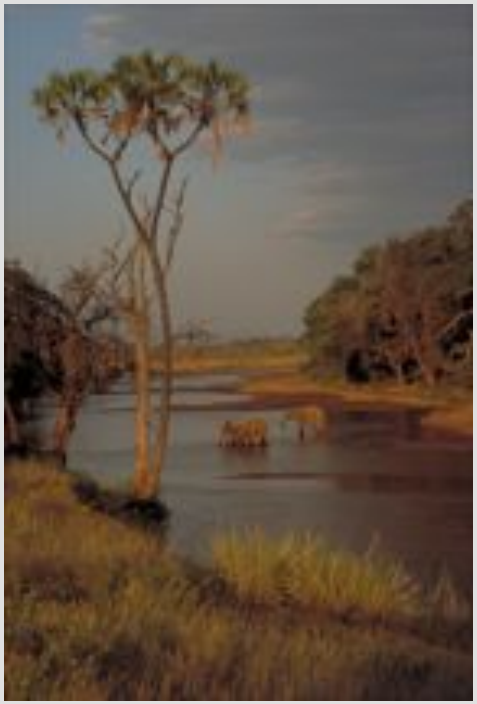
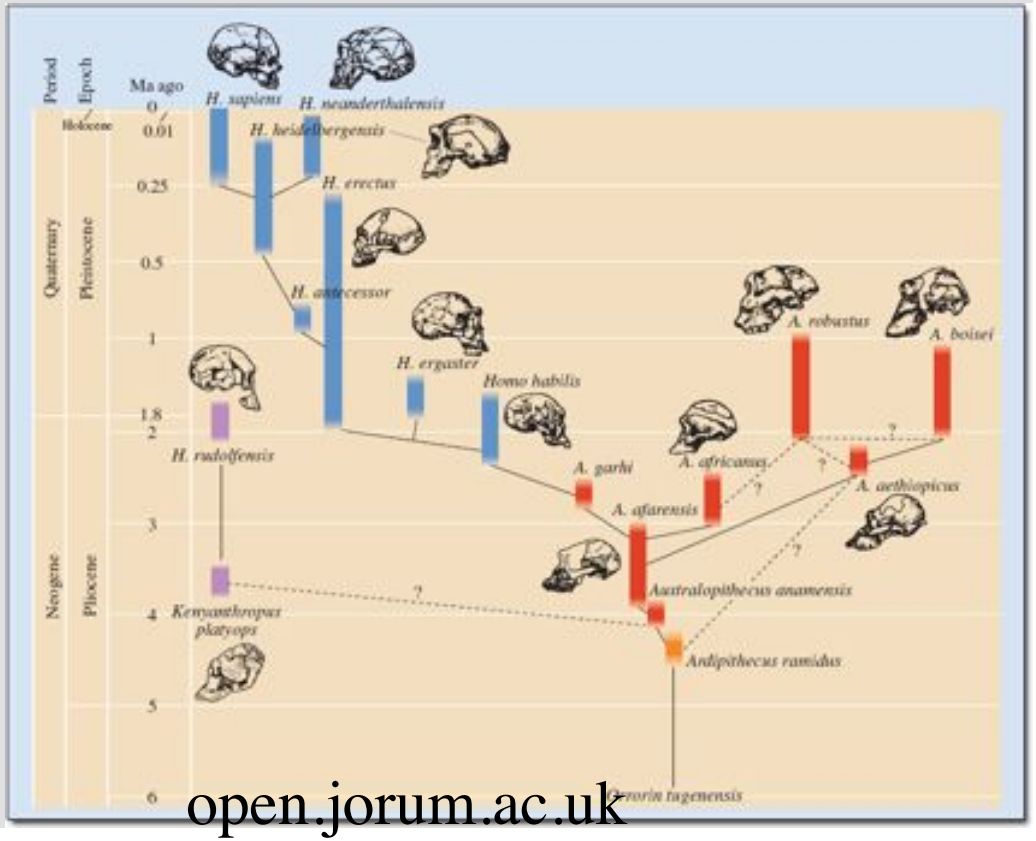
Environments of Human Evolution: The Isotope Evidence



Thure Cerling

University of Utah



Thanks to:

- Samuel Andanje, Michael Bird, Frank Brown, Kendra Chritz, Jim Ehleringer, Patrick Gathogo, Bereket Haileab, John Harris, John Hart, Glynis Jehle, Prince Kaleme, David Kimutai, Francis Kirera, Louise Leakey, Meave Leakey, Richard Leakey, Naomi Levin, William Mace, Anthony Macharia, Kyalo Manthi, Emma Mbua, Benjamin Passey, Christopher Remien, Kevin Uno, Jonathan Wynn
- *Ethiopian Wildlife Conservation Organization, Kenya Wildlife Service, Leakey Foundation, National Museums of Kenya, National Science Foundation, Packard Foundation, Stable Isotope Ratio Facility for Environmental Research (SIRFER), Turkana Basin Institute, University of Addis Ababa, University of Utah*

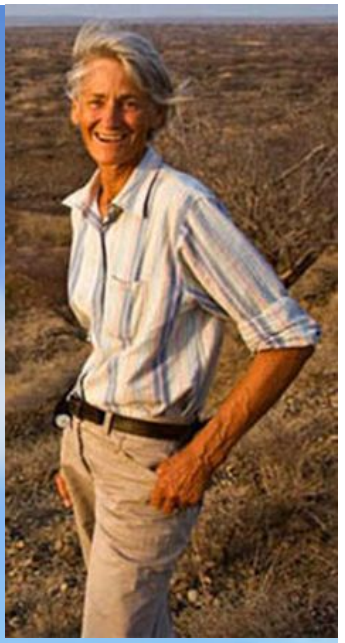
The Fossils

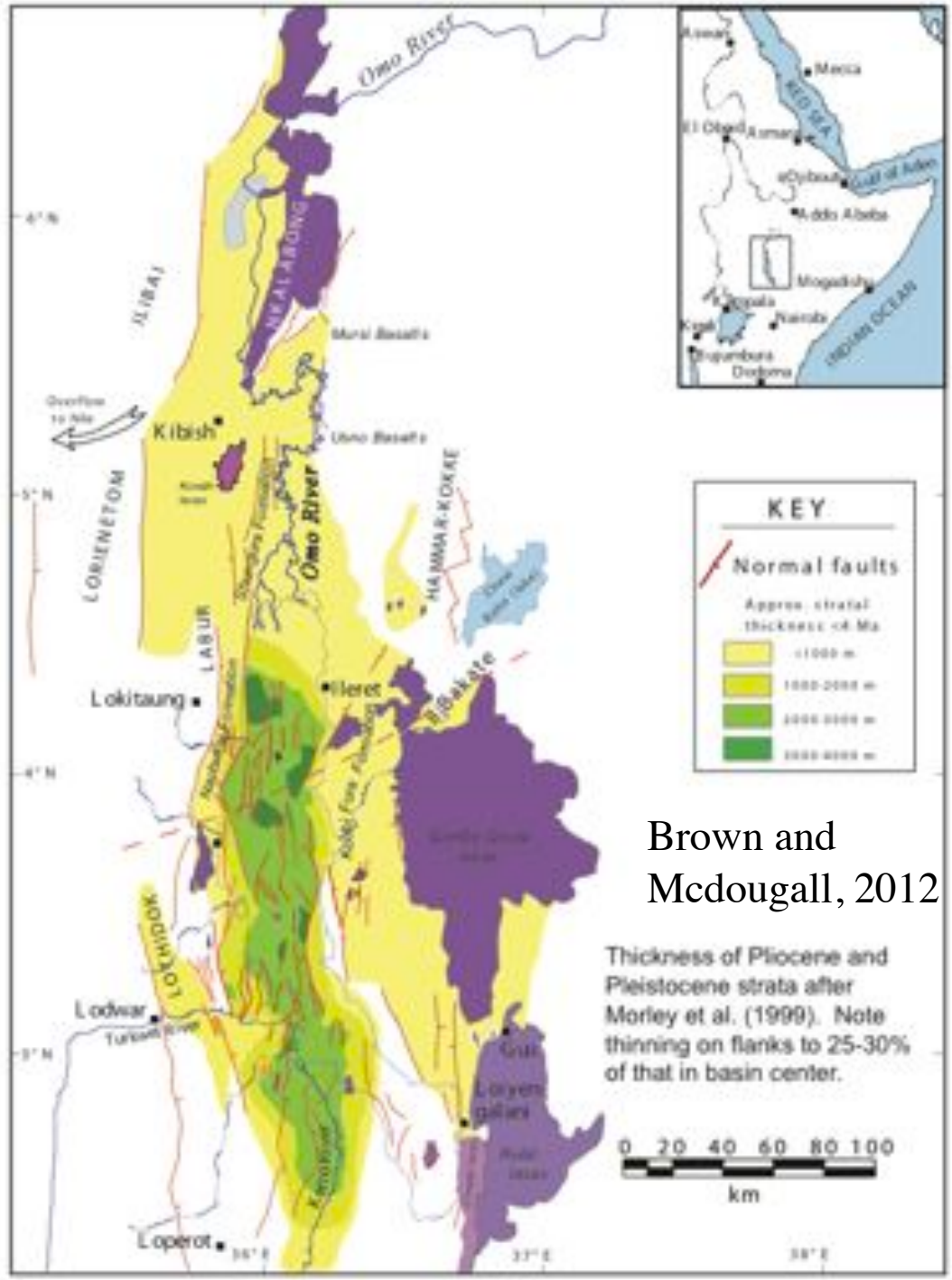
Turkana Basin

Images: National Musuems of Kenya

The Geology

The People





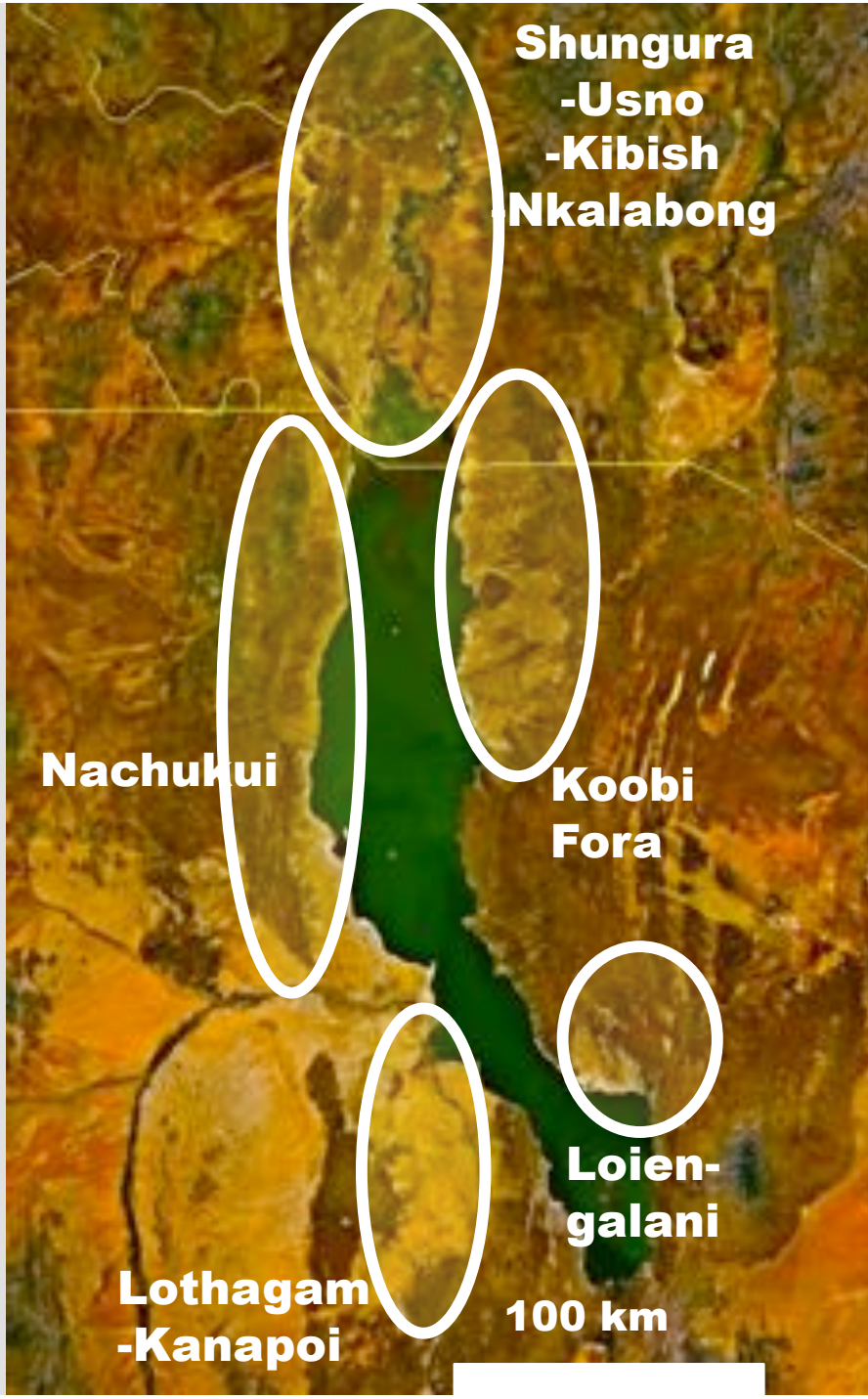
Brown and Mcdougall, 2012

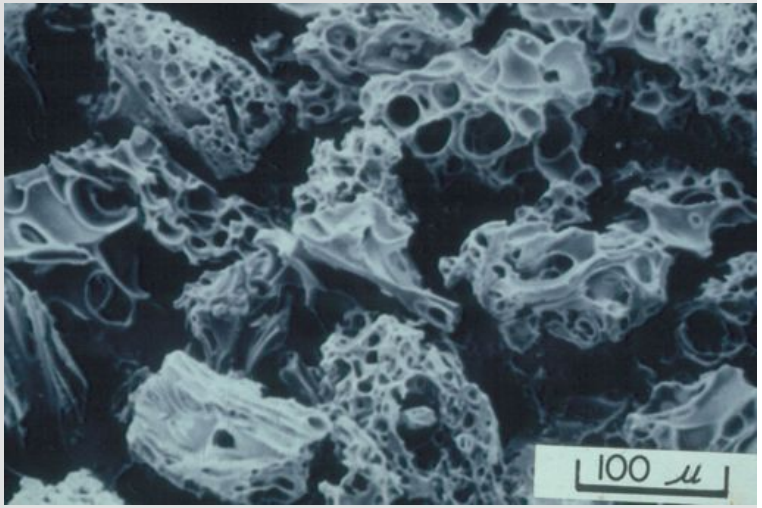

Google earth
US Dept of State Geographer
Image Landsat
200 km
N

Awash sites

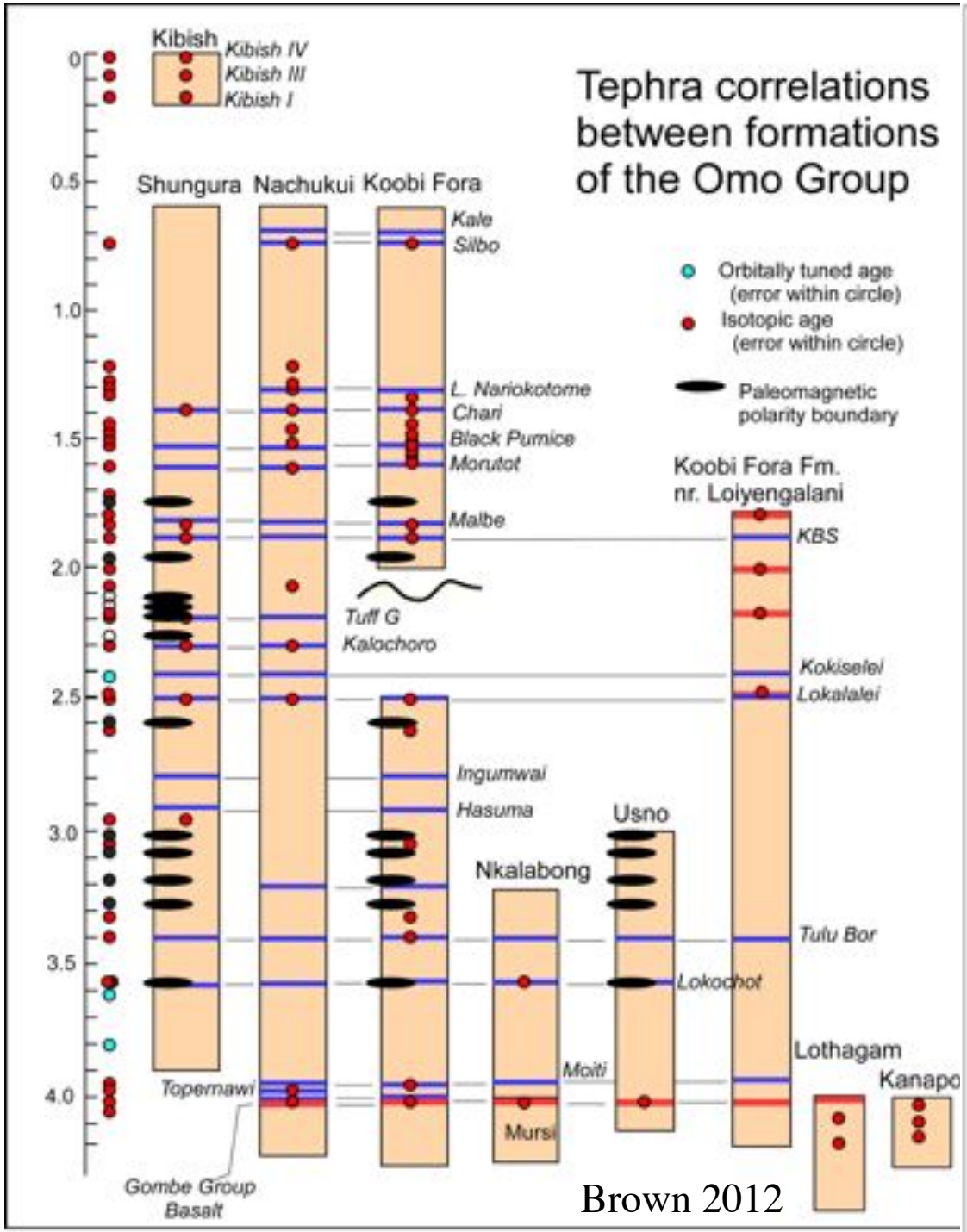

Hadar
Gona
Dikika
Aramis
100 km


Olduvai Gorge
100 km

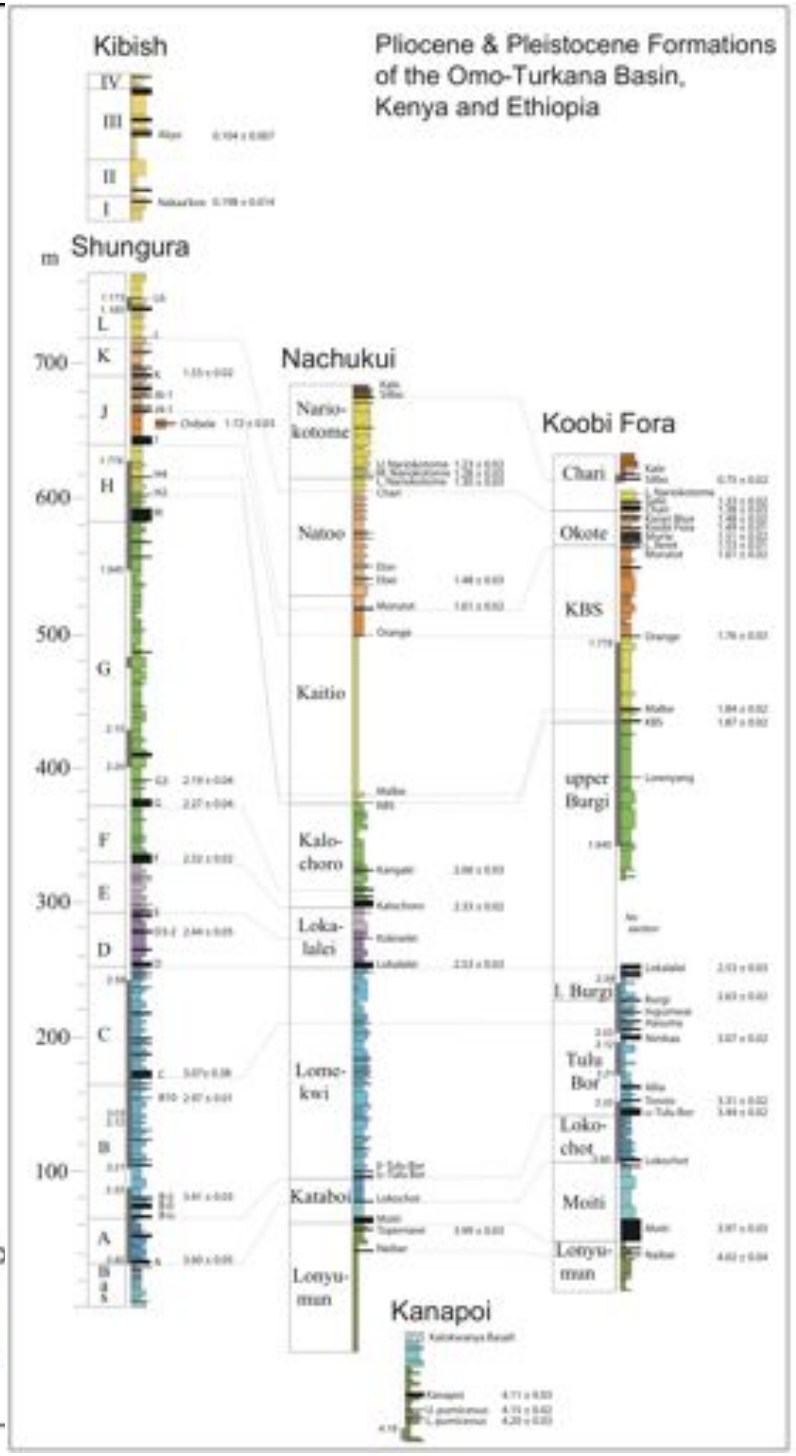

Shungura
-Usno
-Kibish
-Nkalabong
Nachukui
Koobi
Fora
Loien-
galani
Lothagam
-Kanapoi
100 km

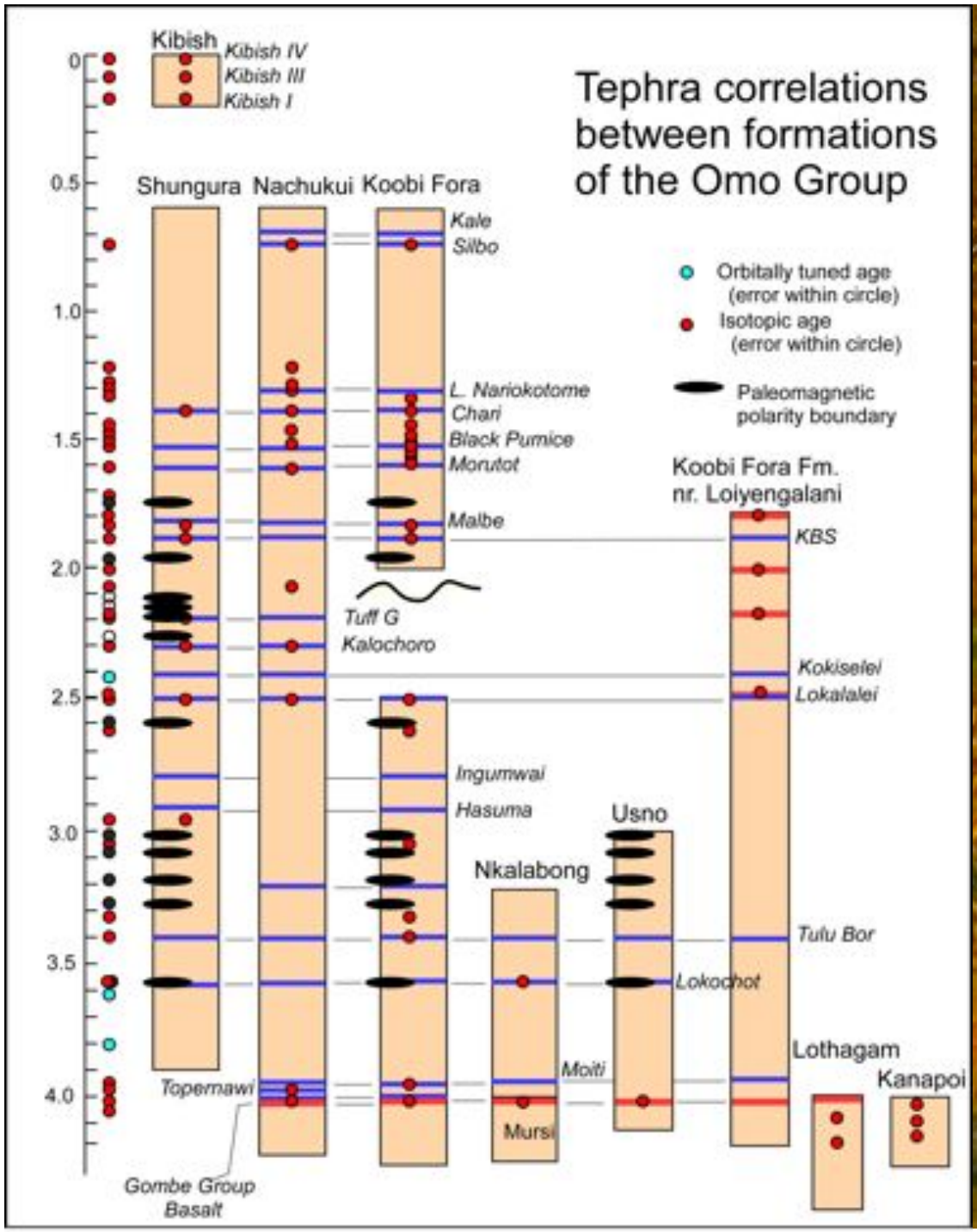

100 μ


Nubian Desert
Red Sea
40E
60E
72
Eritrea
Yemen
Sudan
Djibouti
Gulf of Aden
Ethiopia
10N
Somalia
0


Tephra correlations between formations of the Omo Group
Kibish
Kibish IV
Kibish III
Kibish I
Shungura
Nachukui
Koobi Fora
Kale
Silbo
L. Nariokotome
Chari
Black Pumice
Morutot
Malbe
Tuff G
Kalochoro
Ingumwai
Hasuma
Topernawi
Gombe Group Basalt
Nkalabong
Usno
Mursi
Moiti
Koobi Fora Fm. nr. Loiyengalani
KBS
Kokiselei
Lokalalei
Tulu Bor
Lokochot
Lothagam
Kanapoi
Orbitally tuned age (error within circle)
Isotopic age (error within circle)
Paleomagnetic polarity boundary
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0

Brown 2012


Pliocene & Pleistocene Formations of the Omo-Turkana Basin, Kenya and Ethiopia
Kibish
Shungura
Nachukui
Koobi Fora
m
700
600
500
400
300
200
100
Nario-kotome
Natoo
Kaitio
Kalo-choro
Loka-lalei
Lome-kwi
Katabo
Lonyu-man
Chari
Okote
KBS
upper Burgi
L. Burgi
Tulu Bor
Loko-chot
Moiti
Kanapoi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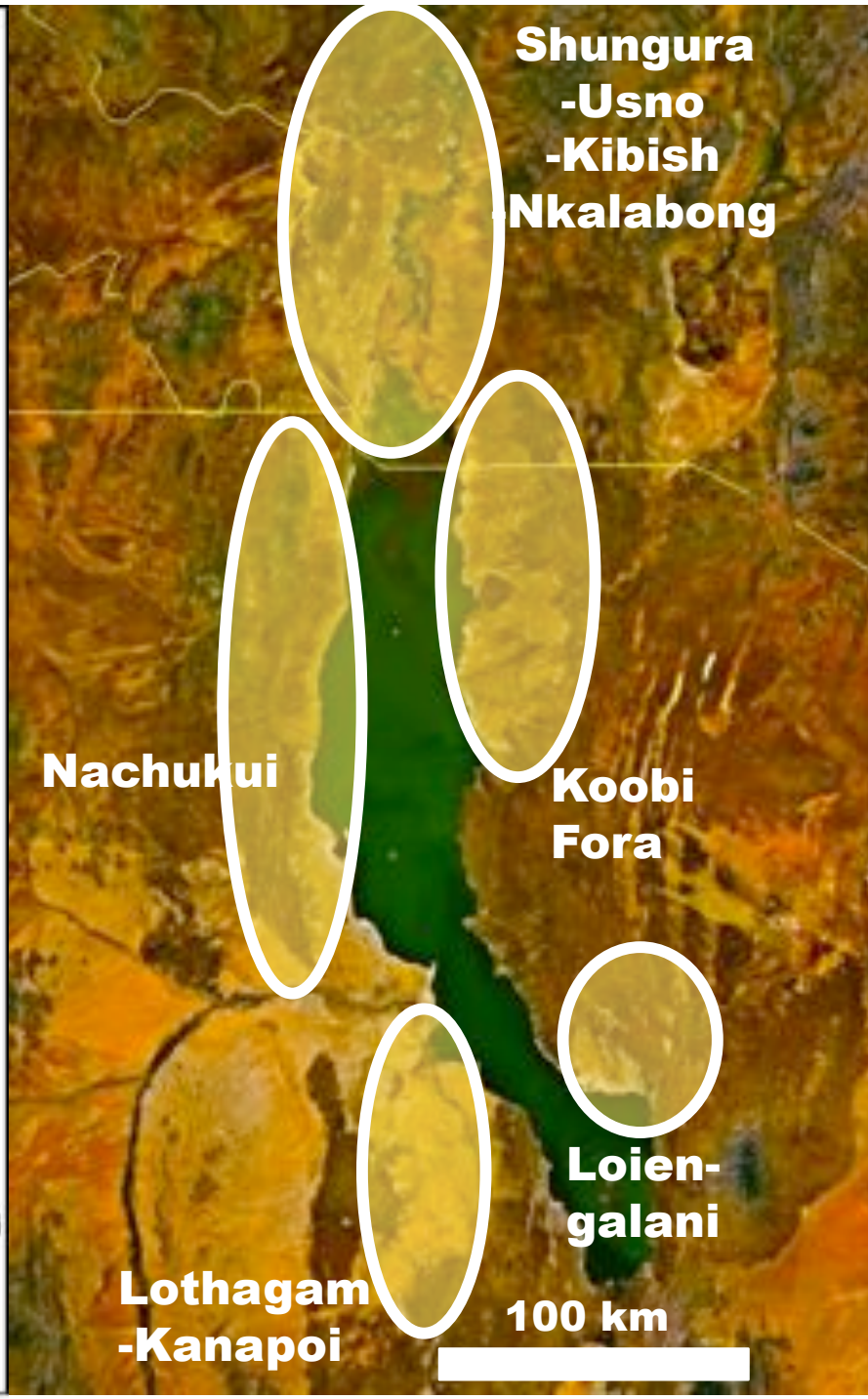
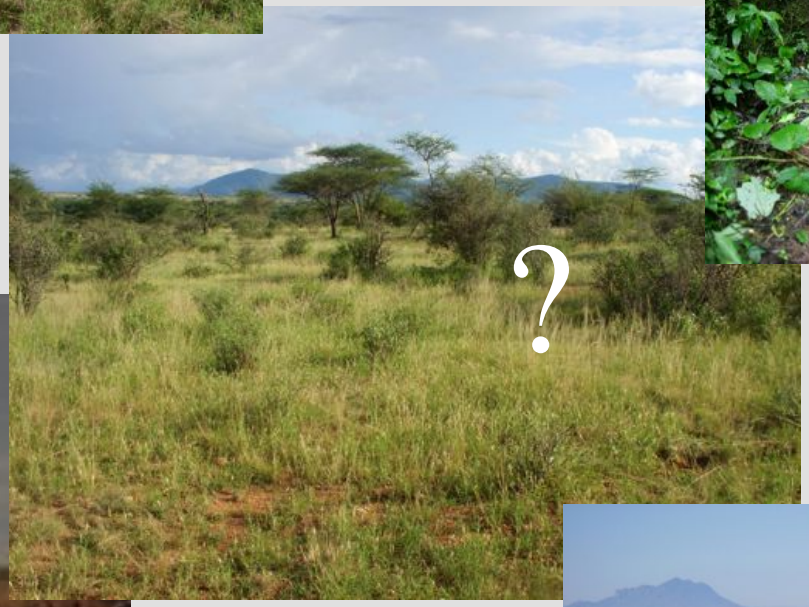
Kokiselei
Lokalalei
Tulu Bor
Lokochot
Lothagam
Kanapoi
Orbitally tuned age (error within circle)
Isotopic age (error within circle)
Paleomagnetic polarity boundary
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0


Shungura
-Usno
-Kibish
-Nkalabong
Nachukui
Koobi
Fora
Loien-
galani
Lothagam
-Kanapoi
100 km

What kind of vegetation?

How hot?

How dry?

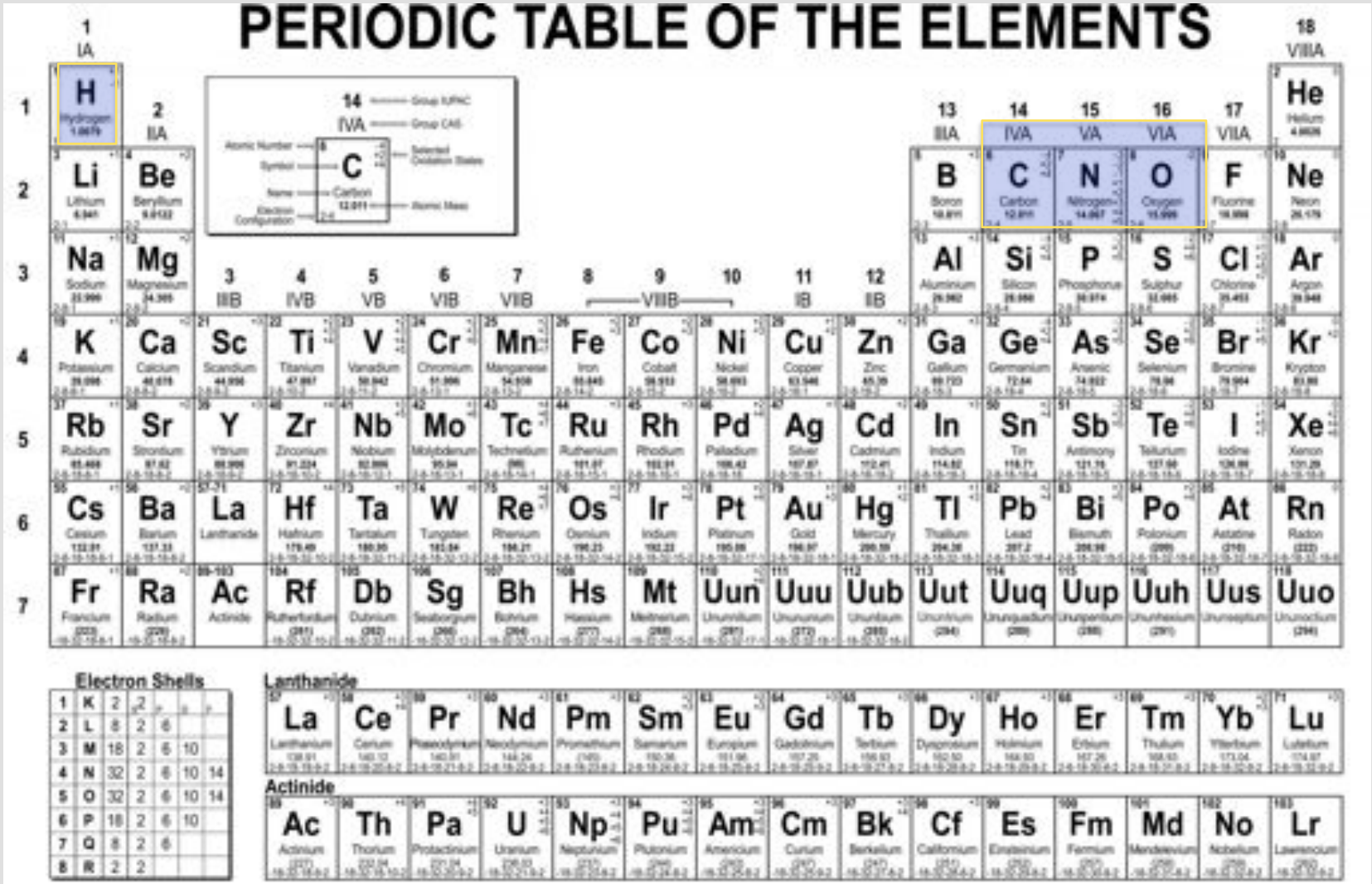


What did animals eat?

How much shade?

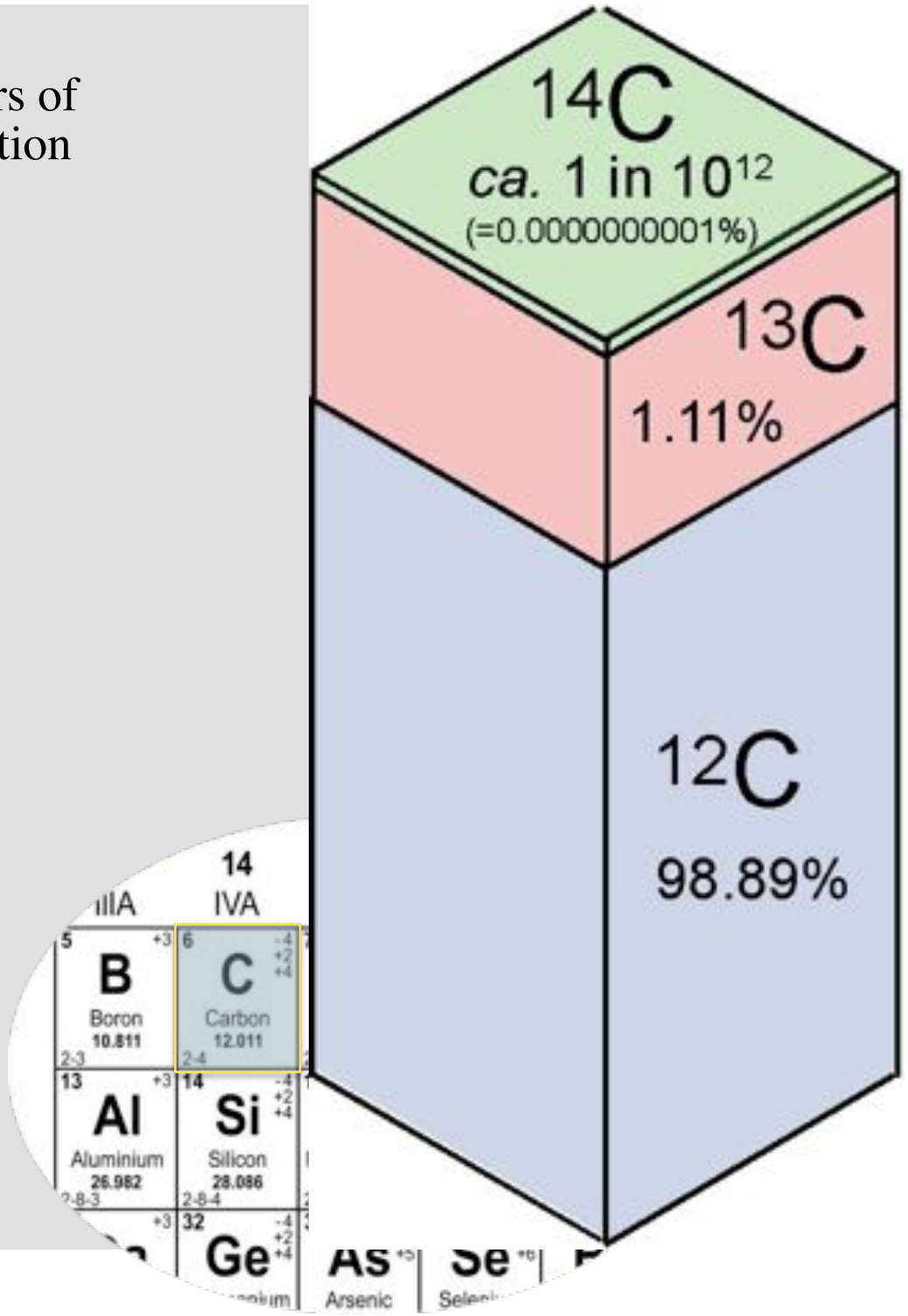
Elements are defined by the number of protons in the nucleus:

1=H, 2=He, 3 = Li, 4 = Be, 5 = B, 6 = C, 7 = N, 8 = O, and so on . . .



Isotopes are the different numbers of neutrons for a given proton configuration

Isotope	protons	neutrons
^{12}C	6	6
^{13}C	6	7
^{14}C	6	8

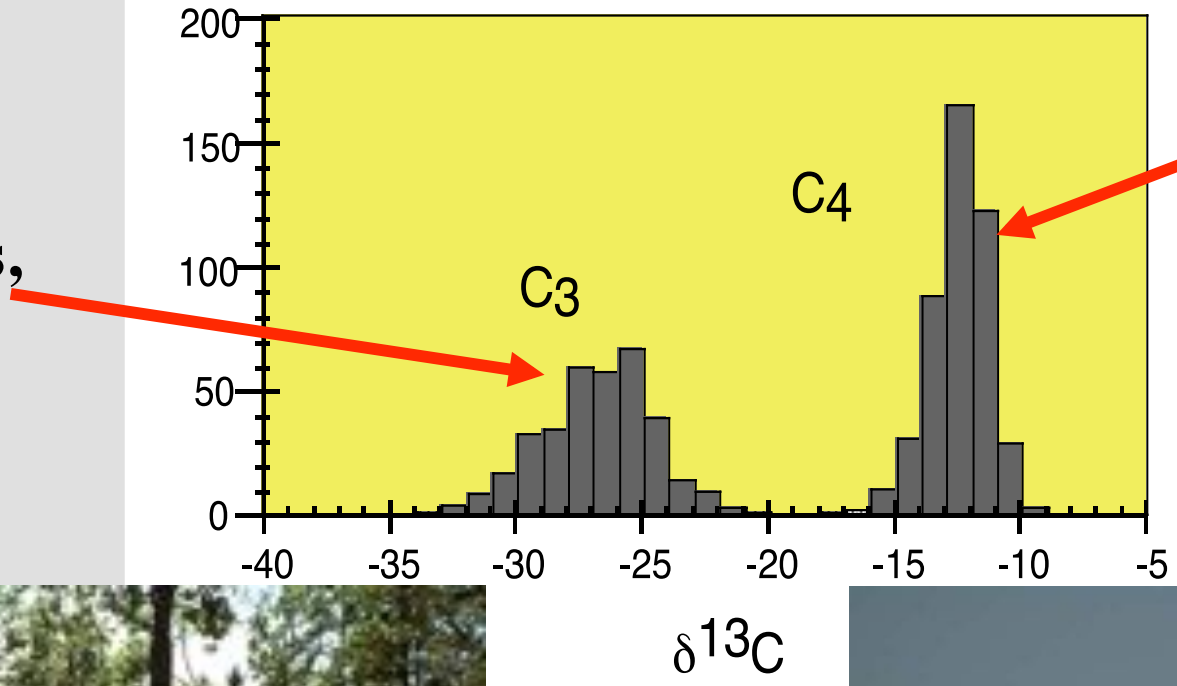


Isotope terminology

- R_{phase} = $^{13}C/^{12}C$ ratio in "phase"
- $\delta^{13}C$ (‰) = (R_{phase} / $R_{standard}$ -1)*1000
- On Earth, ^{13}C ranges from 1.04% to about 1.14% (*ca*. $\delta^{13}C$ range from -65‰ to +25‰)

How do we use isotopes to determine ecology in the tropics? Use $\delta^{13}C$: C_3 and C_4 plants

Trees, Shrubs, *Herbs*



Tropical Grasses

C_4 photosynthesis
Where is it found?

- C_3 plants
- early photosynthetic pathway
- most dicots
- cool-season grasses
- Foods: vegetables, fruits, beans, wheat, barley, rye, meat (from diet)

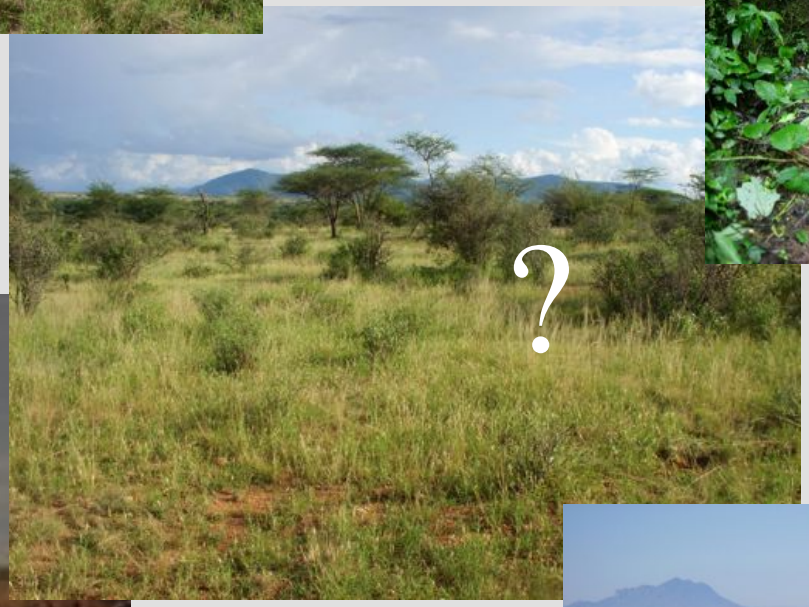
- C_4 plants
- Tropical grasses and sedges
- T(month) > 22 °C
- P(month > 50 mm
- (very rare in dicots)
- Foods: maize, sorghum, sugar cane, millet, tef, fonio, and meat (from diet)

SHADE

What kind of vegetation?

How hot?

How dry?



What did animals eat?

How much shade?

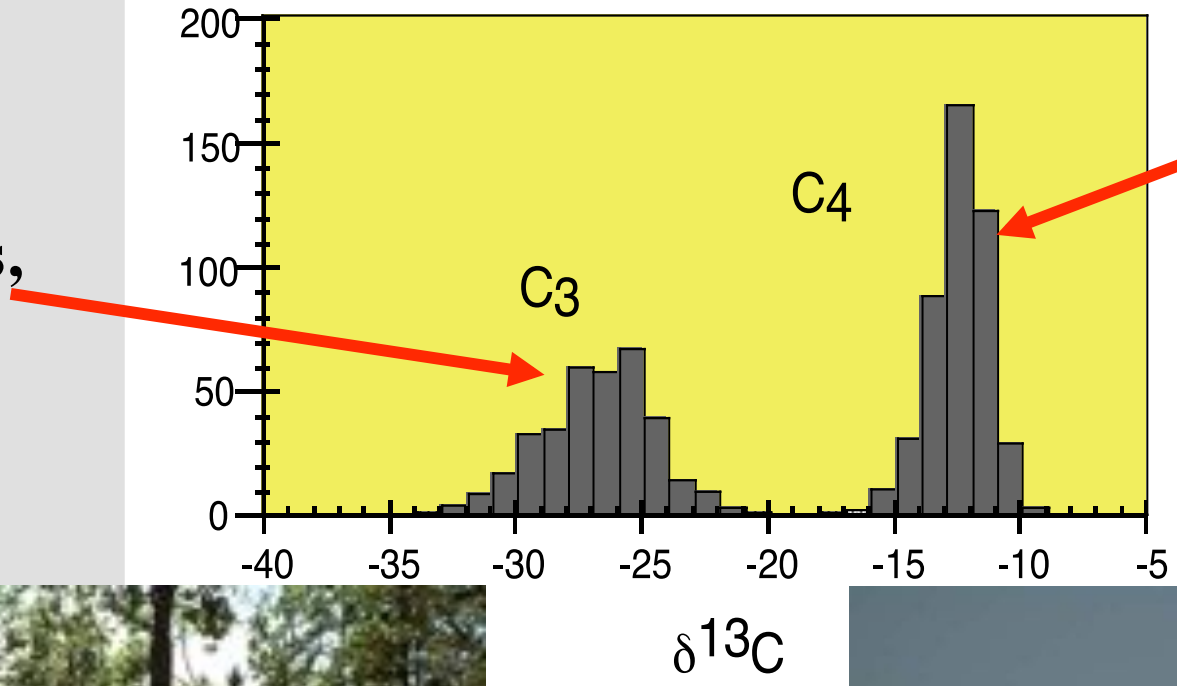
Can we quantify shade?

Shade = "woody cover"

Indicator of ecosystem structure

How do we use isotopes to determine ecology in the tropics? Use $\delta^{13}C$: C_3 and C_4 plants

Trees, Shrubs, *Herbs*



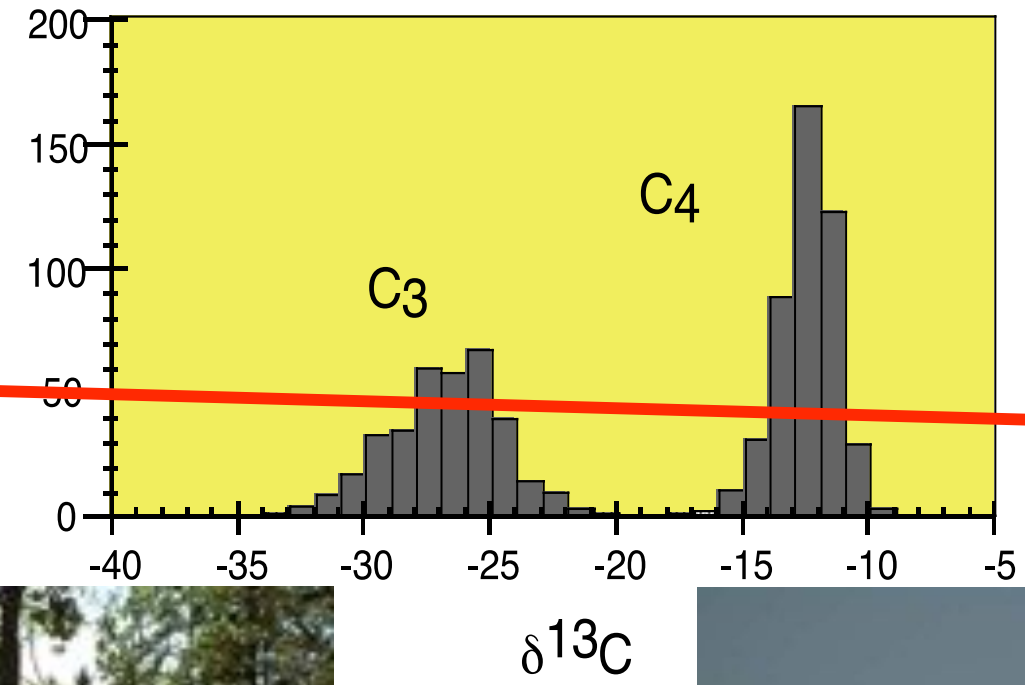
Tropical Grasses

How do we use isotopes to determine ecology in the tropics? Use $\delta^{13}C$: C_3 and C_4 plants

SHADE

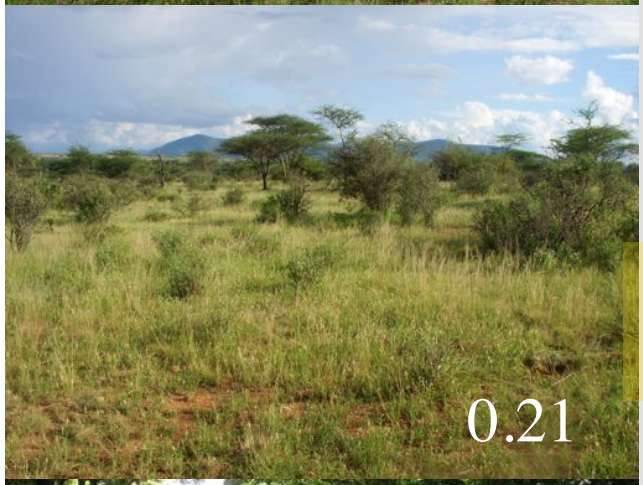
Trees, Shrubs,

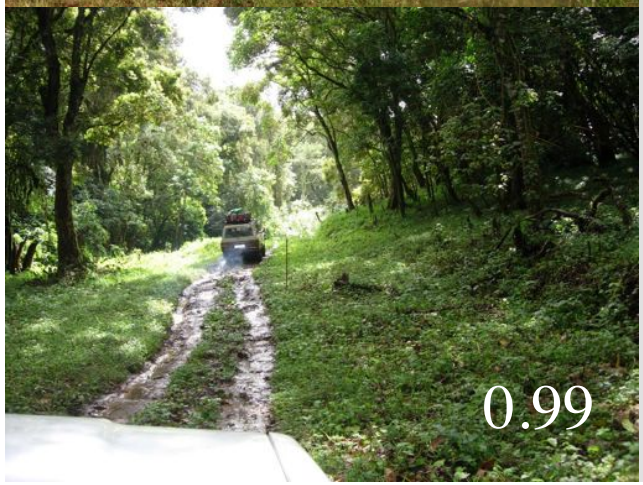
Herbs



Tropical Grasses

Not-SHADE

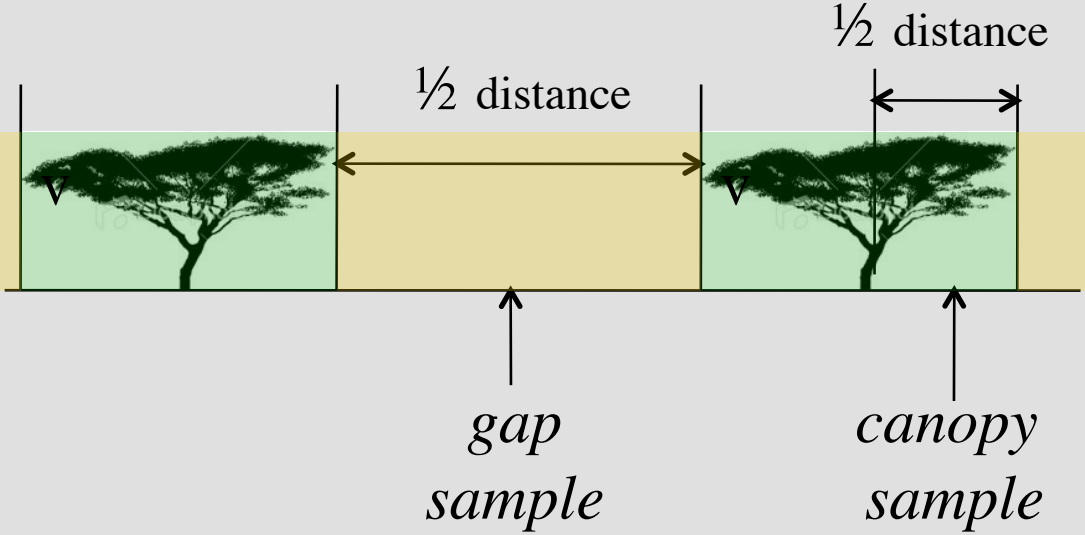




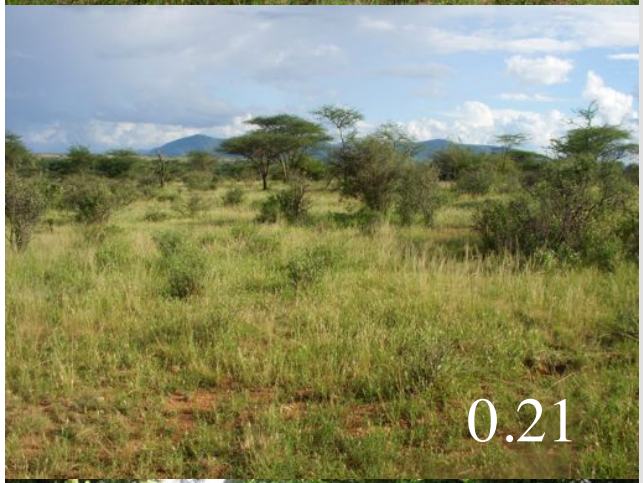
method of Bird et al (2004).

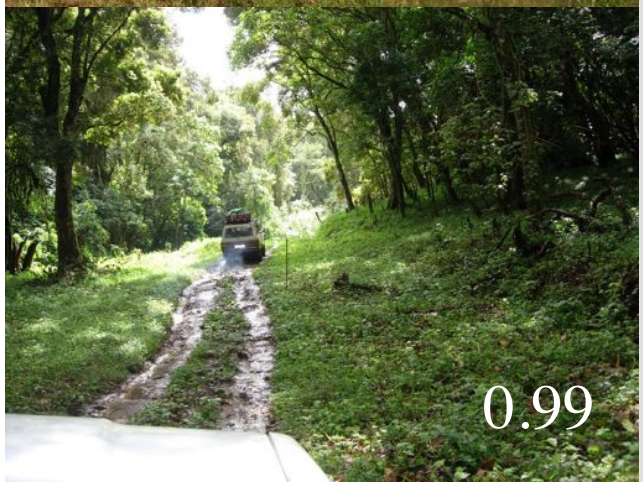
subcanopy (=shade) vs. gap (open)

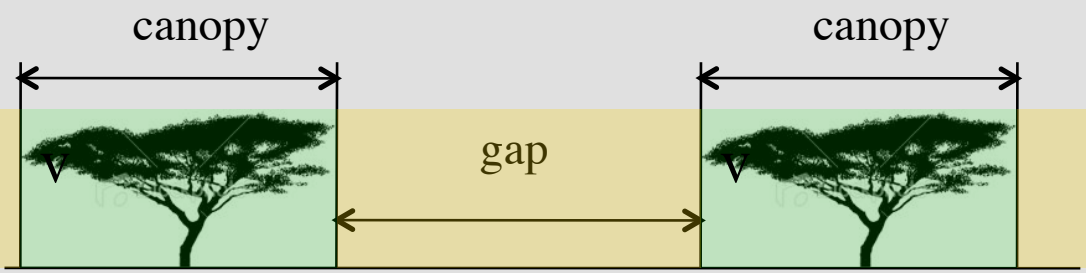
76 sites from tropics:
Kenya, Ethiopia, N. Australia, Brazil,
Botswana, Zambia, Malaysia

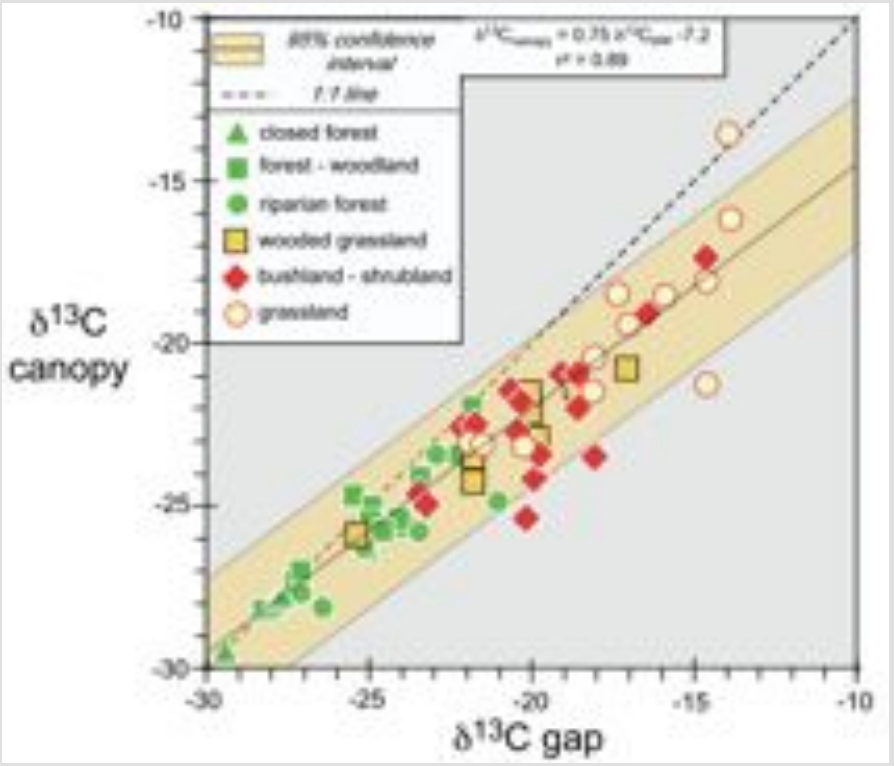


Multiple samples from "gap" and "canopy" used to characterize each "site". Crown canopy measured in the field and using aerial photography









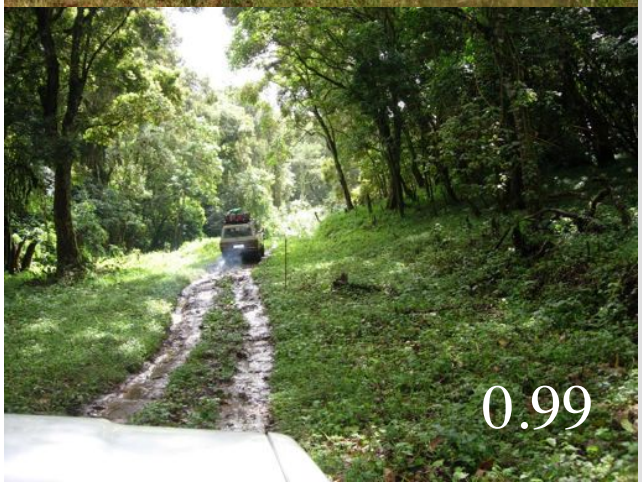
"Canopy" and "gap" samples have similar $\delta^{13}C$ values at each site

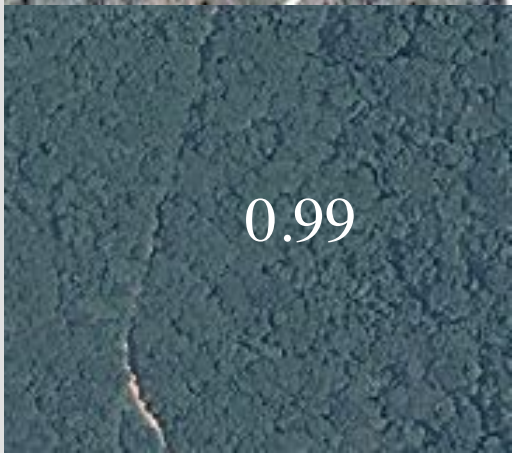
Quantity woody cover:

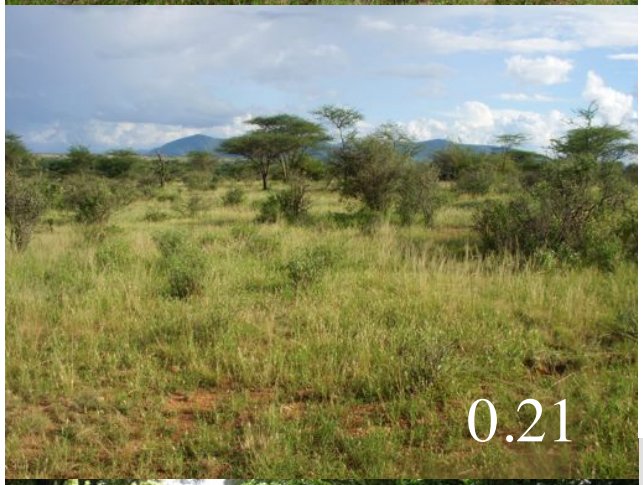
0.6 m resolution imagery

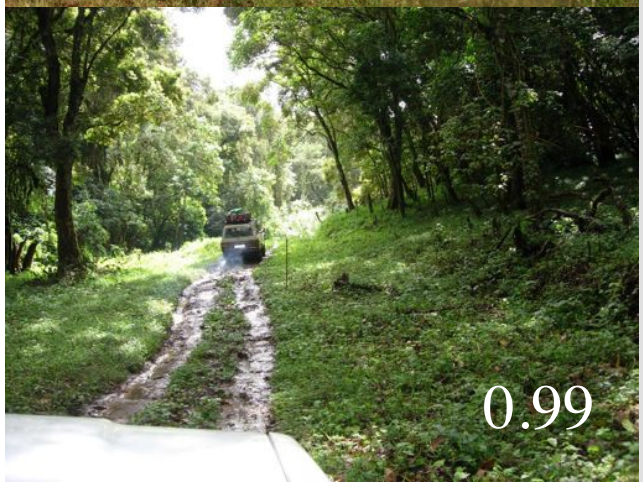
ground transects

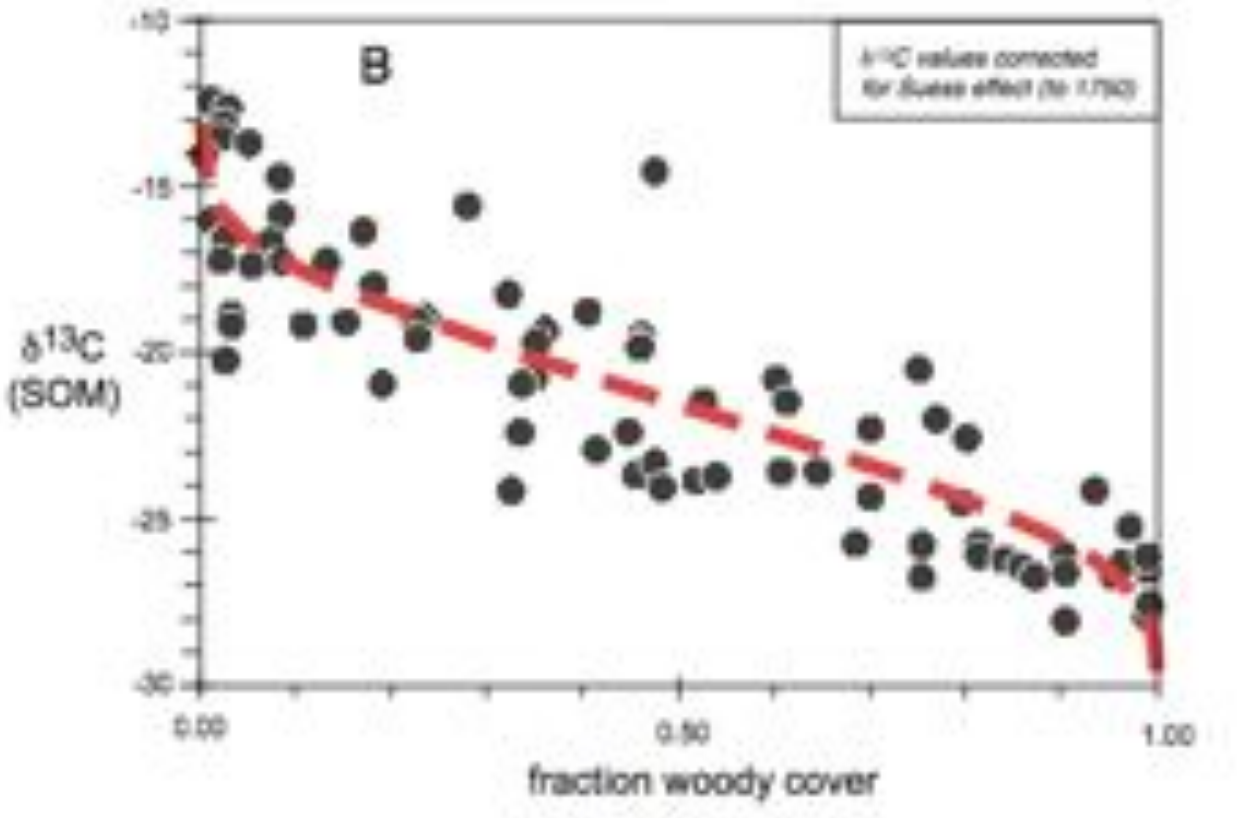
fish-eye photography





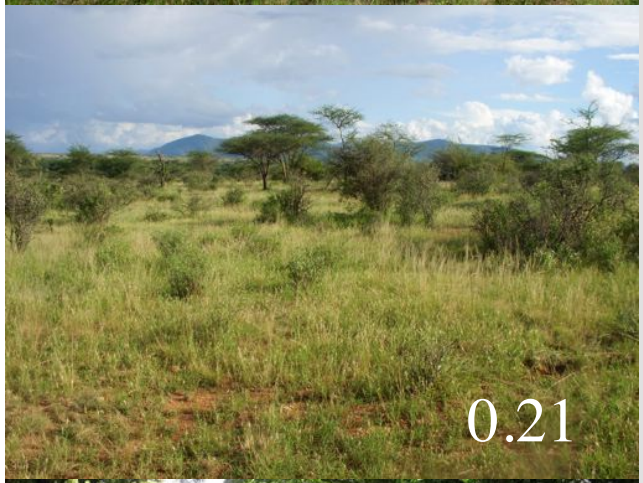


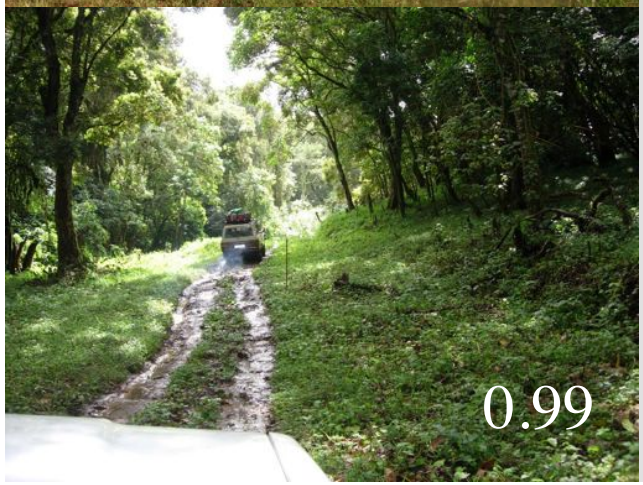


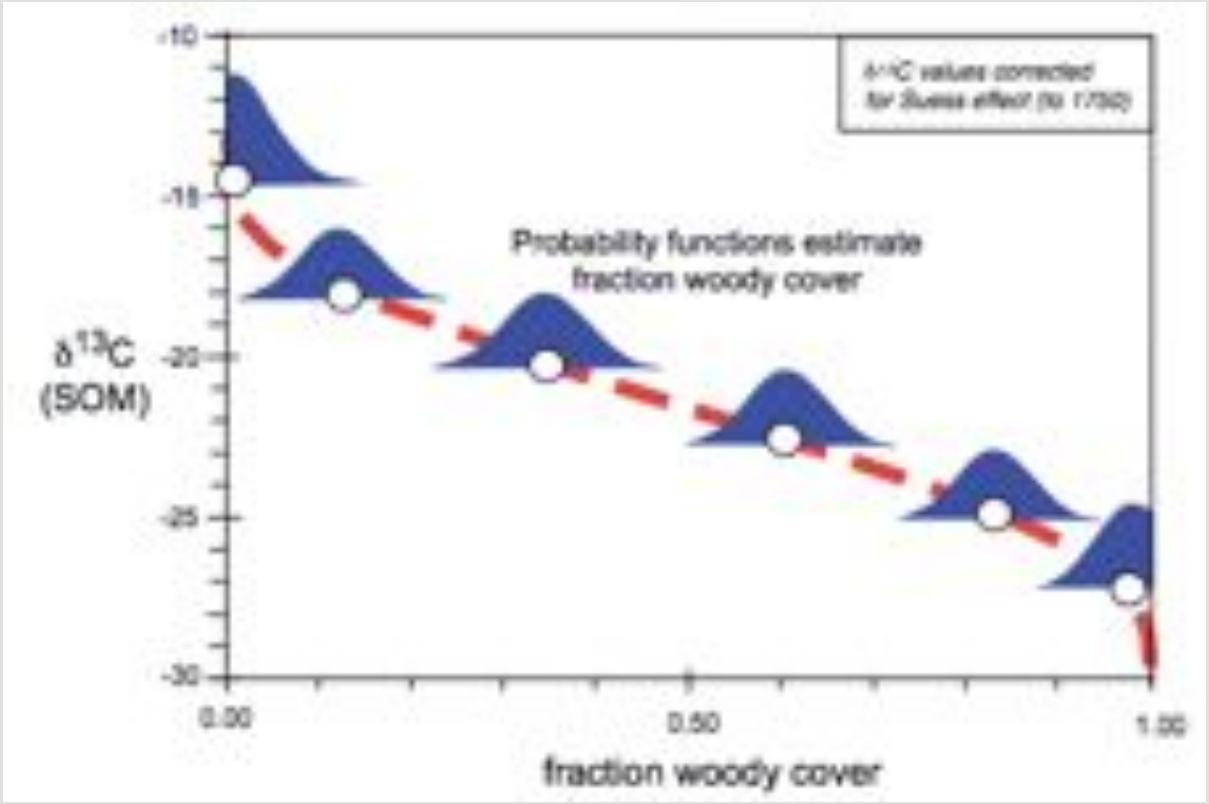


Cerling et al., 2011

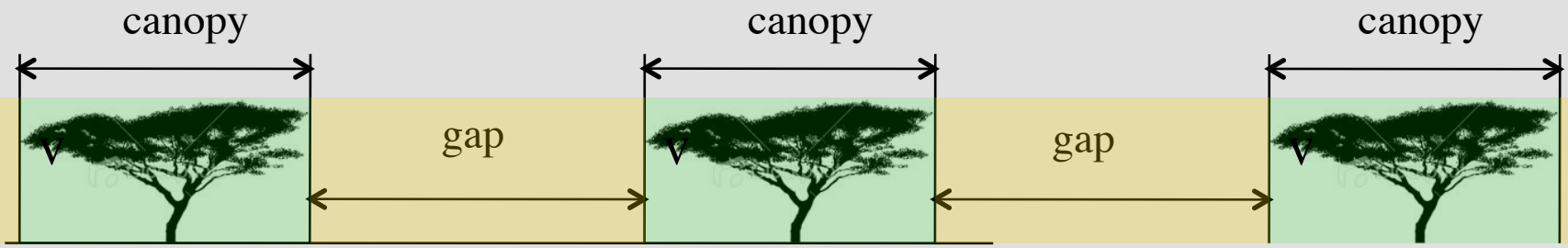
- Crown canopy from 0.01 to 0.99
- Not linear from C_3 to C_4 endmembers
  use arcsin(sqrt) transformation (has limits of 0.0 and 1.0; $r^2 = 0.77$)
- Few C_4 plants until woody cover is < 70%
- Non-woody (herbaceous) plants present in all sites
- Calculate probability density function for shade from soil / paleosol $\delta^{13}C$

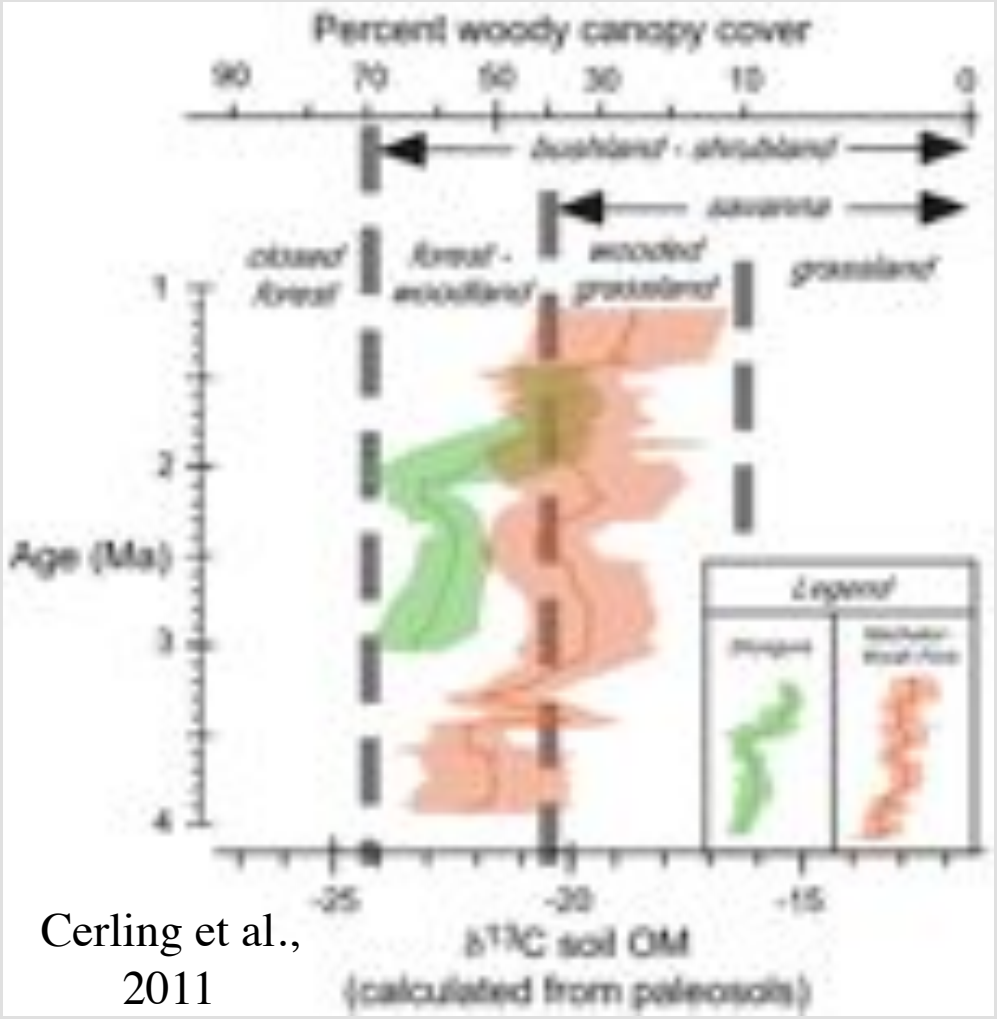






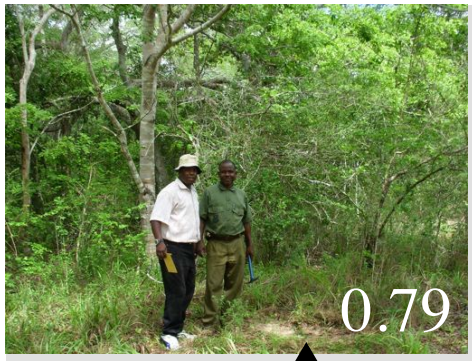
- Calculate probability density function for shade from soil / paleosol $\delta^{13}C$

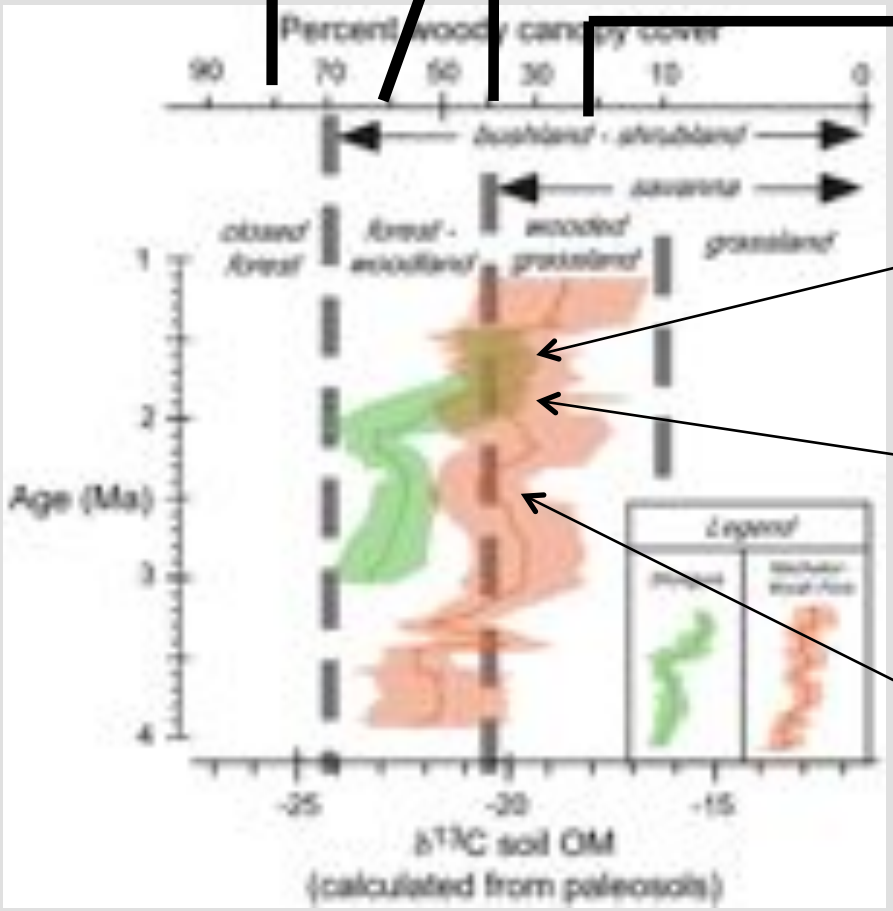




Cerling et al., 2011

What about fossil record? Use paleosols in East Africa





Turkana Boy: KNM-WT-15000

1470

Black skull: 17000


0.6


0.5


0.4


0.3

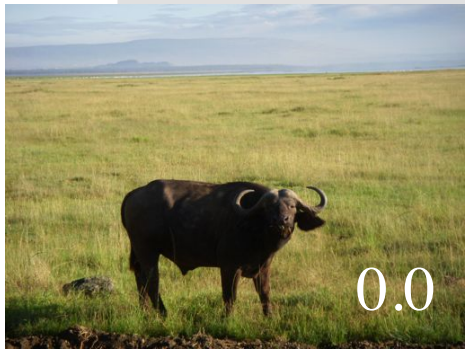

0.7

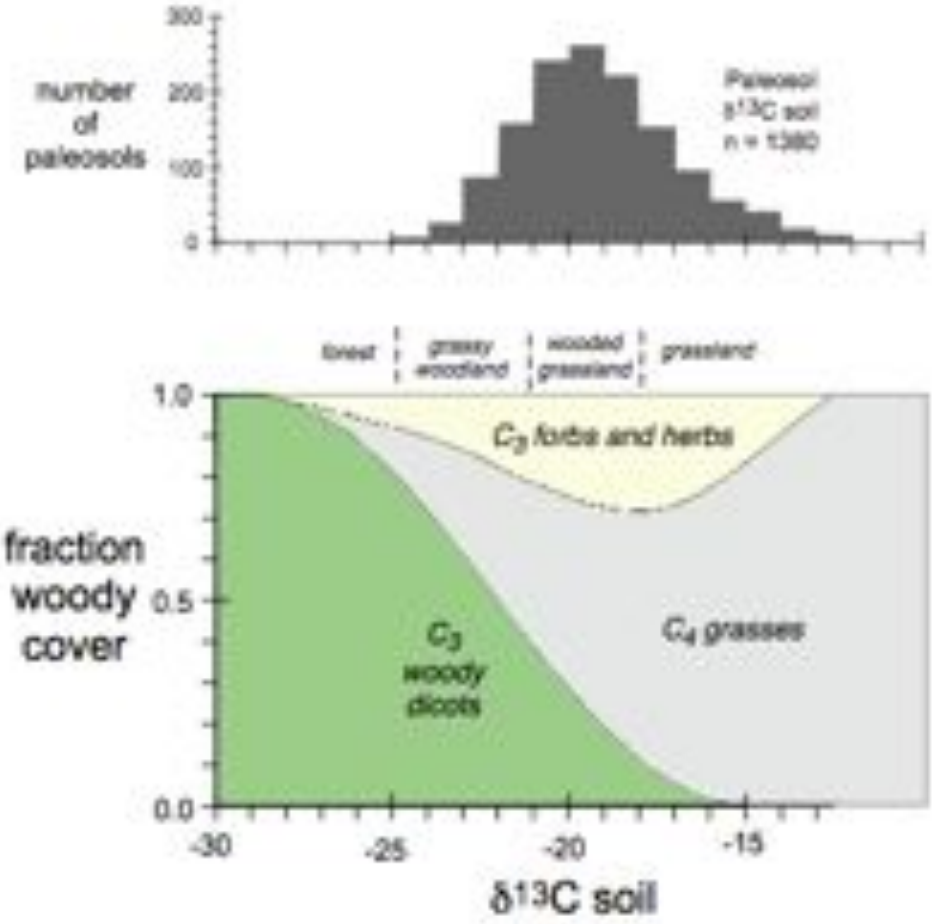

0.2


0.8

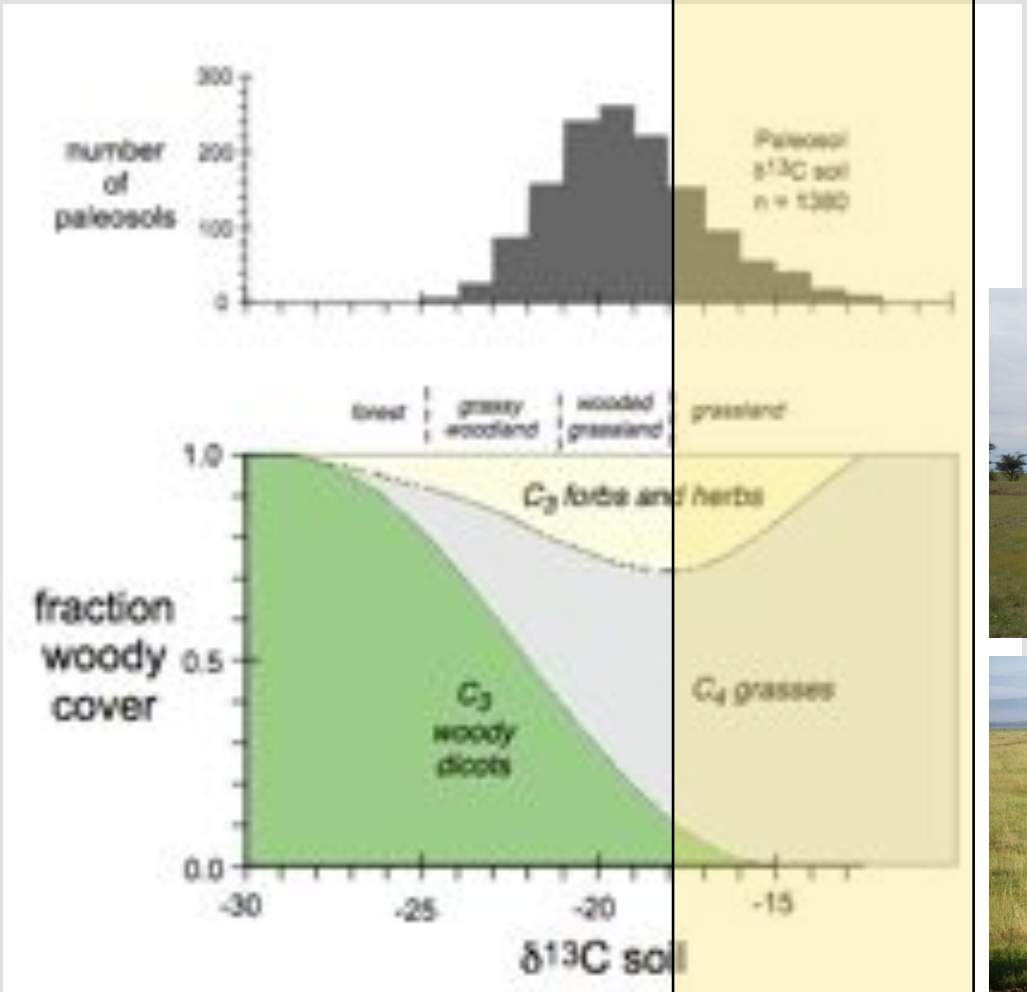

0.1

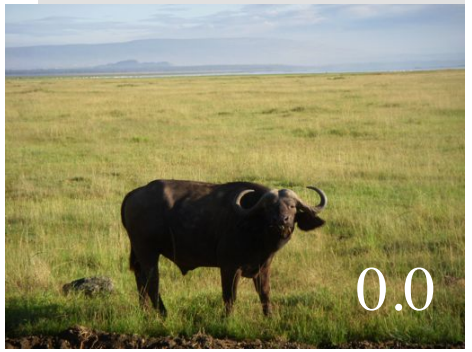

0.9


0.0

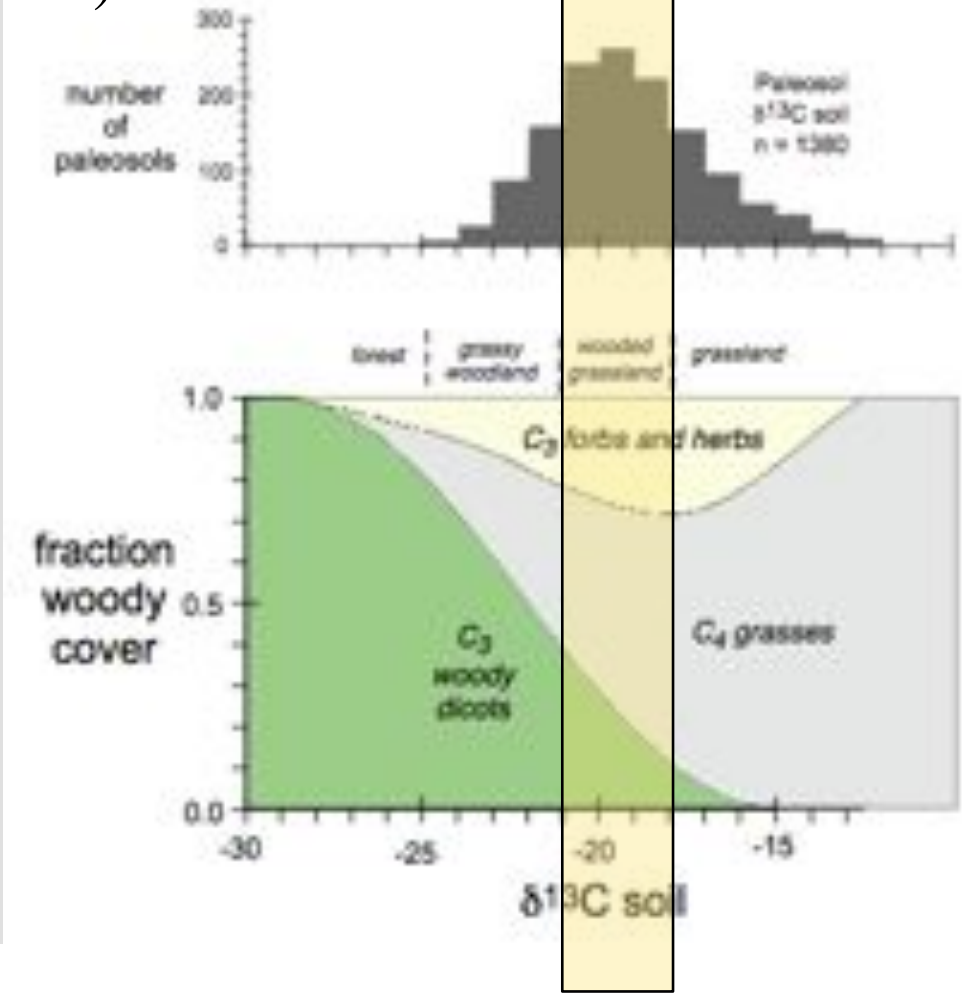

number of paleosols
300
200
100
0
Paleosol δ13C soil n = 1380
forest
grassy woodland
wooded grassland
grassland
1.0
0.5
0.0
fraction woody cover
C3 forbs and herbs
C3 woody dicots
C4 grasses
-30
-25
-20
-15
δ13C soil

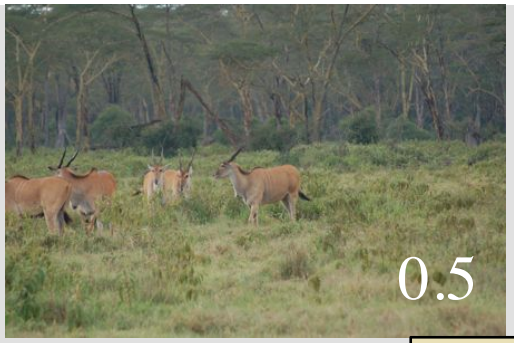
Grassland
(*ca*. 25%)

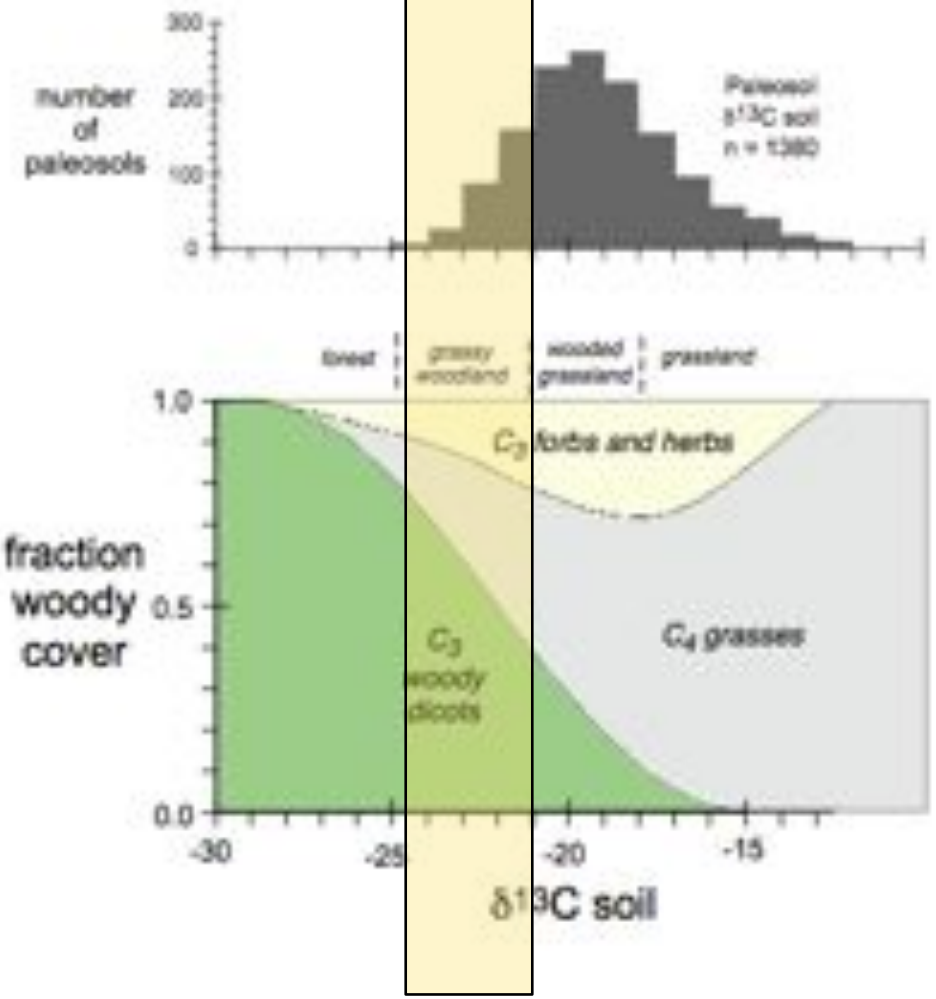




Wooded Grassland (*ca*. 60%)





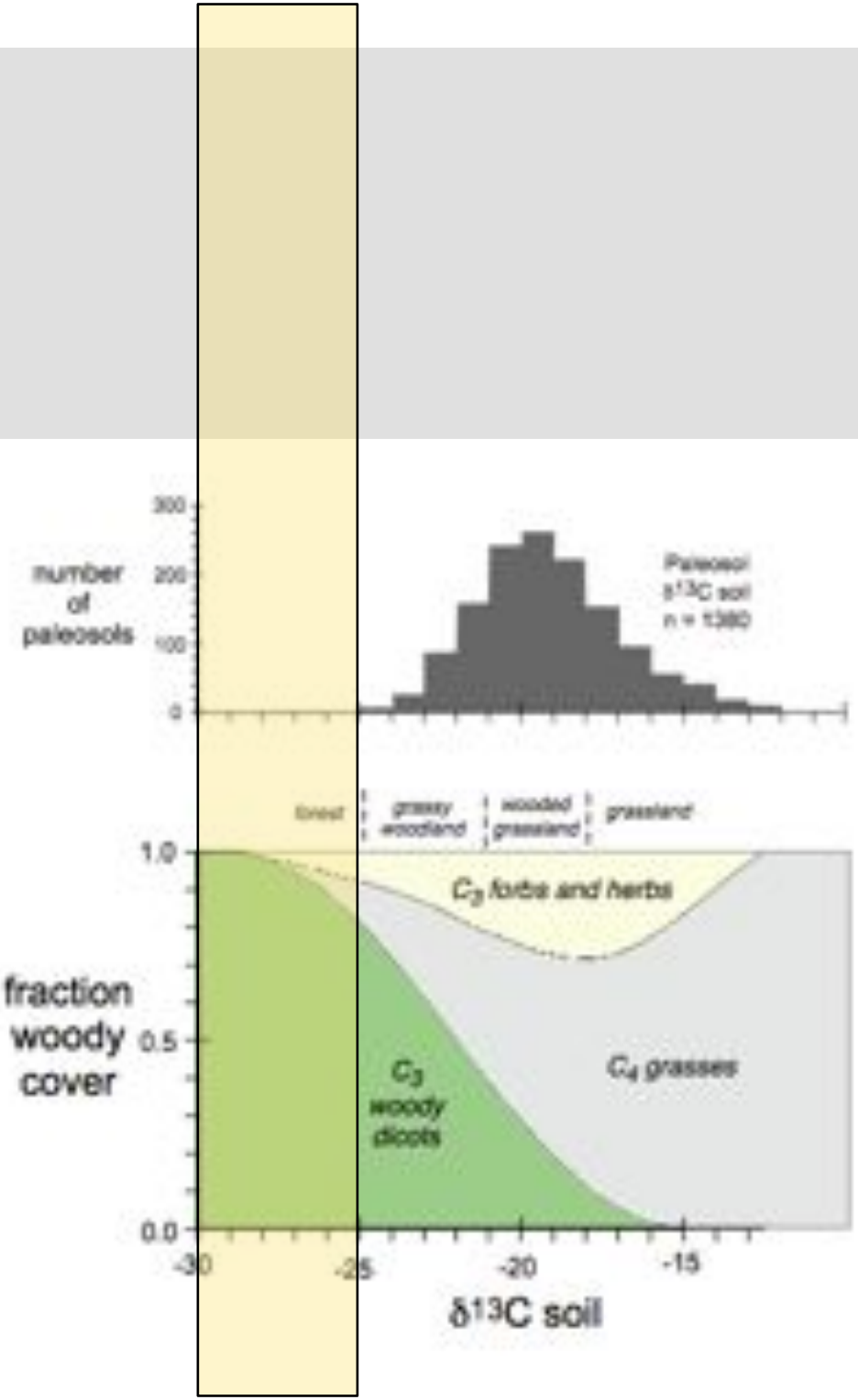


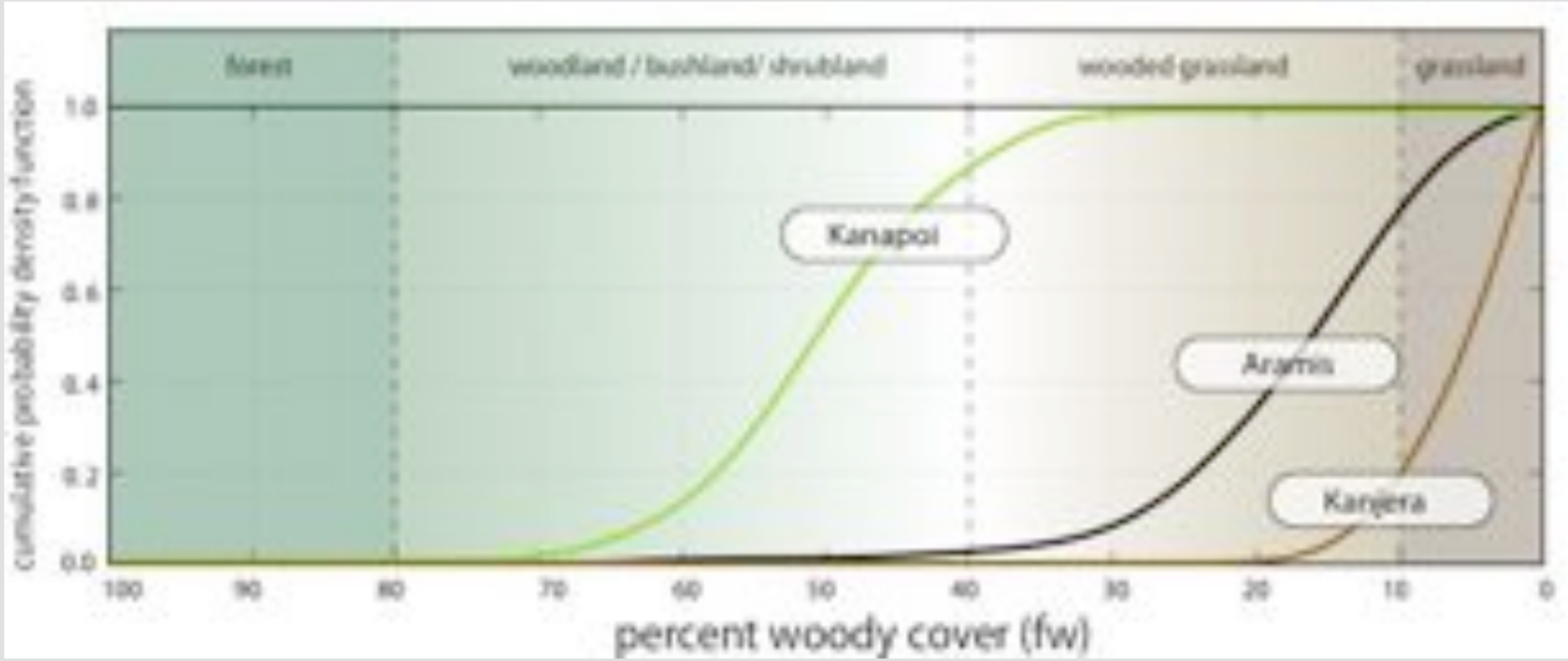
Woodland / Bushland / Shrubland (*ca*. 15%)

Forest
(< 1%)


0.8


0.9

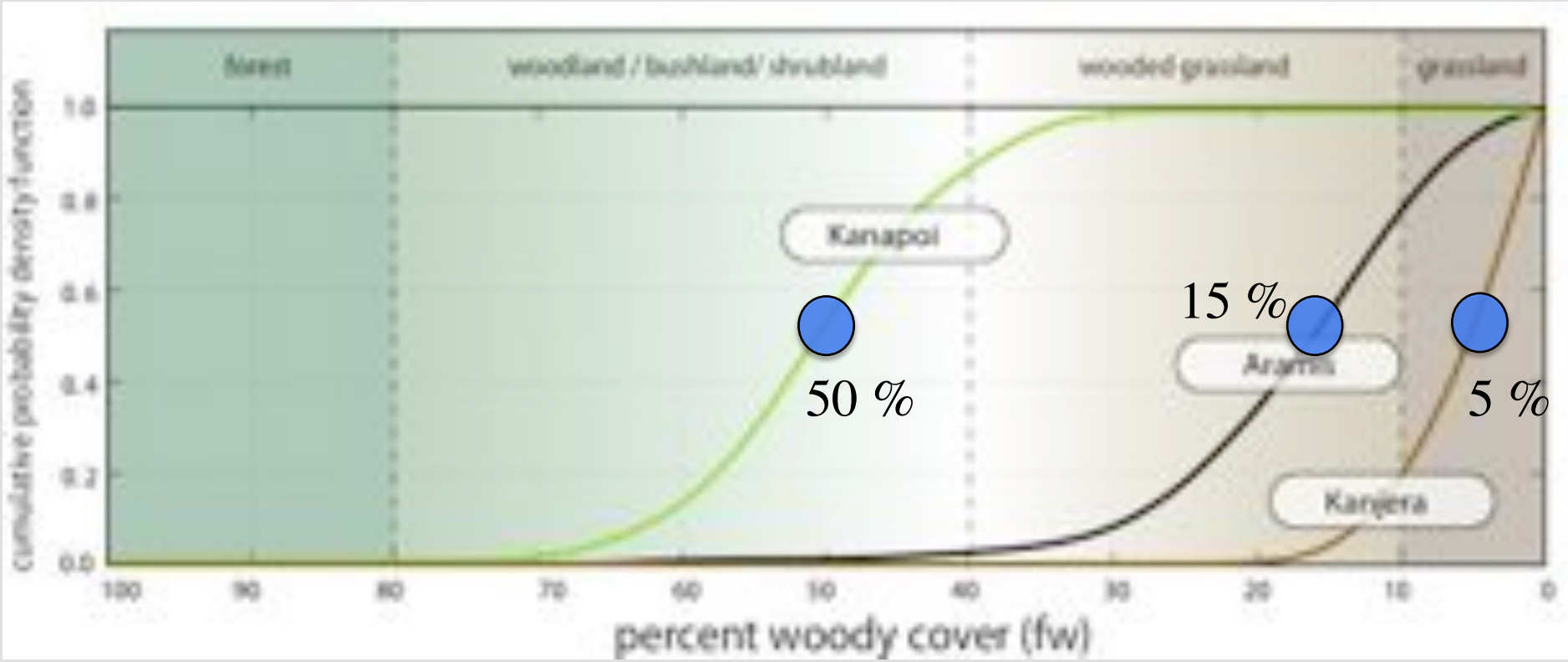

number of paleosols
300
200
100
0
Paleosol δ13C soil n = 1380
forest
grassy woodland
wooded grassland
grassland
1.0
0.5
0.0
fraction woody cover
C3 forbs and herbs
C3 woody dicots
C4 grasses
-30
-25
-20
-15
δ13C soil


forest
woodland / bushland/ shrubland
wooded grassland
grassland
cumulative probability density function
1.0
0.8
0.6
0.4
0.2
0.0
Kanapoi
Aramis
Kanjera
100
90
80
70
60
50
40
30
20
10
0
percent woody cover (fw)

50%

15%

5%


forest
woodland / bushland/ shrubland
wooded grassland
grassland
cumulative probability density function
1.0
0.8
0.6
0.4
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Kanapoi
50 %
15 %
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5 %
Kanjera
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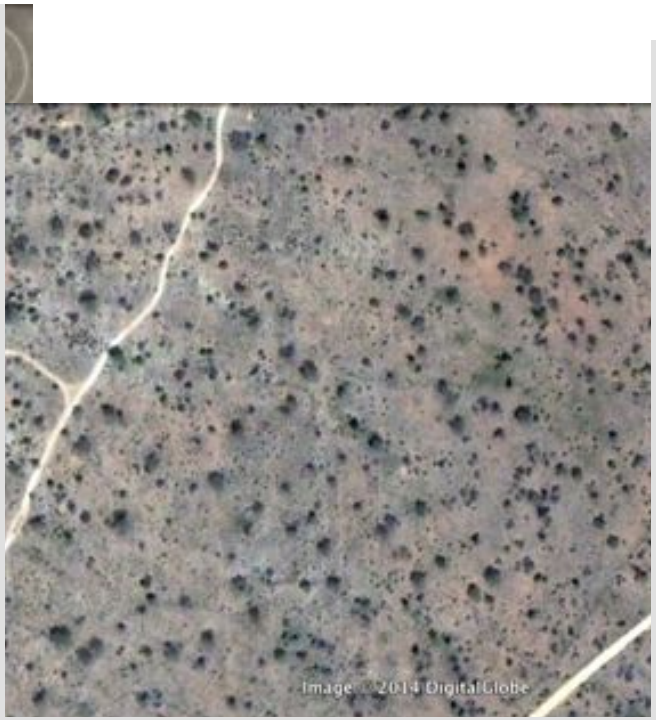
70
60
50
40
30
20
10
0
percent woody cover (fw)

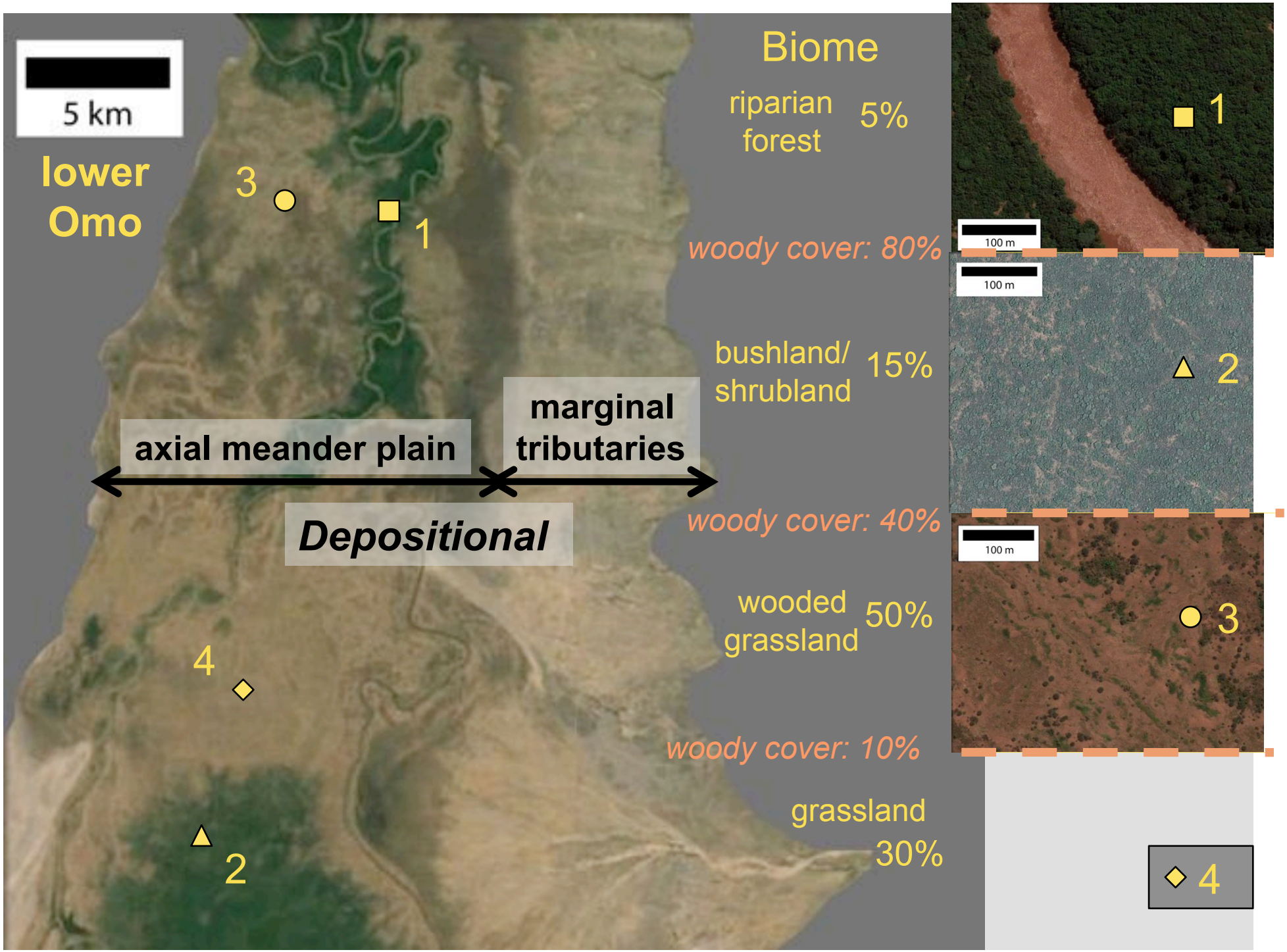


50%

15%

5%

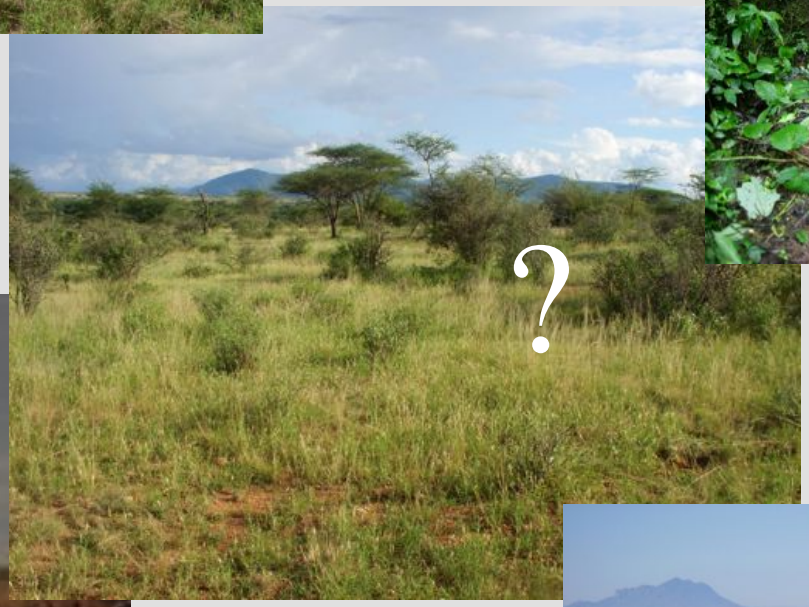
percent woody cover


5 km
lower Omo
3
1
2
4
Biome
riparian forest 5%
woody cover: 80%
bushland/ shrubland 15%
woody cover: 40%
wooded grassland 50%
woody cover: 10%
grassland 30%
axial meander plain
marginal tributaries
Depositional
100 m
100 m
100 m
1
2
3
4

What kind of vegetation?

How hot?

How dry?

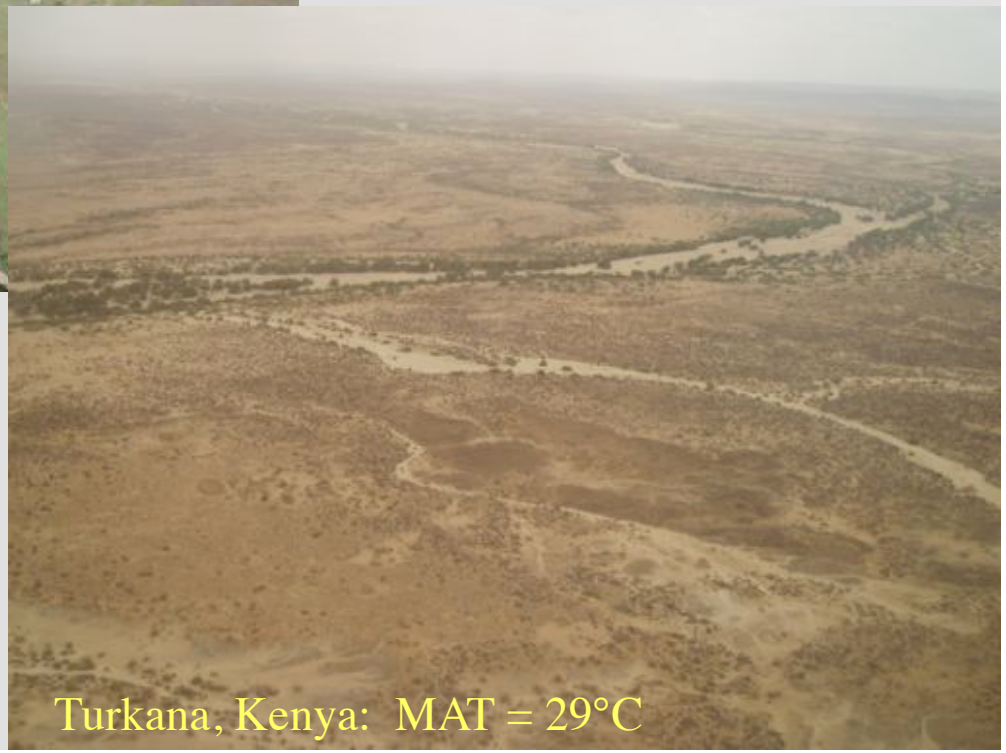


What did animals eat?

How much shade?

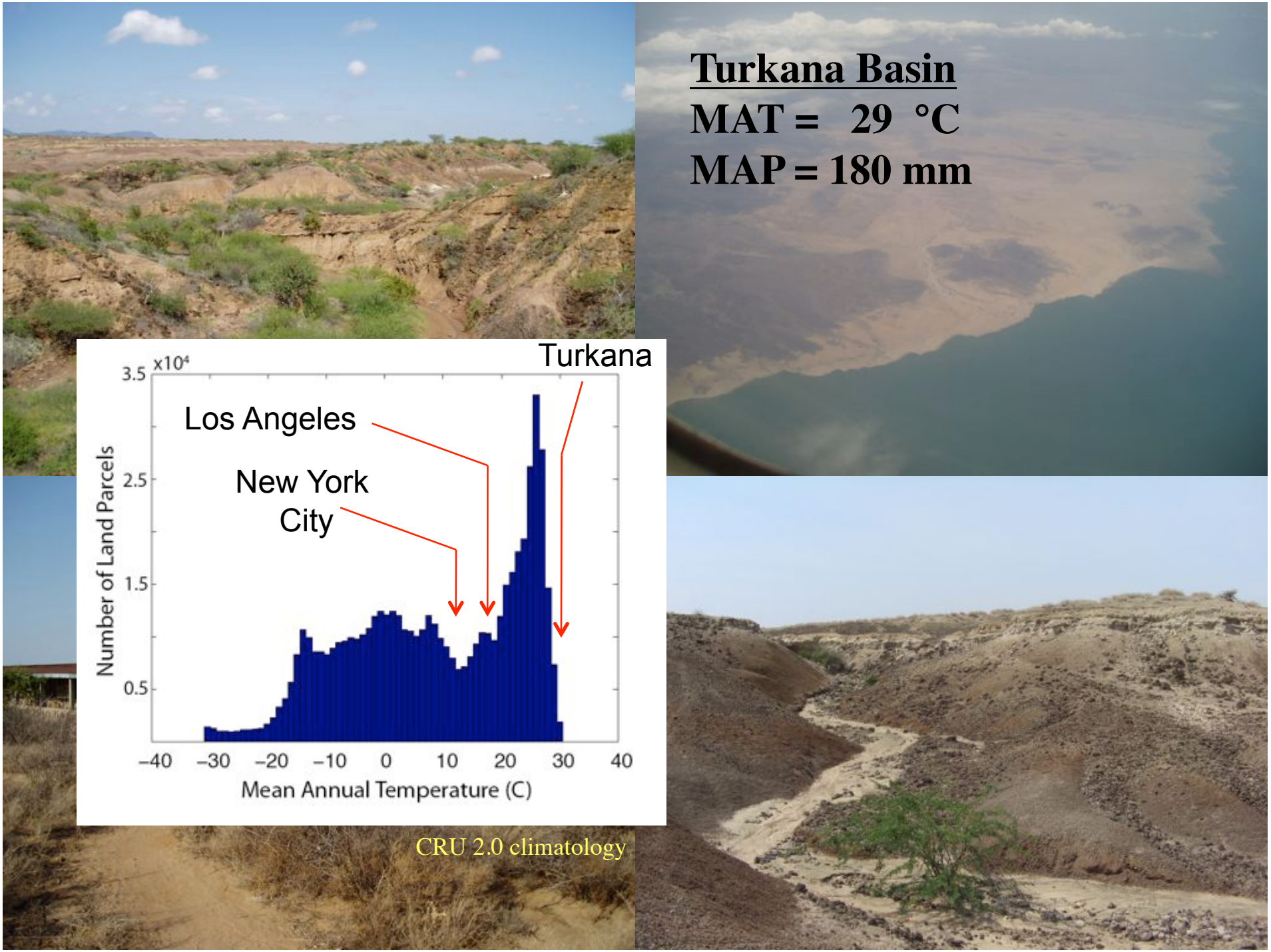
What about Temperature?

Nakuru NP, Kenya. MAT = 17 °C



Turkana, Kenya: MAT = 29°C


nature
Turkana tools
Earliest date yet for Acheulian culture at classic African hominin site
THE THINKING MACHINE
OPEN ALL HOURS
THE NEXT SMALL THING


Turkana Basin
MAT = 29 °C
MAP = 180 mm
Turkana
Los Angeles
New York City
x10⁴
3.5
2.5
1.5
0.5
Number of Land Parcels
−40 −30 −20 −10 0 10 20 30 40
Mean Annual Temperature (C)
CRU 2.0 climatology


THE 'clumped isotope' (Δ_{47}) thermometer

The isotope carbonate paleothermometer:

$$CaC^{16}O_3 + H_2{}^{18}O \leftrightarrow CaC^{18}O^{16}O_2 + H_2{}^{16}O$$

$$K = \frac{\left[CaC^{18}O^{16}O_2\right]\left[H_2{}^{16}O\right]}{\left[CaC^{16}O_3\right]\left[H_2{}^{18}O\right]} = \frac{R_{calcite}}{R_{water}} = f(T)$$

Although we can measure $R_{calcite}$, R_{water} is unknown.

The ^{12}C-^{18}O carbonate paleothermometer:

$$CaCO_3 + CaCO_3 \leftrightarrow CaCO_3 + CaCO_3$$

$$Ca^{12}C^{18}O^{16}O_2 + Ca^{13}C^{16}O_3 \leftrightarrow Ca^{12}C^{16}O_3 + Ca^{13}C^{18}O^{16}O_2$$

$$K = \frac{\left[Ca^{13}C^{18}O^{16}O_2\right]\left[Ca^{12}C^{16}O_3\right]}{\left[Ca^{13}C^{16}O_3\right]\left[Ca^{12}C^{18}O^{16}O_2\right]} = f(T)$$

$$CaCO_3 + 2\,H^{+} = Ca^{+2} + CO_2 + H_2O$$

Isotopologues of CO_2

$^{12}C^{16}O^{16}O$	mass: 44
$^{12}C^{16}O^{17}O$	45
$^{13}C^{16}O^{16}O$	45
$^{12}C^{16}O^{18}O$	46
$^{12}C^{17}O^{17}O$	46
$^{13}C^{16}O^{17}O$	46
$^{13}C^{16}O^{18}O$	47
$^{13}C^{17}O^{17}O$	47
$^{13}C^{17}O^{18}O$	48

Hence: Δ_{47}

The ^{12}C-^{18}O carbonate paleothermometer.

Measure all "isotopologues"

Compare "clumped" value with random (high-temperature) value.

$$\Delta_{47} = M_{47\text{-meas}} - M_{47\text{-random}}$$

Clumped Isotope Paleothermometry

Analytical Precision:
0.010‰ ⇒ 2°C

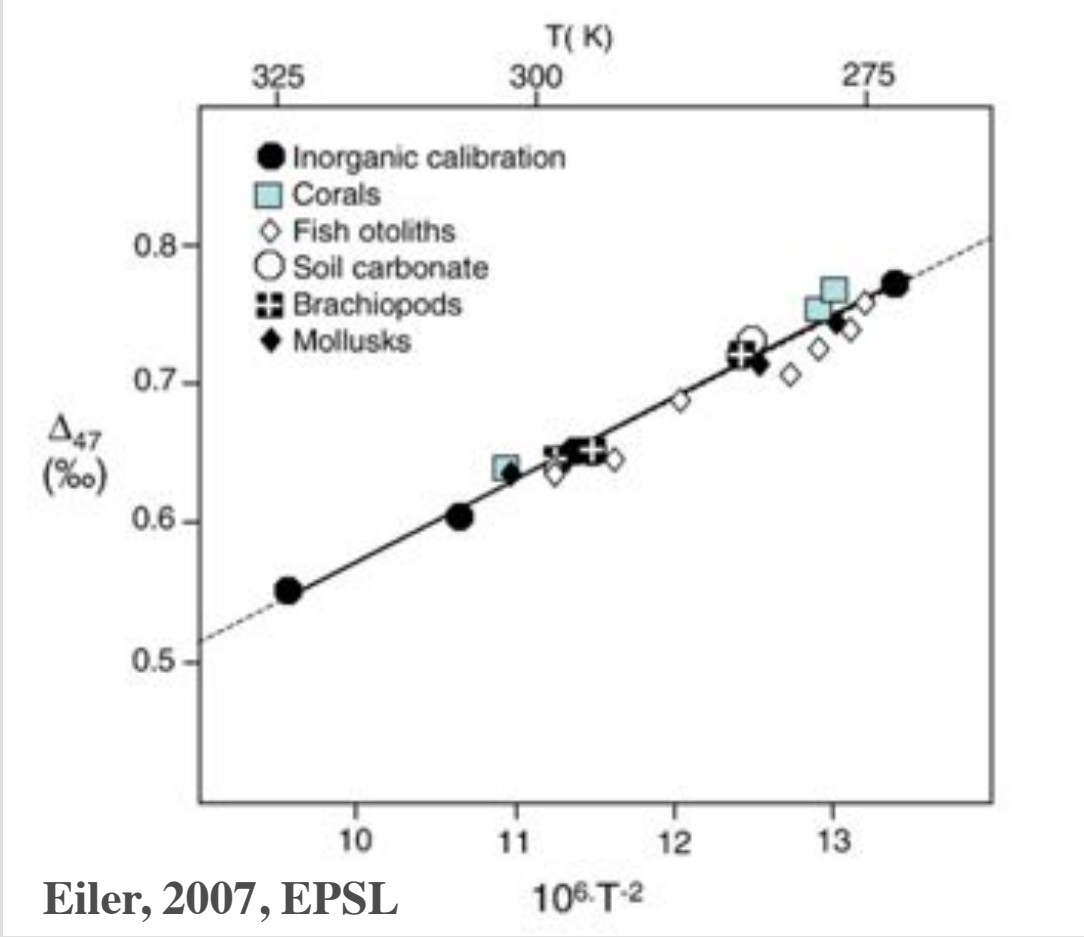
A very small signal(!):

Δ_{47}, 0-50 °C: 0.2 ‰

compare with:

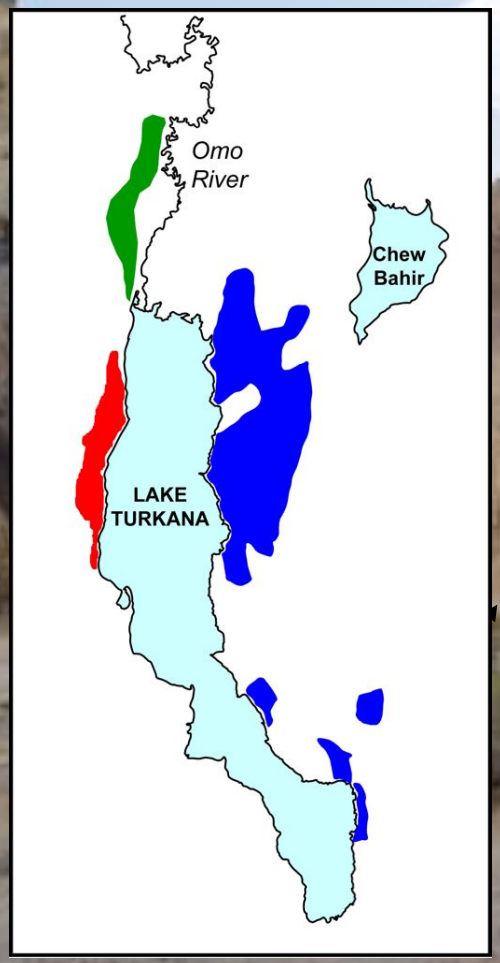
δ^{13}C in plants: ~15 ‰

δ^{18}O in marine carb: ~5 ‰



Eiler, 2007, EPSL

Application to Turkana Paleosol Carbonates



Soil Carbonates

$CaCO_3$ (micritic calcite)

<u>Need:</u>

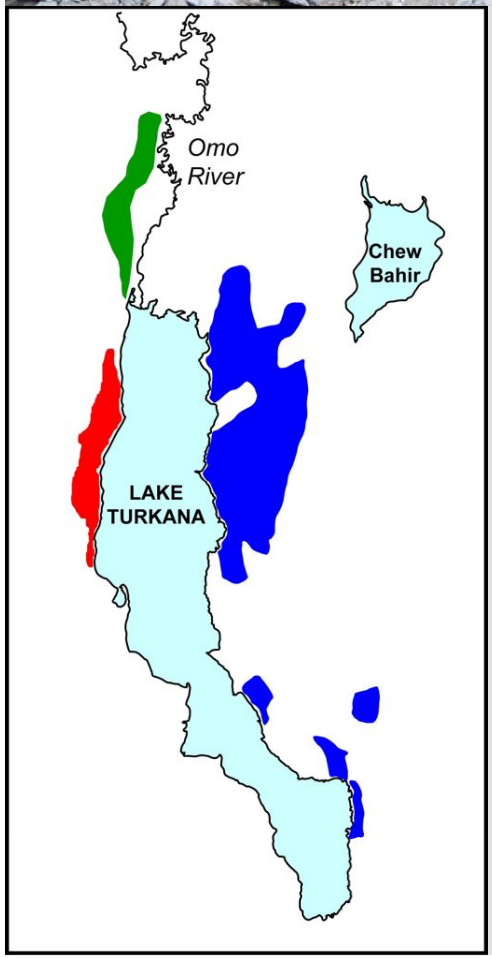
Ca^{++} (mineral weathering, dust flux)

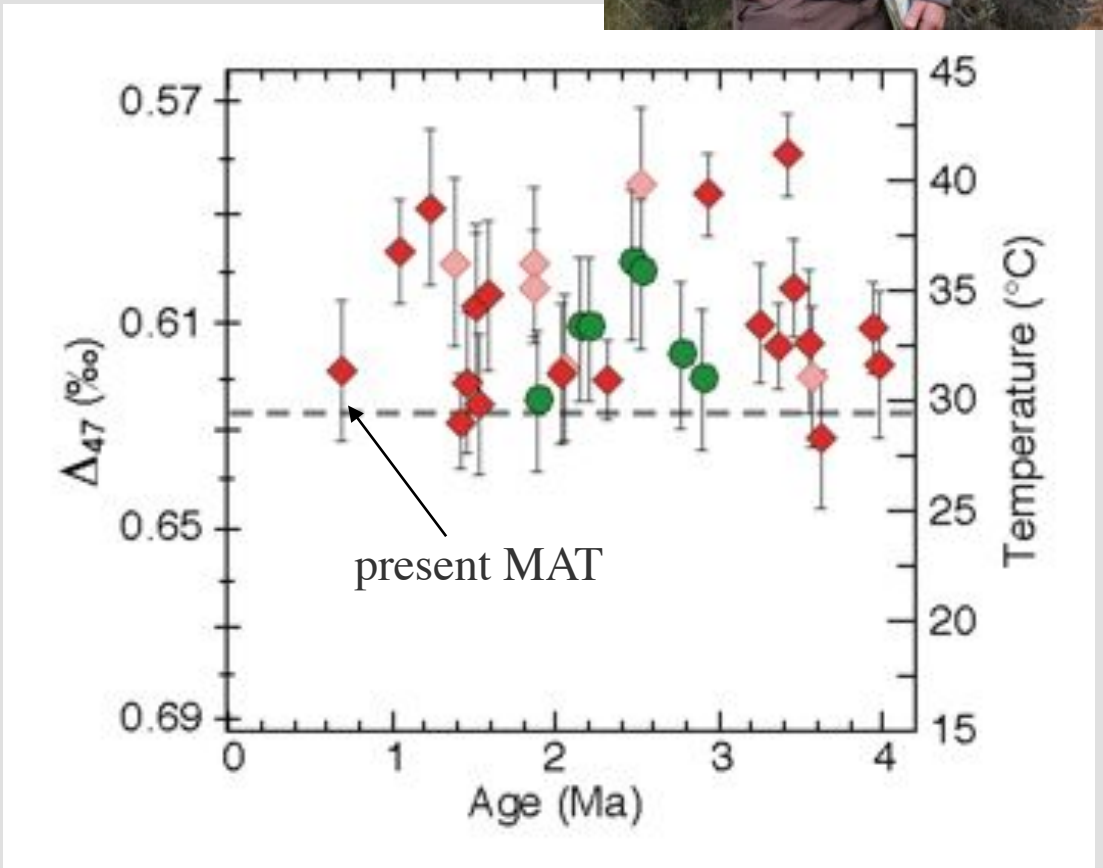
CO_2 (plant respiration, atmosphere)

H_2O (rainfall, groundwater)

depth of formation (below significant daily temperature fluctuation)

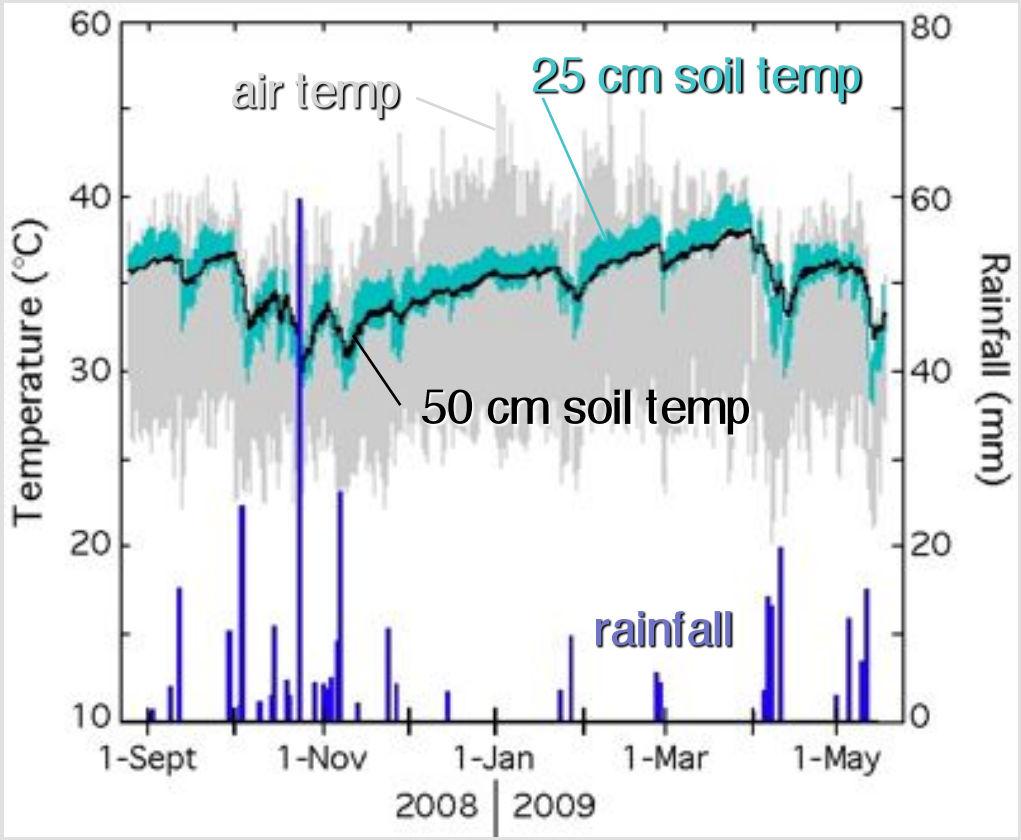
The Results....

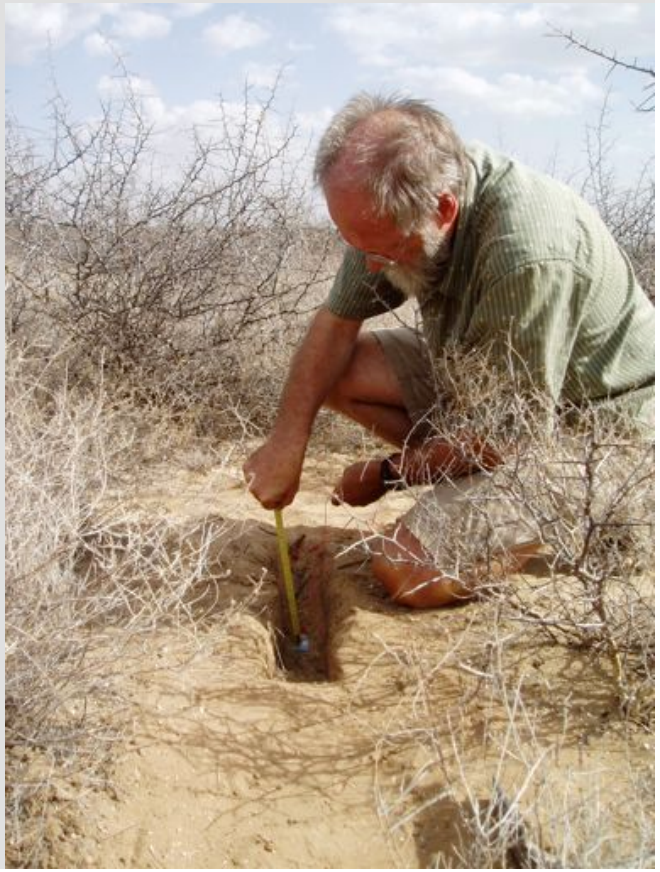




Passey et al., 2010

Measured Soil Temps, Turkana Basin, Kenya

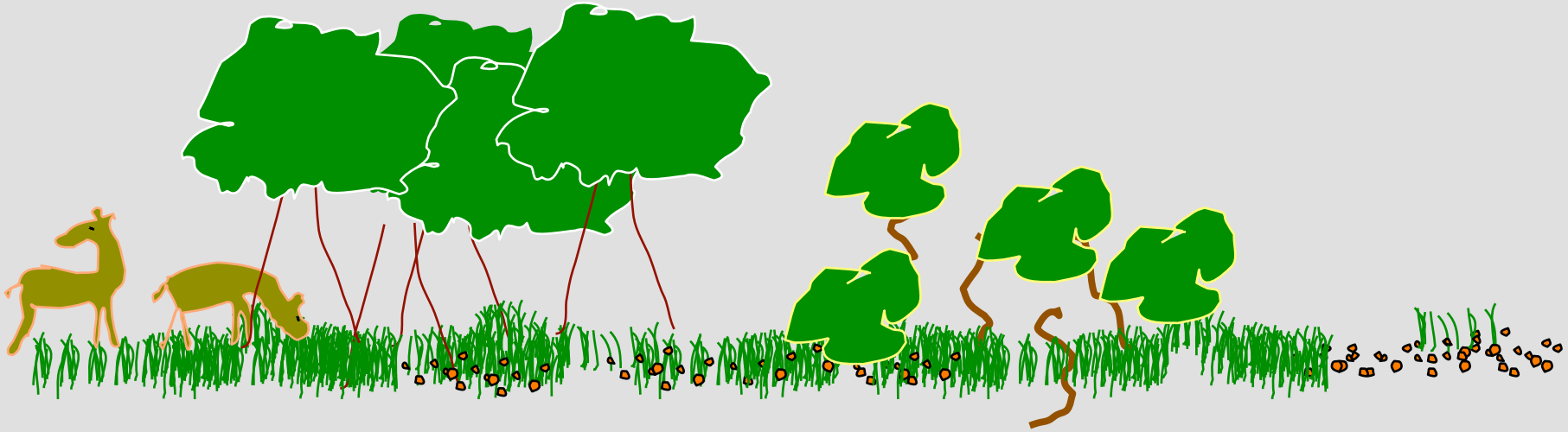




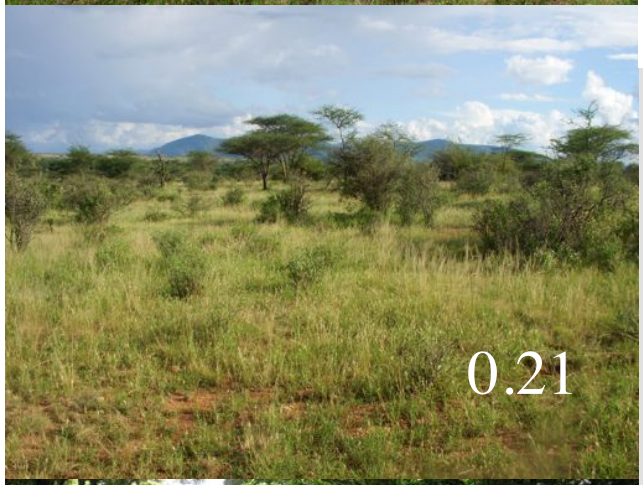
mean air temp: 31.1°C

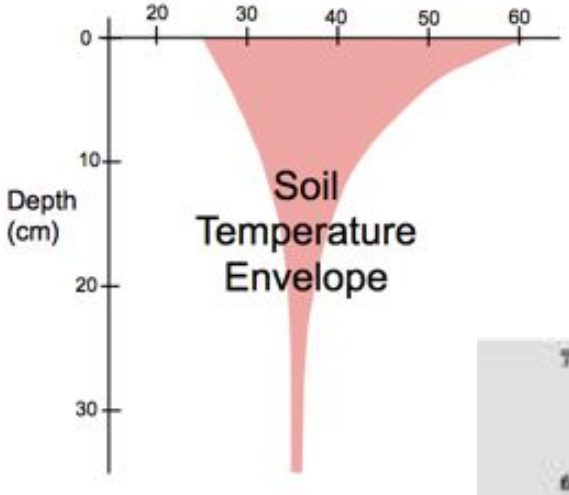
mean 50 cm: 35.9°C

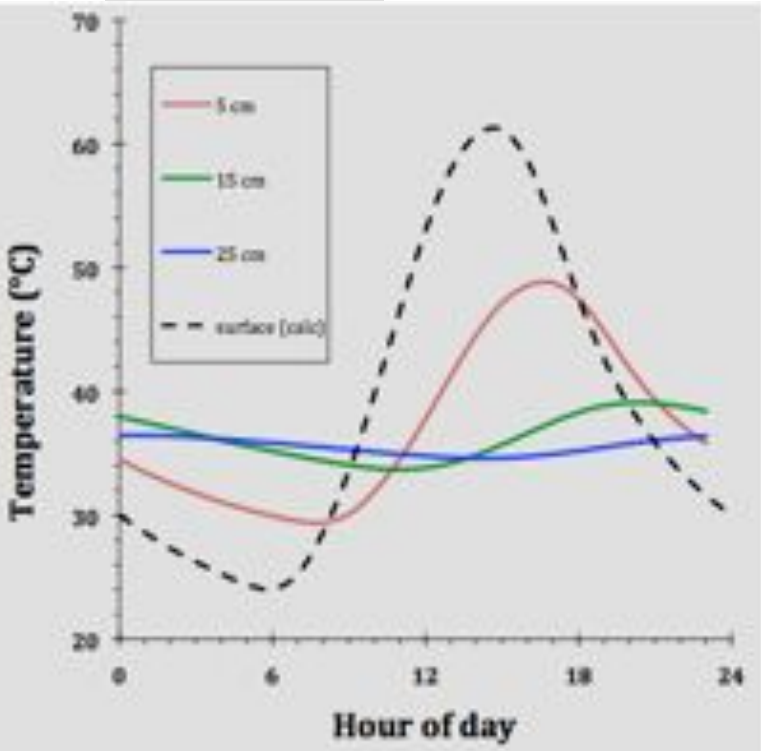
Measured Soil Mean Temperatures, Kenya (one year average at 30 cm)



	Forest	Bush	Open
Ileret (MAT 29°)	30.3	34.1	35.9
Samburu (MAT 24°)	26.2	29.0	33.6
Nairobi (MAT 18°)	18.4	19.5	21.8



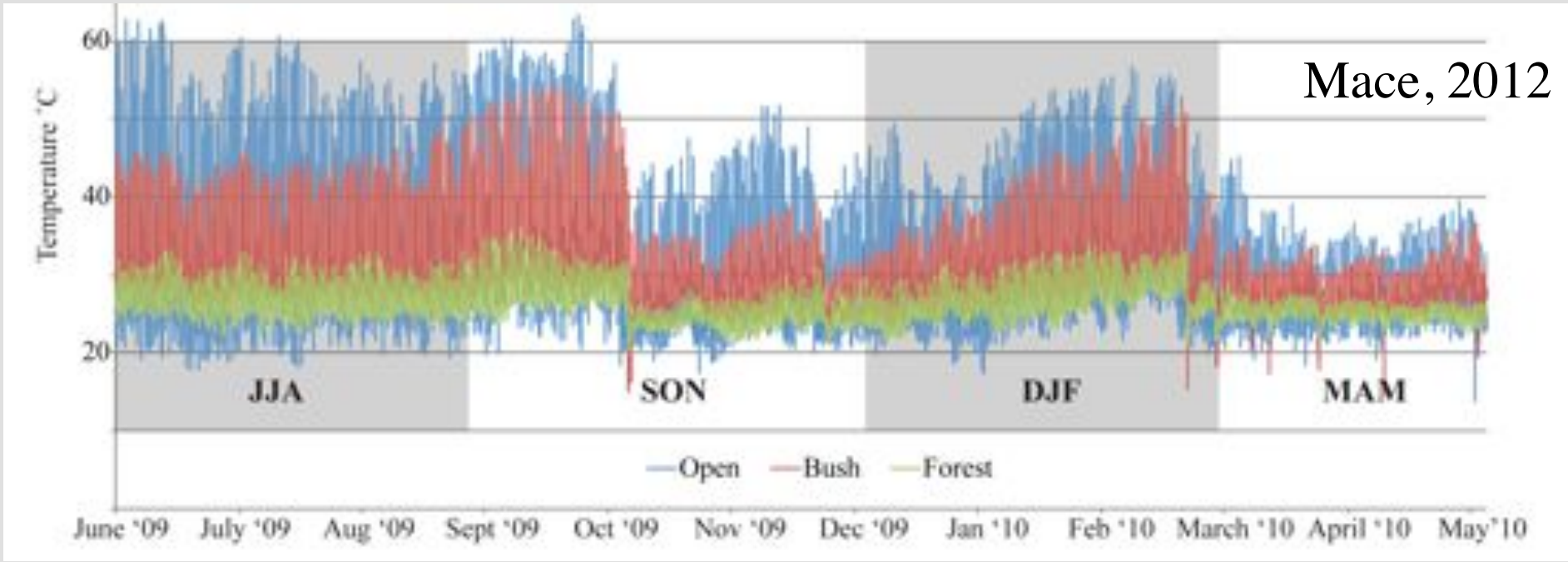




Use time-depth relationship to estimate "composite-temperature day"
(Crank, 1956; Lin et al, 2011; Mace, 2012)

Grassland
June 2009

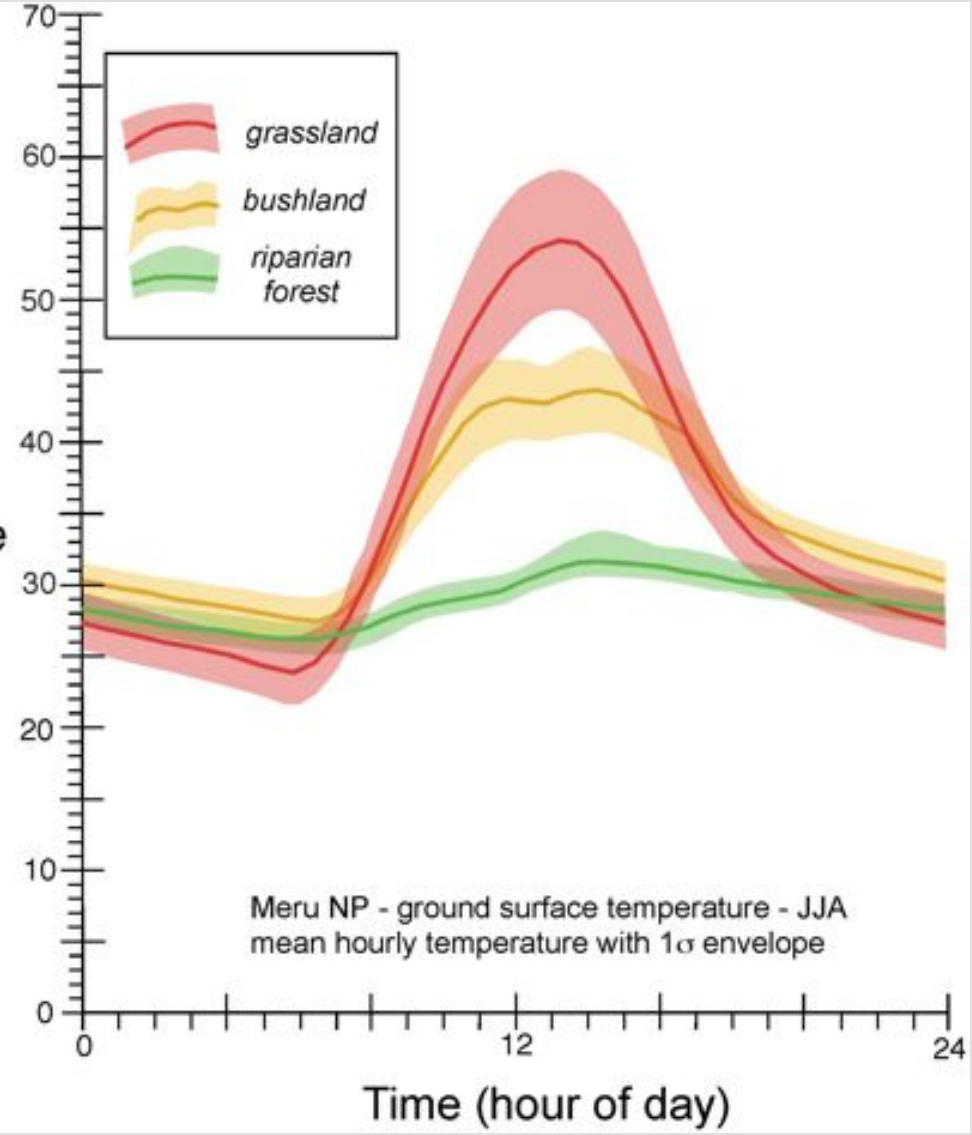
Meru NP.
Tana River



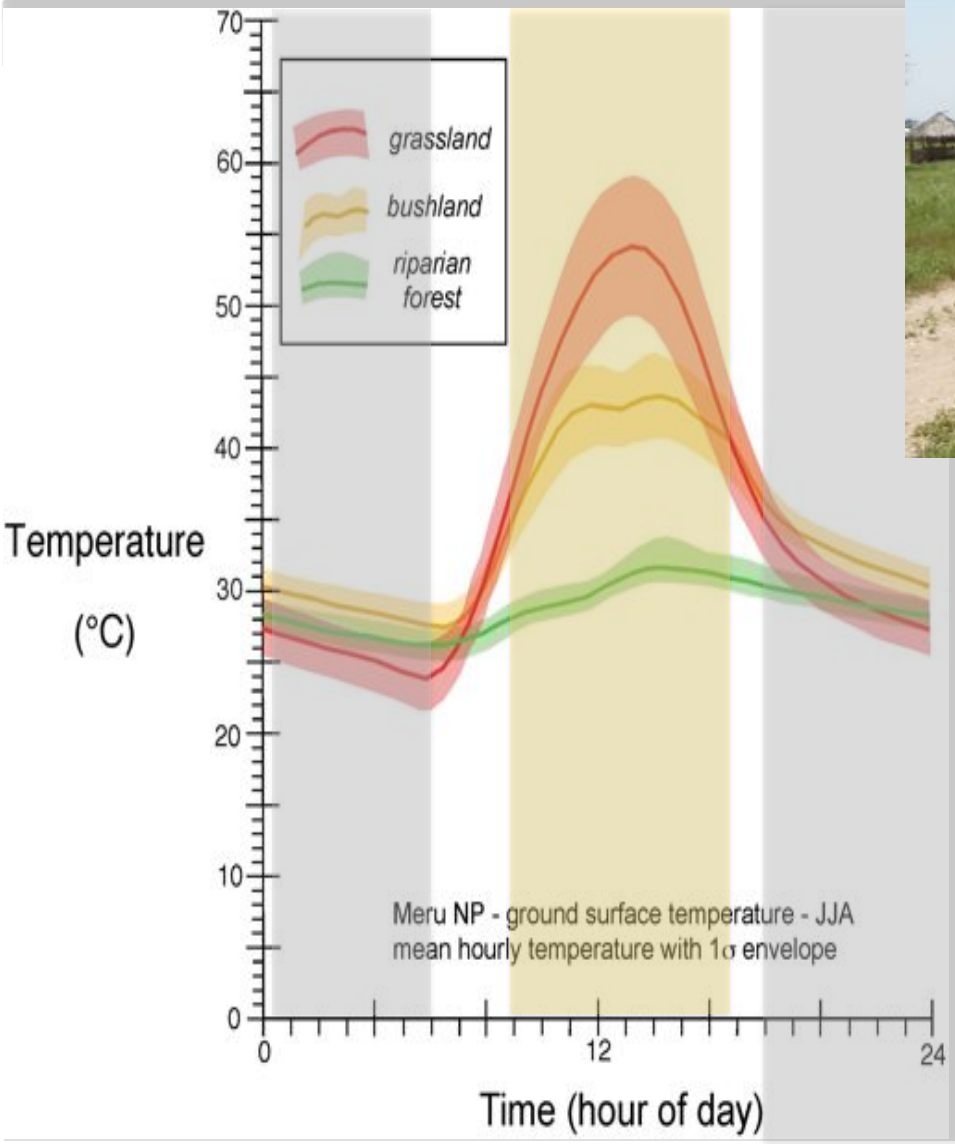
Mace, 2012

Bush
June 2009

Riparian
forest
June 2009


70
60
50
40
30
20
10
0
grassland
bushland
riparian forest
Temperature
(°C)
Meru NP - ground surface temperature - JJA
mean hourly temperature with 1σ envelope
0
12
24
Time (hour of day)

9 am – 5 pm


grassland
bushland
riparian forest
Temperature (°C)
70
60
50
40
30
20
10
0
0
12
24
Meru NP - ground surface temperature - JJA
mean hourly temperature with 1σ envelope
Time (hour of day)

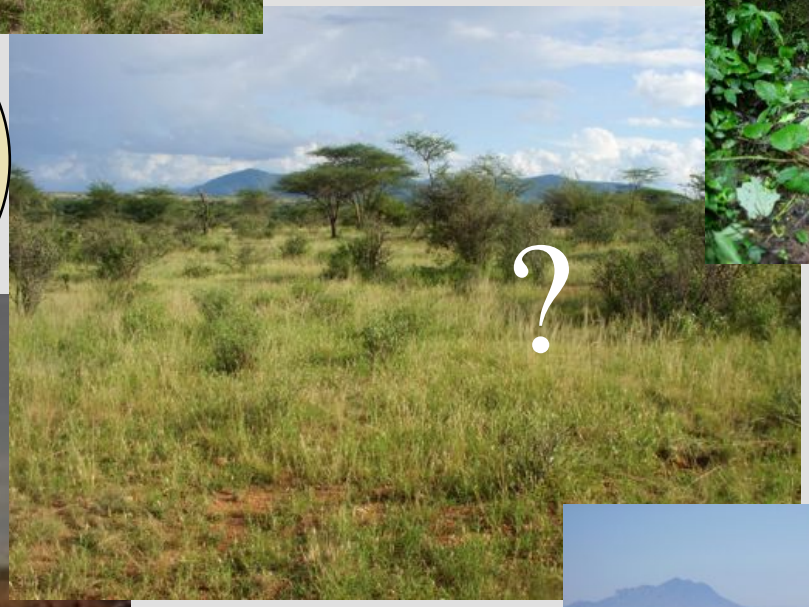

nature
Turkana tools
Earliest date yet for Acheulian culture at classic African hominin site
THE THINKING MACHINE
OPEN ALL HOURS
THE NEXT SMALL THING

ARIDITY

What kind of vegetation?

How hot?

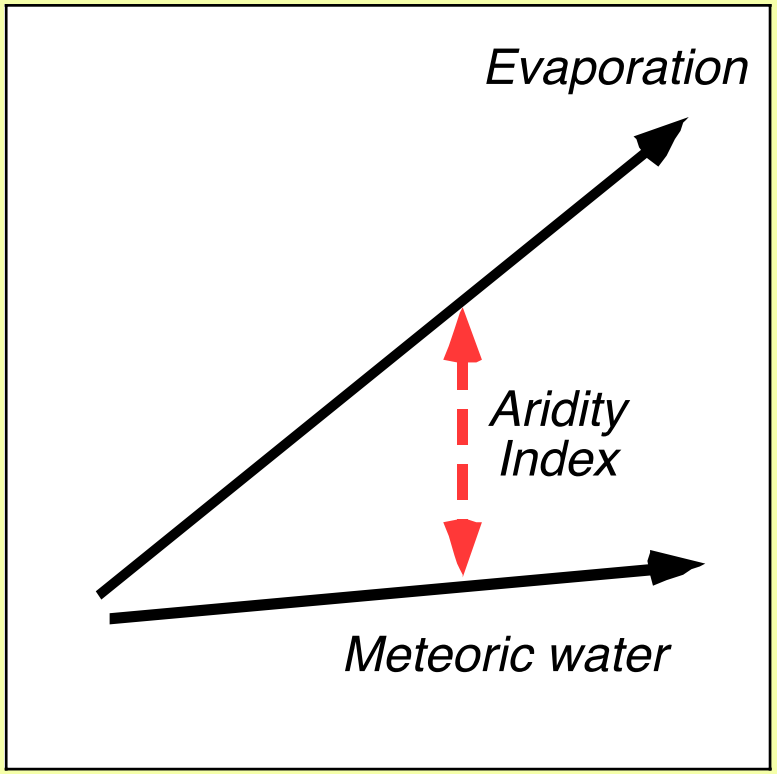
How dry?



What did animals eat?

How much shade?

Conceptual Model



$\delta^{18}O$

water deficit
(=increasing aridity)

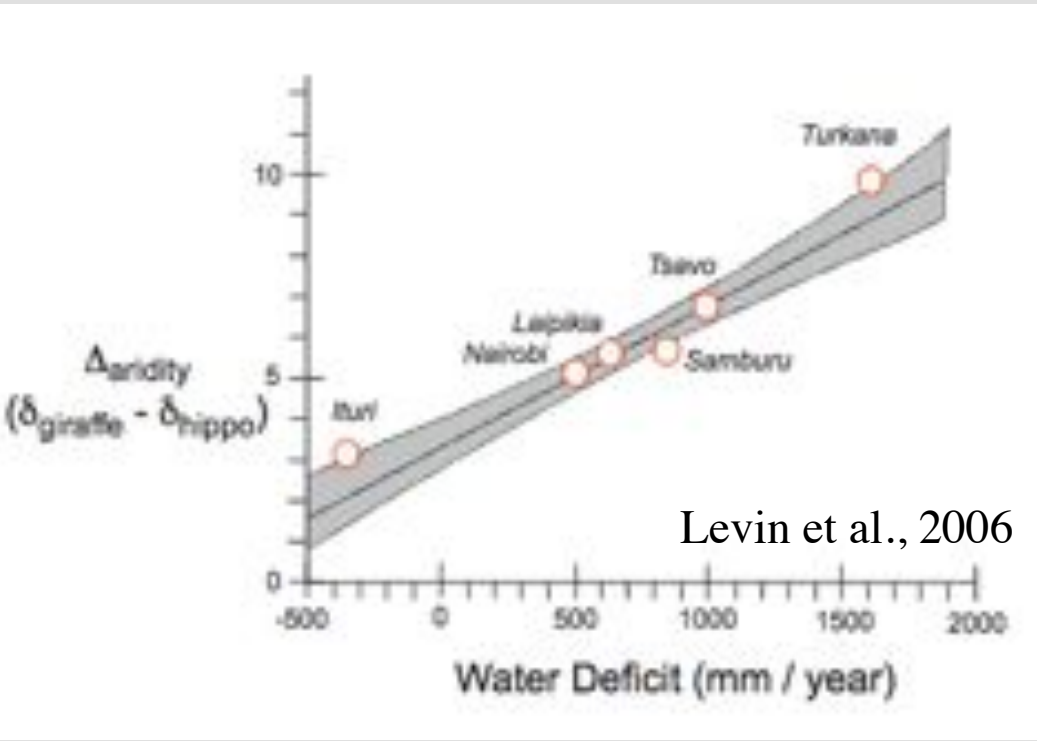
Paleo-aridity

=

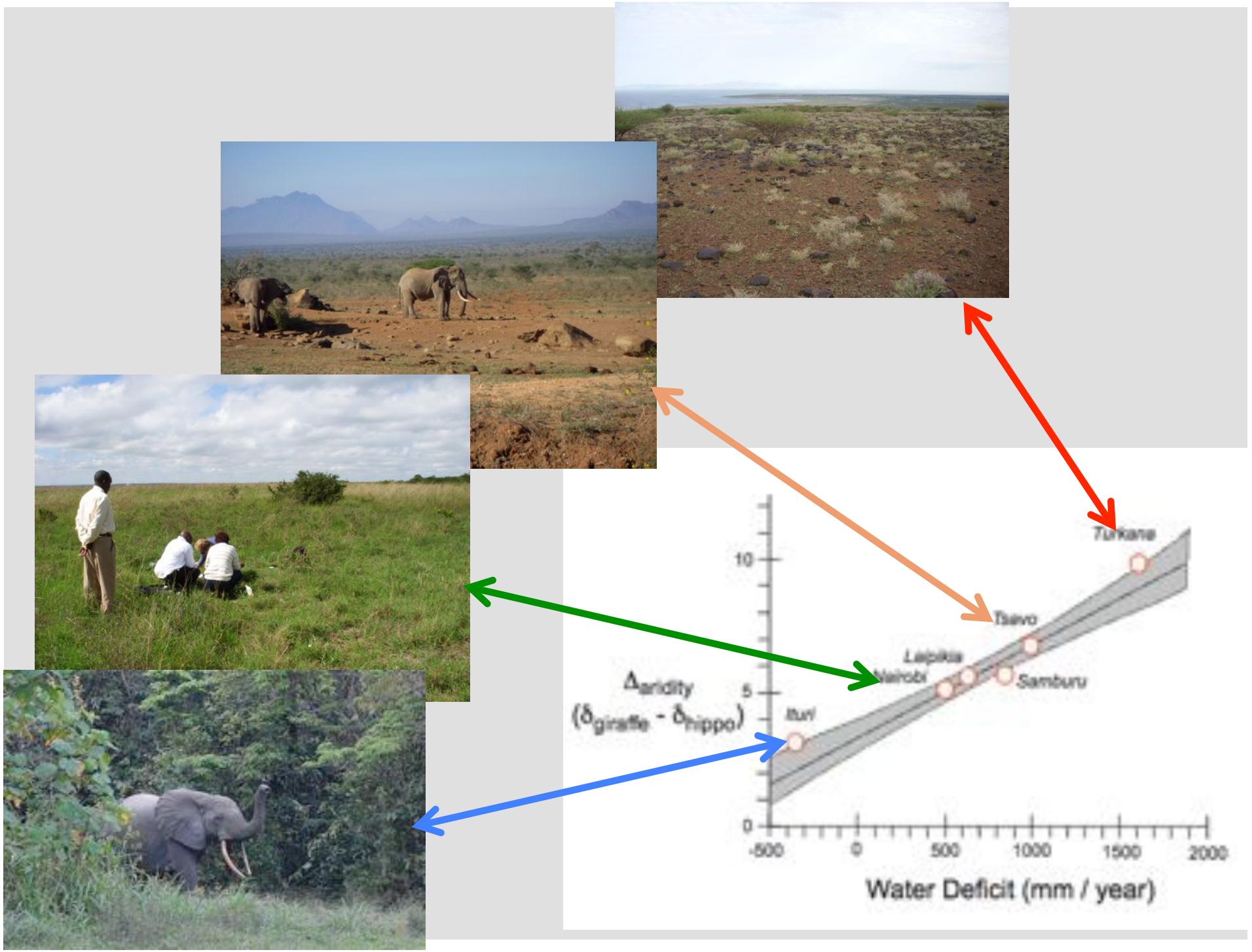
()

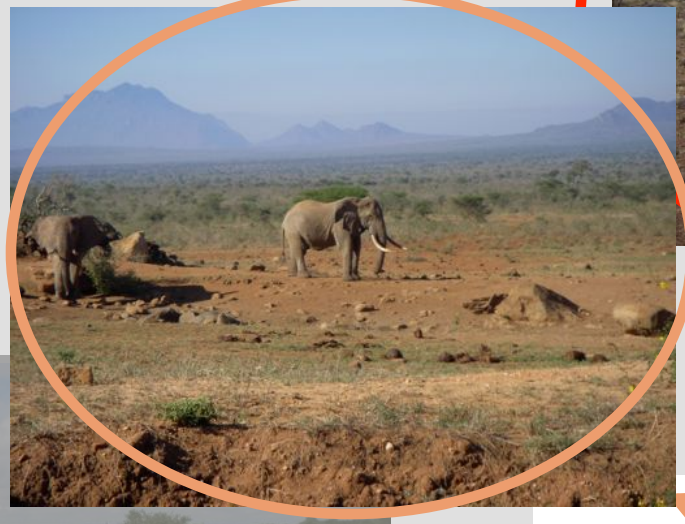
-

()



Levin et al., 2006

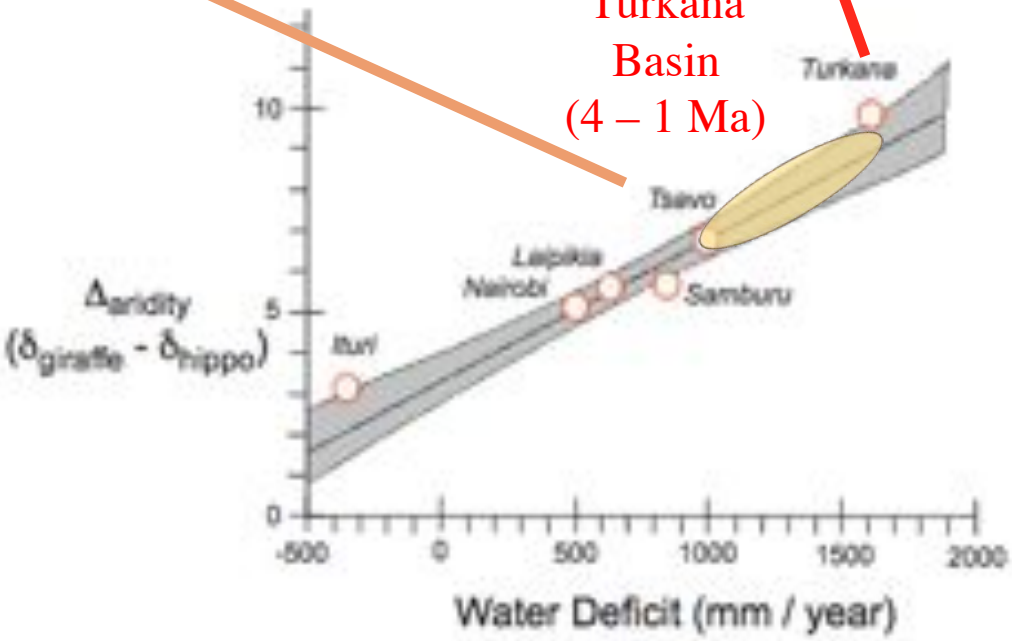

Turkana
Baiyo
Lepikia
Nairobi
Samburu
Ituri
$\Delta_{aridity}$
$(\delta_{giraffe} - \delta_{hippo})$
10
5
0
-500
0
500
1000
1500
2000
Water Deficit (mm / year)



Paleo-aridity:
xeric environments

Not mesic
environments

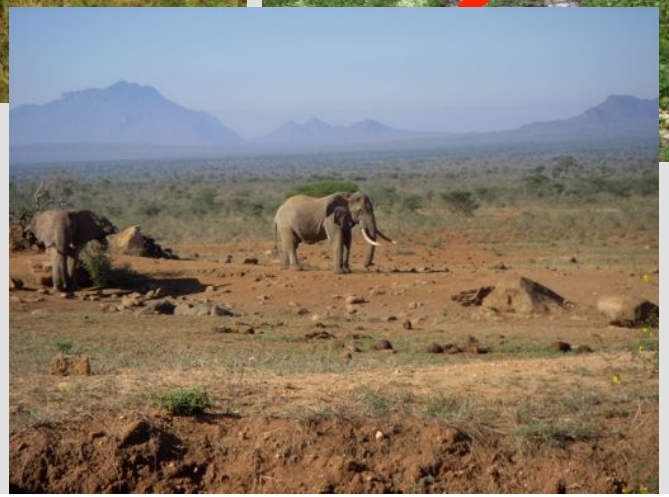
Turkana
Basin
(4 – 1 Ma)



VEGETATION

What kind of vegetation?

- Mixed
- C_3 / C_4

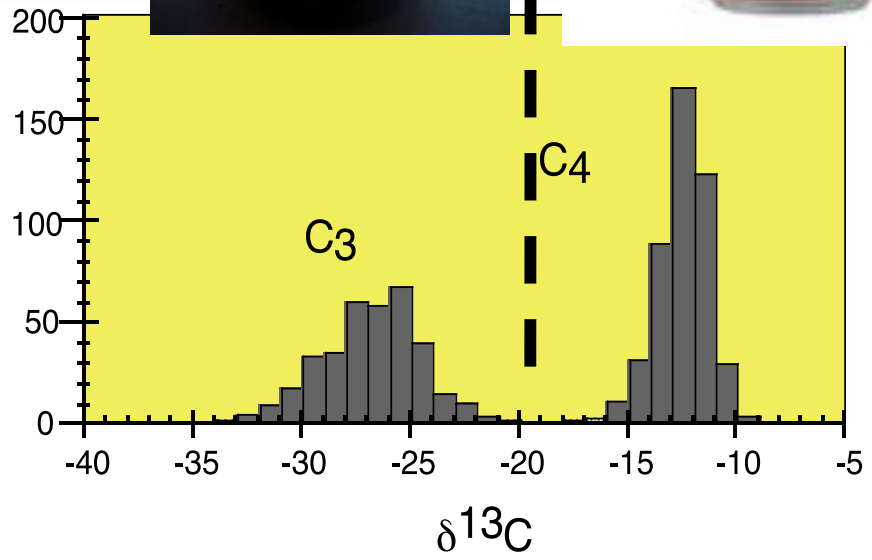


DIETS

C_4 plants: Which foods?

- C_3

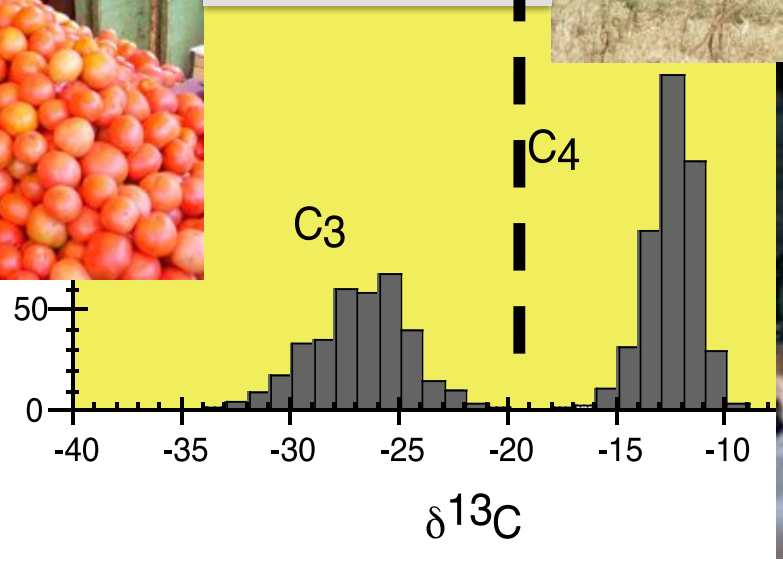
- C_4



C_4 plants: Which foods?

- C_3 plants

- C_4 plants



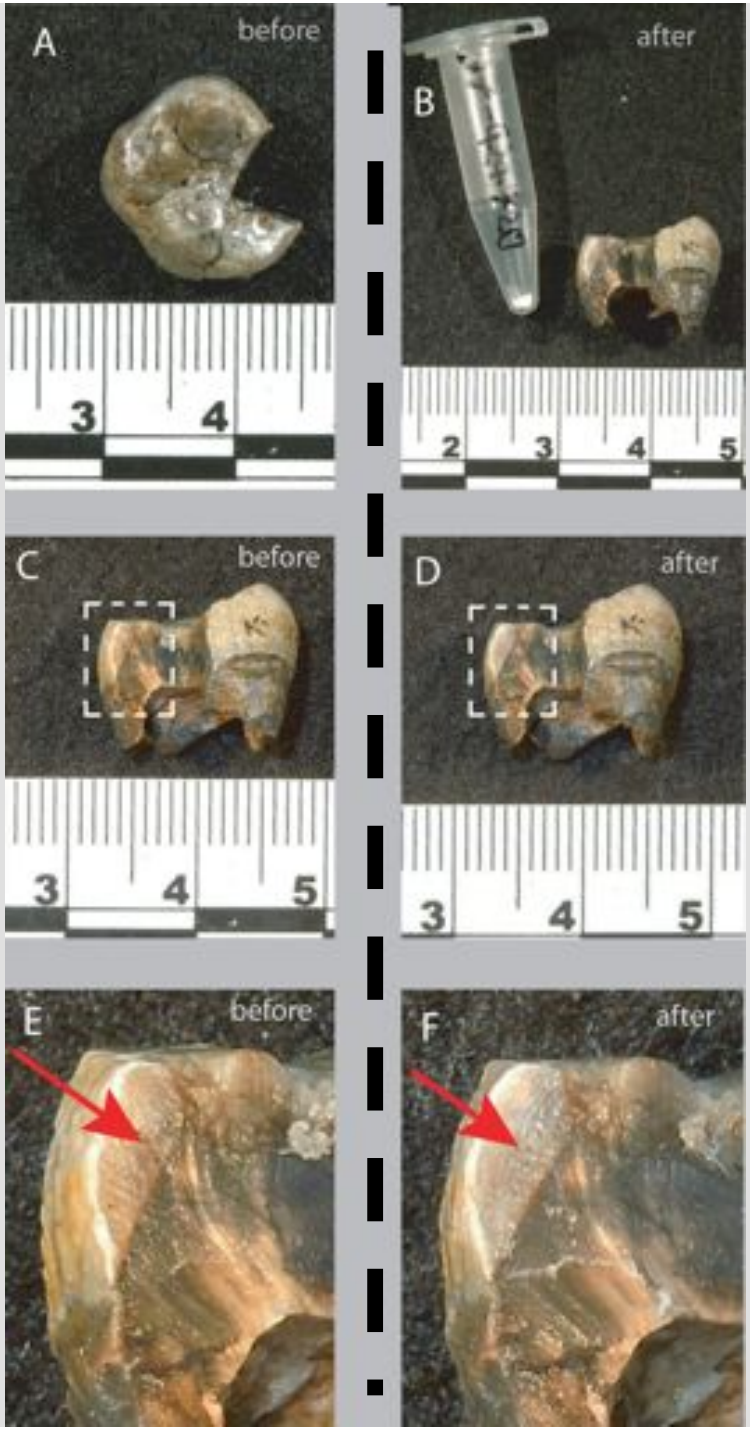
www.awf.org/files/3972_image2_
western_gorilla_MWatson

www.bonoboincongo.com/wp-content/themes/lomami

What did hominins eat?

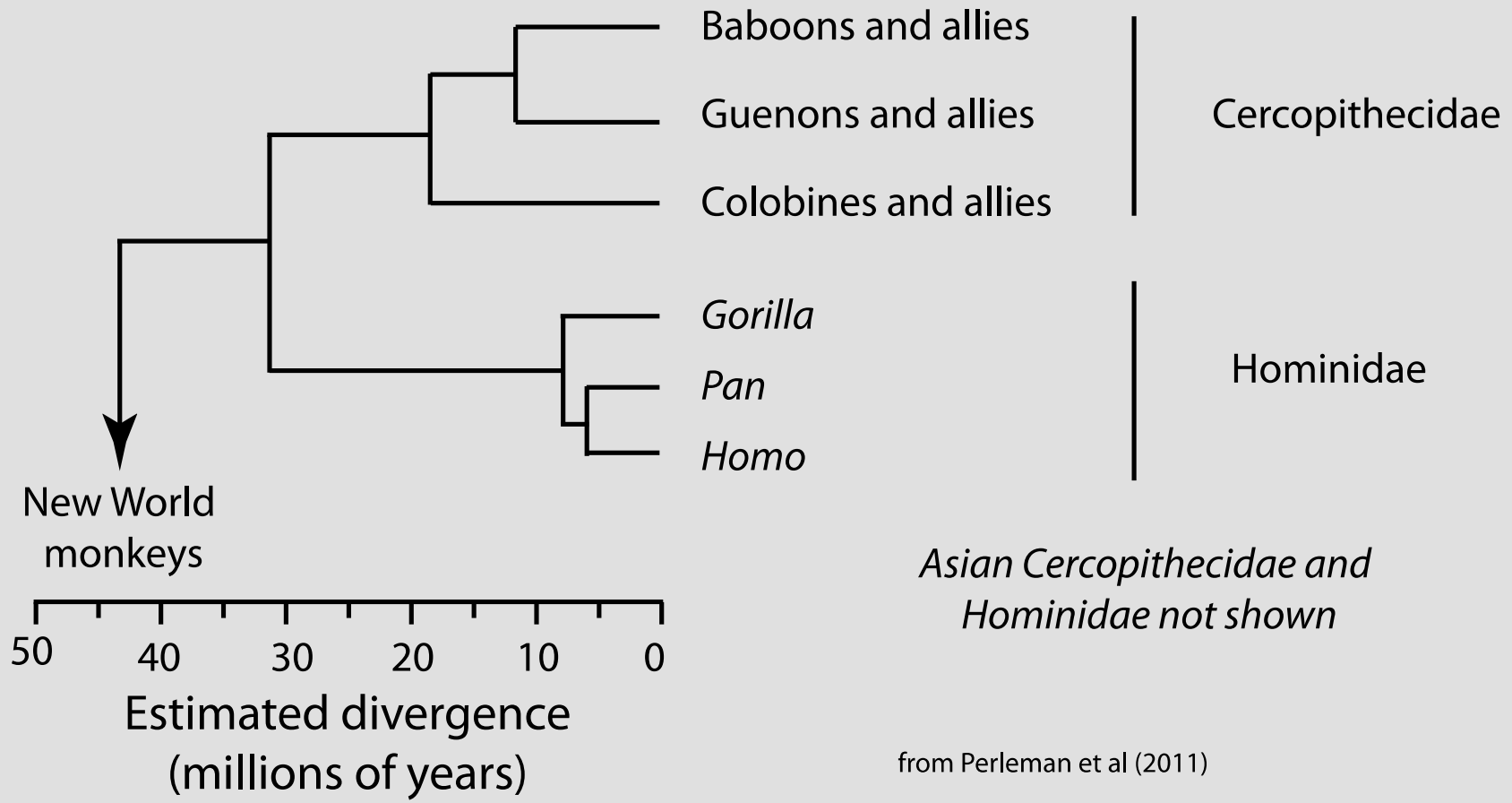
- 1000 km
- 1.9 to 1.5 Ma

BEFORE



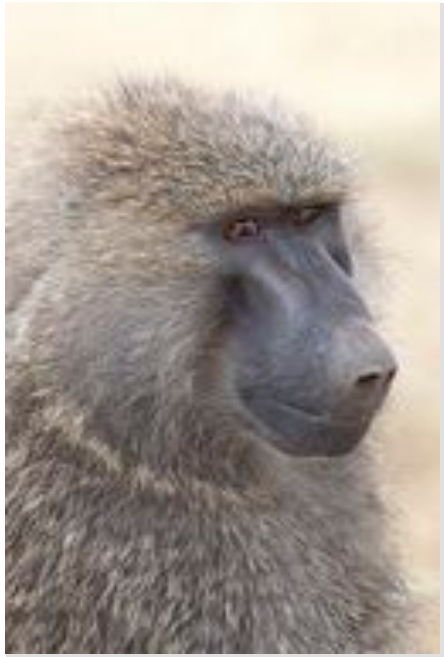
AFTER

African monkeys and apes



Asian Cercopithecidae and Hominidae not shown

from Perleman et al (2011)



Baboon

Guenon

Colobus

All images from -wikipedia

Chimpanzee

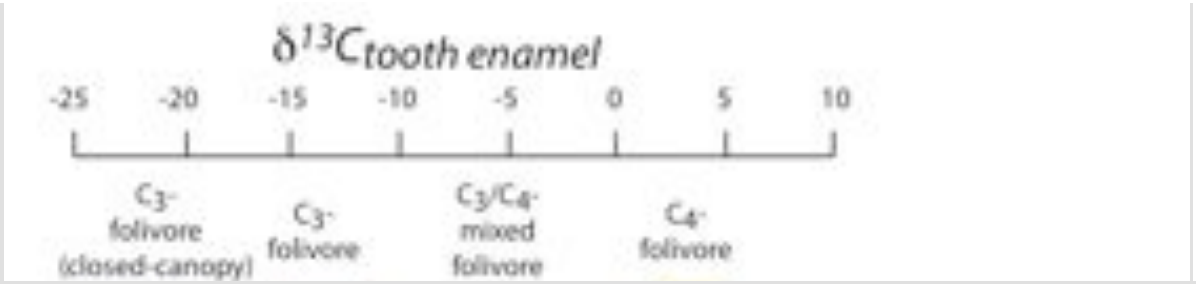
Gorilla

Human

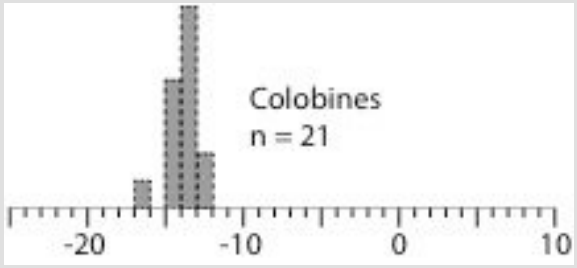
What constitutes a "pure–C_3" diet for primates?

1. Diet of "pure-C_3" folivore

2. Data from:
   Cerling et al., 2004, 2013, unpublished
   Nelson et al., 2013



Modern African primates: monkeys and apes



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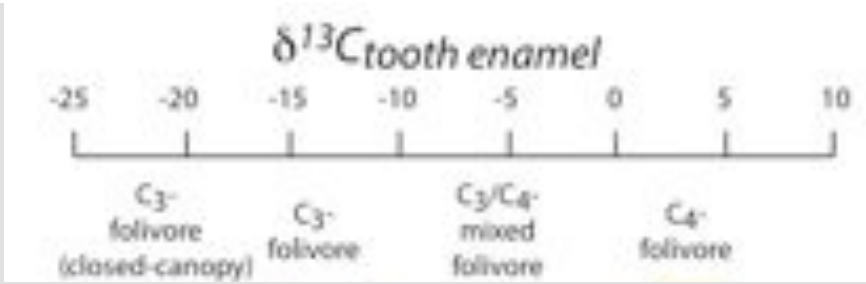
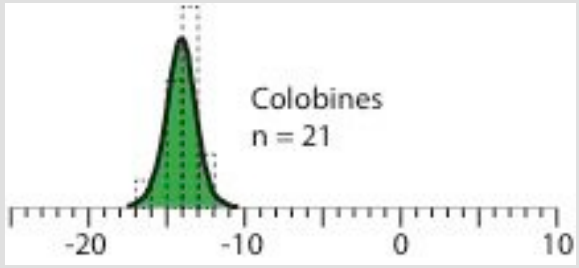


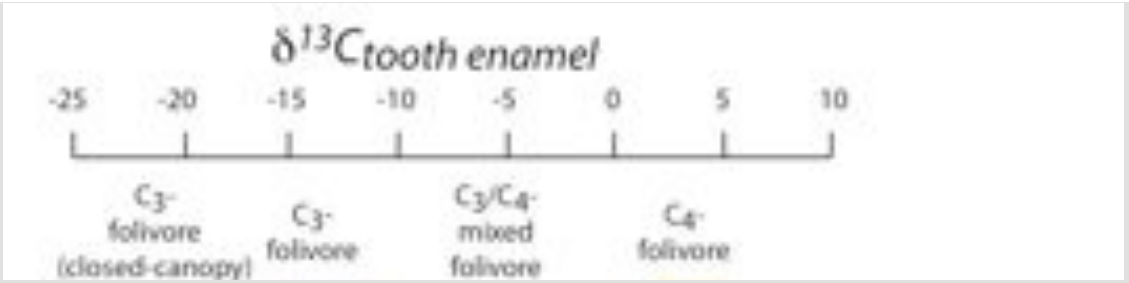
Modern African primates: monkeys and apes

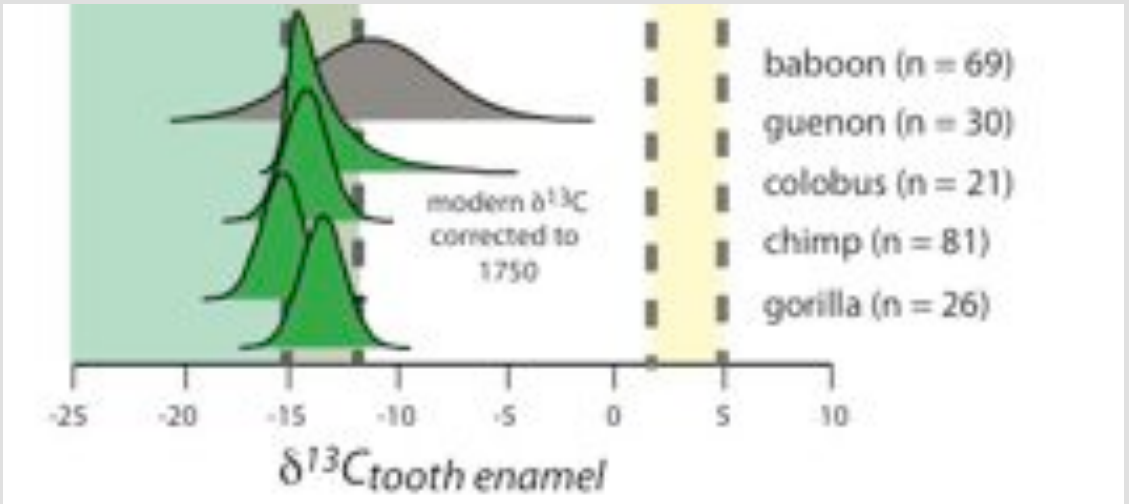


What constitutes a "pure–C_3" diet for primates?

1. Diet of "pure-C_3" folivore

2. Data from:
   - Cerling et al., 2004, 2013, unpublished
   - Codron et al, 2005
   - Levin et al, 2008
   - Carter et al 2010
   - Smith et al. 2010
   - Nelson et al., 2013
   - Martin et al, 2015
   - Sponheimer and Lee-Thorp, unpublished

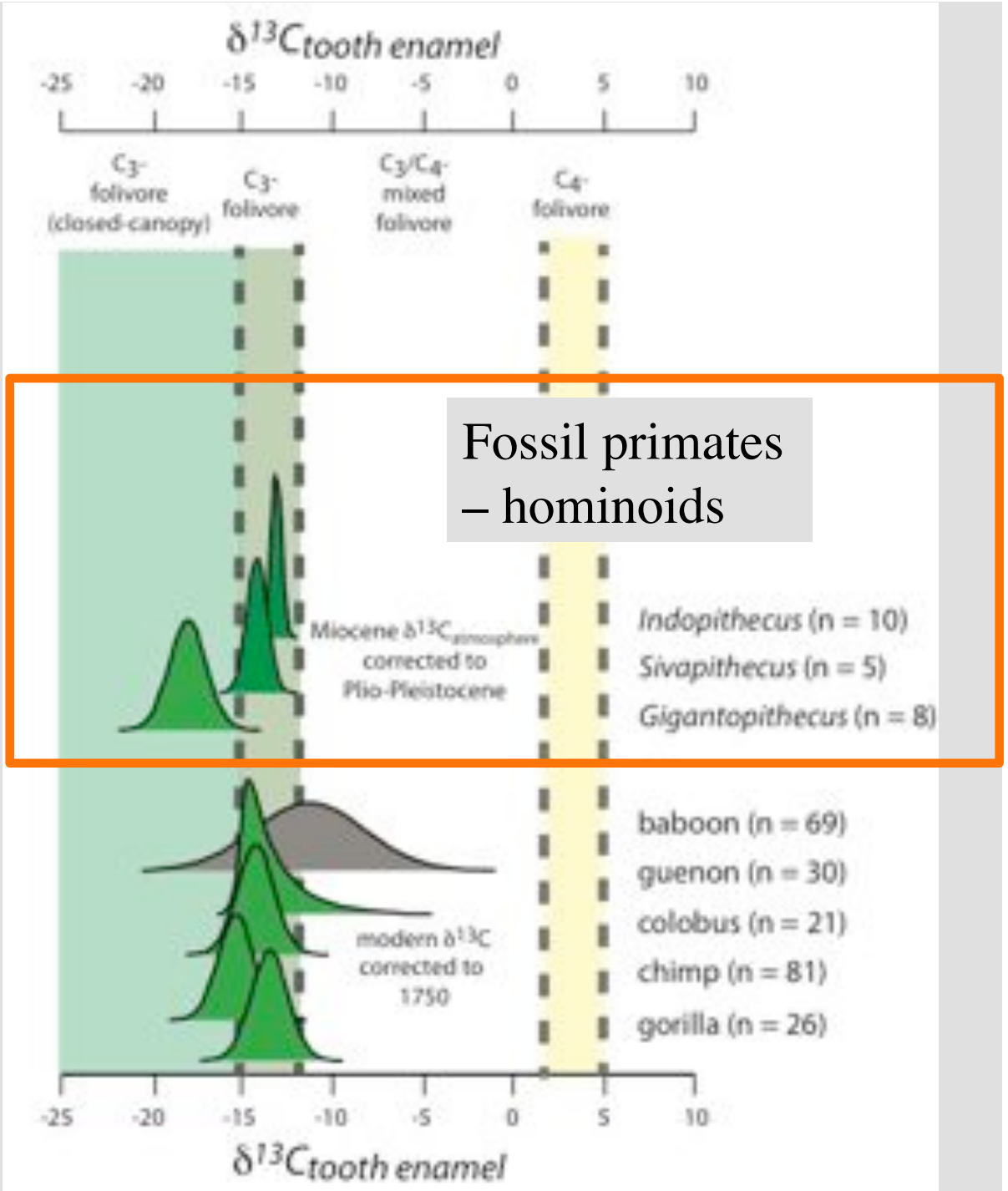


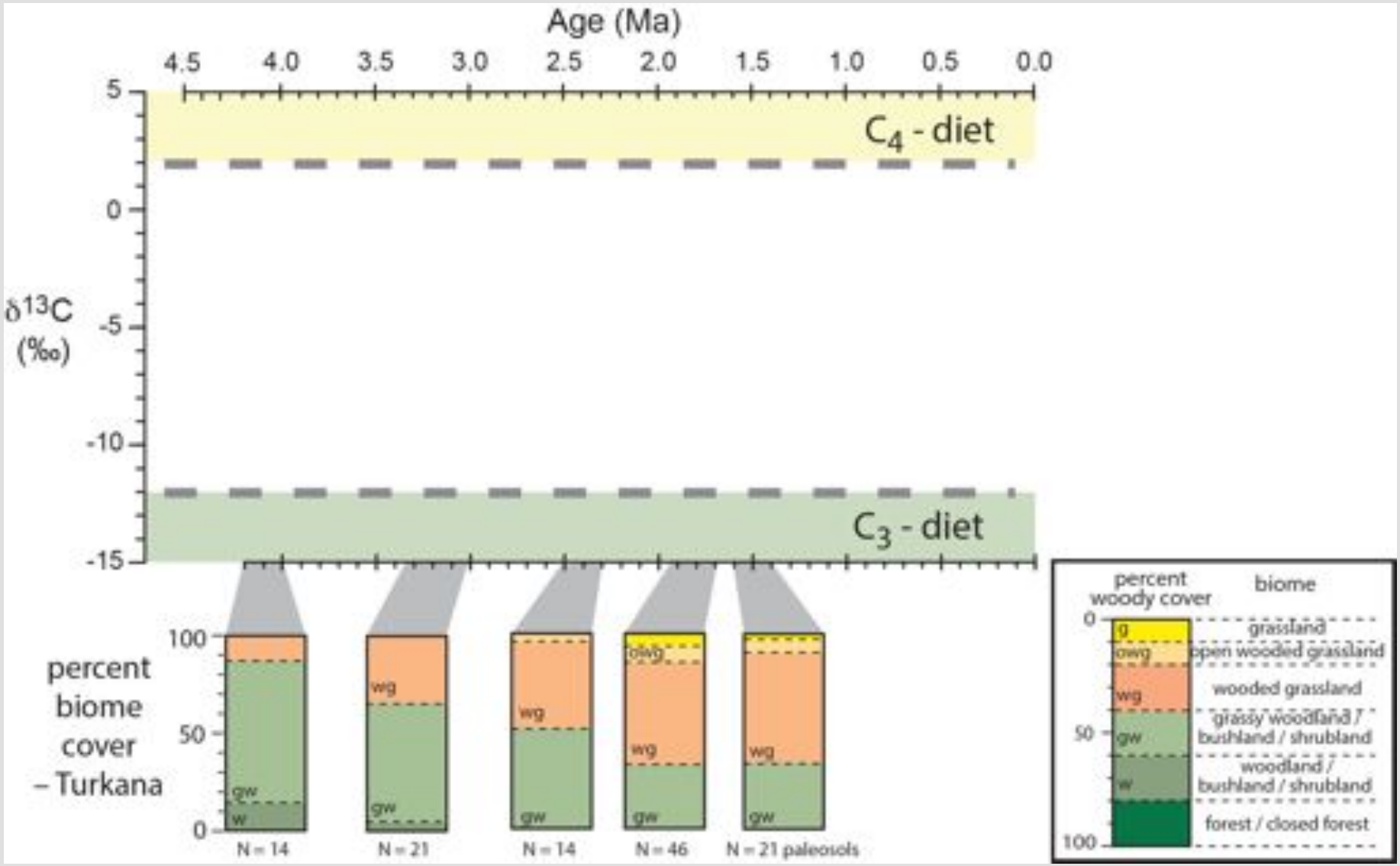


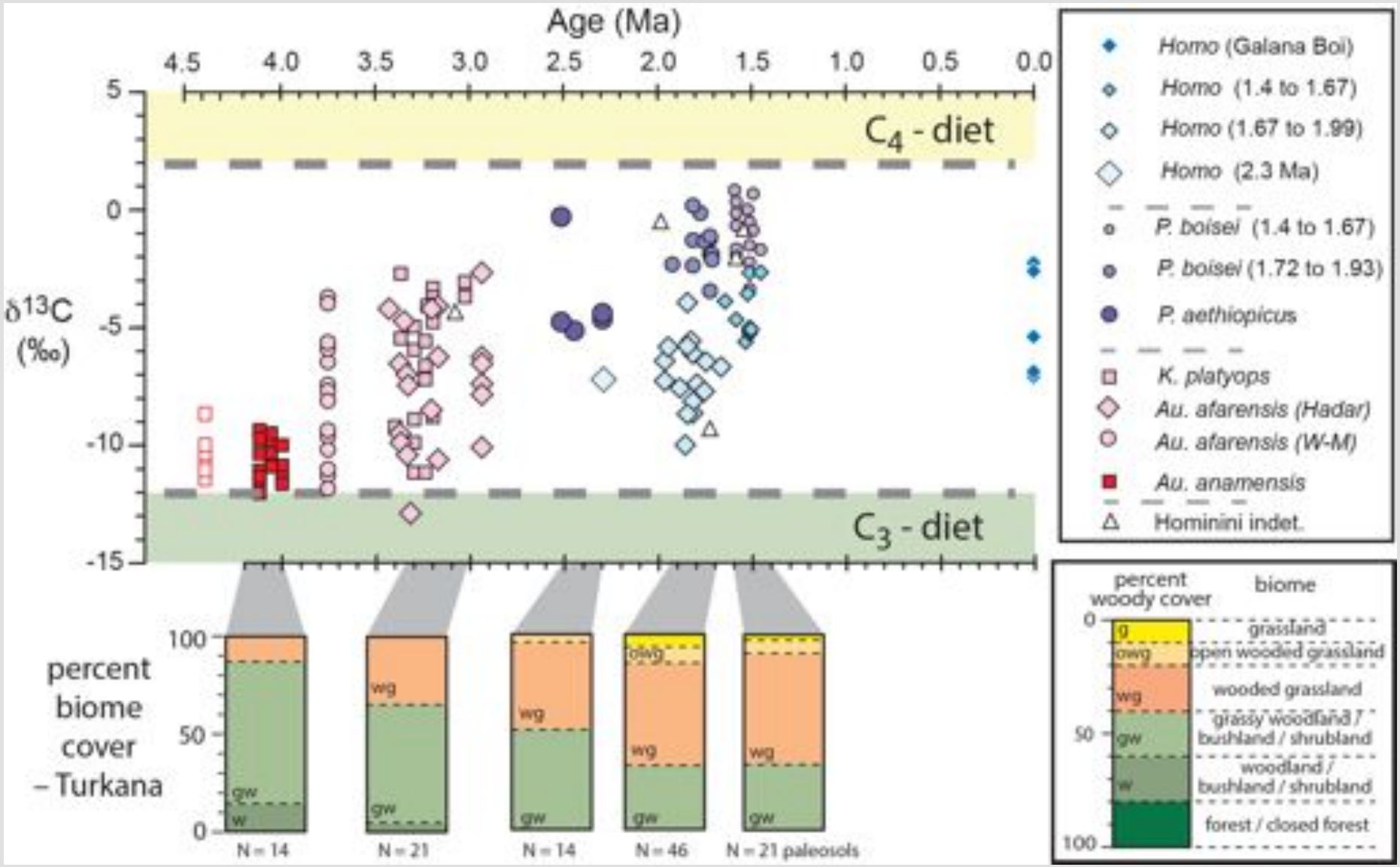
What constitutes a "pure–C_3" diet for primates?

1. Diet of "pure-C_3" folivore

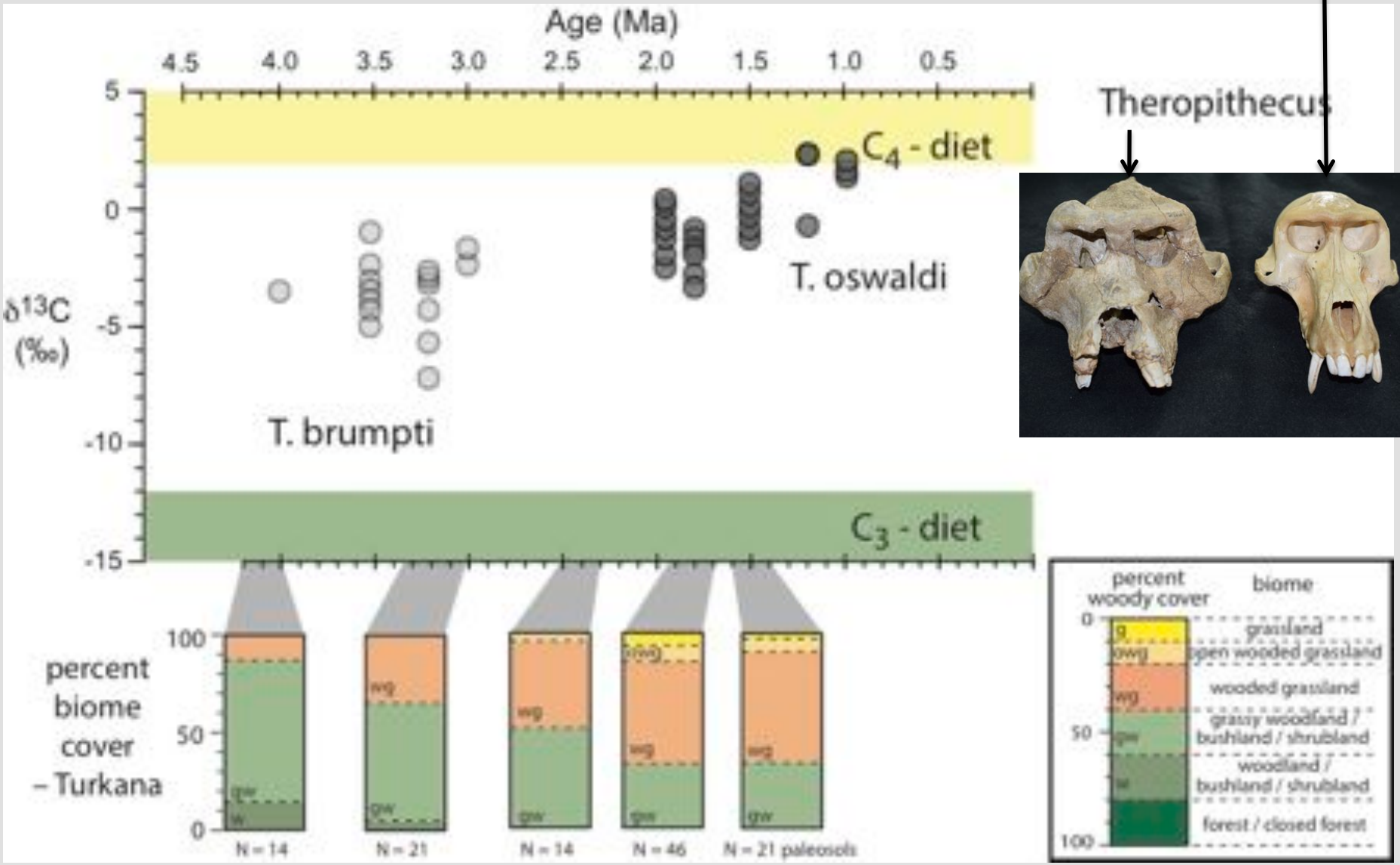
2. Fossil primates:
   - Nelson et al, 2007 (Miocene)
   - Zu et al., 2011 (Pleistocene)
   - Patnaik et al, 2014 (Miocene)




Age (Ma)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5
0
-5
-10
-15
δ13C (‰)
C4 - diet
C3 - diet
percent biome cover – Turkana
100
50
0
gw
w
wg
owg
N = 14
N = 21
N = 14
N = 46
N = 21 paleosols
percent woody cover
biome
0
50
100
g
grassland
owg
open wooded grassland
wg
wooded grassland
gw
grassy woodland / bushland / shrubland
w
woodland / bushland / shrubland
forest / closed forest


Age (Ma)
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5
0
-5
-10
-15
δ13C (‰)
C4 - diet
C3 - diet
Homo (Galana Boi)
Homo (1.4 to 1.67)
Homo (1.67 to 1.99)
Homo (2.3 Ma)
P. boisei (1.4 to 1.67)
P. boisei (1.72 to 1.93)
P. aethiopicus
K. platyops
Au. afarensis (Hadar)
Au. afarensis (W-M)
Au. anamensis
Hominini indet.
percent biome cover – Turkana
100
50
0
gw
w
wg
owg
N = 14
N = 21
N = 14
N = 46
N = 21 paleosols
percent woody cover
biome
0
50
100
g
owg
wg
gw
w
grassland
open wooded grassland
wooded grassland
grassy woodland / bushland / shrubland
woodland / bushland / shrubland
forest / closed forest

Theropithecus: another large-bodied primate



Results of the African primate "experiment" using C_4-diet resources

Paranthropus goes extinct

Theropithecus extinct in lowlands. Found only > 3500 m: C_3-grass diet

Homo survives – omnivore diet

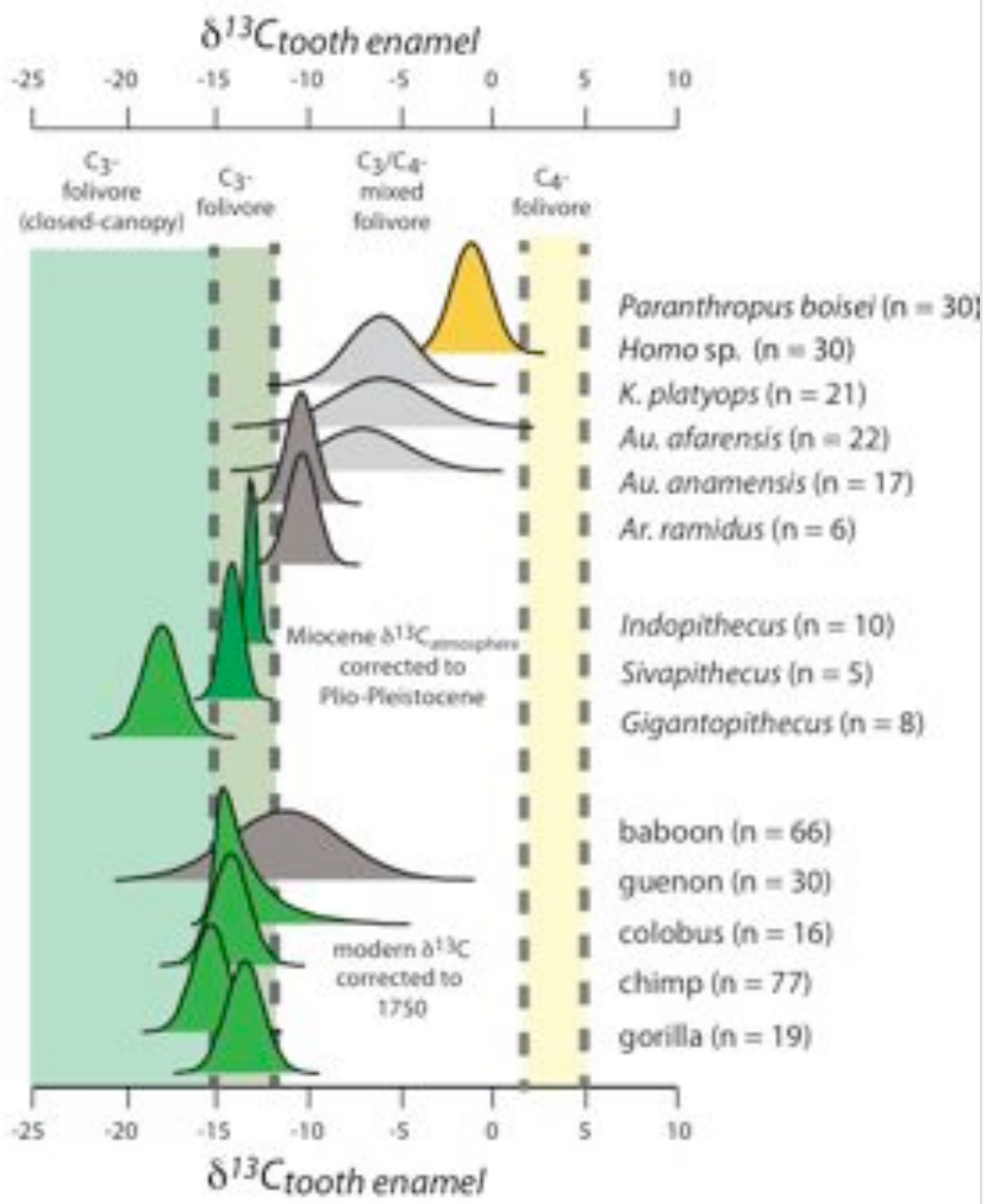
Other primate diet is C_3-dominated

– Behavior (diet) leads evolutionar (morphology) change

– C_4 based resource:

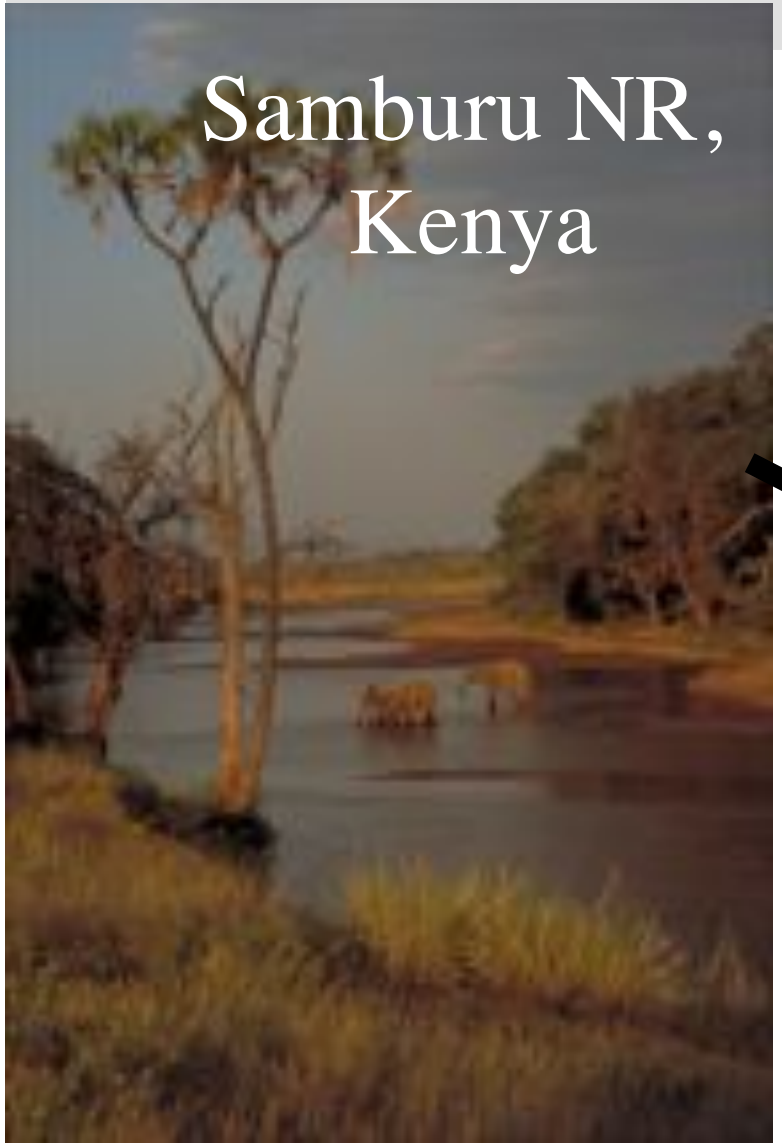
primary. grass / sedge

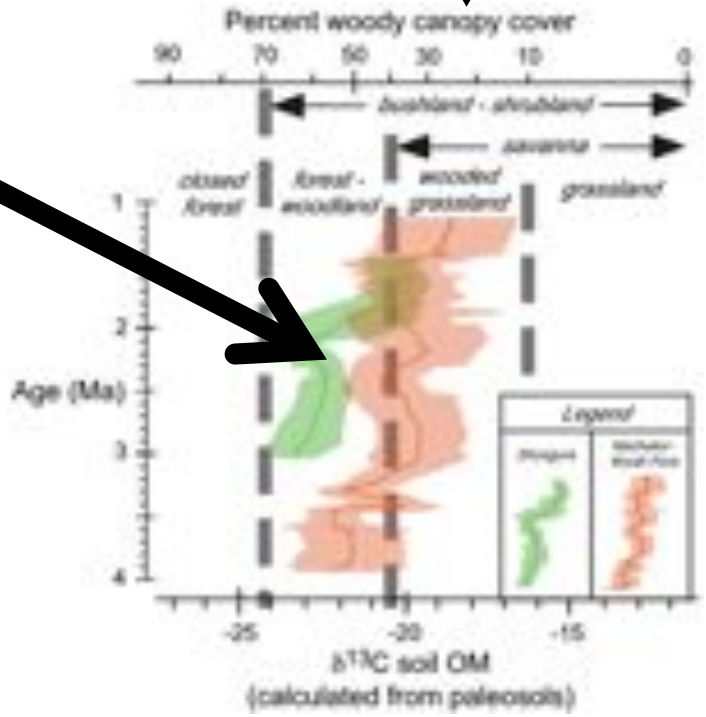
secondary. Insects / mea



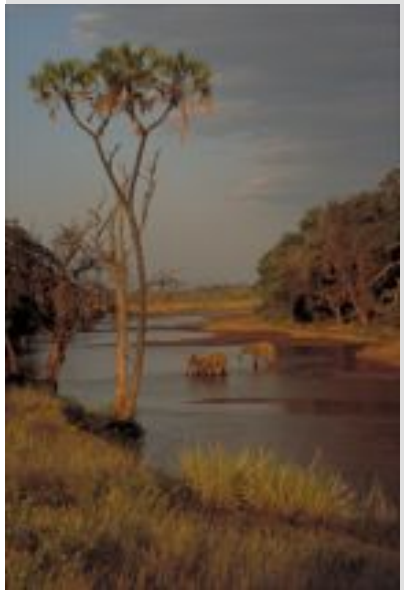
Likely riparian forest near savanna or bushland

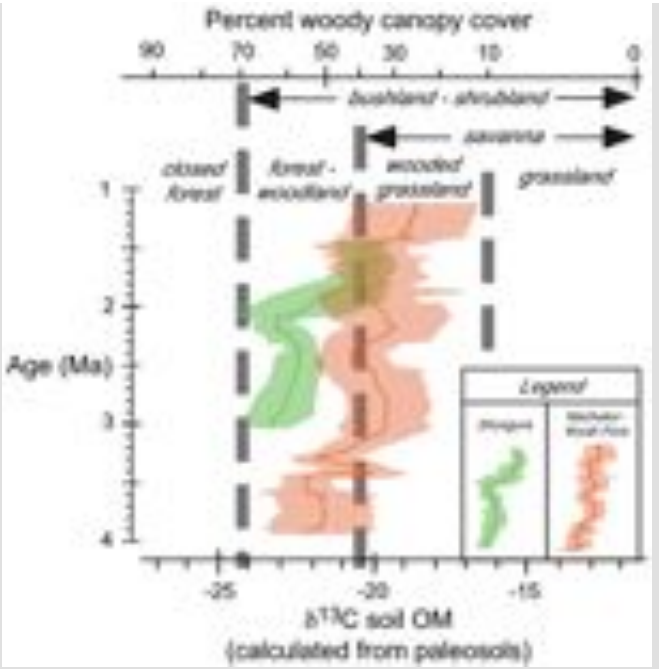
What kind of vegetation?

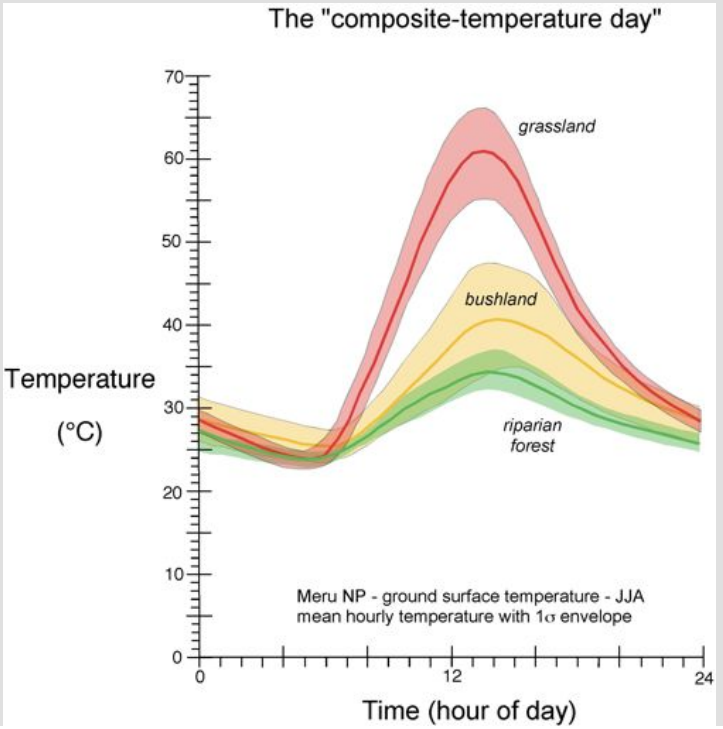




Mostly hot, and dry. Riparian corridors. Human ancestors used savanna resources.







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