Modeling the impact of vegetation changes on erosion rates and landscape evolution

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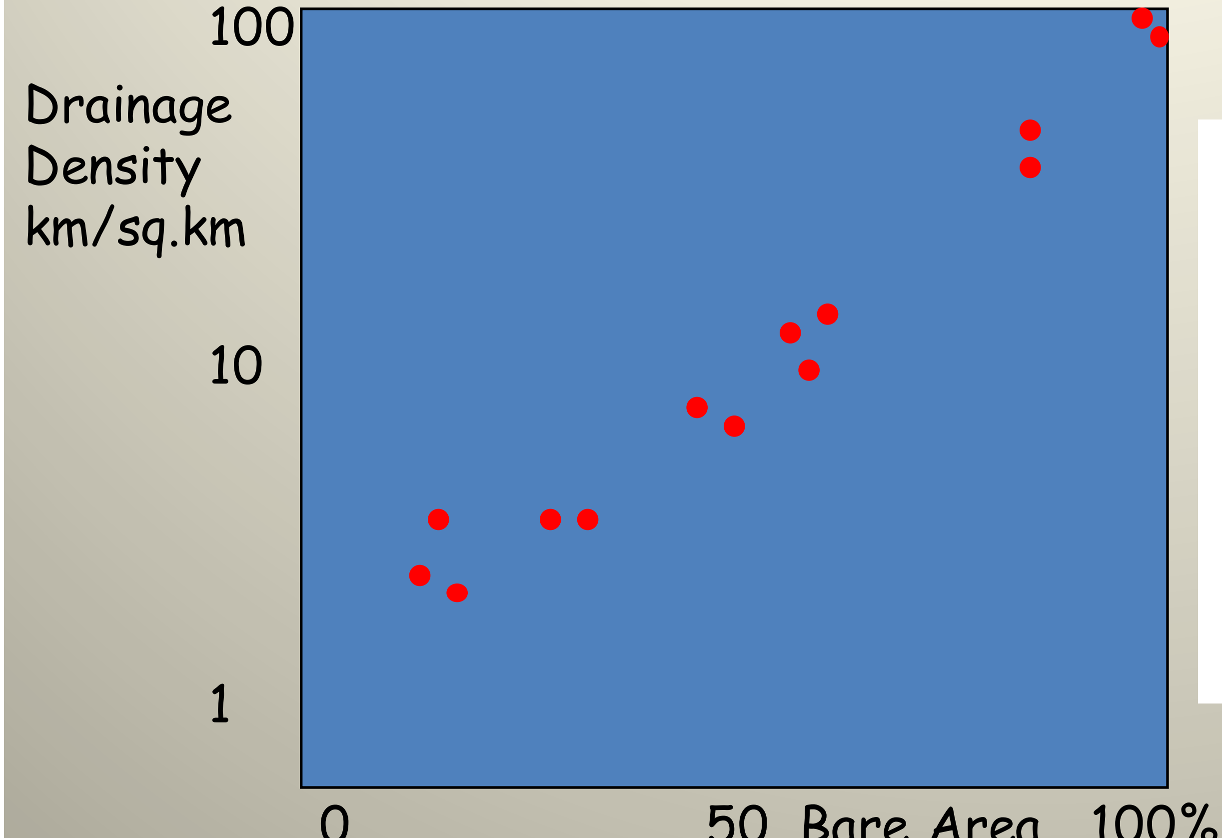
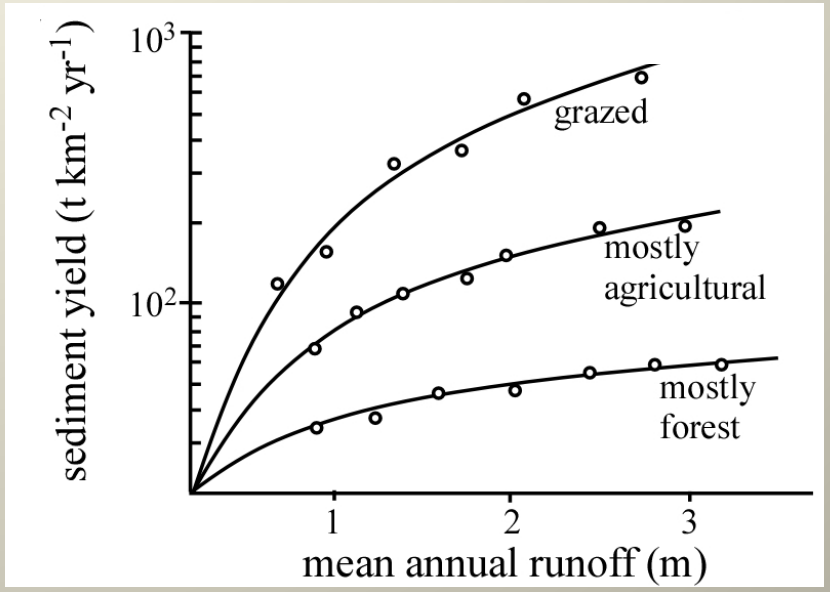
Hillslope-fluvial geomorphologists have often taken climate change to be synonymous with changes in runoff/discharge/precipitation (i.e., driving shear stresses). However, common vegetation cover changes lead to changes in erosion rates and topography that are O(10) larger.



after Melton, 1957



after Dunne, 1979

NSF-sponsored workshop in Tucson

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Earth's Future

REVIEW

10.1002/2014EF000290

Key Points:

- We review models and data useful for forecasting Earth surface changes
- We identify key knowledge gaps required to forecast Earth surface changes
- We strategize how geomorphologists and Earth-systems modelers can collaborate

Forecasting the response of Earth's surface to future climatic and land use changes: A review of methods and research needs

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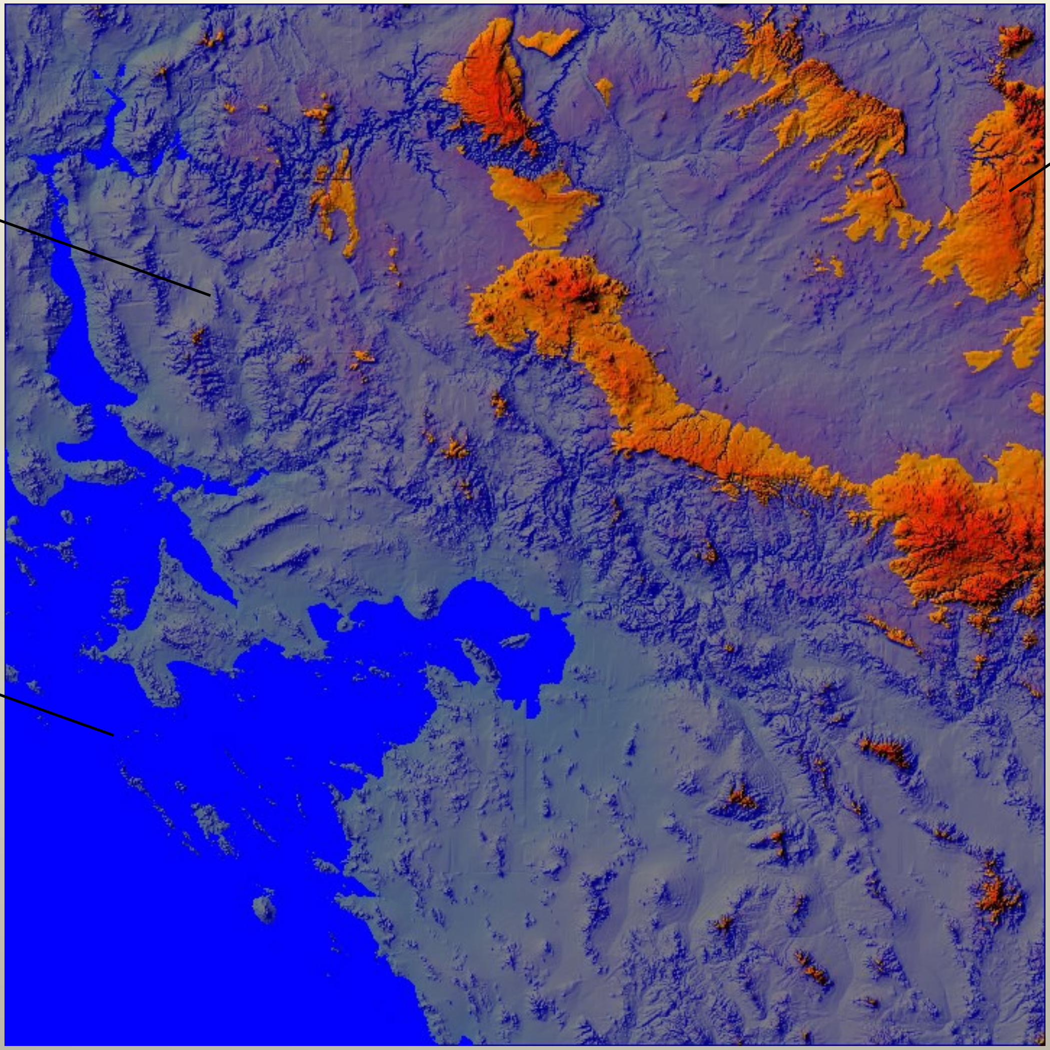
- *Geomorphic responses to veg cover is a key knowledge gap for all process zones*
- *Generating reliable forecasts for the future requires that models be validated against the historical and geologic records over a range of time scales*
- *Geomorphologists should collaborate more with ESMers*

In SW US, forests were at 800 m a.s.l. at LGM and only occur above 1800 m a.s.l. today. So, large areas have fluctuated back and forth between shrubland/grassland and forest during G-I cycles.

800-1800 m

above 1800 m



below 800 m

80% of AZ has fluctuated between shrubland/grassland and forest ~20 times during the Q

Packrat middens: an elevation-specific paleoveg constraint

Modeling framework (transport-limited case):

$$E = \nabla \cdot \mathbf{q}_{s,c} + \nabla \cdot \mathbf{q}_{s,f}$$

where

$$\mathbf{q}_{\mathrm{s,c}} = -D(V)\frac{\nabla z}{1-\left(|\nabla z|/S_{\mathrm{c}}\right)^2}$$

$D\uparrow$ *as* $V\uparrow$ *(more plants = faster bioturbation)* *O(1)*

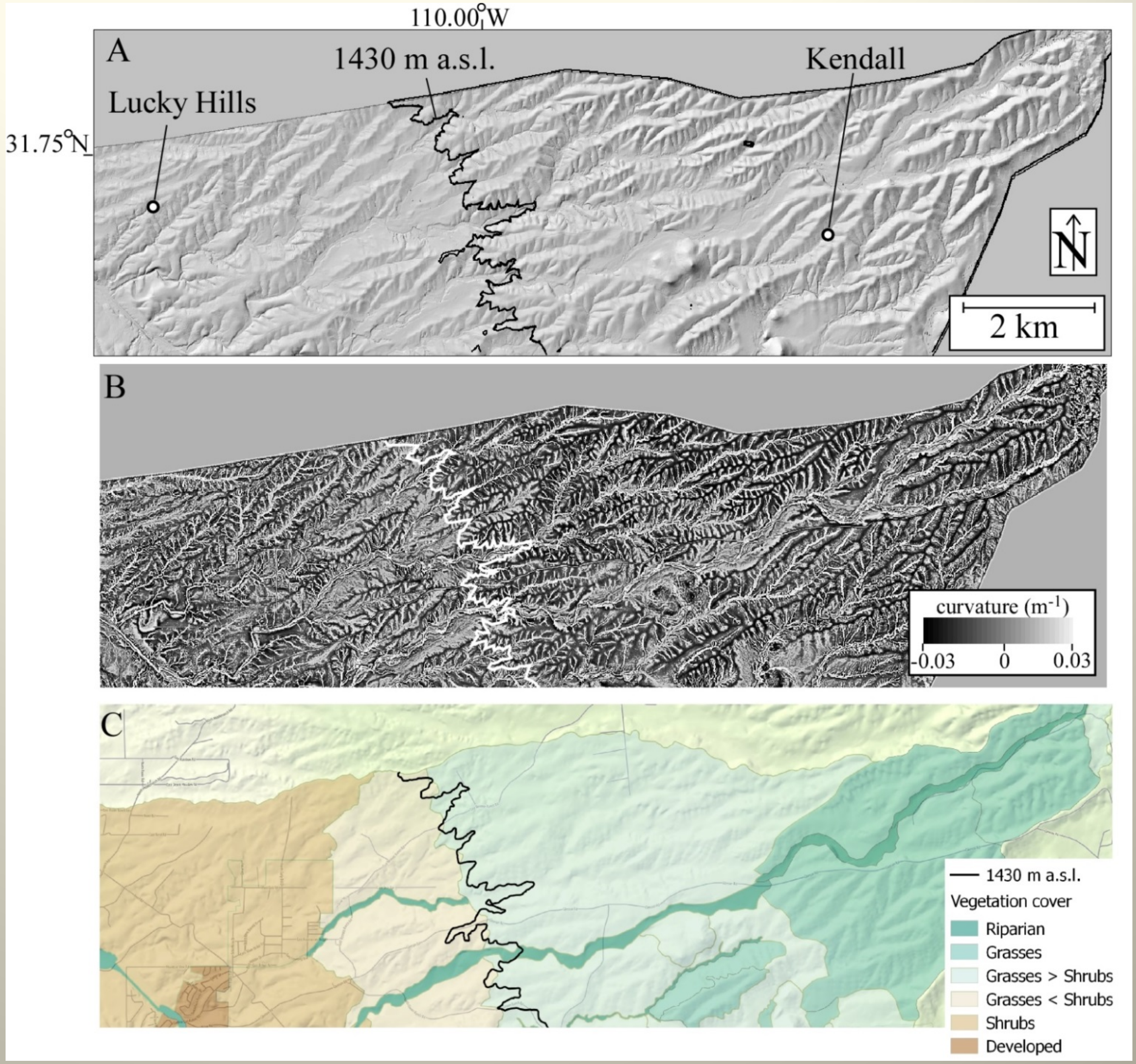
$$\mathbf{q}_{\mathrm{s,f}} = -k(V)\left(\frac{A}{w}\right)^p |\nabla z|^{n-1}\nabla z$$

$k\downarrow$ *as* $V\uparrow$ *(fewer plants = more runoff, more bare area acting as sediment sources)* *O(10)*

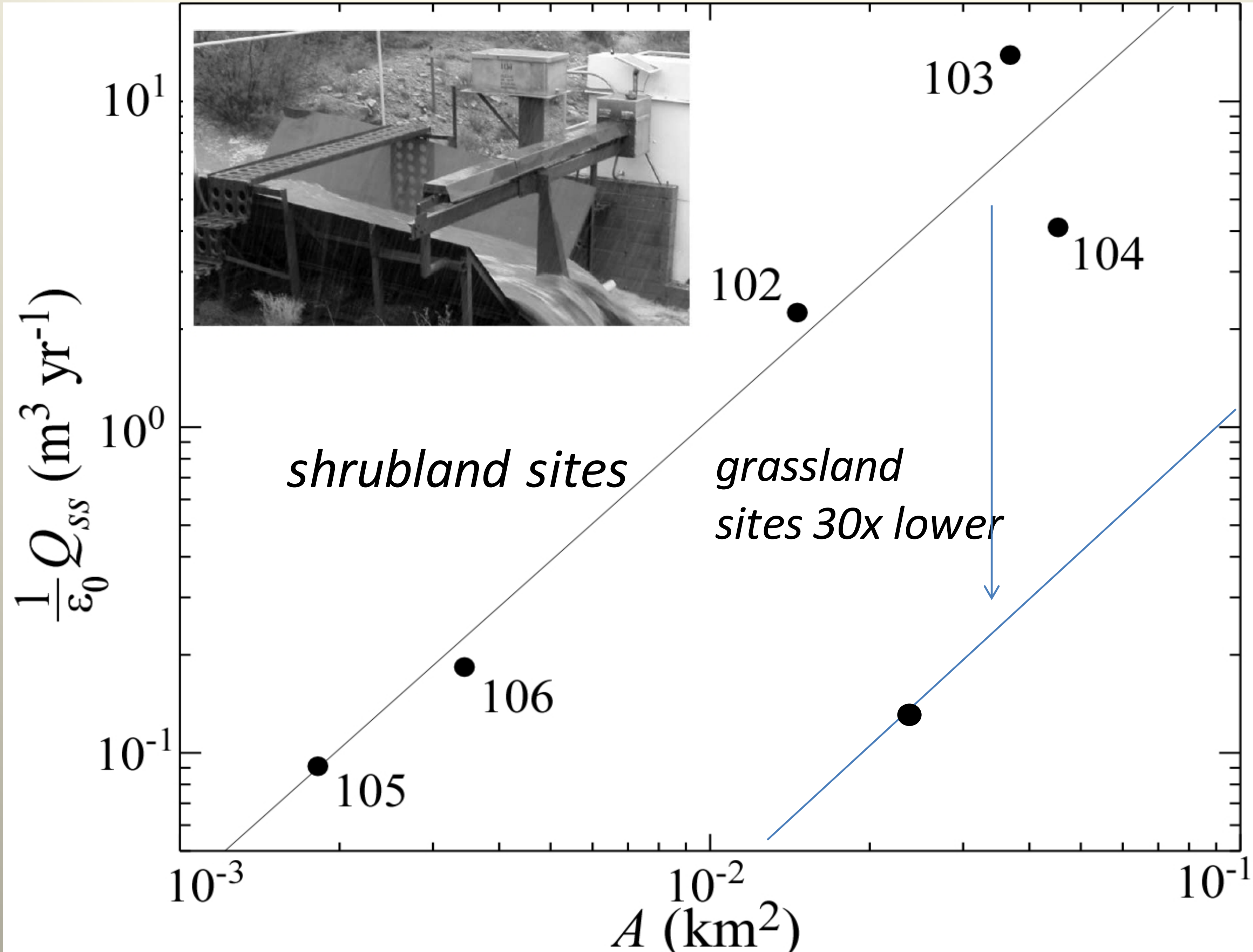
Example at ~10^3 yr: Walnut Gulch Experimental Watershed

Shrubland vs. Grassland:

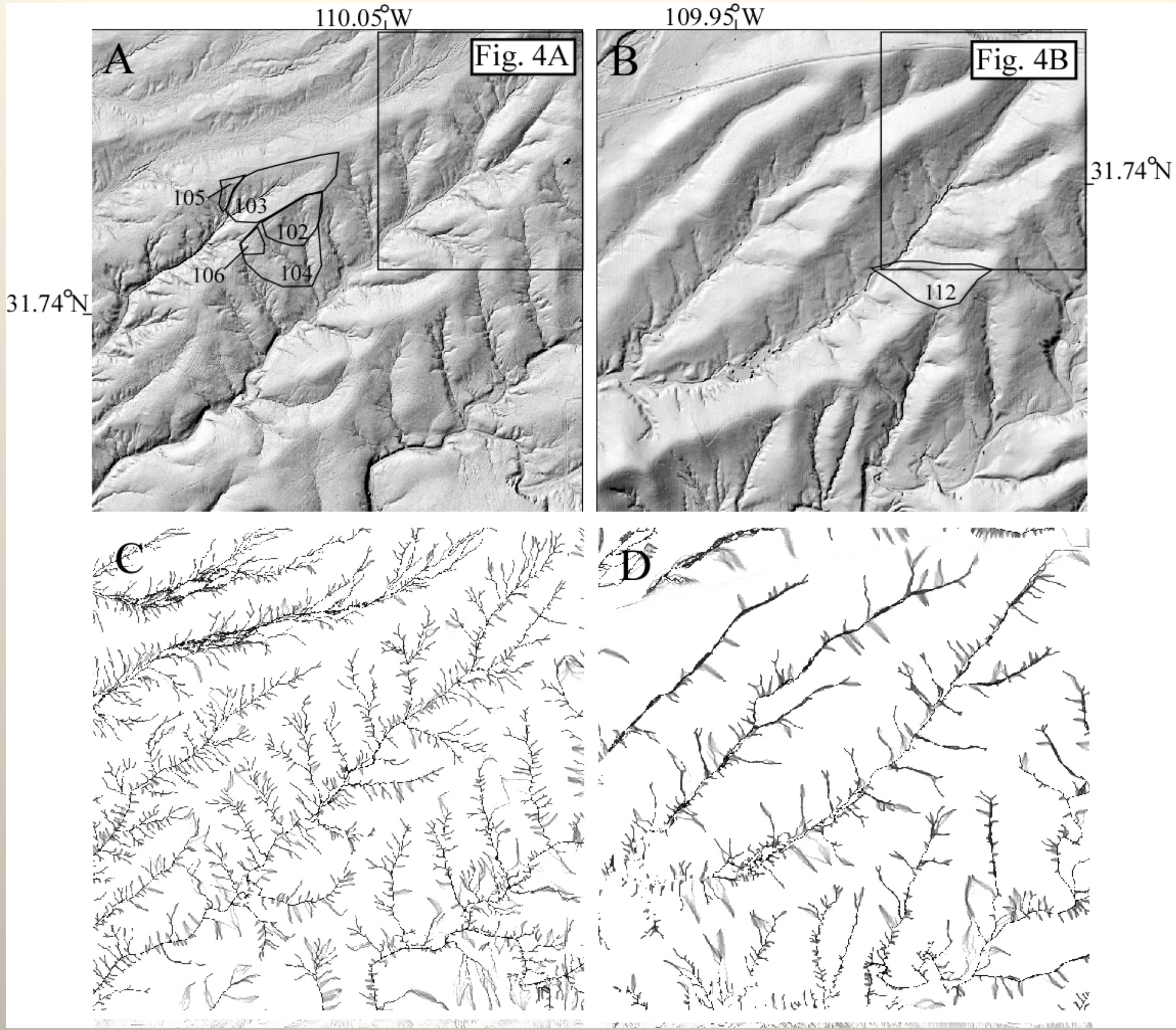
Similar uplift/relief
Precip 10% lower
Sediment yield and erosion rate are 30x higher
D. density 4x higher
Concavity higher



Long-term sediment fluxes well constrained: 30x higher in shrublands

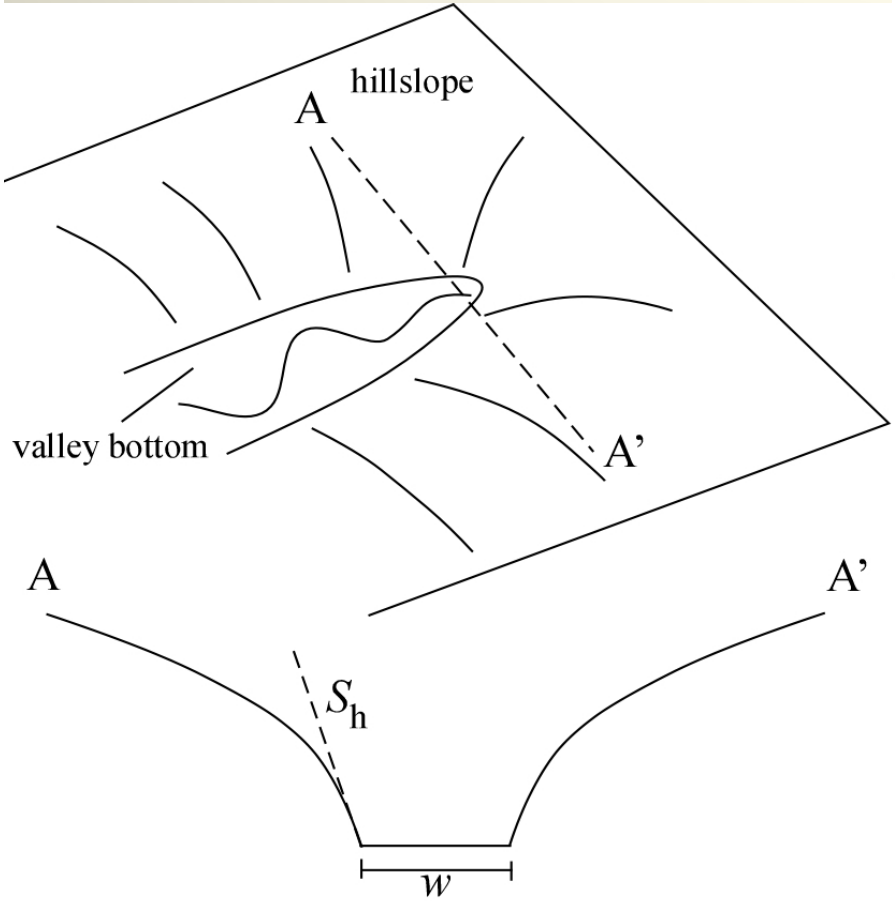


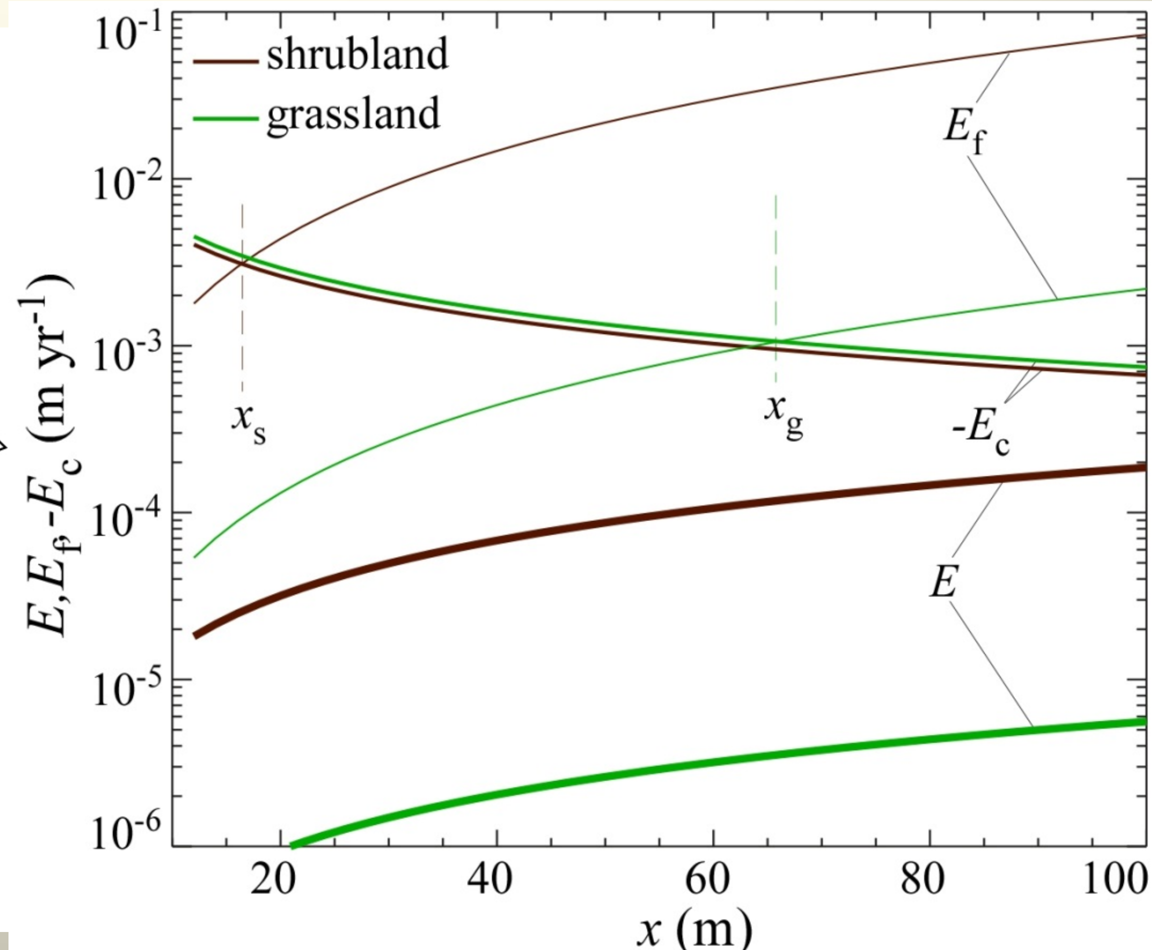
Drainage density is 4x higher in shrubland than grassland



Mean distance to valley = 15 m in shrublands, 60 m in grasslands

At valley heads, the fluvial erosion rate exceeds the colluvial deposition rate slightly (by an amount equal to the net erosion rate). The model predicts drainage density as a function of veg cover and time since the veg transition.

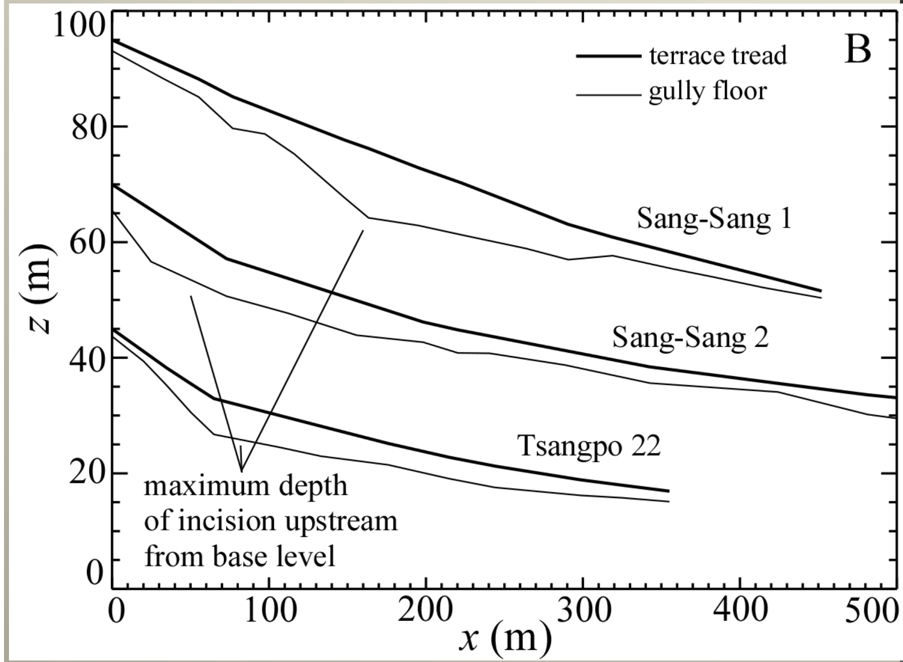


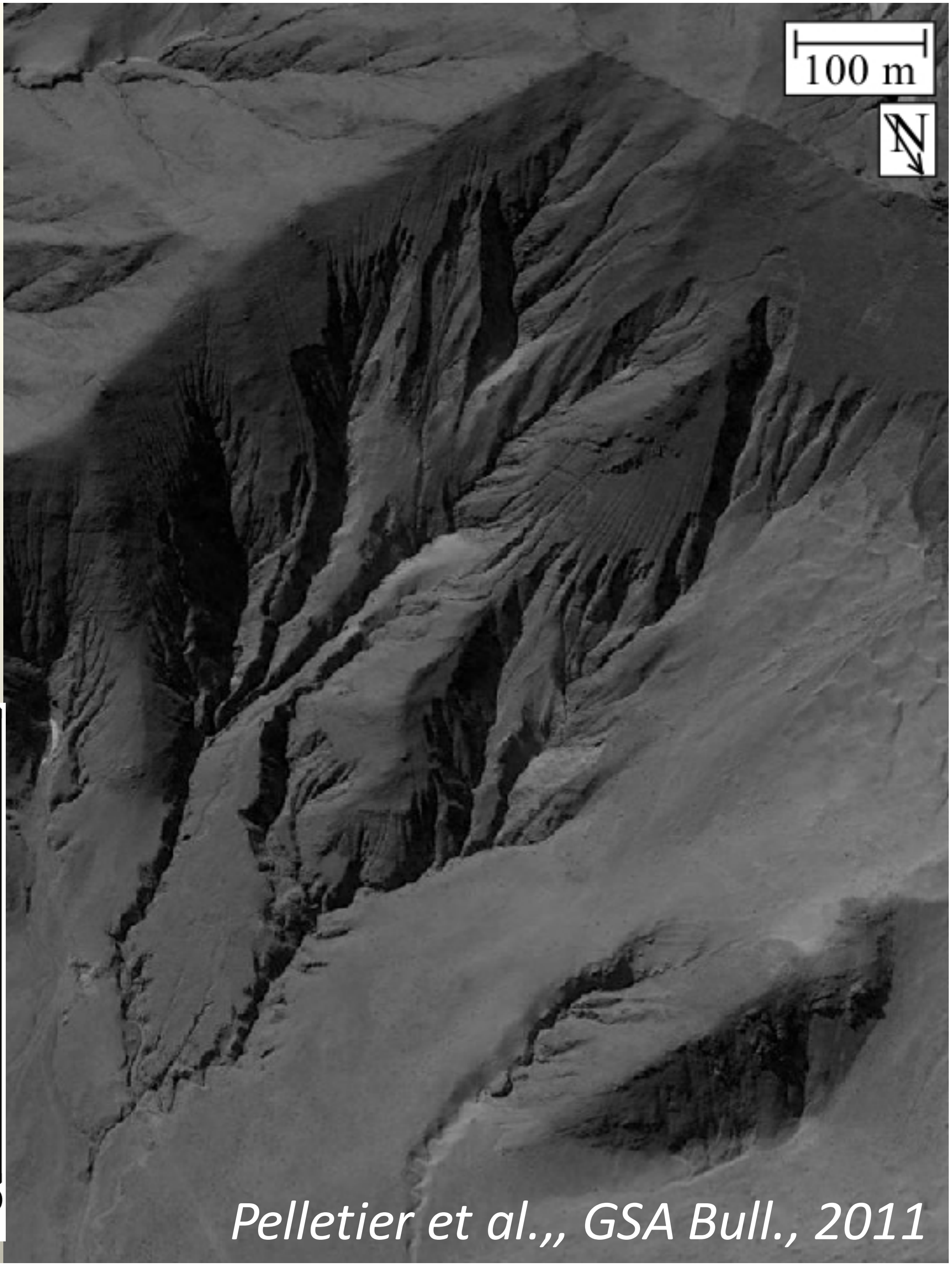


Pelletier et al., Esurf, 2016

Another example over ~10^3 yr

Fan deposits that grade to gullies in Tsangpo V., Tibet, are late Holocene. This constrains the cause to be overgrazing.
Landscape responds with higher drainage density and increased channel concavity.
Numerical models with increase in *K* reproduce this.

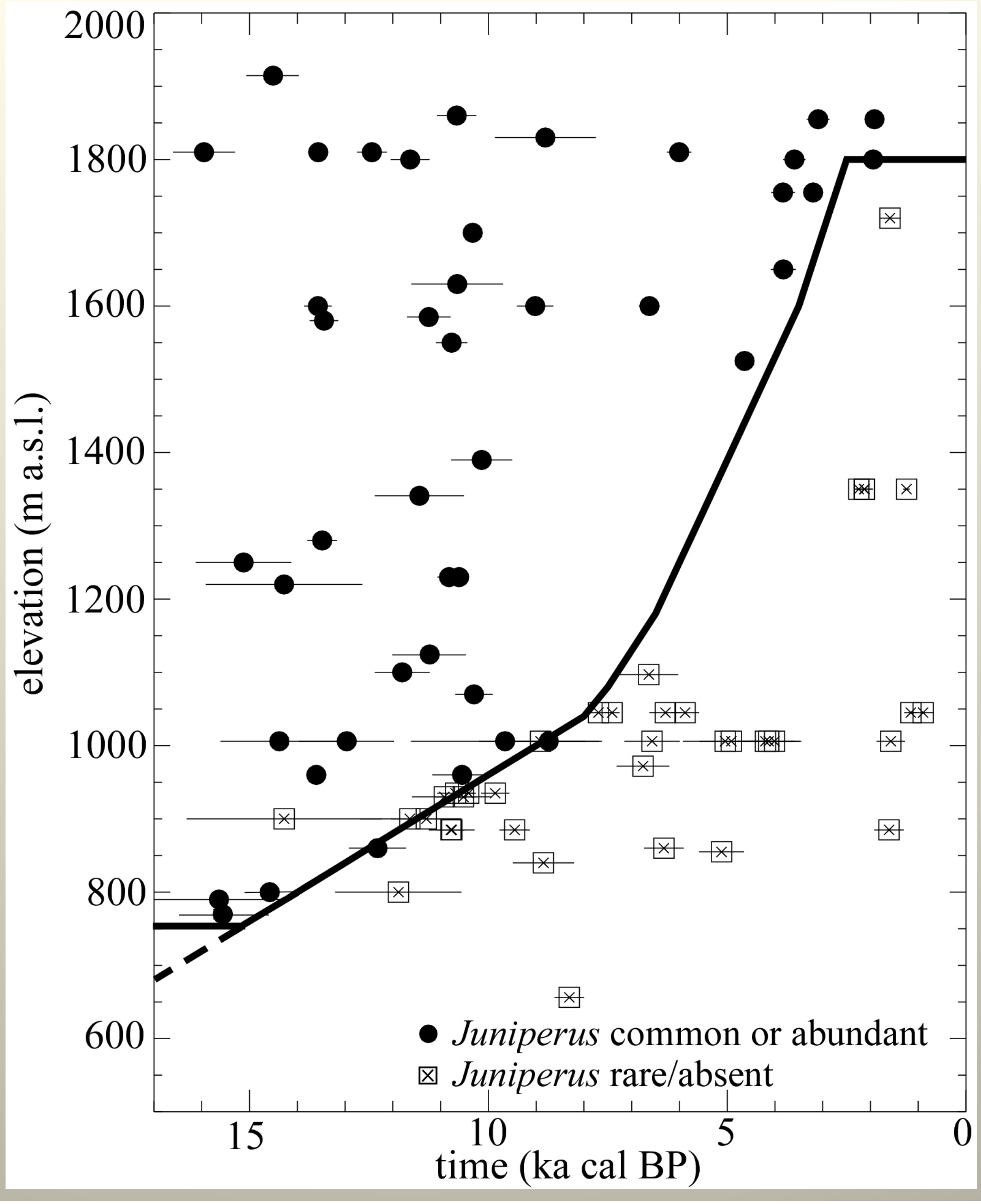




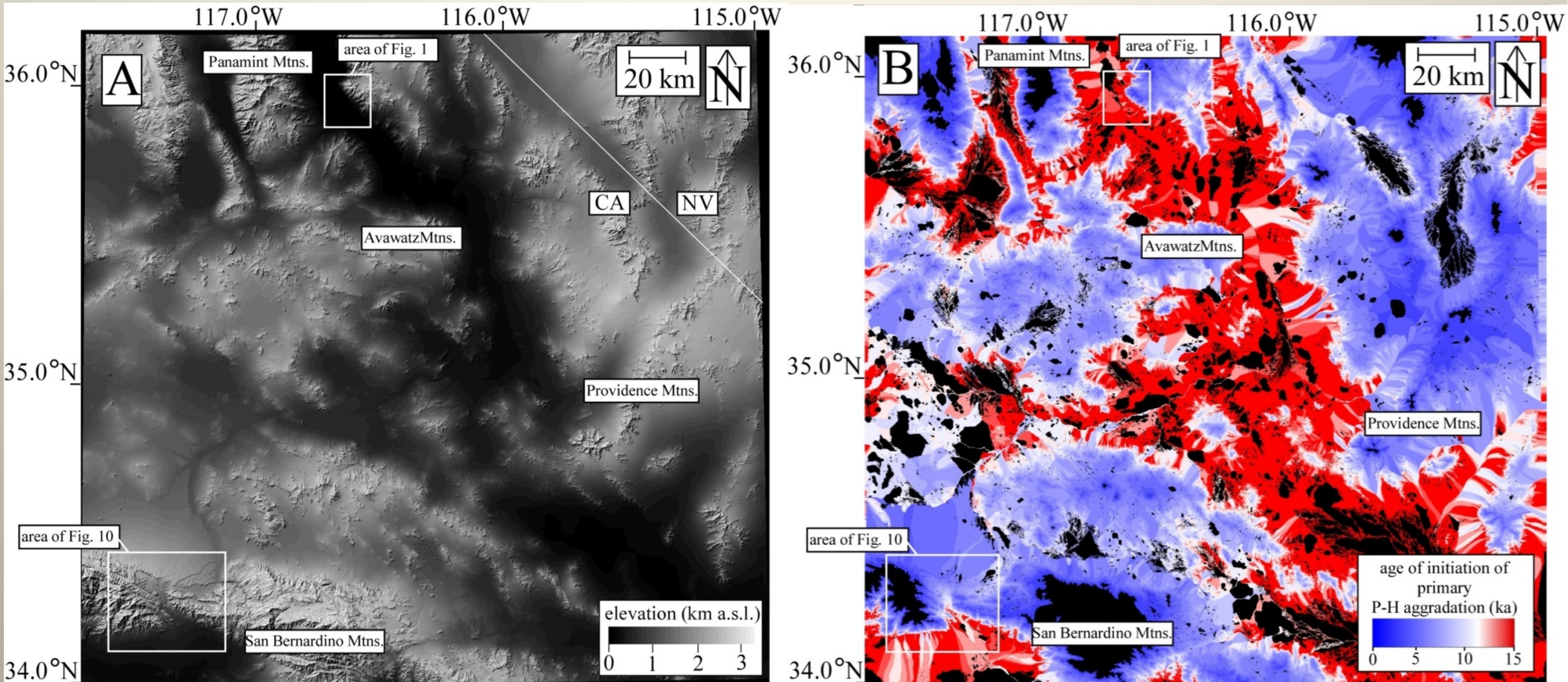
Pelletier et al.,, GSA Bull., 2011

Example at ~10^4 yr: timing of aggradation due to Pleistocene-Holocene transition in SW US

Retreat of forests from 800 to 1800m a.s.l. was time transgressive. Can we predict timing of aggradation and incision?

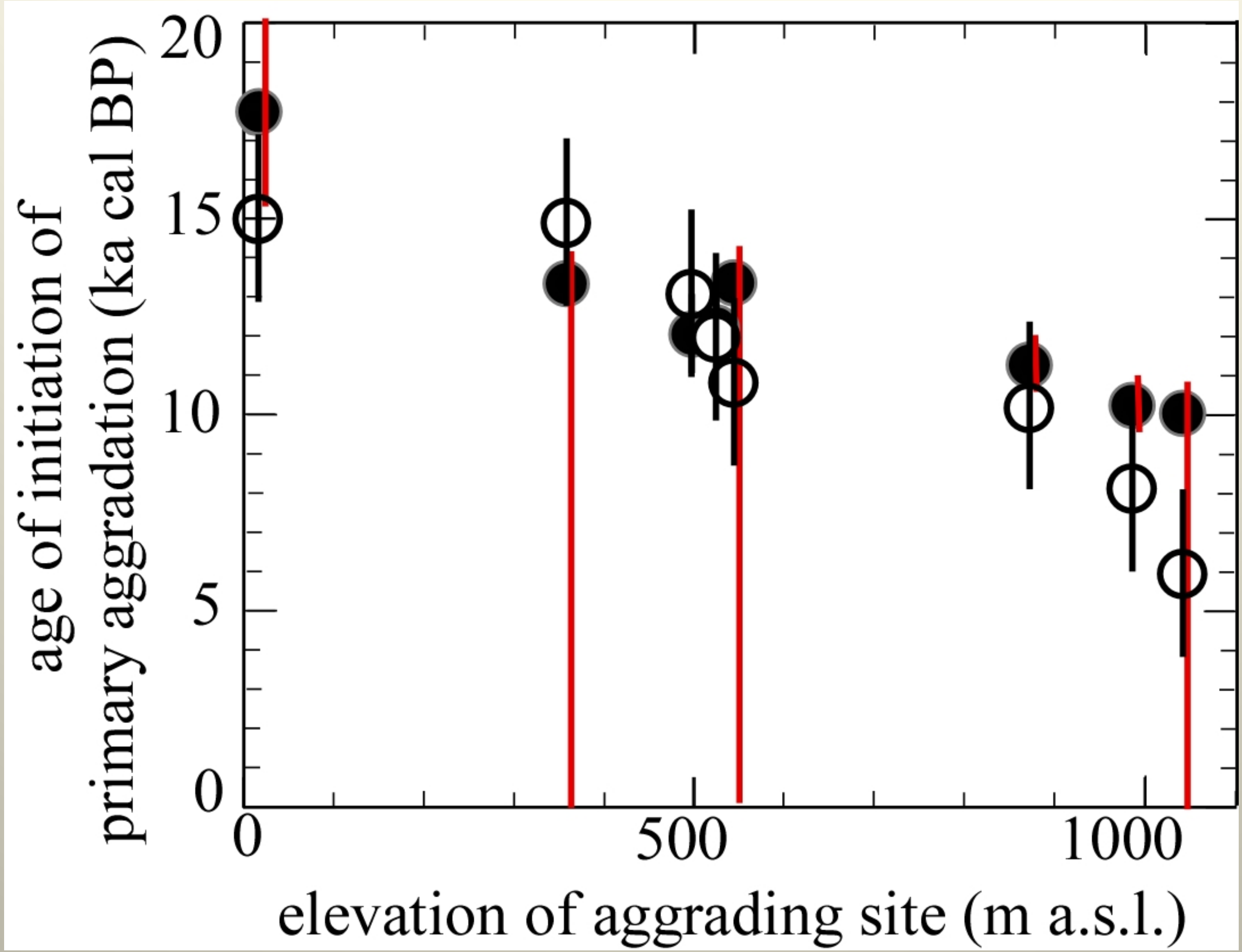


Model predicts timing of primary and secondary aggradation as a function of upstream elevation, following the retreat of P-J. Primary aggradation predicted to begin when 5% of source region undergoes P-J-to-shrubland transition. Secondary aggradation begins when 50% of source region has undergone P-J-to-shrubland transition.



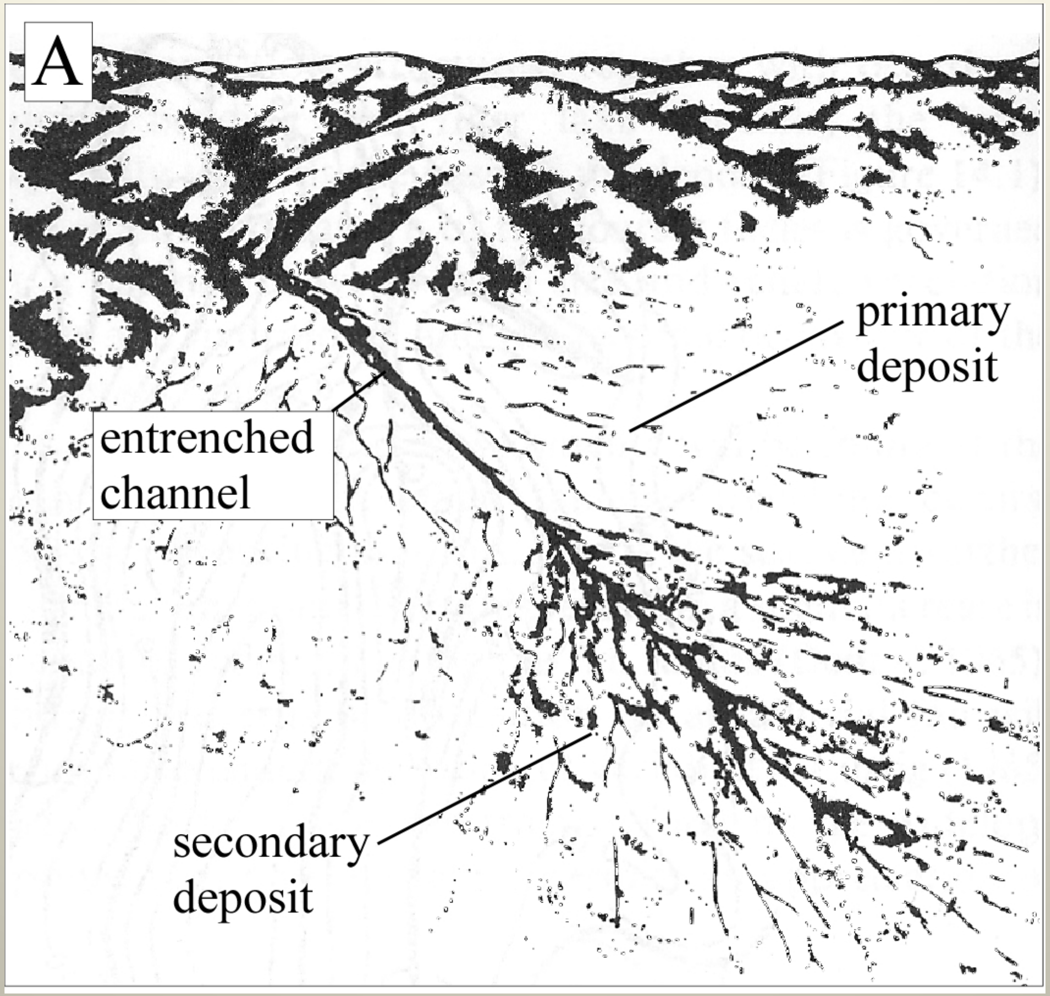
Pelletier, Esurf, 2014

Model predictions vs. data (OSL ages low in Q3a stratigraphy)



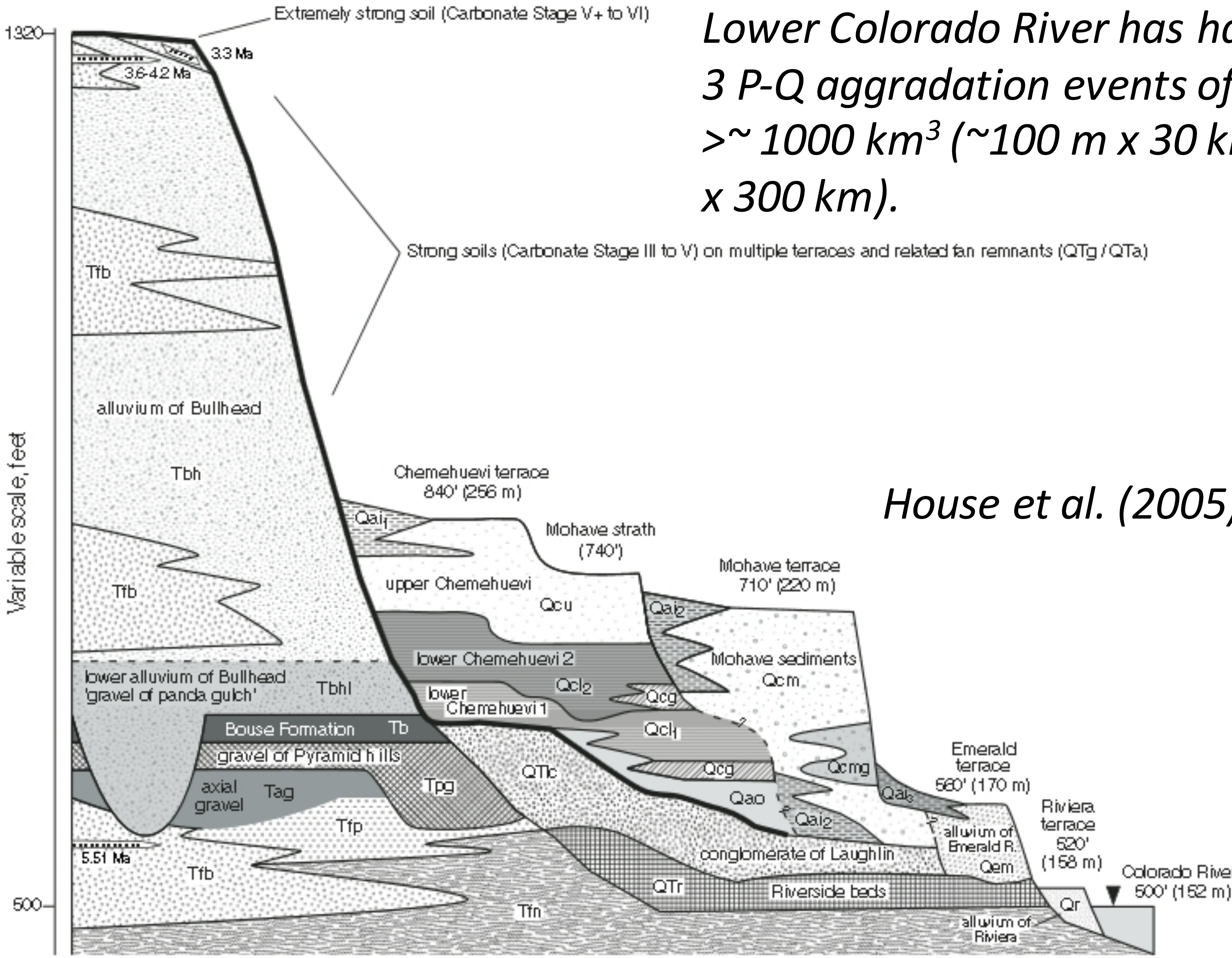
Pelletier, Esurf, 2014

Conceptual model: Decrease in veg cover/Increase in % bare ground triggers increase in drainage density, causing a pulse of sediment input to fans and a complex response, i.e. multiple cycles of aggradation and incision (Q3a and Q3b of Bull, 1991)



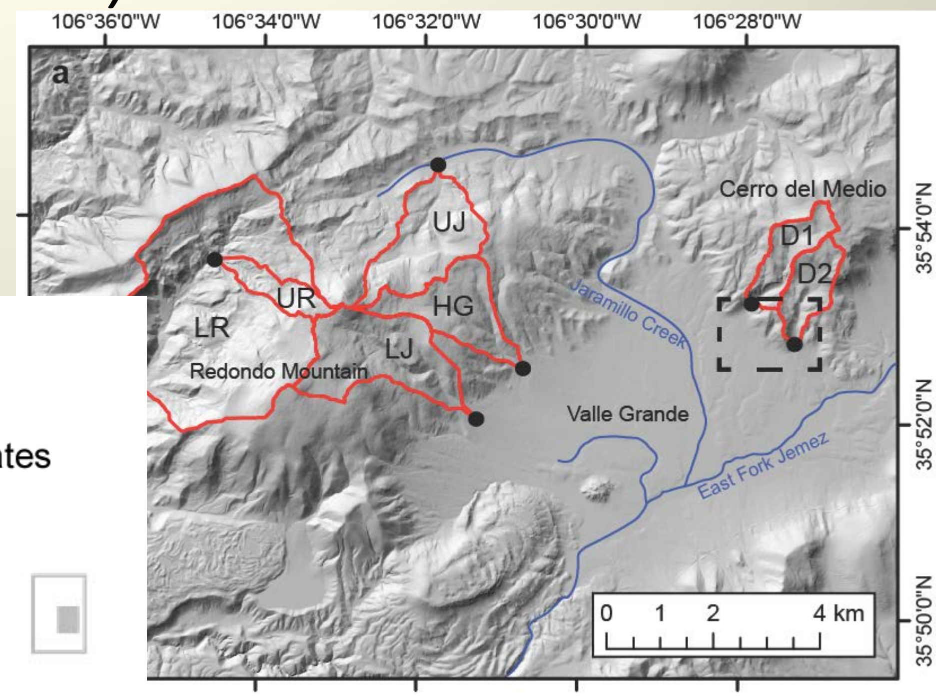
Bull (1991)

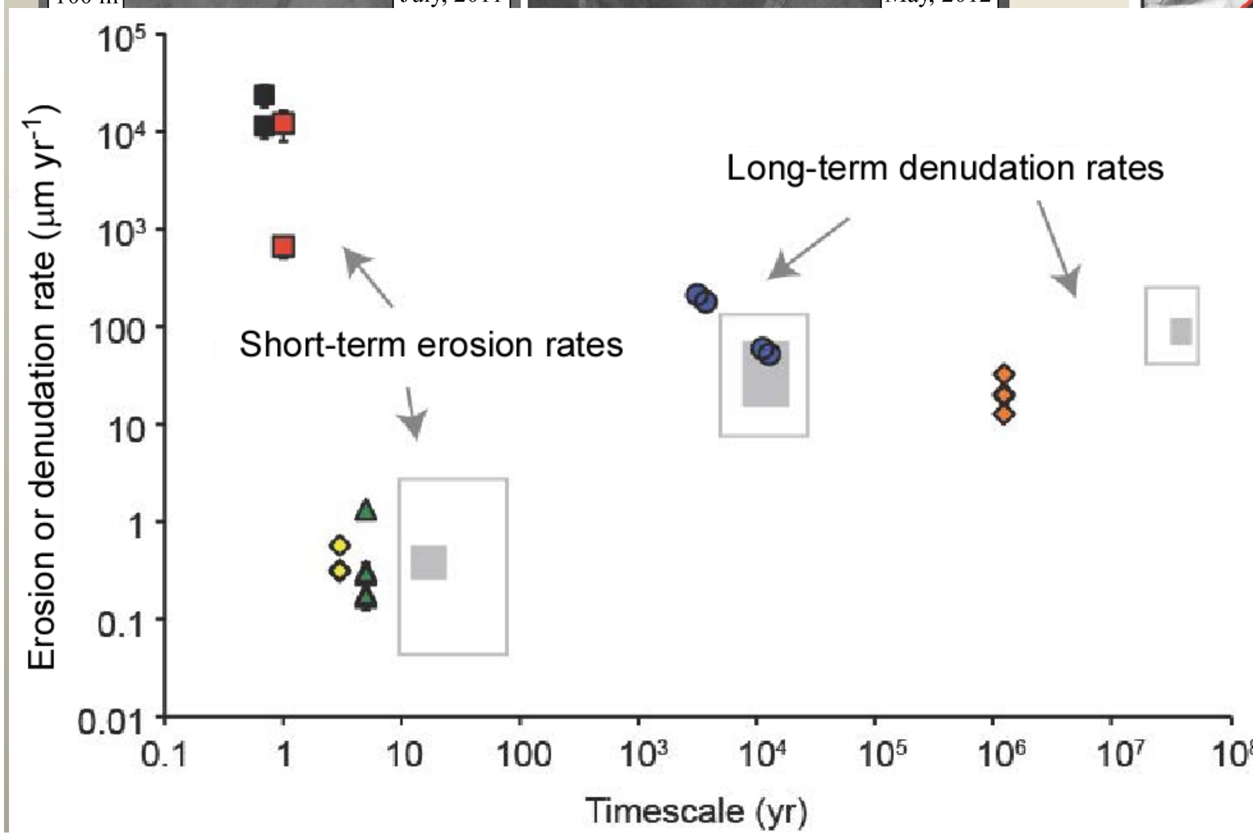
Unsolved problem:
Lower Colorado River has had 3 P-Q aggradation events of >~ 1000 km^3 (~100 m x 30 km x 300 km).



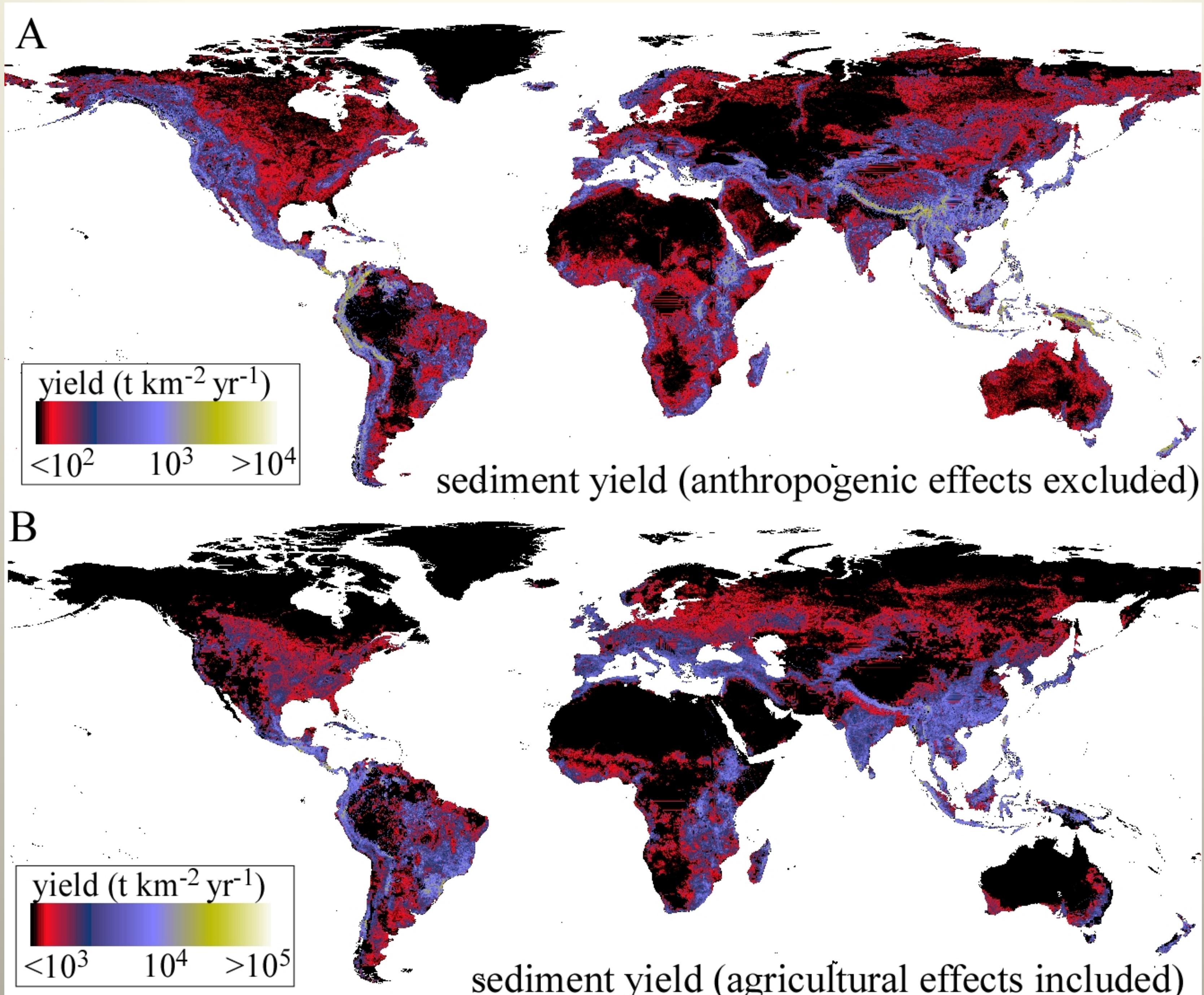
House et al. (2005)

Wildfire is responsible for 99% of all long-term erosion in some forested landscapes, e.g., Valles Caldera (Orem and Pelletier, JGR, 2016)



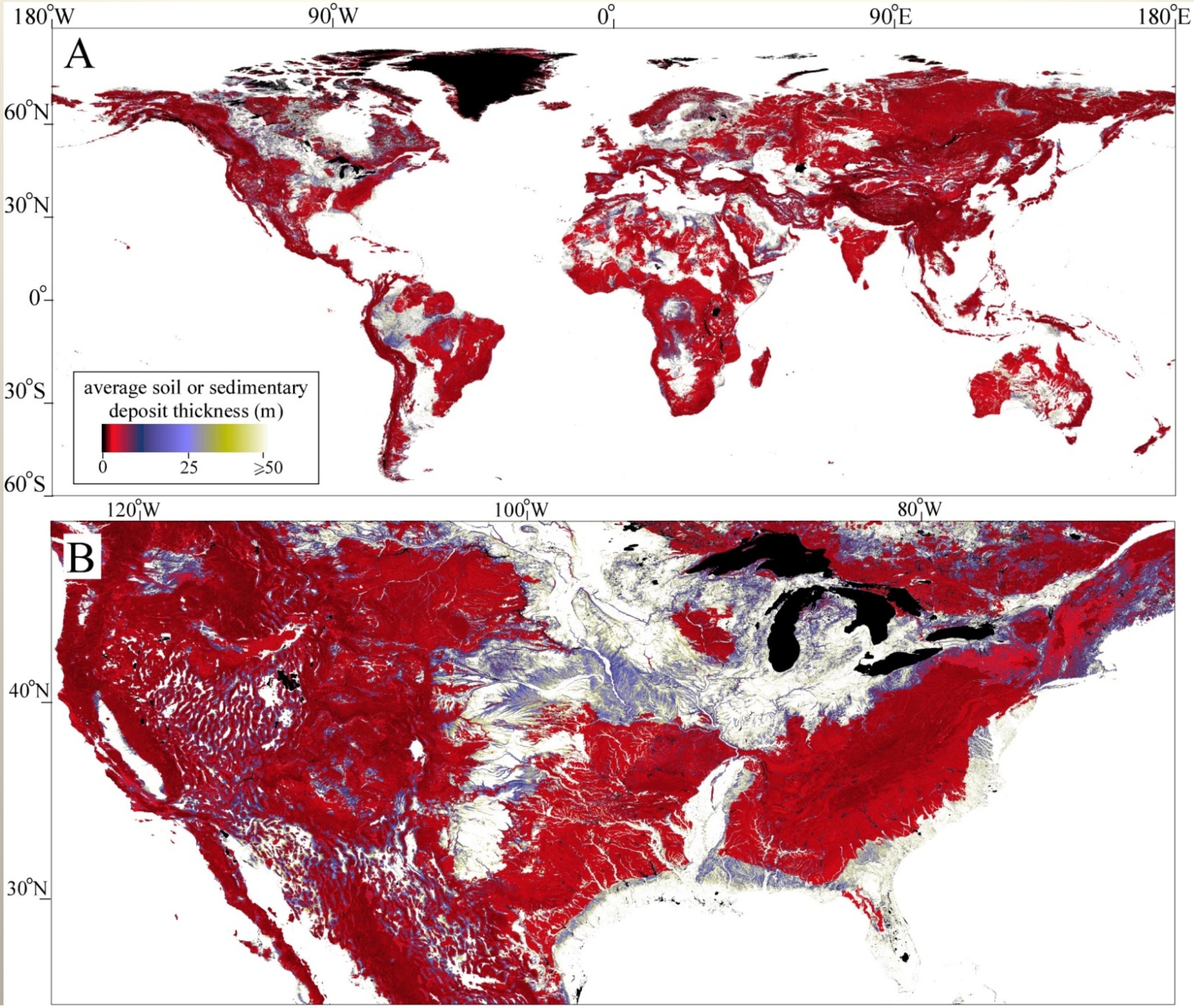


Example model over ~10^2 yr: Impact of ag on sediment yields

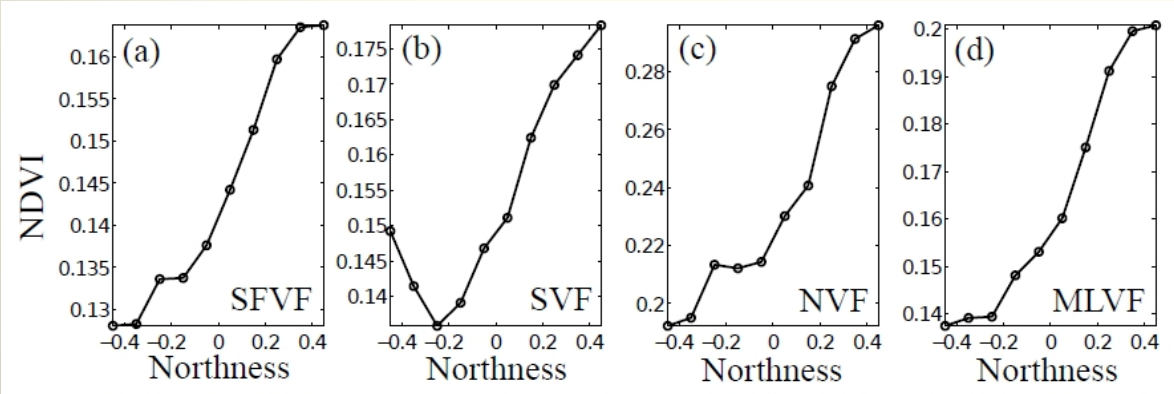


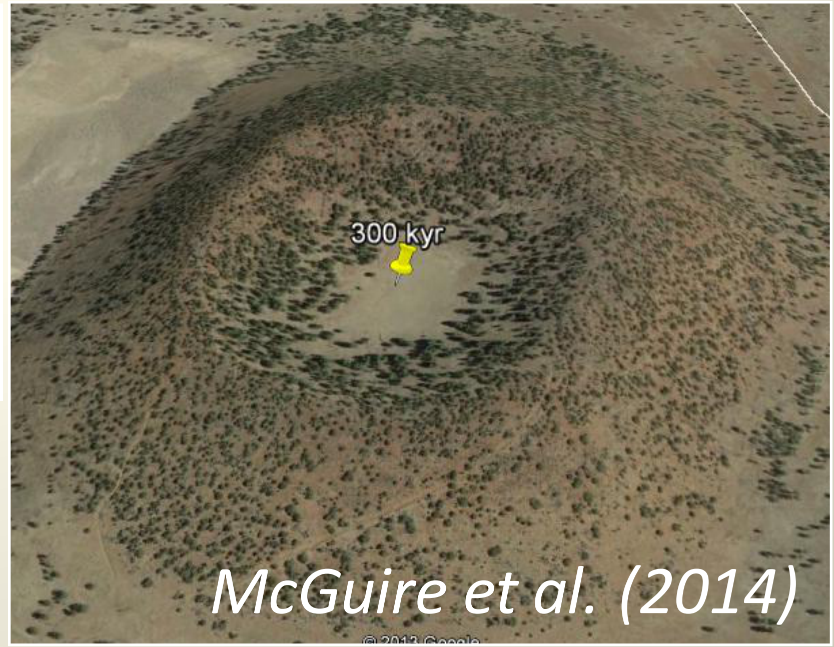
More collaboration with Earth System Modelers:

- *Soil/regolith thickness data (Pelletier et al., JAMES, 2016)*

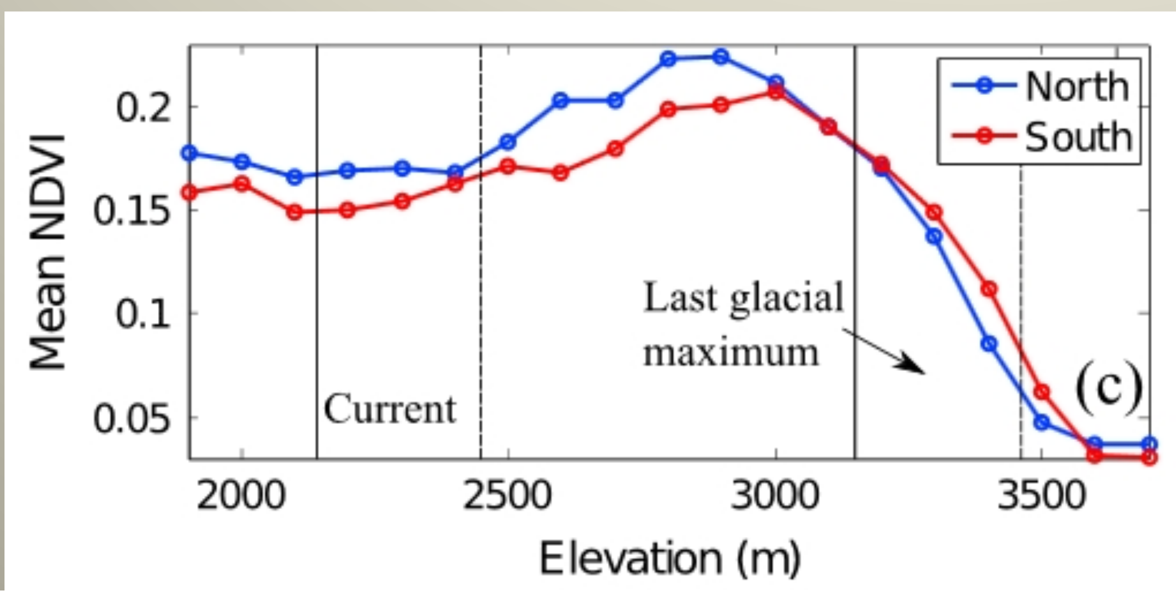


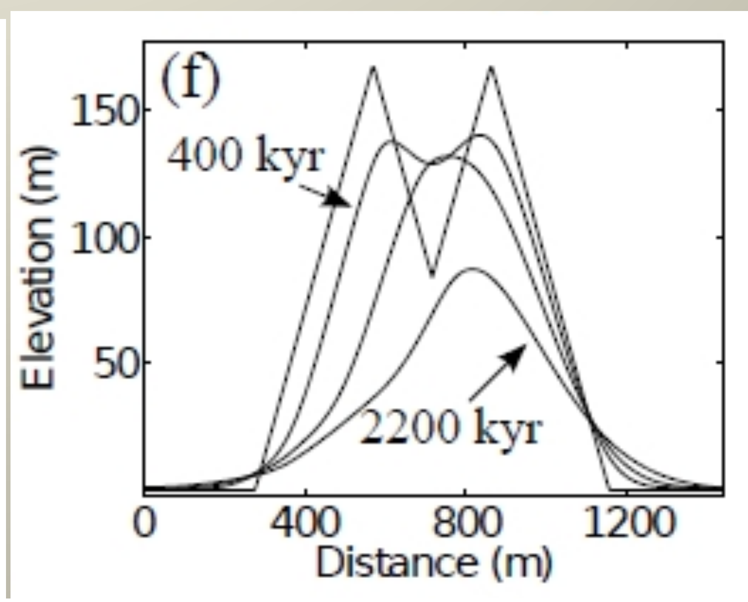
Example model over ~$10^{3\text{-}6}$ yr: Evolution of cinder cones





More colluvial erosion has occurred on S-facing slopes, yet there is more vegetation on N-facing slopes. BUT, veg cover was reversed in glacial times (most of the Quaternary). Data can only be explained by increase in D with V.





Conclusions:

- *Common vegetation changes can trigger O(10) increases in erosion rates and topographic metrics*
- *In hillslope-fluvial systems, an increase in the fluvial erodibility coefficient (K) reproduces the first-order behavior, i.e. a transient increase in drainage density and channel convexity, with a resulting pulse of aggradation on fans.*
- *More vegetation cover can increase colluvial sediment transport rates, but this effect is of smaller magnitude, (O(1)).*
- *Global-scale ESM and dynamic vegetation models can be used to determine future hotspots of geomorphic change. Such models require better component models and input data on geomorphology.*