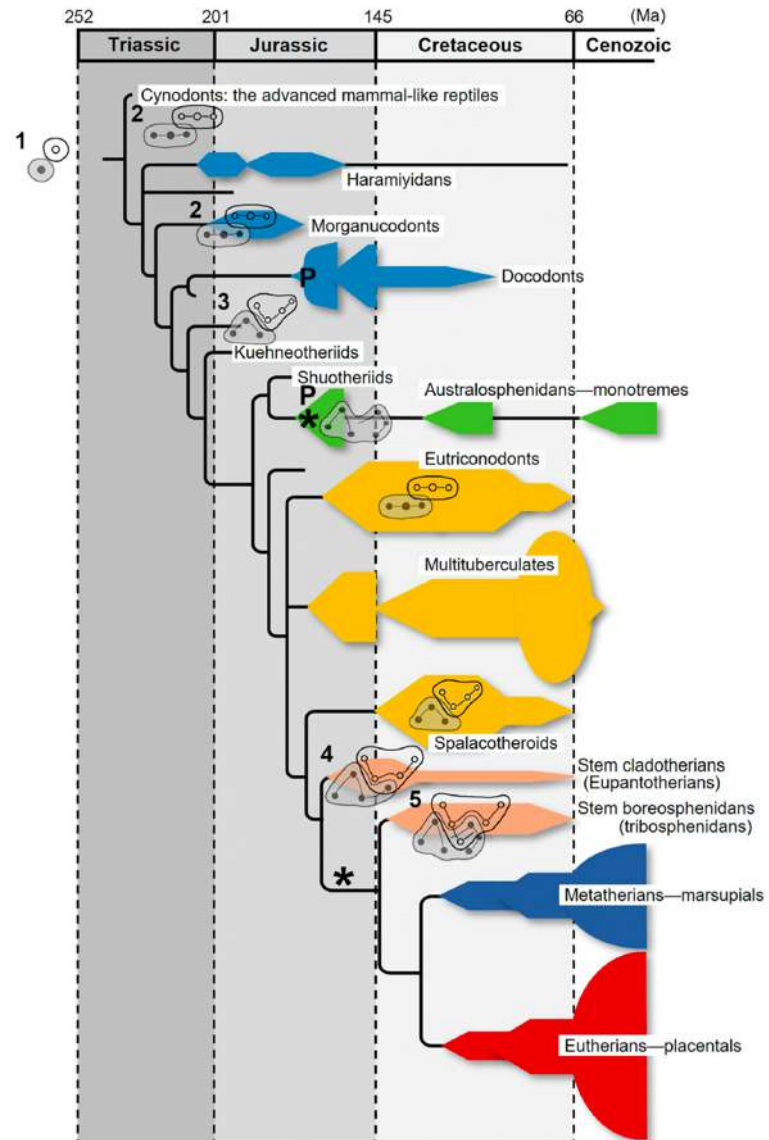




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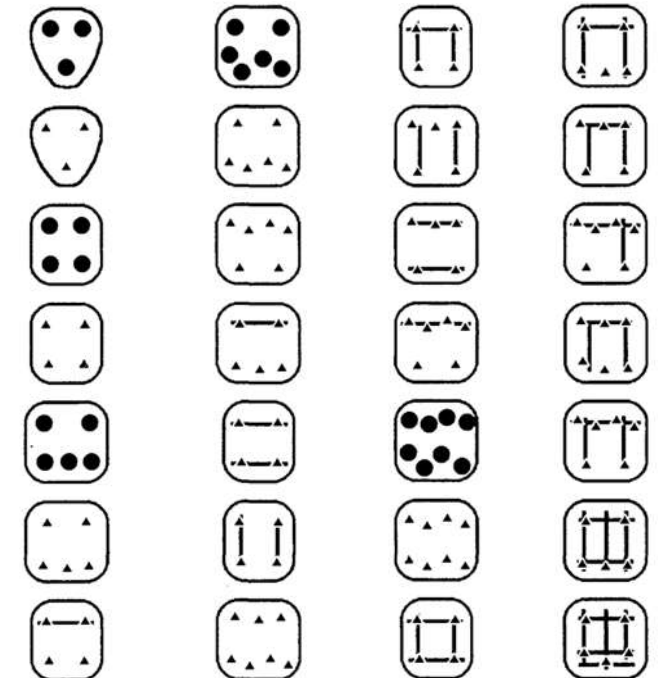
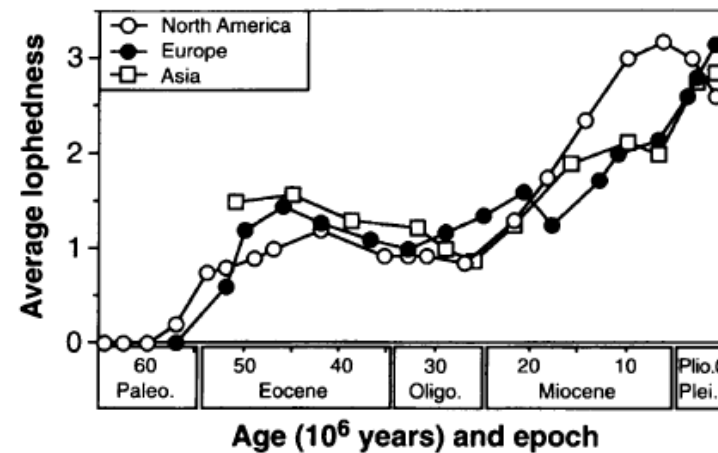
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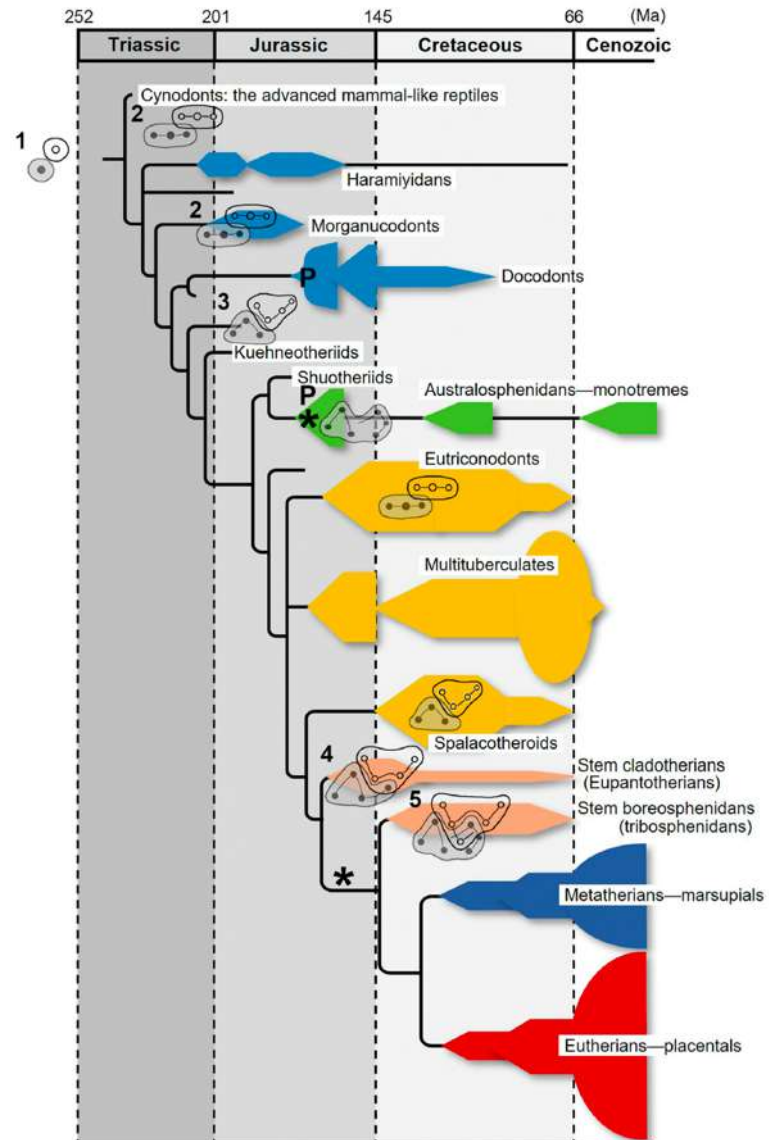




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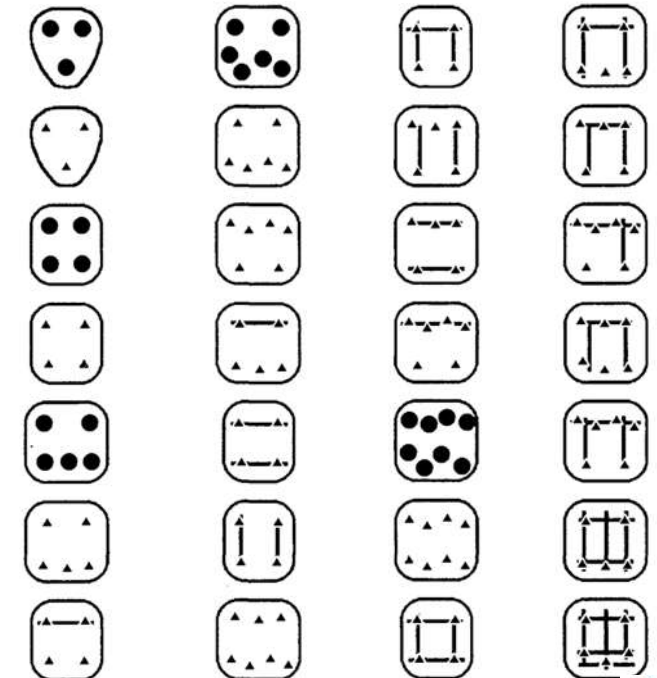
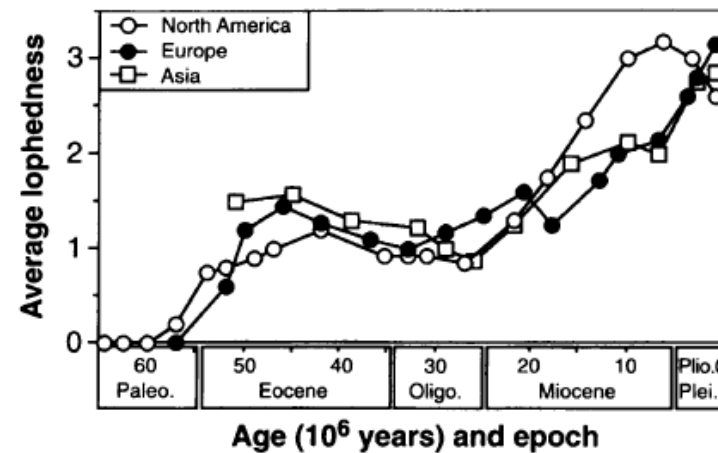
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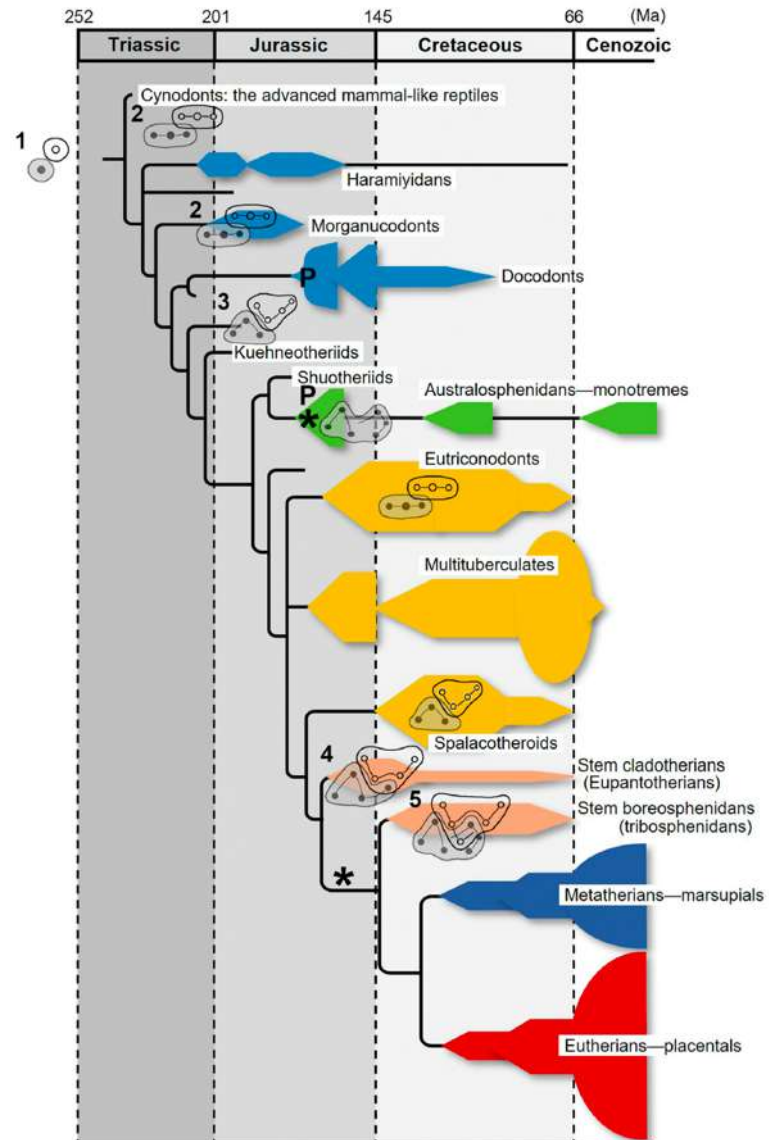




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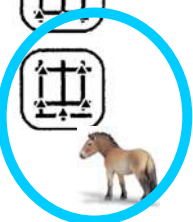
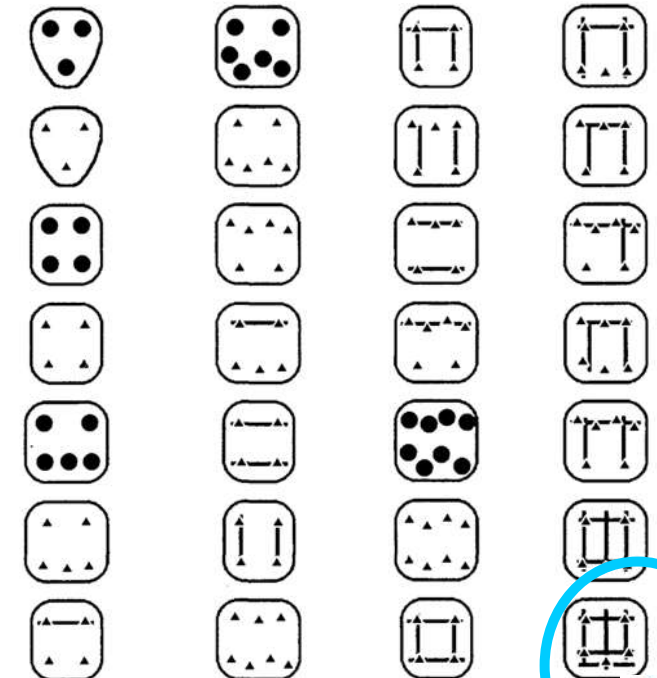
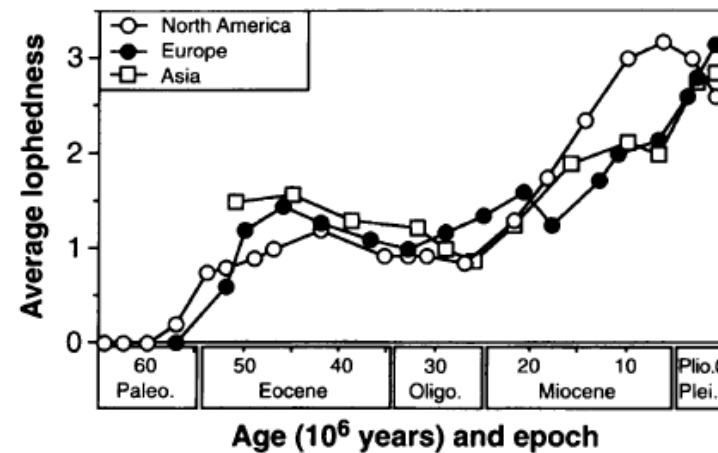
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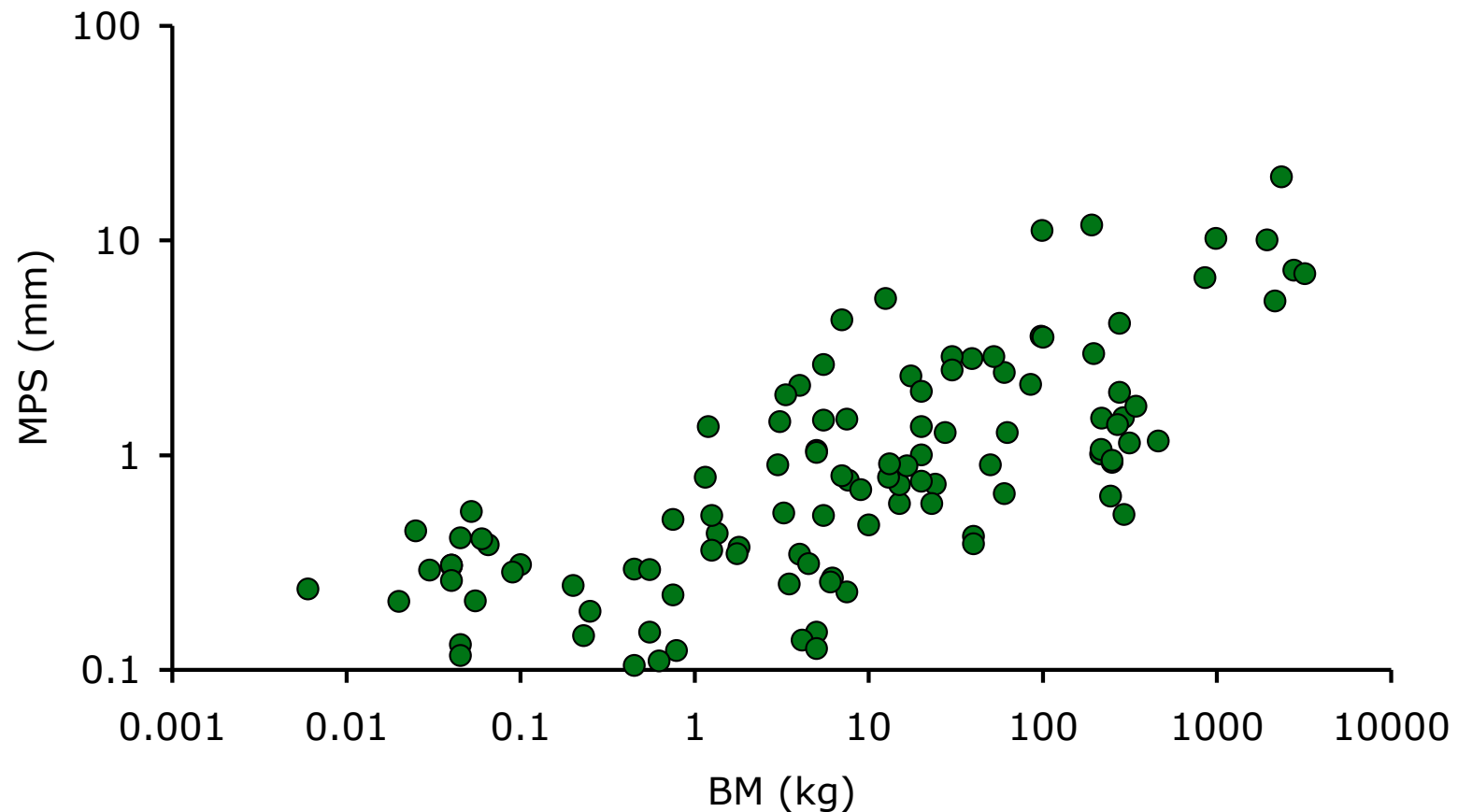




# Comparative chewing efficiency in mammalian herbivores

Julia Fritz, Jürgen Hummel, Ellen Kienzle, Christian Arnold, Charles Nunn and Marcus Clauss

Oikos 118: 1623–1632, 2009

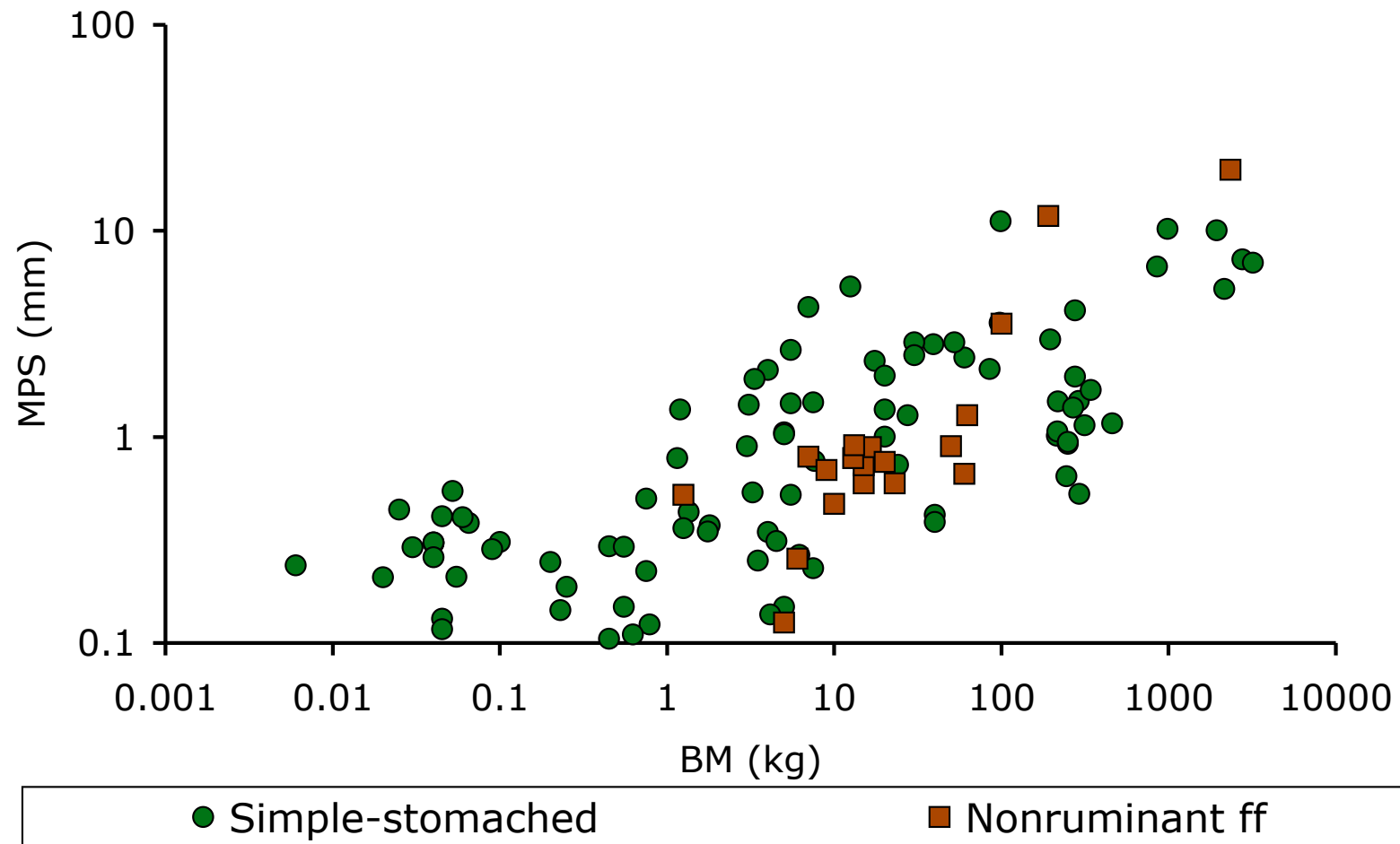




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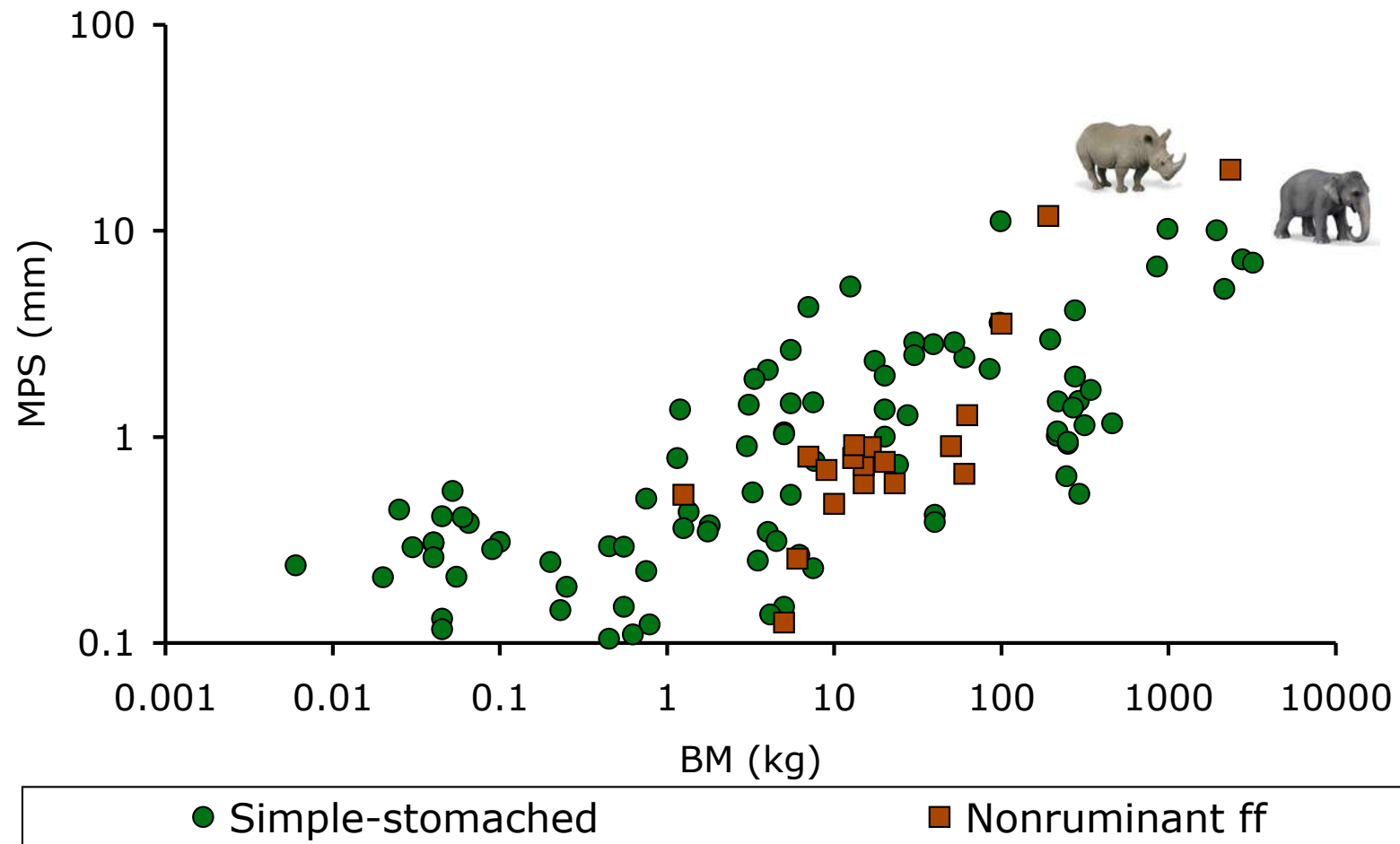




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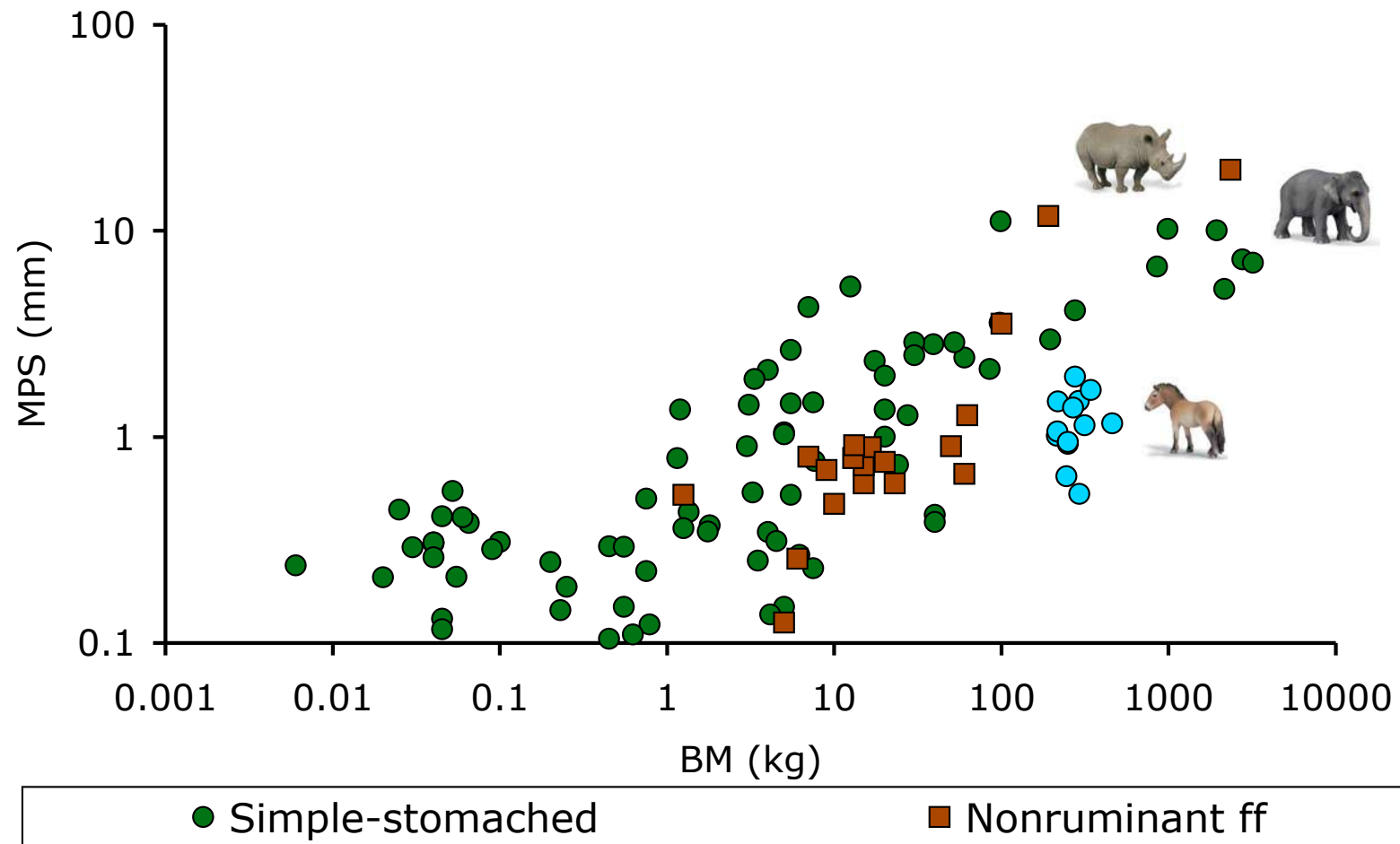




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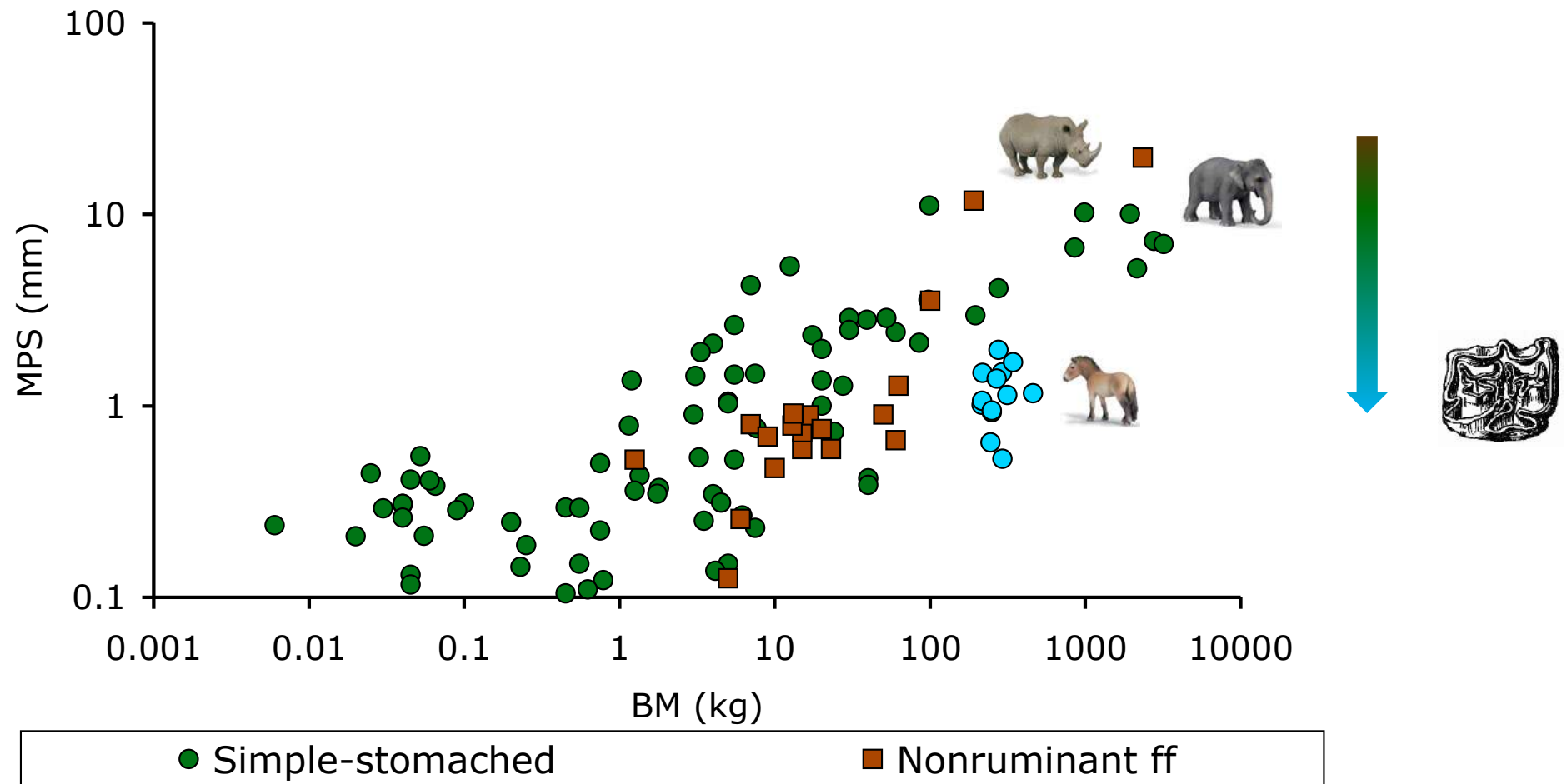




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*Teeth evolve for ... efficiency*



# Continuously Growing Rodent Molars Result from a Predictable Quantitative Evolutionary Change over 50 Million Years

Cell Reports 11, 673–680, May 5, 2015

Vagan Tapaltsyan,<sup>1,8</sup> Jussi T. Eronen,<sup>2,3,8</sup> A. Michelle Lawing,<sup>4</sup> Amnon Sharir,<sup>1</sup> Christine Janis,<sup>5</sup> Jukka Jernvall,<sup>6,\*</sup> and Ophir D. Klein<sup>1,7,\*</sup>



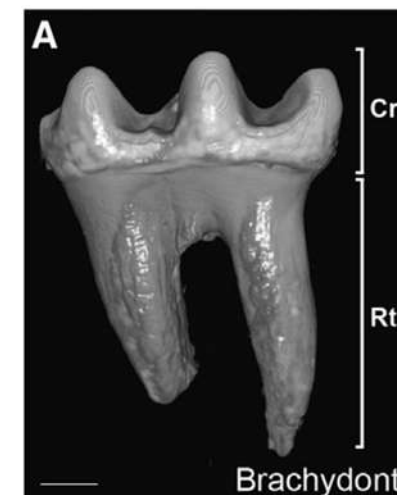
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## Brachydont

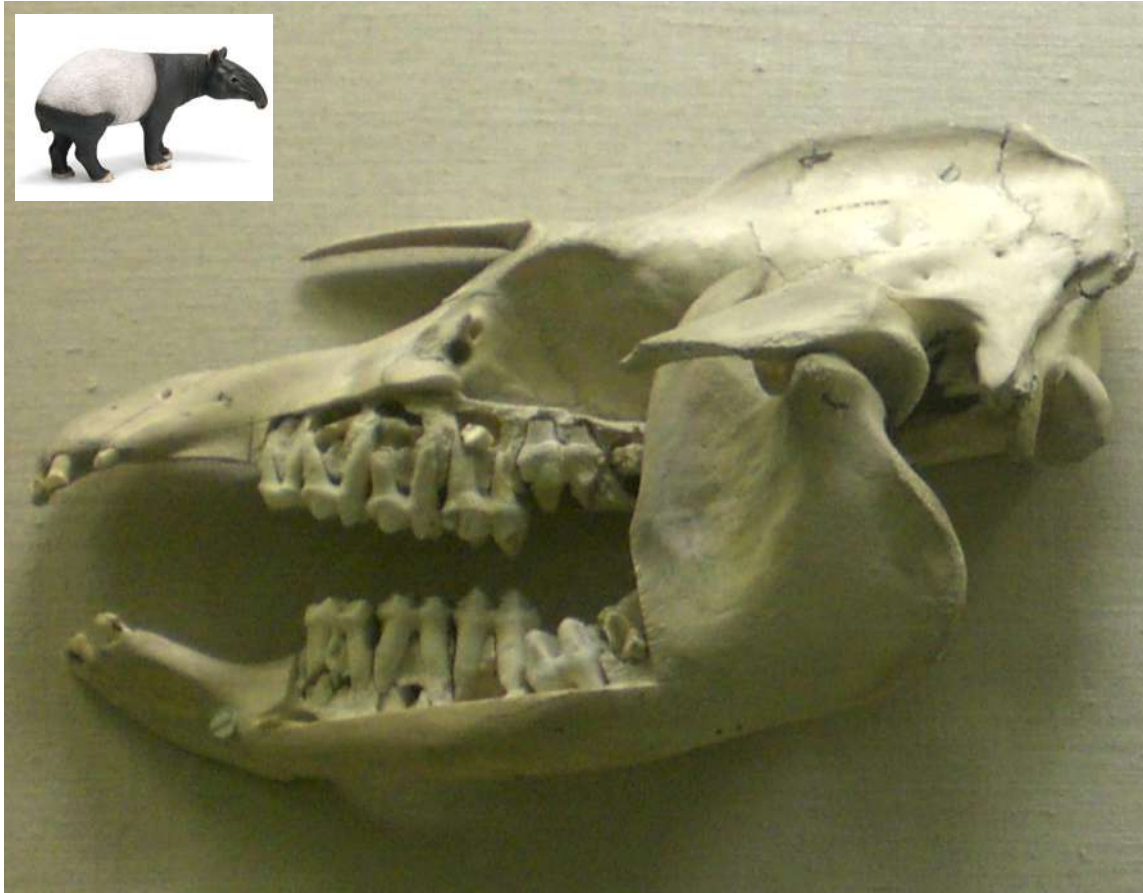


■ Crown  
■ Root





# Brachydonty







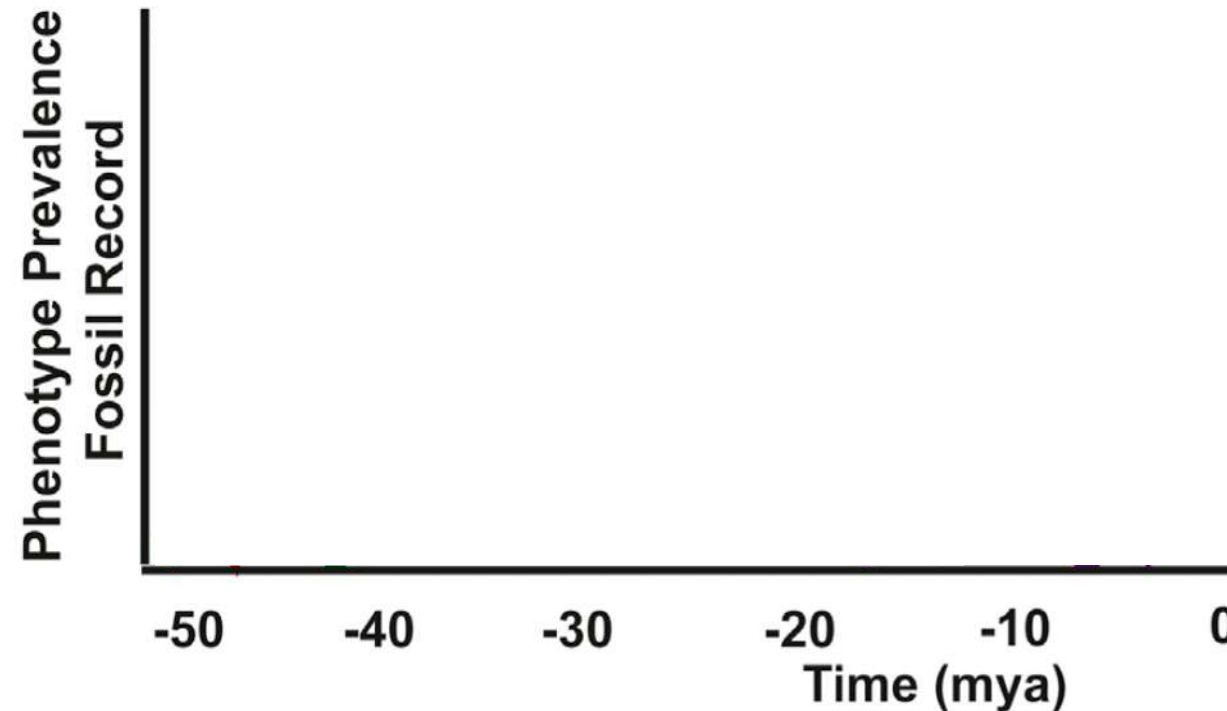
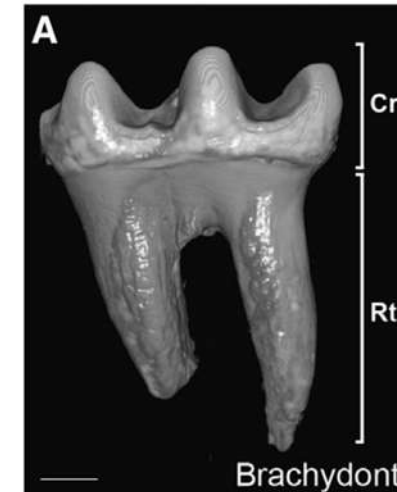
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## Brachydont



■ Crown  
■ Root







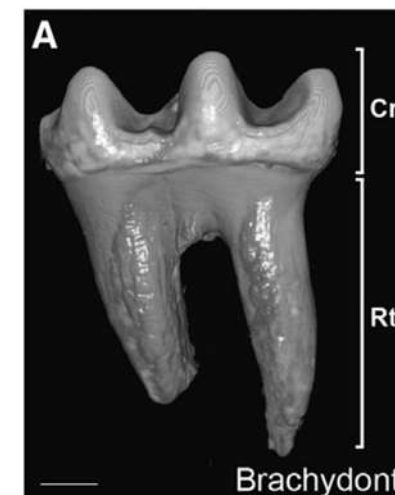
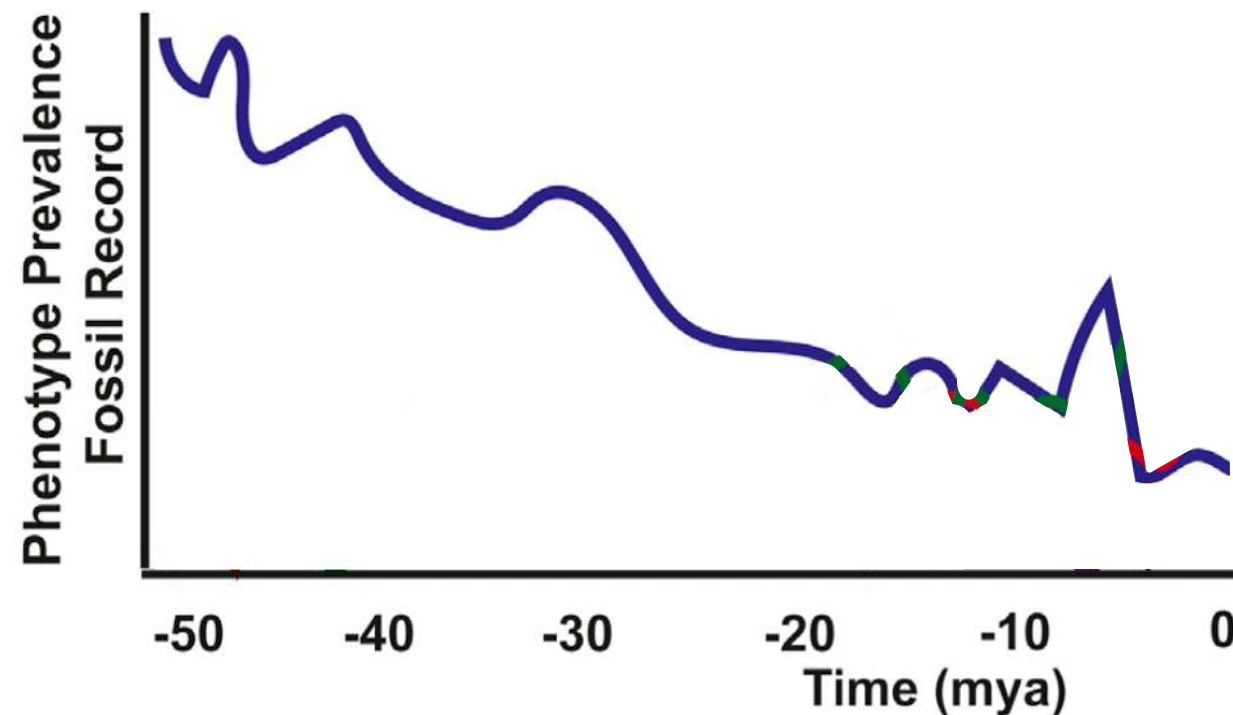
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## Brachydont



■ Crown  
■ Root

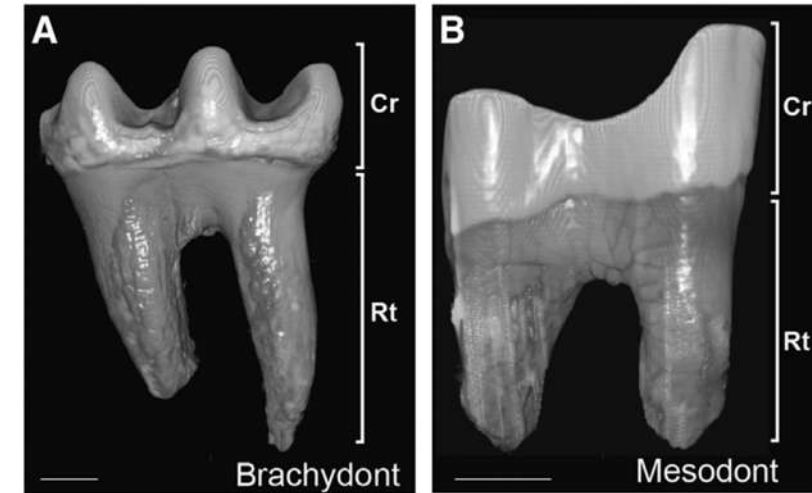
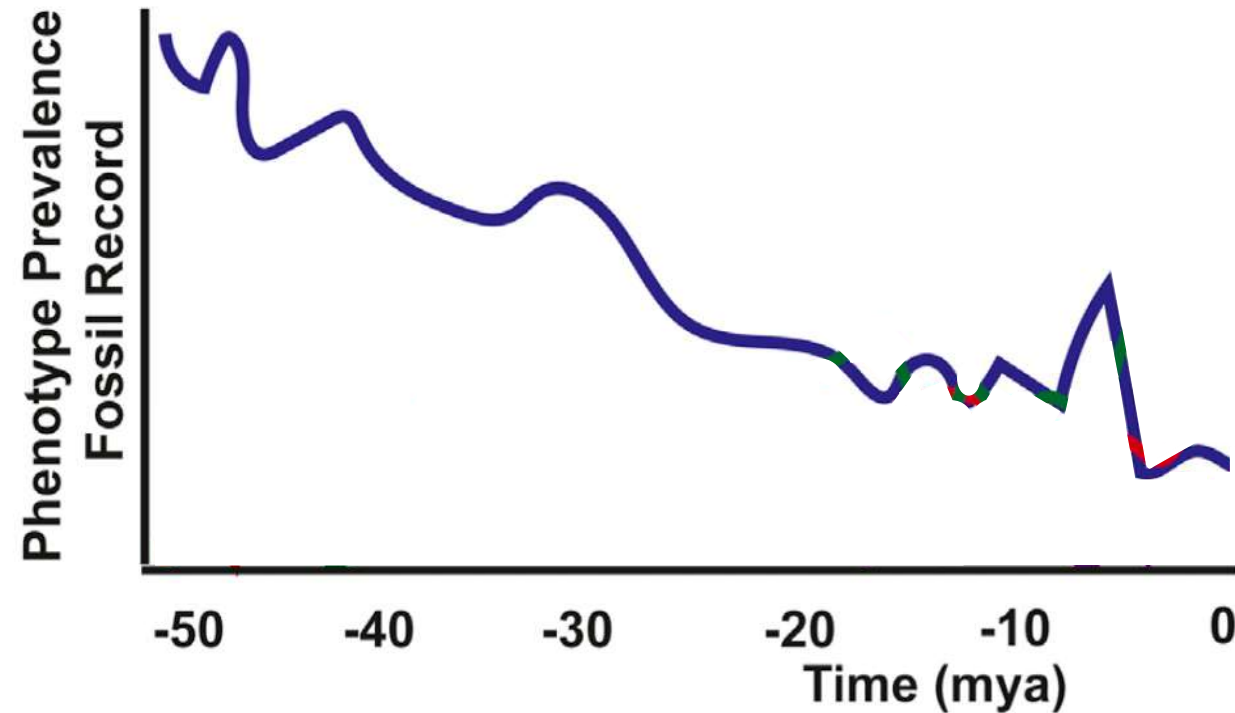




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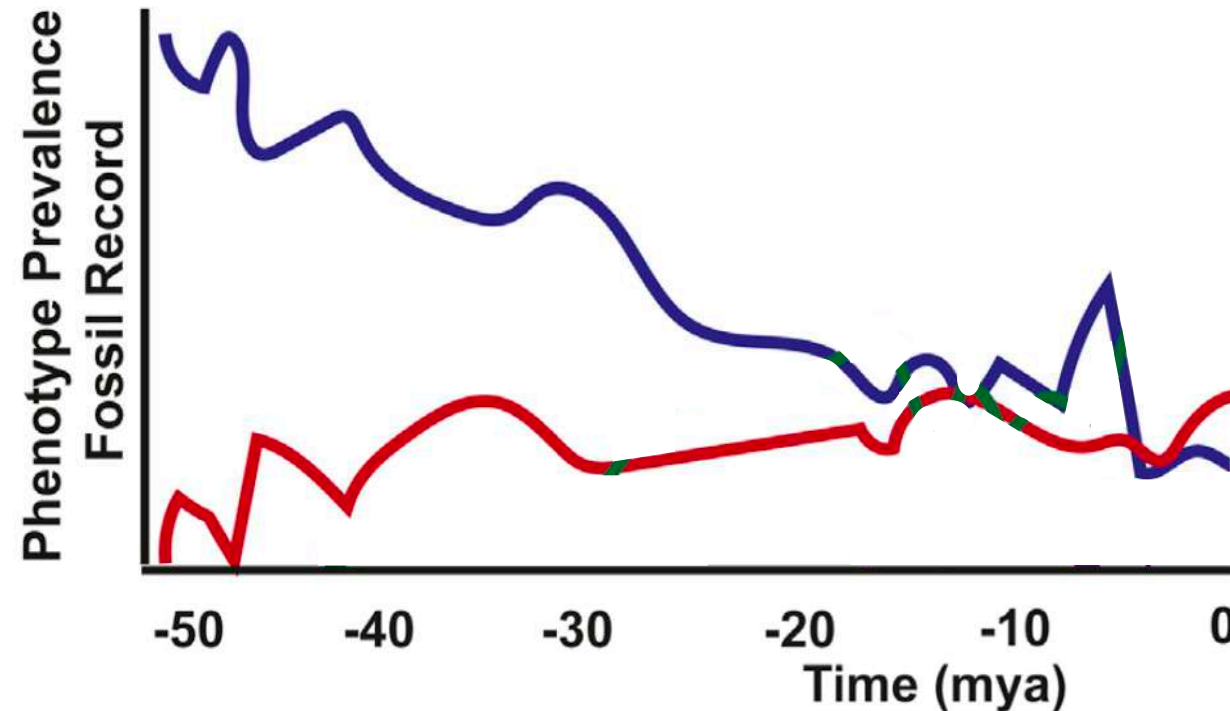
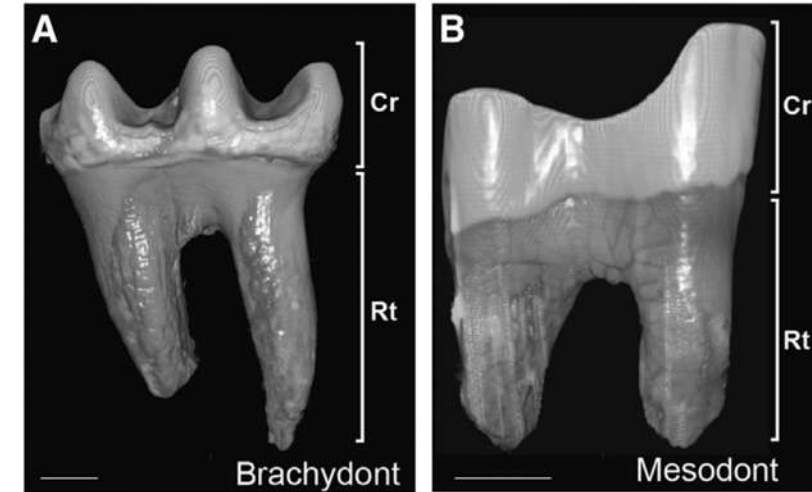
Brachydont



Mesodont



■ Crown  
■ Root

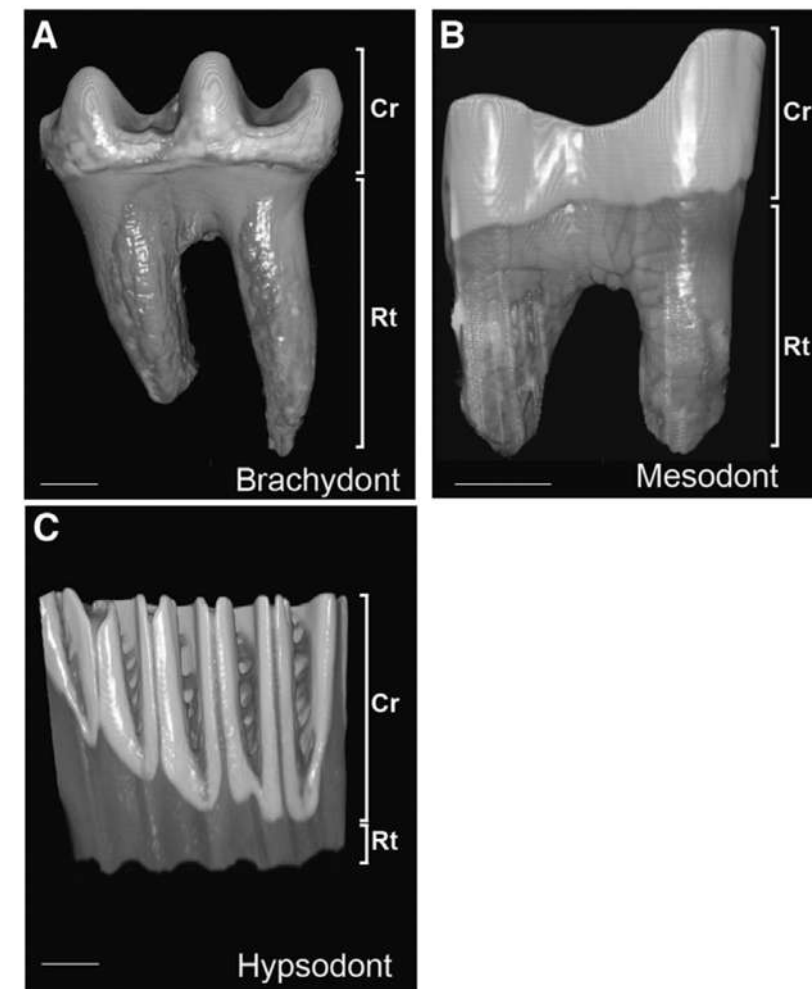
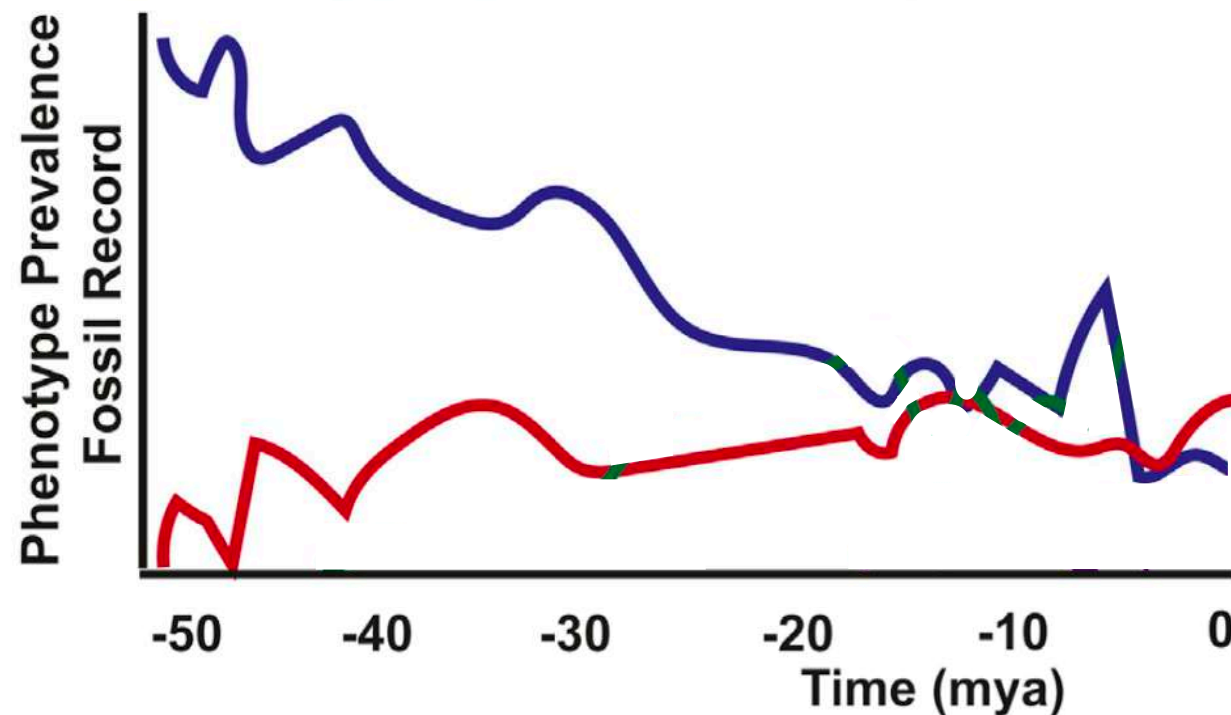
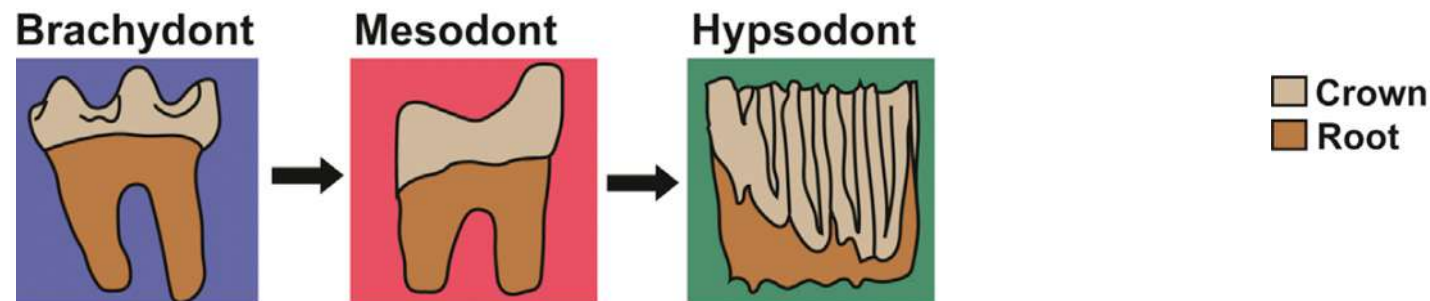






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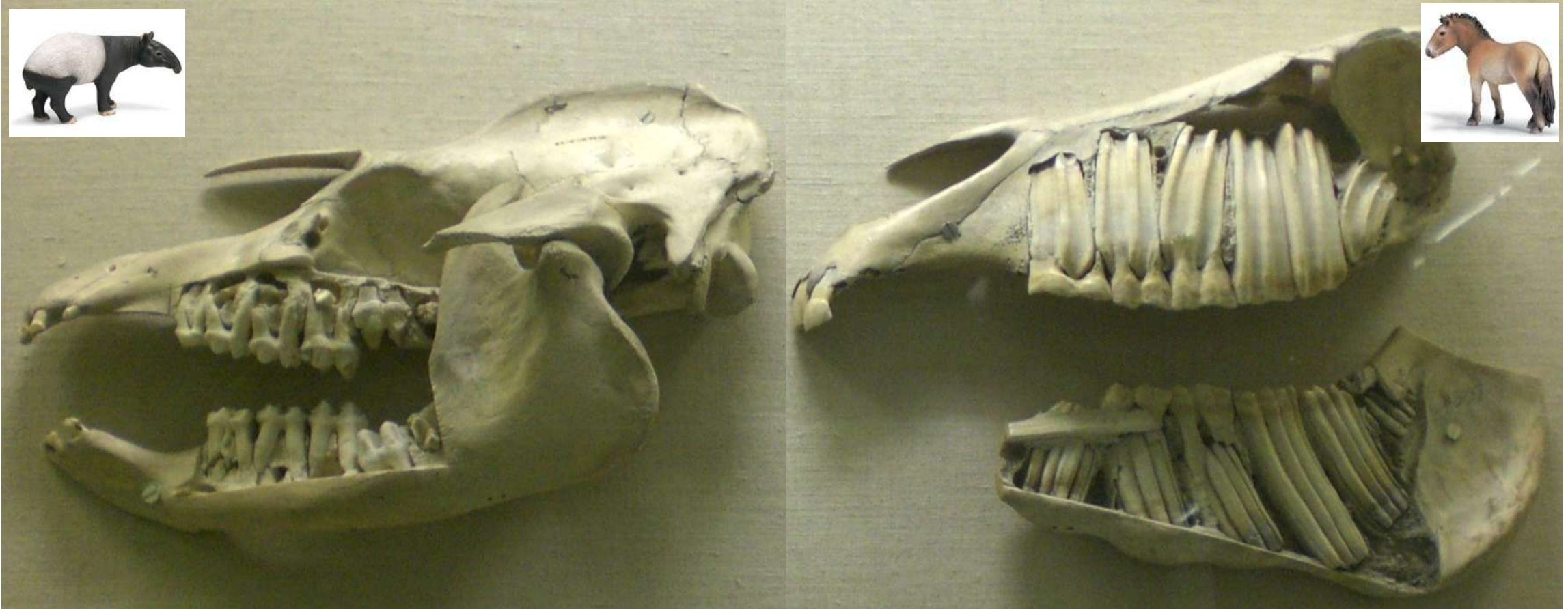




Brachydonty

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Hypsodonty



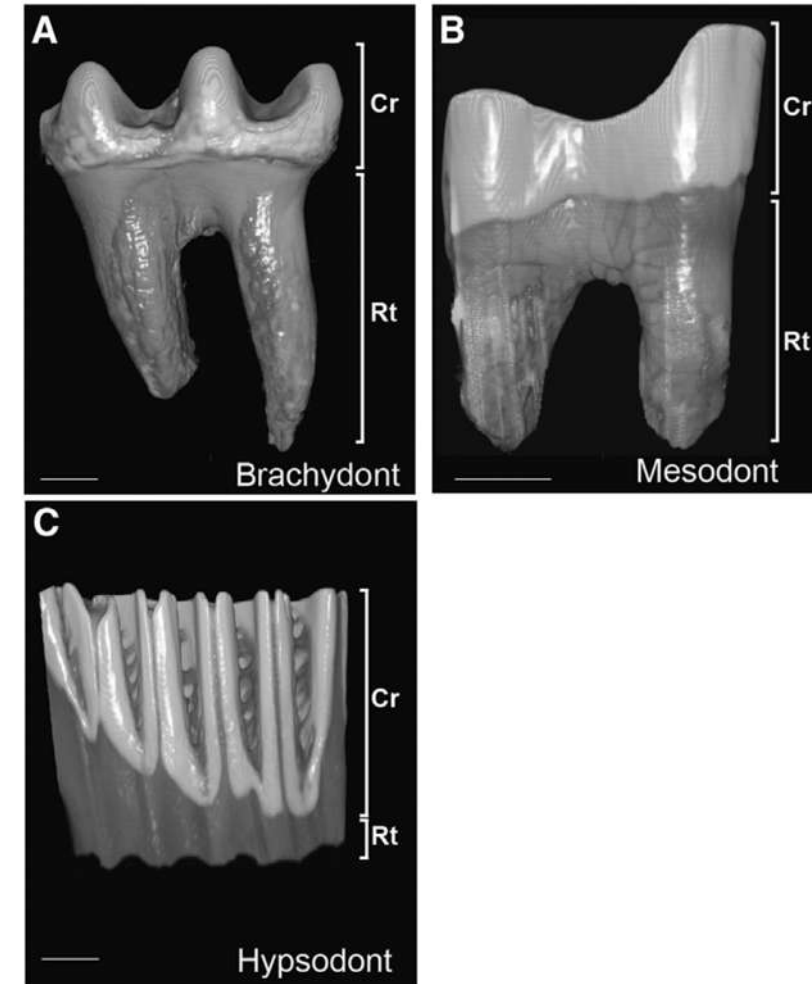
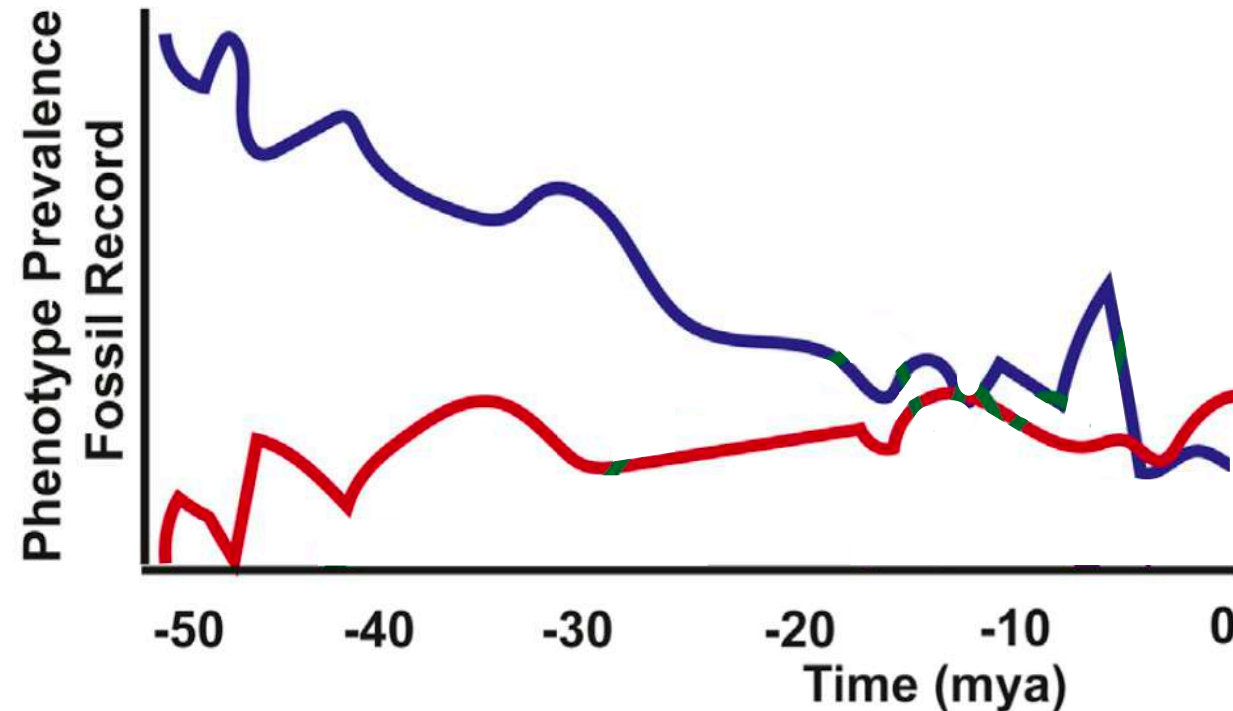
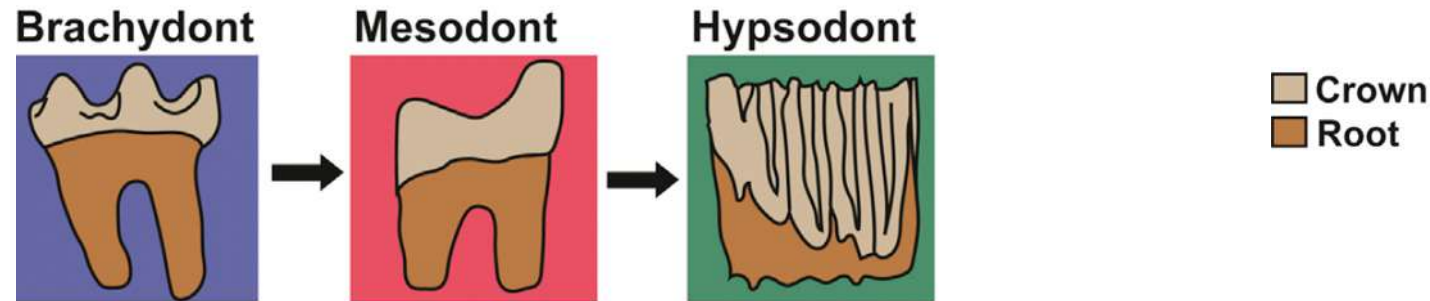




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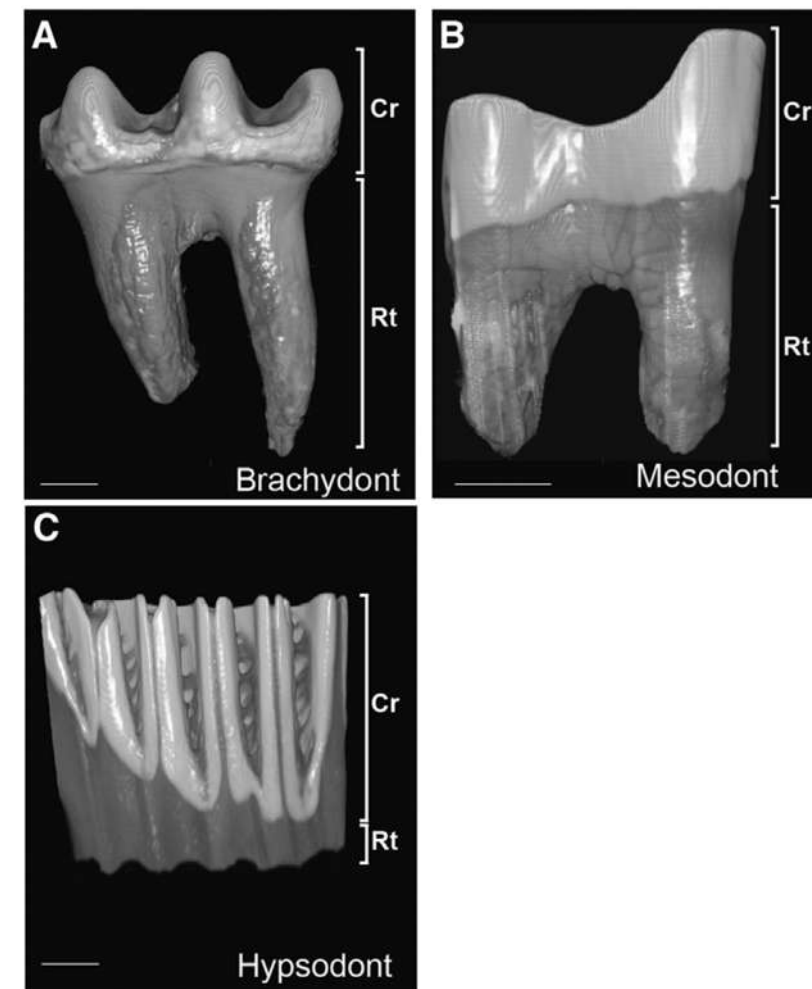
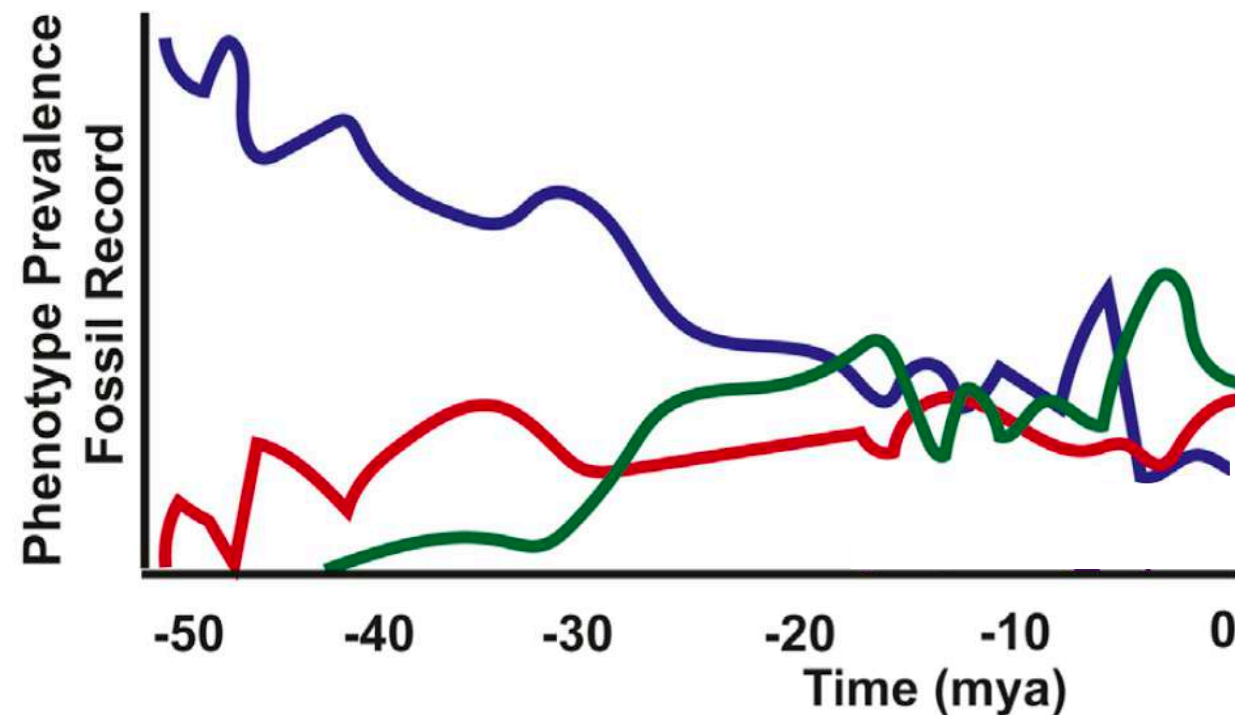
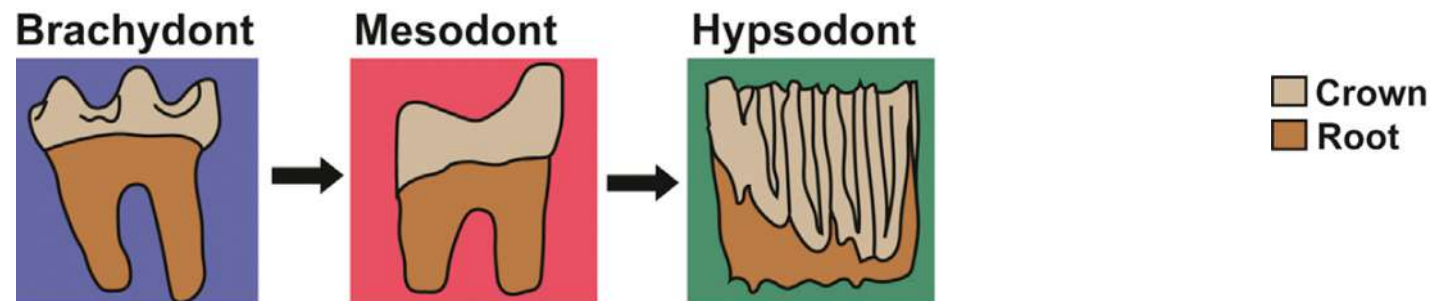
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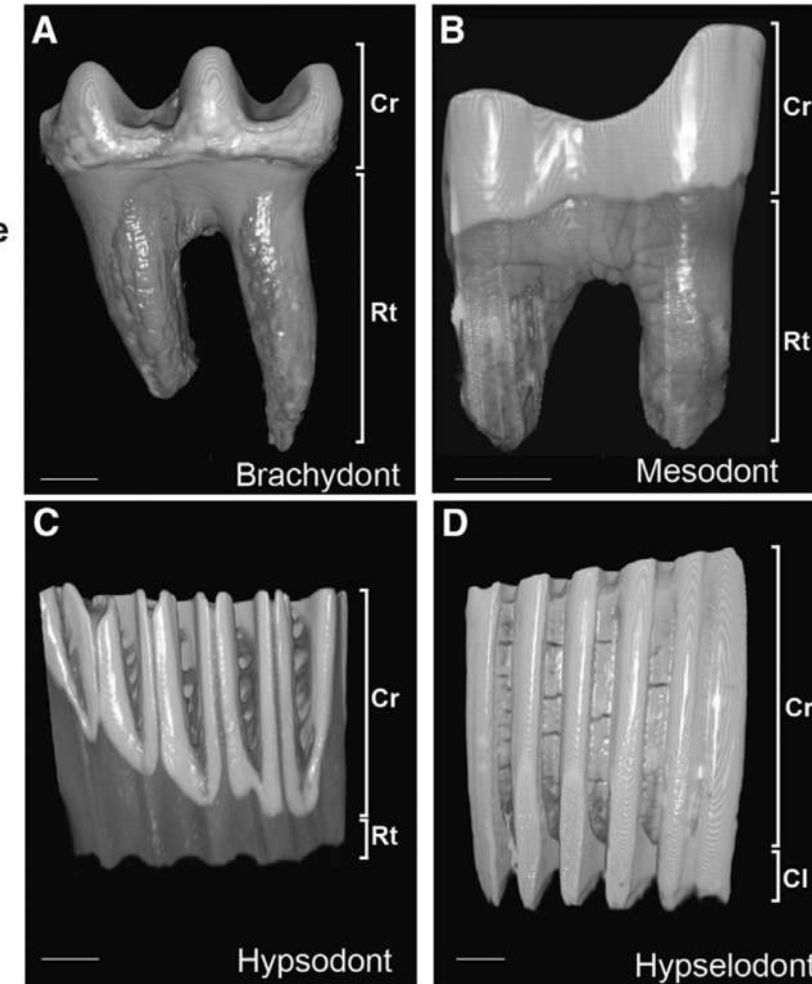
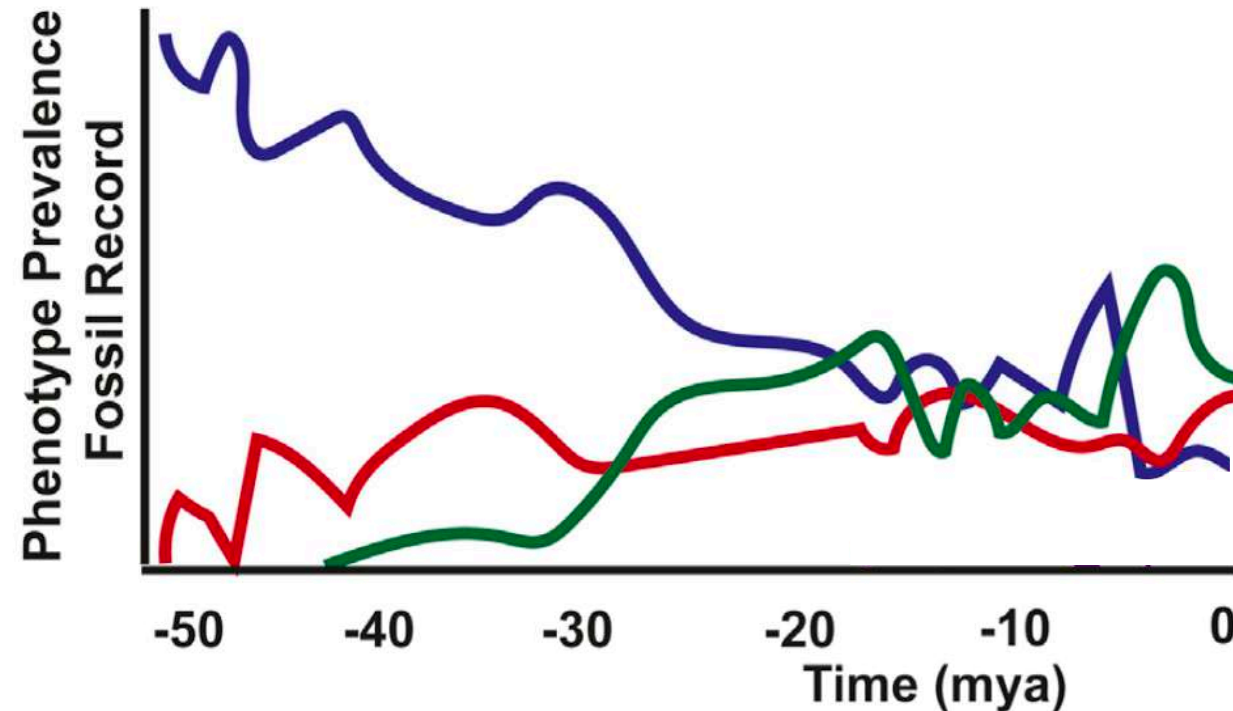
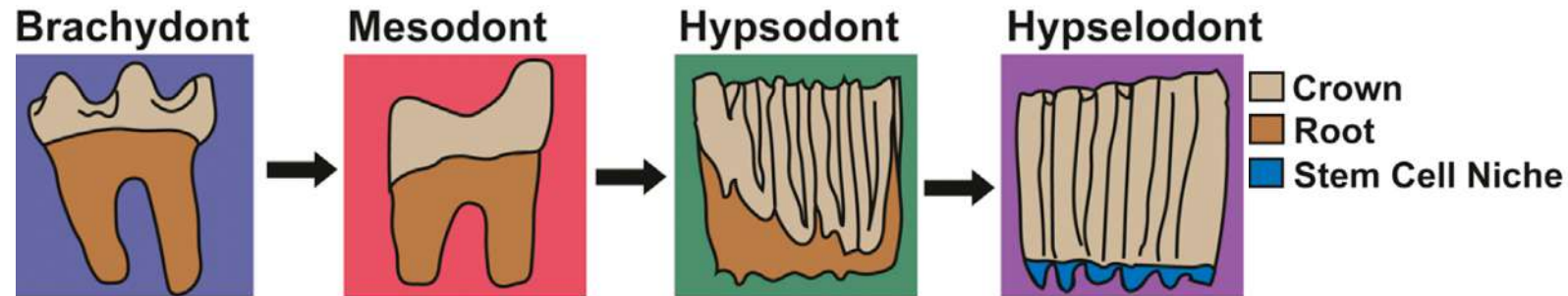




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# Ever-growing teeth – ‘Hypselodonty’

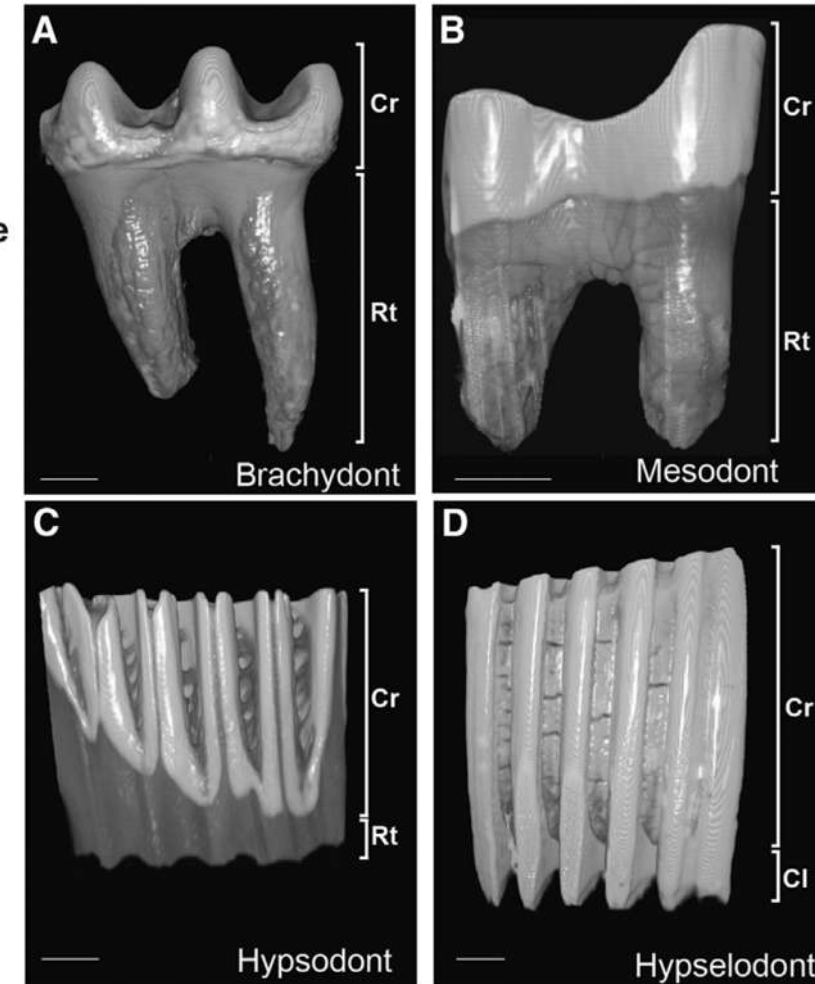
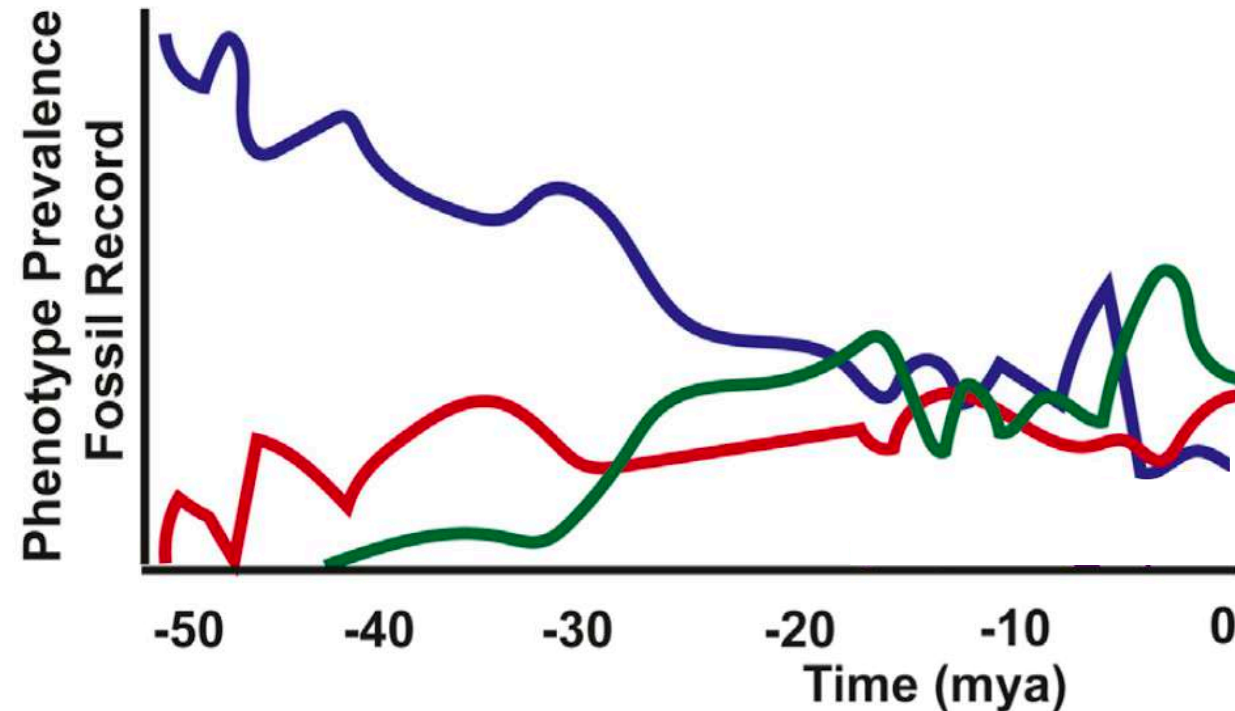
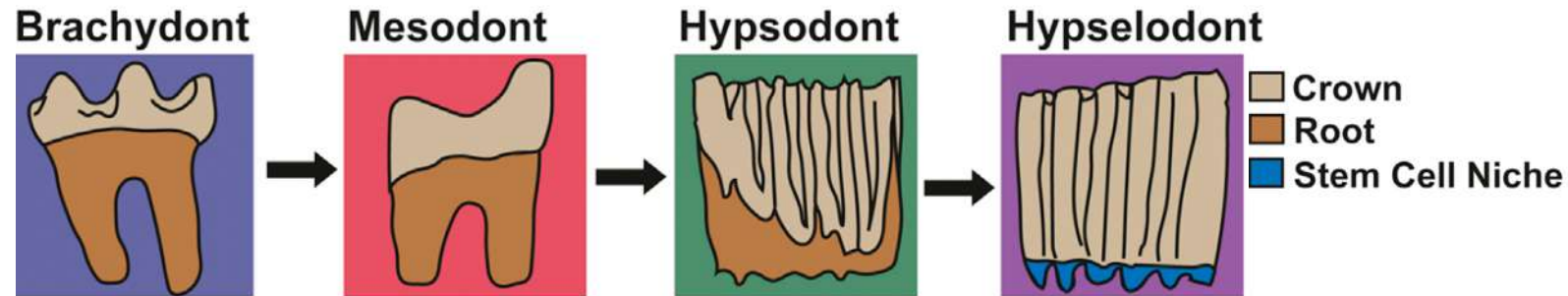




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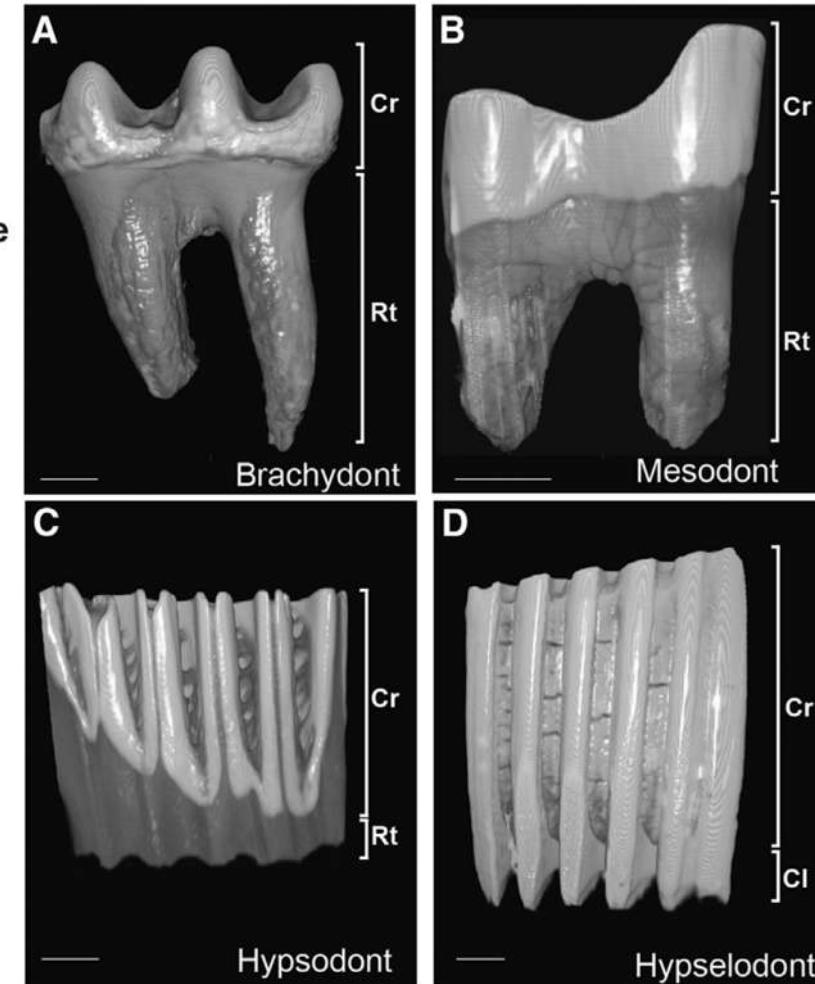
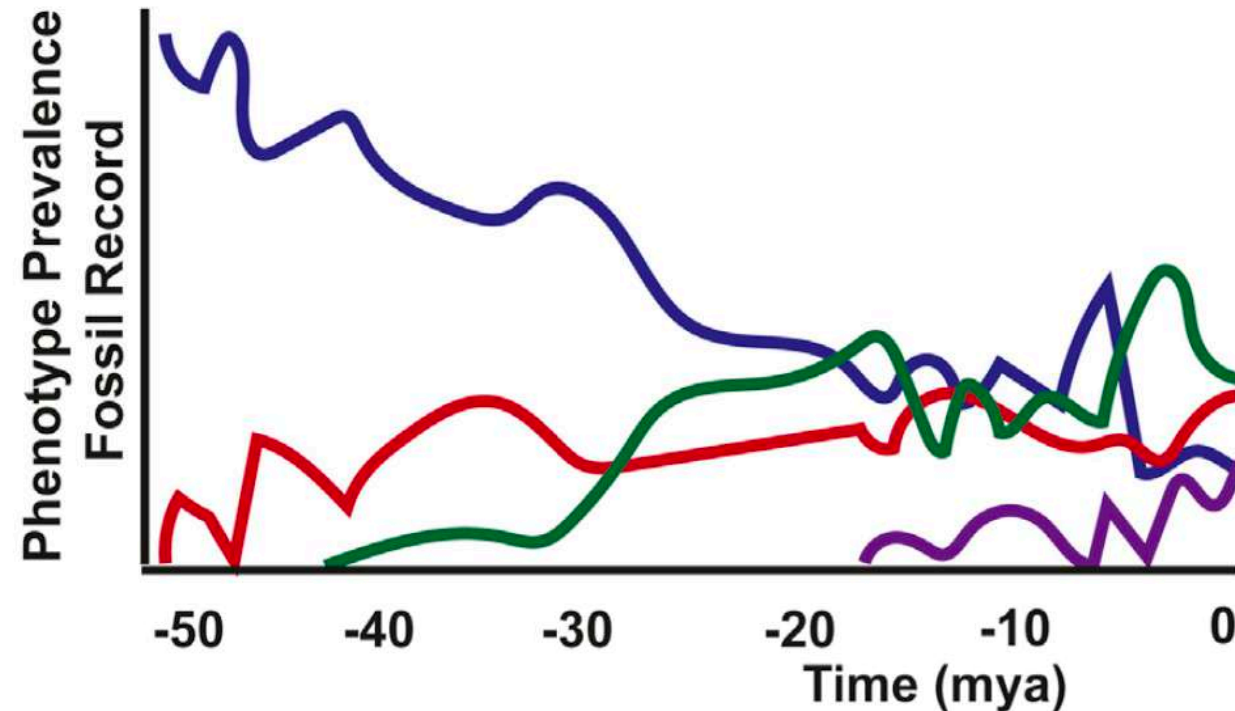
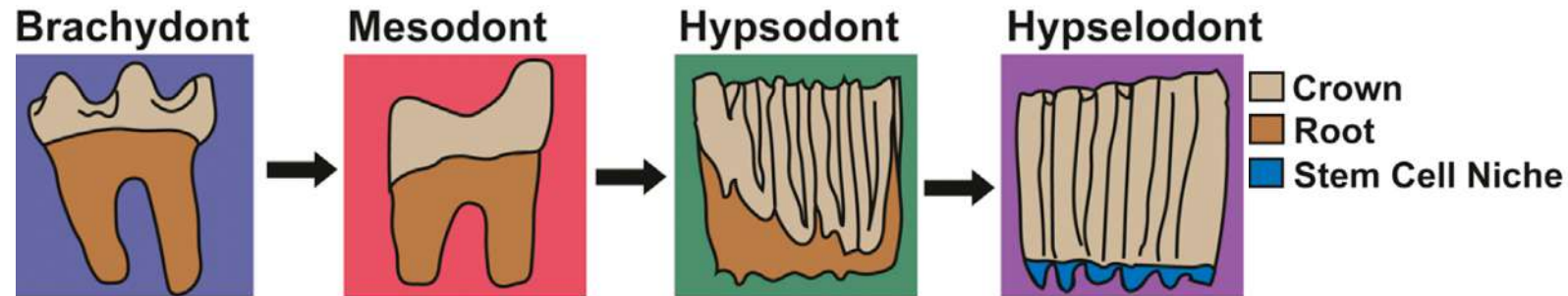




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*Teeth evolve for ... efficiency  
&  
durability*



*Faunivory – Omnivory – Herbivory*



*Faunivory – Omnivory – Herbivory*

...

*and microbe farming*



# Food chains

**A terrestrial  
food chain**

**A marine  
food chain**

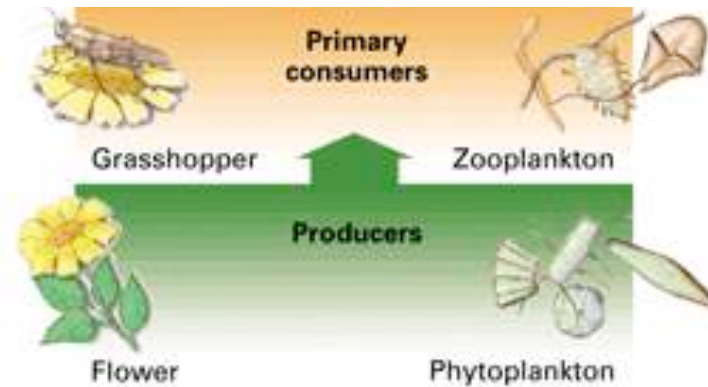




# Food chains

A terrestrial  
food chain

A marine  
food chain



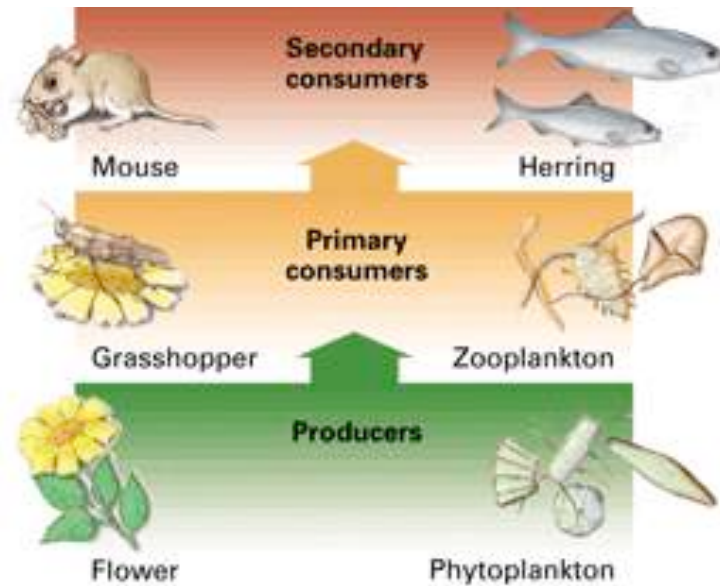




# Food chains

A terrestrial  
food chain

A marine  
food chain

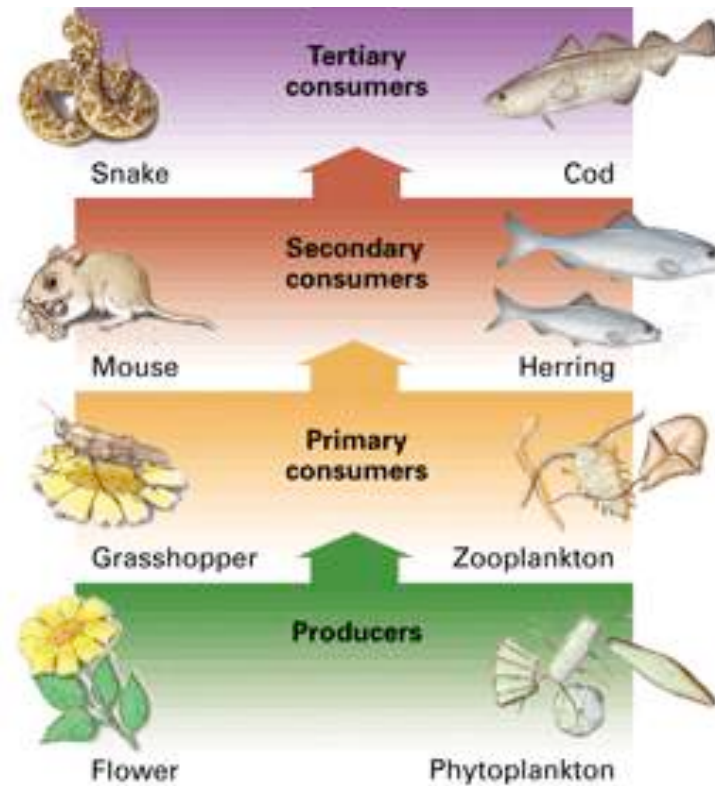




# Food chains

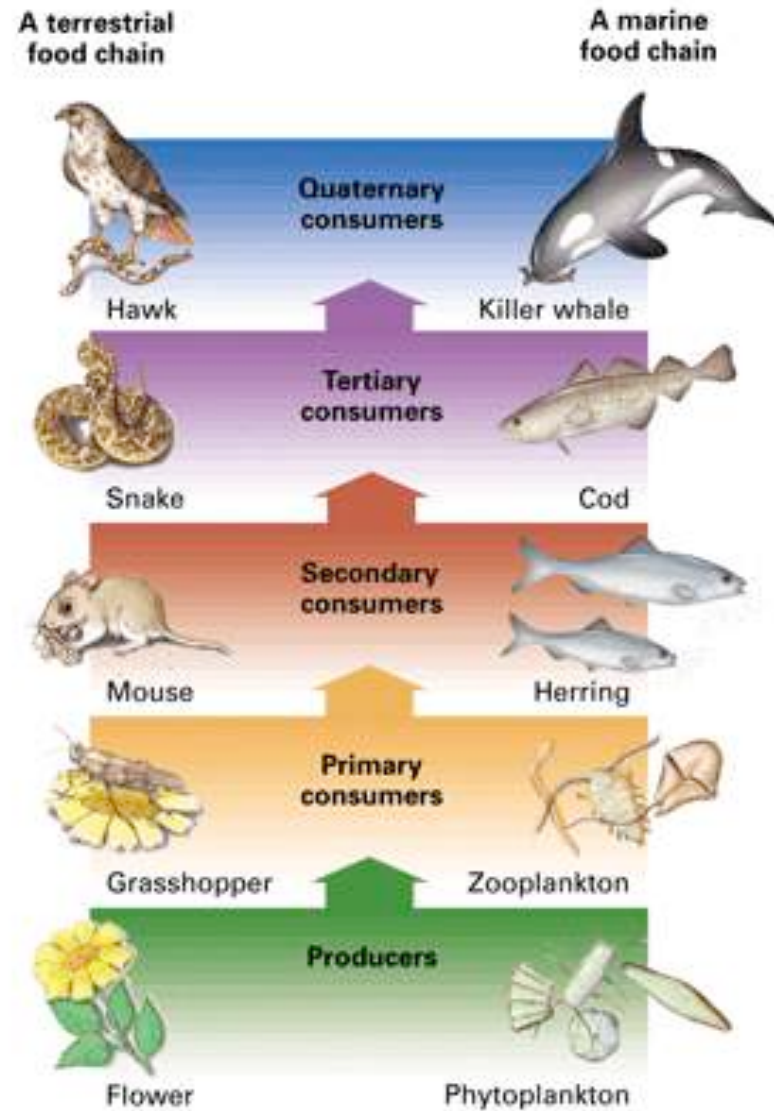
A terrestrial  
food chain

A marine  
food chain



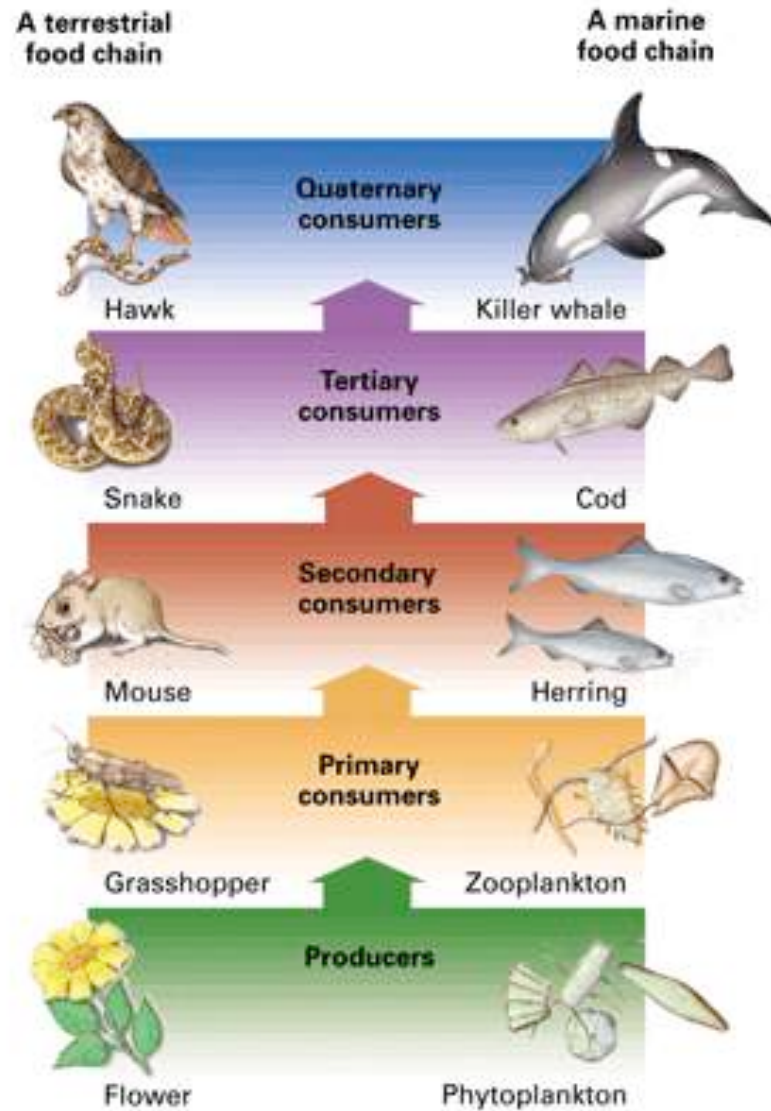


# Food chains



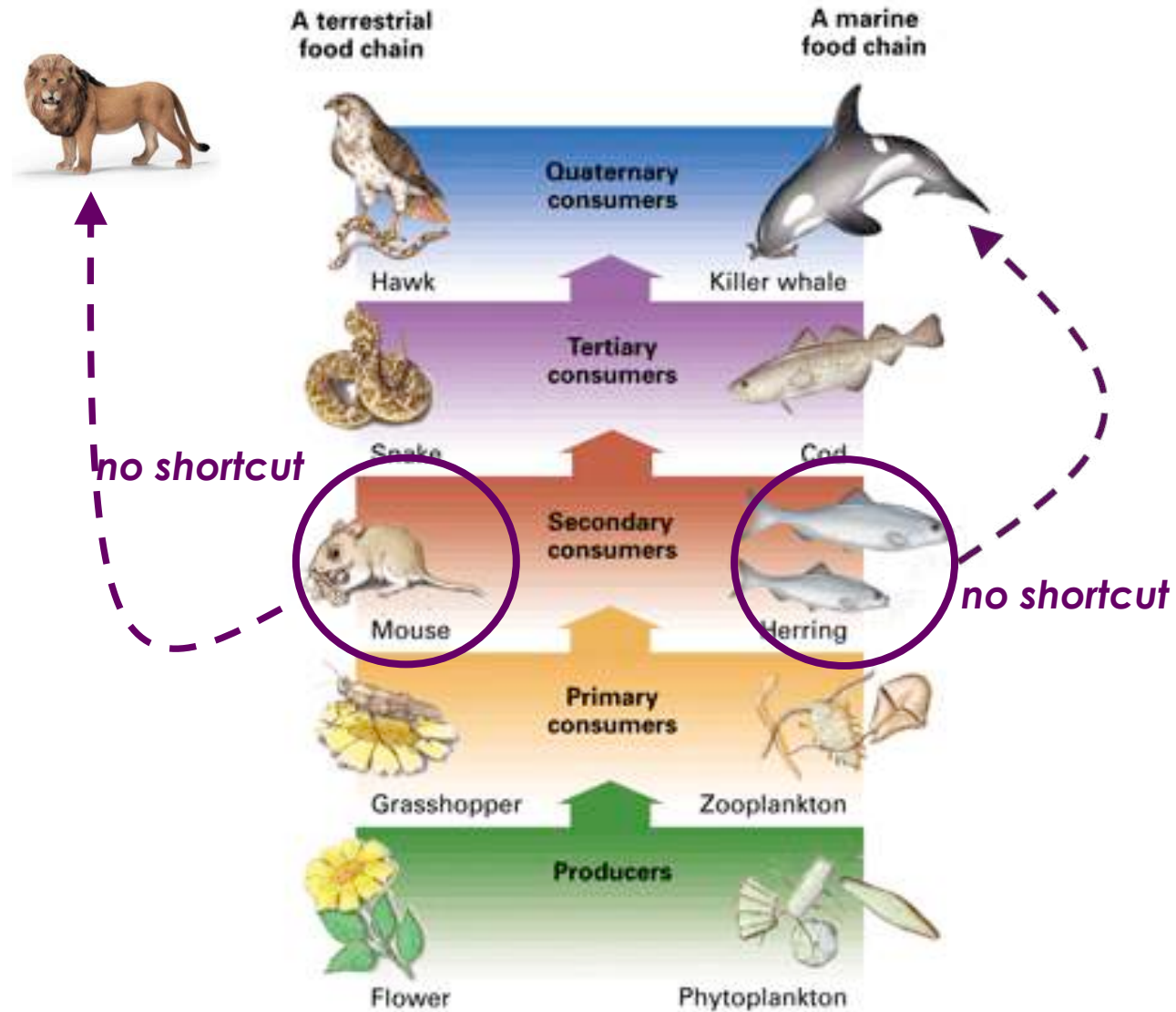


# Food chains ... & shortcuts



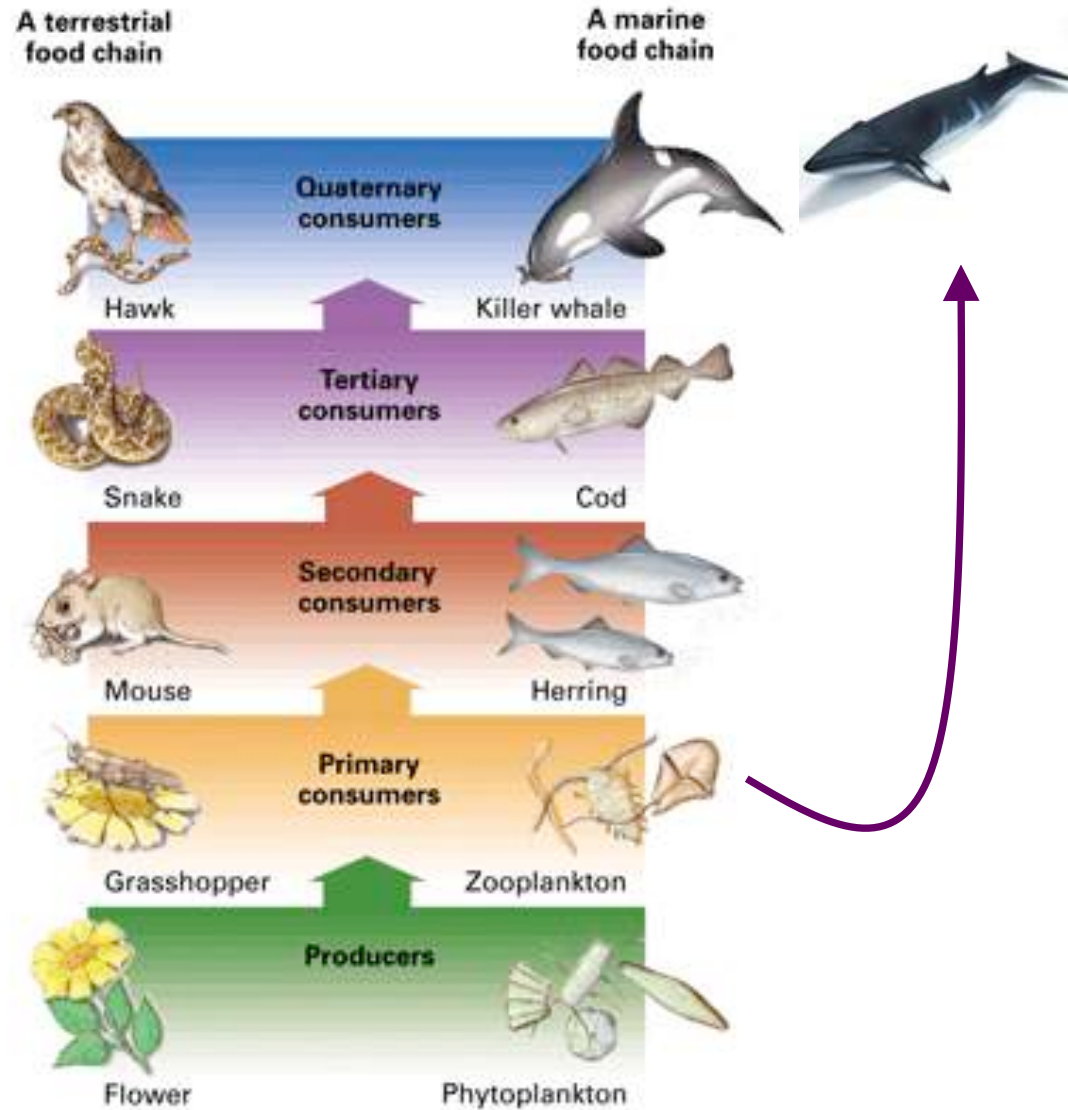


# Food chains ... & shortcuts





# Food chains ... & shortcuts







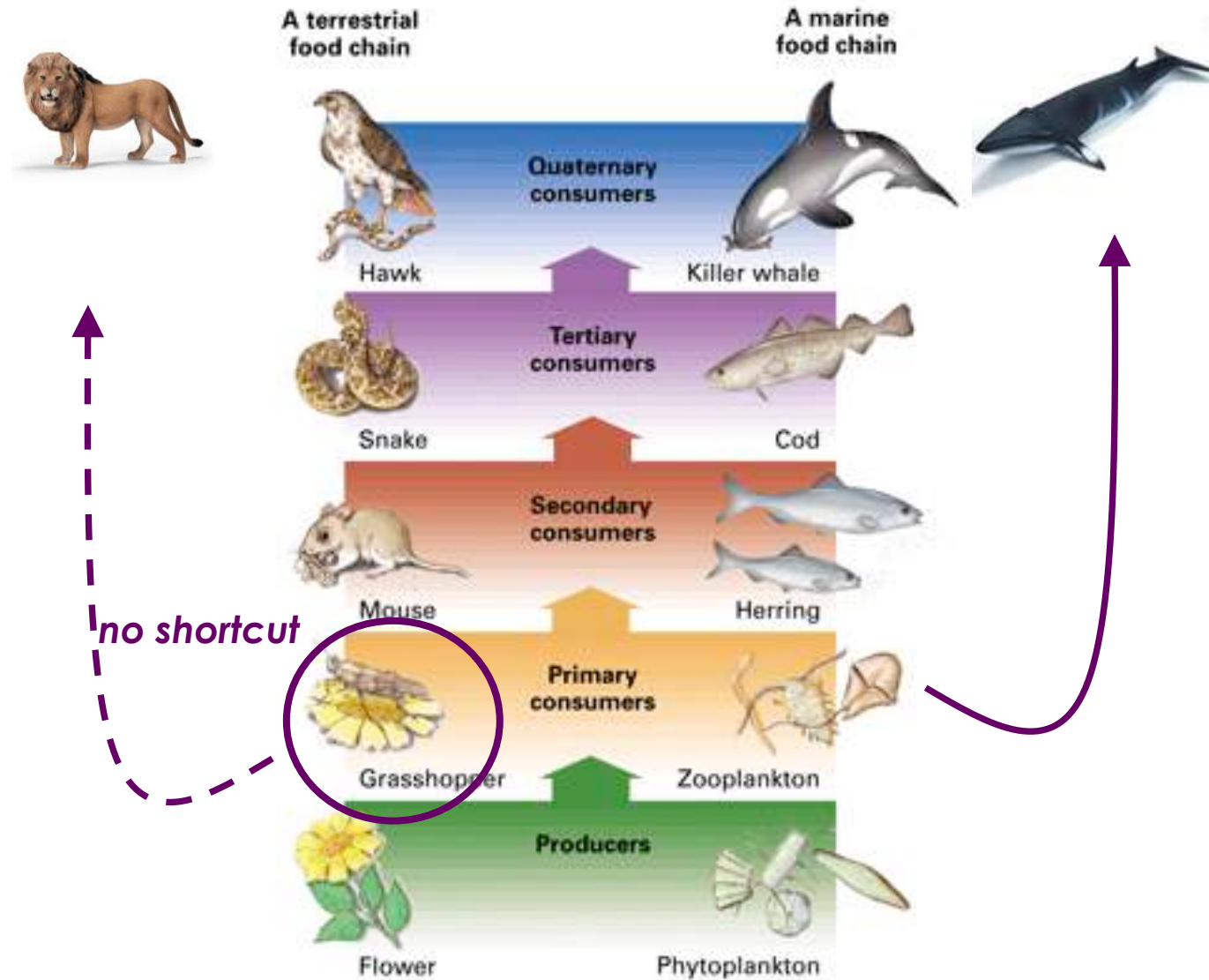
## Easy-to-harvest packages of tiny invertebrates – krill clouds







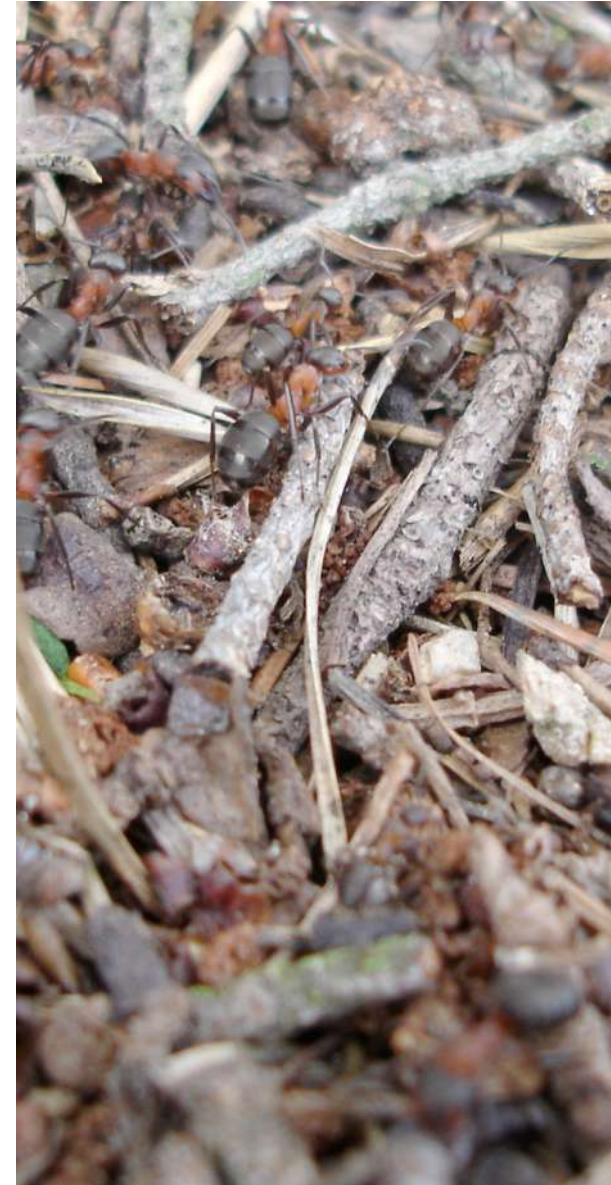
# Food chains ... & shortcuts







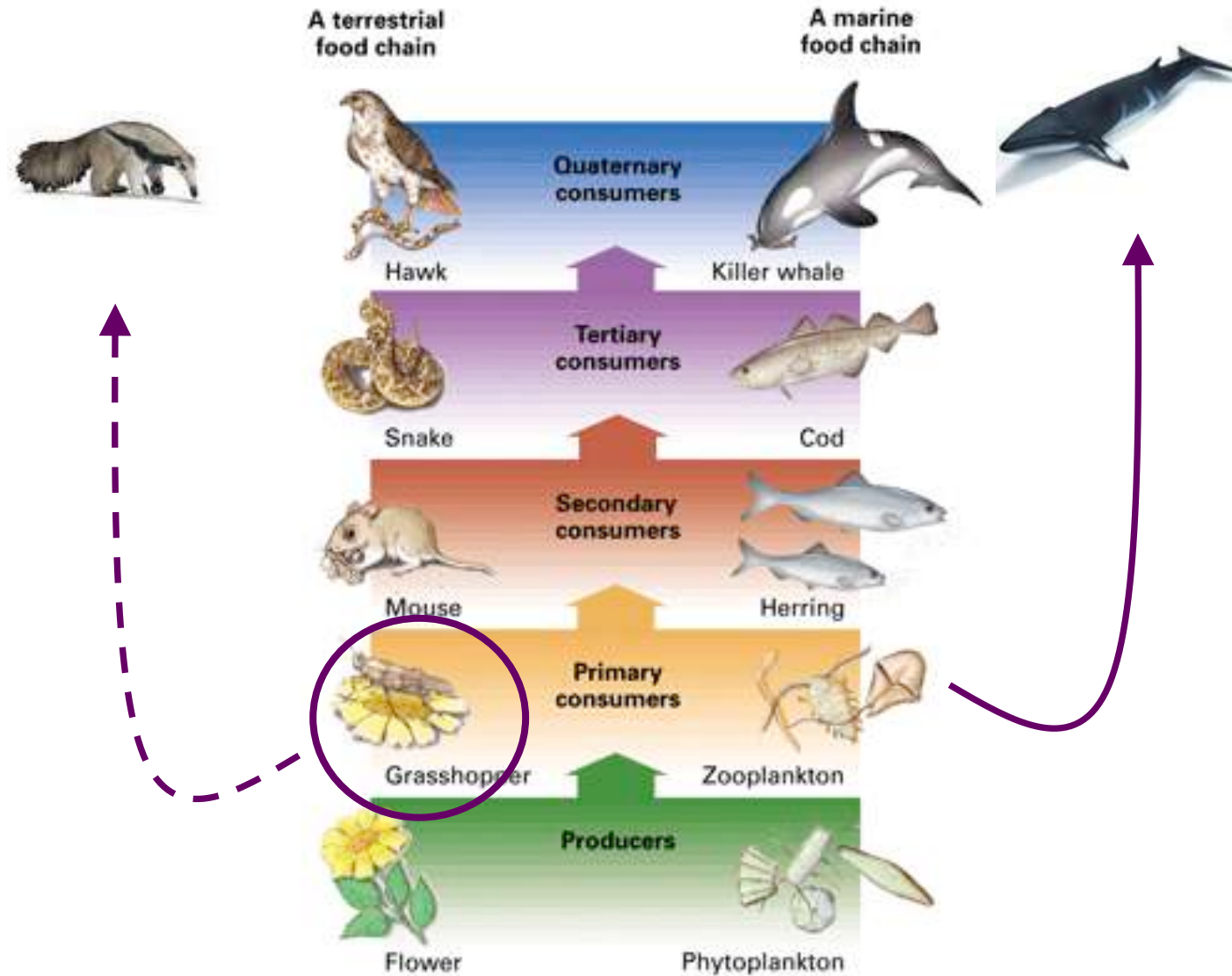
# No easy-to-harvest packages of tiny vertebrates





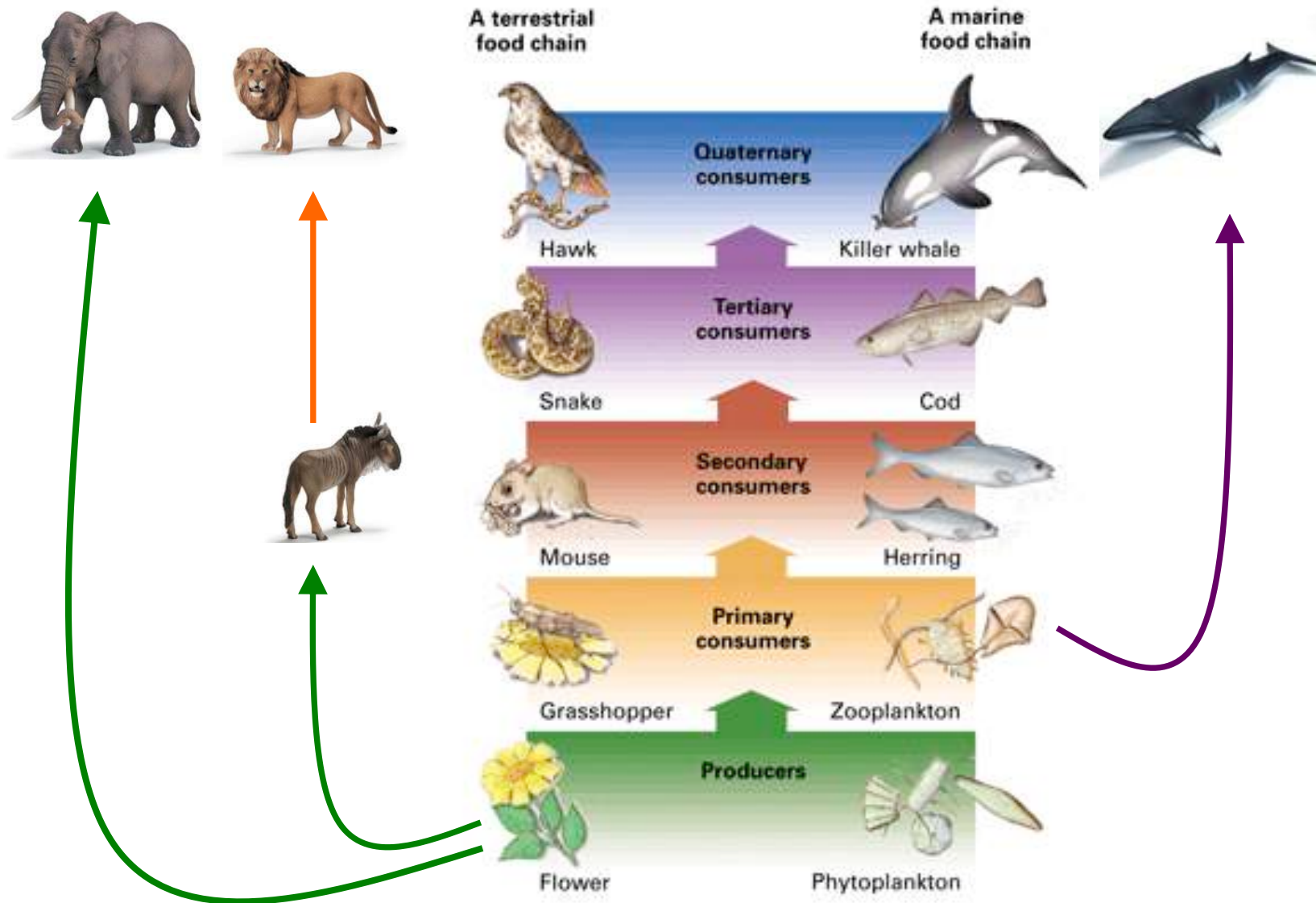


# Food chains ... & shortcuts





# Food chains ... & shortcuts







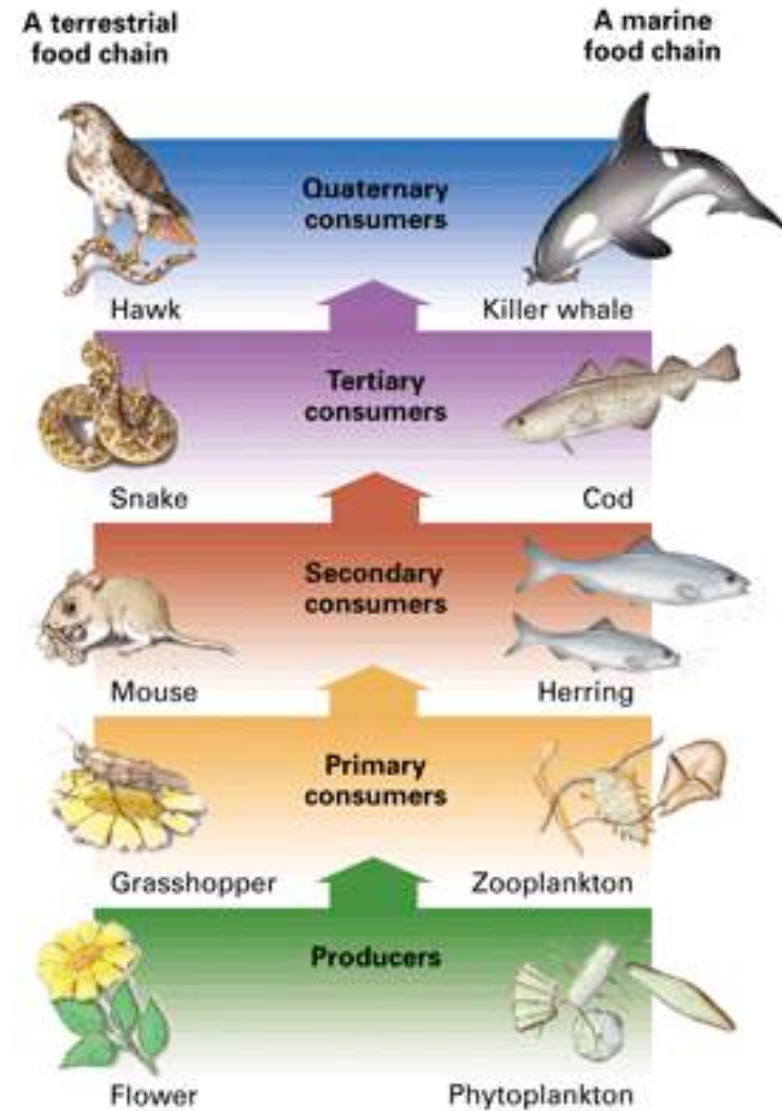
# Ubiquitous dense large packages of plant food in terrestrial systems





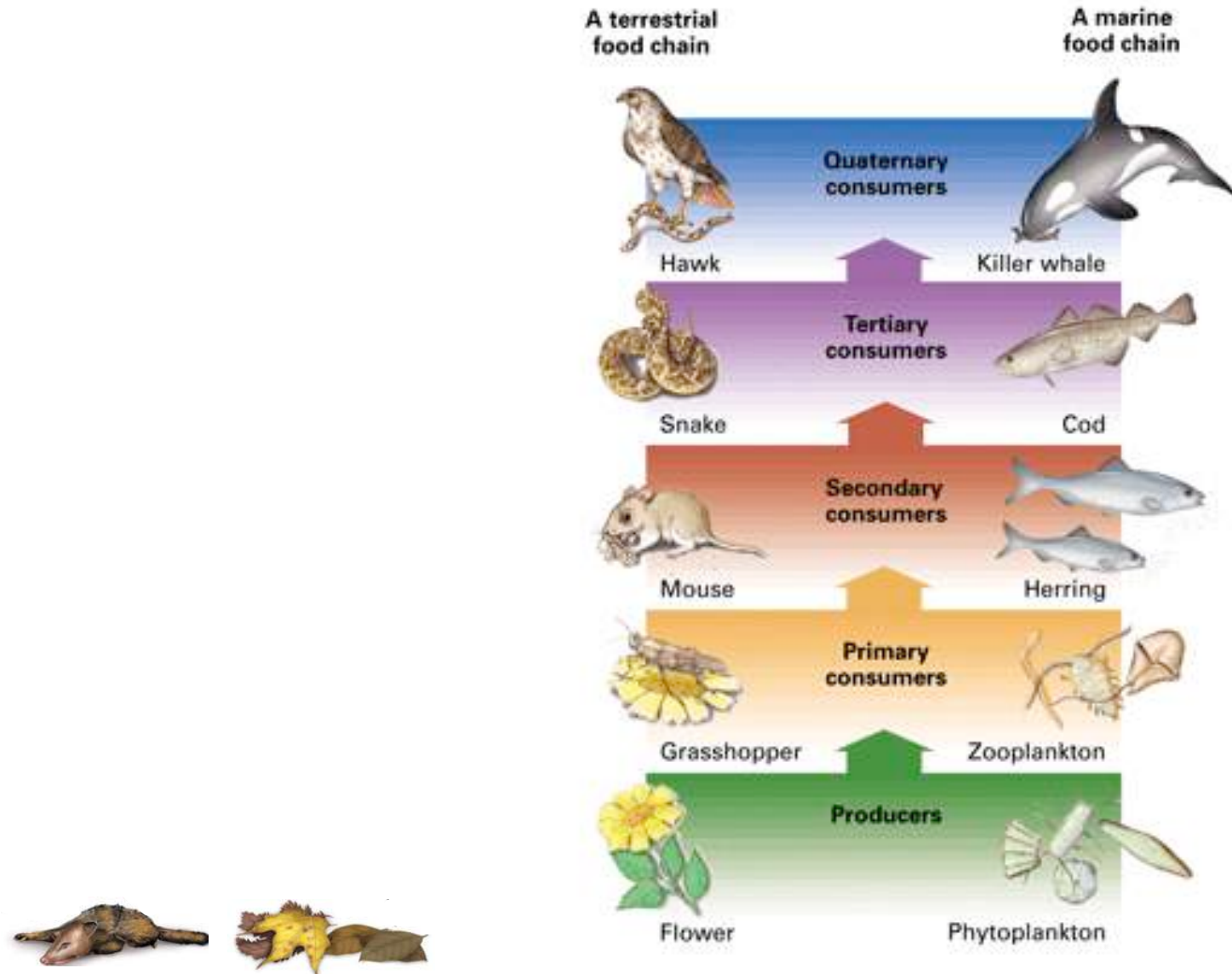


# Food chains ... & shortcuts





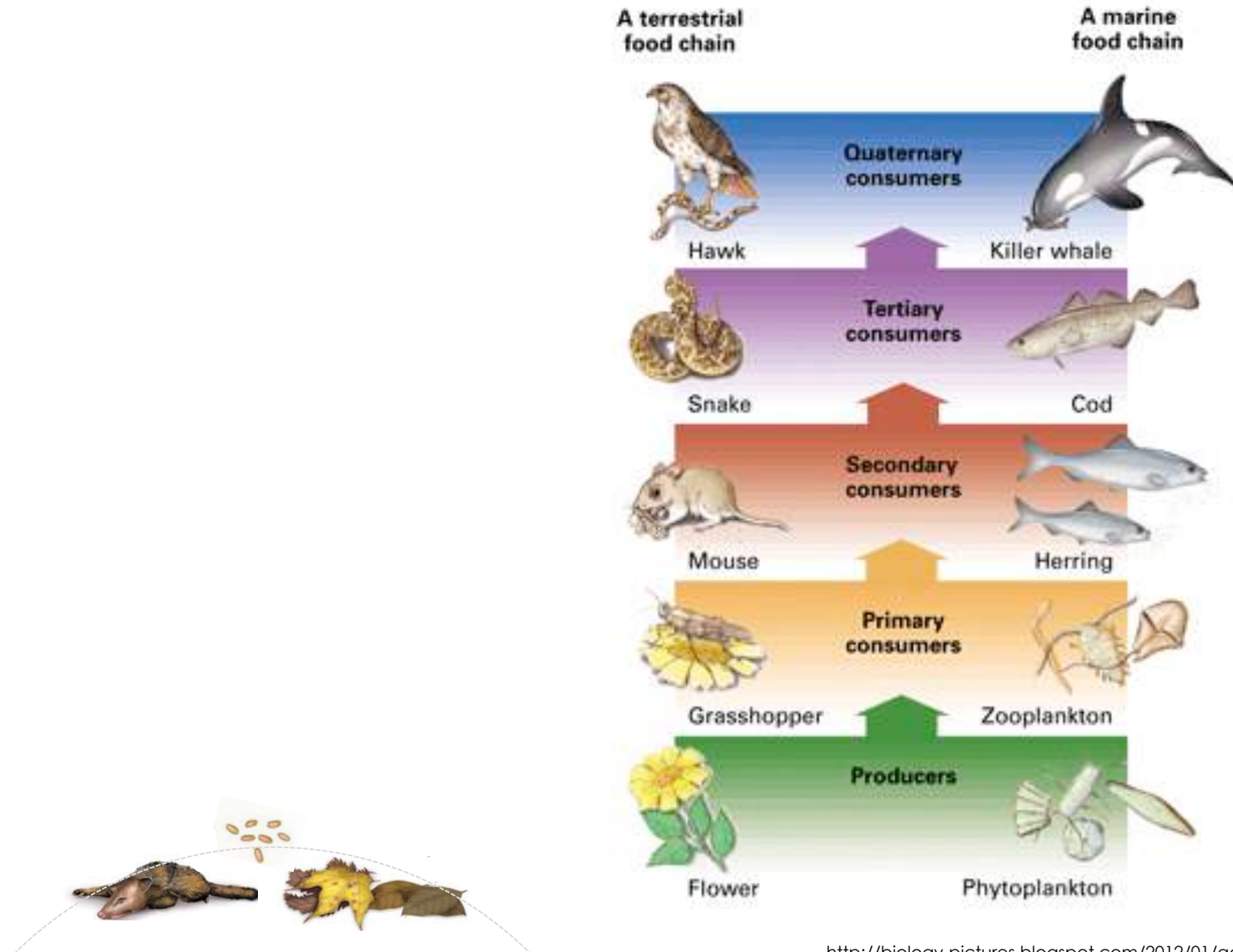
# Food chains ... & shortcuts







# Food chains ... & shortcuts



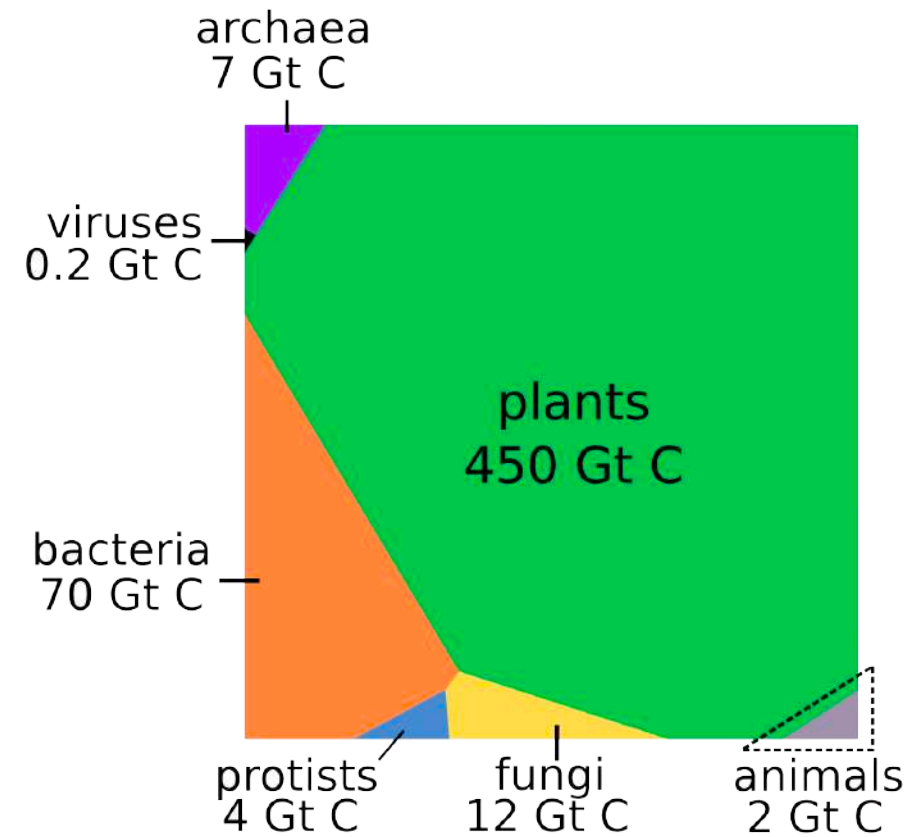


# Food chains ... & shortcuts

## The biomass distribution on Earth

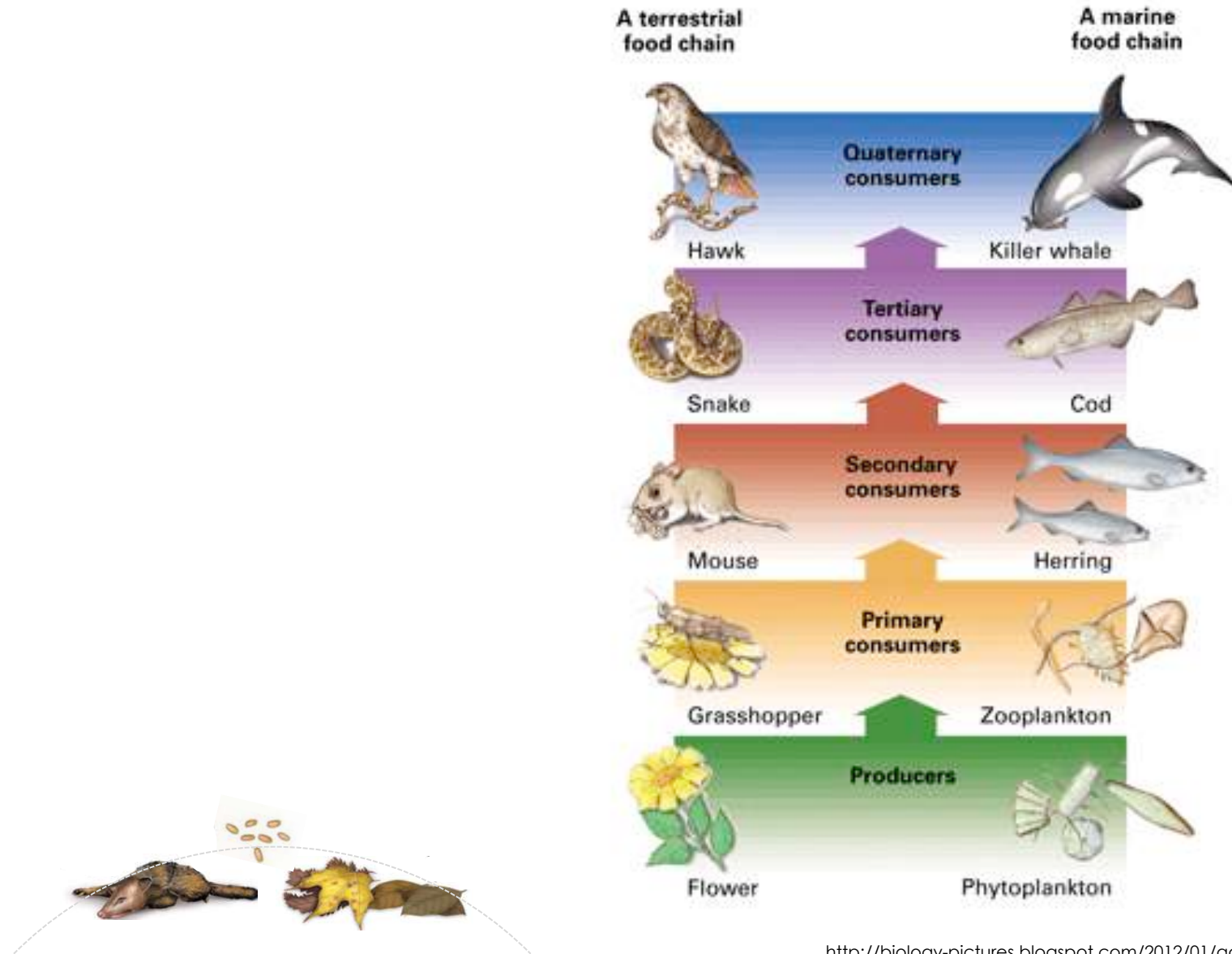
Yinon M. Bar-On<sup>a</sup>, Rob Phillips<sup>b,c</sup>, and Ron Milo<sup>a,1</sup>

6506–6511 | PNAS | June 19, 2018 | vol. 115



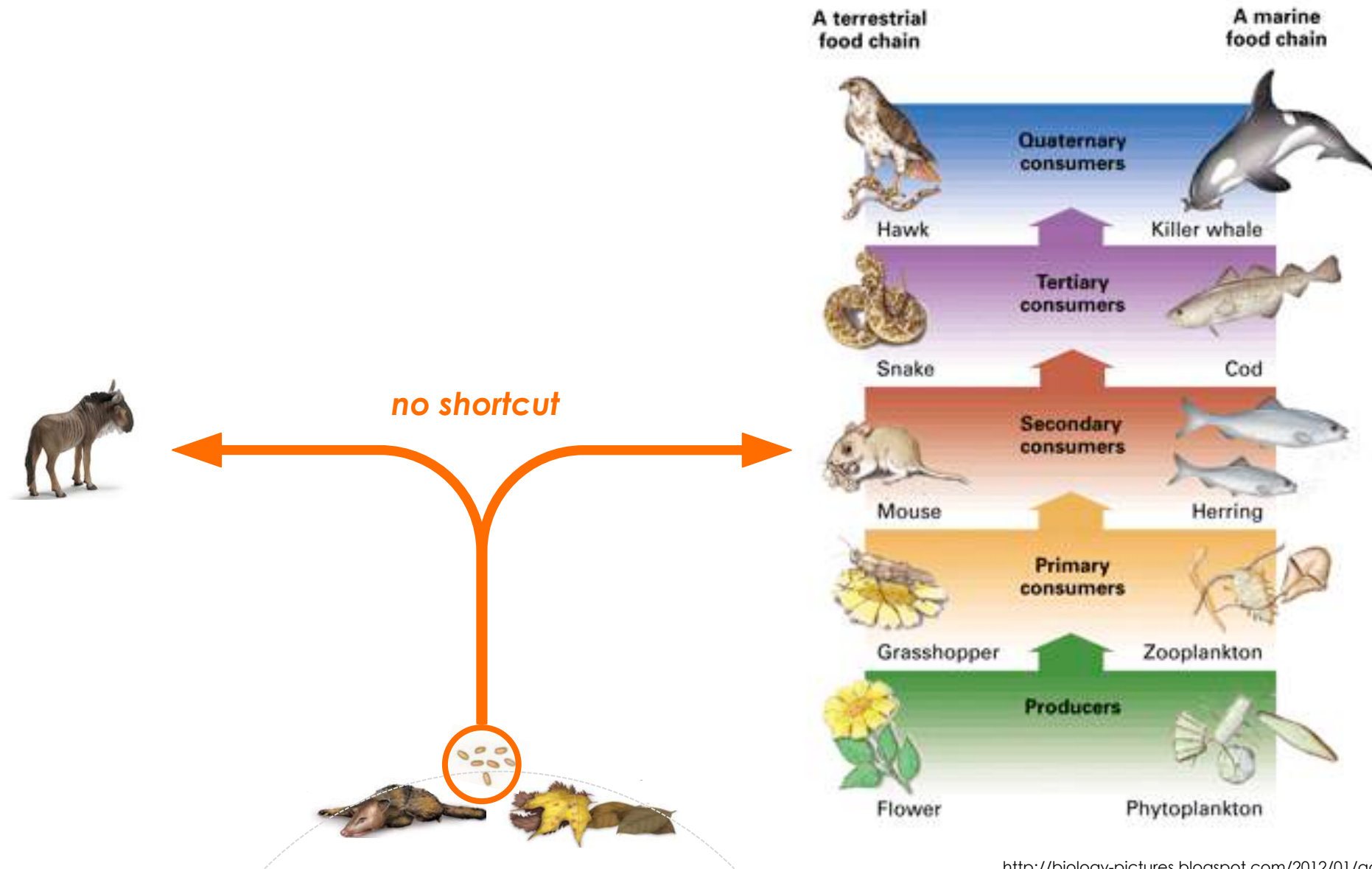


# Food chains ... & shortcuts



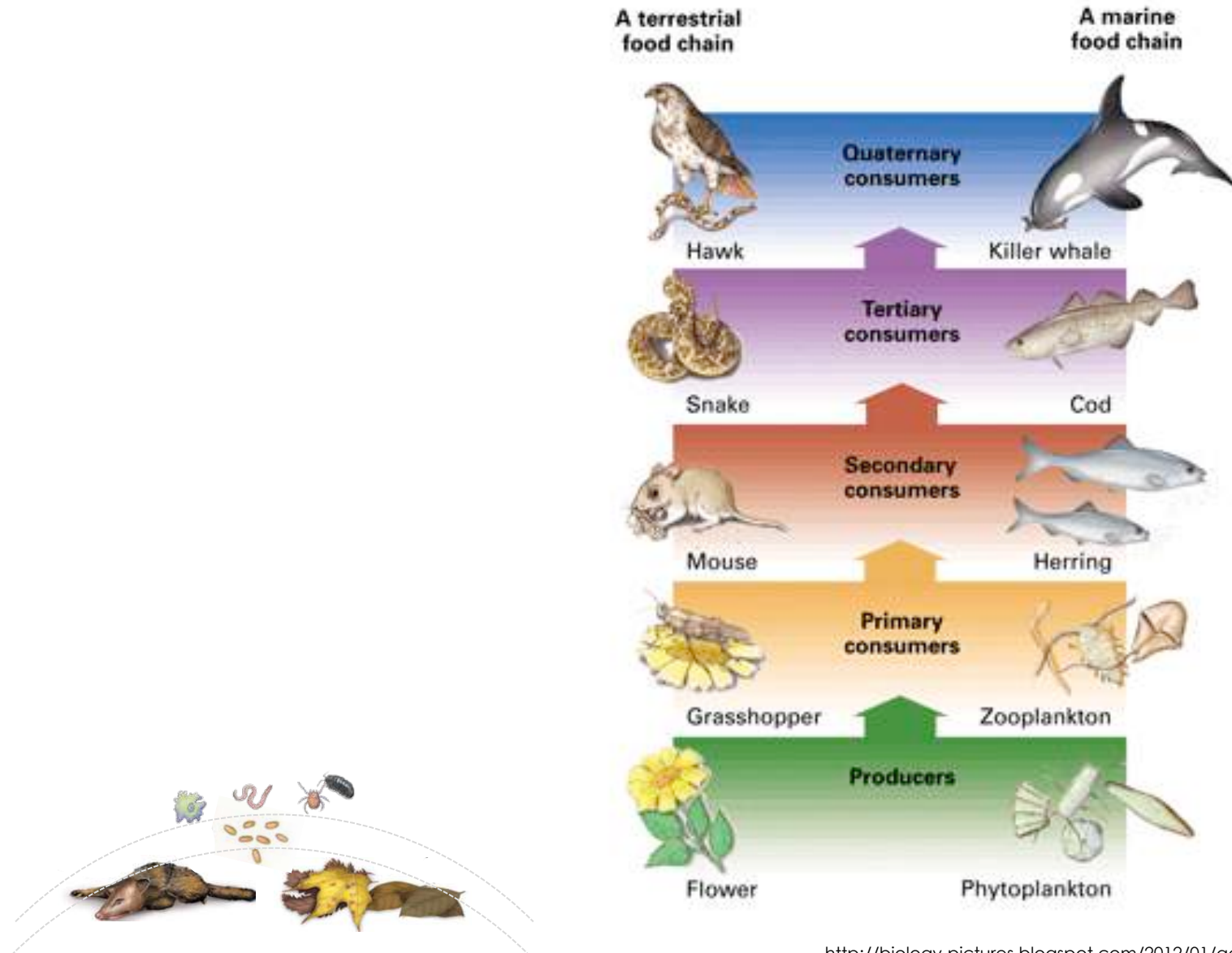


# Food chains ... & shortcuts





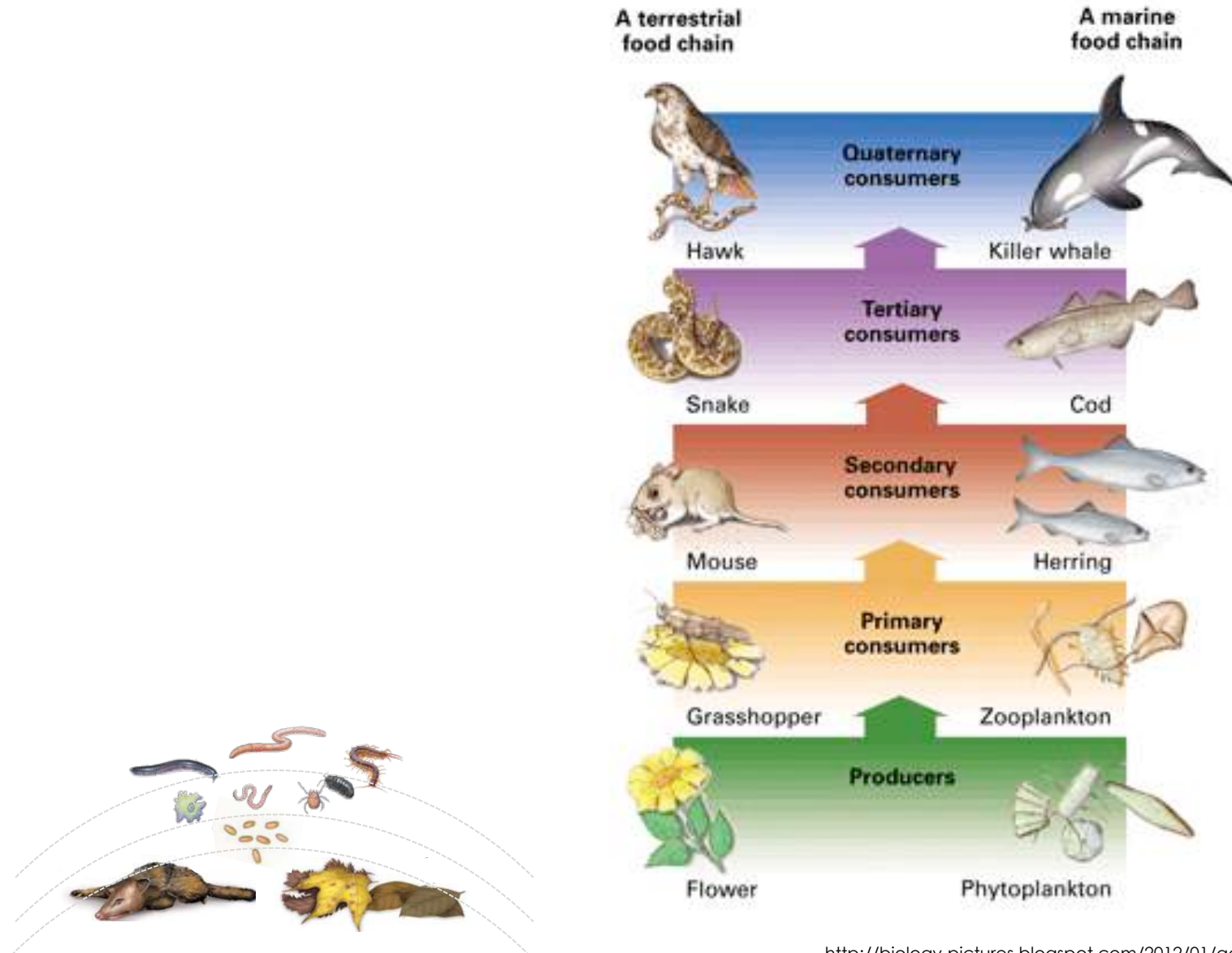
# Food chains ... & shortcuts





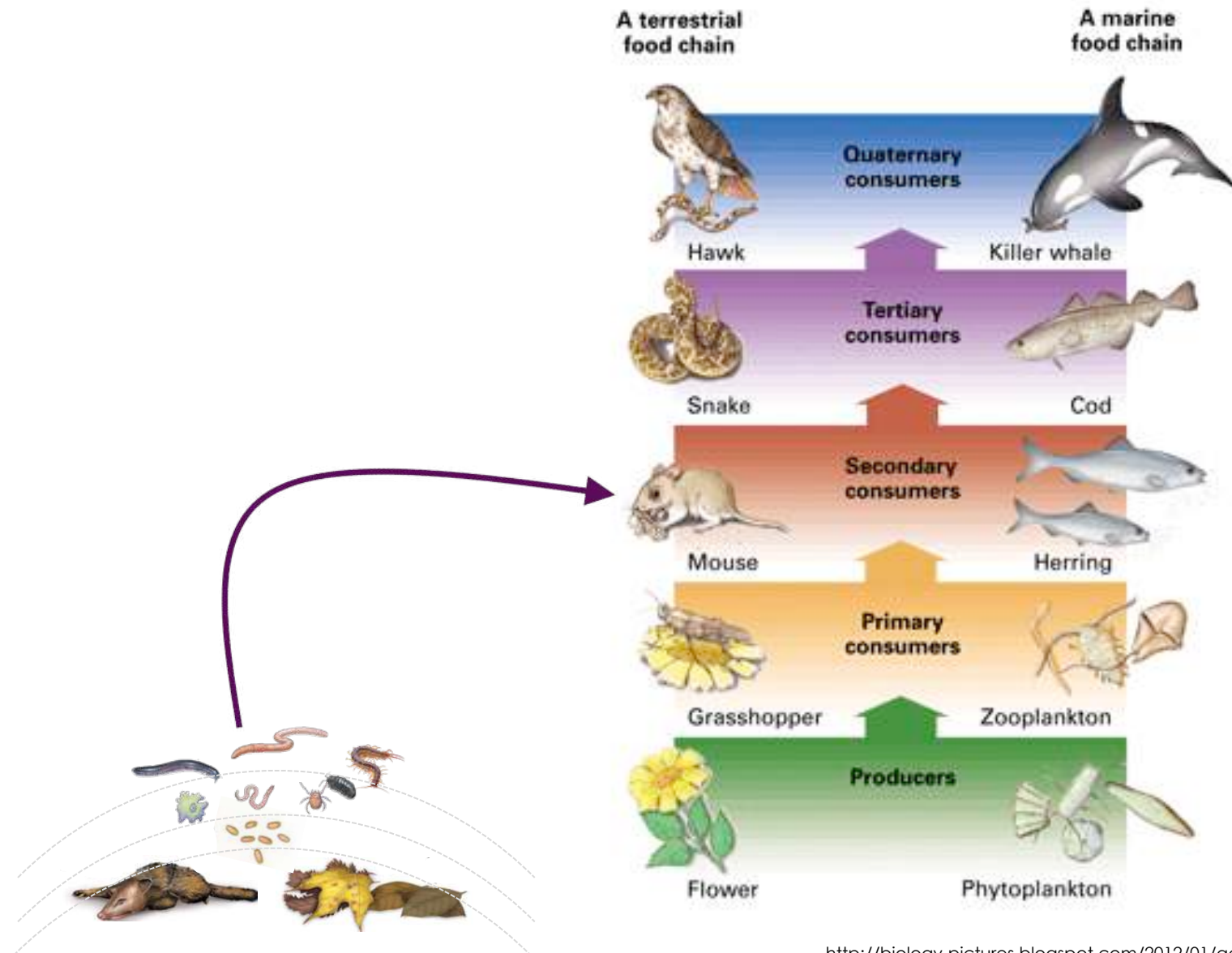


# Food chains ... & shortcuts





# Food chains ... & shortcuts







# Microbes in the digestive tract





# Microbes in the digestive tract

... *“provide a service”*:



# Microbes in the digestive tract

... *“provide a service”*:

- they ‘ferment’ carbohydrates and produce volatile fatty acids



# Microbes in the digestive tract

... *“provide a service”*:

- they ‘ferment’ carbohydrates and produce volatile fatty acids
- they may detoxify certain substances



# Microbes in the digestive tract

... *“provide a service”*:

- they ‘ferment’ carbohydrates and produce volatile fatty acids
- they may detoxify certain substances
- they produce vitamins





# Microbes in the digestive tract

... “*provide a service*”:

- they ‘ferment’ carbohydrates and produce volatile fatty acids
- they may detoxify certain substances
- they produce vitamins
- they ‘*produce microbial protein*’



# Microbes in the digestive tract

... “provide a service”:

- they ‘ferment’ carbohydrates and produce volatile fatty acids
- they may detoxify certain substances
- they produce vitamins
- they ‘produce microbial protein’



a ‘protein  
producer’?



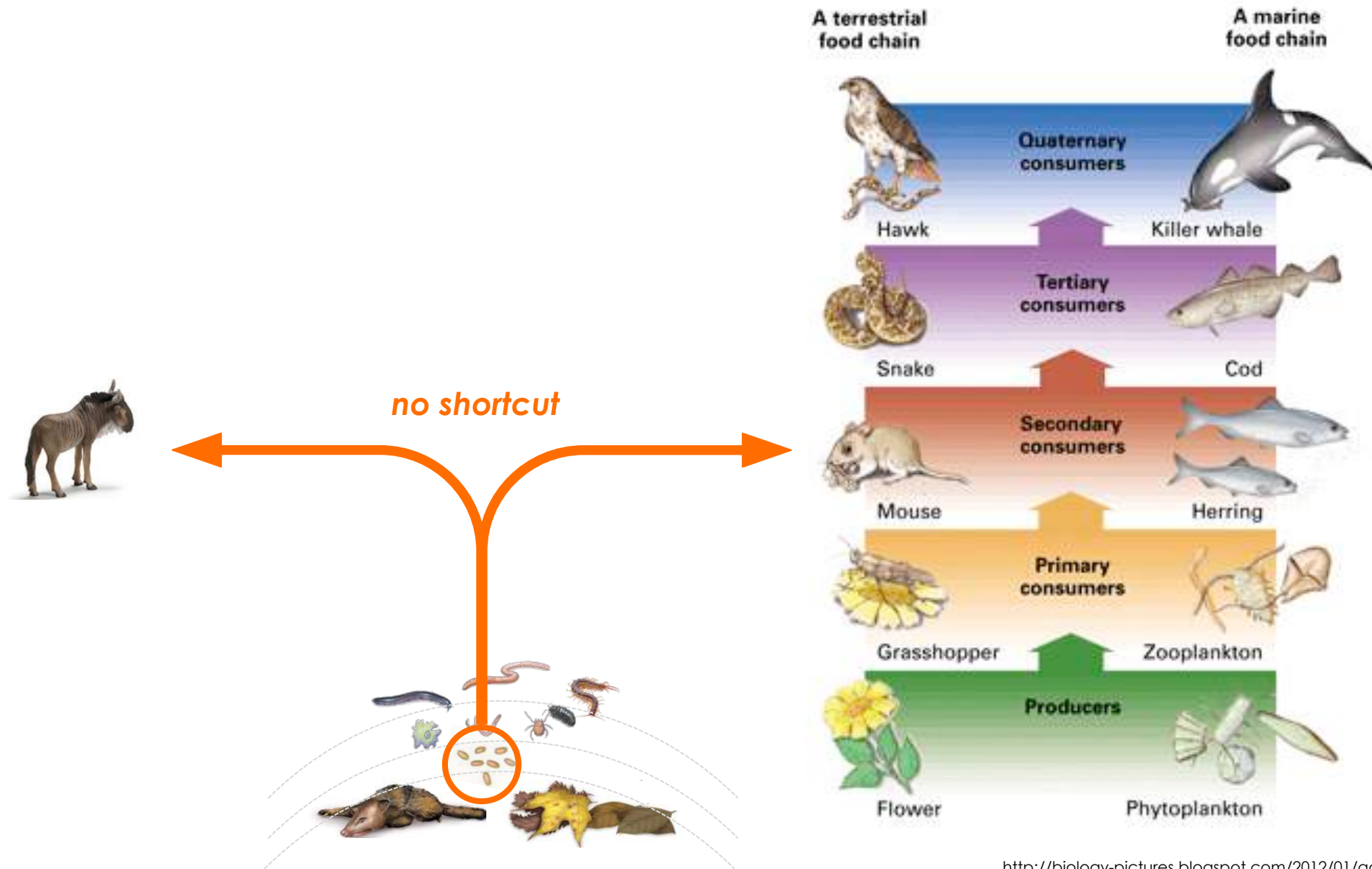
# Microbes in the digestive tract

... *“provide a service”*:

- they ‘ferment’ carbohydrates and produce volatile fatty acids
- they may detoxify certain substances
- they produce vitamins
- they ‘*produce microbial protein*’  
= *microbes are (potential) prey in a trophic chain*



# Food chains ... & shortcuts

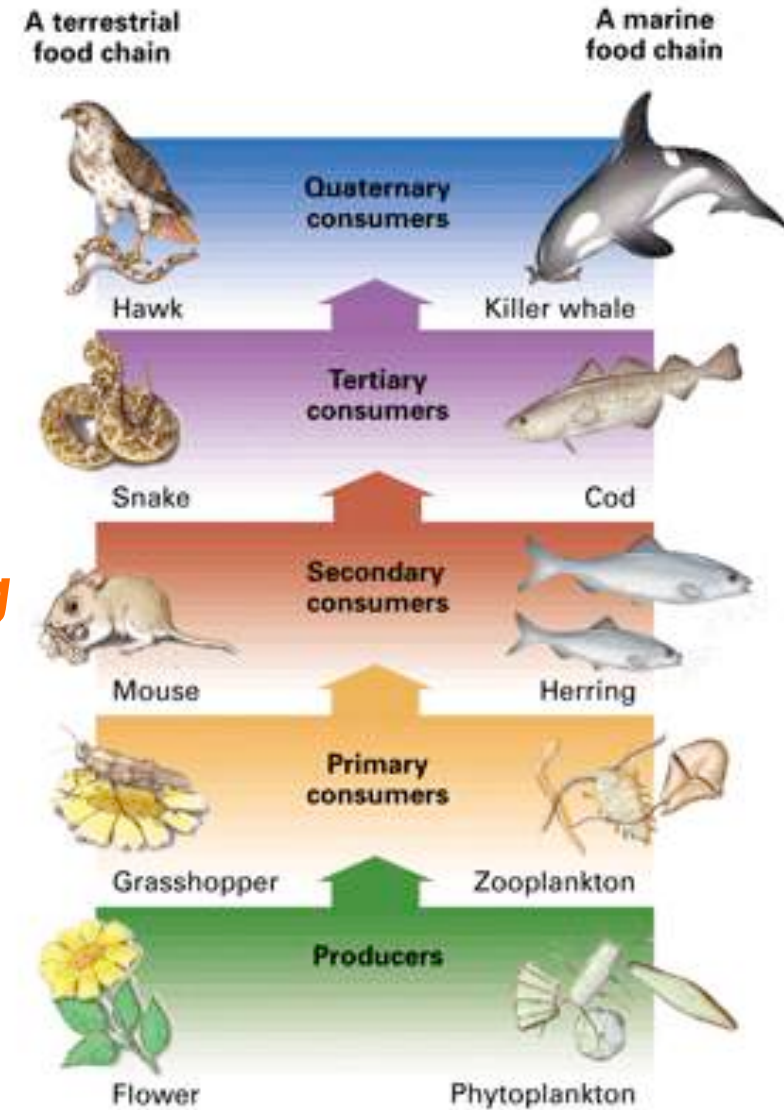
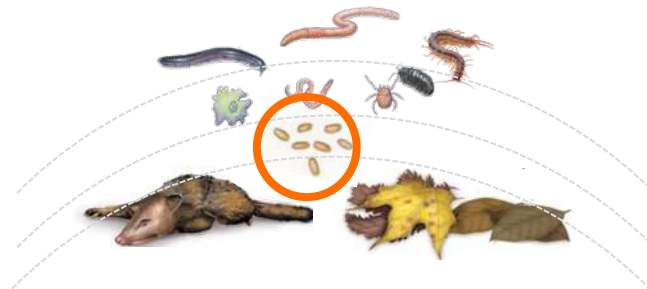




# Food chains ... & shortcuts



*but there is microbe farming*





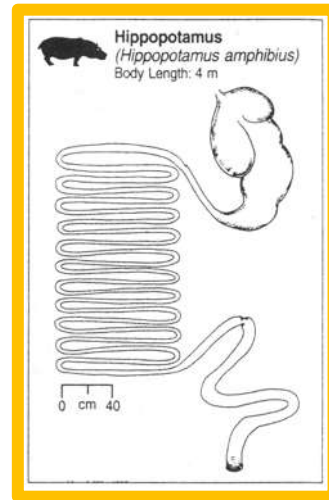
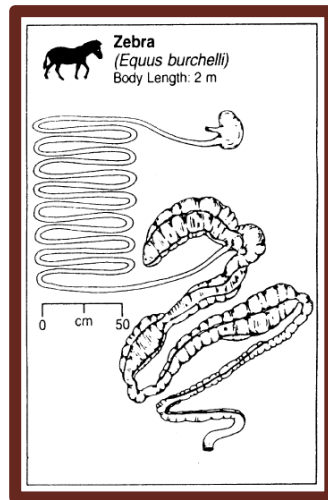


# Farming: contain, nurture, harvest



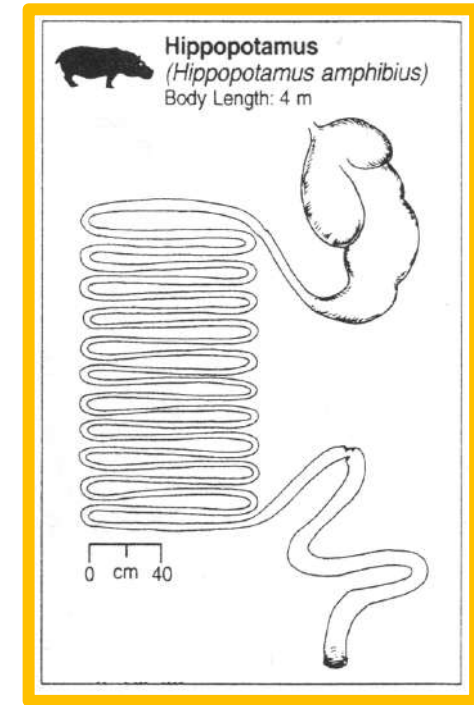
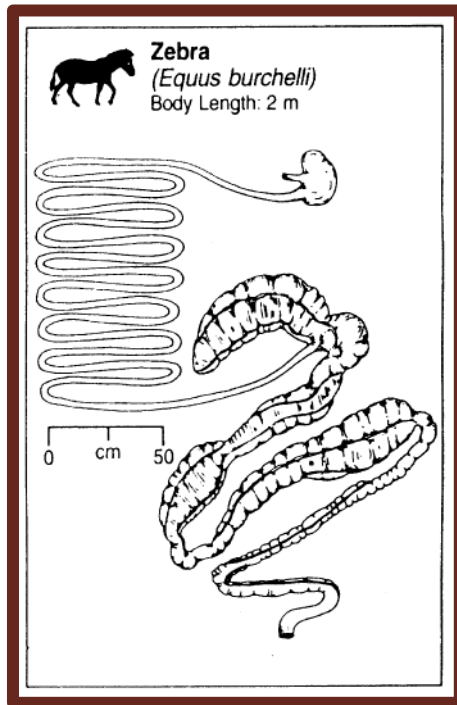


# Farming: contain, nurture, harvest





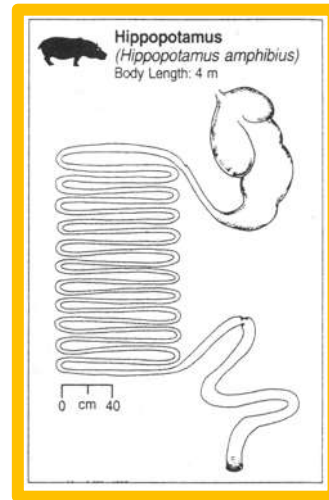
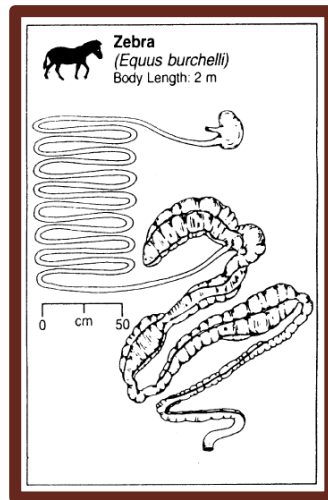
# Hindgut and Foregut fermenters







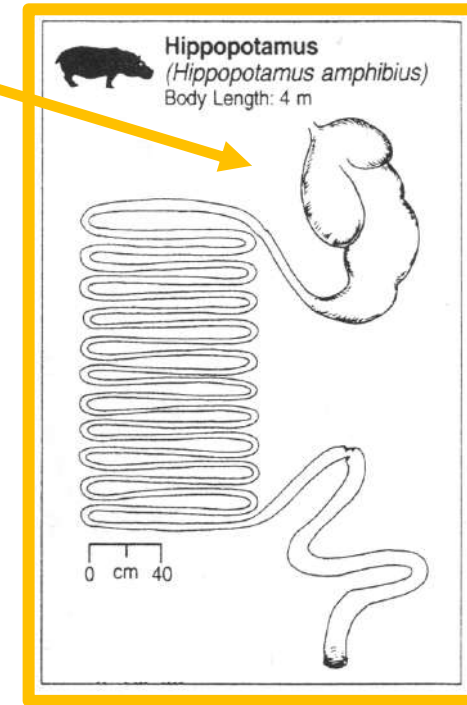
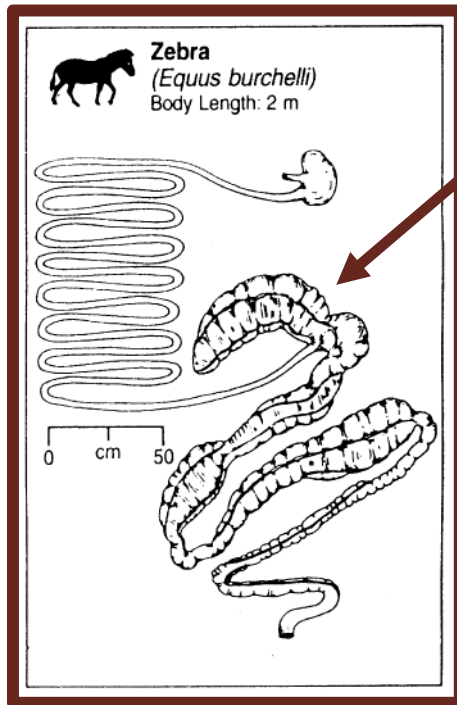
# Farming: contain, nurture, harvest





# Hindgut and Foregut fermenters

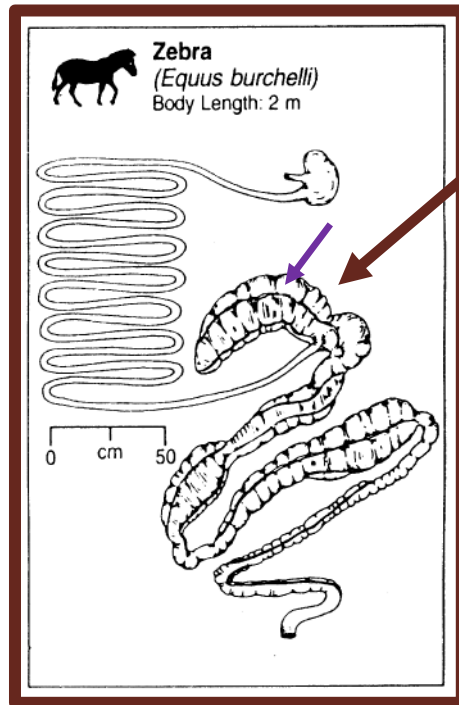
Microbes live and grow by fermenting the **diet** (**rest**) ...  
... and produce volatile fatty acids





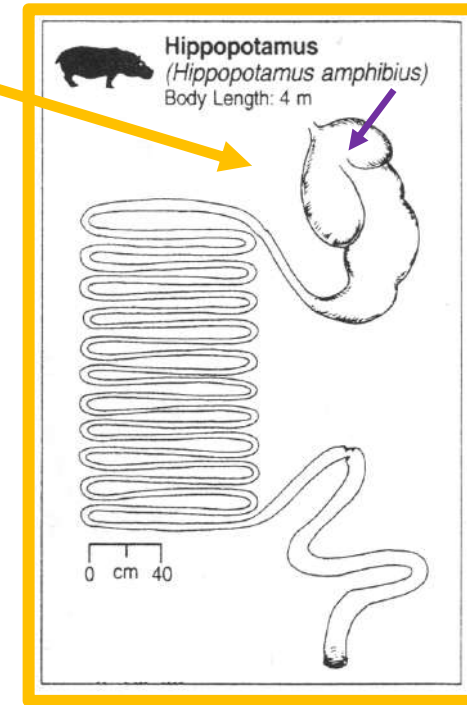


# Hindgut and Foregut fermenters



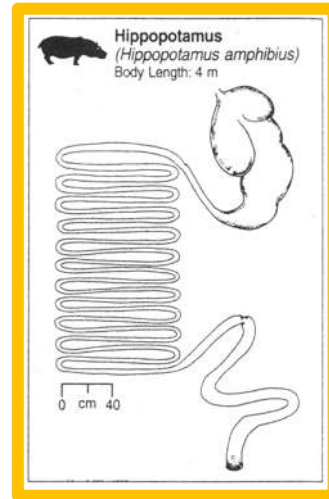
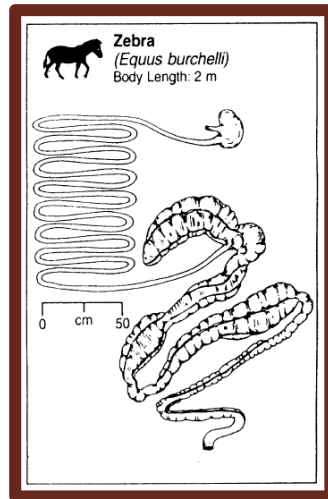
Microbes live and grow by fermenting the **diet** (**rest**) ...  
... and produce volatile fatty acids

... and are supplied with **urea** via **saliva** / **blood**





# Farming: contain, nurture, harvest

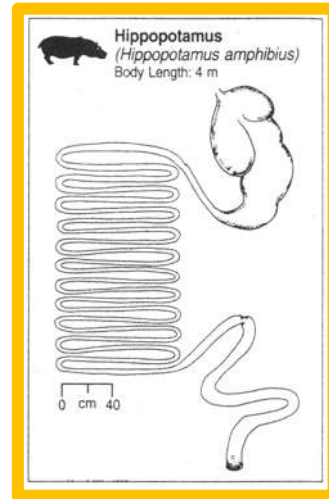
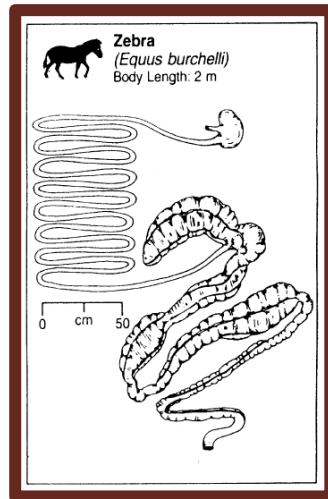


+ supplemental  
(endogenous)  
nitrogen





# Farming: contain, nurture, harvest



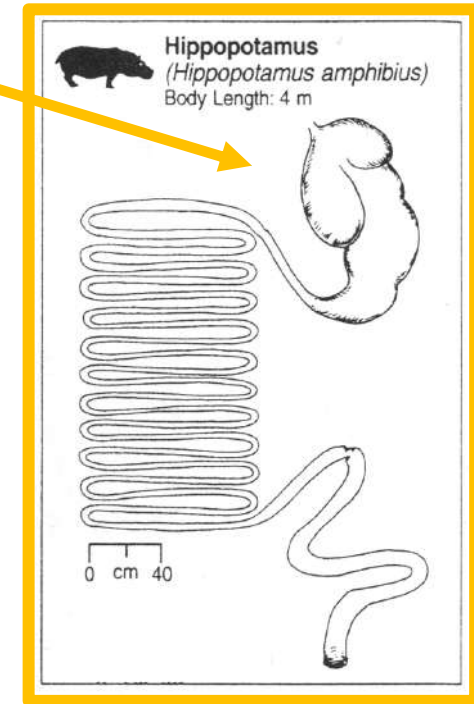
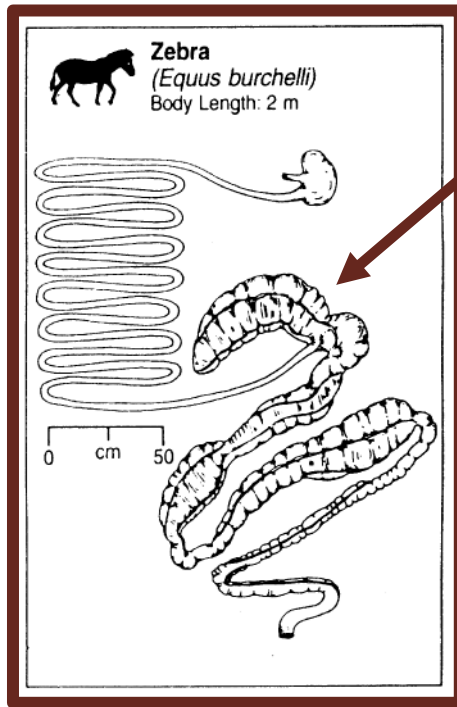
+ supplemental  
(endogenous)  
nitrogen

?



# Hindgut and Foregut fermenters

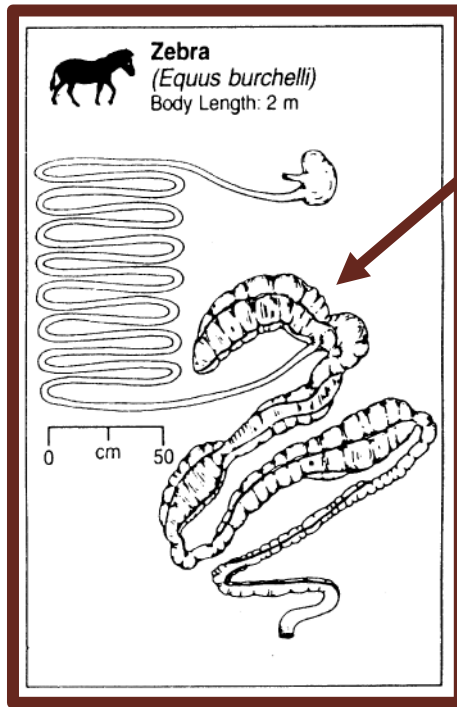
Microbes ferment the  
**diet** (**rest**) ...



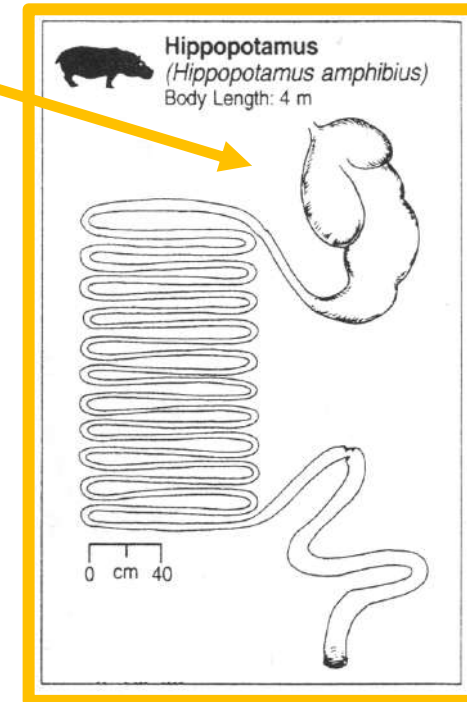


# Hindgut and Foregut fermenters

Microbes ferment the  
**diet** (**rest**) ...



... **after**  
small  
intestine

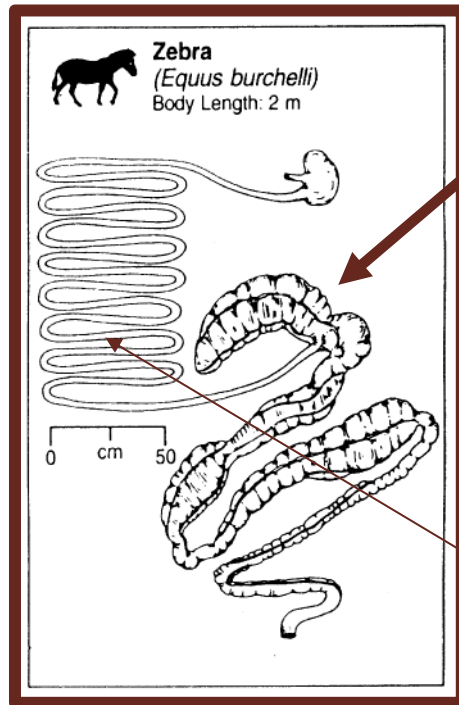






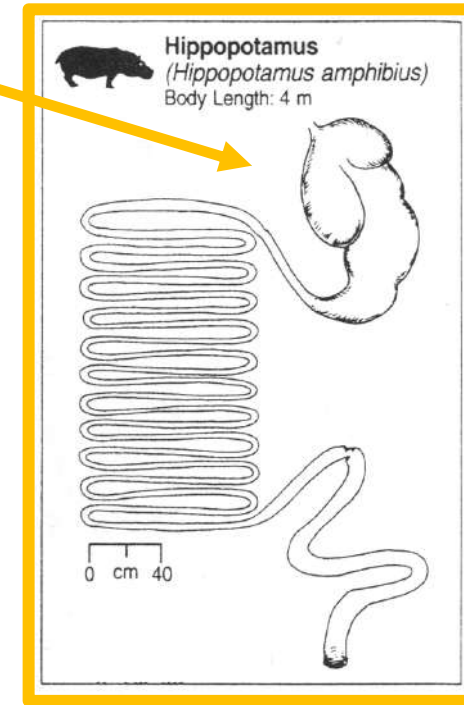
# Hindgut and Foregut fermenters

Microbes ferment the  
**diet** (**rest**) ...



... **after**  
small  
intestine

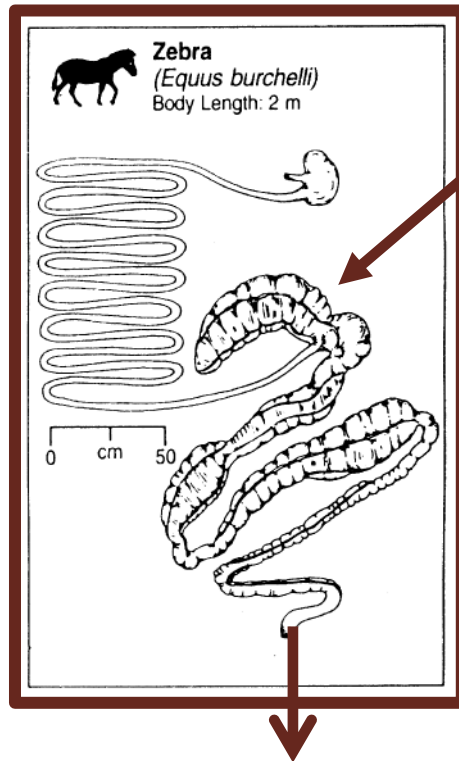
**enzymatic**  
**digestion of**  
**diet**



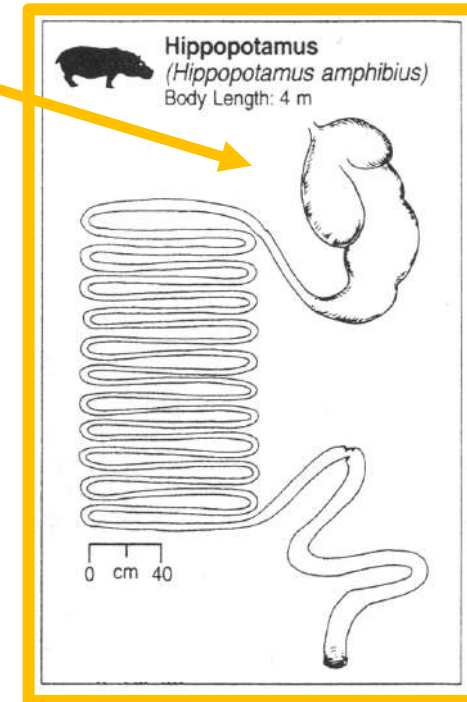


# Hindgut and Foregut fermenters

Microbes ferment the  
**diet** (**rest**) ...



... and are  
excreted





# Extraction not possible ?





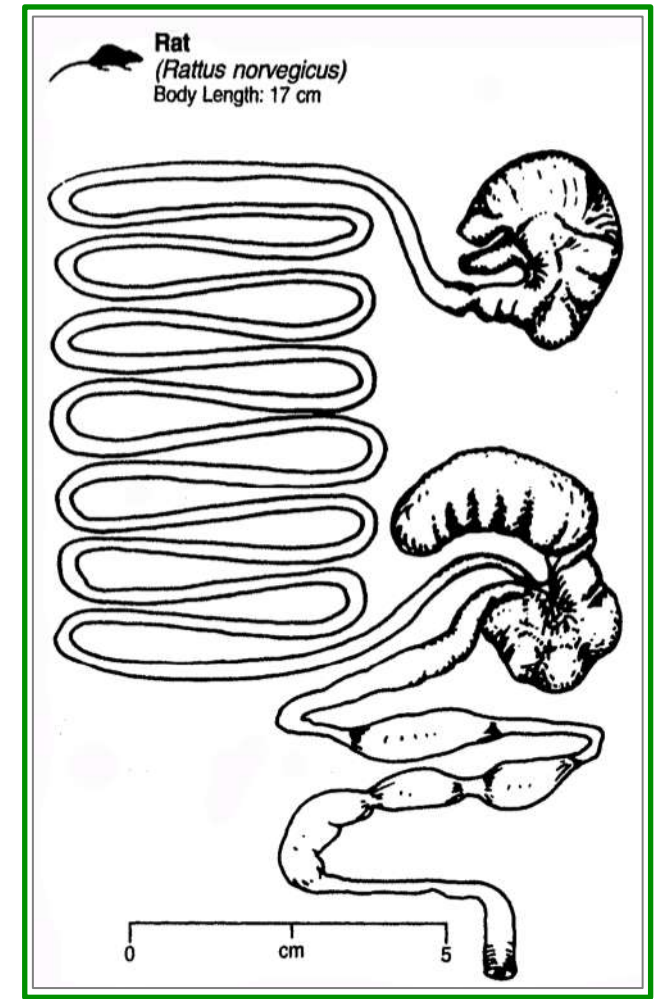
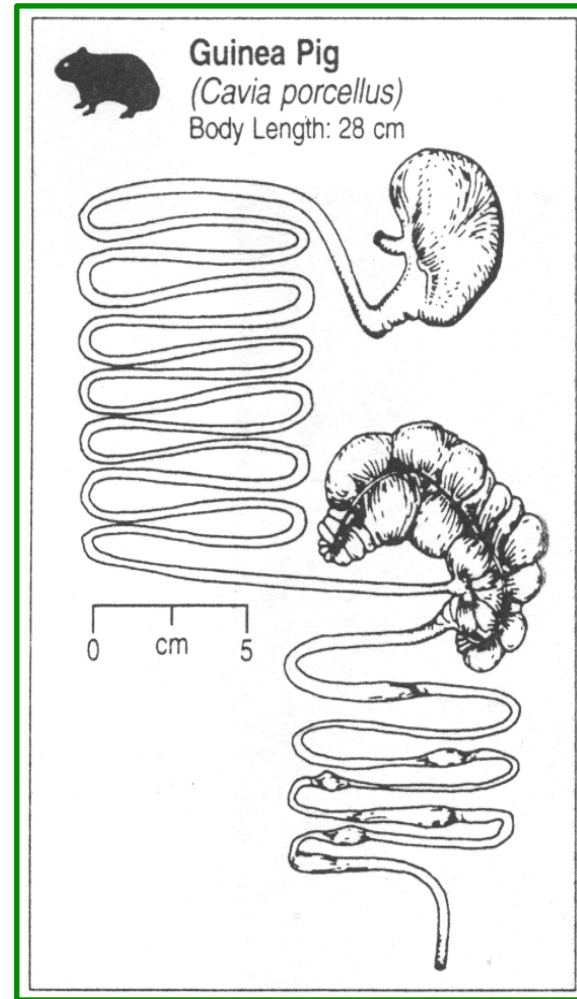
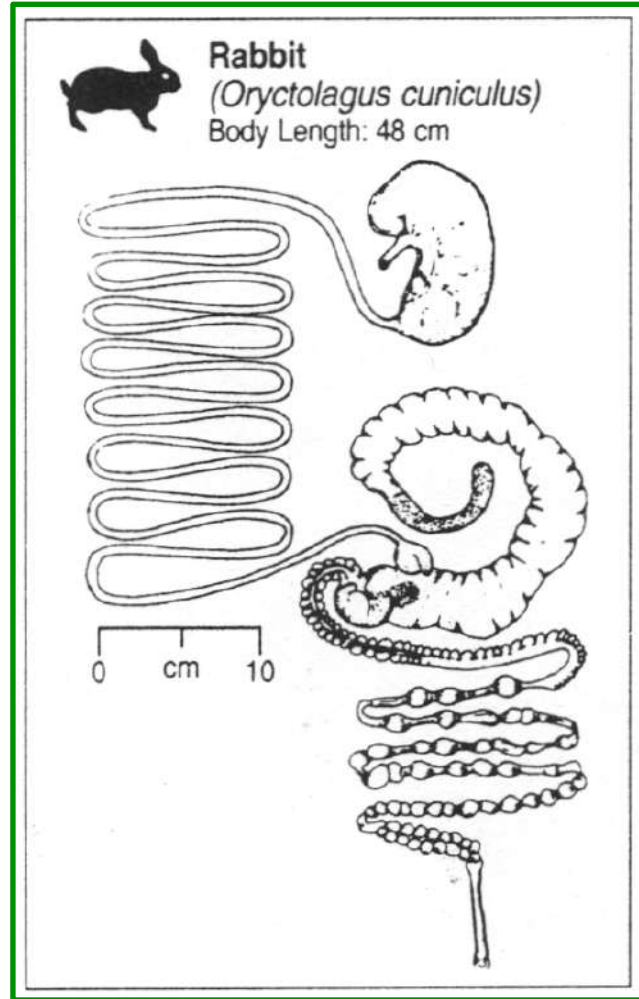


# Extraction not possible ?





# Small hindgut fermenters







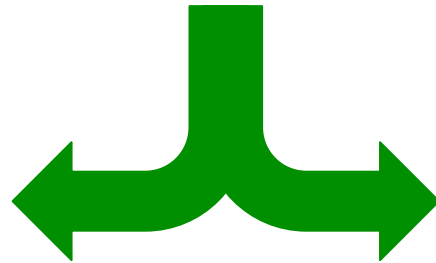
# Separating microbes from indigestible material



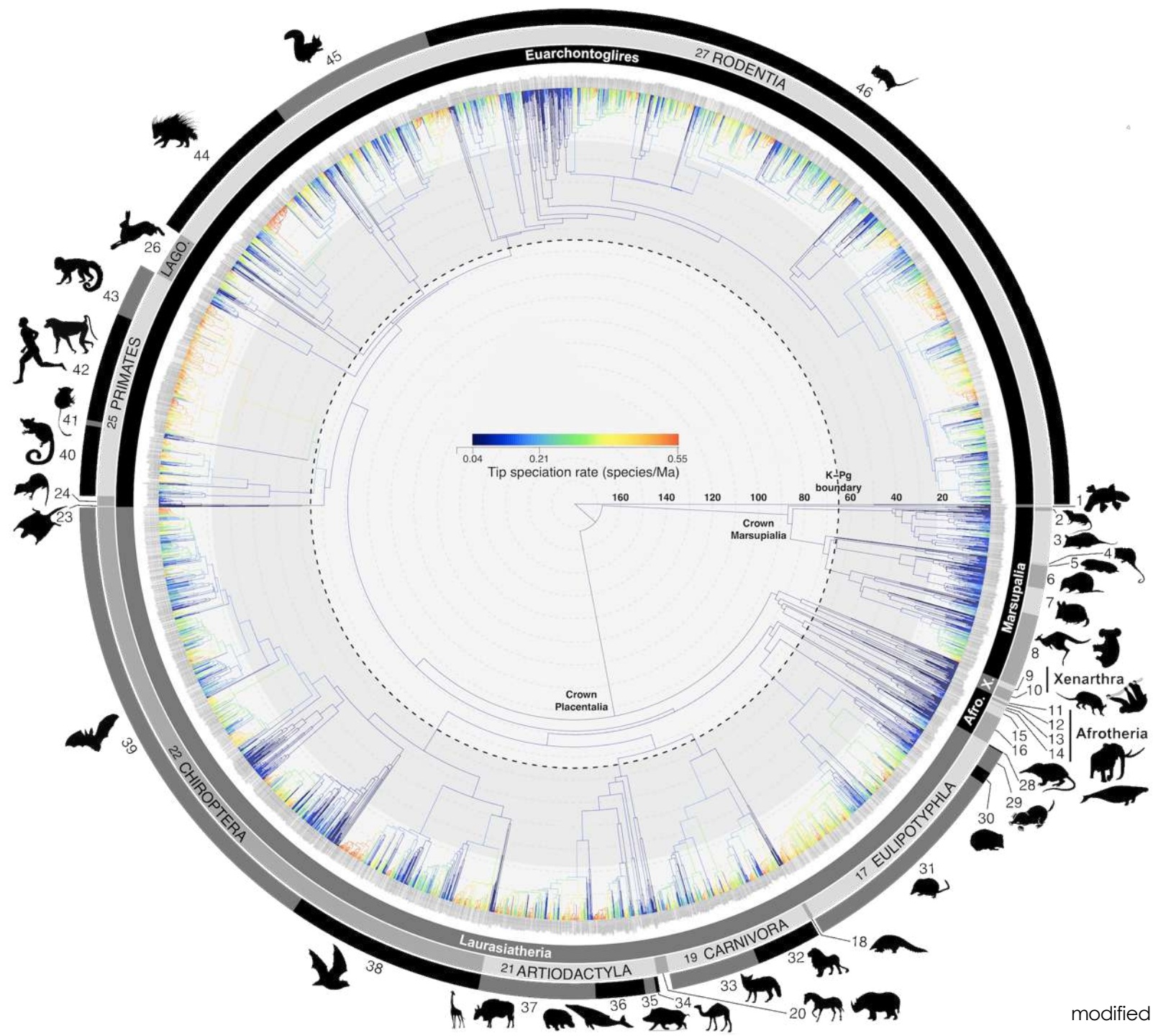
## ***“Colonic separation mechanism”***



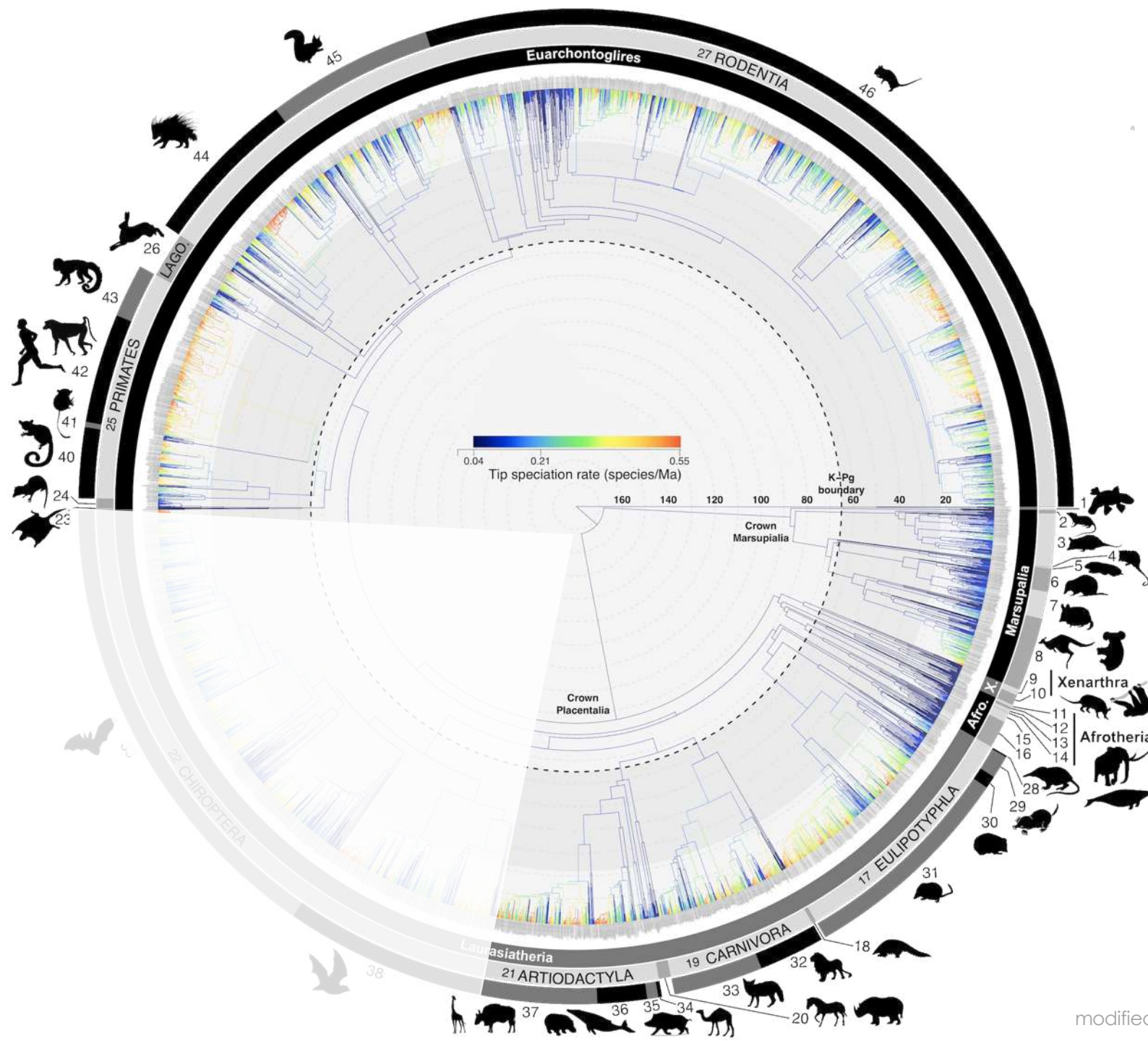
more microbial matter,  
measurable as protein



more indigestible material,  
especially fibre

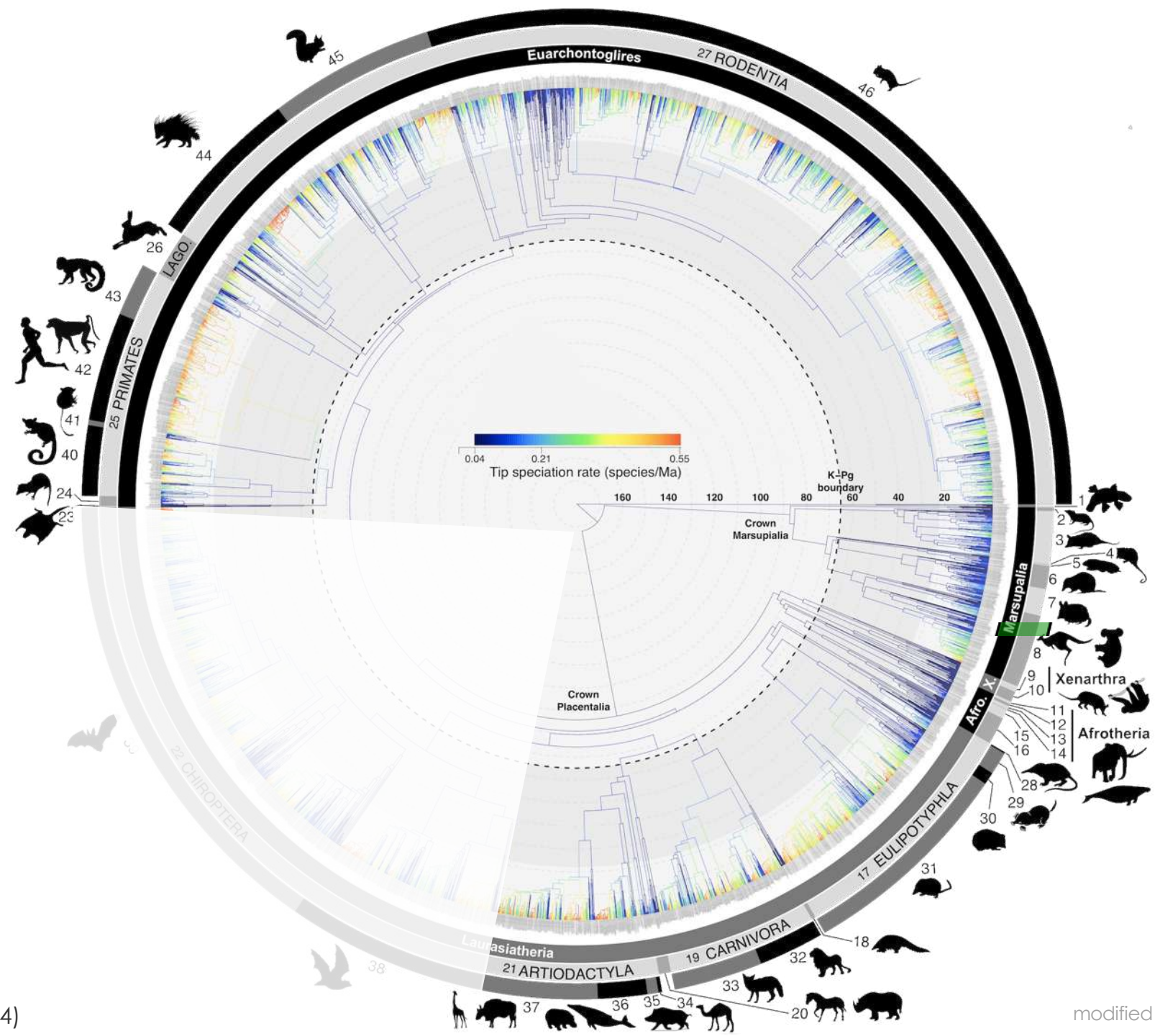


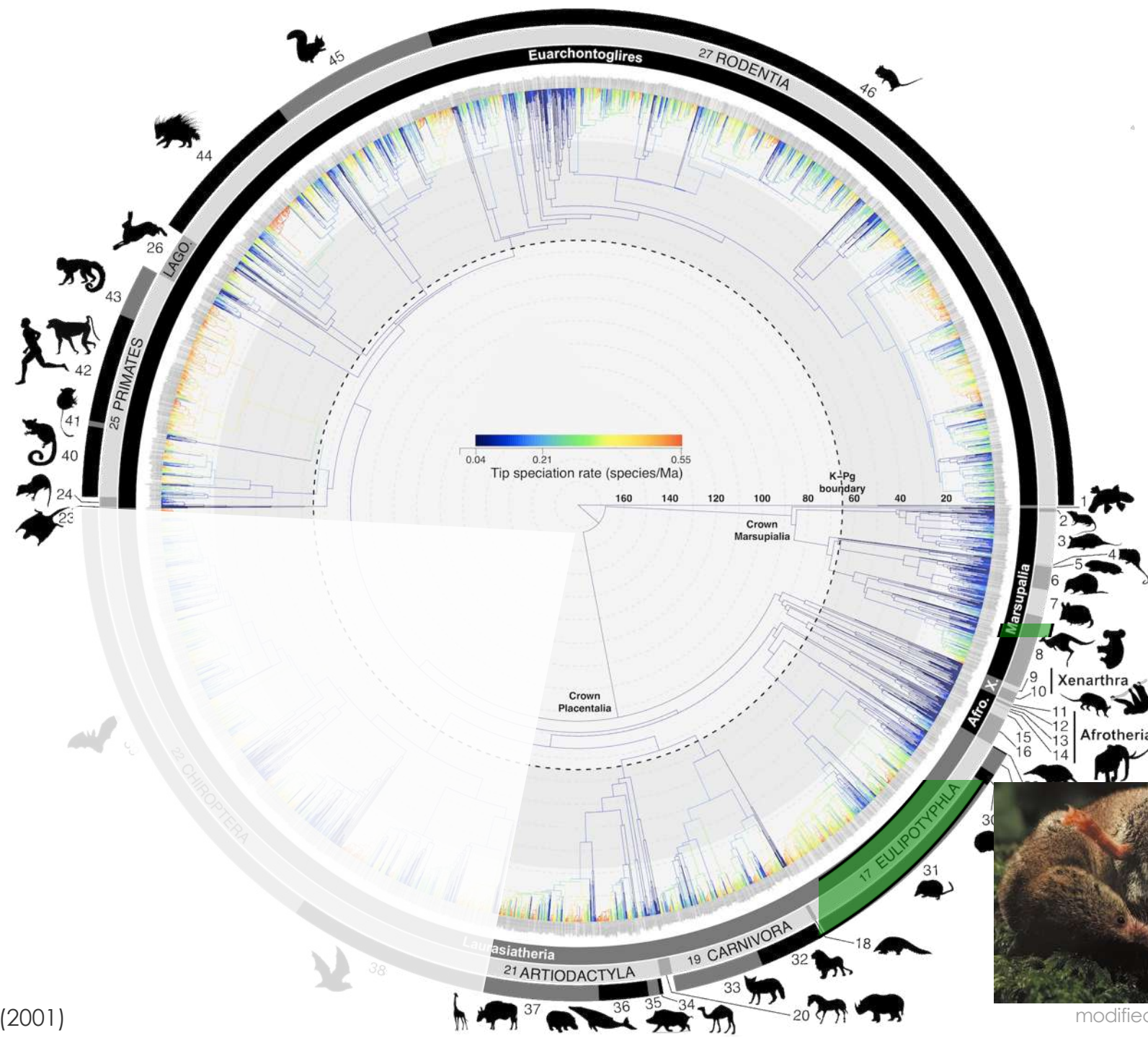
modified from Upham et al. (2019)



modified from Upham et al. (2019)

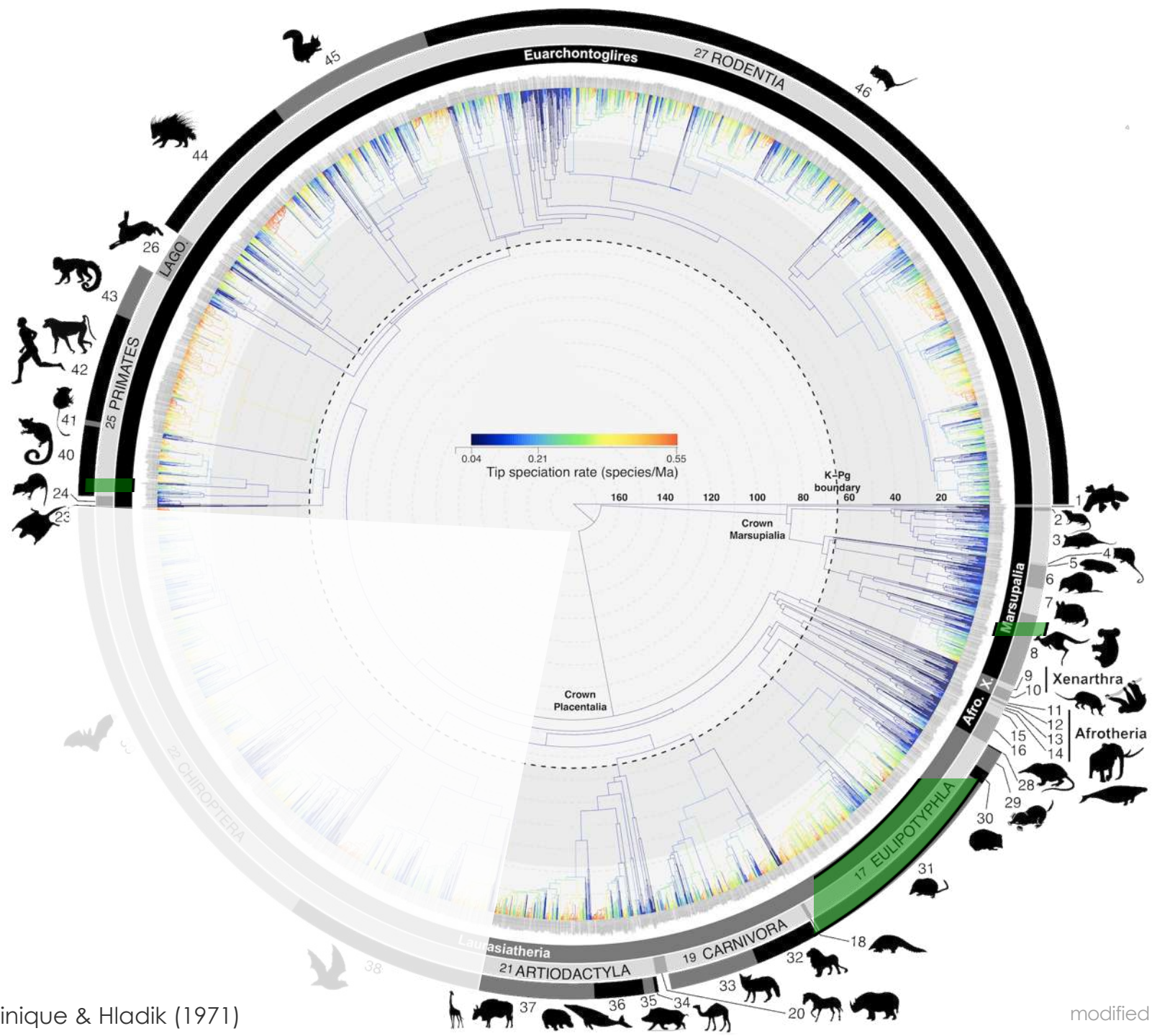


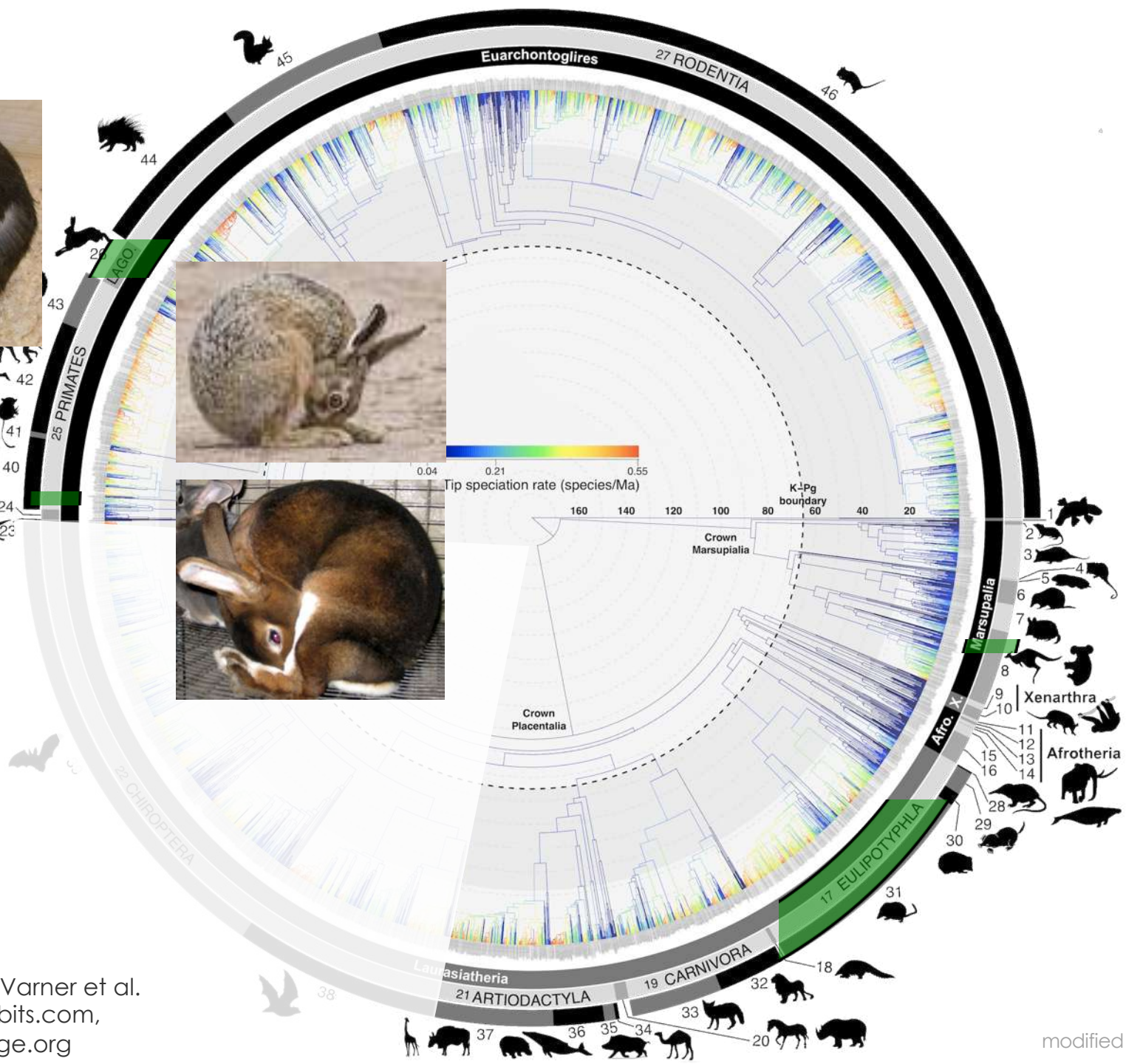




modified from Upham et al. (2019)



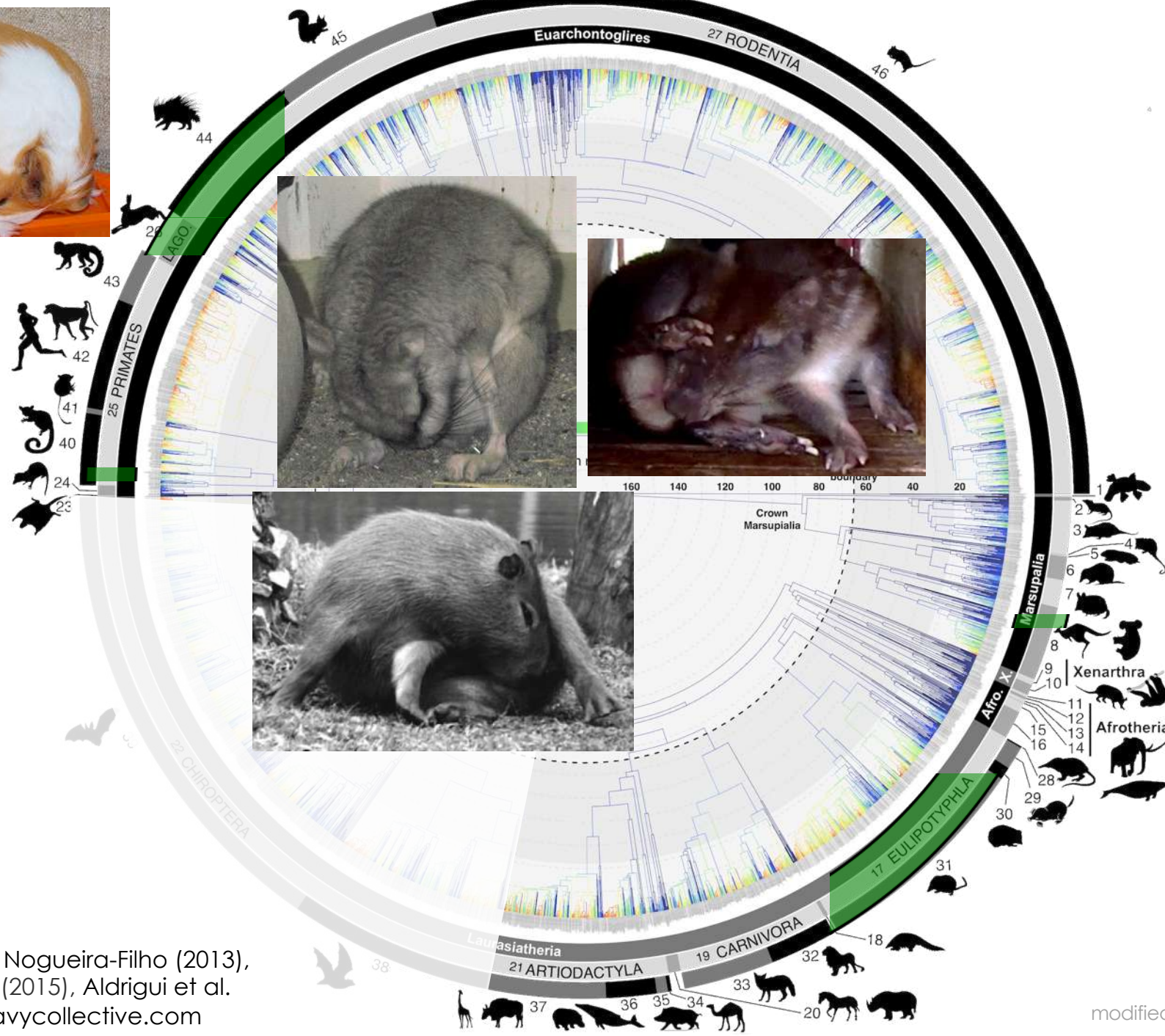




Tschudin (photo), Varner et al.  
(2016), raising-rabbits.com,  
wildscreenexchange.org

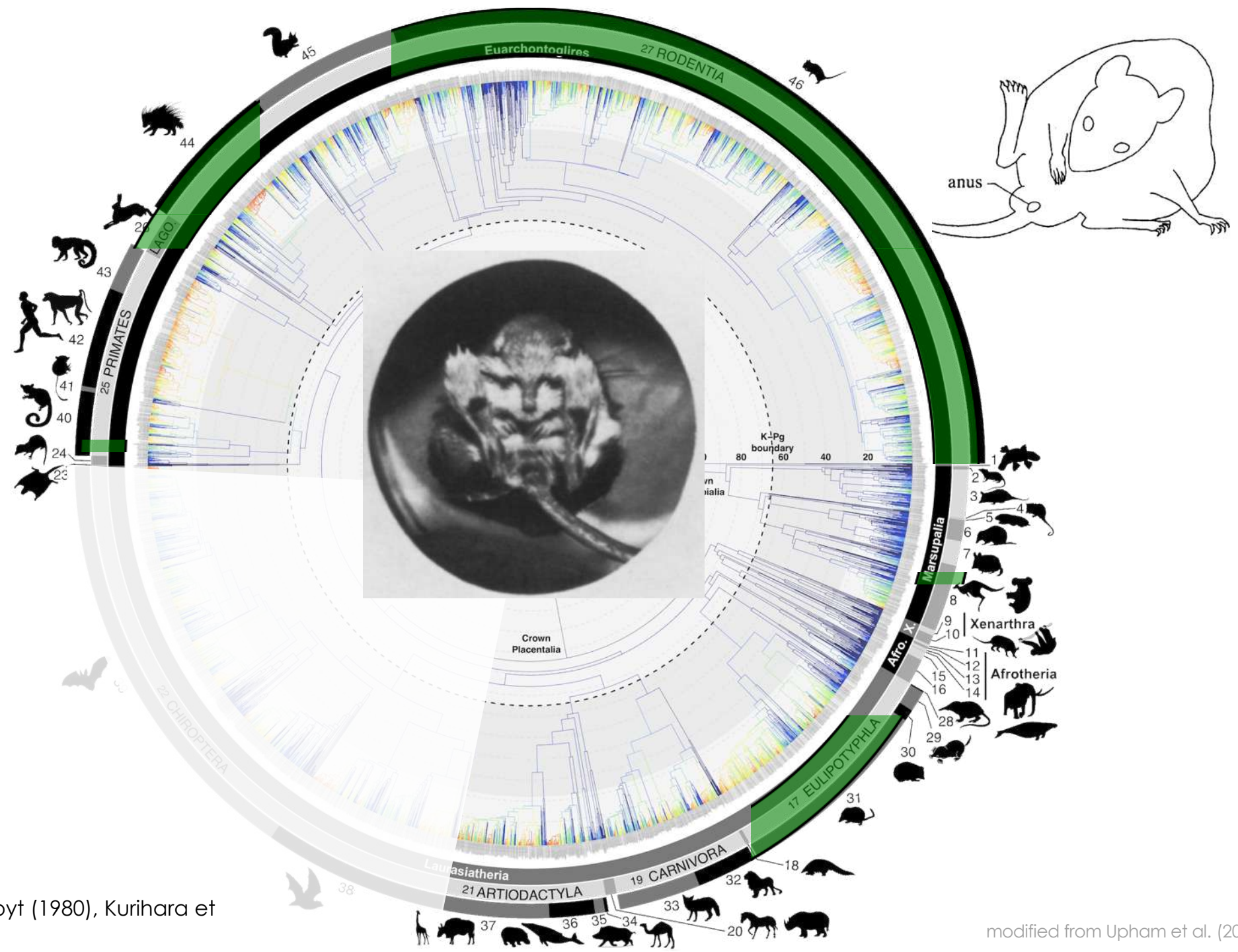
modified from Upham et al. (2019)





Mendes and Nogueira-Filho (2013),  
Hagen et al. (2015), Aldrigui et al.  
(2018), calicavycollective.com

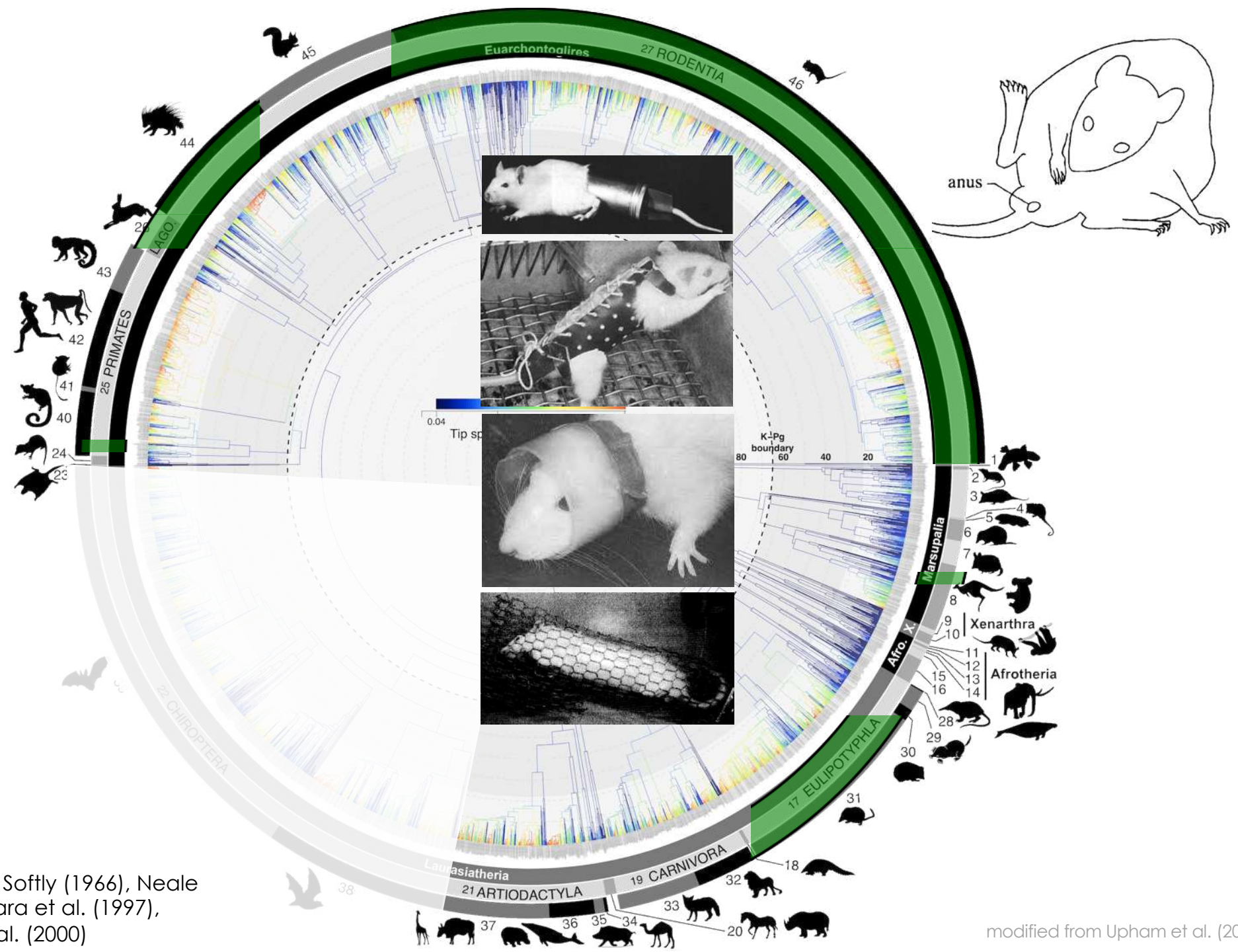
modified from Upham et al. (2019)



Kenagy & Hoyt (1980), Kurihara et al. (1997)

modified from Upham et al. (2019)

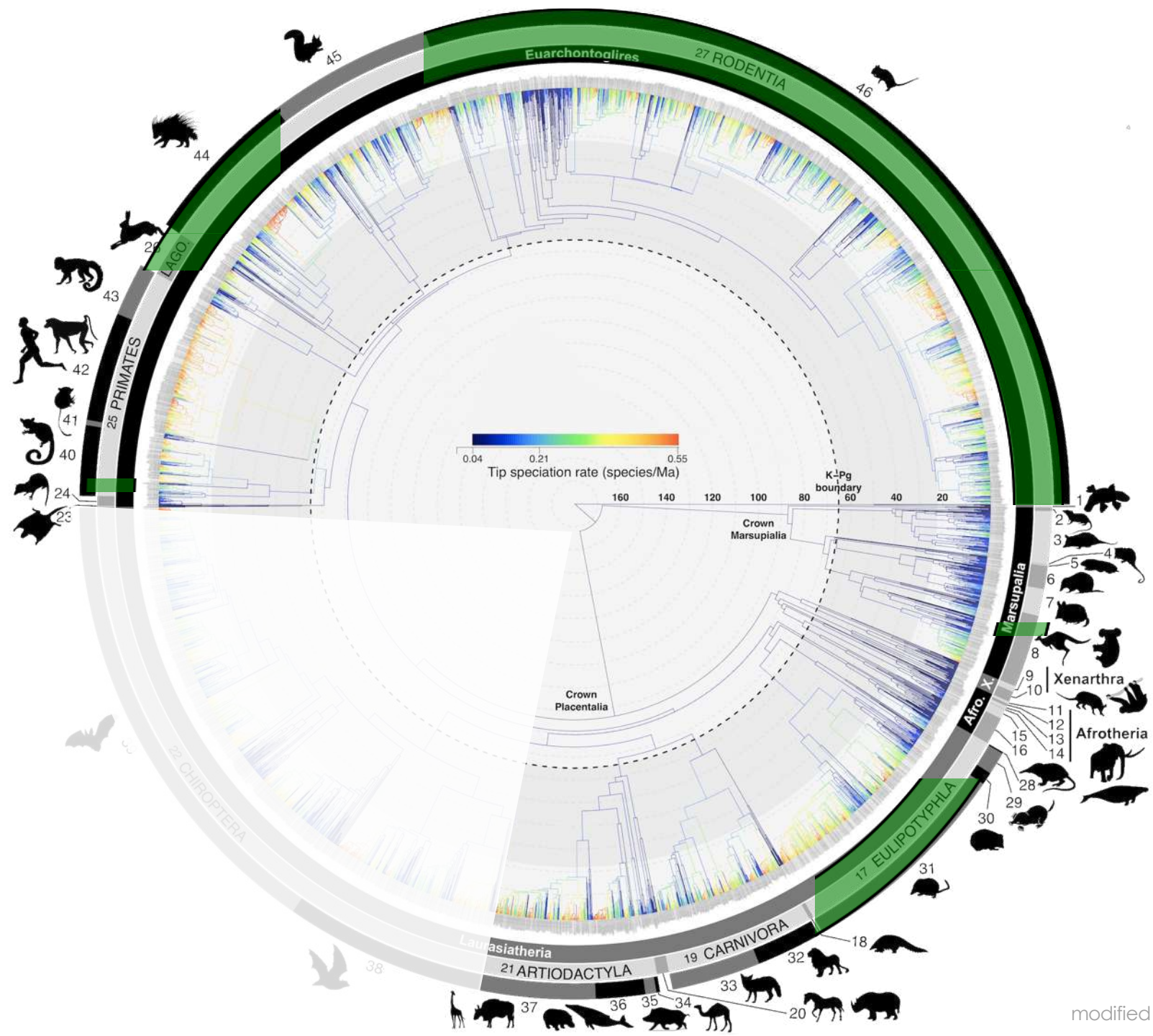




Armstrong & Softly (1966), Neale (1994), Kurihara et al. (1997), Sukemori et al. (2000)

modified from Upham et al. (2019)





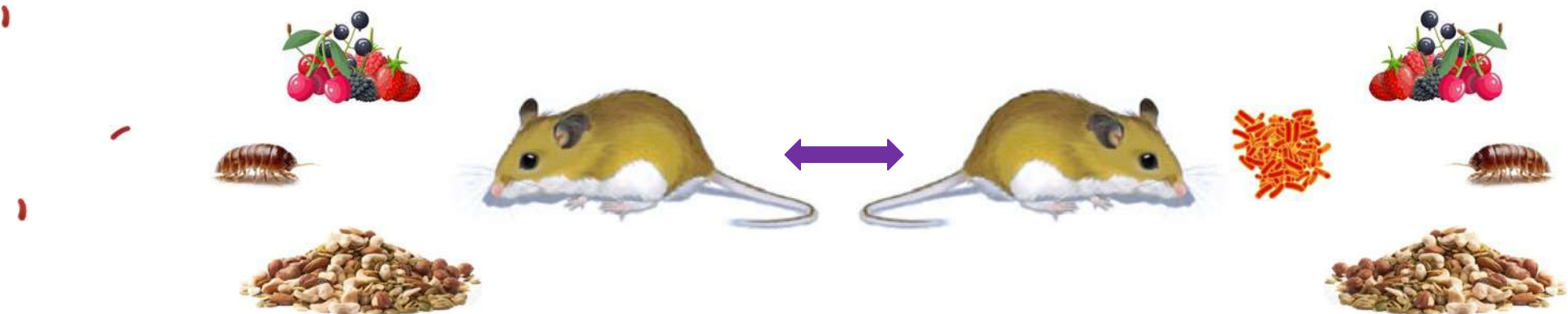
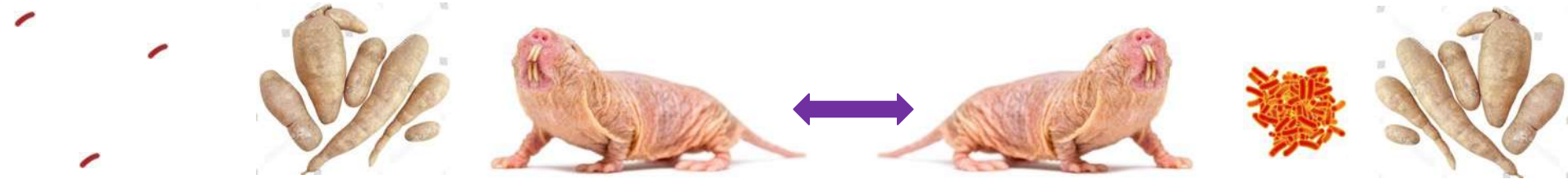
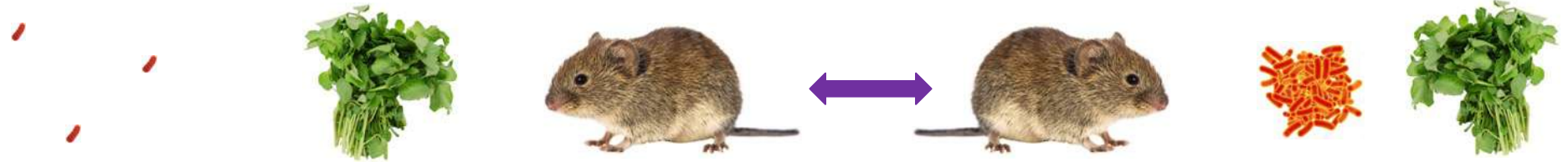


# Limited menus: an ecological challenge





# Expanded menus: an ecological opportunity

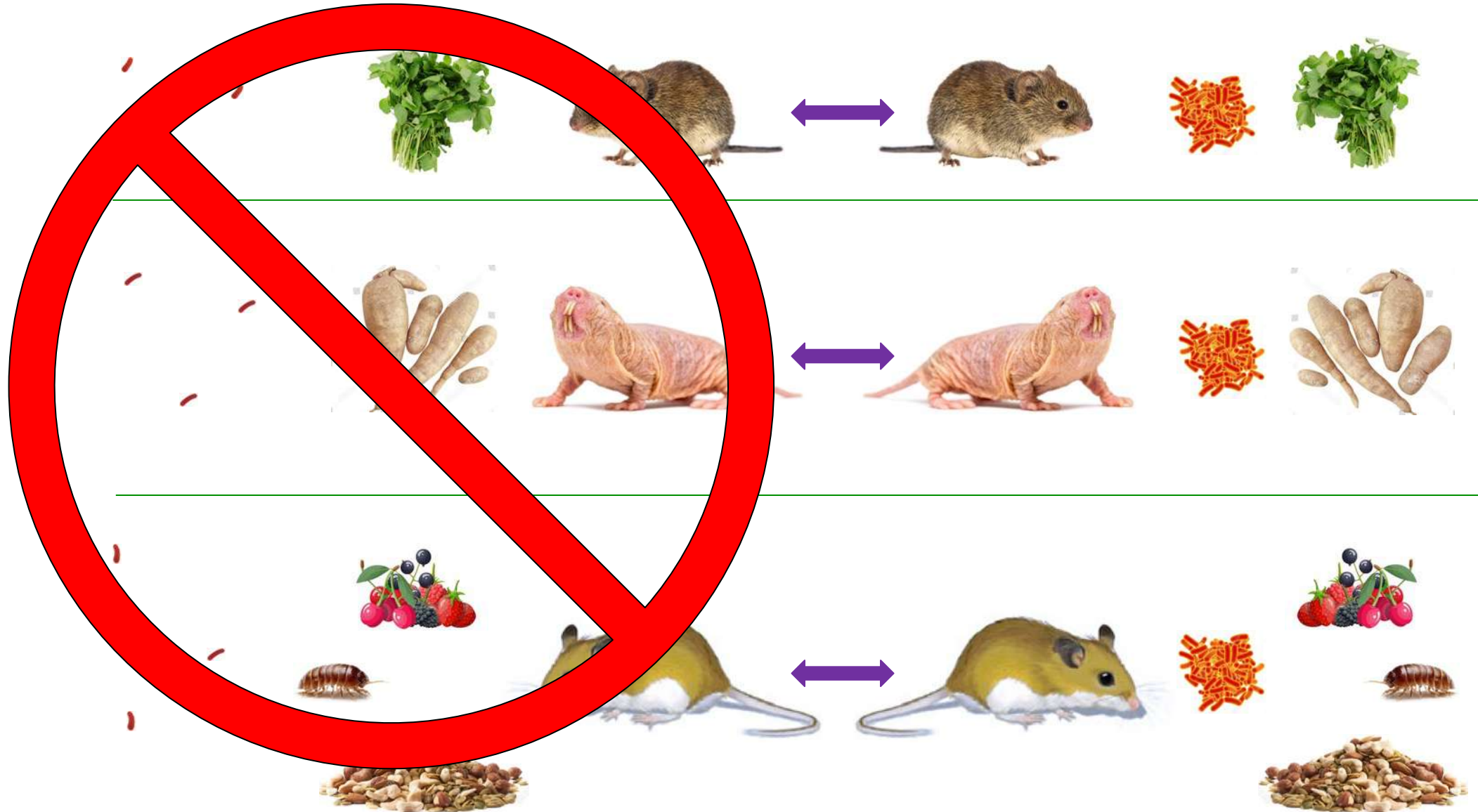






# Expanded menus: an ecological opportunity

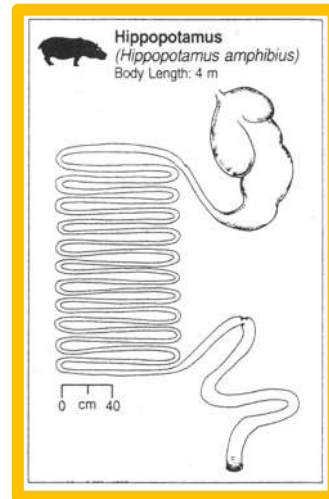
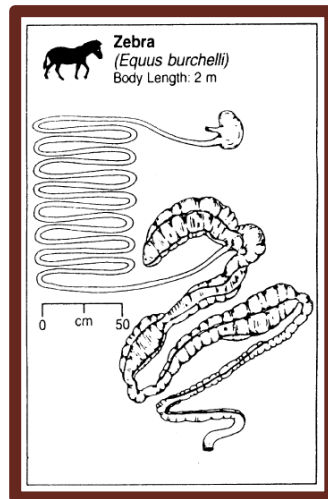
*(without alternative)*







# Farming: contain, nurture, harvest



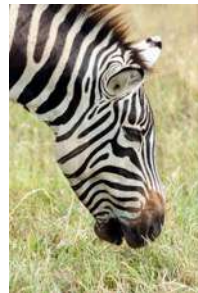
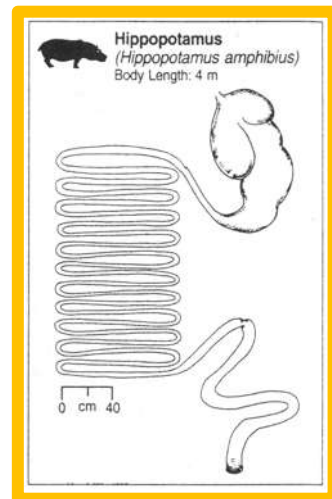
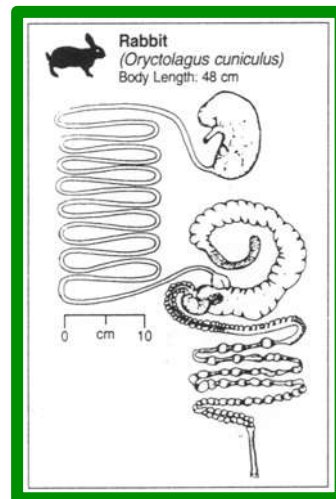
+ supplemental  
(endogenous)  
nitrogen

not  
possible  
?





# Farming: contain, nurture, harvest



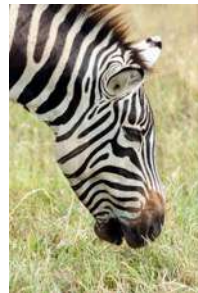
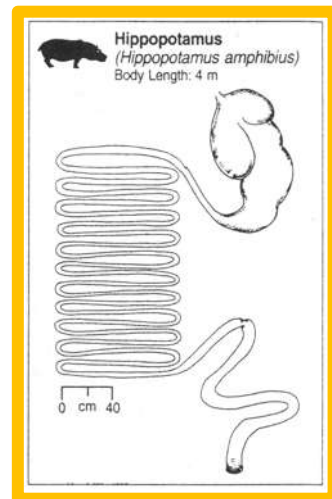
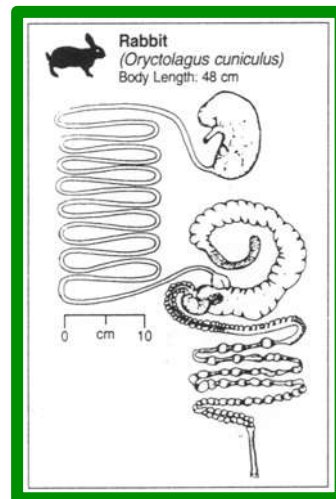
+ supplemental  
(endogenous)  
nitrogen

colonic  
separation  
&  
coprophagy





# Farming: contain, nurture, harvest



+ supplemental  
(endogenous)  
nitrogen

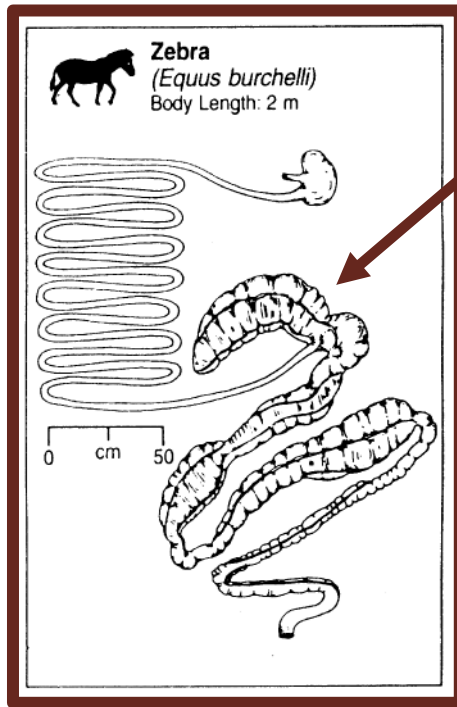
feasible  
at small  
body  
size

(and few extant  
small species do  
not do it)

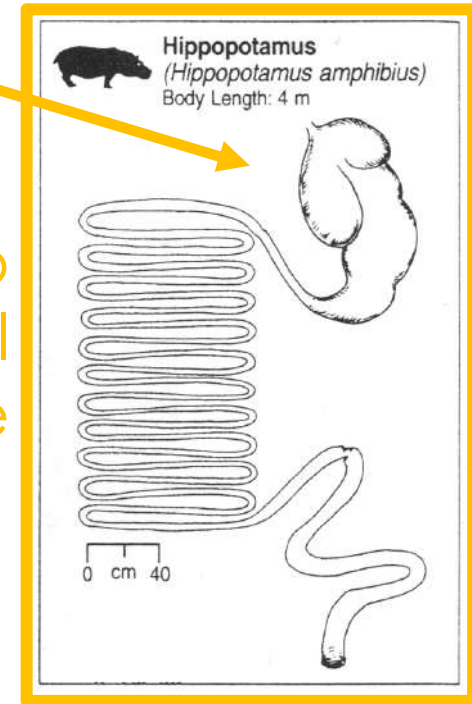


# Hindgut and Foregut fermenters

Microbes ferment the  
**diet** (**rest**) ...



... **prior** to  
small  
intestine

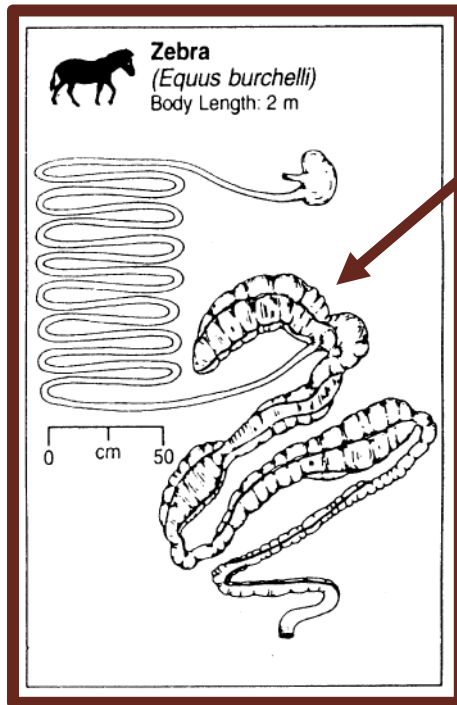






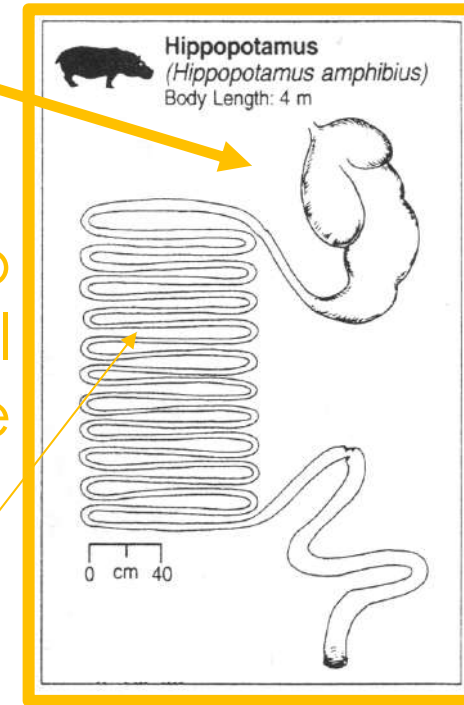
# Hindgut and Foregut fermenters

Microbes ferment the  
**diet** (**rest**) ...



... **prior** to  
small  
intestine

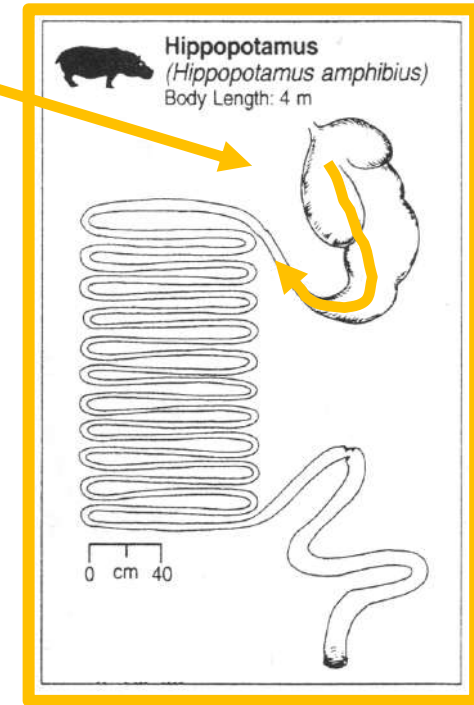
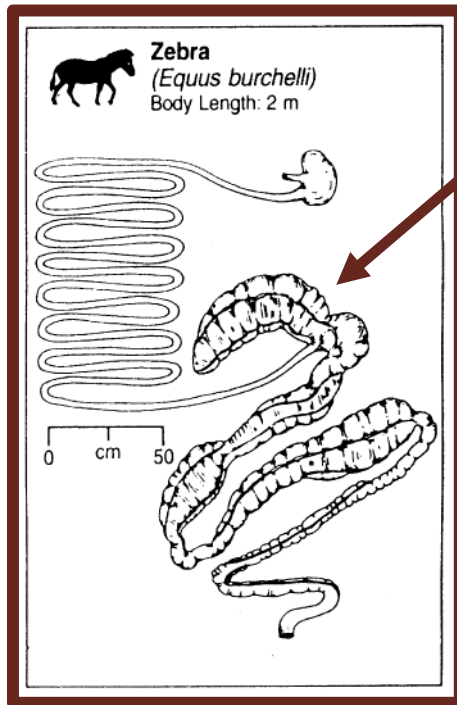
**enzymatic  
digestion of  
processed  
material**





# Hindgut and Foregut fermenters

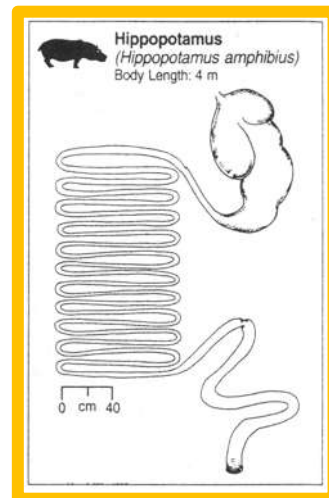
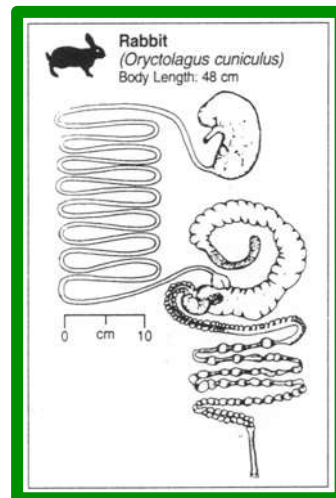
Microbes ferment the  
**diet** (**rest**) ...



... flow out  
and are  
digested



# Farming: contain, nurture, harvest



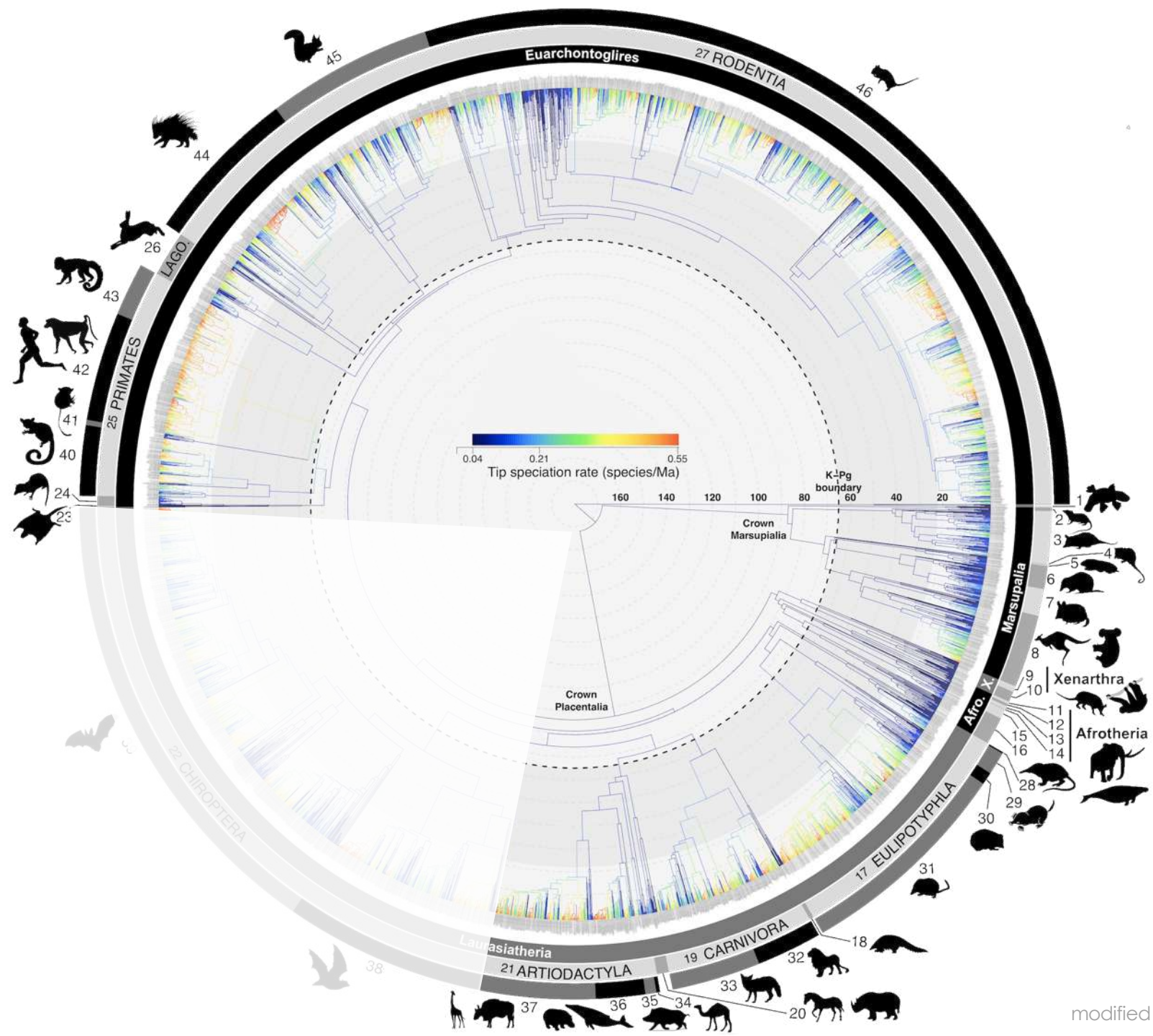
+ supplemental  
(endogenous)  
nitrogen

feasible  
at small  
body  
size

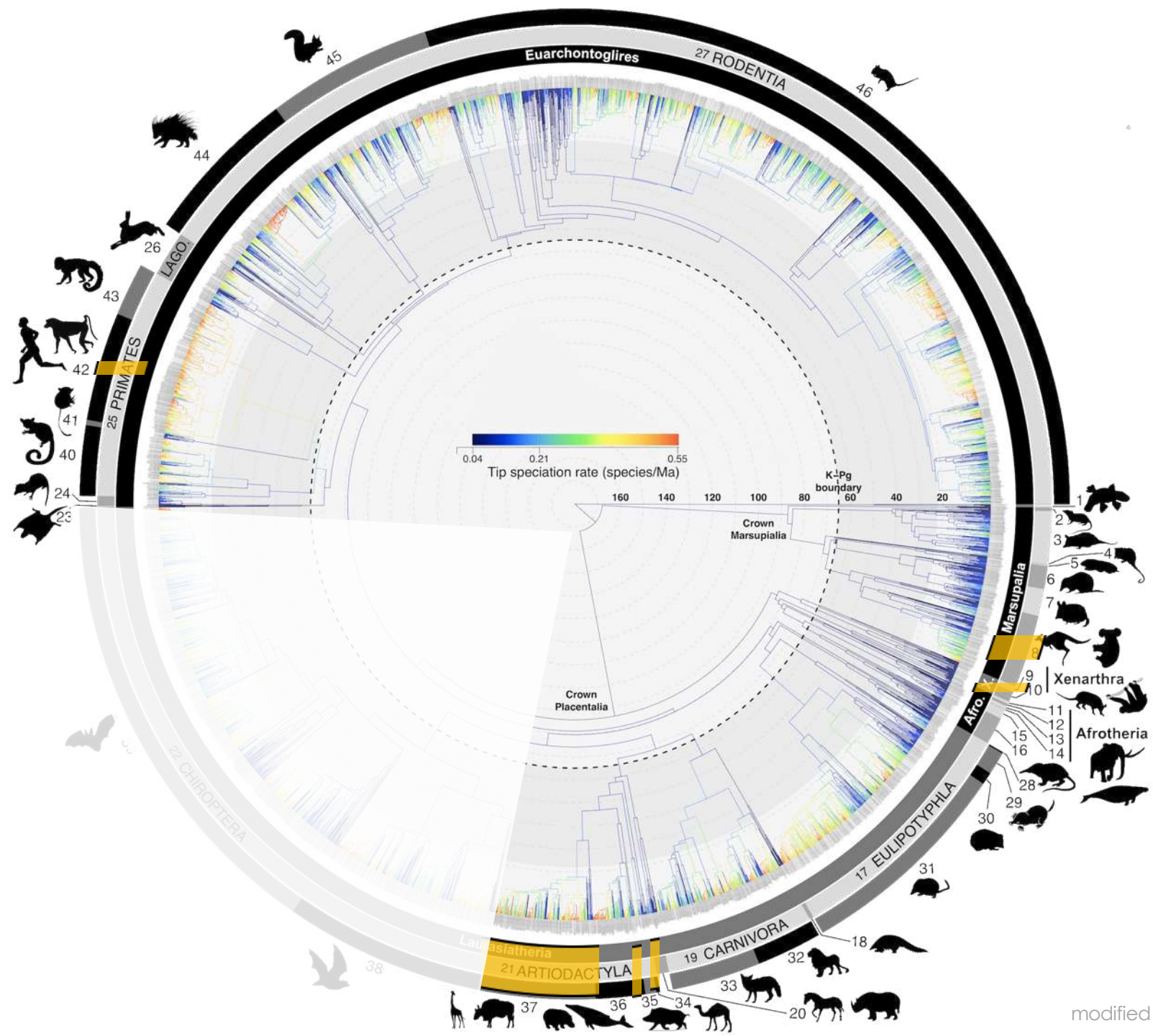
(and few extant  
small species do  
not do it)

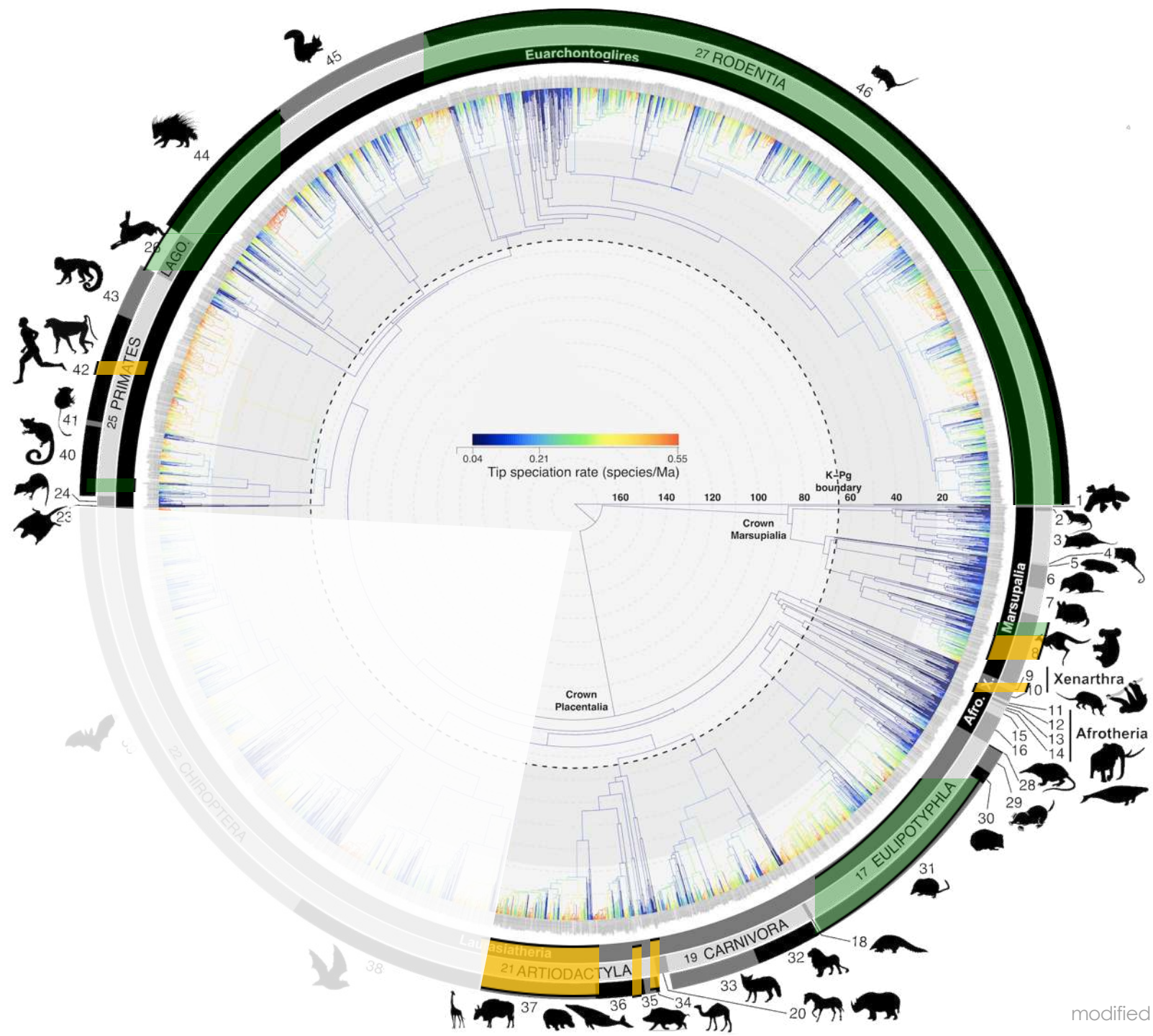
no effort  
required  
?















How do you increase the yield of a growing system ?







How do you increase the yield of a growing system ?







How do you increase the yield of a growing system ?

*frequent harvest to keep the population  
in the growth stage*

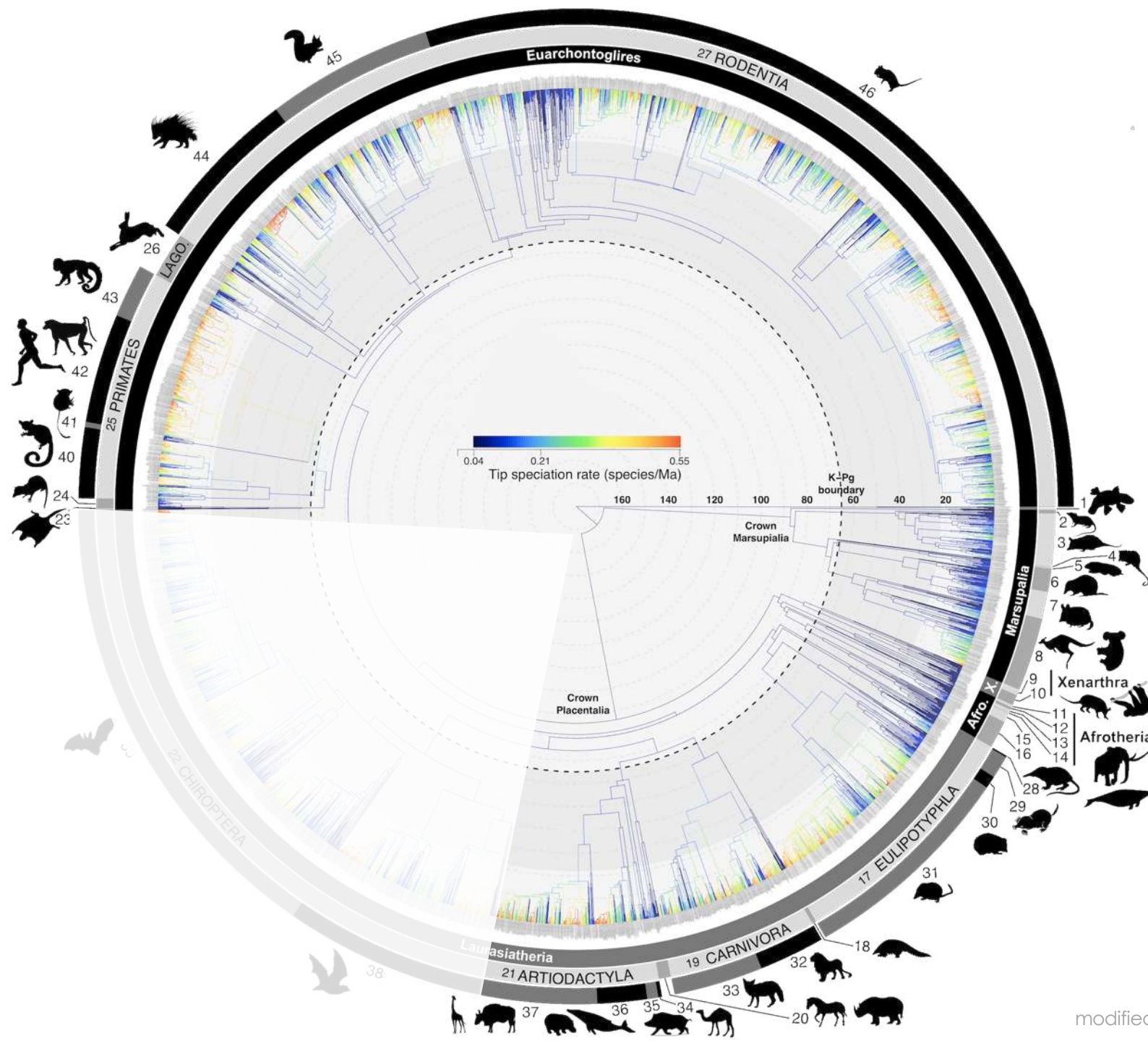


How do you harvest microbes ?



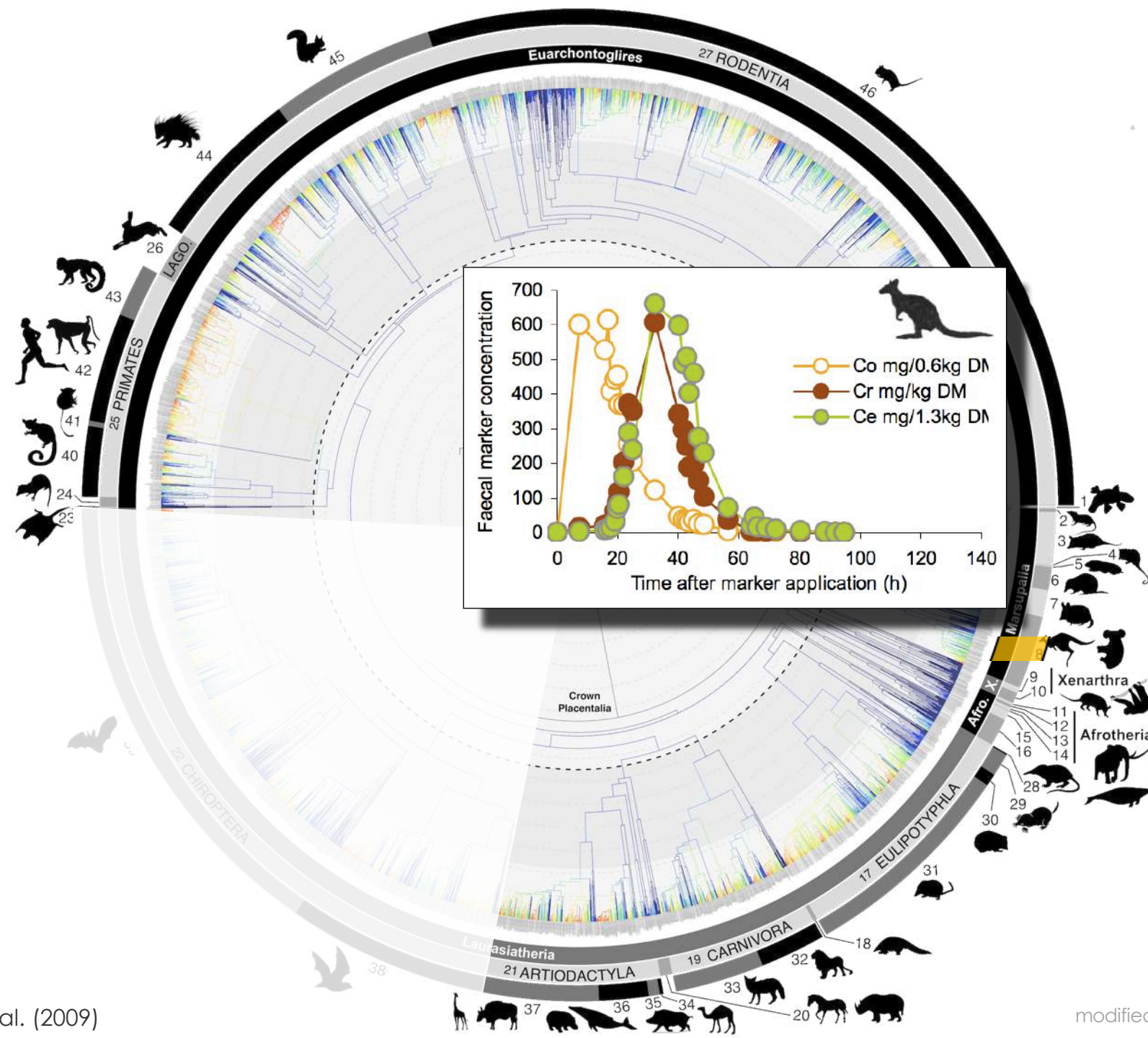
## How do you harvest microbes ?

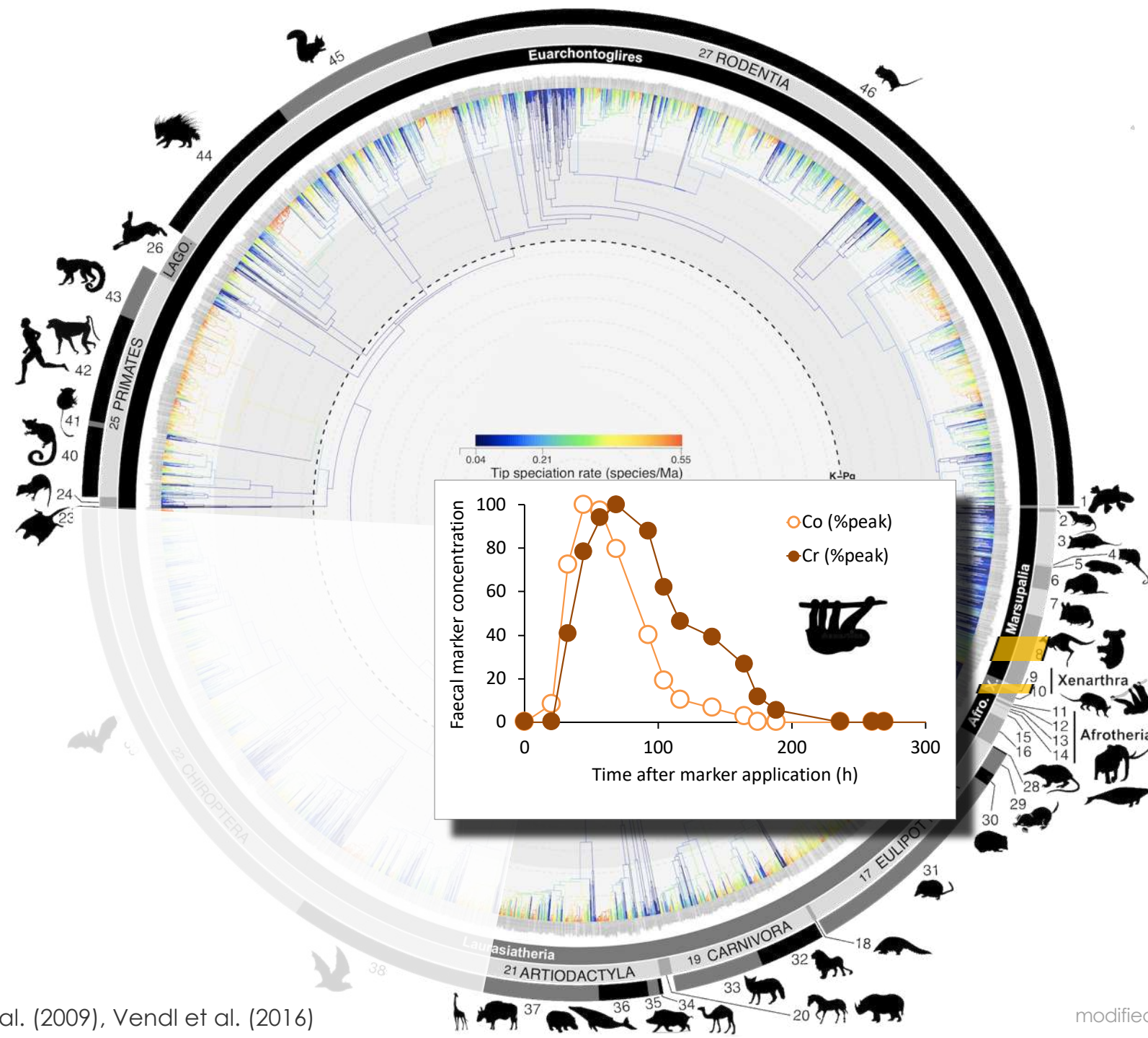
*by flushing them out of the fermenter  
while retaining the substrate*



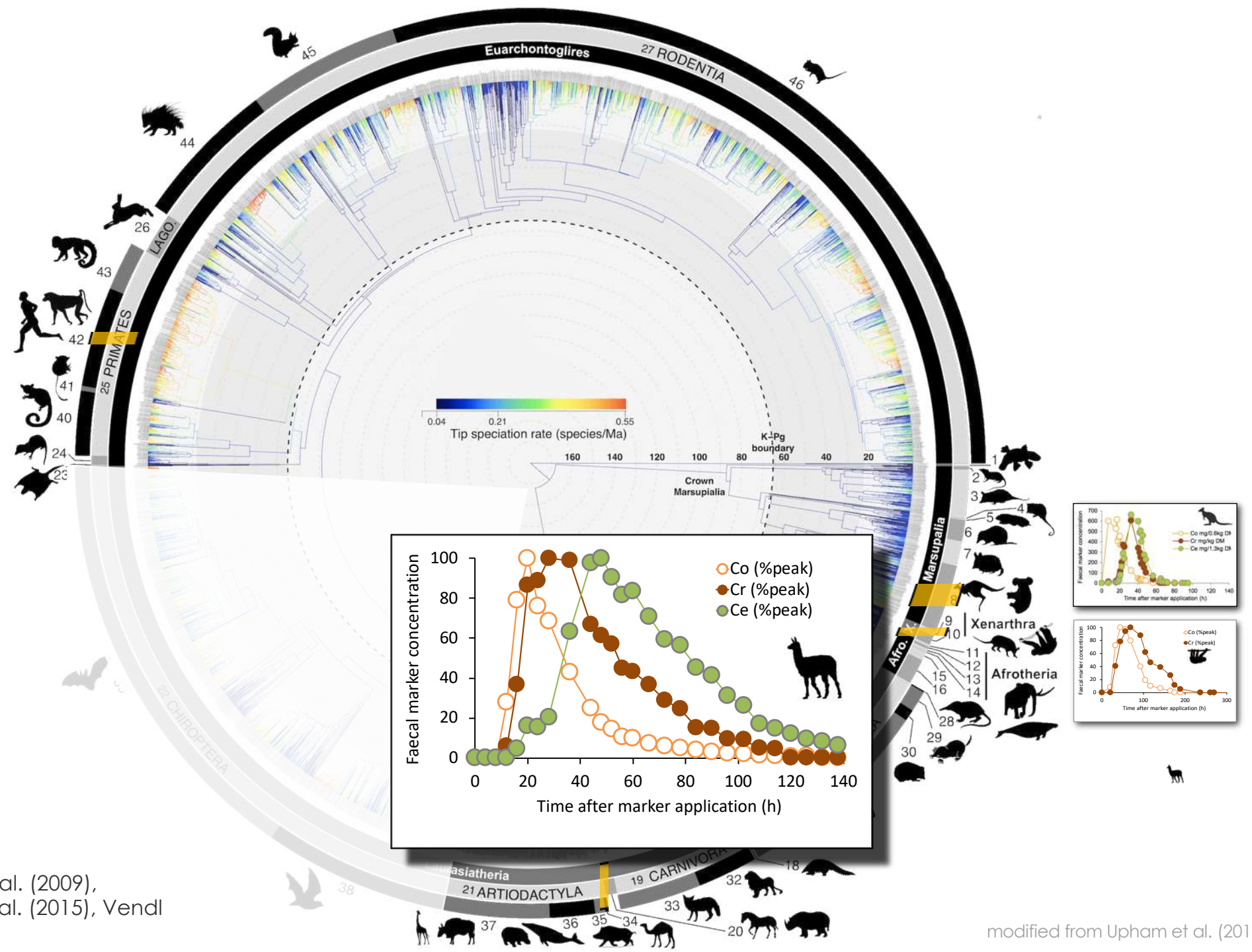
modified from Upham et al. (2019)





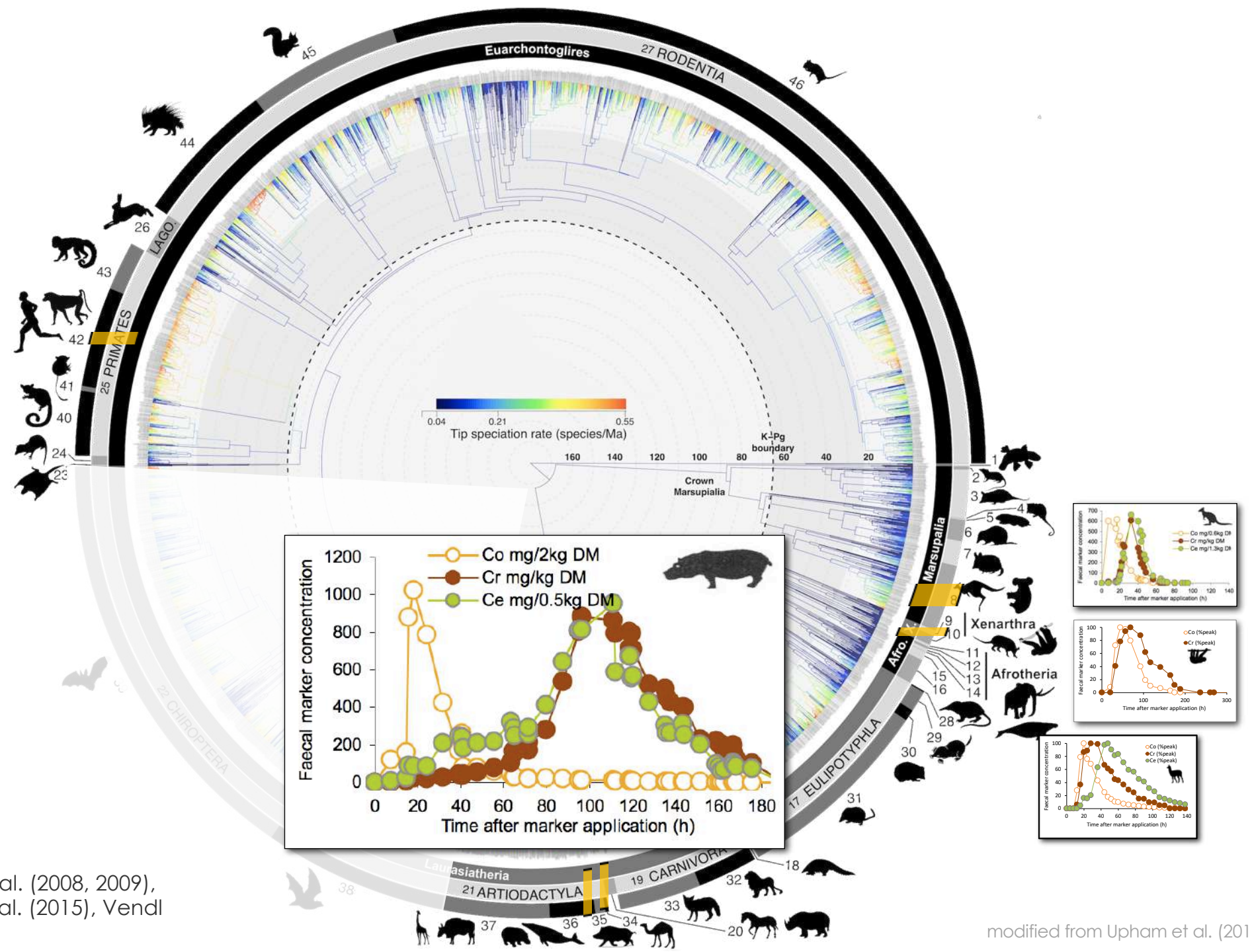






Schwarm et al. (2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)

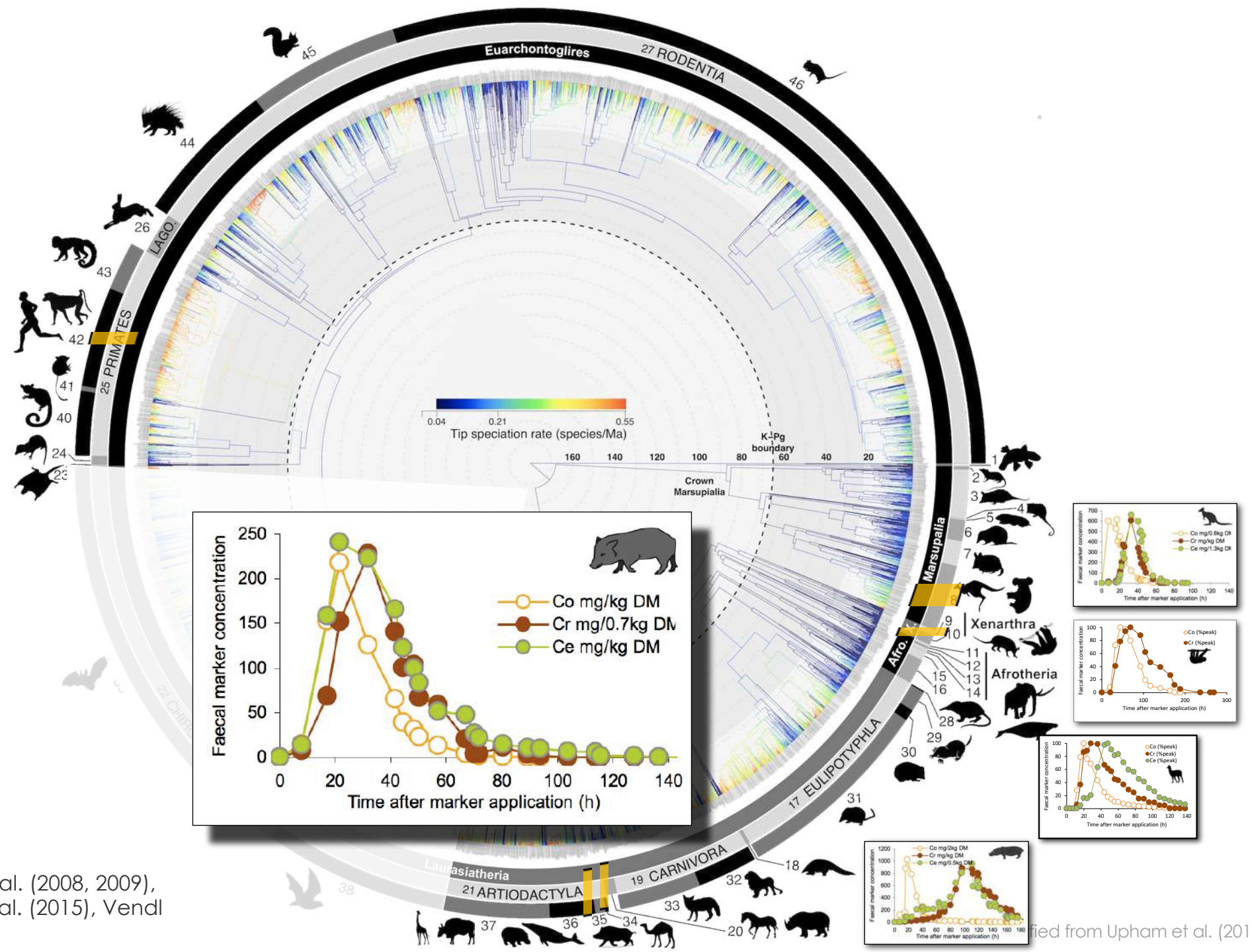
modified from Upham et al. (2019)



Schwarm et al. (2008, 2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)

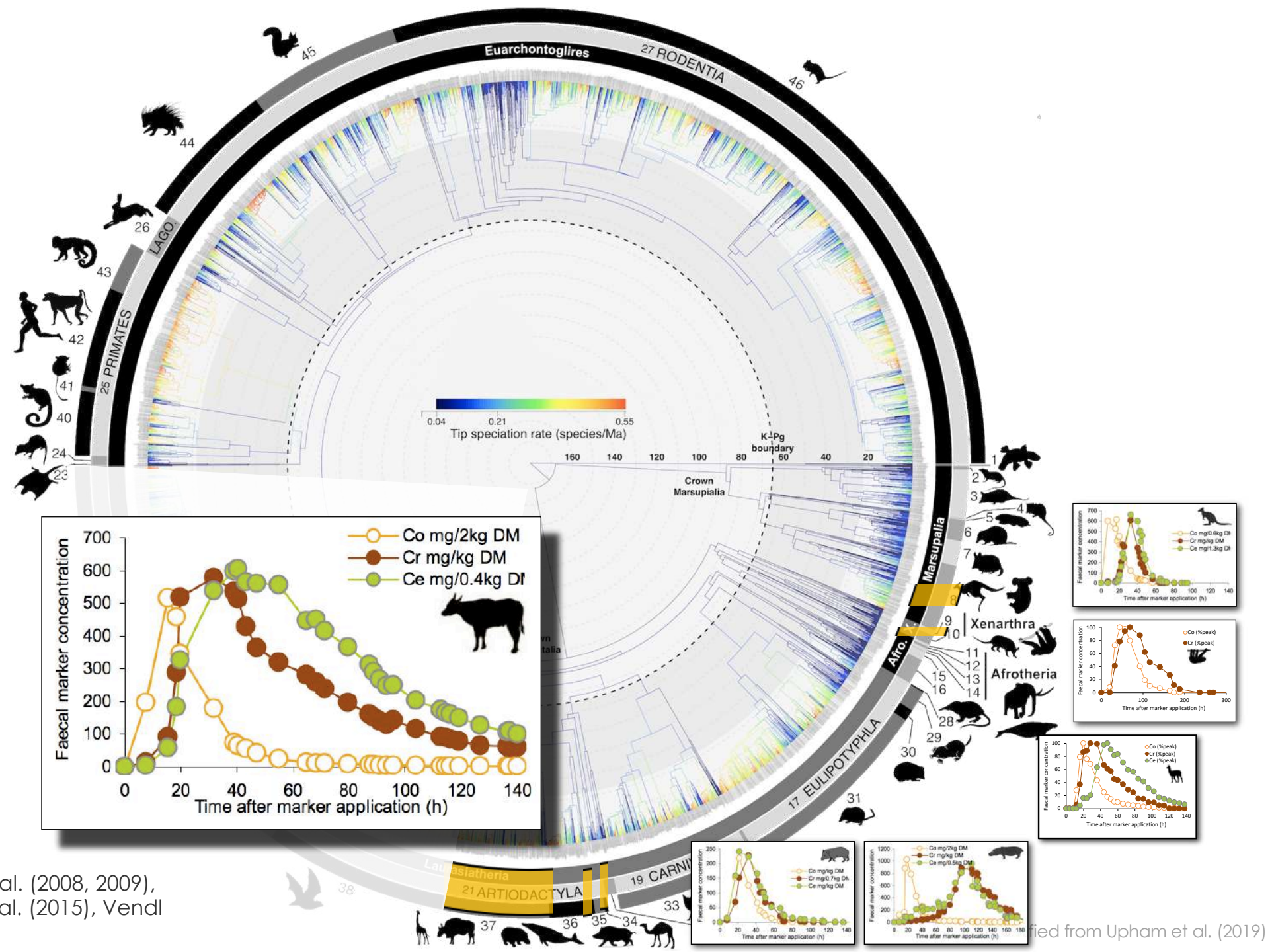
modified from Upham et al. (2019)





Schwarm et al. (2008, 2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)

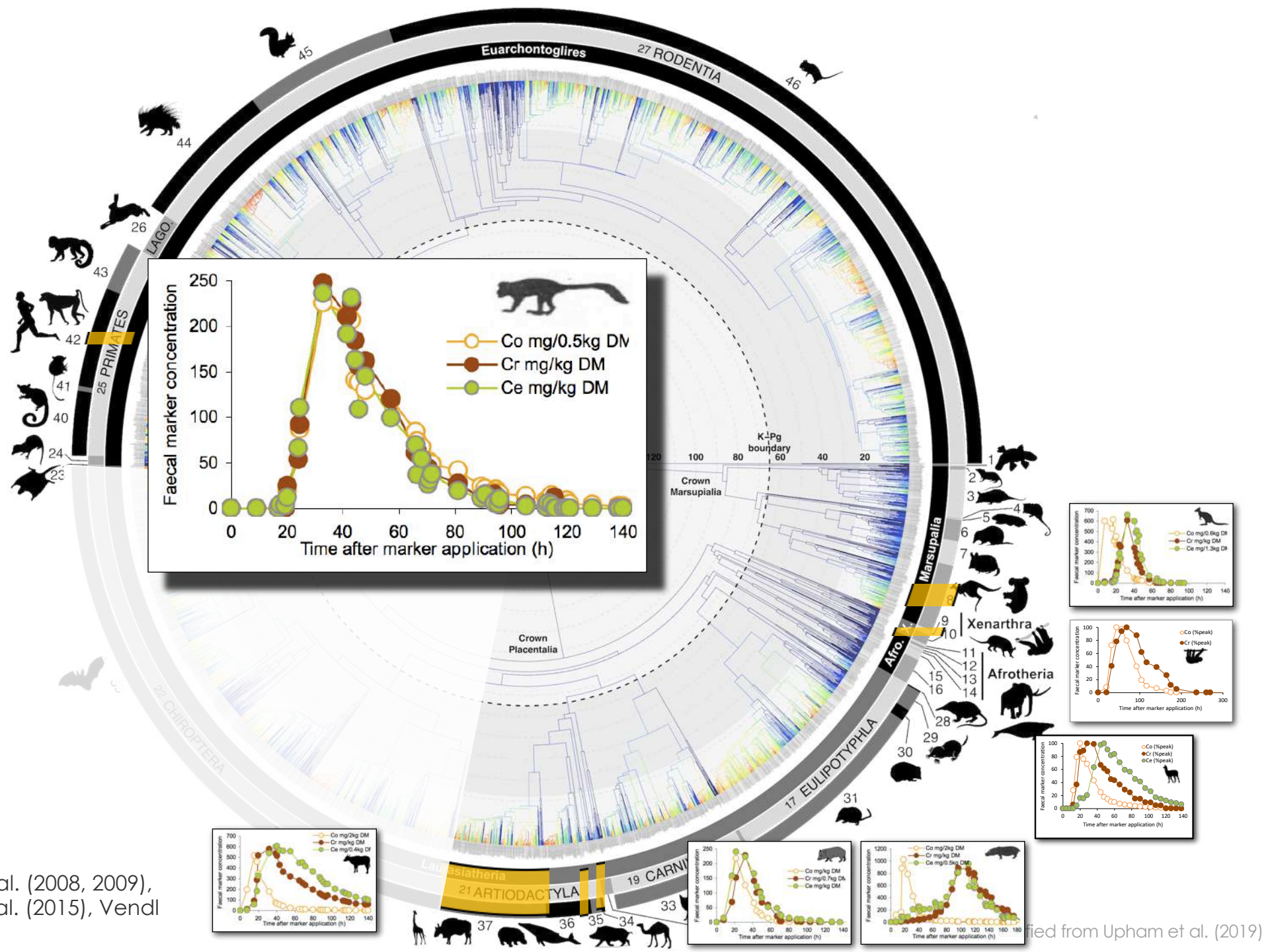
Adapted from Upham et al. (2019)



Schwarm et al. (2008, 2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)

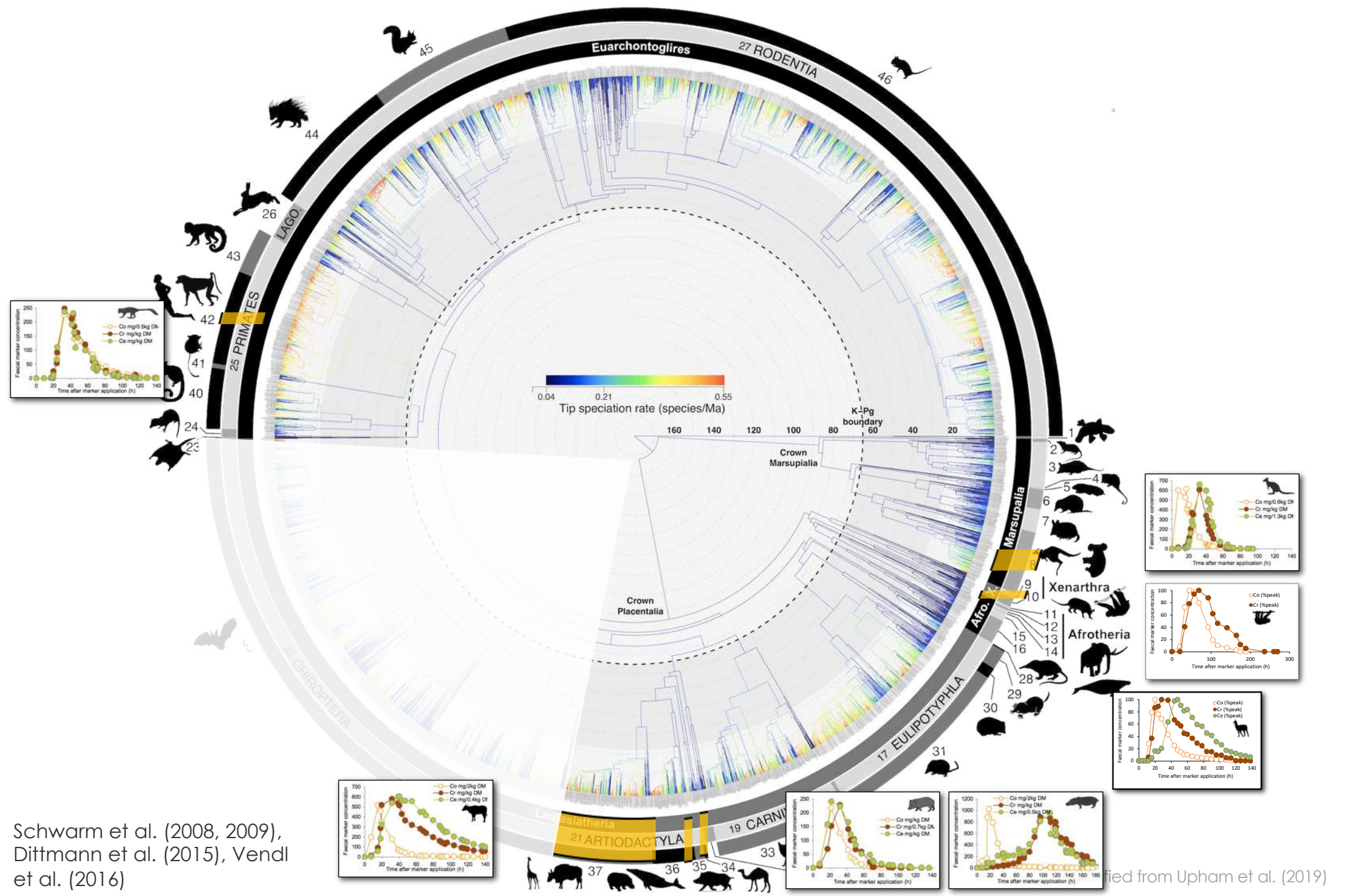
Adapted from Upham et al. (2019)





Schwarm et al. (2008, 2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)

Adapted from Upham et al. (2019)

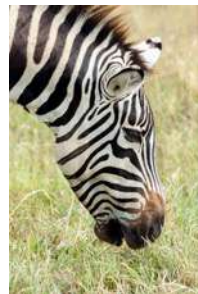
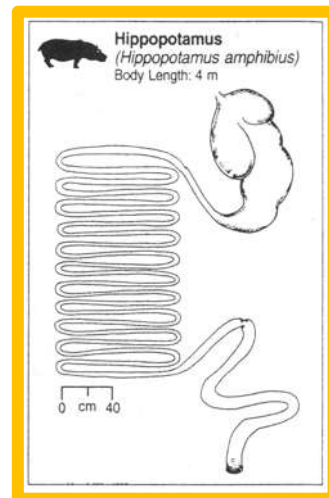
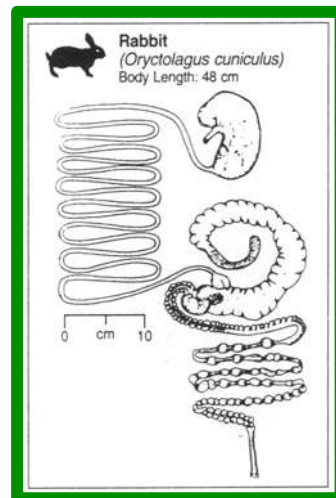


Schwarm et al. (2008, 2009),  
Dittmann et al. (2015), Vendl  
et al. (2016)





# Farming: contain, nurture, harvest



+ supplemental  
(endogenous)  
nitrogen

feasible  
at small  
body  
size

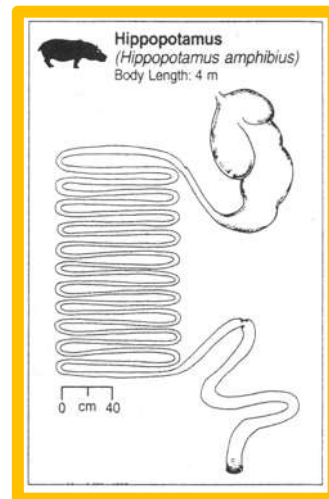
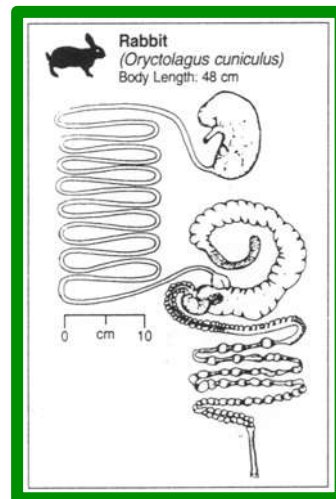
(and few extant  
small species do  
not do it)

no effort  
required  
?





# Farming: contain, nurture, harvest



+ supplemental  
(endogenous)  
nitrogen

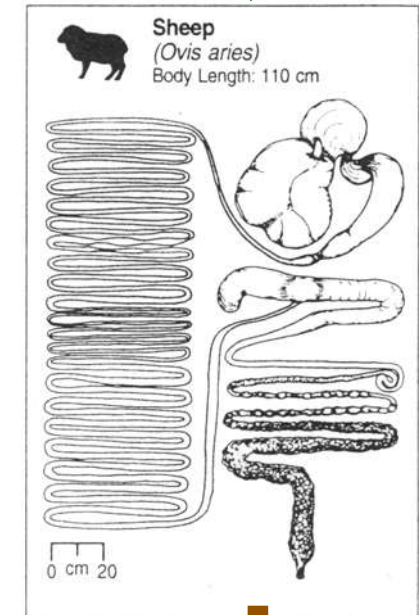
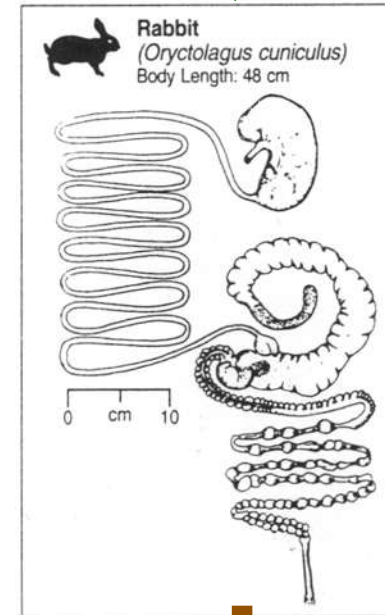
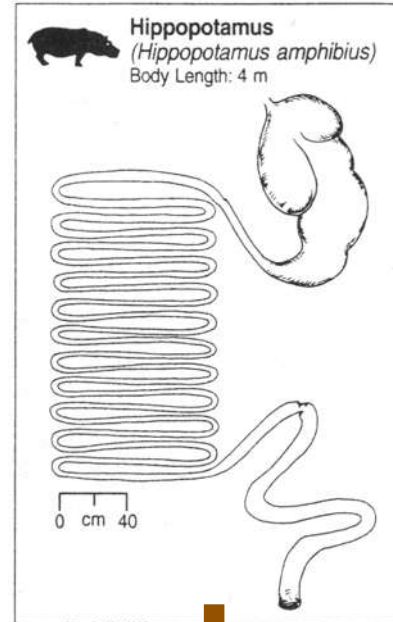
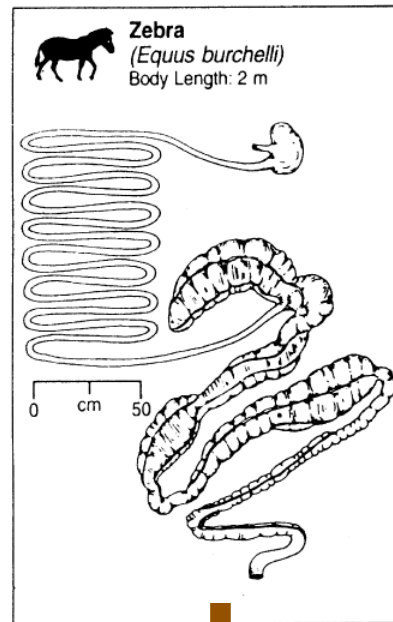
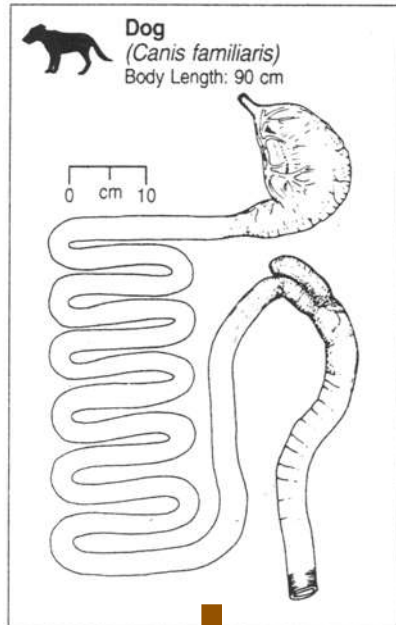
feasible  
at small  
body  
size

(and few extant  
small species do  
not do it)

optimize  
via  
flushing  
(saliva)



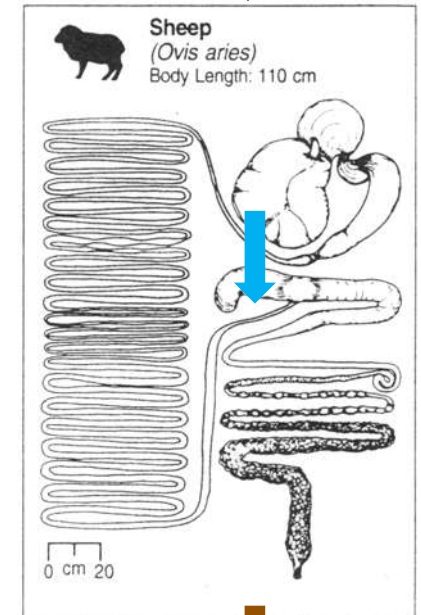
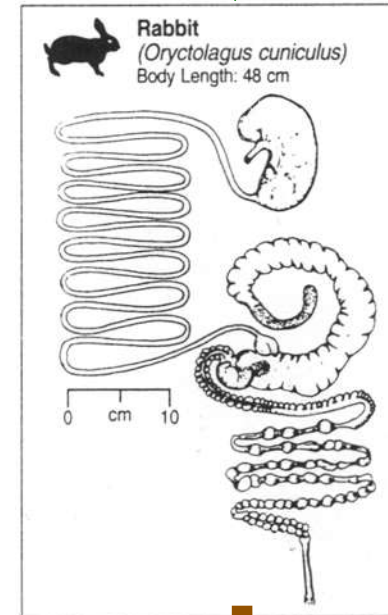
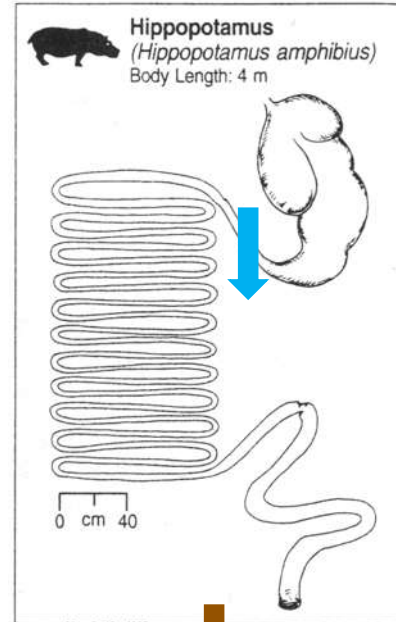
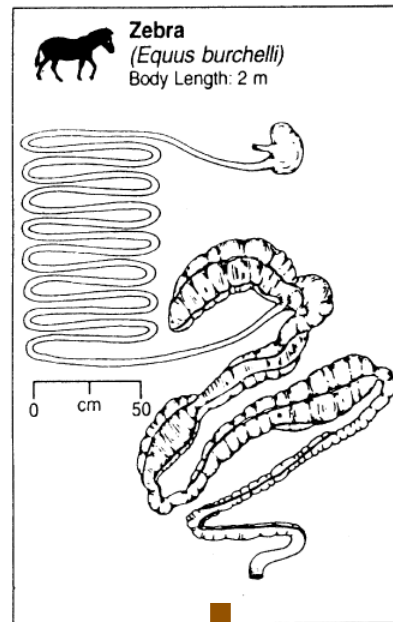
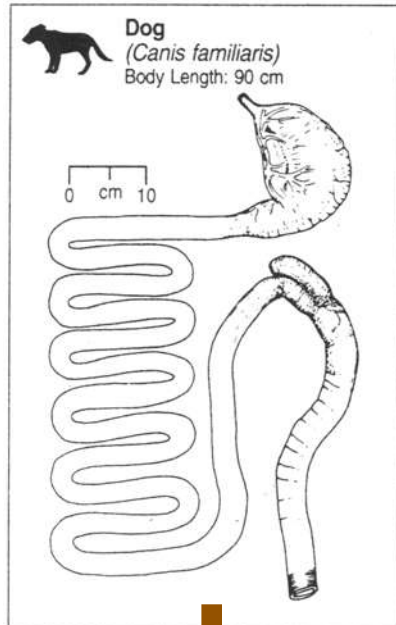
# Teeth and gut do their own thing







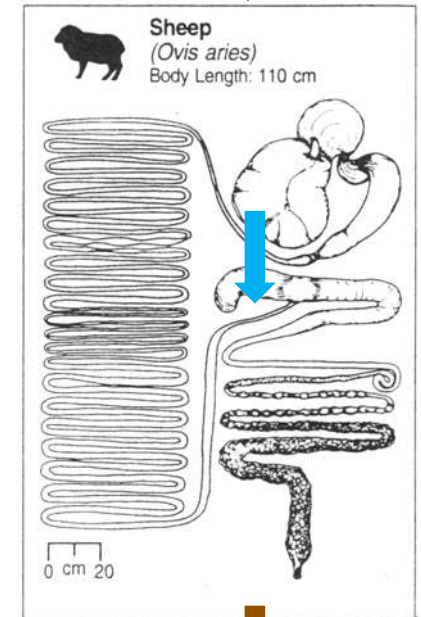
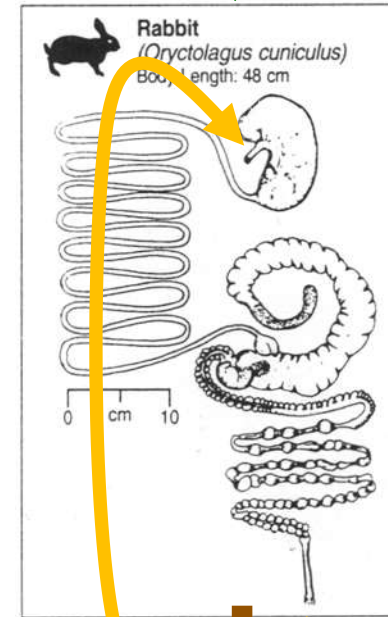
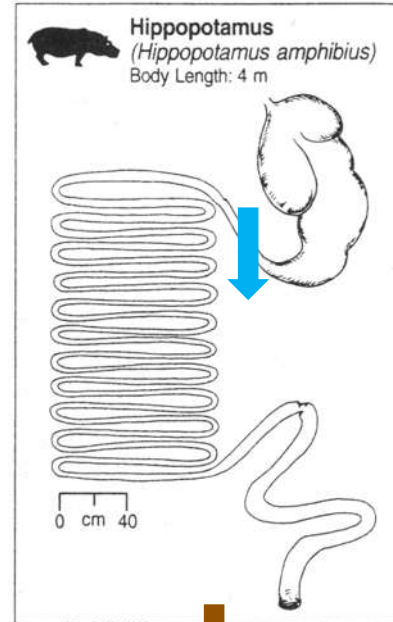
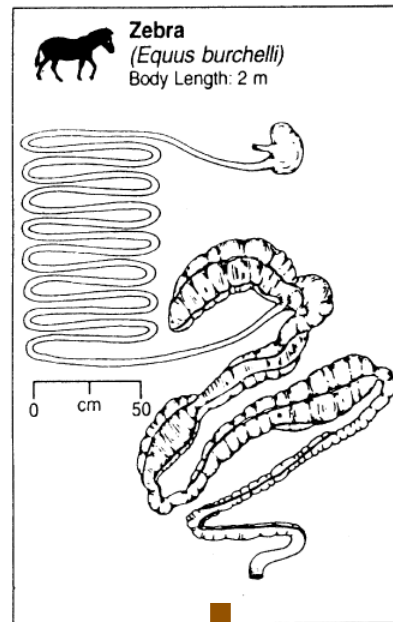
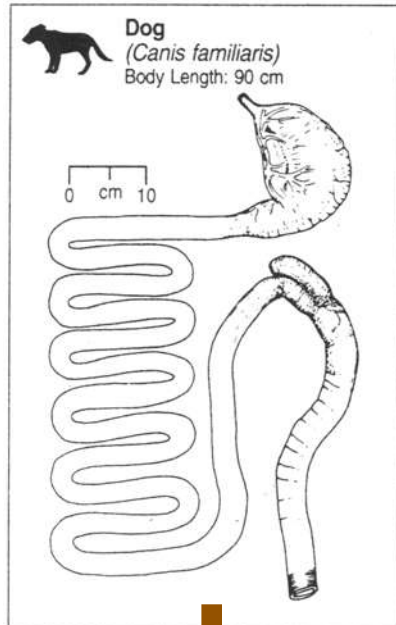
# Teeth and gut do their own thing







# Teeth and gut do their own thing





*What happens if there is a lot of fluid ?*



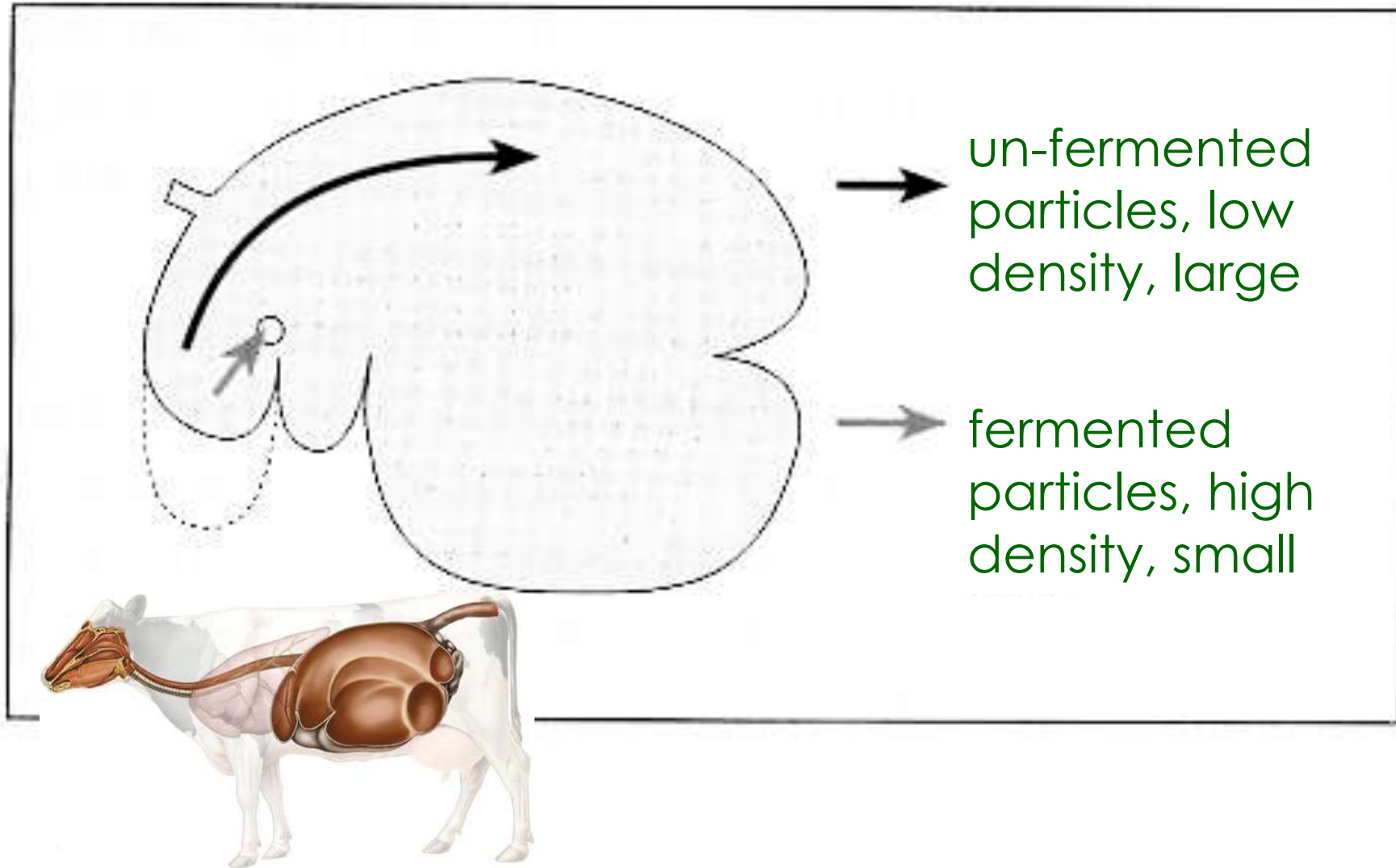
# Particles separate in fluid



Photo I. Lechner



# Particles separate in fluid: Sorting







# Faecal particles in a ruminant and a nonruminant





# Faecal particles in a ruminant and a nonruminant



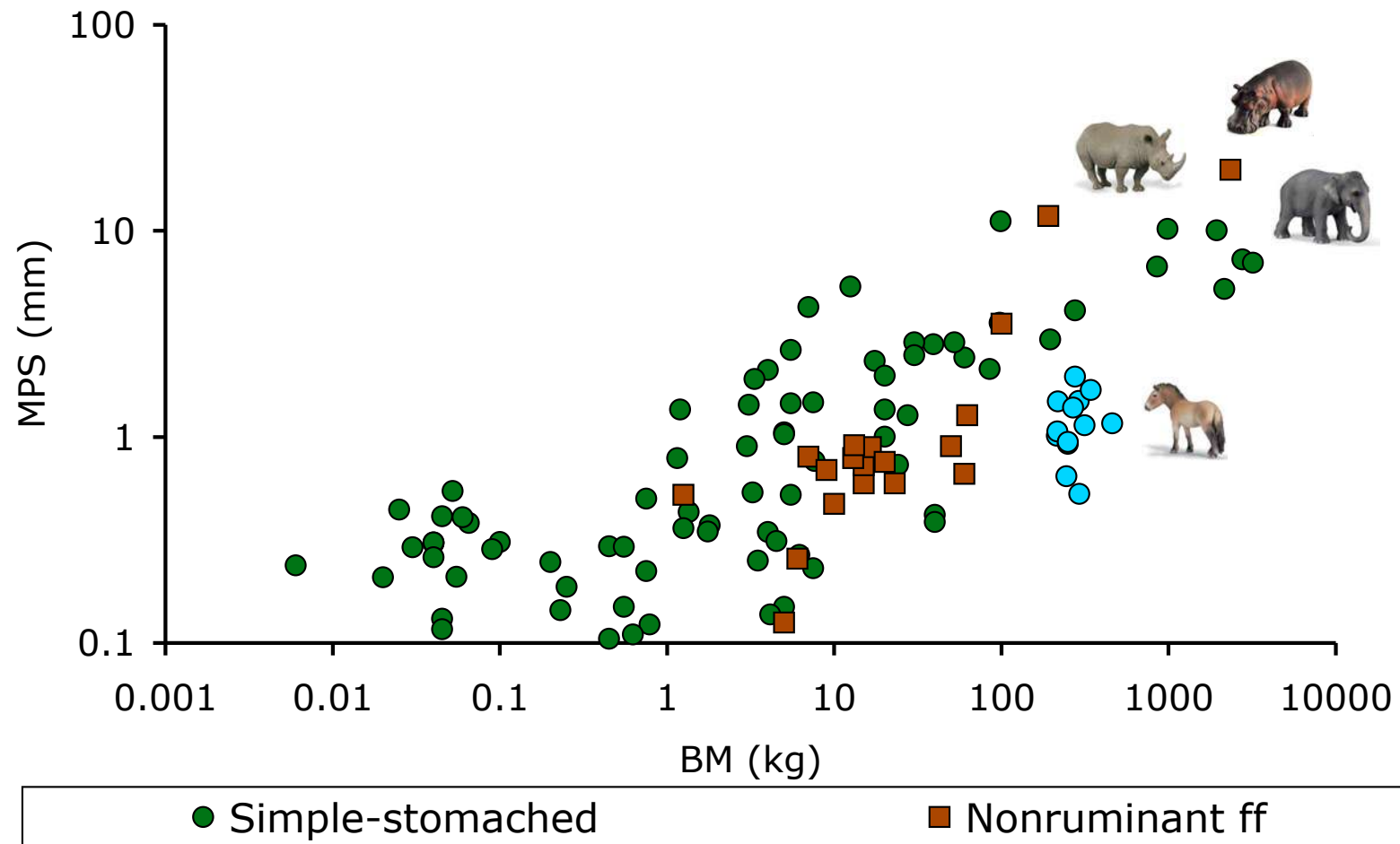
Photo A. Schwarm



# Comparative chewing efficiency in mammalian herbivores

Julia Fritz, Jürgen Hummel, Ellen Kienzle, Christian Arnold, Charles Nunn and Marcus Clauss

Oikos 118: 1623–1632, 2009

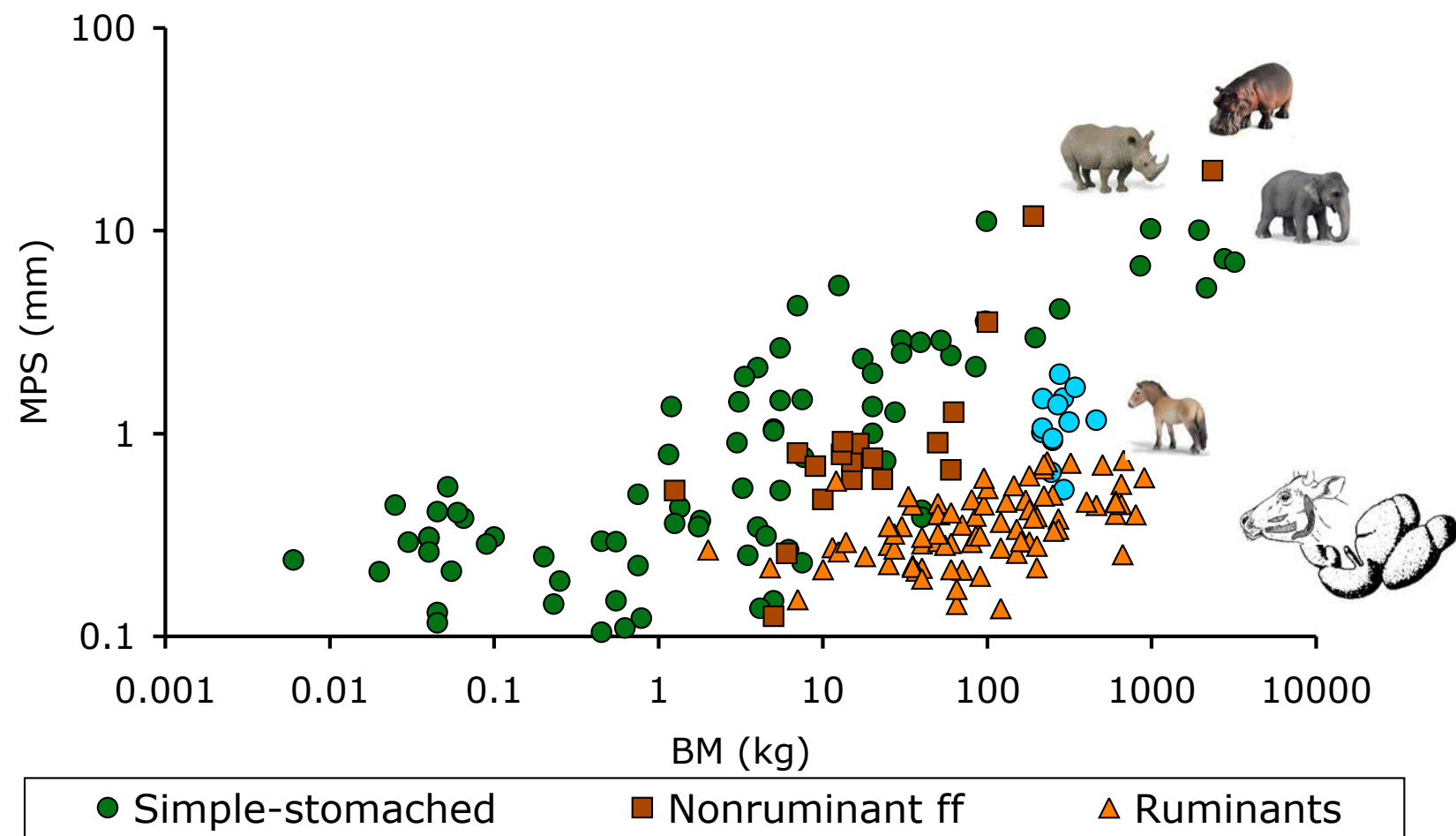




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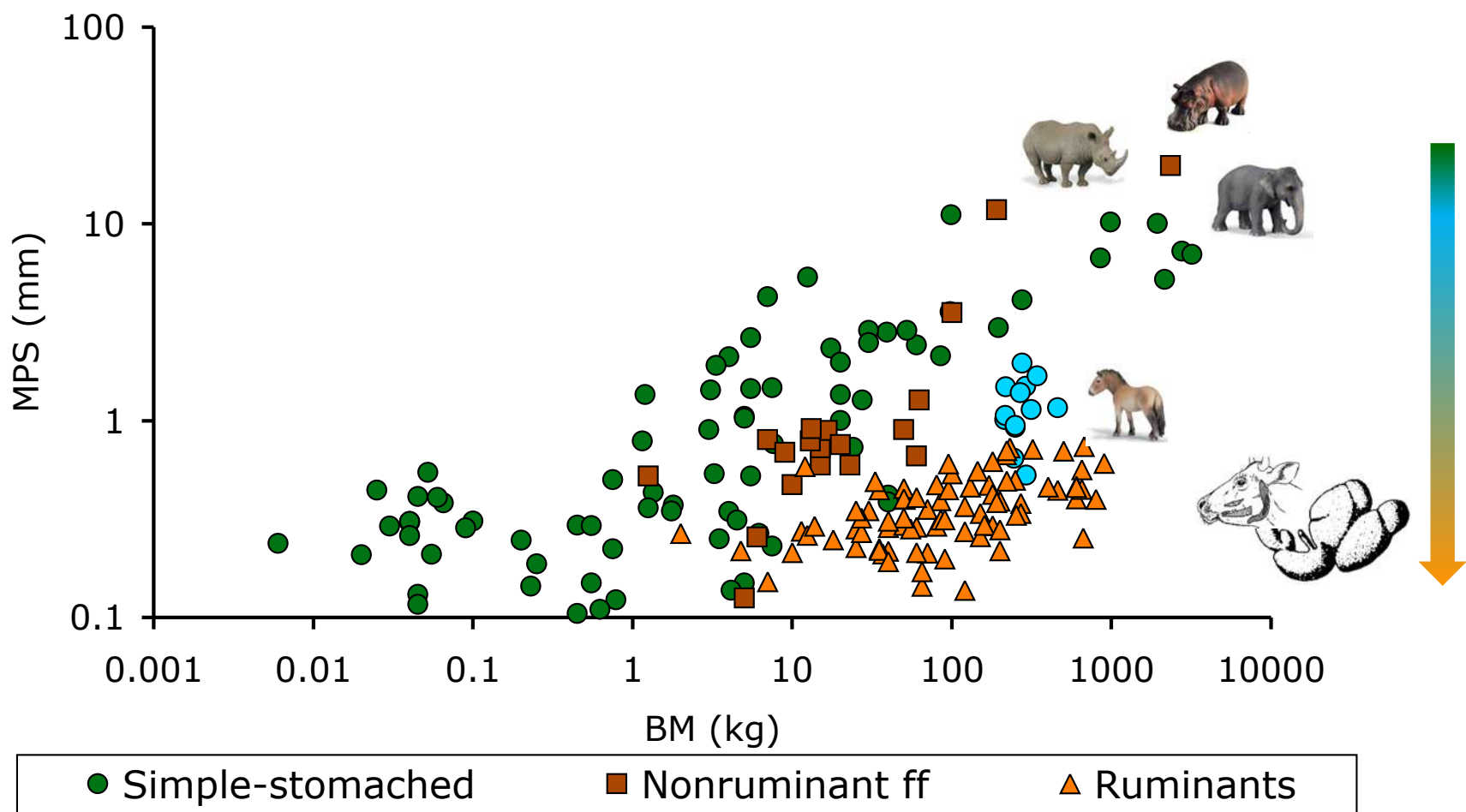




# Comparative chewing efficiency in mammalian herbivores

Julia Fritz, Jürgen Hummel, Ellen Kienzle, Christian Arnold, Charles Nunn and Marcus Clauss

Oikos 118: 1623–1632, 2009





*Teeth evolve for efficiency ...*

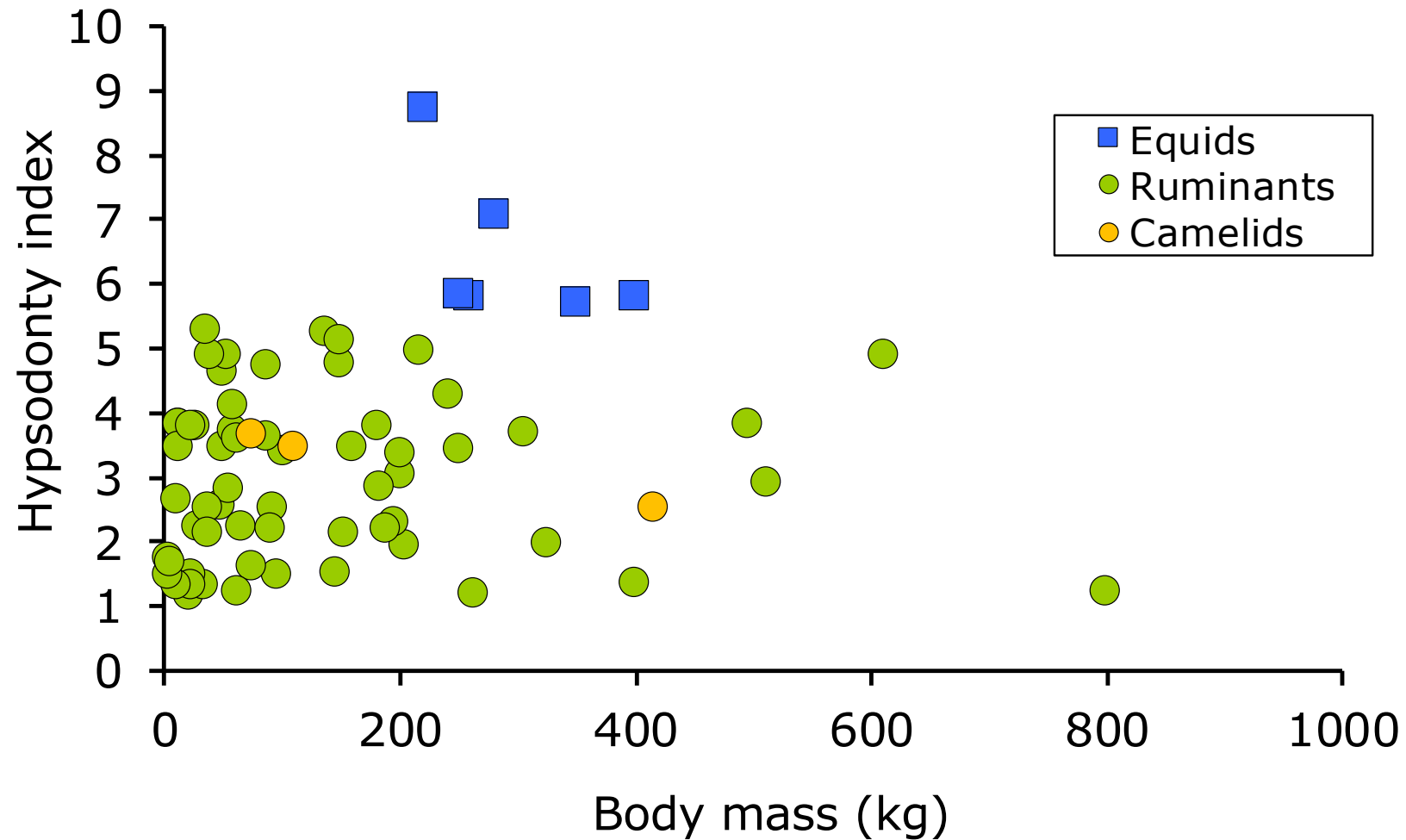


*Teeth evolve for efficiency ...*

*... but achieve the highest efficiency with  
the help of a gut-based sorting  
mechanism.*



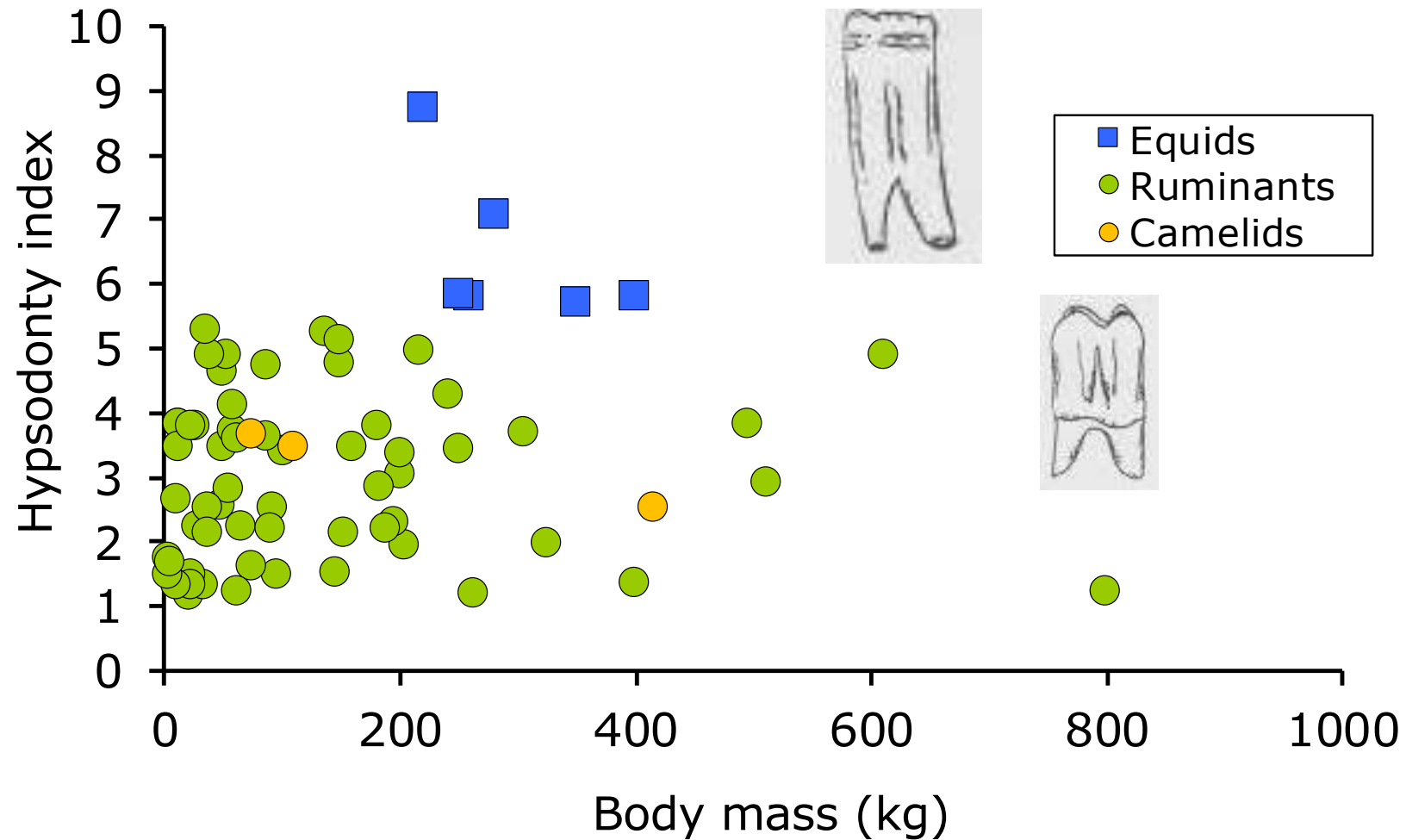
# Ruminants are not super-hypsodont





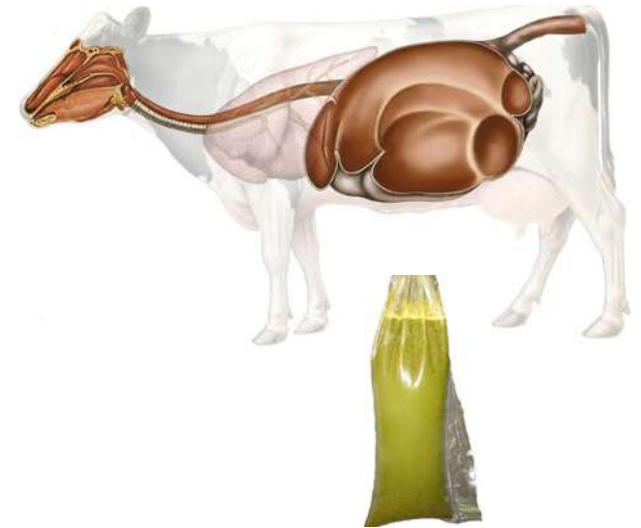
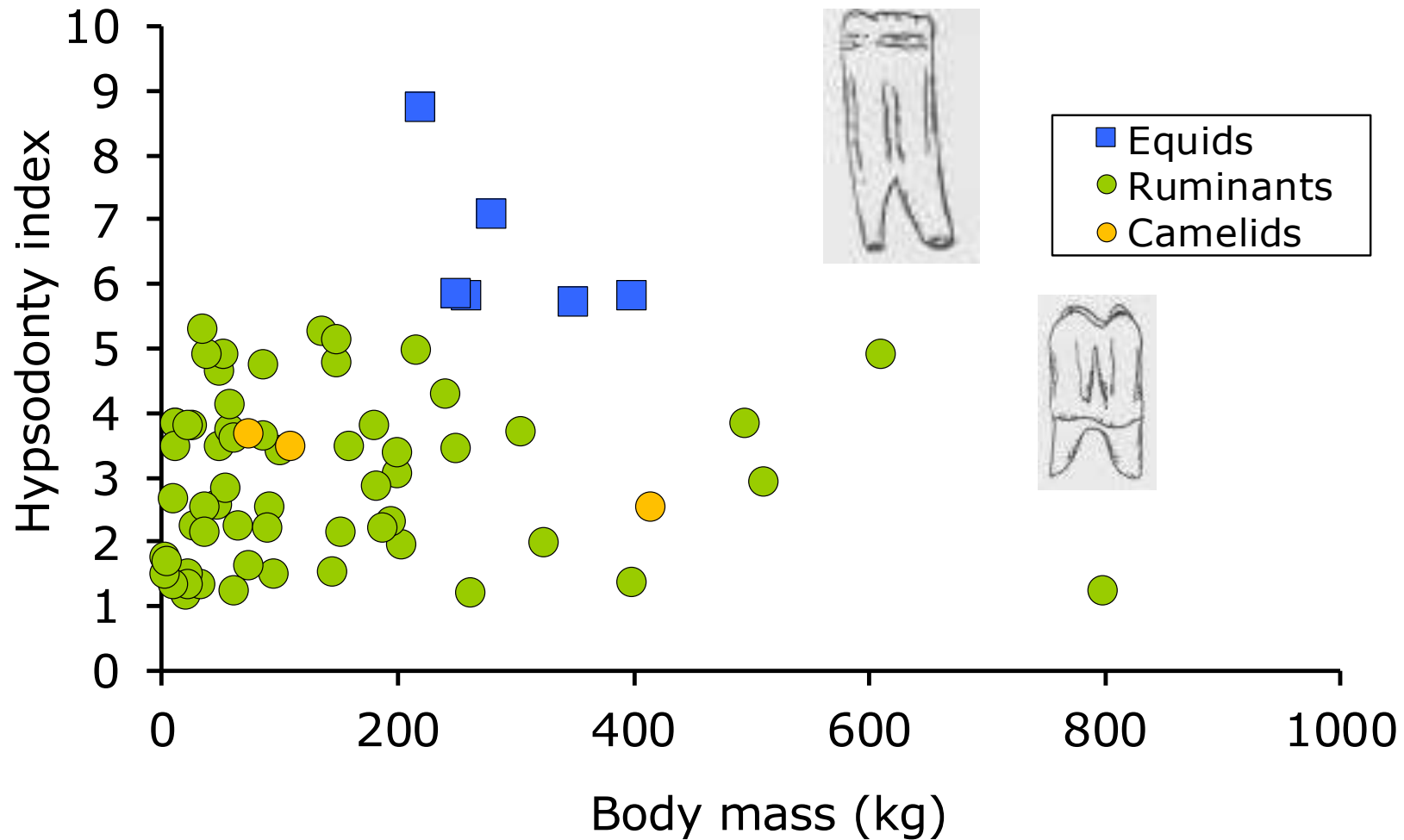


# Ruminants are not super-hypsodont



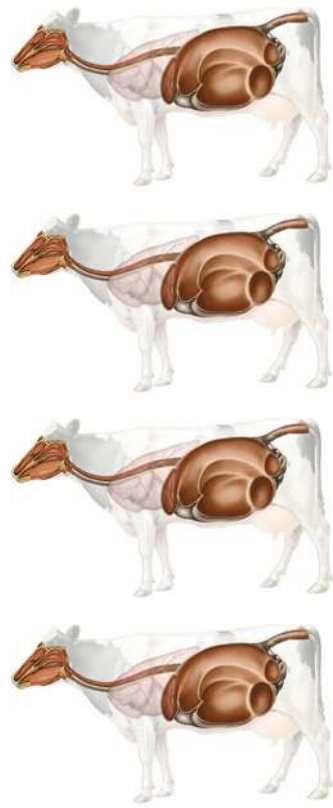
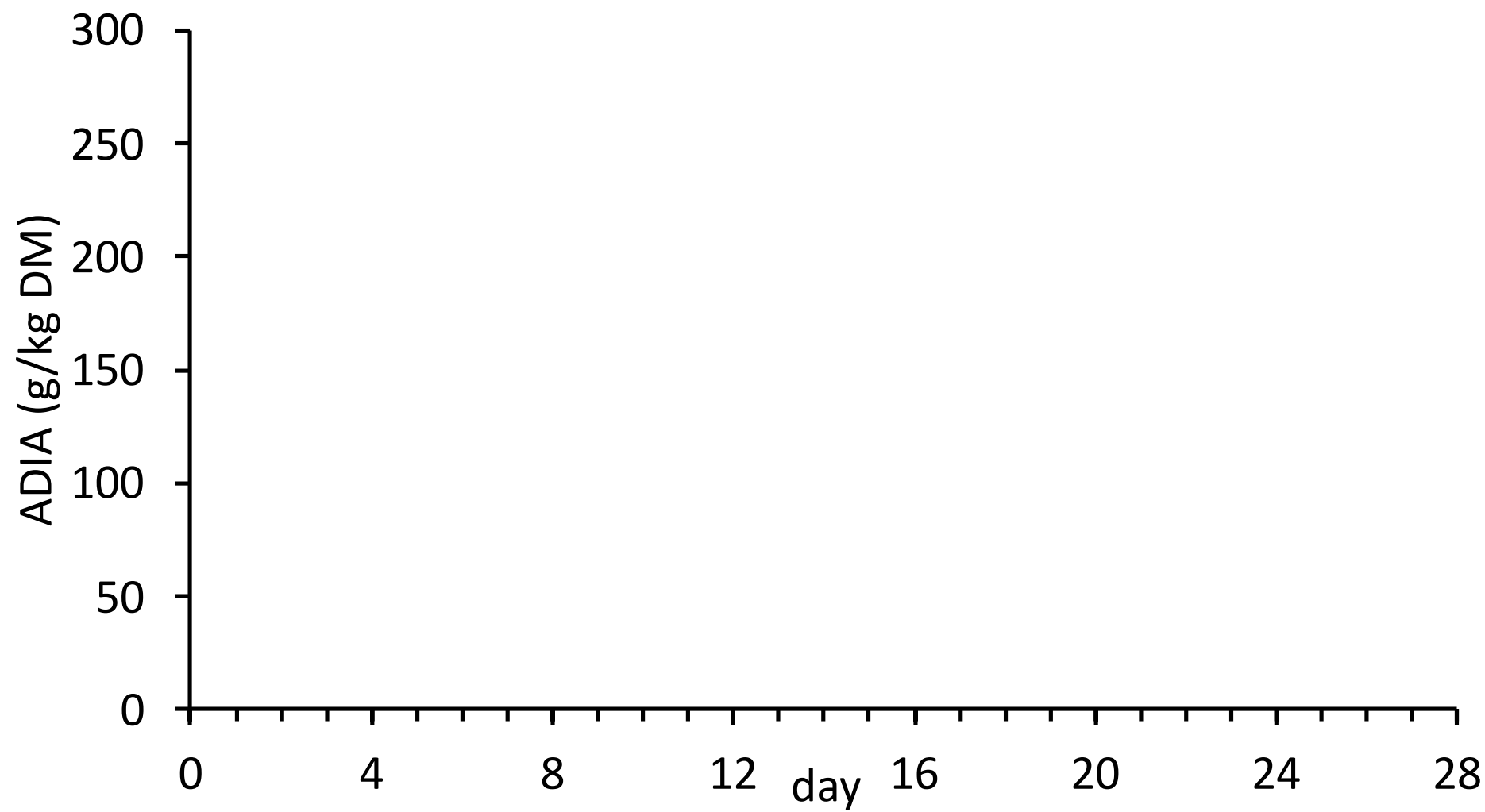


# Ruminants are not super-hypsodont





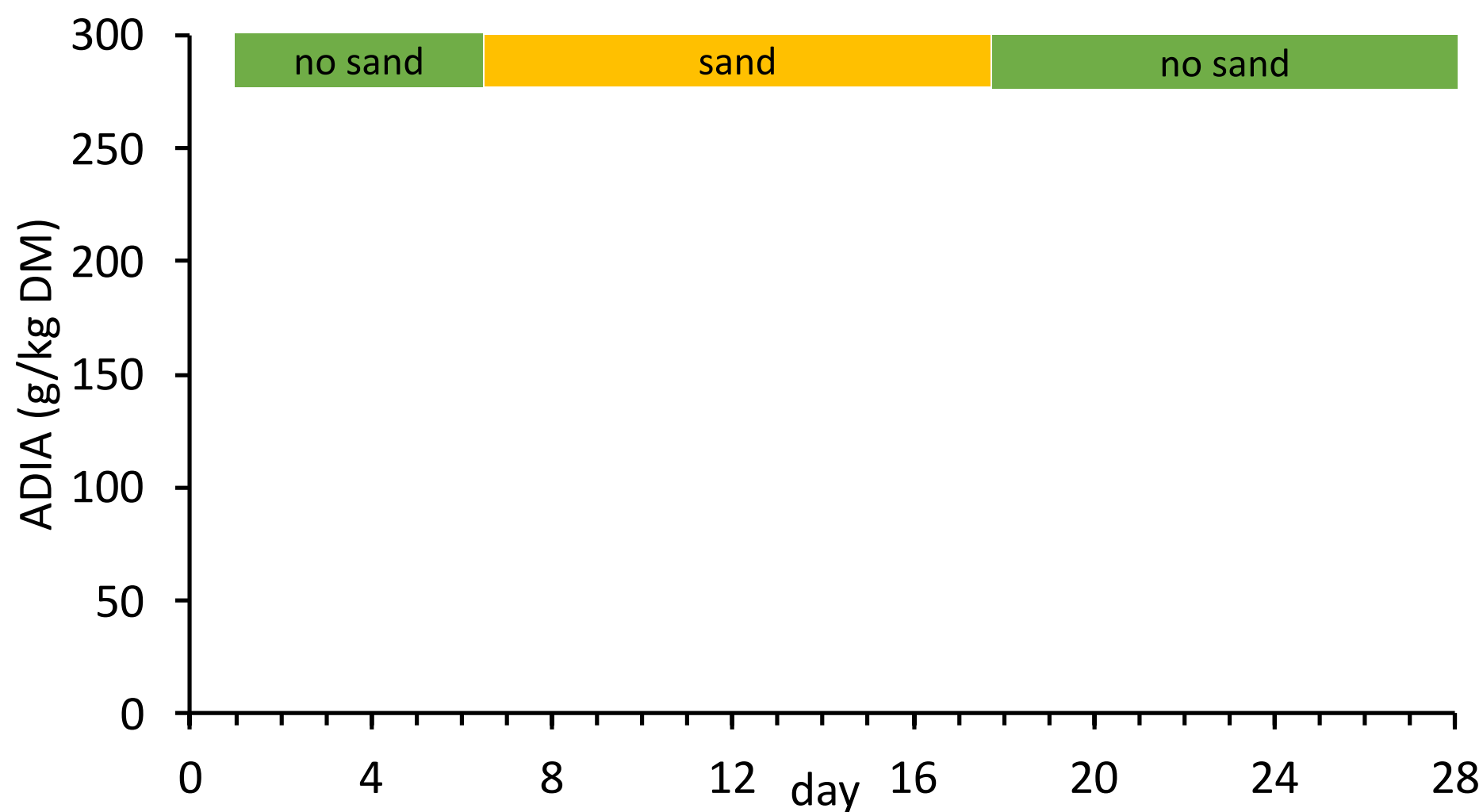
# Sand-feeding experiment



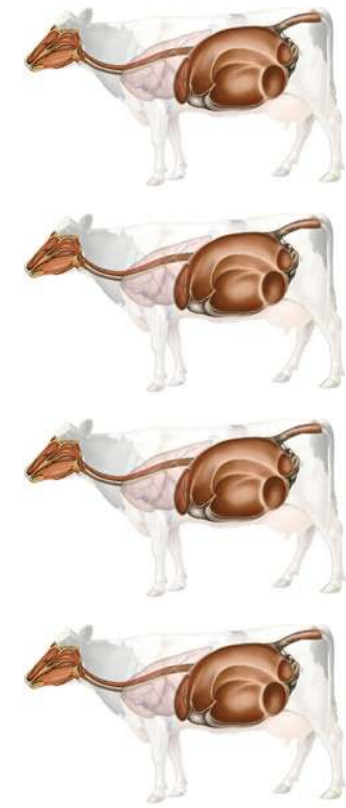
Feed      Leftover      Ing      Rum      Feces



# Sand-feeding experiment



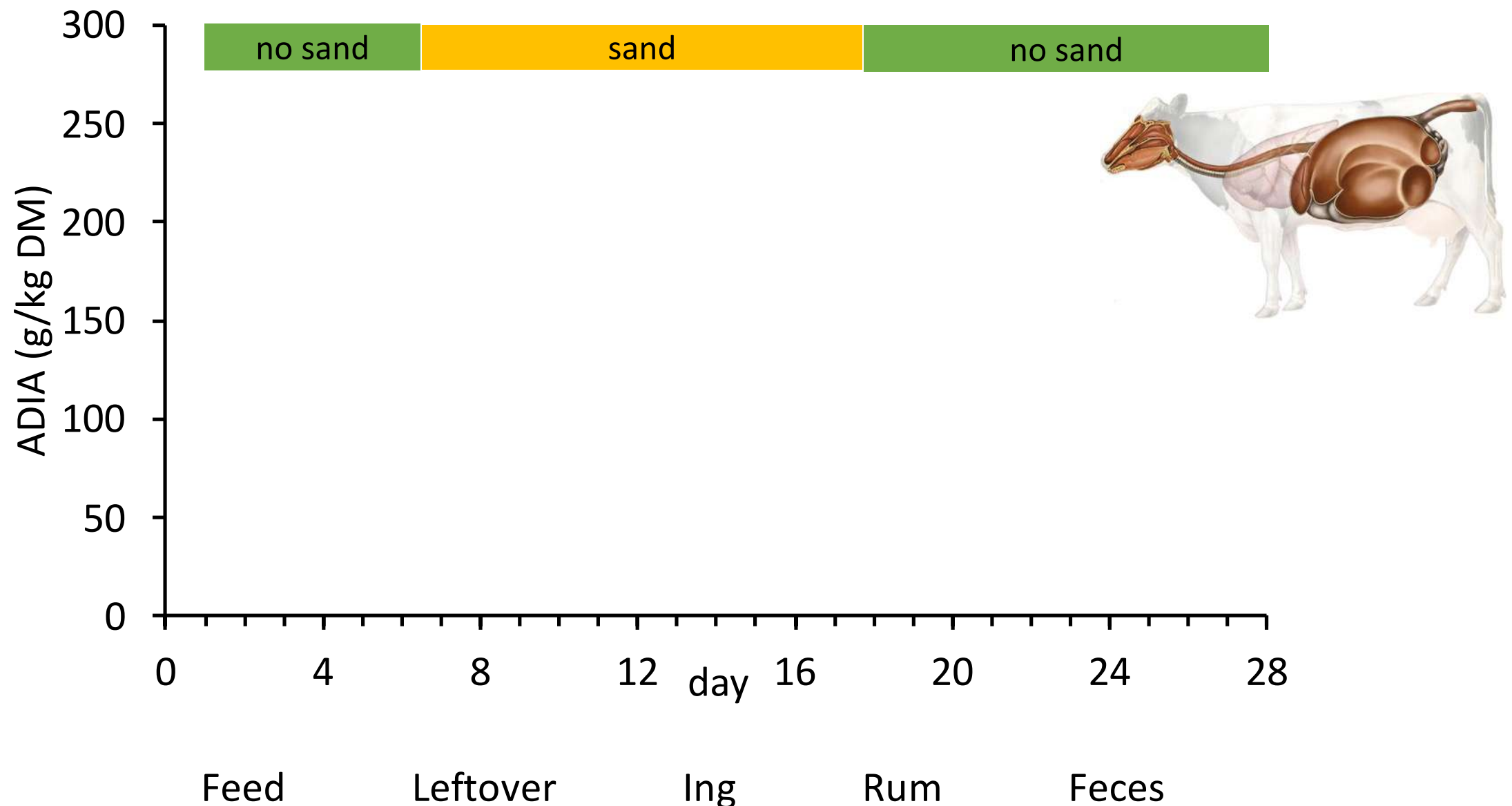
Feed Leftover Ing Rum Feces





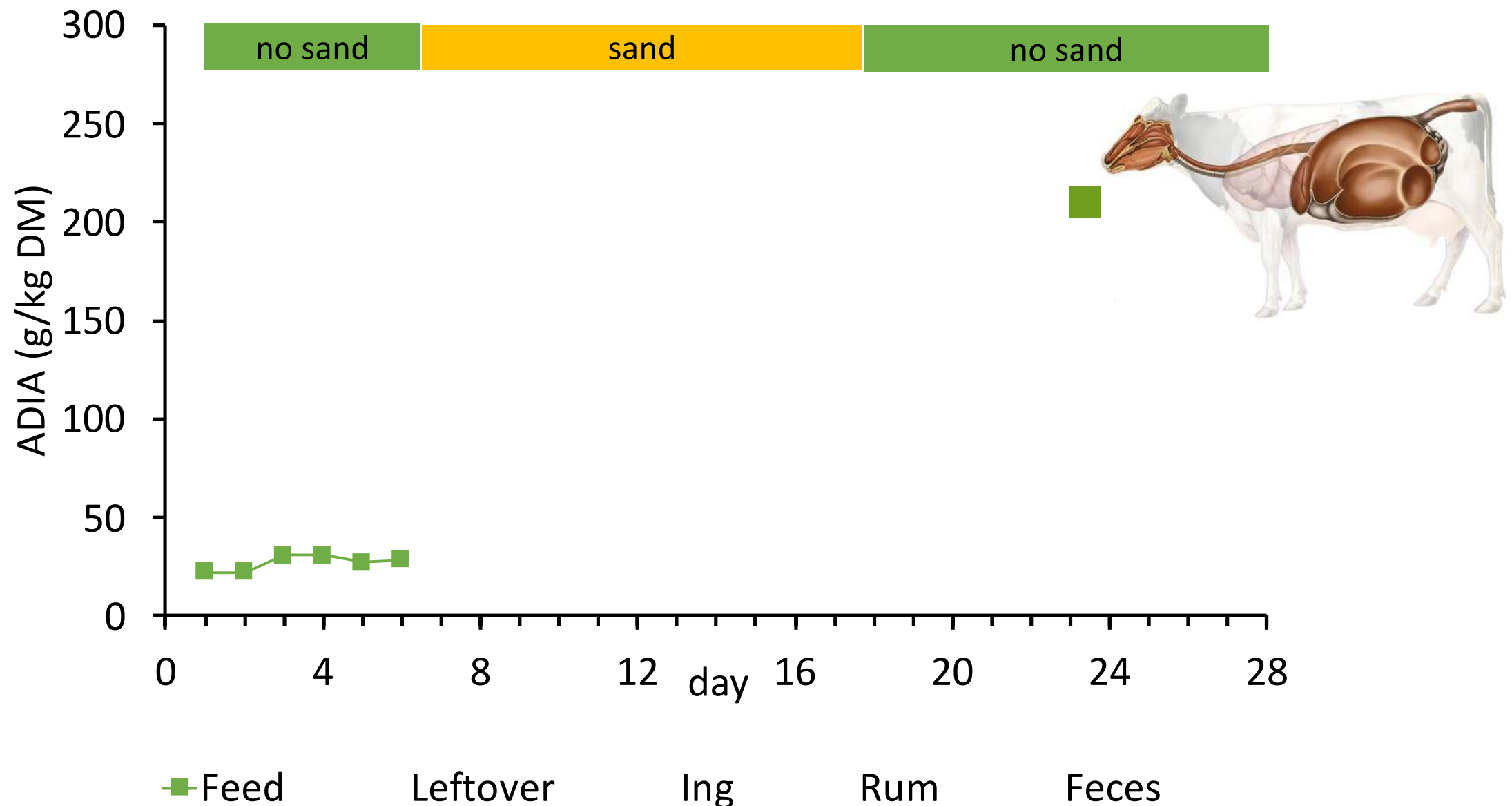


# Sand-feeding experiment



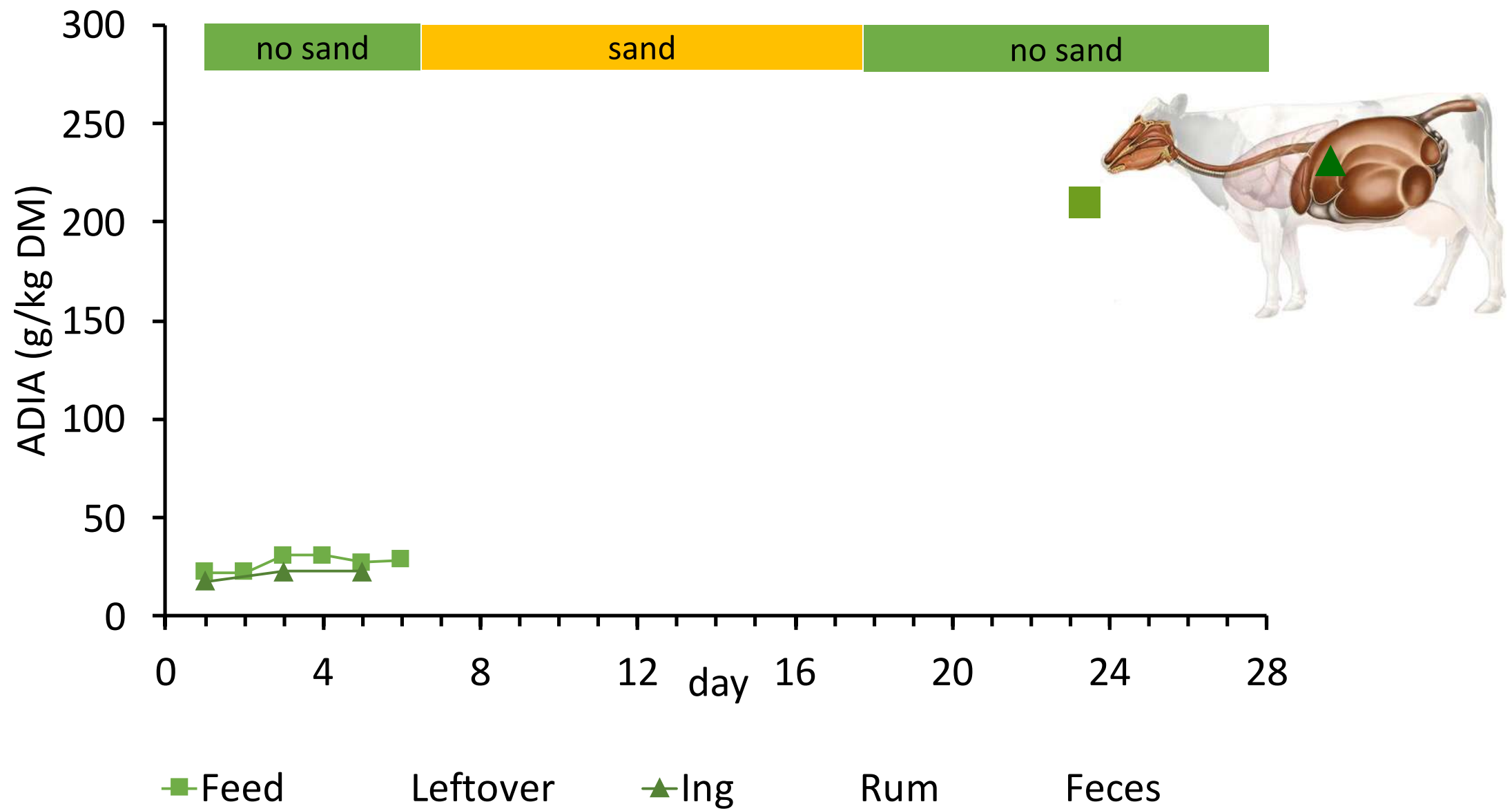


# Sand-feeding experiment



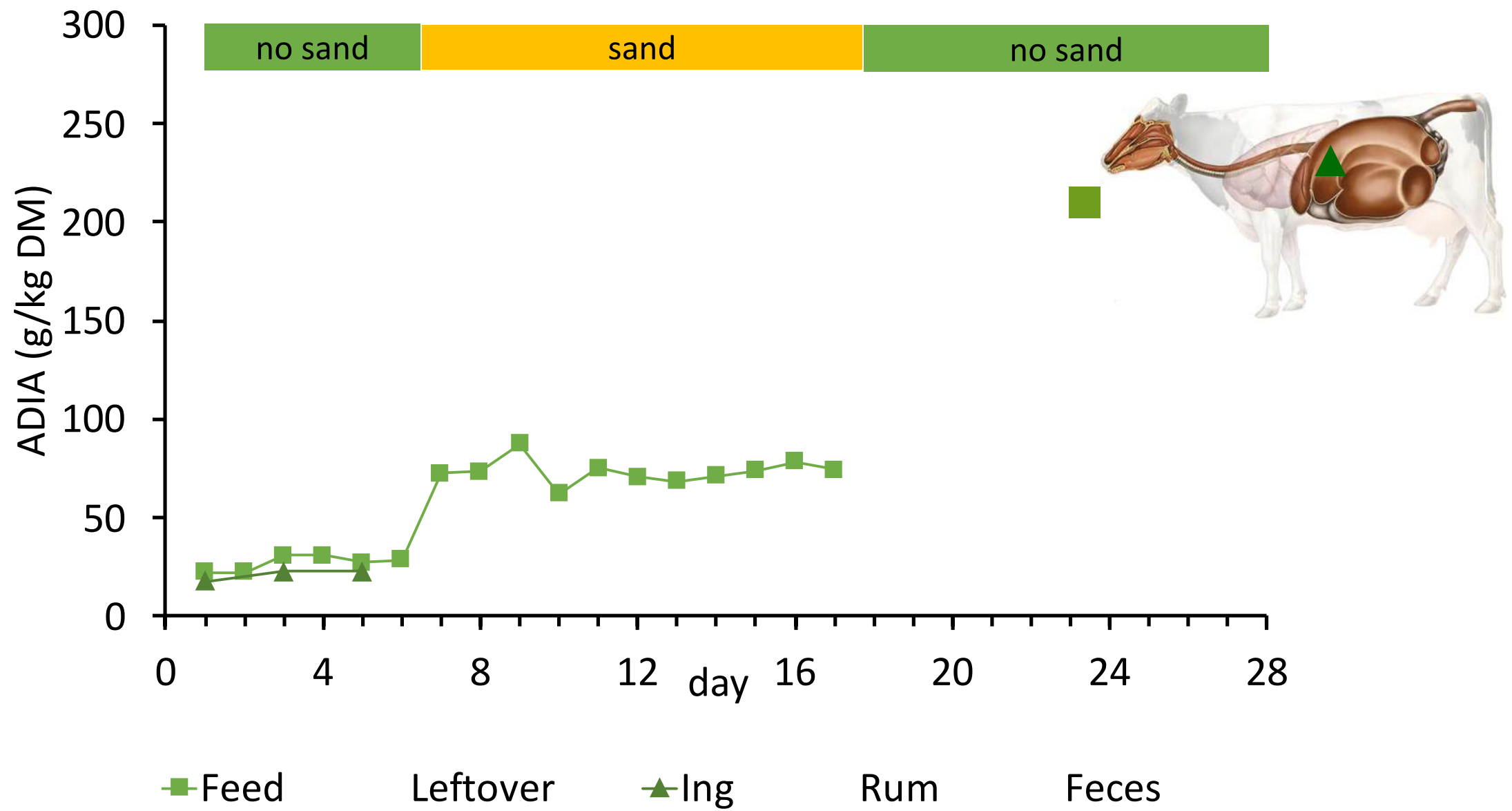


# Sand-feeding experiment





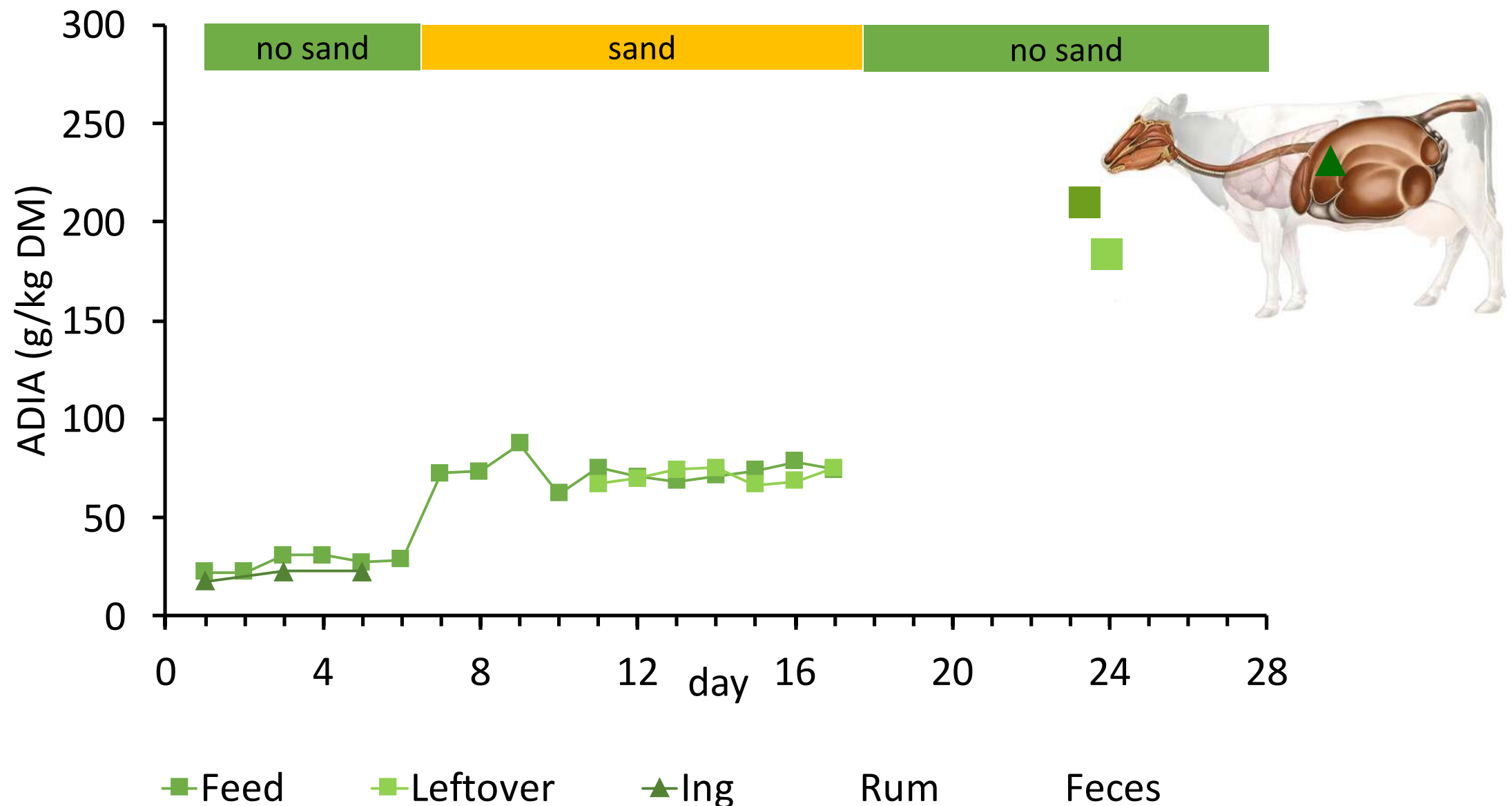
# Sand-feeding experiment





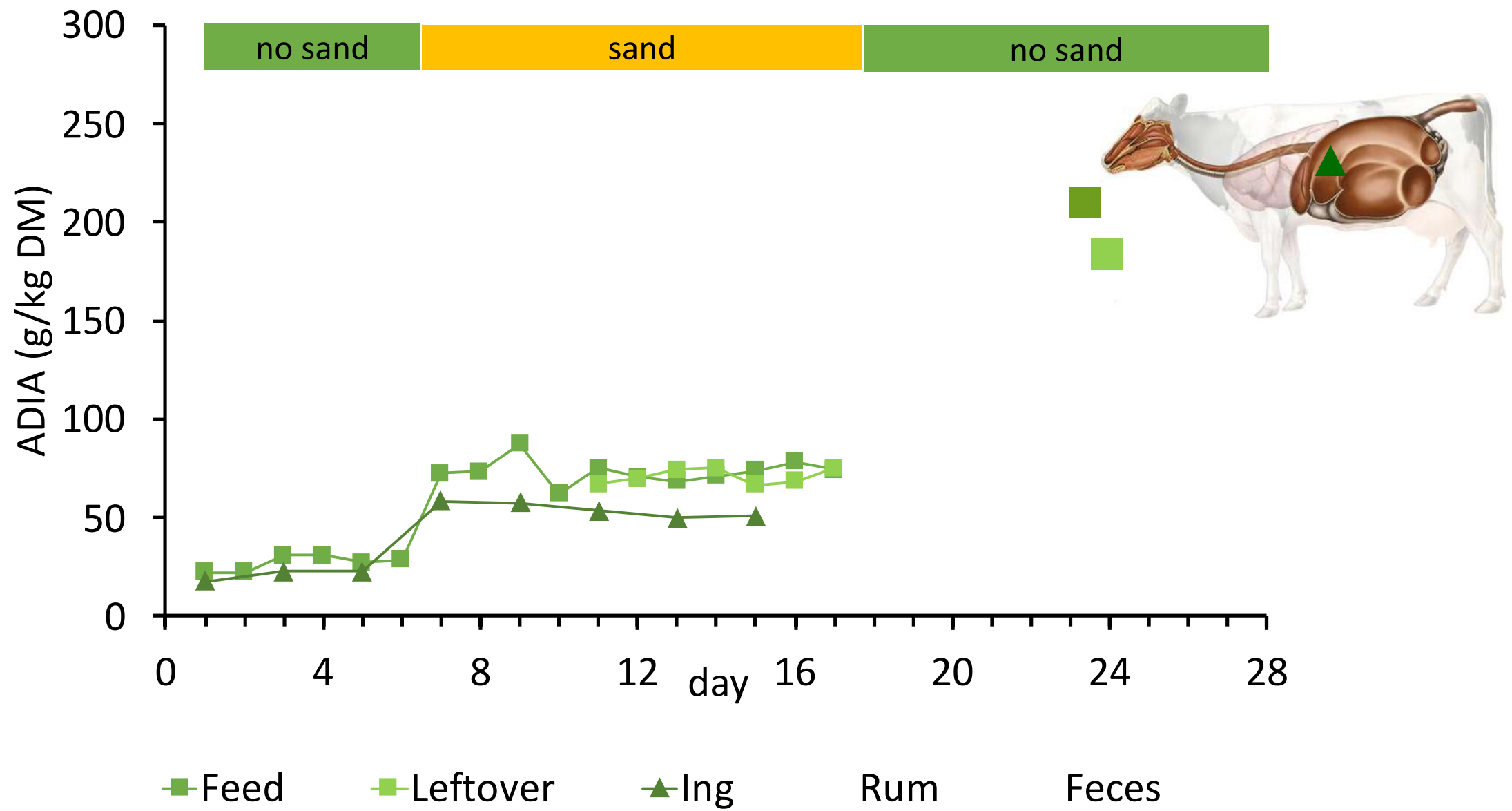


# Sand-feeding experiment



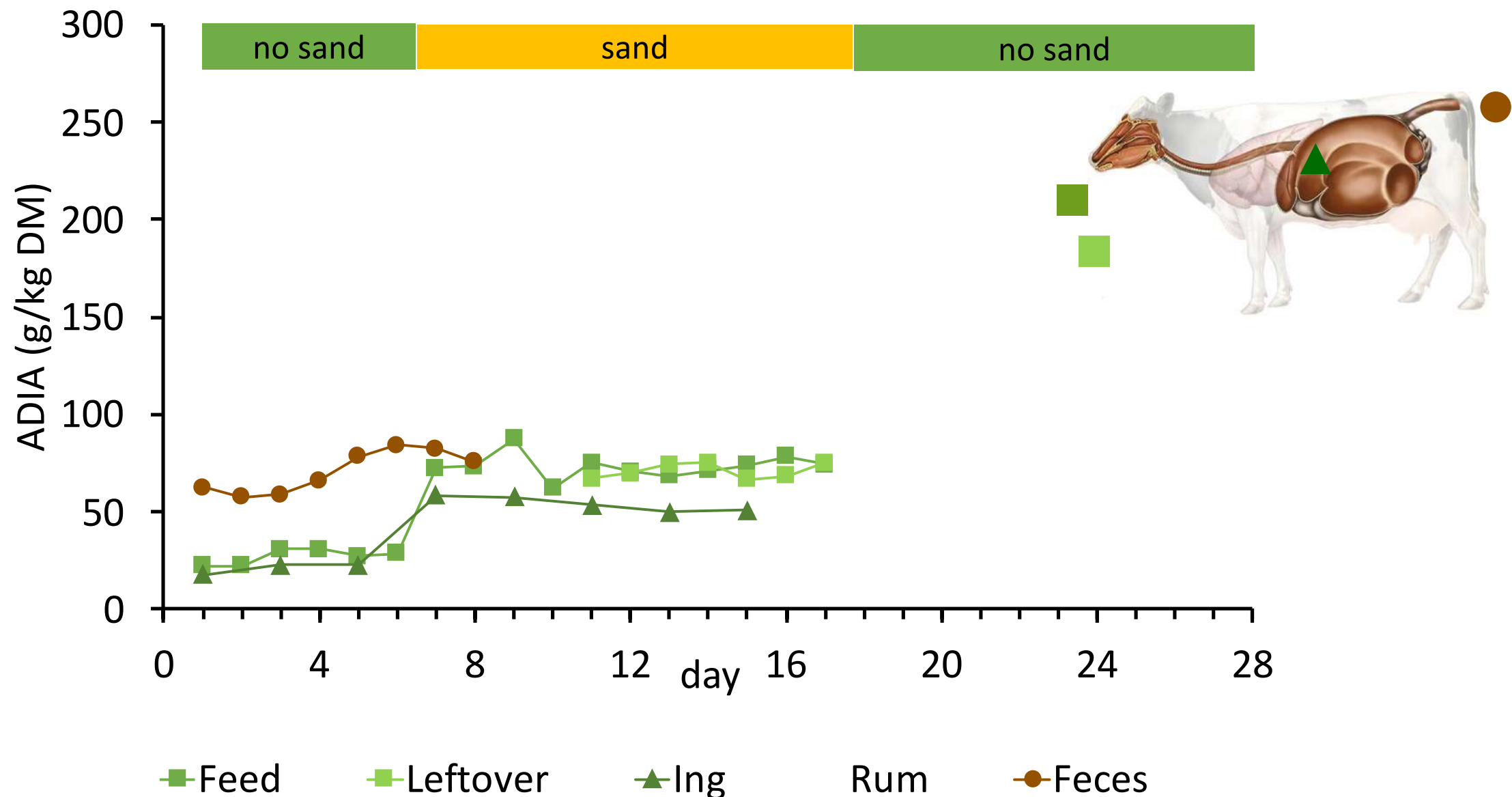


# Sand-feeding experiment



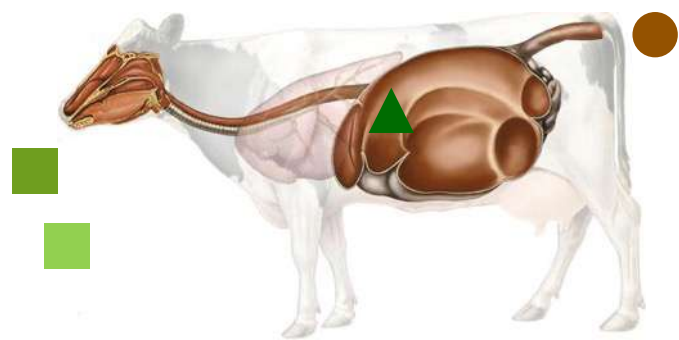
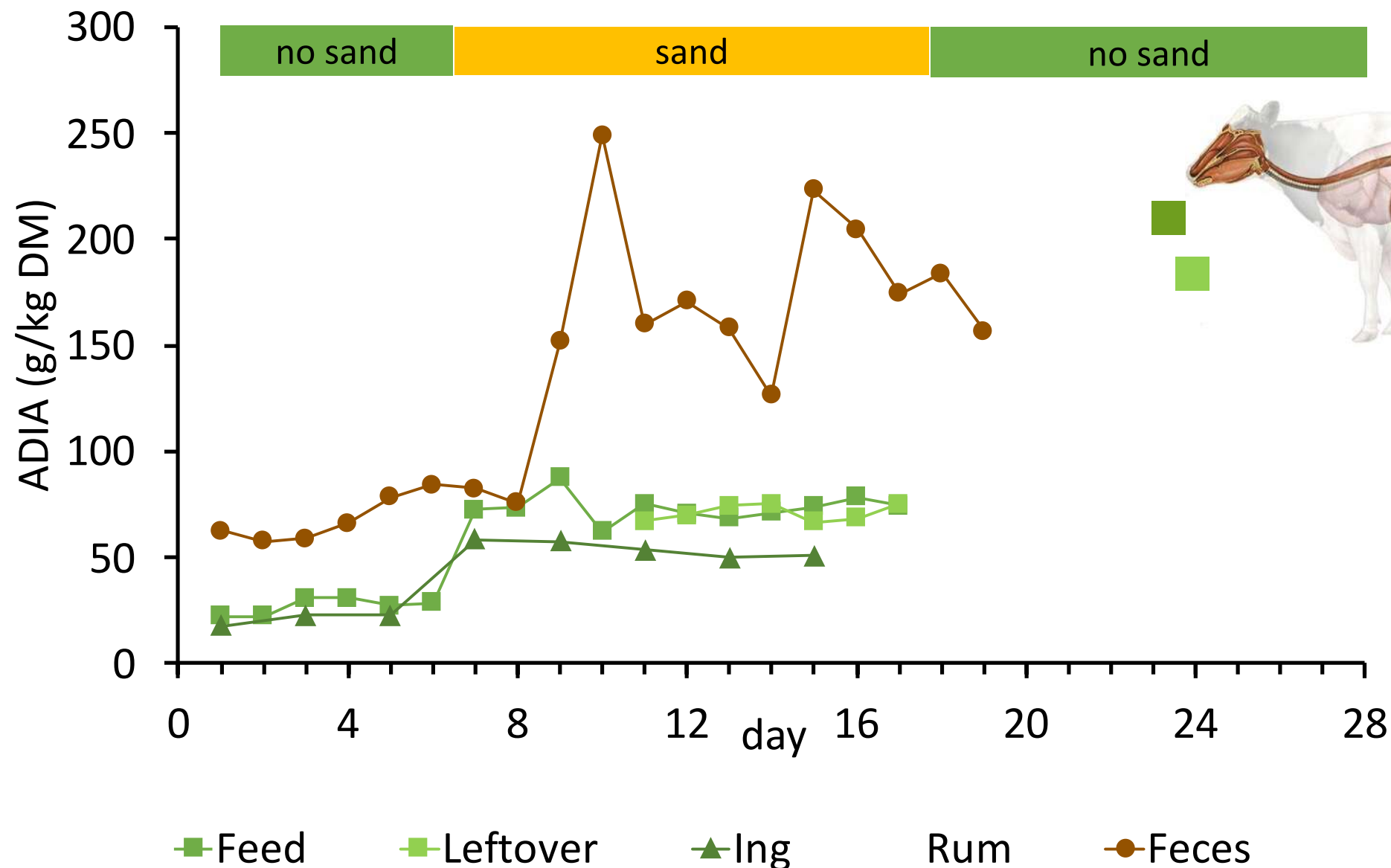


# Sand-feeding experiment





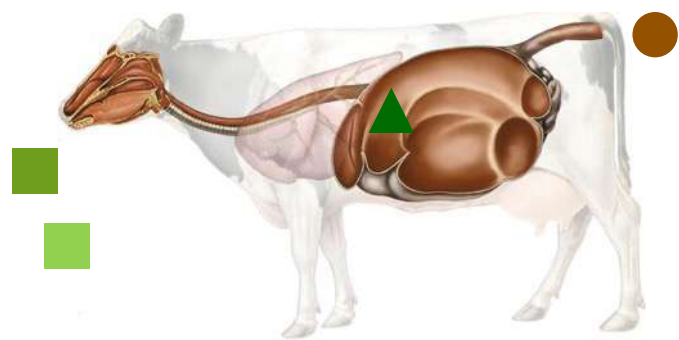
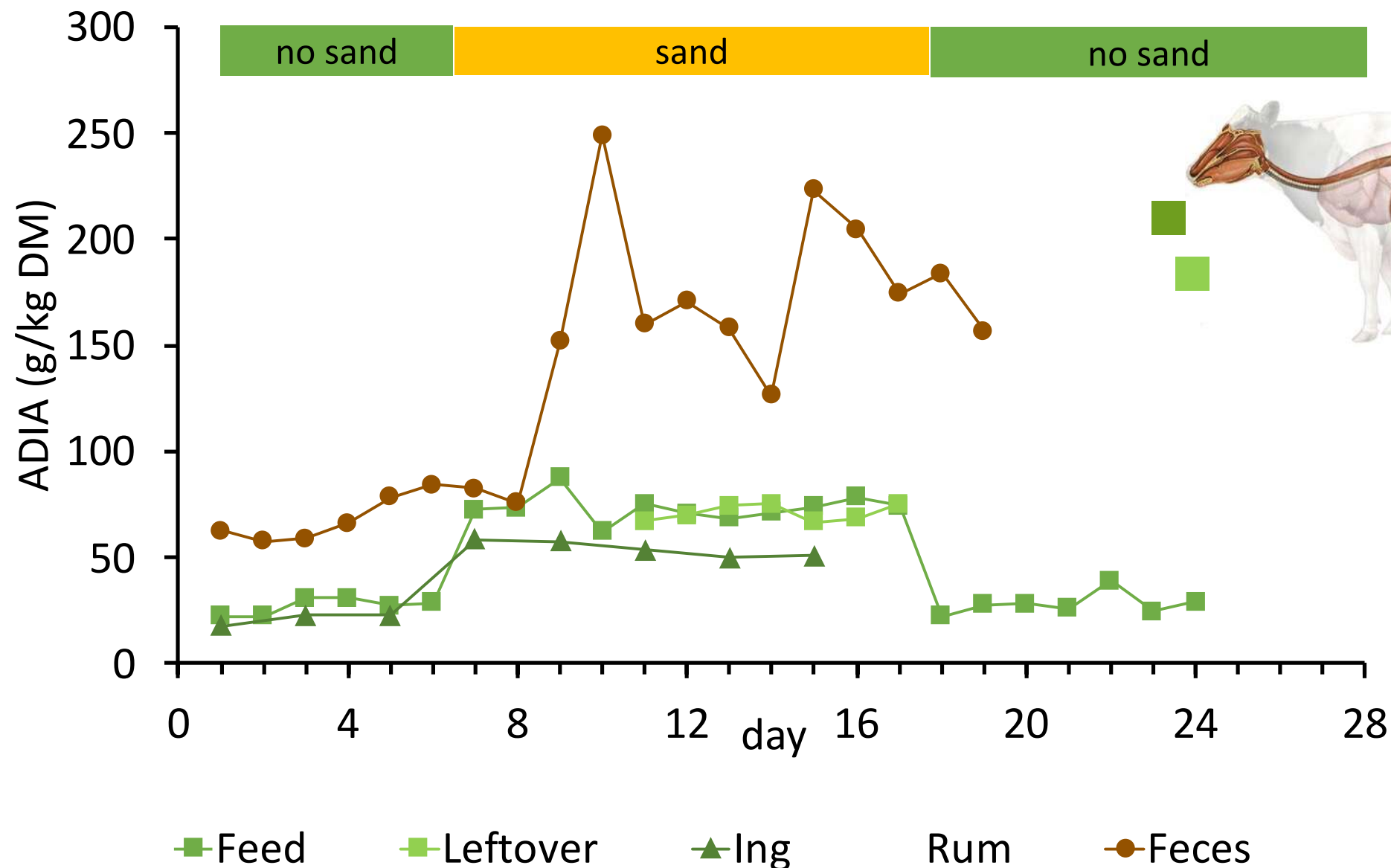
# Sand-feeding experiment





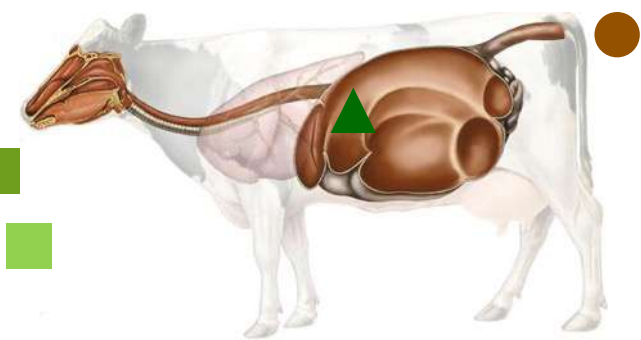
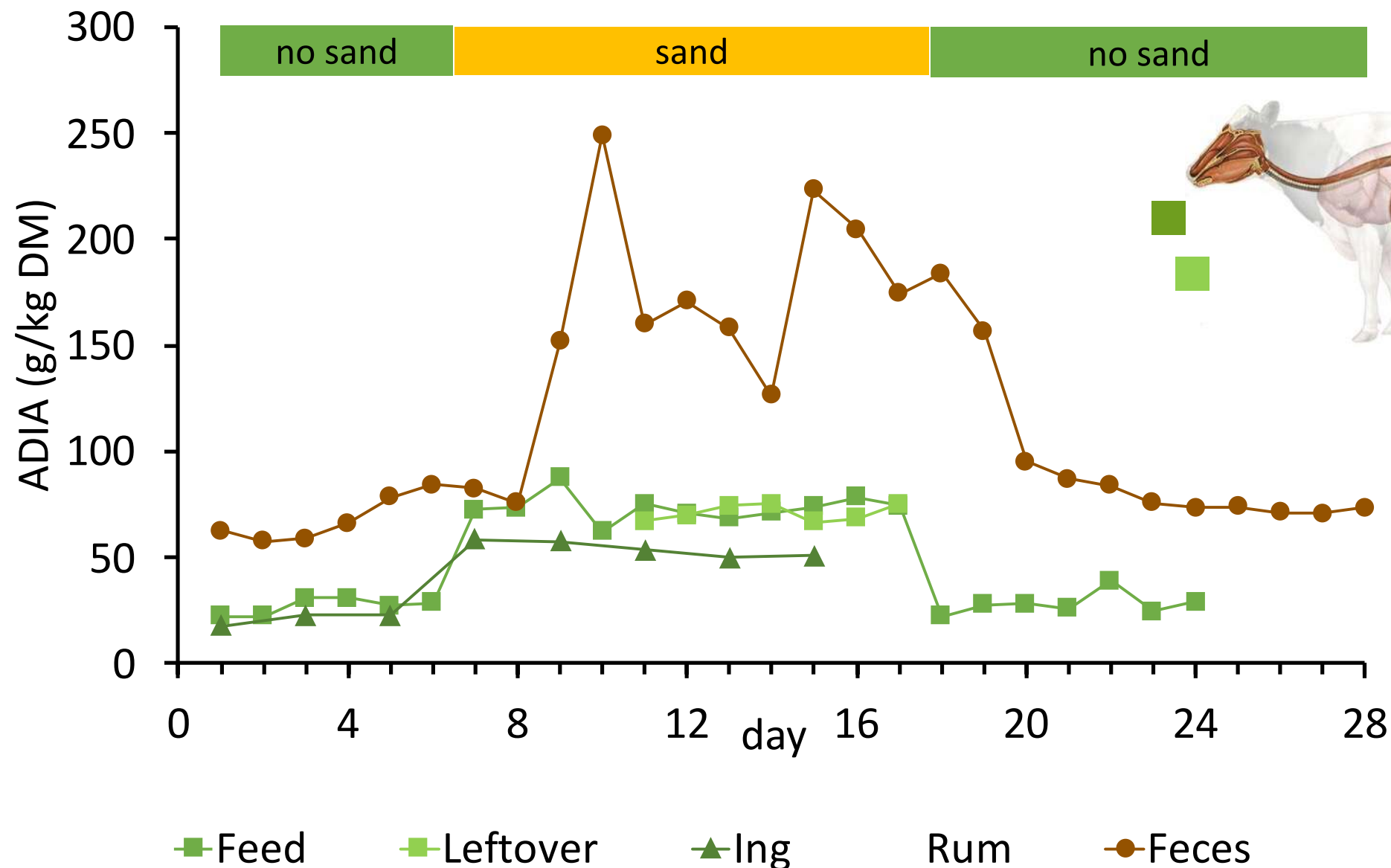


# Sand-feeding experiment



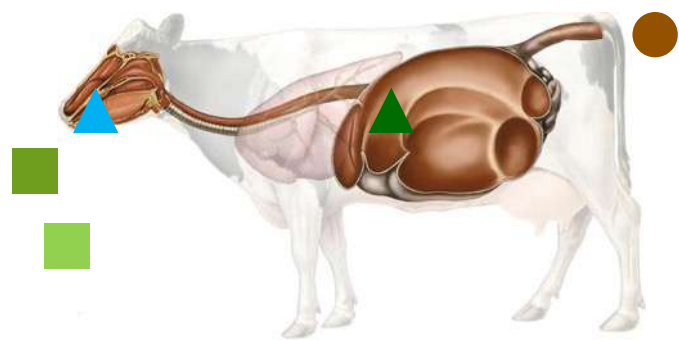
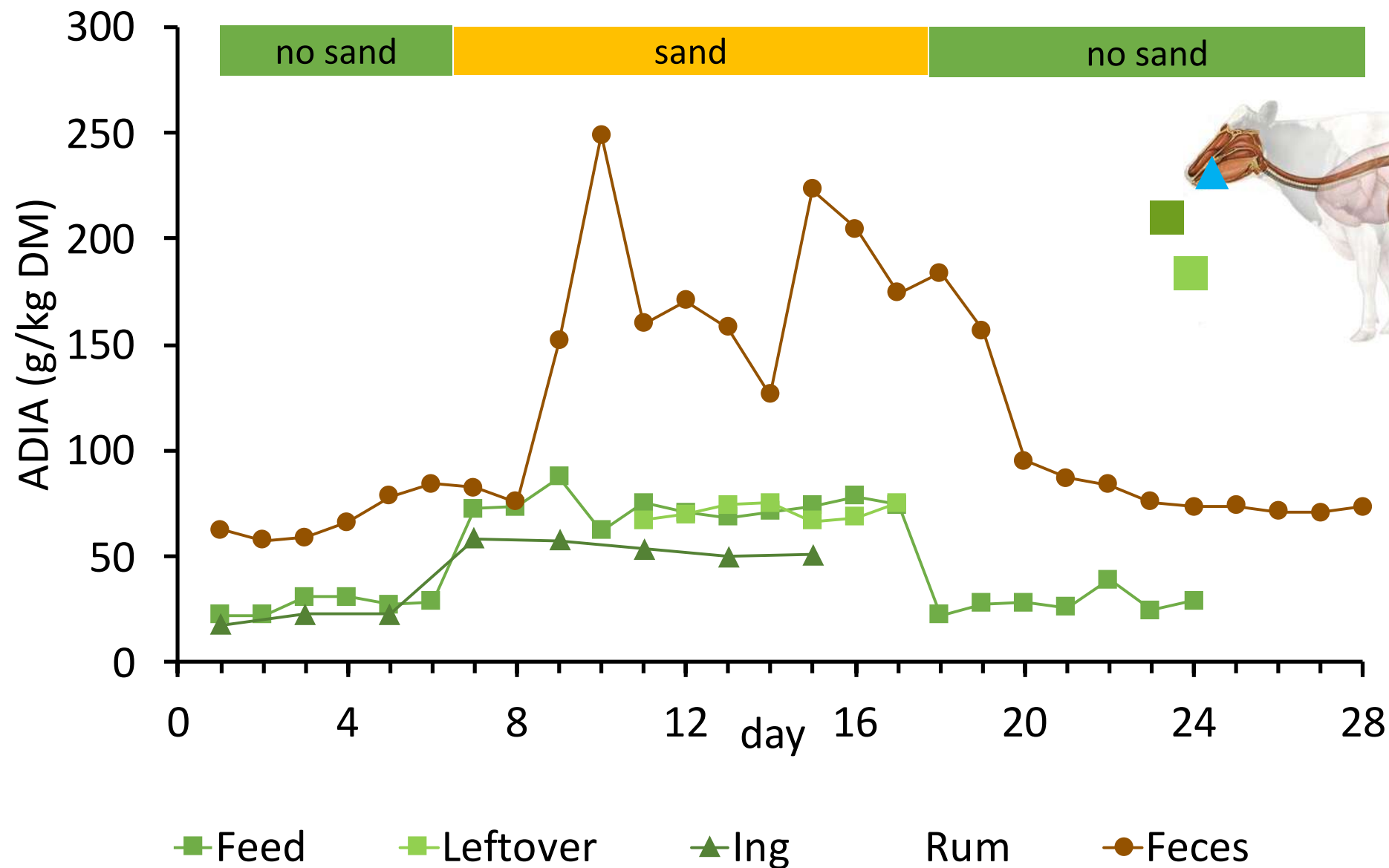


# Sand-feeding experiment



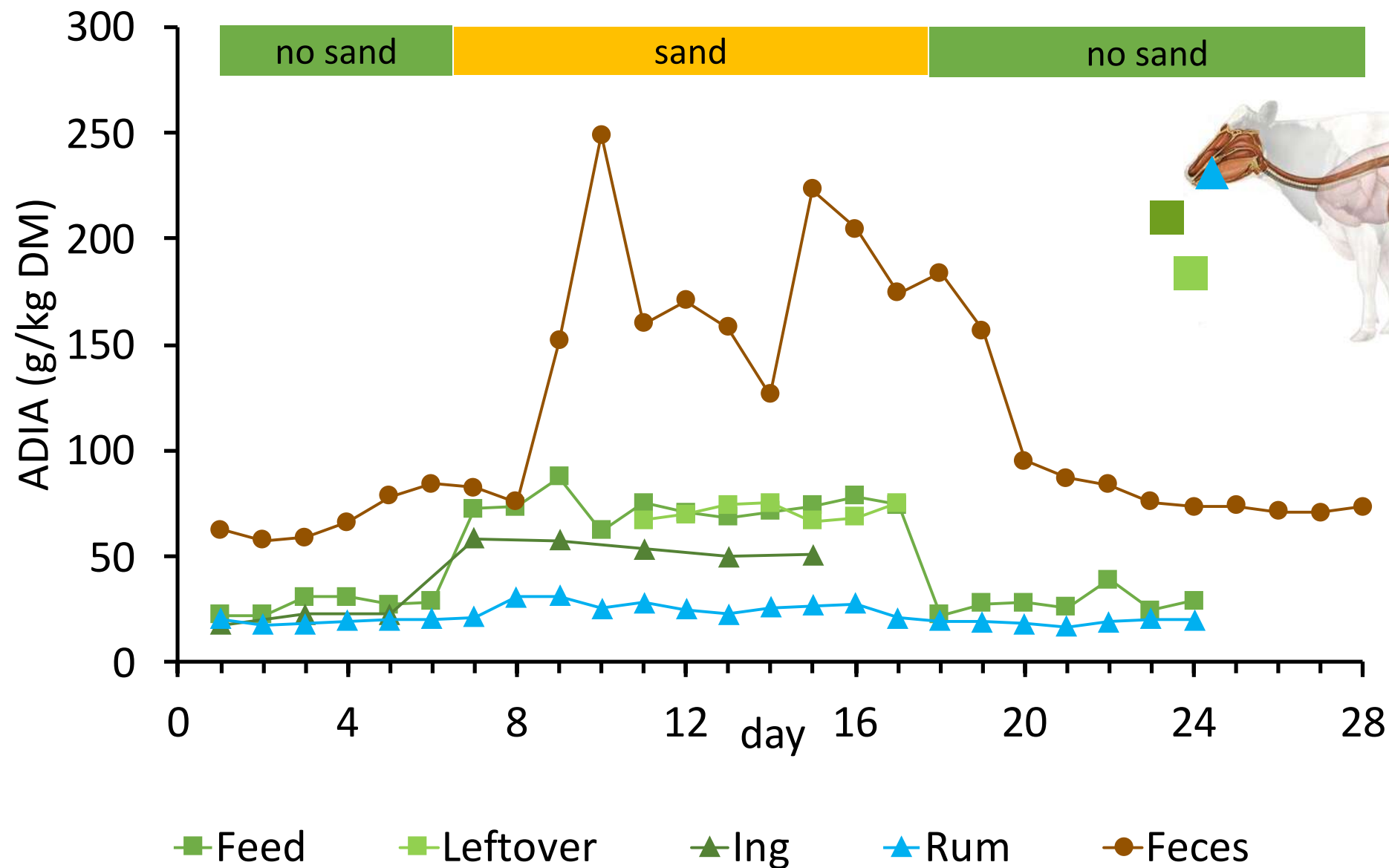


# Sand-feeding experiment





# Sand-feeding experiment







*Teeth evolve for durability ...*



*Teeth evolve for durability ...*

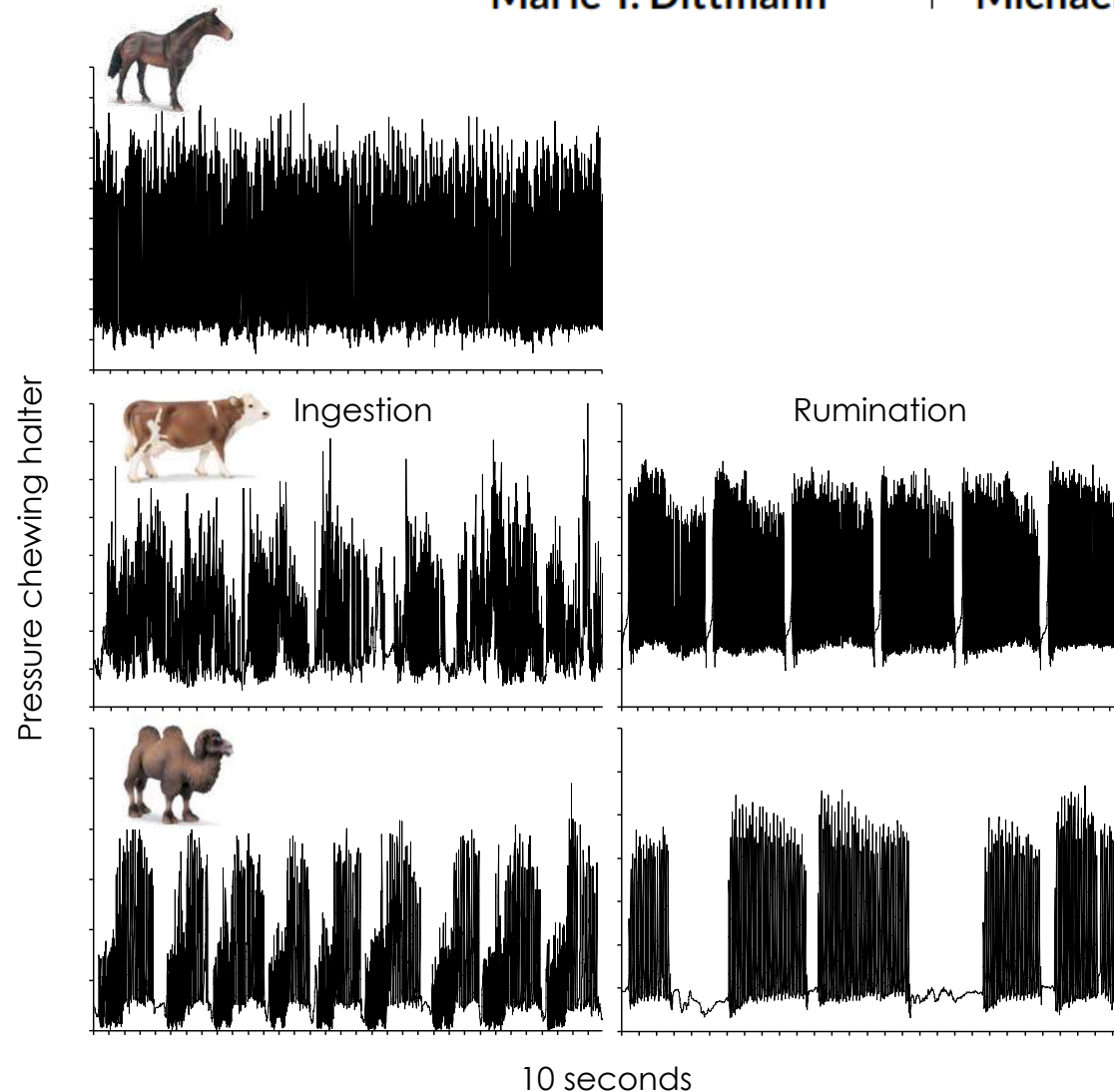
*... but receive particular protection by a  
gut-based washing mechanism.*



# Ingestive mastication in horses resembles rumination but not ingestive mastication in cattle and camels

*J. Exp. Zool.* 2017;327:98–109.

Marie T. Dittmann<sup>1,2,3</sup> | Michael Kreuzer<sup>2</sup> | Ullrich Runge<sup>4</sup> | Marcus Clauss<sup>3</sup>

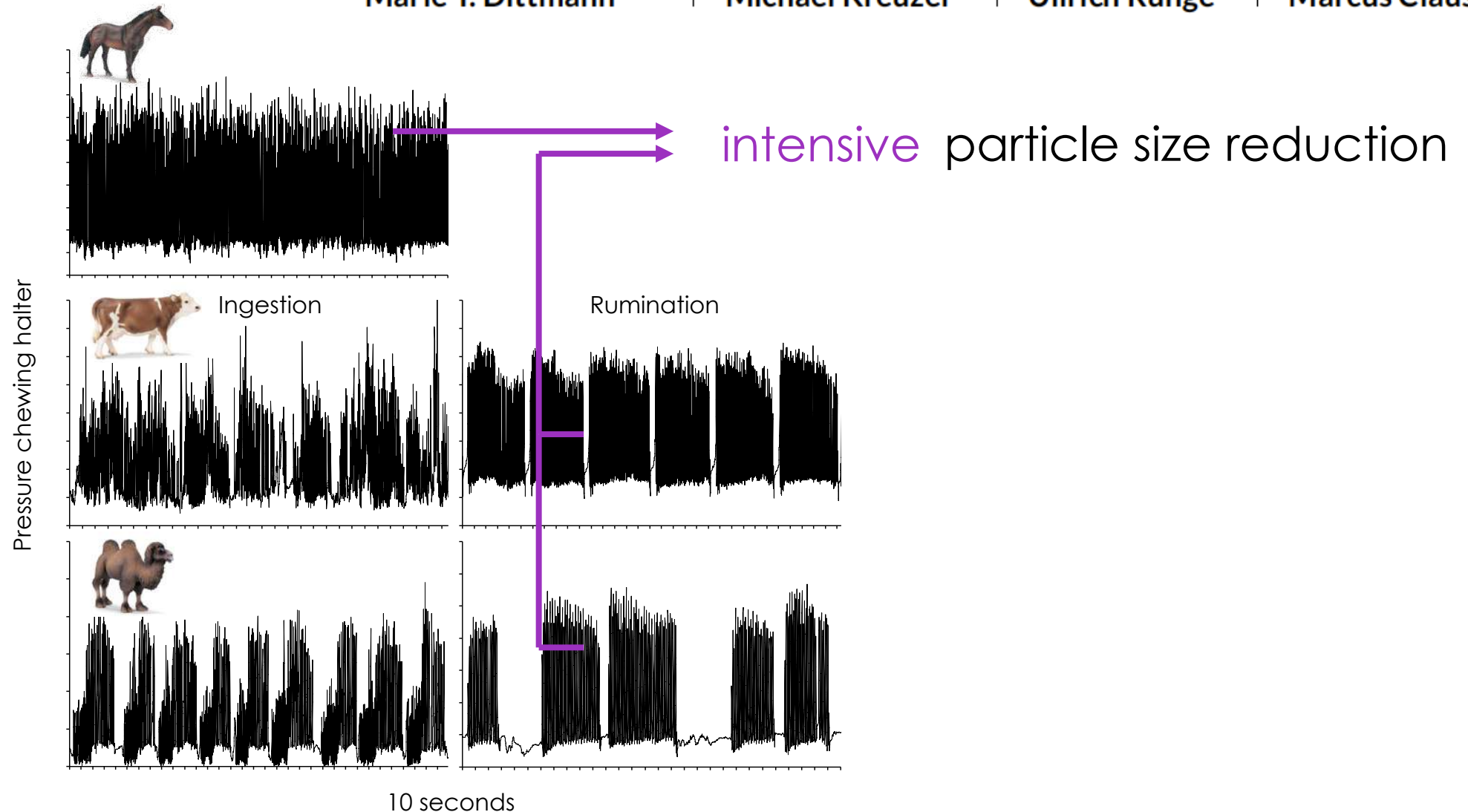




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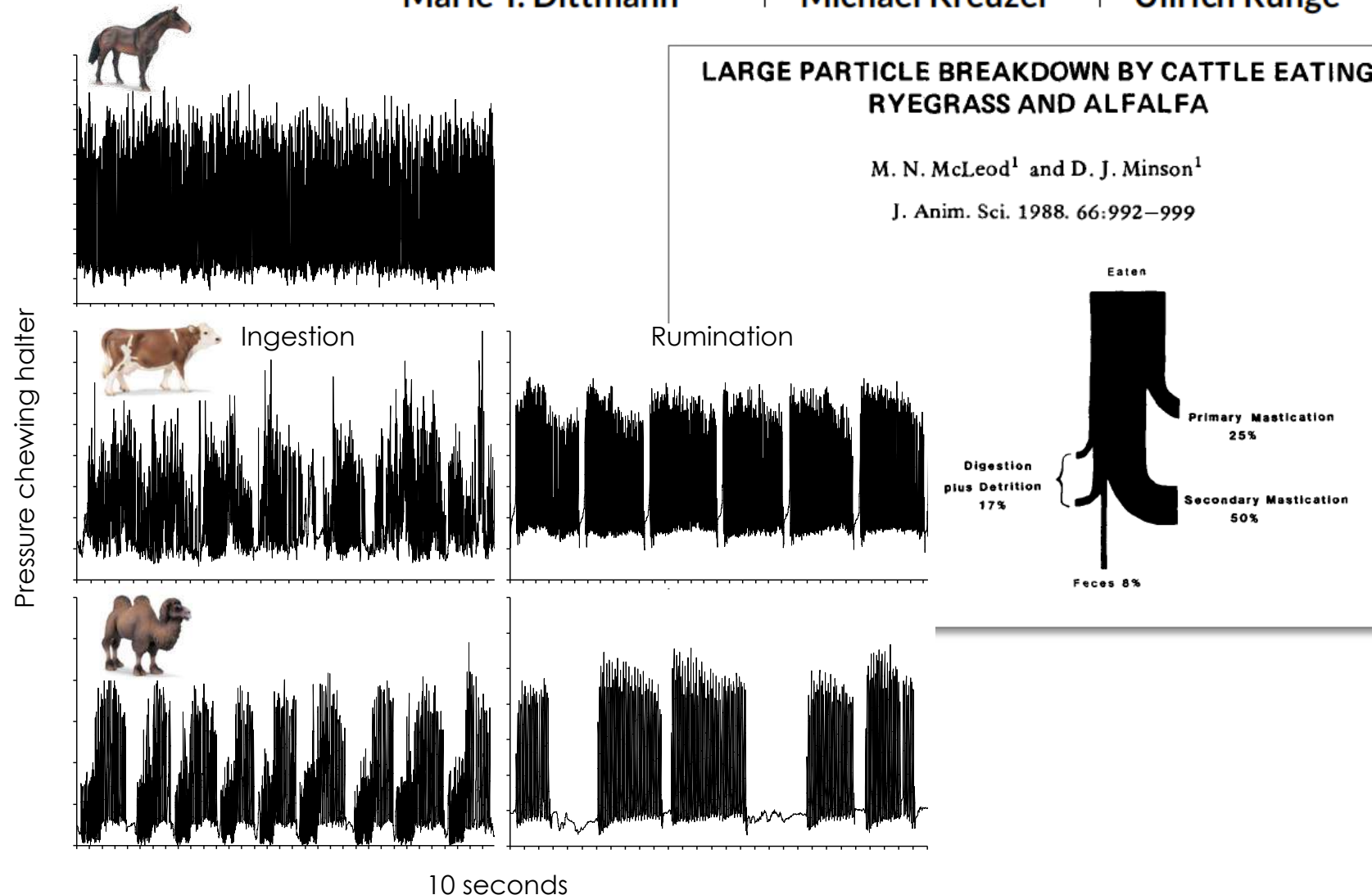




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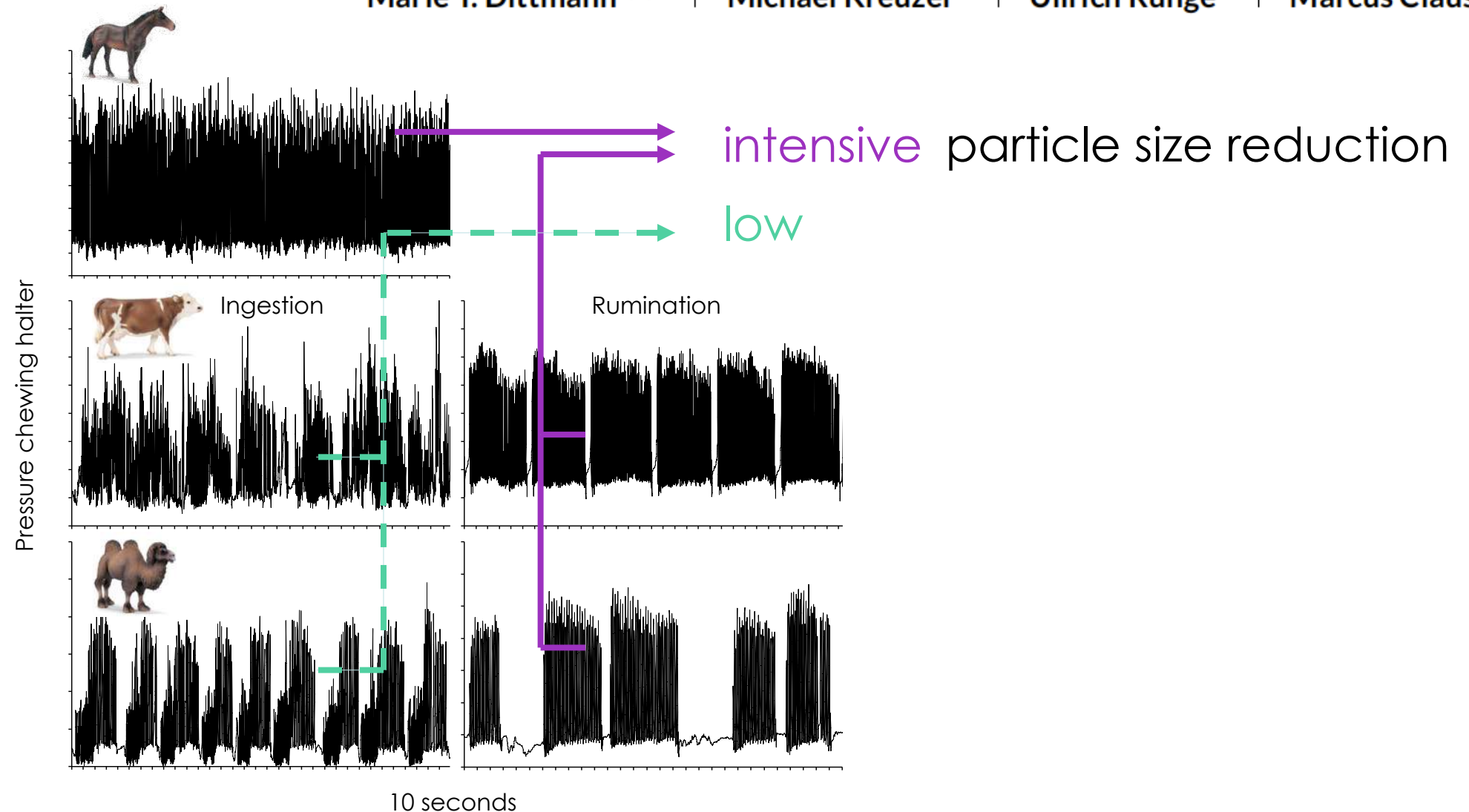




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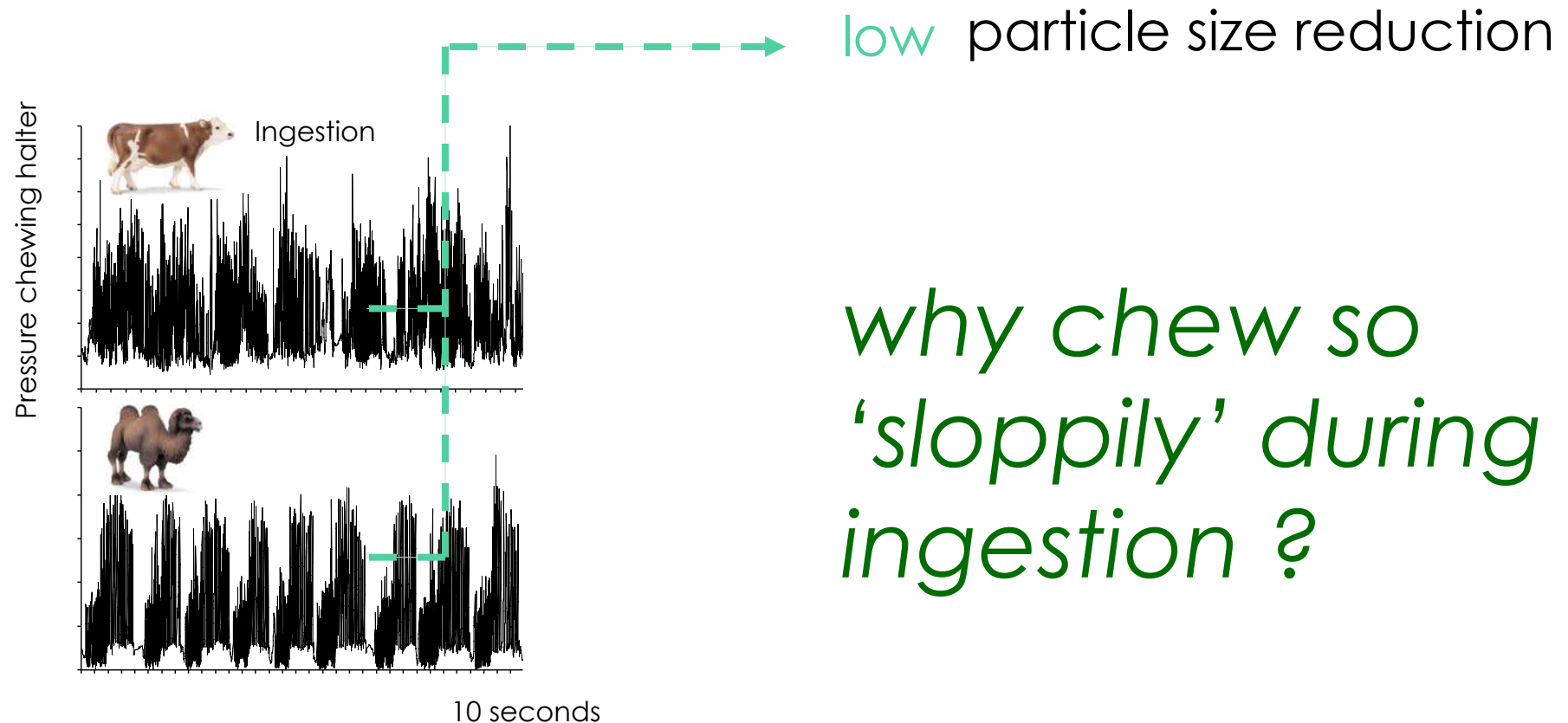




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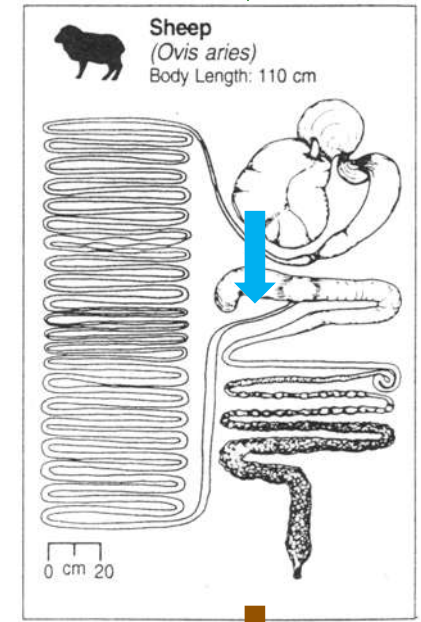
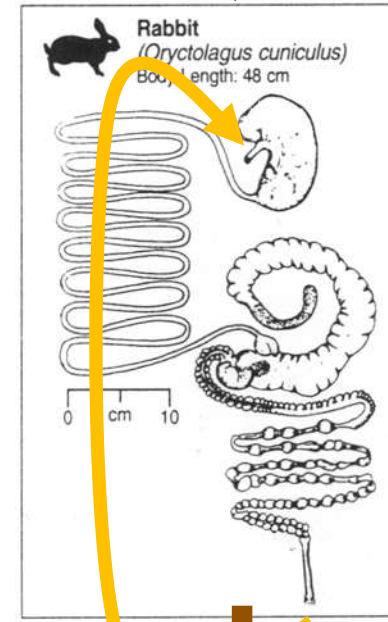
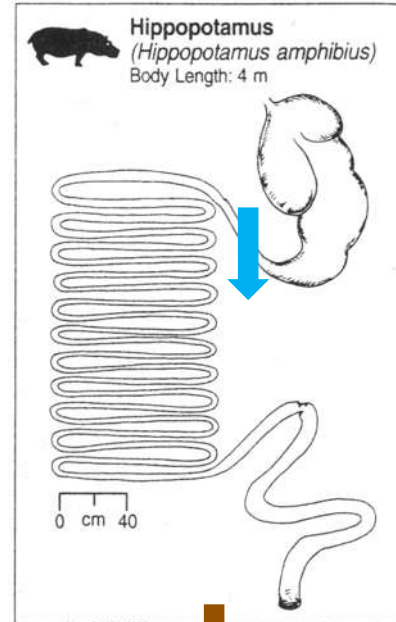
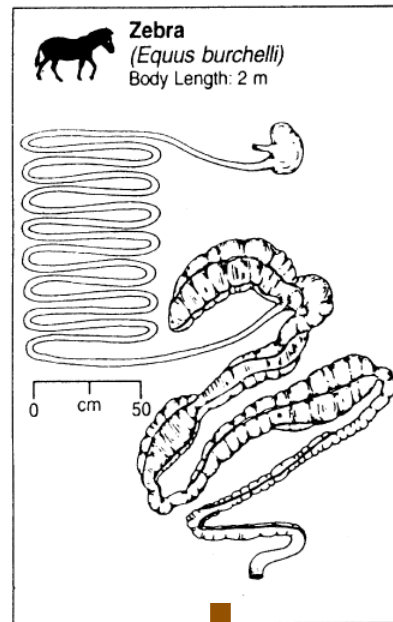
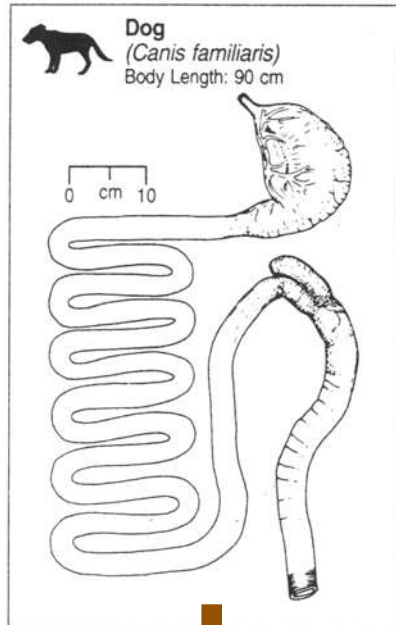
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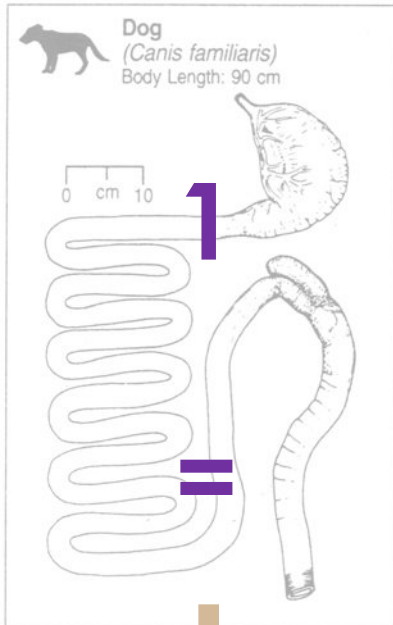
# Teeth and gut do their own thing



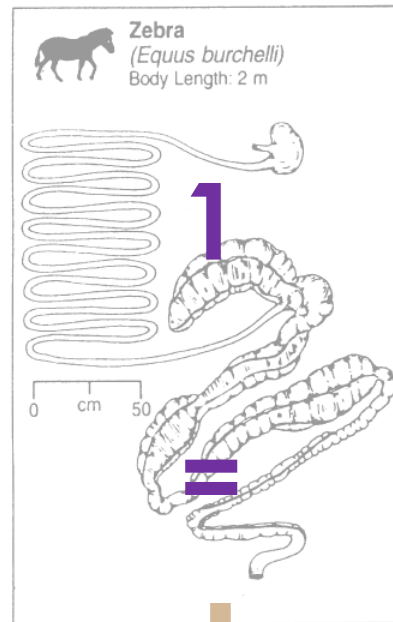




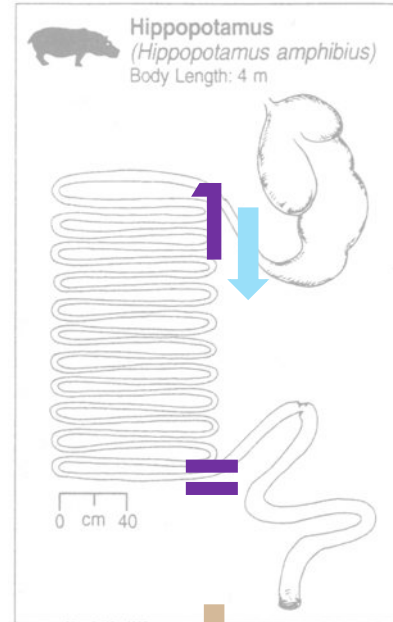
# Teeth and gut do their own thing



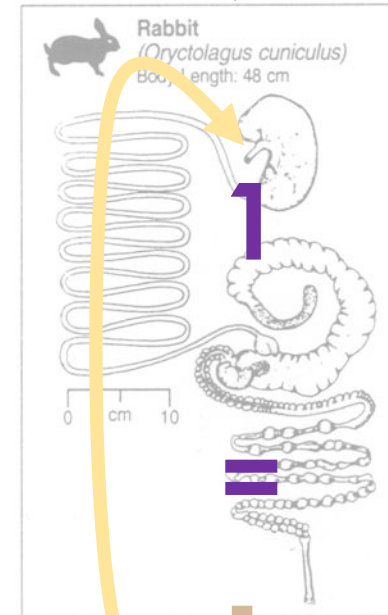
2



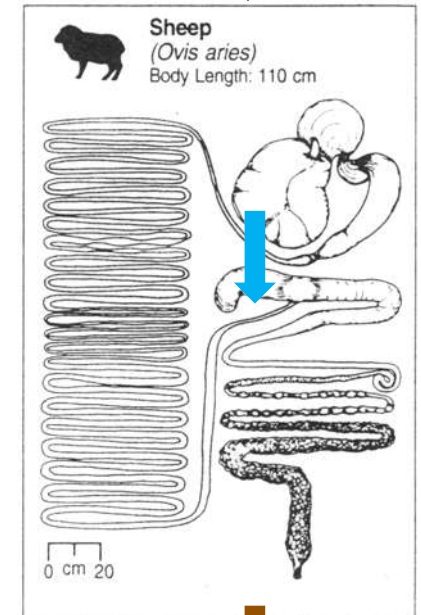
2



2

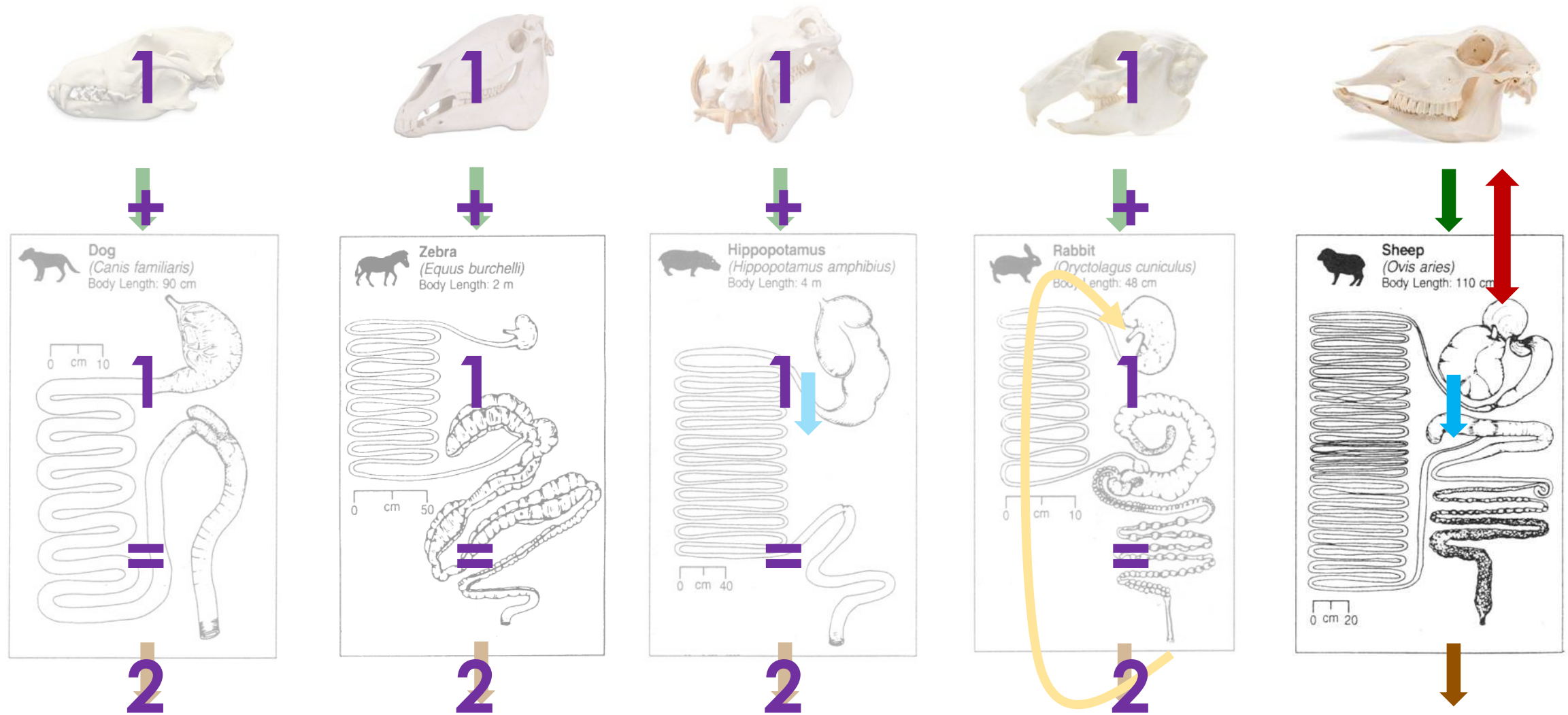


2



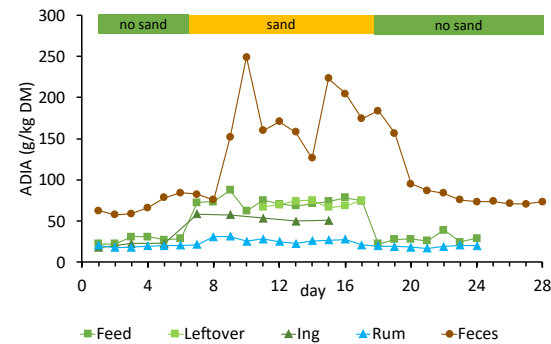
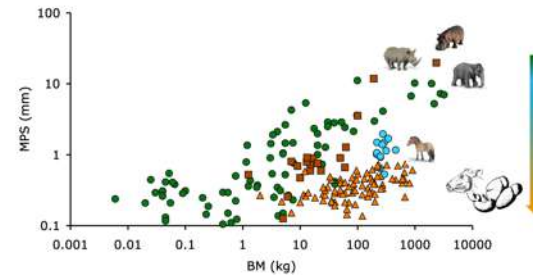


# Teeth and gut do their own thing





# Teeth and gut work together



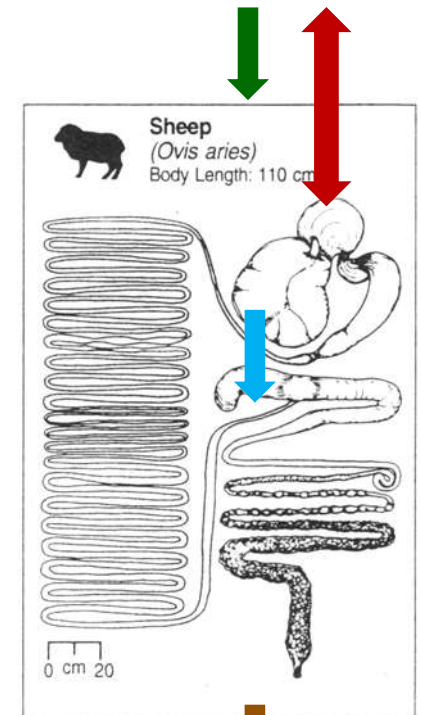
1

+

1

=

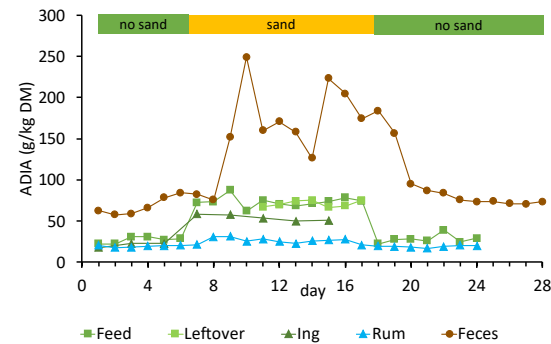
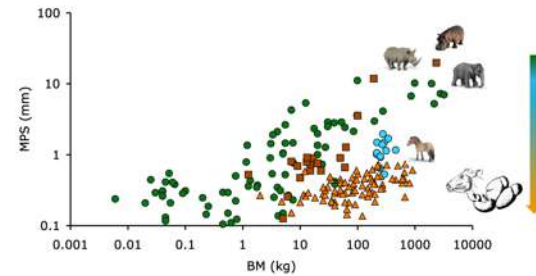
3







# Teeth and gut work together



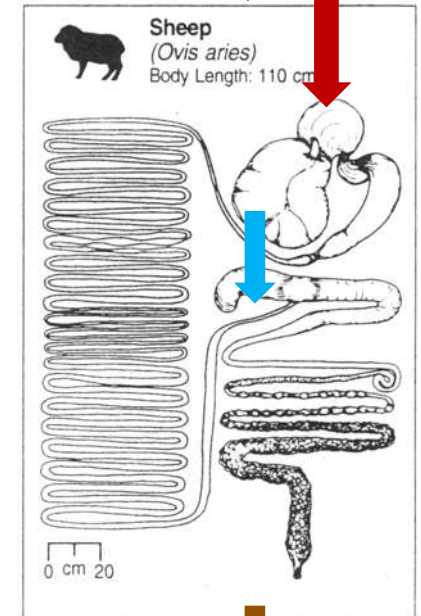
1

+

1

=

3





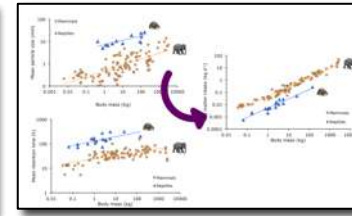
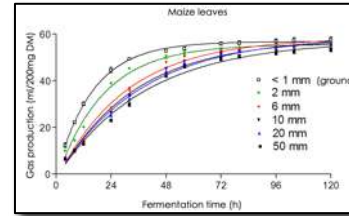


# Summary



# Summary

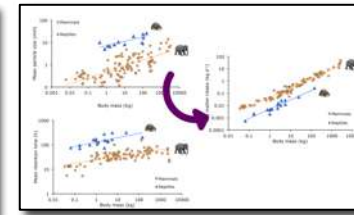
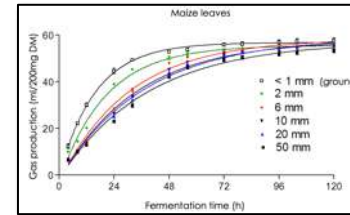
Particle size reduction is a prerequisite for fast digestion, high intake, and endothermy



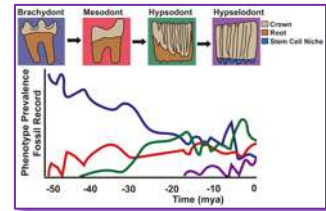


# Summary

Particle size reduction is a prerequisite for fast digestion, high intake, and endothermy



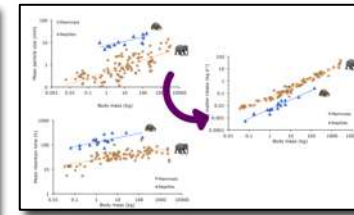
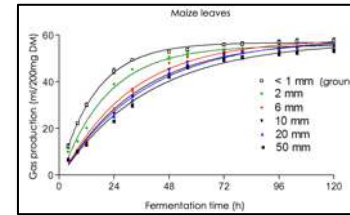
Teeth evolved for increasing efficiency and durability



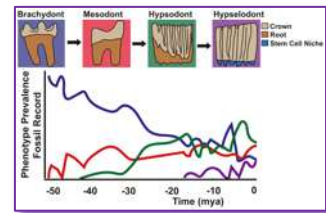


# Summary

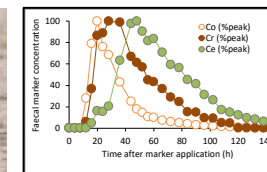
Particle size reduction is a prerequisite for fast digestion, high intake, and endothermy



Teeth evolved for increasing **efficiency** and **durability**



Digestive tract evolution: various adaptations to microbe farming

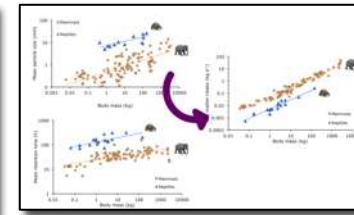
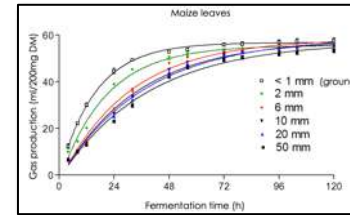




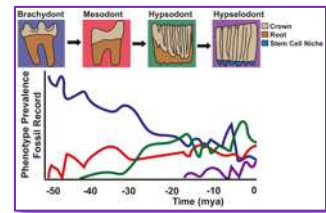


# Summary

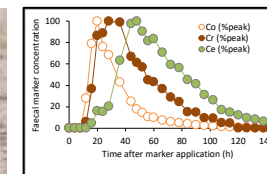
Particle size reduction is a prerequisite for fast digestion, high intake, and endothermy



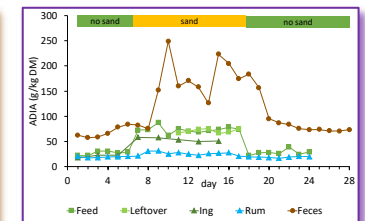
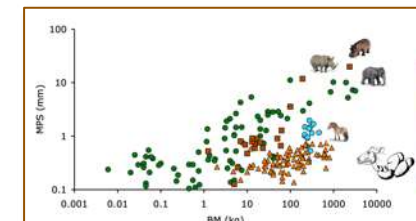
Teeth evolved for increasing efficiency and durability



Digestive tract evolution: various adaptations to microbe farming



Rumination: the ultimate tooth-gut interplay





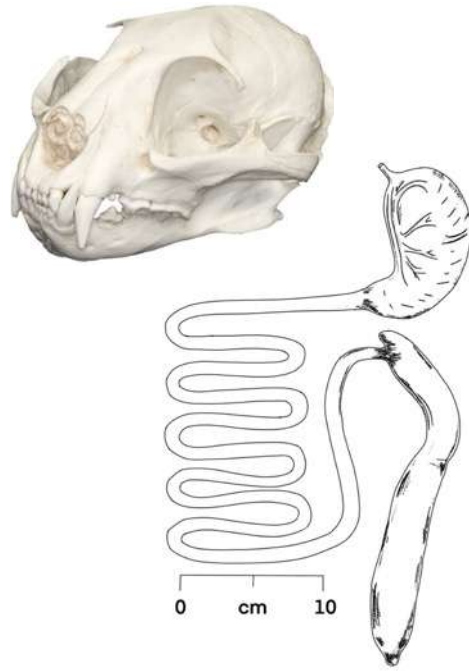
*thank you for your attention*



# Interplay of organ systems



# Principle of the correlation of parts

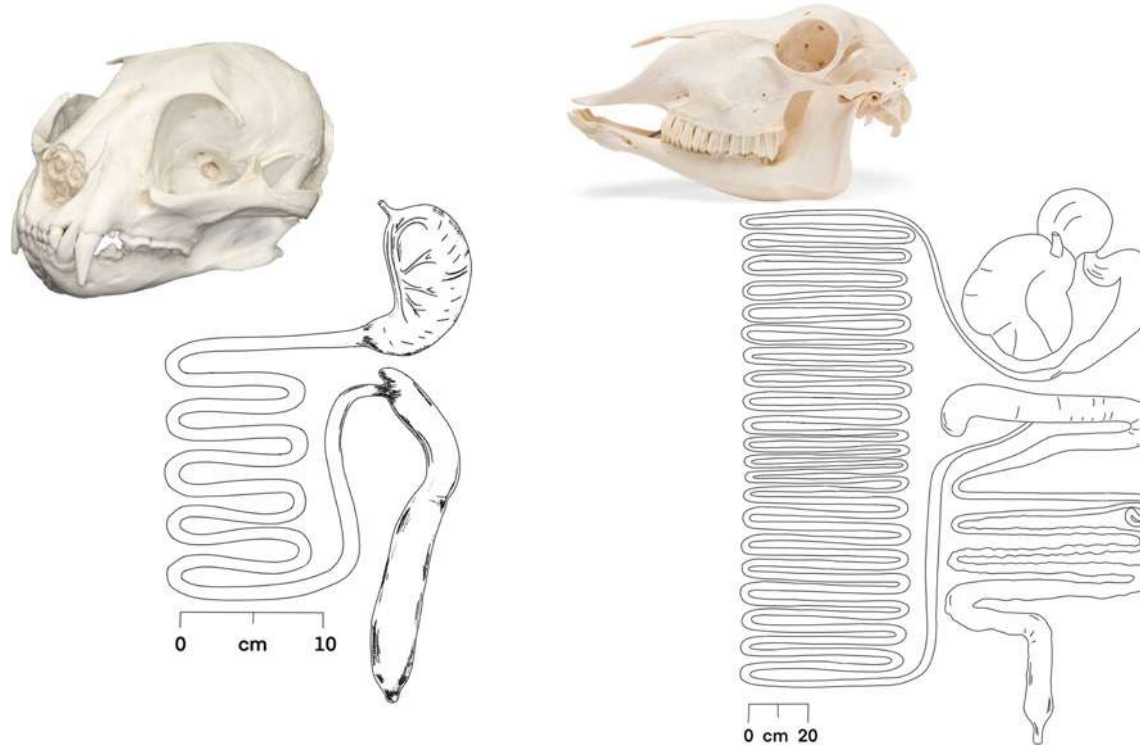


*If an animal's teeth are such as they must be, in order for it to nourish itself with flesh, we can be sure without further examination that the whole system of its digestive organs is appropriate for that kind of food, and that its whole skeleton and locomotive organs, and even its sense organs, are arranged in such a way as to make it skillful at pursuing and catching its prey. For these relations are the necessary conditions of existence of the animal; if things were not so, it would not be able to subsist. (Cuvier)*





# Principle of the correlation of parts



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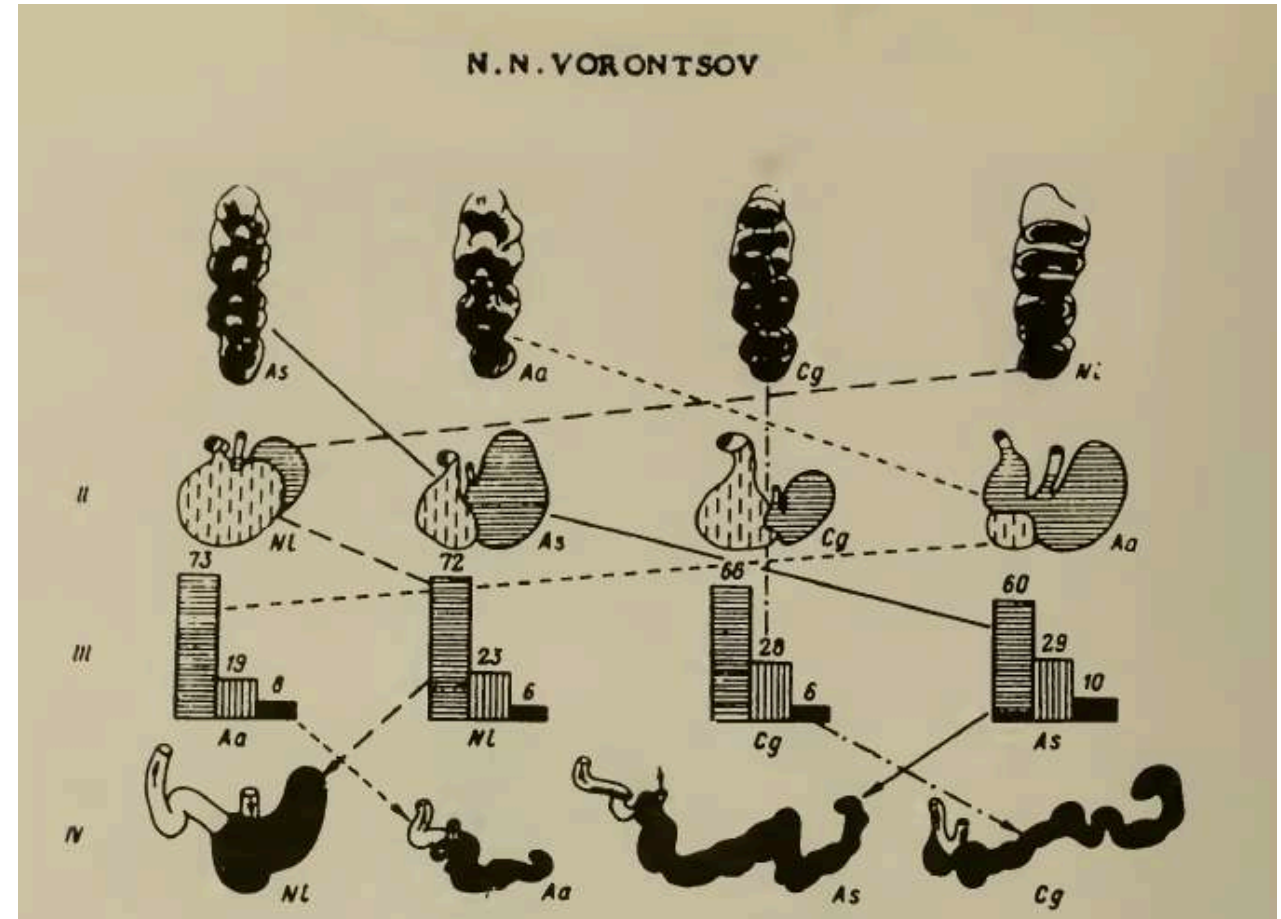
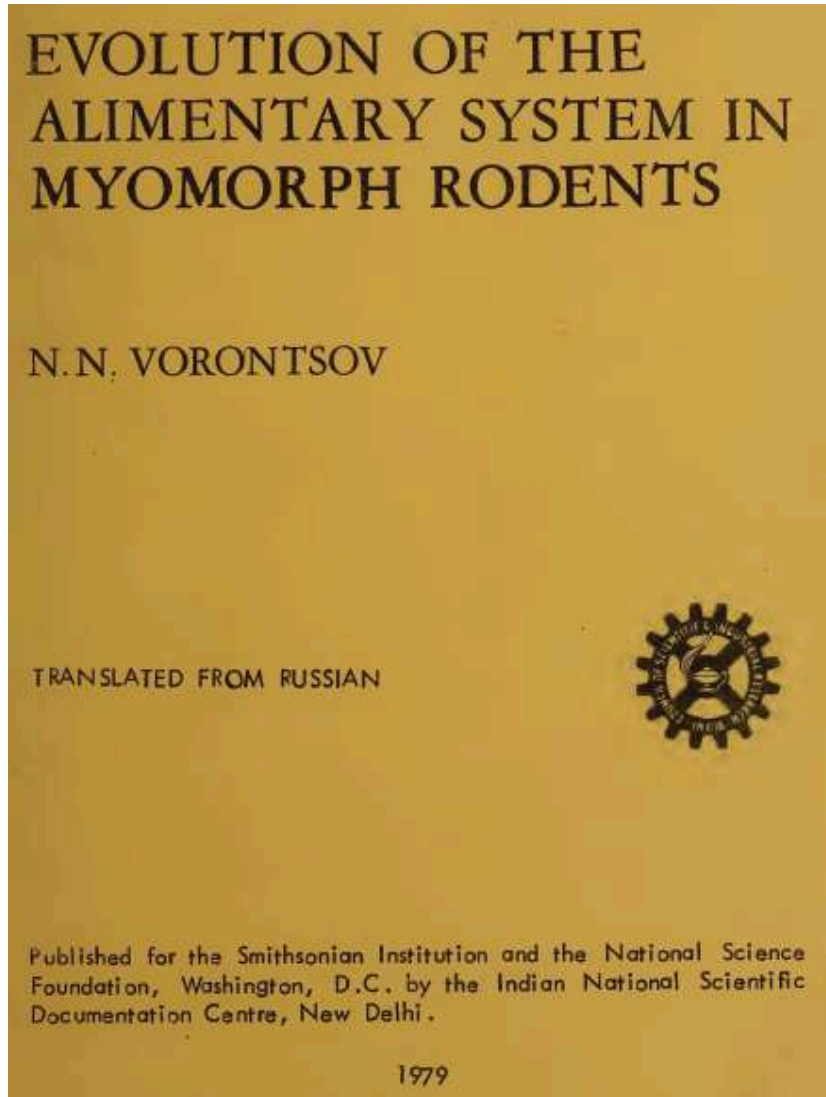
# Principle of the correlation of parts



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# Principle of the compensation of parts ?

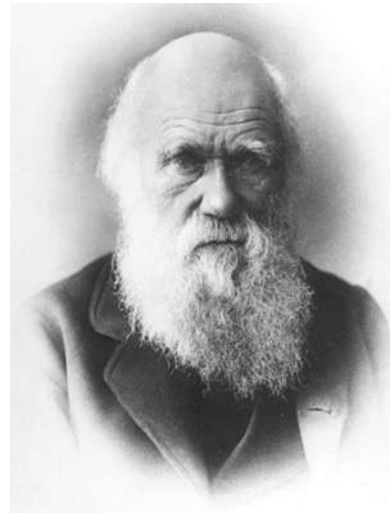


faunivore ← → herbivore



# What separates a creationist from an evolutionist ?

Not so much the agency  
(the old man with the white beard)



but the narrative of the adaptation  
(‘perfect’ vs. ‘adequate at the time’)





# The spandrels of San Marco and the Panglossian paradigm: a critique of the adaptationist programme

BY S. J. GOULD AND R. C. LEWONTIN

*Proc. R. Soc. Lond. B* **205**, 581–598 (1979)

An adaptationist programme has dominated evolutionary thought in England and the United States during the past 40 years. It is based on faith in the power of natural selection as an optimizing agent. It proceeds by breaking an organism into unitary 'traits' and proposing an adaptive story for each considered separately. Trade-offs among competing selective demands exert the only brake upon perfection; non-optimality is thereby rendered as a result of adaptation as well. We criticize this



## Principle of contingency and adequacy

***Stuff works until a better solution  
really kicks off.***

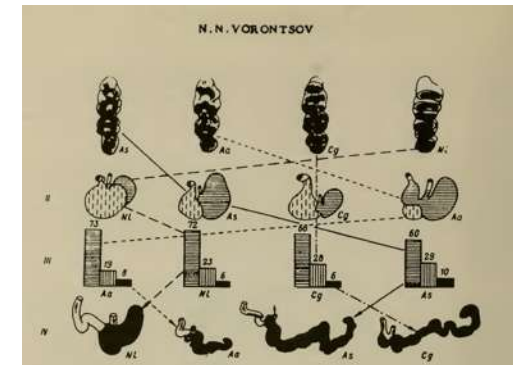
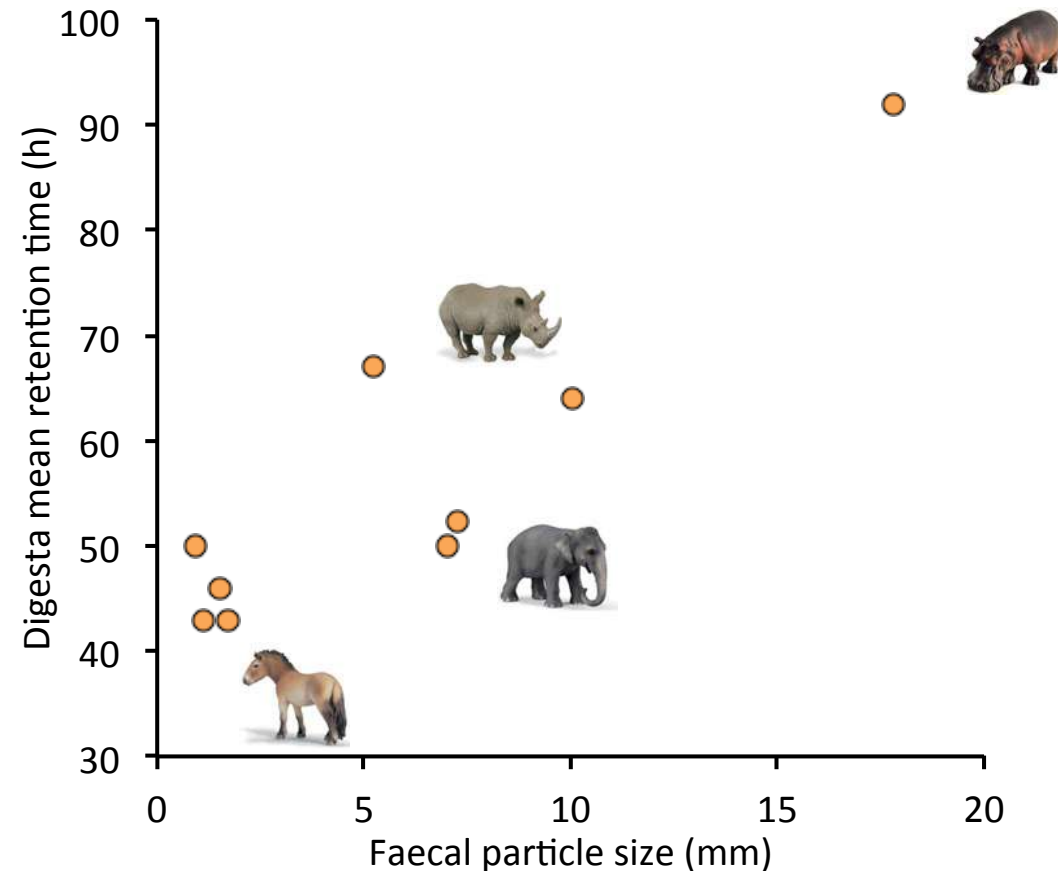


# Chewing – Retention tradeoff ?

## Evidence for a tradeoff between retention time and chewing efficiency in large mammalian herbivores

Comparative Biochemistry and Physiology, Part A 154 (2009) 376–382

Marcus Clauss<sup>a,\*</sup>, Charles Nunn<sup>b,c</sup>, Julia Fritz<sup>d</sup>, Jürgen Hummel<sup>e</sup>







How do you increase the yield of a growing system ?

