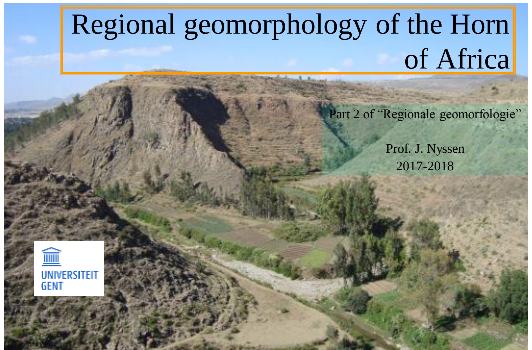
Regional geomorphology of the Horn of Africa

Part 2 of "Regionale geomorfologie"

Prof. J. Nyssen
2017-2018

UNIVERSITEIT GENT



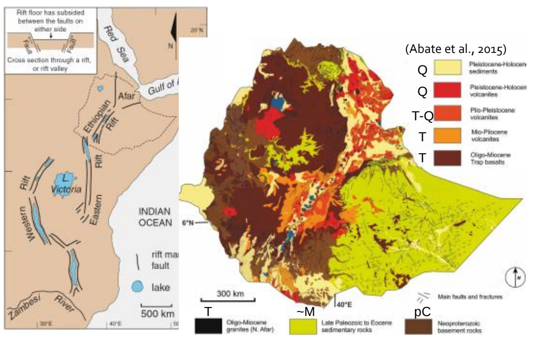
Base document: Nyssen, J., Poesen, J., Moeyersons, J., Deckers, J., Mitiku Haile, Lang, A., 2004. Human impact on the environment in the Ethiopian and Eritrean Highlands – a state of the art. Earth Science Reviews, 64/3-4: 273-320.

Comprehensive book: Billi, P. (ed.), 2015. Landscapes and Landforms of Ethiopia. Dordrecht, Springer: viii + 389 p.

1. Introduction

- Environmental changes / Erosion processes
- Past & present
- Ethiopian Highlands
- Geological background: 500-2000 m uplift in 25 mio years → steep slopes
- Human impact
  - Factor of degradation
  - Factor of environmental recovery

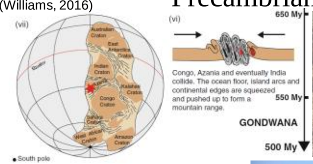
Geology



(Abate et al., 2015)

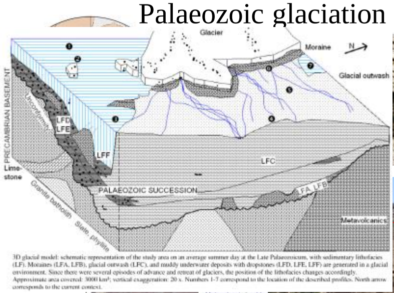
Precambrian

East African orogeny (Williams, 2016)

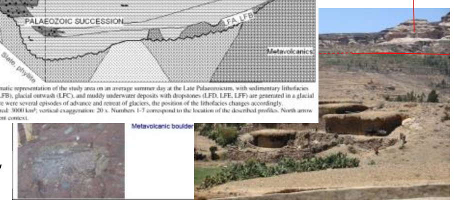


(Planation surface)

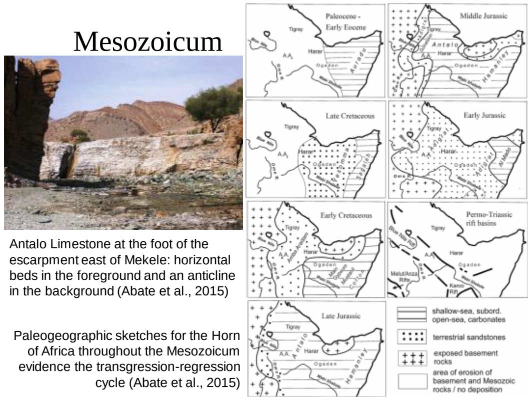
Palaeozoic glaciation

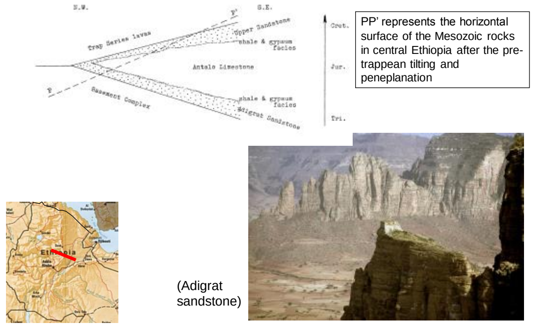


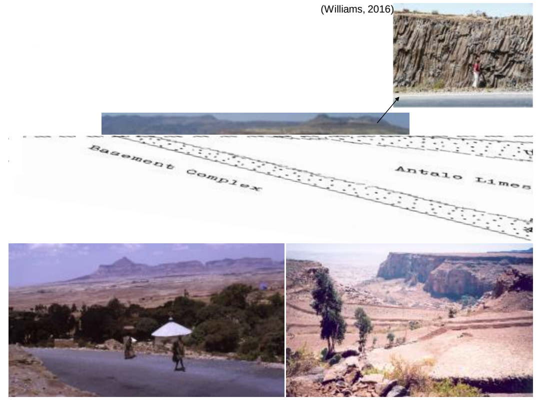
3D glacial model: schematic representation of the study area on an average summer day at the Late Palaeozoicum, with sedimentary lithofacies (LF). Moraines (LFA, LFB), glacial outwash (LFC), and muddy underwater deposits with dropstones (LFD, LFE, LFF) are generated in a glacial environment. Since there were several episodes of advance and retreat of glaciers, the position of the lithofacies changes accordingly. Approximate area covered: 3000 km²; vertical exaggeration: 20 x. Numbers 1-7 correspond to the location of the described profiles. North arrow corresponds to the current context.

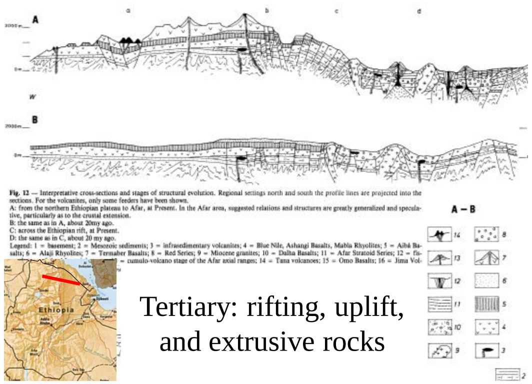


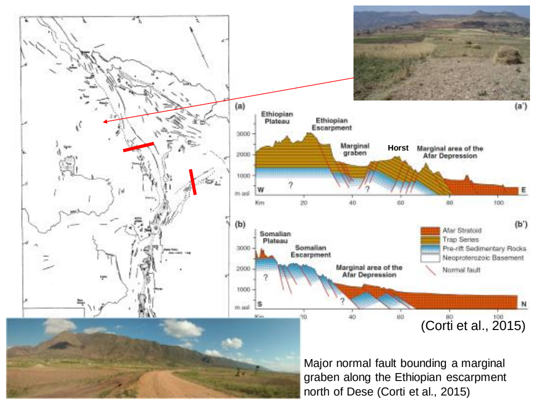
(Dubey et al., 2010)

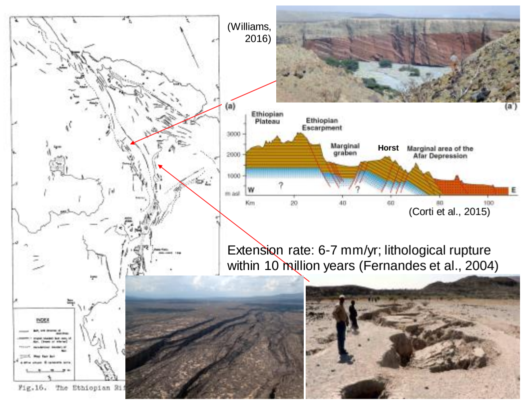

Mesozoicum
Antalo Limestone at the foot of the escarpment east of Mekele: horizontal beds in the foreground and an anticline in the background (Abate et al., 2015)
Paleogeographic sketches for the Horn of Africa throughout the Mesozoicum evidence the transgression-regression cycle (Abate et al., 2015)
Paleocene - Early Eocene
Middle Jurassic
Late Cretaceous
Early Jurassic
Early Cretaceous
Permo-Triassic rift basins
Late Jurassic
shallow-sea, subord. open-sea, carbonates
terrestrial sandstones
exposed basement rocks
area of erosion of basement and Mesozoic rocks / no deposition


PP' represents the horizontal surface of the Mesozoic rocks in central Ethiopia after the pre-trappean tilting and peneplanation
Trap Series lavas
Upper Sandstone
Antalo Limestone
Basement Complex
Adigrat Sandstone
(Adigrat sandstone)


(Williams, 2016)
Basement Complex
Antalo Limes


Tertiary: rifting, uplift, and extrusive rocks
Ethiopia


Ethiopian Plateau
Ethiopian Escarpment
Marginal graben
Horst
Marginal area of the Afar Depression
Somalian Plateau
Somalian Escarpment
Afar Stratoid
Trap Series
Pre-rift Sedimentary Rocks
Neoproterozoic Basement
Normal fault
(Corti et al., 2015)
Major normal fault bounding a marginal graben along the Ethiopian escarpment north of Dese (Corti et al., 2015)


(Williams, 2016)
Ethiopian Plateau
Ethiopian Escarpment
Marginal graben
Horst
Marginal area of the Afar Depression
(Corti et al., 2015)
Extension rate: 6-7 mm/yr; lithological rupture within 10 million years (Fernandes et al., 2004)

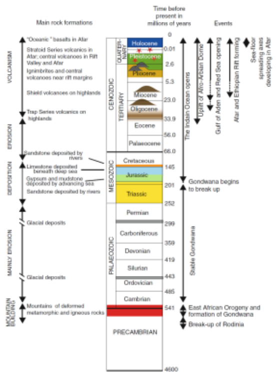
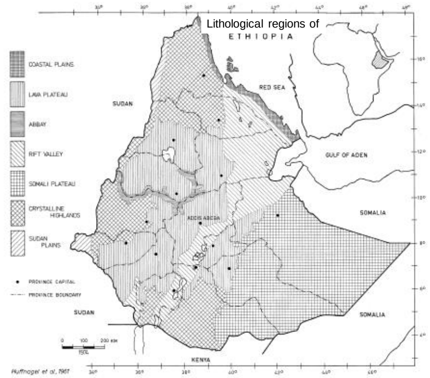
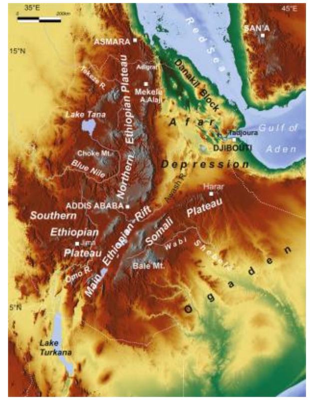
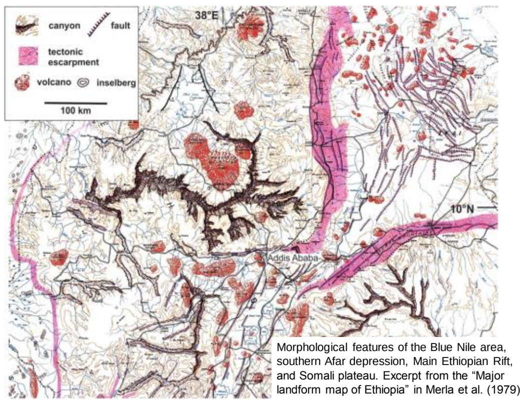


Fig. 8.3 Geological time scale showing the main geological events and corresponding rock formations in Ethiopia (Williams, 2016)





Digital elevation map of Ethiopia (SRTM data) with the main physiographic elements – elevations range between 4550 m a.s.l. and 115 m b.s.l. (Abate et al., 2015)



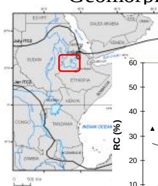
Morphological features of the Blue Nile area, southern Afar depression, Main Ethiopian Rift, and Somali plateau. Excerpt from the "Major landform map of Ethiopia" in Merla et al. (1979)

Plan

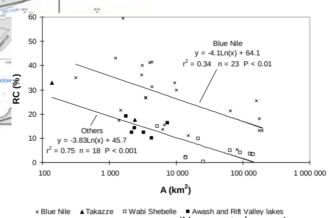
- Palaeo-environmental evolution since Late Quaternary
- Contemporary erosion processes and driving forces
- Assessment of soil loss and sediment yield
- Land degradation and desertification
- Human reactions to land degradation
- Conclusions

2. Research methodologies

- Geomorphological analysis

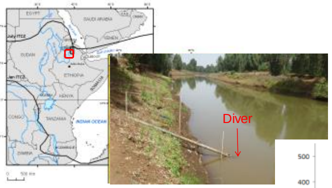


(Map: Jacob et al., 2013)



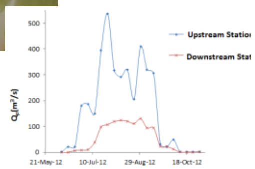
(Nyssen et al., 2004)

Research methodologies



Gumara river

Hydrological measurements



(Mekete et al., 2014)

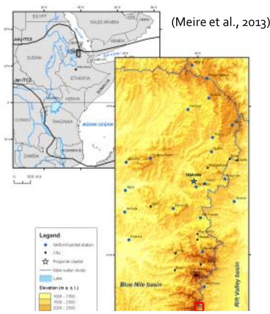
Research methodologies

Repeat photography

1936 Mt. Amba Aradam seen from Mt. Hinda Haswa 2010

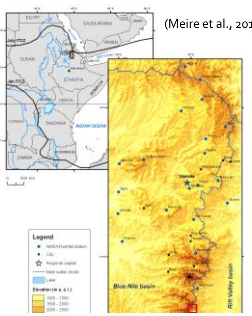
(Nyssen et al., 2014)

Research methodologies

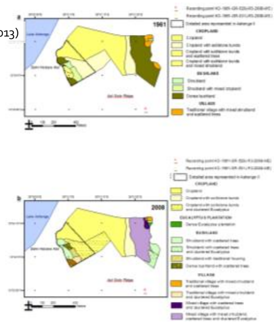


(Meire et al., 2013)

Research methodologies

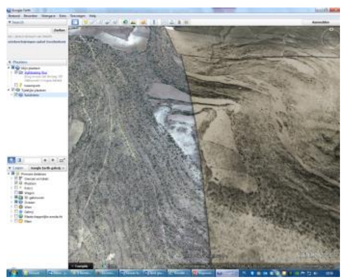


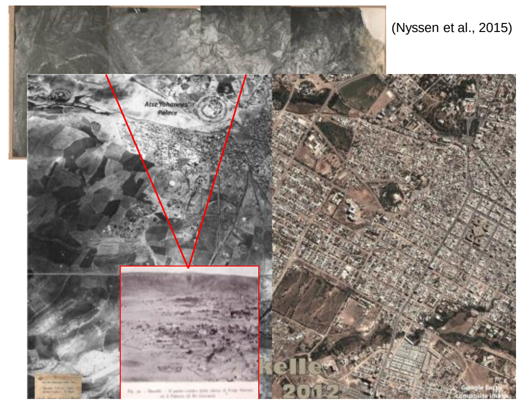
(Meire et al., 2013)



New development: Italian aerial photographs dating back 1935-1941 !

Orthomosaicked by Frankl et al., 2015





(Nyssen et al., 2015)

3. Palaeo-environmental evolution since Late Quaternary times

3.1. Introduction

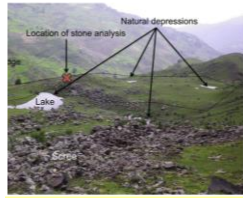
- Know the recent history of environmental degradation in order to understand the present
- Data dispersed over various disciplines: geology, glaciology, geography, soil sciences, palaeontology, hydrology etc.
- Synthetise the results from these various disciplines

Palaeo-environmental evolution

3.2. Quaternary glaciations in the Ethiopian mountains

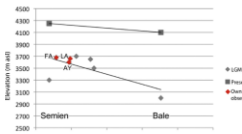
The largest moraine of the last cold period in the Simen Mountains, western escarpment below Ras Dashen (4540 m a.s.l.), seen from an altitude of about 4200 m a.s.l. The main glacier was found towards the photographer, while a smaller glacier was situated behind the moraine, having itself a small moraine on its right side (Hurni, 2015)

Part of a moraine ridge in the Bale Mts. (Williams, 2016)



Avalanche-fed glacier sites in the Abuna Yosef massif, indicating morainic features, screes and natural depressions (Hendrickx et al., 2015b).

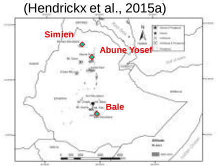
Garba Guracha, a cirque lake in the summit region of the Bale Mountains. The cirque, or hollow, in which the lake is contained, was carved by ice at the head of a glacier (Williams, 2018)



Lower limit of periglacial processes (at right: solifluction lobes at Ferrah Amba) in Ethiopia during the LGM and currently, for different latitudes (Hendrickx et al., 2015b)

A lowering of periglacial activity by 100 m corresponds to a 1 °C cooling in the Ethiopian mountains. This corresponds to the dry adiabatic lapse rate.

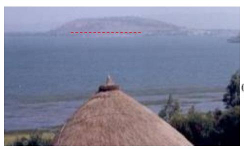
(Hendrickx et al., 2015a)



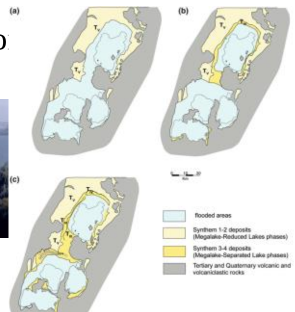
- Last glaciation (20 000 to 12 000 y ago) was dry and cold: 5-6° less (Hendrickx et al. 2015b, in small mountain rainges) -7° less (Hurni 1981, in Simien Mts.)
- First palaeosols appear in those areas 14 000 y ago

Palaeo-enviro

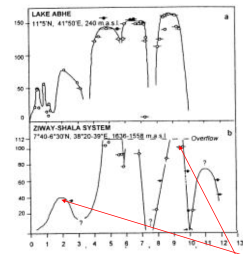
3.3. Lake levels



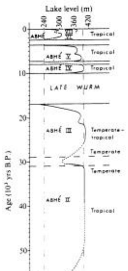
(Lake Hawassa)

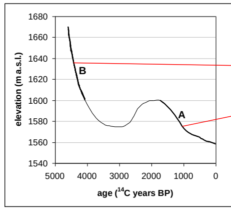


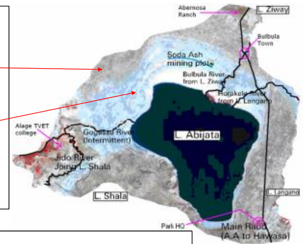
Holocene palaeogeography of the Ziway–Shala basin. (a) The maximum macrolake extension reached during Zw-Sh IV–VI highstands. (b) Early separation of Lake Ziway from the southern lake at the beginning of the Separated Lakes phase. (c) The lakes during the 2,500 years BP highstand when a southern lake, though reduced, still existed. TV–III: lacustrine terraces; Dps degraded paleoshorelines (Benvenuti & Carnicelli, 2015)

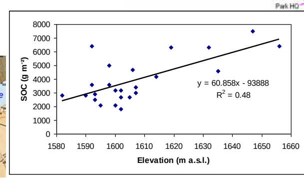


Time period	Years BP	Temperature (°C, departure from present)	% of present precipitation
Late Holocene maximum	2000	0	122
Early Holocene maximum	9400–8500	0 to −2	128–147
Terminal Pleistocene minimum	13,500	−3 to −6	68–91









(Nyssen et al., 2008)

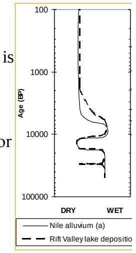
Palaeo-environmental evolution

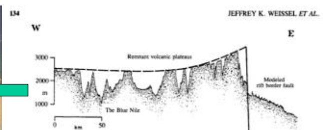
3.4. Fluvial and lacustrine deposits in Ethiopia and along the Nile

- Sediment successions inform on past erosion processes and rates in the Highlands
- Sediment production, under natural conditions, is dependent on annual and seasonal rain
- Influence of vegetation cover changes and deforestation too often omitted!
- Fournier's (1962) degradation coefficient (C) for large catchments (> 2000 km²)

$$C = p^2/P \quad (1)$$

where: p = monthly precipitation (mm) in the catchment during the wettest month; P = yearly precipitation (mm) in the catchment.

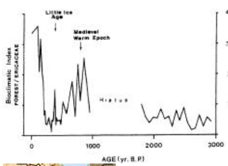


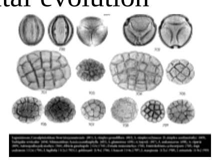


Layers of salt and mud in the Danakil salt plains. (Williams, 2016)

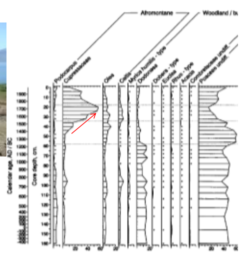
Palaeo-environmental evolution

3.5 Pollen analysis

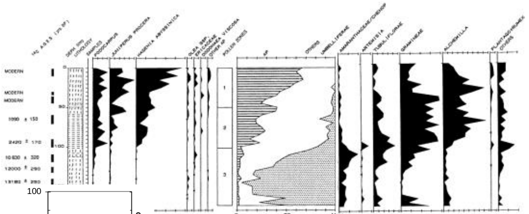


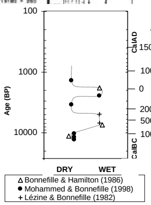


Palaeo-environmental evolution

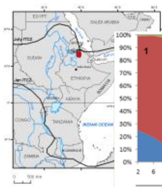


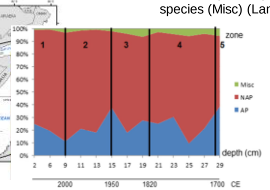
(Darbyshire et al., 2003)





Relative pollen abundances of non-arboreal species (NAP) in Lake Ashenge core, plotted against relative pollen abundances of arboreal species (AP) or miscellaneous species (Misc) (Lanckriet et al., 2015)



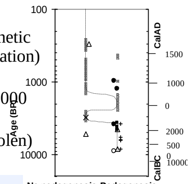


A Juniperus/Eucalyptus forest on a hill near Lake Ashenge, which was planted and regenerated since the 1980s (Lanckriet et al., 2015).

Palaeo-environmental evolution

3.6. Soil formation

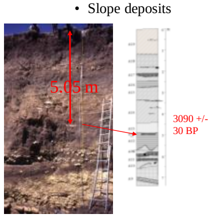
- Only general indications of pedogenetic conditions (temperature, rain, vegetation) at moment of soil formation
- Most vertisols in Tigray: between 9000 and 4000 years old
- Exceptions: until 300 y ago (Adi Kolen)
- Periods with thick vegetation cover



Palaeo-environmental evolution

3.7 Past geomorphic processes

- Tsigaba case
  - Travertine dams
  - Fire levels
  - Slope deposits

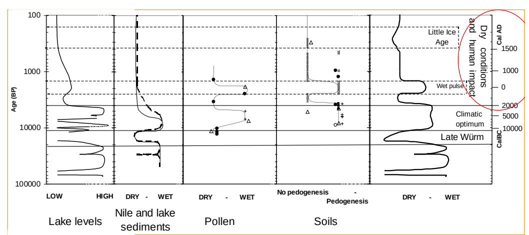


– Correlated with other findings (landslides, lake deposits), this indicates that:

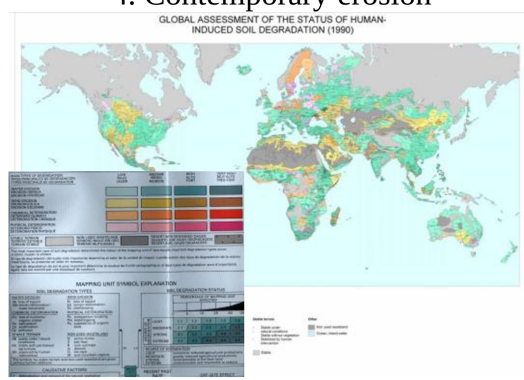
- Deforestation was carried out by mankind (fire!)
- Starting from 4000 y ago
- Results: land degradation (soil erosion, travertine dams destroyed and gullying)

Palaeo-environmental evolution

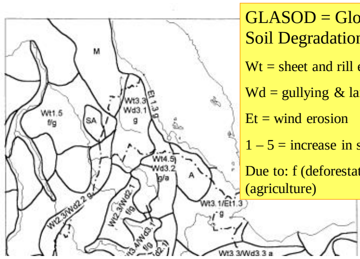
3.8 Synthesis



4. Contemporary erosion



Contemporary erosion processes



GLASOD = Global Assessment of Soil Degradation (1991)

Wt = sheet and rill erosion

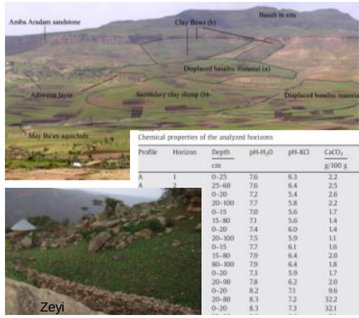
Wd = gullying & landslides

Et = wind erosion

1 – 5 = increase in severity and area

Due to: f (deforestation), g (grazing), a (agriculture)

4.1 Current land management



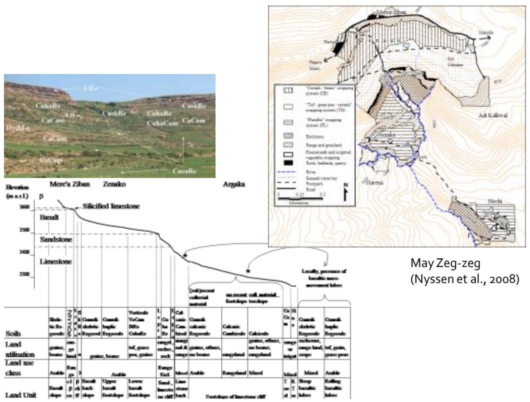
Adi Werat

(Van de Wauw et al., 2008)

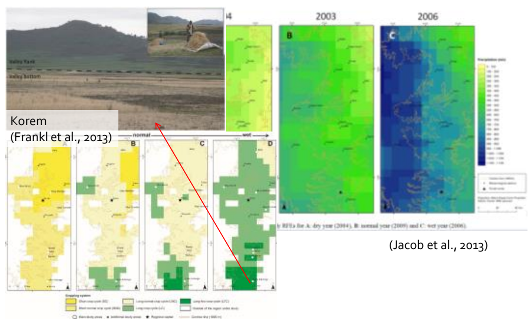
Chemical properties of the analyzed horizons

Profile	Horizon	Depth	pH-H_2O	pH-KCl	$CaCO_3$	P_{av}	Clay	Silt	Sand	C_{org}	N_{tr}
		cm			g/100 g	mg/100 g	g/100 g			g/100 g	
A	1	0–25	7.6	6.3	2.2	55.8	45	27	29	2.1	0.1
A	2	25–60	7.6	6.4	2.5	76.1	36	30	34	1.7	0.1
		0–20	7.2	5.4	2.6	8.5	62	27	11	1.1	0.0
		20–100	7.7	5.8	2.2	7.4	57	34	9	1.1	0.0
		0–15	7.0	5.6	1.7	9.4	61	32	7	1.4	0.1
		15–80	7.1	5.6	1.4	23.8	44	49	8	1.5	0.1
		0–20	7.4	6.0	1.4	20.6	34	29	37	1.5	0.1
		20–100	7.5	5.9	1.1	19.3	54	29	18	1.6	0.0
		0–15	7.7	6.1	1.6	7.2	48	26	26	1.1	0.1
		15–80	7.9	6.4	2.0	4.9	57	26	18	0.6	0.0
		80–100	7.9	6.4	1.8	17.4	65	23	12	0.4	tr
		0–20	7.3	5.9	1.7	14.0	60	27	14	1.1	0.0
		20–90	7.8	6.2	2.0	3.6	47	44	9	1.2	0.0
		0–20	8.2	7.1	9.6	11.1	43	38	18	1.6	0.1
		20–80	8.3	7.2	32.2	6.5	53	34	13	1.0	0.1
		0–20	8.3	7.3	32.1	12.3	78	19	2	1.0	0.1

(Nyssen et al., 2011)

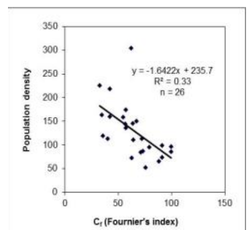


May Zeg-zeg
(Nyssen et al., 2008)



Korem
(Frankl et al., 2013)

(Jacob et al., 2013)

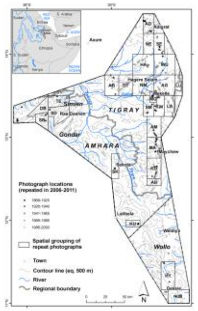


$C_f = p^2/P_y$

p = average monthly precipitation (mm) during the wettest month

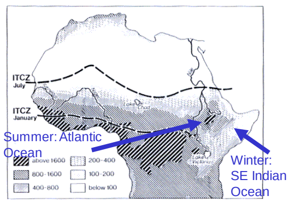
P_y = average yearly precipitation (mm).

(Nyssen et al., 2014)

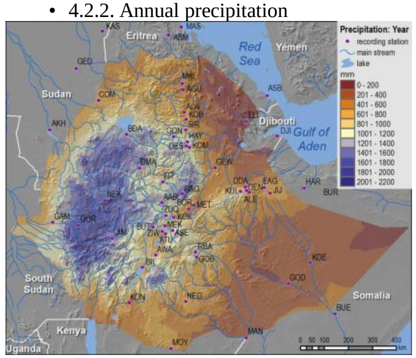


4.2 Rain and runoff as driving forces for erosion processes

4.2.1. Rain in relation to seasonal circulation patterns



- 4.2.2. Annual precipitation



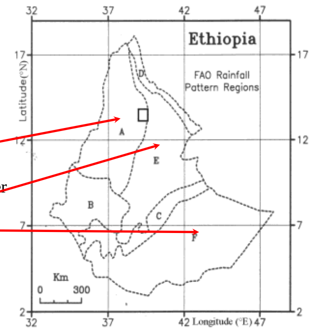
(Fazzini et al., 2015)

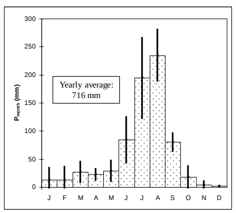
- 4.2.2. Annual precipitation

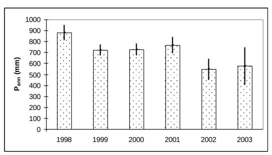
short, summer

minor spring, major summer

short, spring







(Nyssen et al., 2005)

4.2.3. Rain erosivity in the Ethiopian Highlands

$R = \Sigma (EI_{30}) / N$ (Renard et al., 1997)

where

E = total storm energy

I_{30} = maximum 30-min intensity

N = period of observation (y).

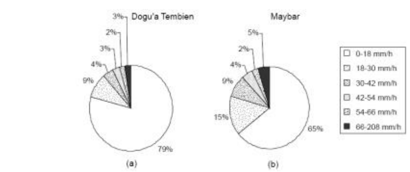


Fig. 7. Proportion of rain corresponding to different intensities. (a) Dogu'a Tembien (1998–2000) (this study); (b) Maybar/Wollo (1991–1994) (SCRP, 2000, MAPLREall.XLS database).

$$E_k = (m * v^2) / 2$$

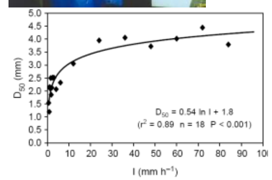
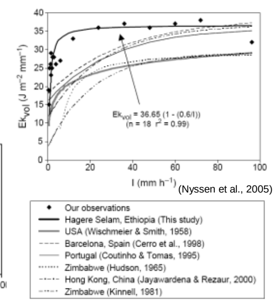


Fig. 8. Median volume drop diameter (D_{50}) vs. rain intensity (I).



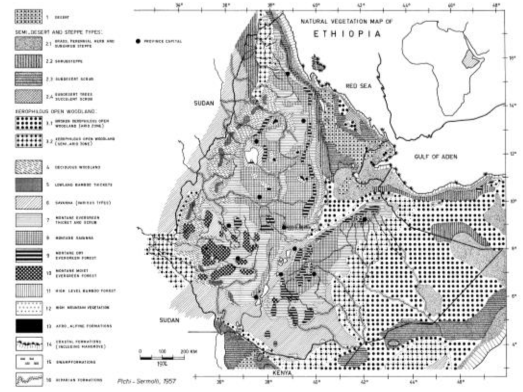
(Nyssen et al., 2005)

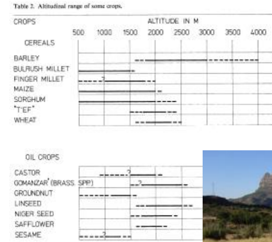
Fig. 10. Equations representing volume-specific kinetic energy (Ek_{vol}) vs. rain intensity (I).

4.2.4. Runoff and infiltration

Runoff data for selected experimental plots in the Ethiopian highlands

Location	Slope gradient (%)	Area (ha)	Period	Mean annual precipitation P (mm)	Mean annual runoff R (mm)	Runoff coefficient ($100 \times RP^{-1}$)	Land use
Melkassa	10–11	0.008	2 years	806		45.5	bare fallow
Afdeyu	31	0.018	2 years	475	240	50.5	arable
Afdeyu	31	0.018	2 years	475	115–155	24.2–32.6	arable with SWC
Debre Zeit	4–8	0.002	74 days	350[b]	80	22.9	very heavy grazing
Debre Zeit	4–8	0.002	74 days	350[b]	22	6.3	no grazing



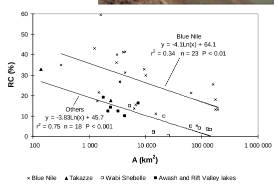


4.4.4. Runoff and infiltration

Table 3
Runoff data for selected small watersheds in the Ethiopian Highlands

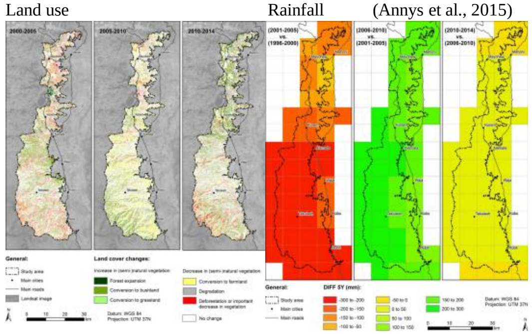
Catchment	Altitude range (m)	Area (km²)	Period (years)	Mean annual precipitation[a] P (mm)	Mean annual runoff[a] R (mm)	Runoff coefficient ($100 \times RP^{-1}$)	Source
Anjeni (Godjam)	100	1.13	10	1615.8 (± 238.4)	731.0	45.2	Bosshart, 1998b
Dombe[b] (without SWC)	125	0.94	12	1308.0 (± 249.4)	246.3 (± 158.2)	18.8	Bosshart, 1998a
Dombe[b] (with SWC)	105	0.73	12	1308.0 (± 249.4)	148.7 (± 111.1)	11.4	Bosshart, 1998a
Hunde Lafto	352	2.37	11	935	80	9	Herweg and Stillhardt, 1999
Maybar (W of Dessie)	328	1.13	12	1211	324	27	Herweg and Stillhardt, 1999
Andit Tid (Ankober)	504	4.77	10	1379	754	55	Herweg and Stillhardt, 1999
Dizi (Western Ethiopia)	224	6.73	4	1512	73	5	Herweg and Stillhardt, 1999
Afdeyu (Eritrea)	210	1.61	7	382.5 (± 123.7)	19.6 (± 16.5)	5.1	Bosshart, 1997

[a] Standard deviation between brackets.
[b] West of Lake Shala.

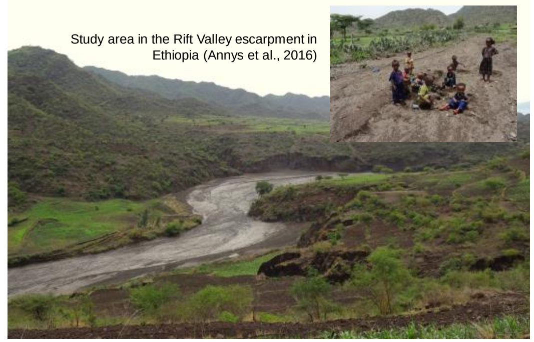


Negative feedback effect: more rainfall may also lead to increased vegation (and hence less runoff?) – particularly in semi-natural areas.

Land use Rainfall (Annys et al., 2015)



Negative feedback effect: more rainfall may also lead to increased vegation (and hence less runoff?) – particularly in semi-natural areas.



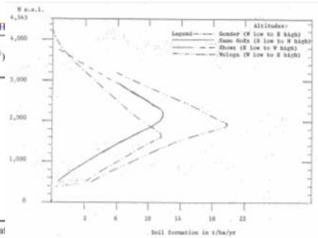
4.3. Weathering and soil formation

- Extrapolated from data on soils developed on periglacial slope deposits

Average soil formation rates in Ethiopia (after H

Agroclimatological zone[a]	Altitudinal limits (m a.s.l.)	Annual rain (mm year^{-1})
High Wurch	>3700	
Wet Wurch	3200–3700	>1400
Moist Wurch	3200–3700	900–1400
Wet Dega	2300–3200	>1400
Moist Dega	2300–3200	900–1400
Wet Woina Dega	1500–2300	>1400
Moist Woina Dega	1500–2300	900–1400
Dry Woina Dega	1500–2300	<900
Moist Kolla	500–1500	900–1400
Dry Kolla	500–1500	<900
Berha "desert"	<500	

[a] Delimitation of agroclimatological belts a and Hurni (1986).



(Hurni, 1983; based on profile studies and modelling)

4.3. Weathering and soil formation

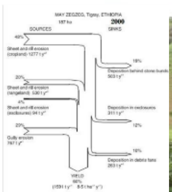
- Extrapolated from data on soils developed on periglacial slope deposits
- Rates are only valid in those areas where the soil mantle results from pedogenesis rather than from sediment deposition

Debark

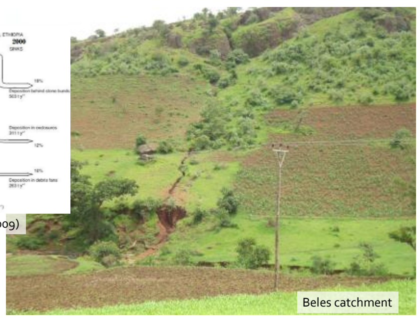
4.4. Sheet and rill erosion

- Most research on soil erosion in Ethiopia
- Wide range of measured rates ($0 - > 200$ t ha^{-1} y^{-1})
- 'Ethiopian USLE' (Hurni, 1985; Nyssen et al., 2009)
  - Not applicable as a quantitative model at a regional level

Lasta



(Nyssen et al., 2009)



Beles catchment

APPENDIX A. The Revised Universal Soil Loss Equation (RUSLE) – adapted for field assessments in Ethiopia

Equation: **annual soil loss rate A** = R * K * S * L * C * P (Mg ha^{-1} y^{-1})

1. **R: annual rain erosivity** (MJ mm ha^{-1} h^{-1} y^{-1})

$R = 5.5\ Pr - 47$

Pr = annual precipitation (mm)

2. **K: soil erodibility** (Mg h MJ^{-1} mm^{-1}), including effects of rock fragment cover

$K = [2.1\ M^{1.14}\ (10^{-4})(12\text{-}a) + 3.25\ (b\text{-}2) + 2.5\ (c\text{-}3)] * e^{-0.04\ (d-10)} * 0.001317$

M = particle size parameter = (% silt and very fine sand) * (100 - % clay)
a = percentage of organic matter
b = soil structure code, ranging between 1 (very fine granular) and 4 (blocky, platy or massive), with default value 2
c = permeability class, ranging between 1 (rapid) and 6 (very slow), with default value 3
d = stone (rock fragment) cover (in %)

3. **S: slope steepness factor** (dimensionless)

$S = -1.5 + 17 / (1 + e^{(2.3 - 6.1 \sin\theta)})$

θ = slope angle (°)

4. **L: slope length factor** (dimensionless)

$L = 0.232\ \lambda^{0.48}$ $(5\ m \leq \lambda \leq 320\ m)$

λ = slope length (horizontal projection, in m)

5. **C: cover-management factor** (dimensionless)

Dense forest	0.001	Degraded rangeland (< 50 % vegetation cover)	0.42	Badlands hard	0.05
Dryland forest; exclosure	0.004			Badlands soft	0.40
Dense grass	0.01	Degraded grass	0.05		
Sorghum, maize	0.10	Tef (in high rainfall areas)	0.25	Fallow hard	0.05
Cereals, pulses	0.15	Tef (in semi-arid areas)	0.07	Fallow ploughed	0.60

6. **P: supporting practices** (dimensionless)

$P = P_C . P_N . P_M$ (on cropland); $P = P_N$ (on other land)

Ploughing and cropping practices	P_C	Conservation structures	P_N	In situ conservation practices	P_M
Ploughing up and down	1	No conservation structures	1	Stubble grazing; no mulching	1
Ploughing along the contour	0.9	Stone bund (average condition; smaller value for new s.b. and larger for older s.b.)	0.3	Applying mulch	0.6
Strip cropping	0.8	Grass strip (1 m wide; slope ≤ 0.1 m m^{-1})	0.4	Zero grazing	0.8
Intercropping	0.8	Grass strip (1 m wide; slope > 0.2 m m^{-1})	0.8		
Dense intercropping	0.7				

Source: Renard et al., 1997. Adaptations: R correlation by Hurni (1985): K adjustment for rock fragment cover by Poesen (1994); L correlation by Hurni (1985); C values by Hurni (1985) and Nyssen et al. (this study); P model by Nyssen et al. (this study); P values by Hurni (1985), Nyssen (2001), Desta et al. (2005), Nyssen et al. (2007, 2008b). Limitations as mentioned in section 4.4 of

4.5 Gullying

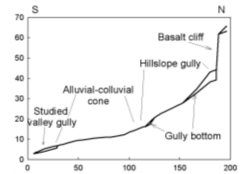
Gullies, like this one in Harena (Dogu'a Tembien), do not only result in soil loss, but also drain out the landscape (lowering of the water table) and are major obstacles to communication (Nyssen et al., 2015).

Types of gullies

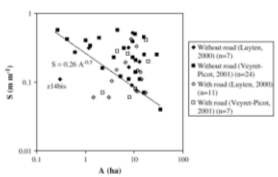
- Hillslope gullies
- Valley bottom gullies

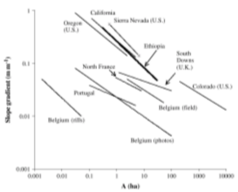
Types of gullies

- Hillslope gullies
- Valley bottom gullies
- Discontinuous ephemeral streams



Topographical thresholds





Causes and processes

- Land degradation
- Land use changes
- Clear water effect
- Vertisols
- Road building

Land degradation

- Change in hydrological conditions
  - Increased runoff coefficients
  - Rapid runoff response

Land use changes

- Change in hydrological response
  - Urbanisation
    - Decreased perviousness
  - From forest to range- or cropland
  - From cropland to rangeland
    - Increased runoff coefficient because of:
      - Absence of tillage
      - Trampling (soil structure decay, decreased hydraulic conductivity, decreased infiltration)
      - Soil and water conservation structures are no longer maintained

Clear water effect

- clear water erodes more than water that carries sediment
- relatively clear water flowing through checkdams again carries soil from the lower gully

Vertisols

- Major factor in development of valley bottom gullies
- Sometimes very flat land is gullied
- Subsurface erosion and piping

Road building

- Major cause of gully erosion

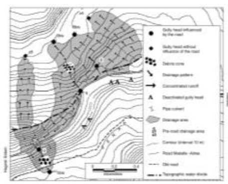
1994

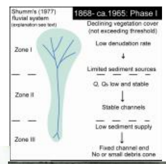
1998

2010

Road building

- More rapid runoff response due to drainage channels etc.
- Increased catchment size due to culvert
- Solutions:
  - 'Irish' ford
  - Greater number of crossings
  - Use S/A threshold

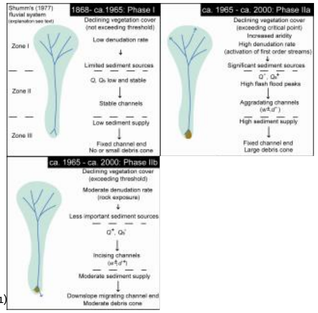




1939

(Frankl et al., 2011)

Korem

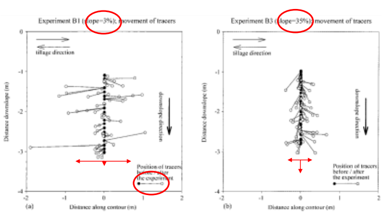


(Frankl et al., 2011)

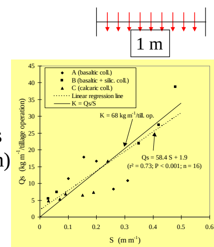
- Control techniques
  - Catchment treatment
  - Exclosure in gully
  - Checkdams (maintenance needed)
  - Current stabilisation of gully systems

4.6. Tillage erosion

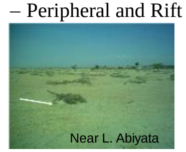
- Displacement of tracers



- Soil flux, or Unit soil transport rate
  - diffusion-type geomorphic process of soil displacement
  - Amount/mass of soil transported downslope across 1 m along the contour (kg / m)



4.7 Wind erosion
- ‘Dust devils’ (trampling)
- Isolated mountains
- Peripheral and Rift Valley lowlands



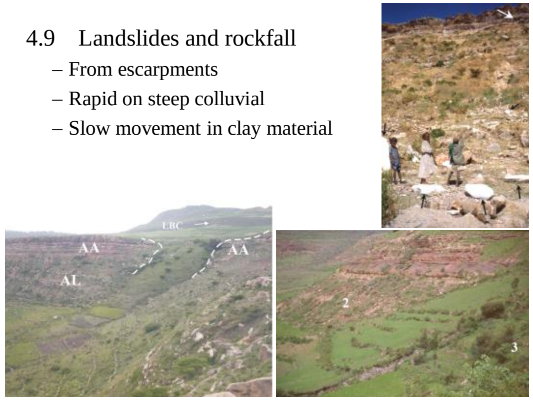
Atsbi Dera, 3100 m a.s.l.

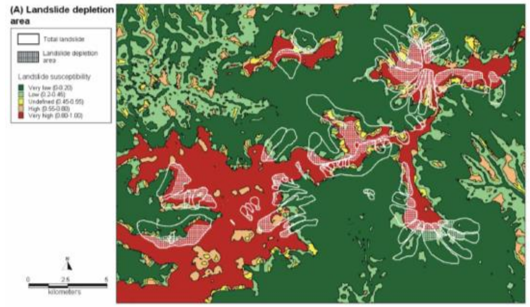
4.8 Soil creep

– Over a thickness > 1 m
– In cm y^{-1}
– On steep slopes → terracettes

4.9 Landslides and rockfall

– From escarpments
– Rapid on steep colluvial
– Slow movement in clay material





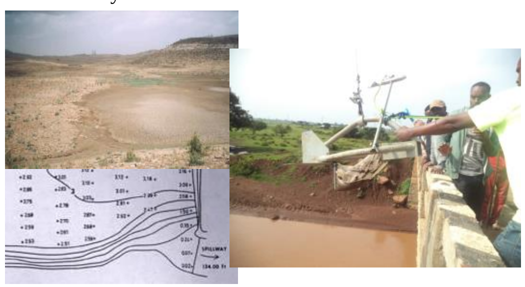
(Van den Eeckhaut et al., 2009)

4.10. Sediment deposition

– Most eroded soil deposited within the catchment
– Preferred locations: vegetation strips, stone bunds, exclosures

5. Assessment of soil loss and sediment yield

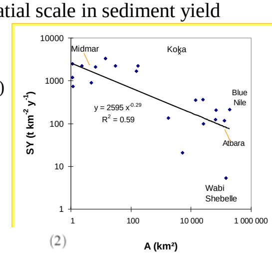
Sediment yield measurements



5. Assessment of soil loss and sediment yield

5.1. The importance of spatial scale in sediment yield assessment

– Large catchments: more total sediment yield (t y^{-1})
– Less specific sediment yield (t ha^{-1} y^{-1})
– Deposition!



$$SY = 2595A^{-0.29} \quad (n = 20;\ r^2 = 0.59) \qquad (2)$$

where: SY = area-specific sediment yield, in t km^{-2} $year^{-1}$, and A = drainage area, in km^2.

5.2. Soil loss from runoff plots and sediment deposition

5.2. Soil loss from runoff plots and sediment deposition

– Average soil loss rates for different types of land use
– NOT extrapolated to catchments!
  - Ridge situation
  - Only small part is lost from catchment
  - Rill and gully not taken into account

Table 6
Estimated rates of soil loss by sheet and rill erosion on slopes, for various land uses in Ethiopia (after Hurni, 1990; updated in Bojö and Cassells, 1995)

Land cover	Area (%)	Soil loss ($t\ ha^{-1}\ year^{-1}$)
Grazing	47	5
Uncultivable	19	5
Cropland	13	42
Woodland/bushland	8	5
Swampy land	4	0
Former cropland	4	70
Forests	4	1
Perennial crops	2	8
Total for the highlands	100	12

5.3 Dissolution

Lapiez S of Hechi (Dogu'a Tembien)

Dissolution morphologies on limestone rock surfaces at May Kinetal (Machado, 2015)

Tors generated by granite weathering along joints and fractures (May Kinetal intrusive granitoid) (Machado, 2015)

Table 7
Mean annual fluxes of dissolved major elements transported by th
Nile (after Kempe, 1983; Probst et al., 1994)

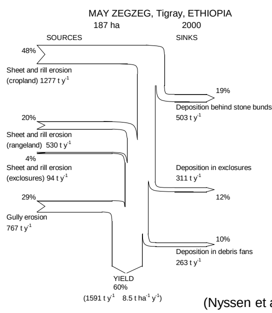
Element	Dissolved flu ($10^6\ t\ year^{-1}$
Ca^{2+}	2.57
Mg^{2+}	1.01
Na^{+}	3.03
K^{+}	0.59
Cl^{-}	2.84
SO_4^{-}	2.48
HCO_3^{-}	14.01
Organic C	0.17

5.4. A sediment budget for the Ethiopian Highlands

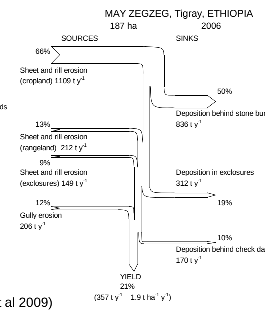
– "detailed account of the sources and deposition of sediment as it travels from its point of origin to its eventual exit from a drainage basin" Sources − Sinks = Yield

2000

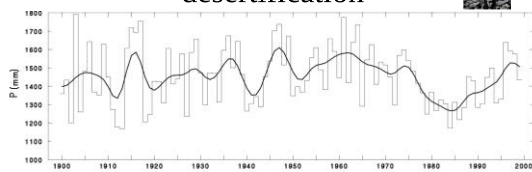
2006



(Nyssen et al 2009)



6. Land degradation and desertification

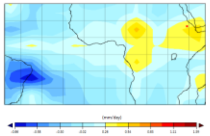


6.1. Rain variations and drought

– Long term changes in annual rainfall not observed
– Drought 1980s
– Negative impact on already degraded environment
– Probably: change in seasonality: more spring rains

Impacts of climate change

- Use of fossil fuel → climate deregulated
- Global warming
- Models predict increased rainfall in the Horn of Africa
  - Agric. productivity
  - Increased RC and erosion
  - Lowland irrigation



IPCC scenario A1FI; difference of average precipitation between 2040-2045 and 1972-1984 (Lanckriet et al., 2012)

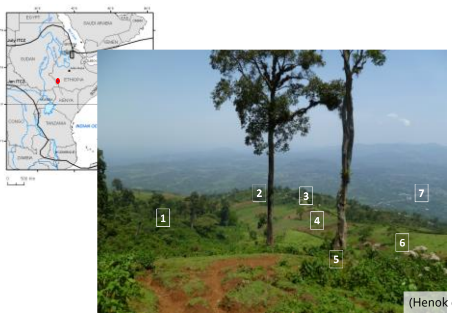
Inatye ridge (4070 m a.s.l.) and changes in upper tree line
1968 1996 2012

(Nyssen et al., 2014)

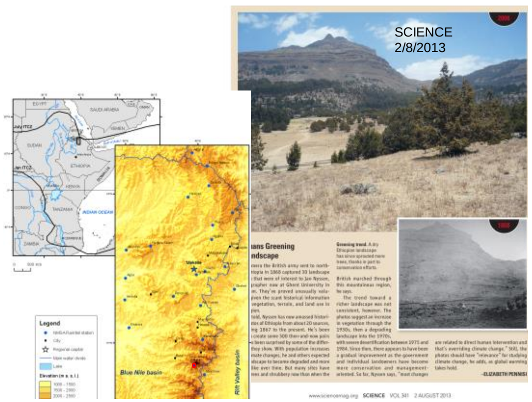
6.2. Human settlement, change in land use and land cover

6.2.1 Deforestation

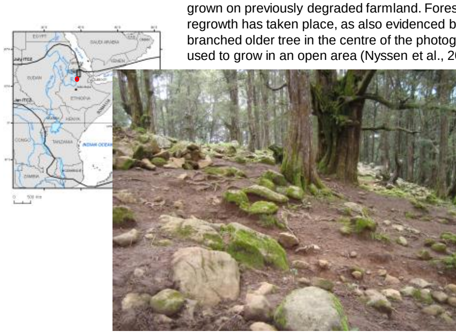
- The 40 % myth
- no study ever produced such data
- Very old phenomenon (2000 – 4000 y)
- Cyclic, not linear
- Increase of eucalyptus forests
- Decrease of semi-natural forests



(Henok et al., 2015)



Plough marks on large rock fragments and pedestal-supported boulders indicate that this 100–200-year-old Juniperus forest at Kuskuam near Debre Tabor has grown on previously degraded farmland. Forest regrowth has taken place, as also evidenced by the well-branched older tree in the centre of the photograph that used to grow in an open area (Nyssen et al., 2015)



6.2.2. Grazing

- Stocking rates in excess of optimum
- Stubble grazing
- Increased runoff, because:
  - –decreased surface roughness
  - –Soil compaction; increased bulk density
  - –decreased soil organic matter content
  - –soil structure decay and decreased hydraulic conductivity

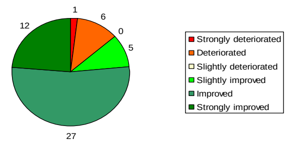
Current and optimum livestock densities (after EFAP, 1993; Bojö and Cassells, 1995)

Zone	Current ($TLU^a ha^{-1}$)	Optimum ($TLU^a ha^{-1}$)
High potential pasture zone (highlands)	0.67	0.69
High potential cereal zone (highlands)	0.78	0.66
Low potential cereal zone (highlands)	0.66	0.31
Lowlands	0.18	0.25

[a] TLU = Tropical Livestock Unit, equivalent to a standard zebu ox of 250 kg (FAO, 1988); for each other type of domestic animal there is a conversion equivalent.

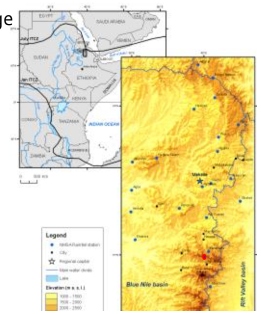
6.3. Assessment of the evolution of land degradation

- Rates of deposition (example near Axum):
  - Last 1000 y: 13 m
  - From 3000 til 1000 BP: 4 m only
- General gully entrenchment in Tigray started in the 1950s – 1960s (aerial photos, interviews)
- Locally reversal in recent years



6.4 Social and historical impulses of land use and cover changes

- Rain variations cannot explain degradation
- Human impact (changes in land use and cover)
  - Agricultural stagnation over centuries
  - Macroeconomic decisions
  - Immediate returns at the expense of environmental degradation
- Reference: Crummey, D., 2000. Land and society in the Christian kingdom of Ethiopia, from the thirteenth to the twentieth century. Addis Ababa University Press, 373 p.

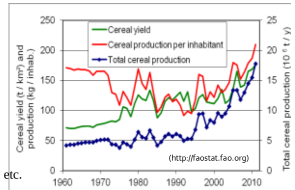


7. Human reactions to land degradation

7. Human reactions to land degradation

7.1. Agricultural intensification and land rehabilitation

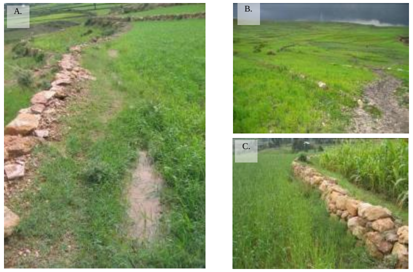
- Improved climatic conditions
- Human interventions (society reacts with innovative process)
  - Integrated SWC
  - Exclosures
  - Fertiliser (not always mineral)
  - Irrigation
  - Extension, seed selection, credit, etc.
- First signs of future steps
  - Gardening and minimum tillage
  - Haying instead of free (stubble) grazing



(Nyssen et al., 2015)

7.2 Soil and water conservation

– Case of stone bunds

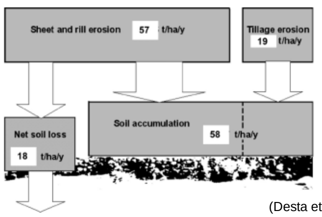


Catchment rehabilitation in the sub-humid May Zeg-zeg catchment (Tigray); trenches behind the stone bunds enhance infiltration and decrease catchment runoff response (Nyssen et al., 2015)

Soil and water conservation activities in the Tsinkaniet plain have led to a situation where overland flow strongly decreased in 2006 (right—photograph J. Nyssen) as compared to 1975 when evidence of flooding is clearly visible at the footslope (left—photograph R.N. Munro). At the far end, in 2006, a reservoir mainly fed by groundwater is visible (Nyssen et al., 2015)

7.2 Soil and water conservation

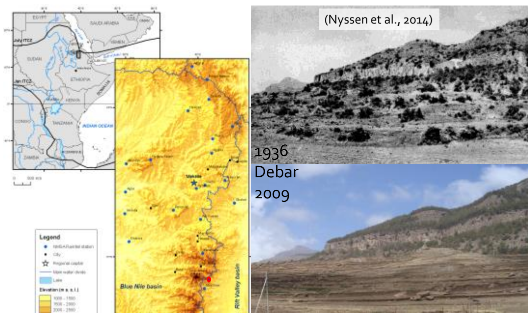
– Acceptance: more than 25 y old structures still in place
– Positive impact at catchment size
– Profitability at farm level under discussion

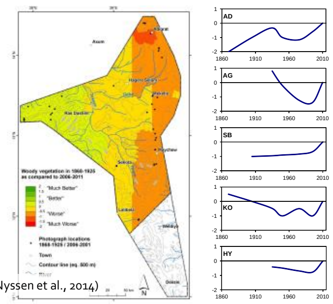


(Desta et al., 2005)

Fig. 4. Average sediment budget for cropped plots with stone bunds in Tigray Highlands (after Desta, 2003).

7.3 Deforestation and reforestation





(Nyssen et al., 2014)

- Establishment of exclosures, in relation to changes in land tenure

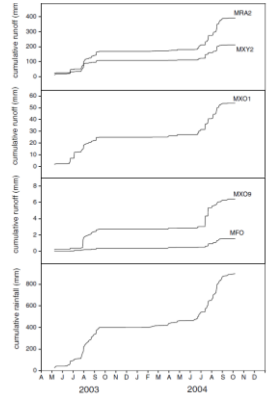
2013

Nebelet

High-oblique AP, 1935 (Lanckriet et al., 2015)

- Decision-making
  - Process guided by authorities
  - Largely interiorised by population
  - Participation
    - Location, area, guarding decided by community
    - Enhanced by remunerated activities
    - Overall it is a genuine participation (Kumasi and Asenso-Okyere, IFPRI, 2011)

- Effects on hydrology, biomass, ecology, ecosystem services (Muys et al., 2014)
- Effect on runoff studied in 30 runoff plots (Descheemaeker et al., 2006, 2008)

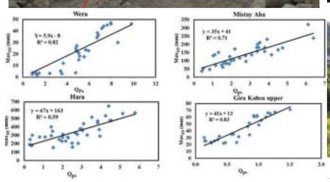


- Effects on hydrology, biomass, ecology, ecosystem services (Muys et al., 2014)
- Effect on runoff studied in 30 runoff plots (Descheemaeker et al., 2006, 2008)
- Springs improve = less drudgery for women

Harena

- Hydrogeomorphological effects of reforestation: fining of transported bedload (Tesfaalem et al., 2015a)

Relationship between specific event peak discharge (Qp_s, $m^3 s^{-1} m^{-1}$) and average size of the 10 coarsest bedload particles moved (Max_{10}) in each event in 4 of the 11 monitoring stations

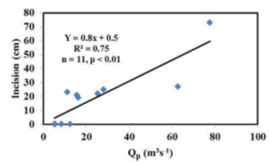


Gra Kahsu

1970 Photo © Larry Workman

2006 Photo © Jan Nyssen

- Hydrogeomorphological effects of reforestation: river downcutting ("clear water effect") (Tesfaalem et al., 2015b)



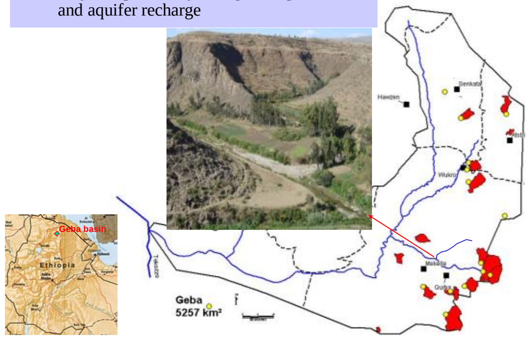
River incision (downcutting) rate (cm/yr) after reforestation as a function of river peak discharge (Qp) – case study in 11 catchments along the Rift Valley escarpment (Tesfaalem et al., 2015b)

7.4 Reservoir construction

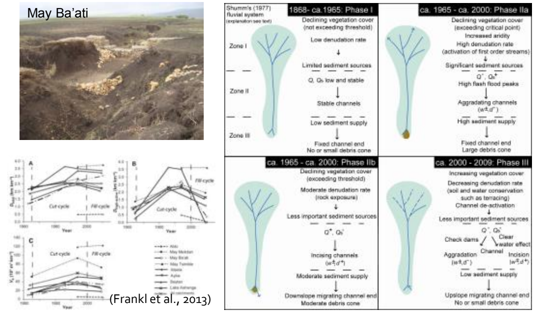
- Main purpose: irrigation
- Often short life expectance (siltation, leakages, technical problems...

7.4 Reservoir construction

- Major impact on hydrological regularisation and aquifer recharge



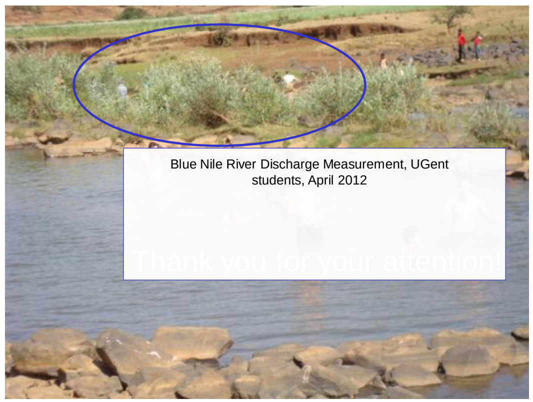
7.5 Land resilience



(Frankl et al., 2013)

8. Conclusions

- Starting from 5000 y ago: human interference and slope instability
- Most important present-day degradation processes:
  - sheet and rill erosion throughout the country
  - gullying especially in the Highlands
  - wind erosion (Rift Valley, peripheral lowlands)
  - tillage erosion (steep cropland)
- Action at different levels of society
  - Much SWC work is going on
  - Benefits for society are evident: public support is needed
- Underlying causes not discussed in this review
  - past and present regional social relations
  - international unequal development
- Land husbandry can be sustainable (needs improved socio-economic conditions)



Blue Nile River Discharge Measurement, UGent students, April 2012