Global cooling by grassland soils in the geological past and near future

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Eocene-Oligocene paleosols Badlands National Park, South Dakota
Over 35 Ma, grassland expansion (0-25% of land area) changed the world.

OUTLINE
A. Quaternary paleosols
B. Cenozoic paleosols
C. pre-grassland like mallee of Australia
D. why Cenozoic global cooling?
E. Farming for carbon

Crumb structure (mollic epipedon) in tall grassland paleosol (Mollisol) Dayville, OR: late Miocene (7 Ma)
QUATERNARY RECORD
1: PALEOSOLS
Quaternary Palouse Loess, eastern Washington

Paleosols near Kahlotus, WA

Paleosols near Dayton, WA
Palouse Loess near Clyde, Washington, alternation of deep-calcic grassland and shallow-calcic sagebrush

Earthworm fabric in 46 ka Nix grassland paleosol

Taenidium (cicada) burrow in 40 ka Tlal sagebrush paleosol

Mt St Helens ash S

23.7 ka

36.1 ka

40.1 ka

46.2 ka

Mt St Helens ash C

thermoluminescence dates from Busacca (1998)
Alternation of grassland and sagebrush phytoliths (plant opal) in Palouse Loess near Kahlotus, Washington (Blinnikov et al. 2002)
Modern dry grassland near Benge, Washington

Modern sagebrush near Denio, Nevada
CENOZOIC 1: PALEOSOLS IN DEEP TIME

Longview Ranch, Oregon, with green Oligocene paleosols in hill
CENOZOIC 2: JOHN DAY FM OLIGOCENE

Well dated (Ar/Ar, paleomagnetic) fossiliferous sequence
CENOZOIC 3: MILANKOVITCH BEATS

105 beats, 365 paleosols, 5.1 Ma (28.7-23.6 Ma)

“MONROECREEKIAN” of Alroy    “HARRISONIAN” of Alroy
ARIKAREEAN of Wood committee
CENOZOIC 3: PALEOPRECIPITATION FROM PALEOSOLS

Precipitation = 139.6 + 6.39(depth) - 0.013(depth)^2
for 407 modern soils worldwide,
(from Retallack 2005)
CENOZOIC 4: SHRUB/GRASS TRACES

- **Taenidium**
  - cicada burrow of sagebrush

- **Edaphichnium**
  - earthworm chimney of grassland

- **Pallichnus**
  - dung beetle nests of grassland

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**Histograms**
- Frequency of **Taenidium**
- Frequency of **Pallichnus**
- Frequency of **Edaphichnium**
- Depth to Bk (cm)
CENOZOIC 5: SHRUB/GRASS SNAILS

Two common genera
Four common species

“Polygrya” expansa
Vespericola dalli
Monadenia dubiosa
Monadenia marginicola

Narrower aperture in drier climate
CENOZOIC 6: SHRUB/GRASS MAMMALS

Wetter climate-bigger animal

Hypertragulus hesperius dry climate mouse deer

Merycochoerus superbus wet climate oreodont
CENOZOIC 7: CHEMICAL CLIMATE

- Oregon
- Montana
- Nebraska

Modern transfer function from Sheldon et al (2002)

-warm goes with wet!
-Eocene-Oligocene decline
-mid-Miocene high
-PlioPleistocene decline

mean annual precipitation (mm)
mean annual temperature (°C)

y = 221.12e^{0.0197x}
R^2 = 0.72

Mean Annual Precipitation (mm)
CIA-K

millions of years ago
CENOZOIC 8: Bk RECORD

- better, cheaper record
- different advent of Bk
  (Eocene Montana desert!)

- Eocene-Oligocene decline
- mid-Miocene high
- PlioPleistocene decline

*Taenidium* (cicada) burrows from Pipestone Springs, MT (34 Ma)
CENOZOIC 9: VEGETATION FROM SOIL

Crumb structure (mollic epipedon) in tall grassland paleosol (Mollisol) Dayville, OR: late Miocene (7 Ma)

Blocky structure red forested paleosol (Alfisol), Painted Hills, OR: Oligocene (31 Ma)

*Merychippus seversus* Dayville, OR: mid-Miocene (16 Ma)

Crumb structure (mollic epipedon) in short grassland paleosol (Mollisol) Kimberly, OR: mid-Miocene (19 Ma)
PHYTOLITHS
-36-0 Ma abundant grassland phytoliths (Strömberg, 2002, 2004)

PEDOGENIC $\delta^{13}$C$_{\text{carb}}$
-40 Ma of 20-40% C4 (Fox and Koch, 2003)

PALEOSOLS
-bunch then sod grasslands at warm-wet times
-dry times expanded sagebrush (not grassland)
PRE-GRASSLAND 1: RAIN FOREST?

- expect deeply weathered paleosols (non-calcareous Ultisols and Oxisols): BUT mainly calcareous Alfisols and Aridisols
  [Willwood, North Horn Fm]

- expect large leaves with drip tips, vines, dicot wood: BUT largely small leaves, legumes and cypress wood, few vines
  [Green River, Fort Union Fm]

- expect boehmite, kaolinite: BUT largely smectite
  [Willwood, North Horn, Green River, Fort Union Fm]

Paleocene mammals from Wyoming (Gould 1994 The book of life)
PRE-GRASSLAND 2: MALLEE?

_Maireana sedifolia_ shrubland Koonenberry Mt.

_Eucalyptus viridis_ mallee, Balranald, NSW

_Eucalyptus haemastoma_ woodland Widden Brook
<table>
<thead>
<tr>
<th>Eucalyptus melliodora, E. microtheca</th>
<th>Casuarina cristata Back Creek, NSW</th>
<th>Callitris columellaris, Acacia aneura Goolgowi, NSW</th>
<th>Eucalyptus socialis Balranald NSW</th>
<th>Atriplex nummularia, Maireana pyramidata L Mungo</th>
</tr>
</thead>
</table>

PRE-GRASSLAND 3: MALLEE SOILS

- Eucalyptus melliodora, E. microtheca
- Casuarina cristata Back Creek, NSW
- Callitris columellaris, Acacia aneura Goolgowi, NSW
- Eucalyptus socialis Balranald NSW
- Atriplex nummularia, Maireana pyramidata L Mungo

Soil depths:
- 52 cm Bk
- 65 cm Bk
- 34 cm Bk
- 37 cm Bk
- 23 cm Bk
PRE-GRASSLAND 4: COMPARISON

MALLEE
- low multiple bole trees (ca. 8 m)
  - sclerophyll leaves
  - bunch grasses
  - bare ground showing
- low carbon soil (2 wt % C)
  - low soil moisture
  - blocky angular soil peds

GRASSLAND
- dense grasses (<1 m)
  - mesophytic leaves
  - sod grasses
  - complete ground cover
- high carbon soil (8-10 wt % C)
  - high soil moisture
  - granular-crumb soil peds

![Graph showing relationships between mean annual precipitation and plant height or depth to Bk for Australian mallee and African grassland, with regression equations and R^2 values provided.](image-url)
Pleistocene Australia

MALLEE
- paws
- cursorial bipeds
- noncursorial quadrupeds
- egg or pouch reproduction
  - brachydont molars
  - plagiaulacid premolars

GRASSLAND
- hooves
- rare bipeds
- cursorial quadrupeds
- placental reproduction
  - hypsodont molars
  - conical premolars

PRE-GRASSLAND 5: MAMMAL FAUNA

Pleistocene Australia
by Peter Murray
PRE-GRASSLAND 6: MALLEE MAMMALS

- most nocturnal
- Arboreal taxa remain common in open country

**Phascogale tapoafata-tuan** (Gary Lewis) **Petaurus breviceps**-sugar glider

**Insectivores**

**Ningaui yvonneae** - mallee ningaui by Peter Robertson

**Potorous longipes** - long-footed potoroo by John Seebeck

**Fungivores**
PRE-GRASSLAND 7: EXTINCT FAUNA

- cursorial bipeds, still with emus
- diverse lizards, still with goannas

**Dromornis stirtoni**
Miocene, Alcoota, NT.
by Peter Murray

**Megalania prisca & Genyornis newtoni**
Pleistocene, Lake Callabonna, SA
by Peter Trusler
PRE-GRASSLAND 8: GROUND NESTS

mallee fowl fermentation nest
warmth from plant decay

Leipoa ocellata by Dorling Kindersley

Kingston SA by James Darling
PRE-GRASSLAND 9: JURASSIC PALEOSOL

Morrison Form. paleosols Notom, UT

Reconstructed paleosols and outcrop, Dinosaur NM, CO, Jurassic, Morrison Formation.
Pre-Grassland 10: Jurassic Browse

Neck posture high, low, or just right?

Reconstructed Diplodocus carnegii Jurassic Morrison Formation by Tim Haines
PRE-GRASSLAND 11: JURASSIC BIPED

*Allosaurus fragilis* Jurassic, Morrison Formation, UT by Joe Tucciarone
PRE-GRASSLAND 12: EARLY MAMMALS

nocturnal, insectivore, arboreal
(fungivore)

Volaticotherium antiquum - triconodont, Early Cretaceous, China, by C. Zhao & L. Xing

Eomaia scansoria - placental, Early Cretaceous, China, by Zhe-Xi Luo

Hadrocodium lui - morganucodont, Early Jurassic, China by Mark Kingler
Duckbill dinosaurs (among many taxa) nested like mallee fowl

Maiasaura peeblesorum, Early Cretaceous, Two medicine Formation, Choteau MT, by John Gurche (left) and Dorling Kindersley (right)
Red forested non-calcareous paleosols (Alfisols) pass upwards into brown calcareous grassland paleosols (Andisols) by mid-Oligocene (30Ma).

Painted Hills, Oregon

Paleoprecipitation estimated from paleosol Bt (blue) or Bk (red) follows decline in atmospheric CO$_2$.  

WHY? 1: PATTERN TO EXPLAIN
Atmospheric carbon dioxide from Ginkgo stomatal index (Retallack, 2001, 2002)

WHY? 2: GLOBAL PATTERN + CO$_2$

Paleoclimatic long-term ramps interrupted by short term spikes, in paleosols (Retallack 2001, 2007)

Atmospheric carbon dioxide from Ginkgo stomatal index (Retallack, 2001, 2002)
WHY? 3: TRANSIENT PERTURBATIONS

35 Ma (Priabonian) and 16 Ma (Langhian) transient spikes of warm-wet CO$_2$ due to impacts and flood basalts

Columbia River Basalts, Oregon, Washington (17-15 Ma) (Camp and Ross 2004)

Chesapeake impact structure
35 Ma (from Voytek, 2005)

Steinheim Crater, Germany 15 ma (3.8 km) by E. Stabenow

Ethiopian flood basalts 35 Ma (from Wood and Guth 2010)
WHY? 4: HIMALAYAN COOLING RAMP

PRO. Mountain uplift promotes weathering and albedo
(Ruddiman and Raymo 1988)

CON. Physical not chemical weathering, metamorphic CO₂
PRO.
Thermal isolation ices Antarctica, consumes $\text{H}_2\text{O}$, raises albedo (Kennett 1978)

CON.
Warms mid-latitudes, minor reductions of atmospheric $\text{H}_2\text{O}$, $\text{CO}_2$ and albedo
WHY? 6: GRASSLAND EXPANSION

Grasslands not due to drying, expanding into wetter regions -from 35-0 Ma expanded from 0-25% of land

Mollic and near-mollic paleosol records from 3 continents (Retallack 2001)
WHY? 7: GRASSLAND EXPLANATION

- first tall sod grassland
- first short sod grassland
- first bunch grassland
- archaic "mallee"
WHY? 8: STRATEGIC TERRAIN

- average global mean annual precipitation on land is 762 mm
- <300 mm is too dry, >1200 mm is too poor in nutrients

Data from global network of 17,689 terrestrial precipitation gauges (Greiser & Rudolf 2005)
WHY? 9: COEVOLUTION RAMP

BIOLOGICAL MECHANISM

- adaptation to others not to environment

-grasses best withstand grazers

-grazers best cope with phytoliths and growth of grasses

from Retallack 2007
WHY? 10: PACK HUNTING IN DOGS

- **Paratomarctus euthos**
  - middle Miocene, Valentine Formation, Gordon Quarry, Nebraska

- **Hesperocyon gregarius** 32 Ma

- **Mesocyon sp.** 27 Ma

- **Canis mesomelas** (living)

- **Tomarctus euthos** 16 Ma

Prorean gyrus

- Prorean gyrus found in pack hunting wolves and dogs, not foxes

- Prorean gyrus appears in borophagine dogs of Nebraska 19 Ma

from Radinsky 1969
WHY? 11: 19 Ma ADVENT OF SOD

Agate Springs, NE: Miocene (19Ma)
by Jay Matternes

- pack hunting
- running escape
- prey herding
- hypsodont grazing
- siliceous grasses
- dung cakes
- weedless sod
- mollic soil

Silica husk of grass (*Panicum elegans*)

bear dog den (*Daphaenodon*)

Dung cake of ruminant

Mollisol paleosol

cursorial, hypsodont, tridactyl (*Parahippus tyleri*)
WHY? 12: REASONS FOR COOLING

1. Soil C-rich (10% to 1 m)
2. Hydrolytic weathering (consumes carbonic acid)
3. Moist soil, dry air
4. High albedo

Miohippus intermedius, Nimravus brachyops Toadstool Park, NB, Oligocene (32 Ma) reconstructed by Jay Matternes

Mollisol paleosol, Miocene Dayville OR
WHY? 13: CARBON STORAGE COOLS
- organic C like net primary productivity increases with precipitation
- grasslands rule strategic zone (300-1200 mm mean annual precip.)

\[ y = 1.7492 \ln(x) - 8.4142 \]
\[ R^2 = 0.7439 \]

Mean annual precipitation (mm)

Soil organic carbon (kg/m$^2$)

Australia from Wynn et al. 2005, Africa from Zinke et al 1984
WHY? 14: WEATHERING COOLS
- grassland soils deepen root zone in strategic climate zone
- carbonic acid weathers cations for plants, exported as bicarbonate
  (2-8% more in grassland than adjacent woodland)

Carbon cycle from Demenocal 2004
WHY? 15: TRANSPERSION COOLS

- Grasslands have moist soil, dry air.
- Woodlands have drier soil (20-30%), moist air.
- Water vapor is a greenhouse gas, although easily rained out.

Nairobi National Park, Kenya
Kakamega Forest, Kenya
WHY? 16: ALBEDO COOLS

- Grasslands light (albedo 15-19%), covered by snow (albedo 40-85%)
- Woodlands dark (albedo 8-13%) hard to cover with snow
CARBON FARMING 1: MOTIVATION

- global warming due to CO$_2$ could be offset by C storage in farm soils
- tests already underway in Australia, baseline soil C assay, then carbon credit payment for gains
1. CELL GRAZING
   Pen cattle with electric for each days grazing: grazing takes out weeds leaving sod grasses.

2. PASTURE CROPPING
   Drill seed and raise crop through sod: prevents soil oxidation by plowing.

3. CONTOUR COPPICING
   Plant trees at inflexion point in slopes: prevents gully erosion.
CARBON FARMING 3: THE SOURCE
Grazing succession of African savanna (Vesey-Fitzgerald 1973)

- Agroecosystems are paleotropical
- Succession keeps down parasites

Elephants smash trees (Loxodonta africana)
Buffalo graze tall grass (Syncerus caffer)
Wildebeest on shorter grass (Connochaetes taurinus)
Tommy on short grass (Gazella thomsoni)
Warthog tearing up turf (Phacochoerus africanus)

Grassland soil (Mollisol)
Lake Nakuru, Kenya
CONCLUSIONS-PROSERPINA PRINCIPLE
PLANTS COOL, ANIMALS WARM THE PLANET (Retallack, 2004)
- late Devonian evolution of trees gives Permo-Carboniferous ice age
- Triassic evolution of termites and dinosaurs give Mesozoic greenhouse
- Oligocene evolution of grasslands gives Neogene ice age