From fluxes to flows:
Incorporating the soil for greater realism in predictions of hydrological impacts of land-cover change

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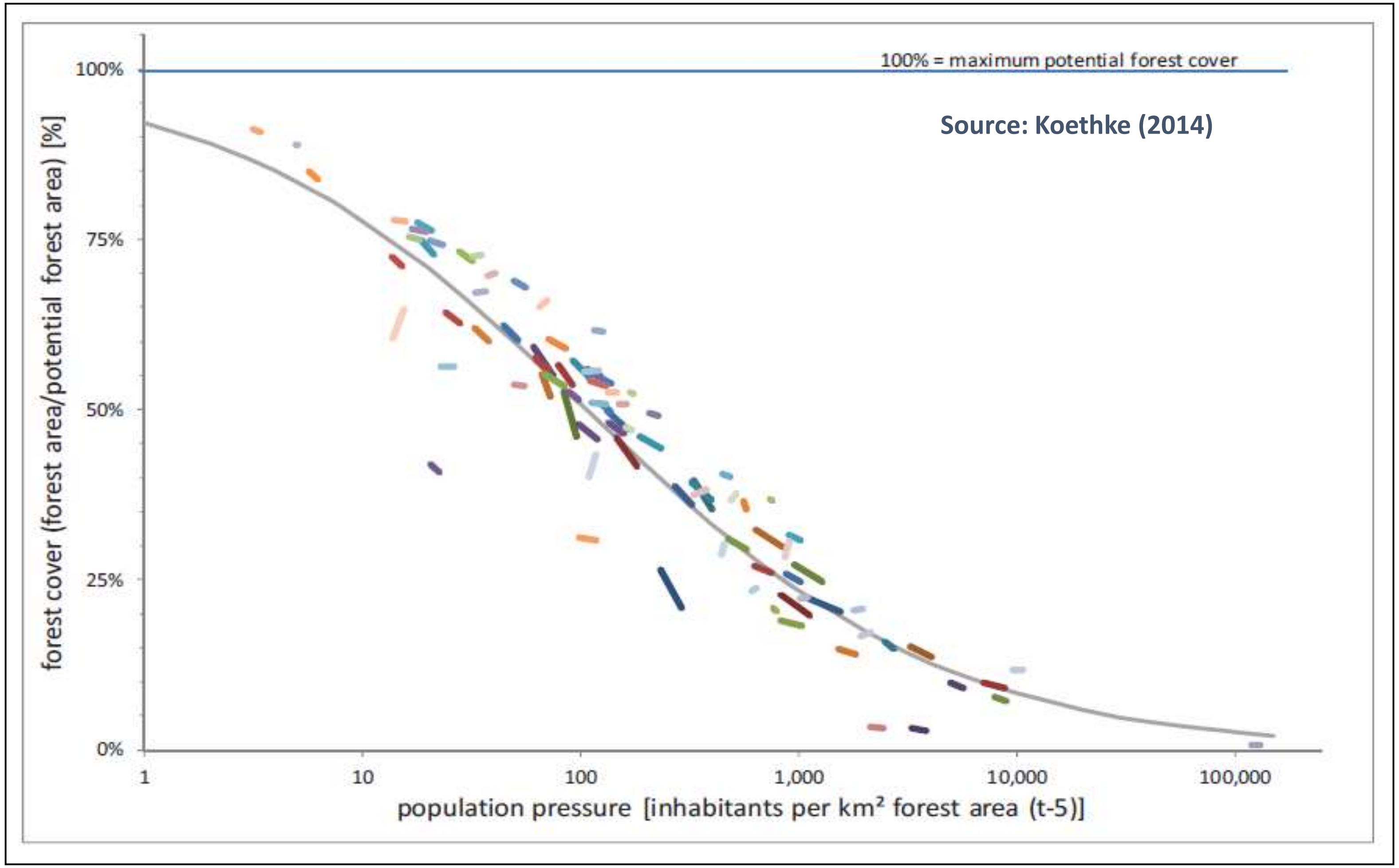
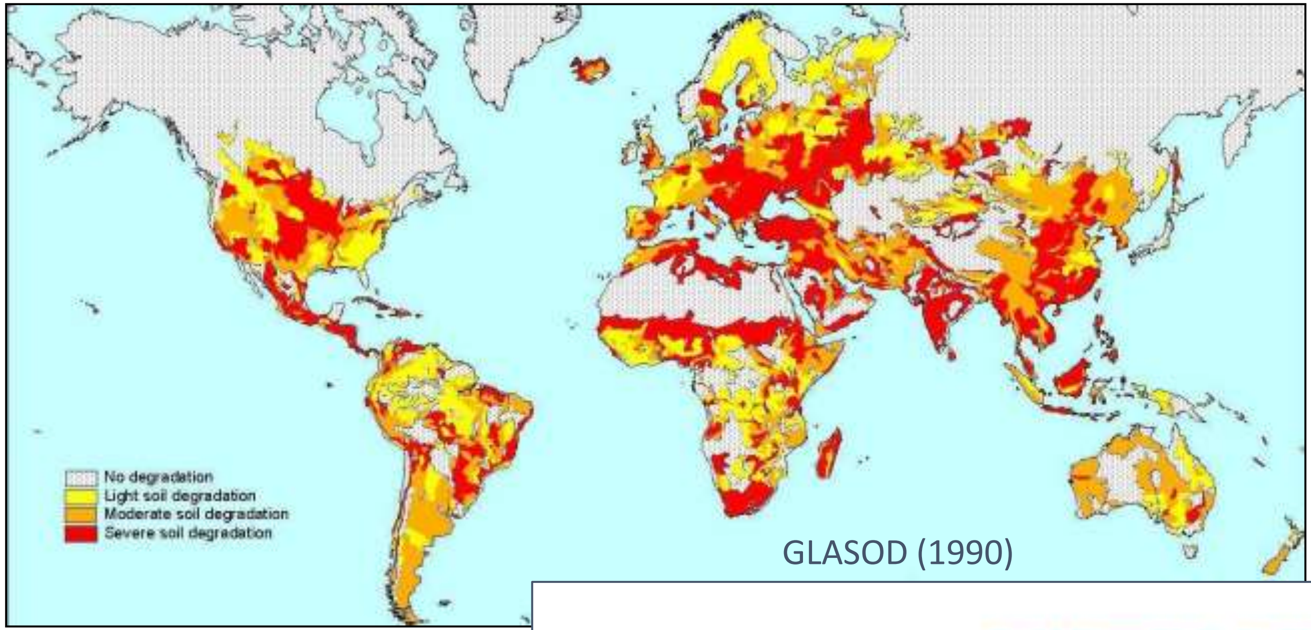
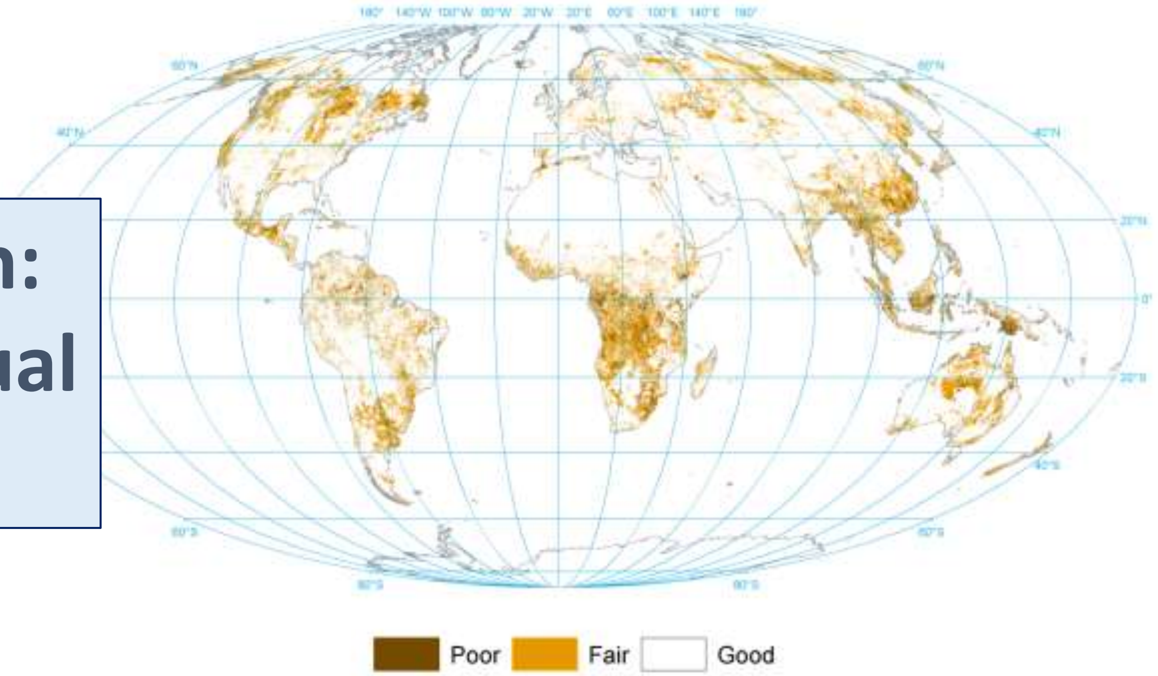
Tropical forests on the decline…



As populations and demands for food (= land), timber *and housing* increase, undisturbed ('pristine') forests found increasingly in remote (upland) areas…



Soil degradation: potential vs. actual patterns



Soil condition (after Bai et al., 2008)

Surface degradation: many forms and faces


Instant degradation (compaction)


Fire (loss of organic matter)


Metalled roads (impervious)


Gradual degradation (crusting)


Gradual long-term compaction

2021–2030: UN Decade of Ecosystem Restoration

Bonn Challenge (2011): restore 150 Mha by 2020 & 350 Mha by 2030.

FAO (2022): 46 Mha planted in 2000–2018; 25% of which replaced tropical regrowth…

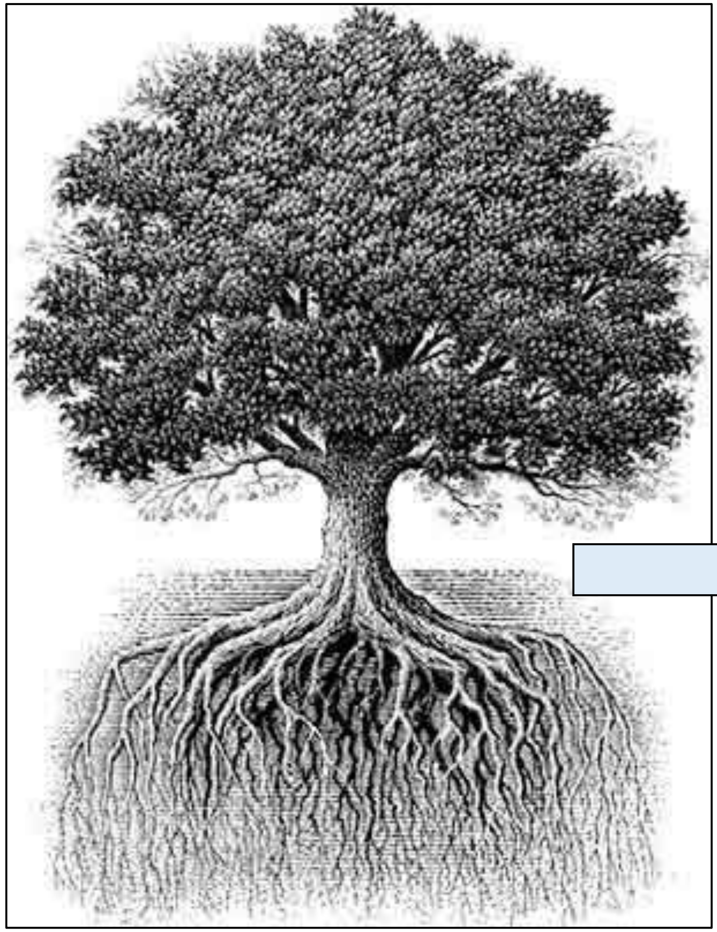
Not all forests are equal…

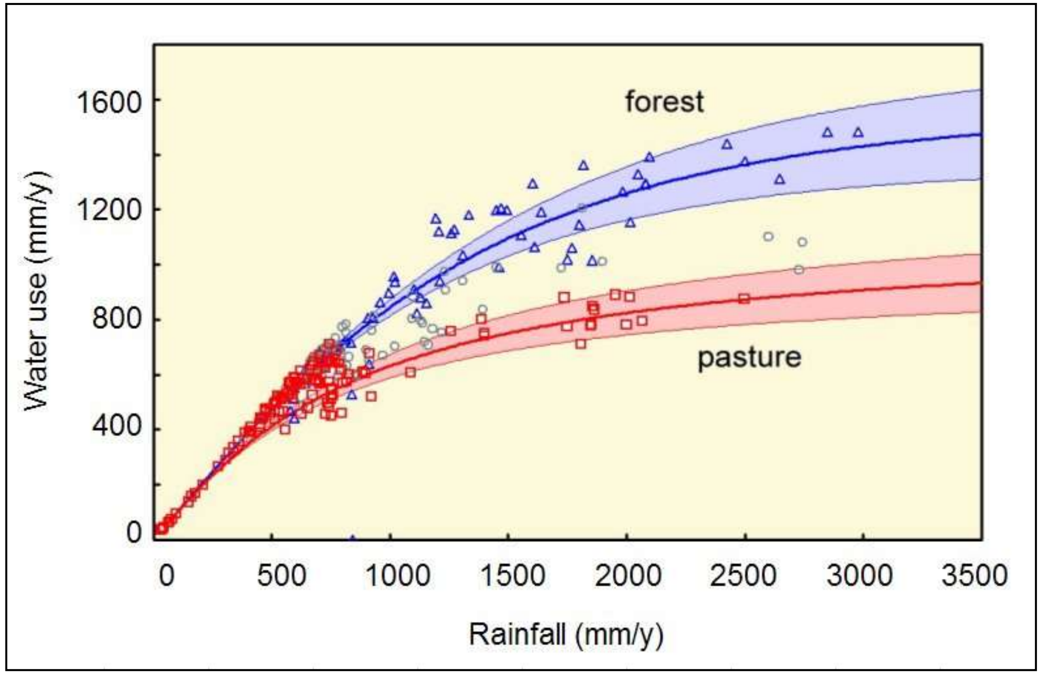
Contrasting canopy roughness: eucalypt clones & natural forest

Teak plantation (Java)

Caribbean pine plantation (Fiji)

Forest water use (ET) exceeds that of shorter vegetation types





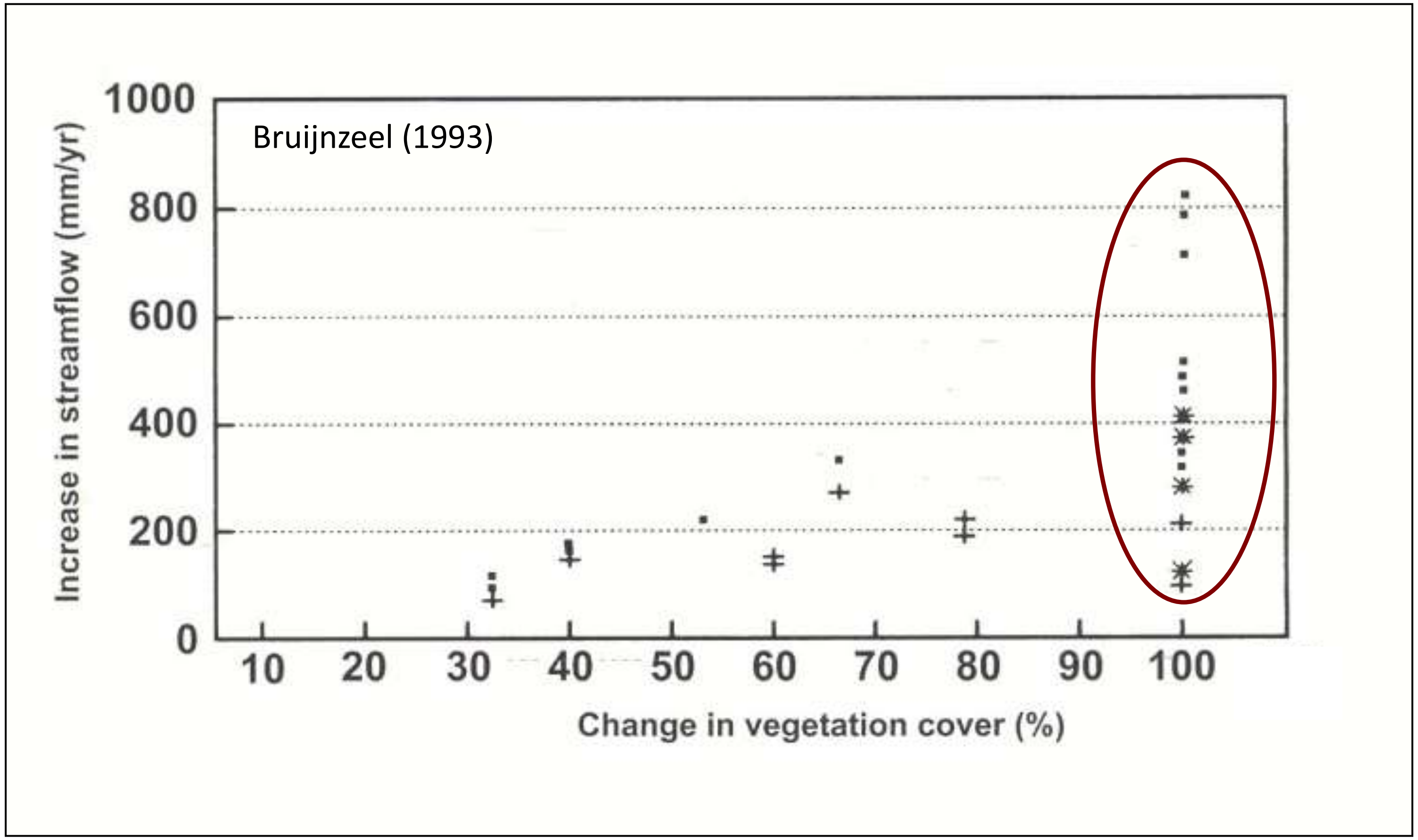
Zhang et al. (2001)

Trees / forests have greater leaf surface area (LAI), deeper roots and greater aerodynamic roughness than do scrub, grass or crops. Hence, tree / forest water use (ET) is typically higher.

Streamflow from mature forests most dependable

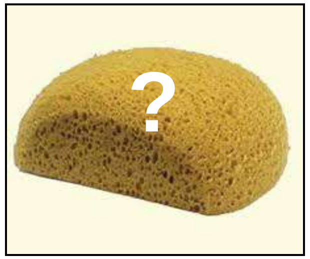
- *High forest ET* creates room for absorption and storage of rainfall.
- *High infiltration* during (heavy) rain afforded by intact litter layer and macropores created by soil biotic activity and root decay.
- Comparatively stable streamflows from mature forests have led to the concept of the '*forest sponge*' (~*shui yuan han yang*): absorption during rain & slow subsequent release (maintaining baseflow).

Less forest => more streamflow *per year*…

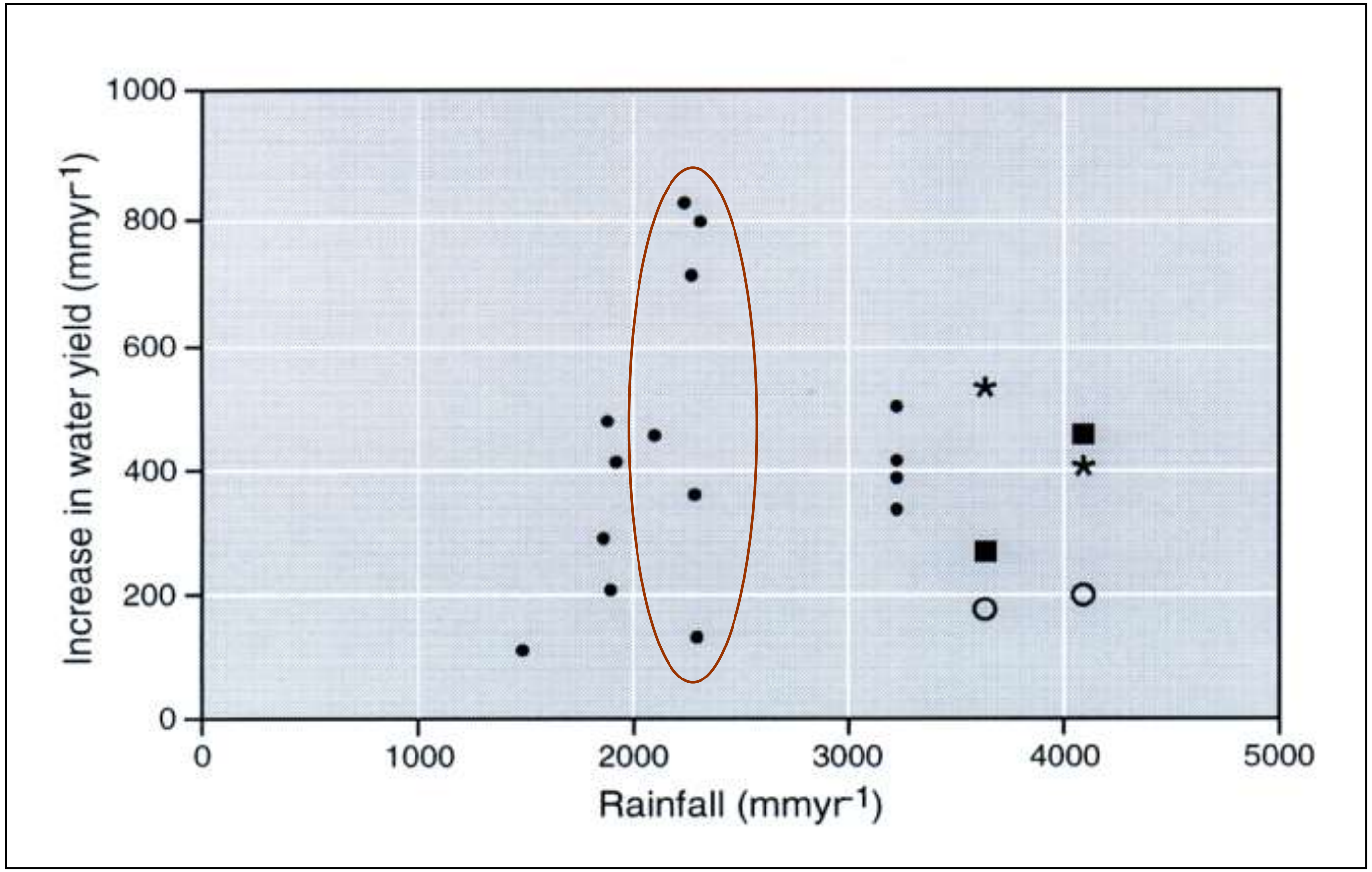


Annual flow totals increase proportionally with degree of forest removal (situation for initial three years after clearing).

Final effect on water yield depends on post-forest land use.



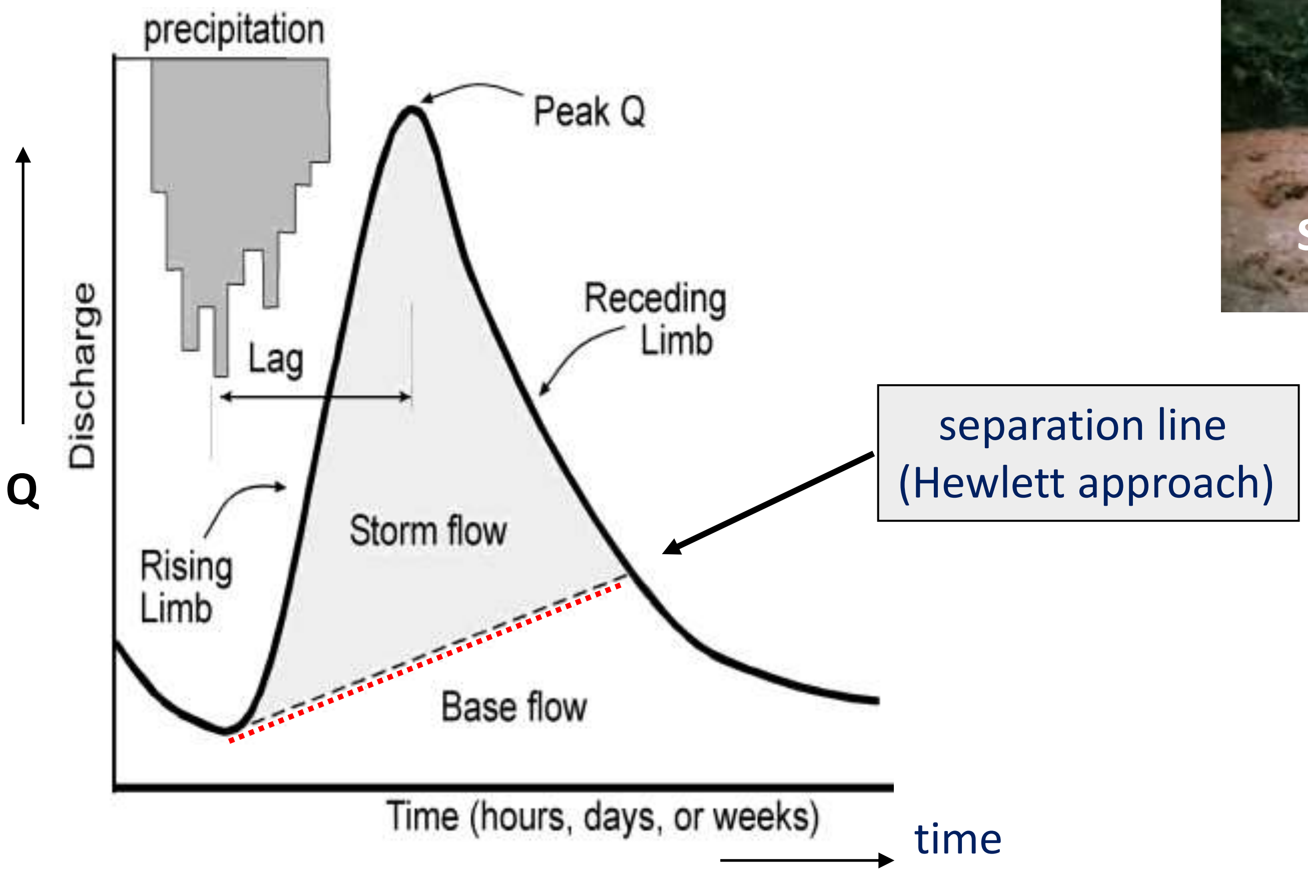
Forest cleared => higher water yields, but soil conditions (may) change too…



Bruijnzeel (1997)

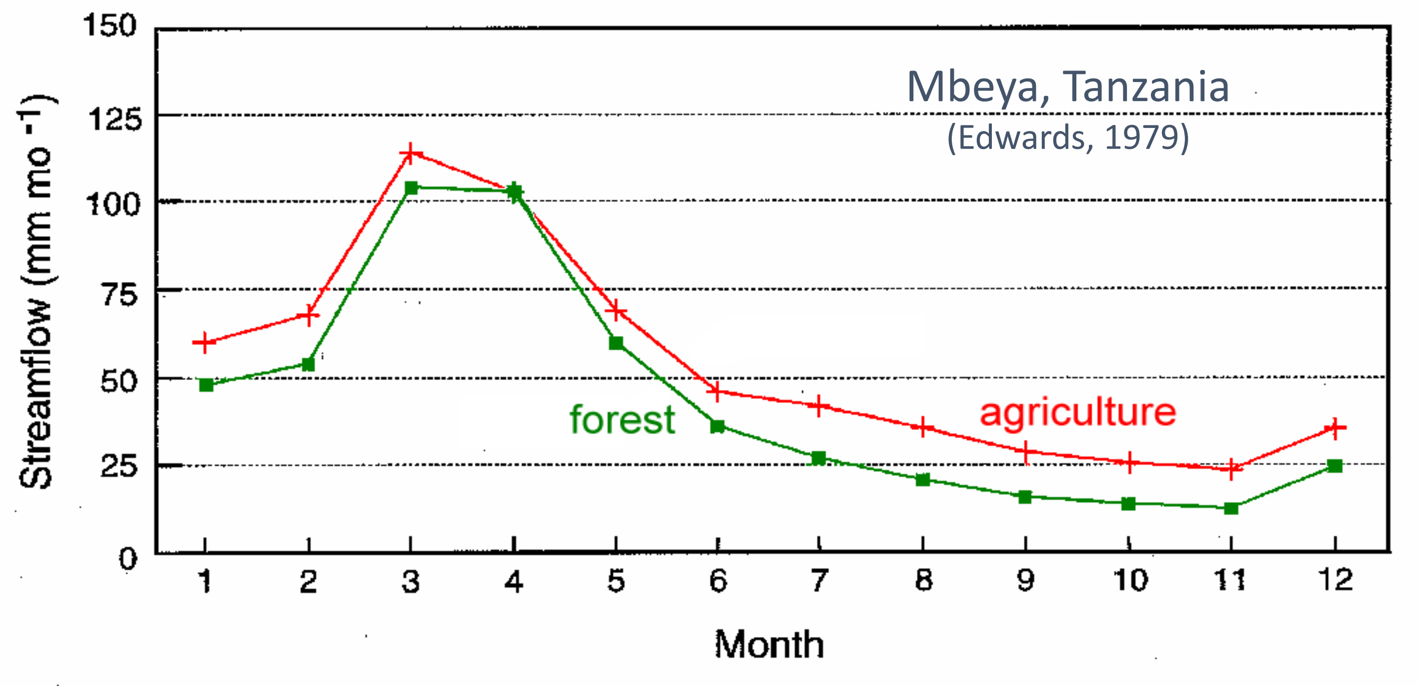
Definition of terms: ‘base flow’ and ‘storm flow’

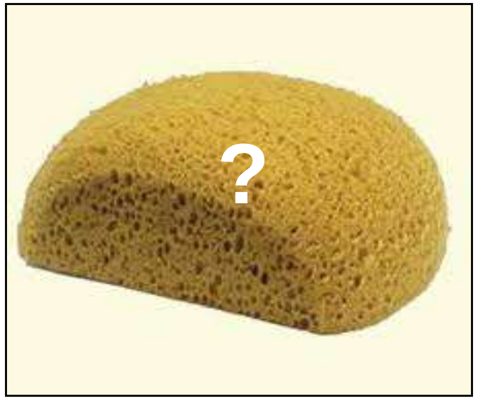
During rain, the extra water from the hillsides leads to increased streamflow. This ‘***storm flow***’ is usually separated from ‘***base flow***’ using an (arbitrary) separation line…



Importance of dry-season flows (baseflows)

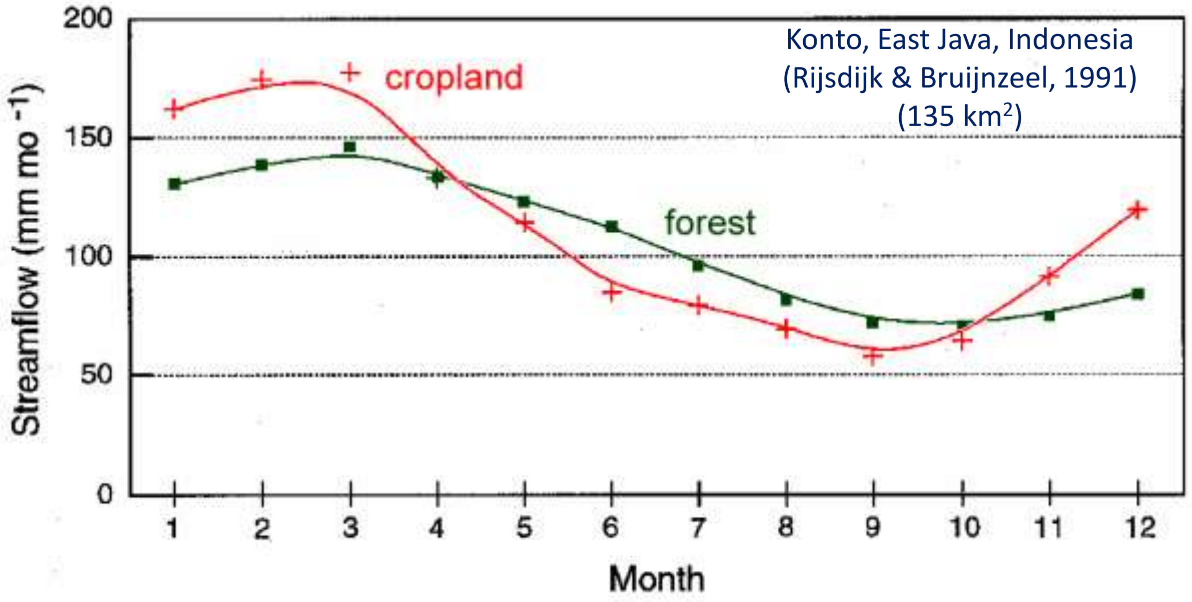
Maintaining infiltration after deforestation: increased streamflow *all through the year*…

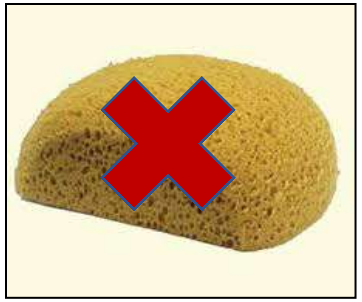




- **Without major soil degradation:**
Deforestation ***increases*** dry-season flows due to lower ET of annual crops.

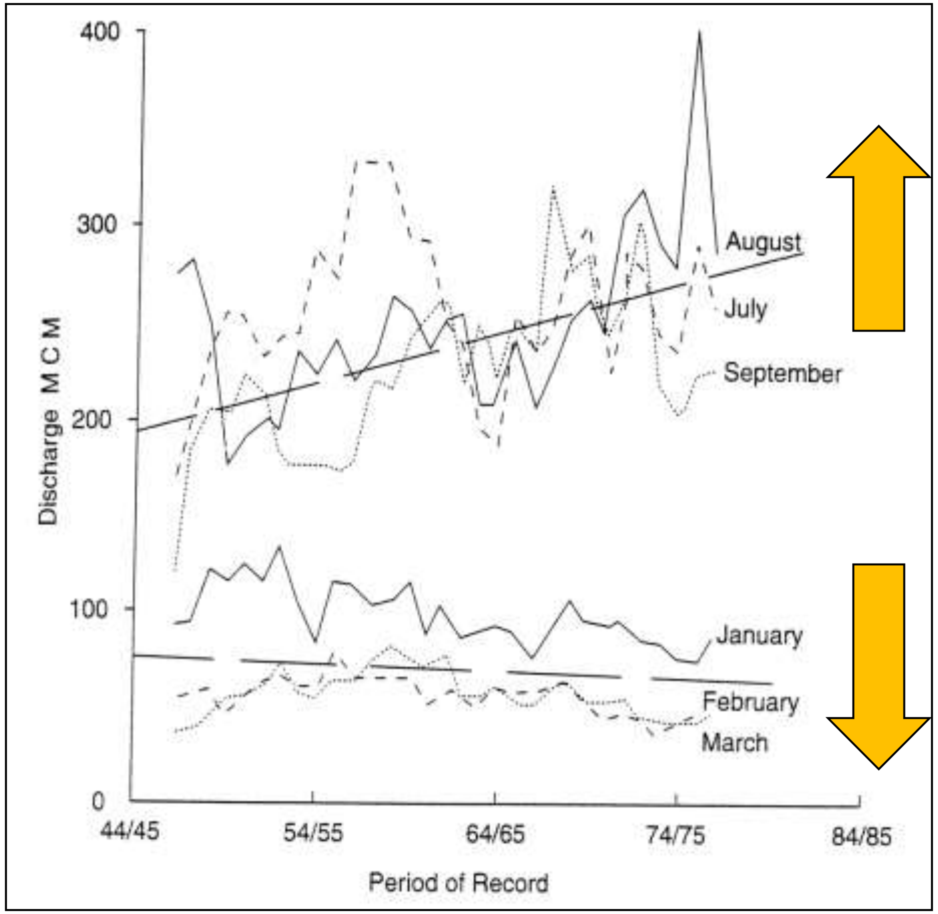
Strongly reduced infiltration opportunities disrupt seasonal streamflow regime





- **Advanced soil degradation:** ***reduced*** dry-season flows due to increased water loss via wet-season stormflow (less groundwater recharge)…

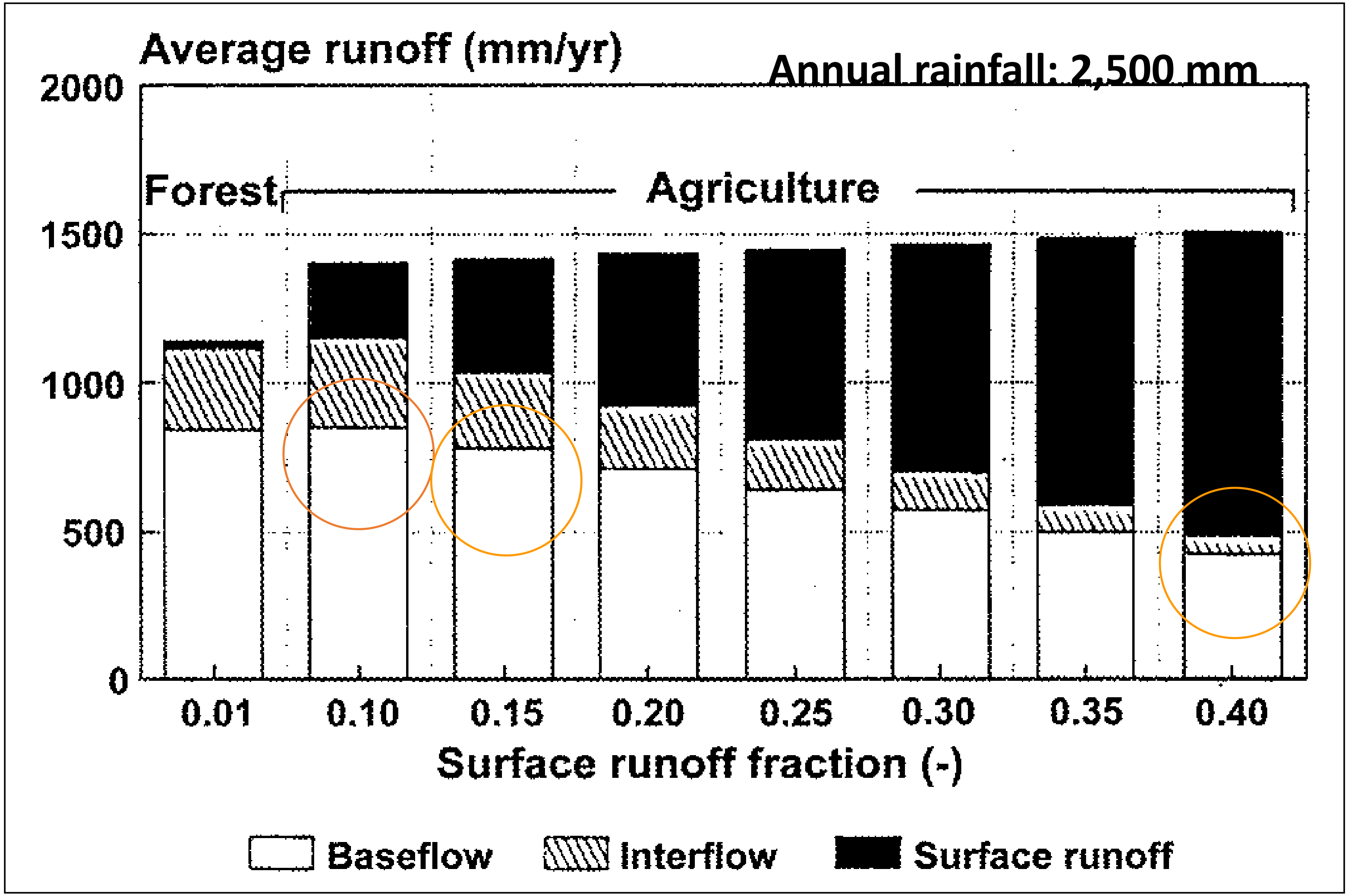
Hydrological change due to soil degradation: gradual and rarely demonstrated in the literature…



Upper Mahaweli, Sri Lanka (1,100 km^2)

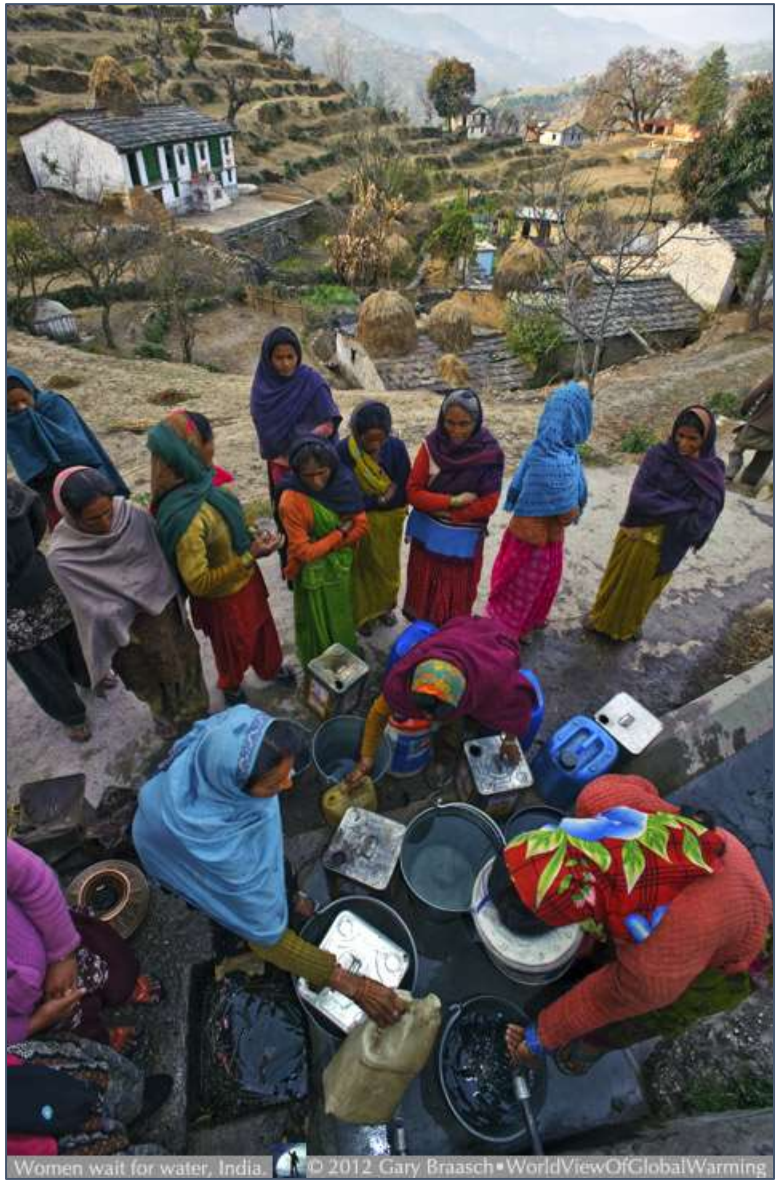
Madduma Bandara (1997)

Modeled change in baseflow versus change in surface runoff



(After Van der Weert, 1994)

Boosting springs / base flows: a key issue…



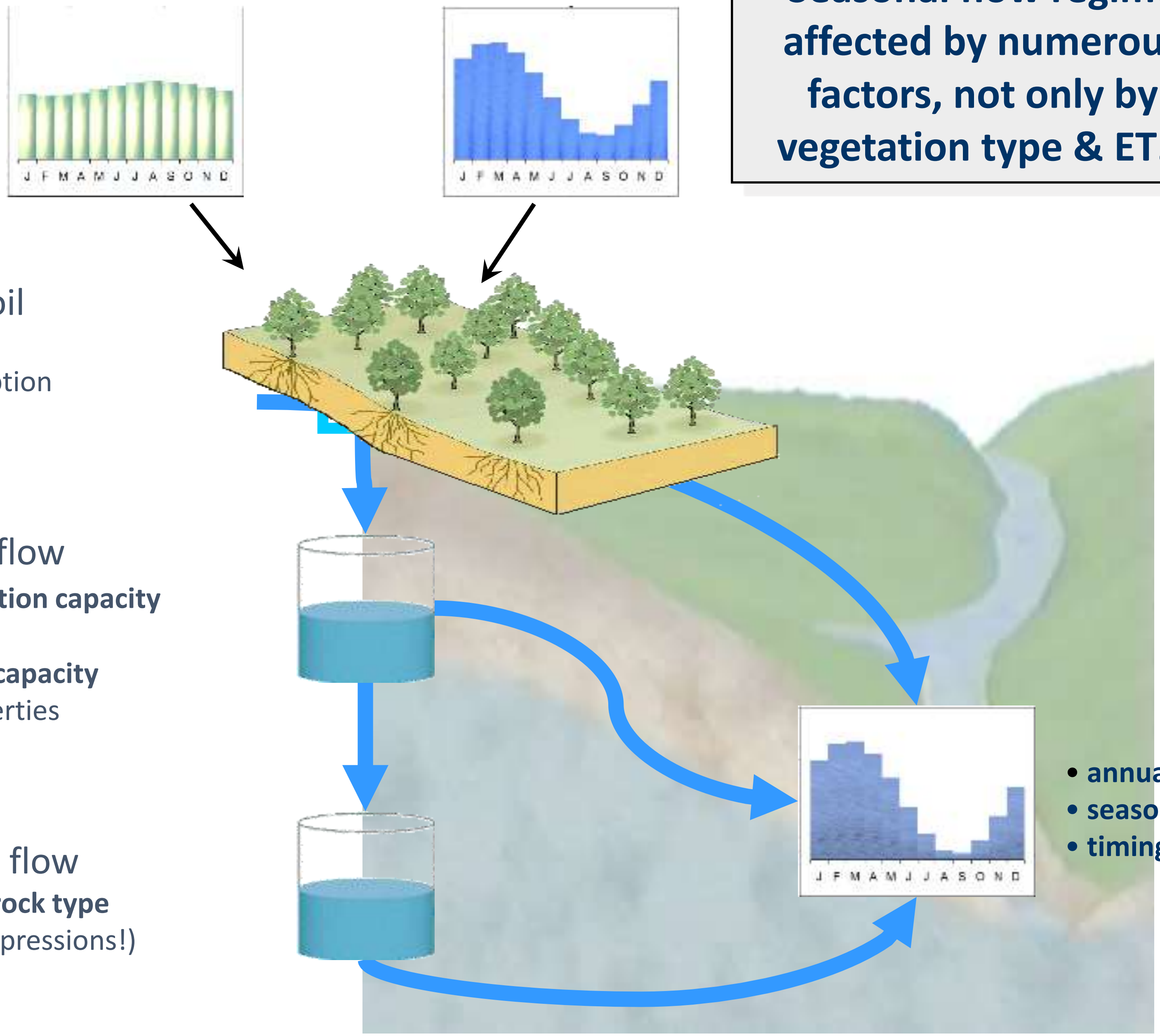
Can decreased springs and baseflows be restored again?
And if so, how is this achieved best?
Natural regrowth?
Plant trees?
Agroforestry?
Terracing?

Hydrological systems knowledge is required for model parameterization to separate climate and land-use effects.

Seasonal flow regime affected by numerous factors, not only by vegetation type & ET…

Potential ET

Rainfall



Vegetation-soil

- transpiration
- rainfall interception
- **rooting depth**

Unsaturated flow

- **surface infiltration capacity**
- **soil depth**
- **water holding capacity**
- hydraulic properties
- topography

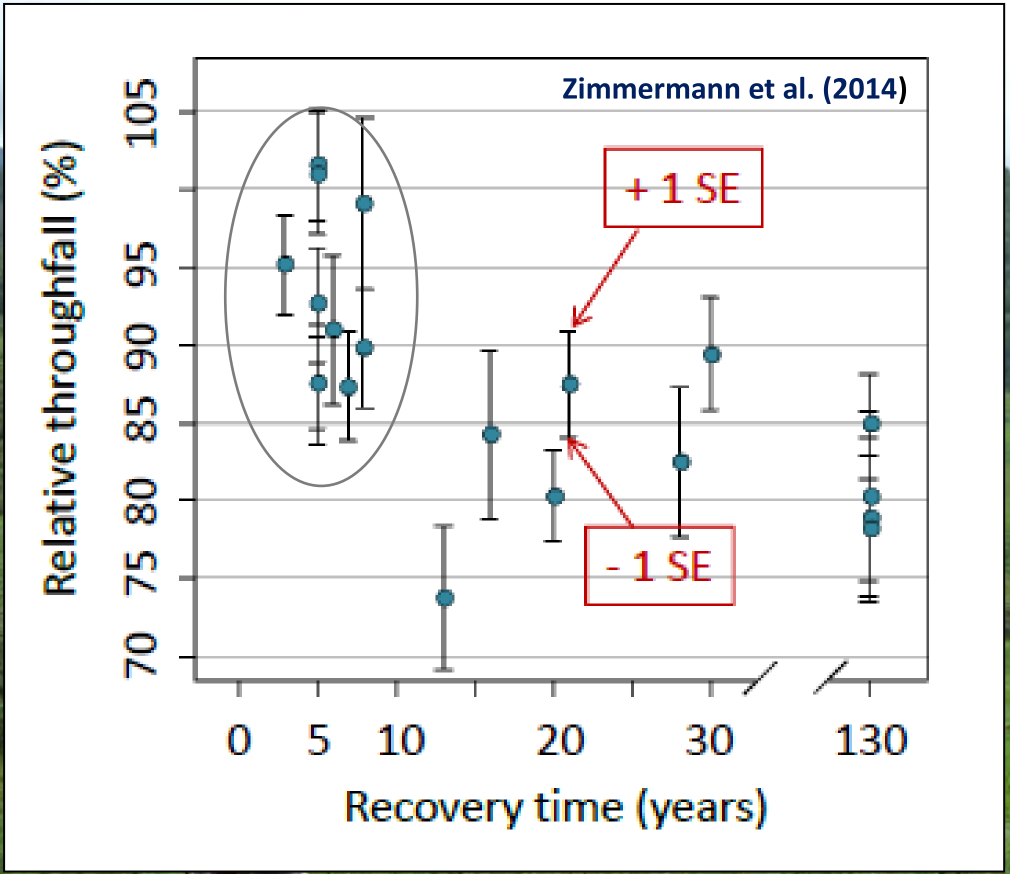
Groundwater flow

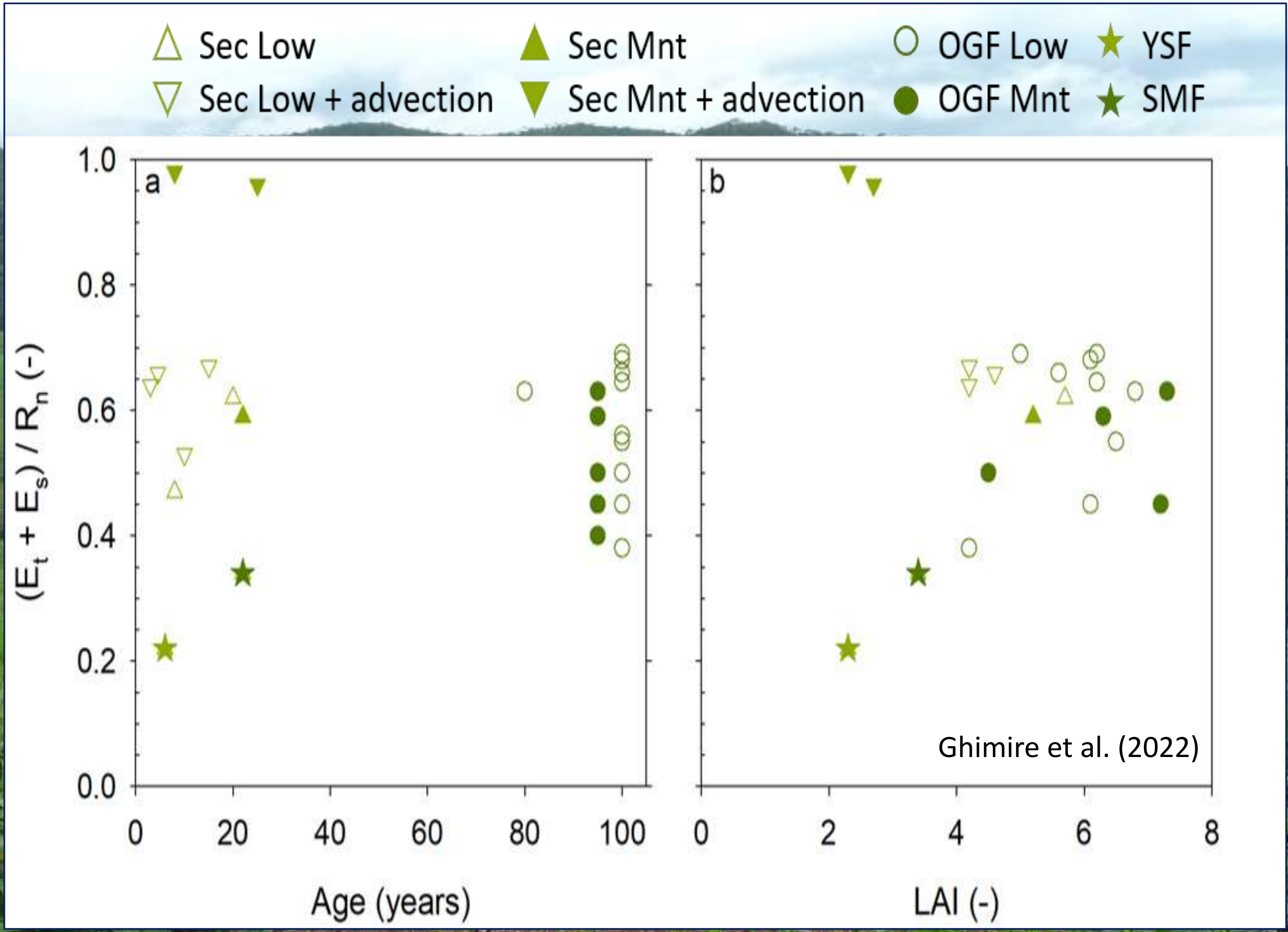
- hydrogeology, **rock type**
- topography (depressions!)

- **annual total**
- **seasonality**
- **timing**

Courtesy: Albert van Dijk (ANU, Canberra)

ET of regenerating tropical forests: still poorly documented





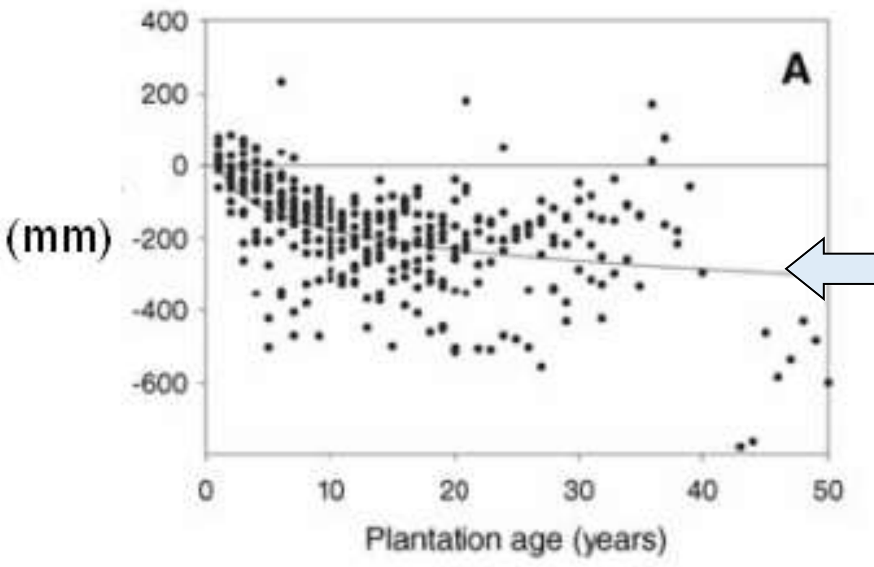
Interception stabilizes after ~10 yrs

Transpiration stabilizes at LAI = ~4

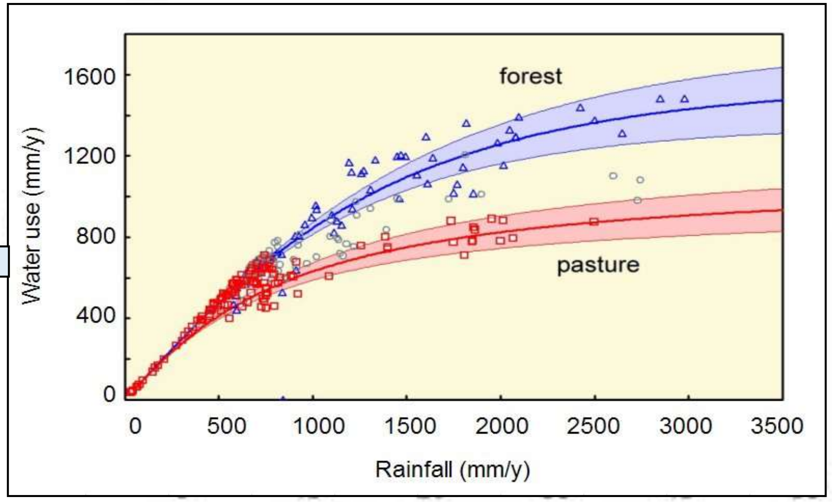
Madagascar (B.W. Zwartendijk)

Meta-analysis of tree plantation impact on annual streamflow: More trees = less flow *at all times of the year…*

Change in *annual* streamflow following grassland forestation

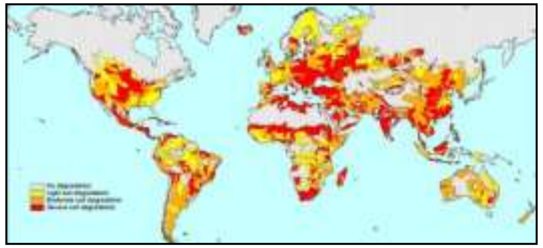


Jackson et al. (2005)

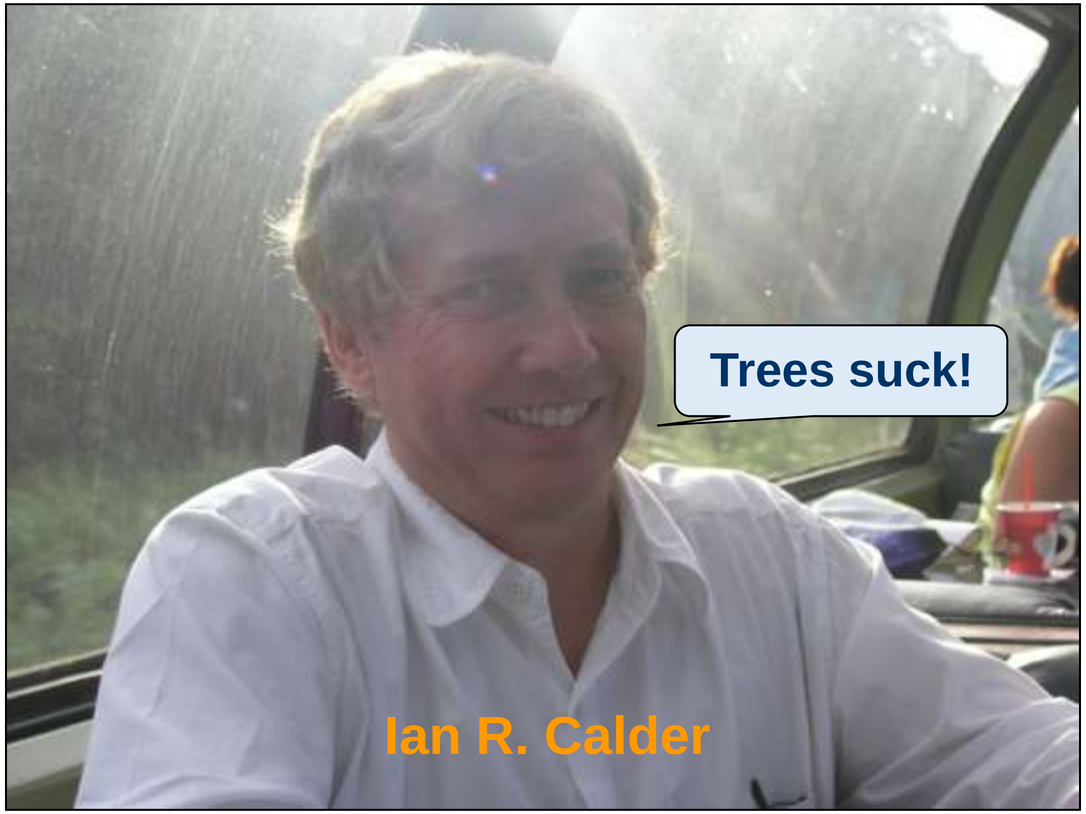


Zhang et al. (2001)

Only three catchments located in tropics, ***none degraded***;
No soil improvement effect included, only water use effect;
Data-set dominated by relatively dry sites => exaggerated.



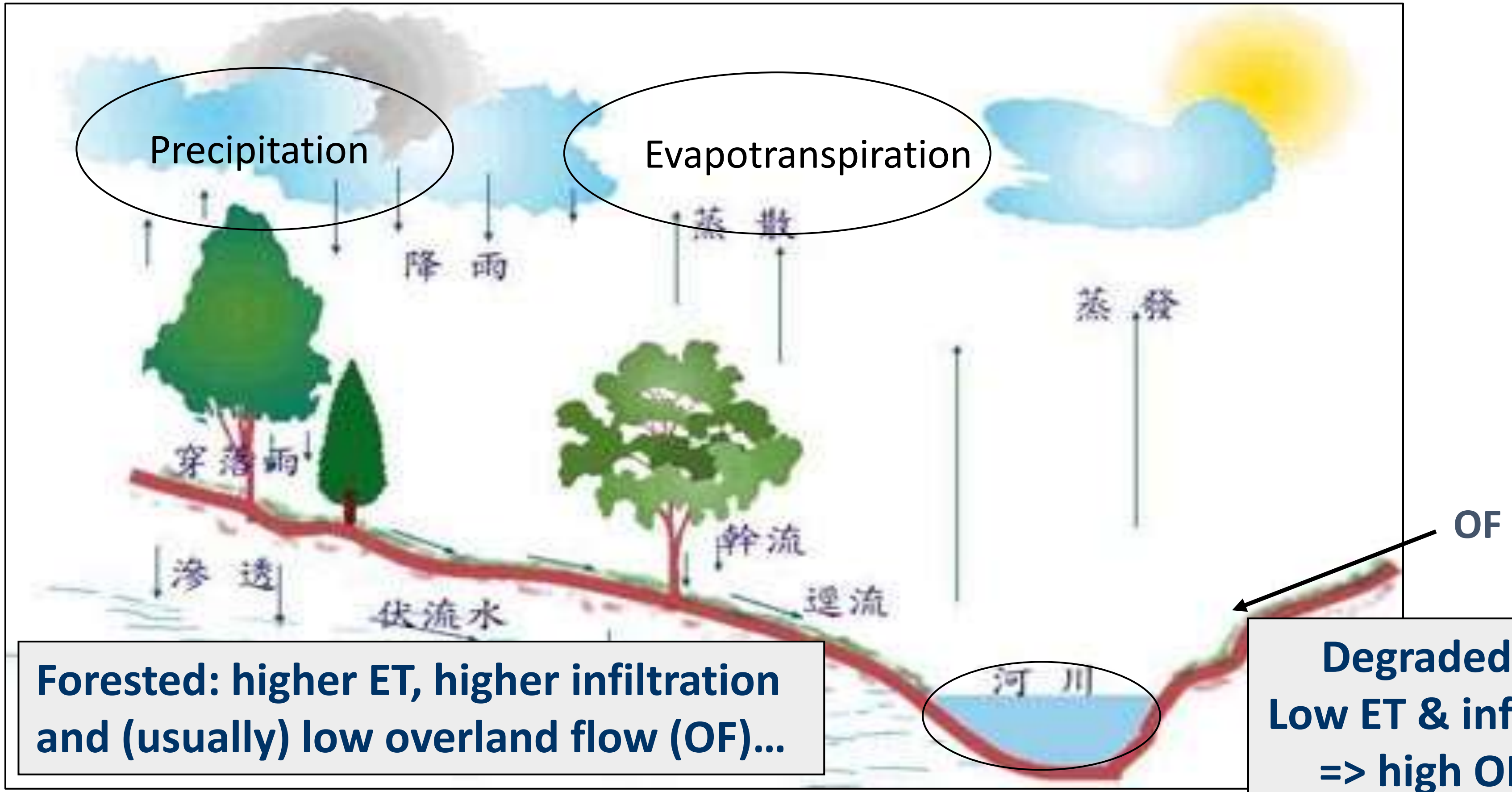
Tropical forestation and streamflow: the debate in a nutshell…



The 'scientific' view

The 'layman's' view

Two key processes: water use (ET) *and infiltration*

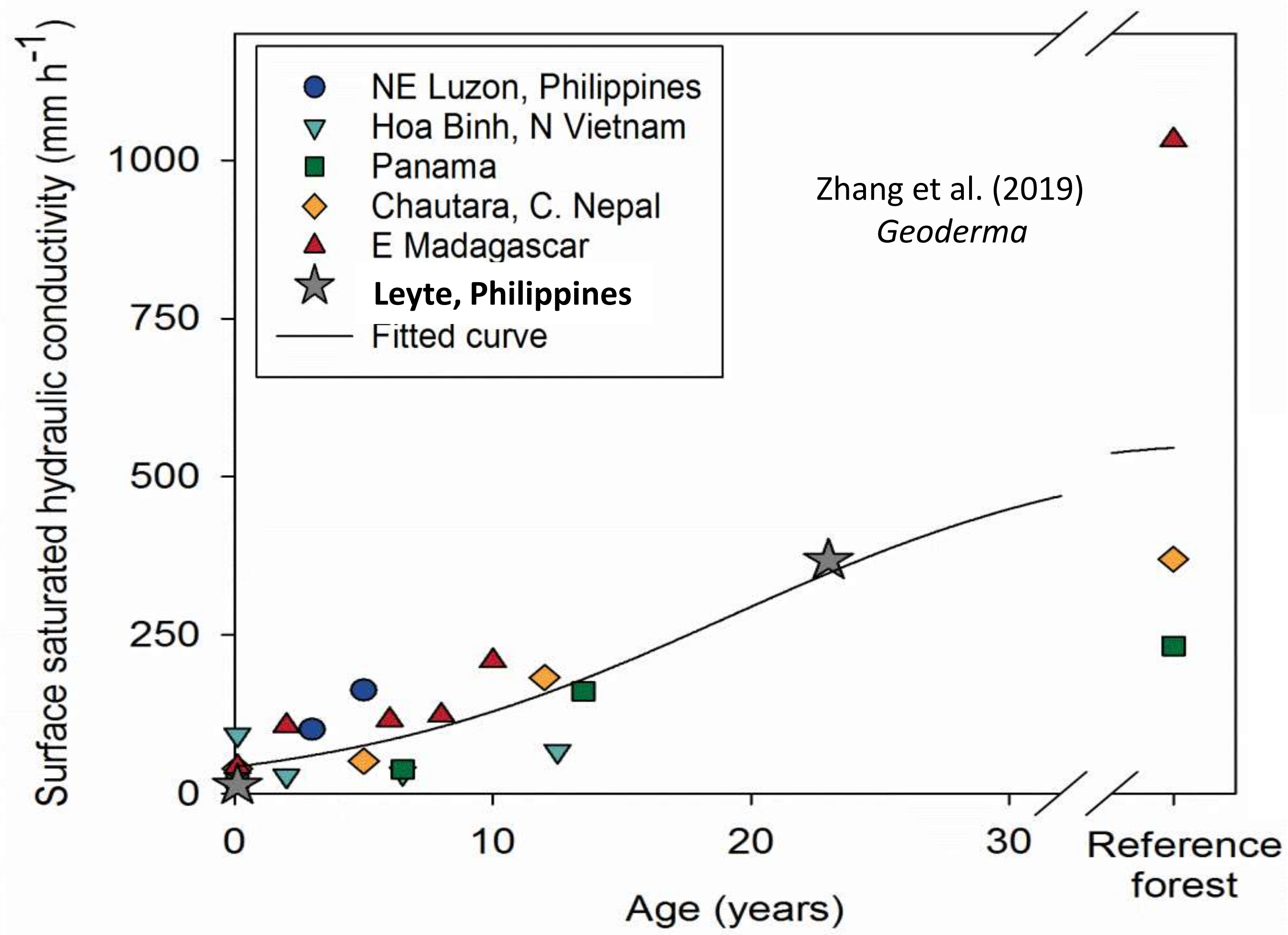


Forested: higher ET, higher infiltration and (usually) low overland flow (OF)…

Degraded:
Low ET & infiltr.
=> high OF

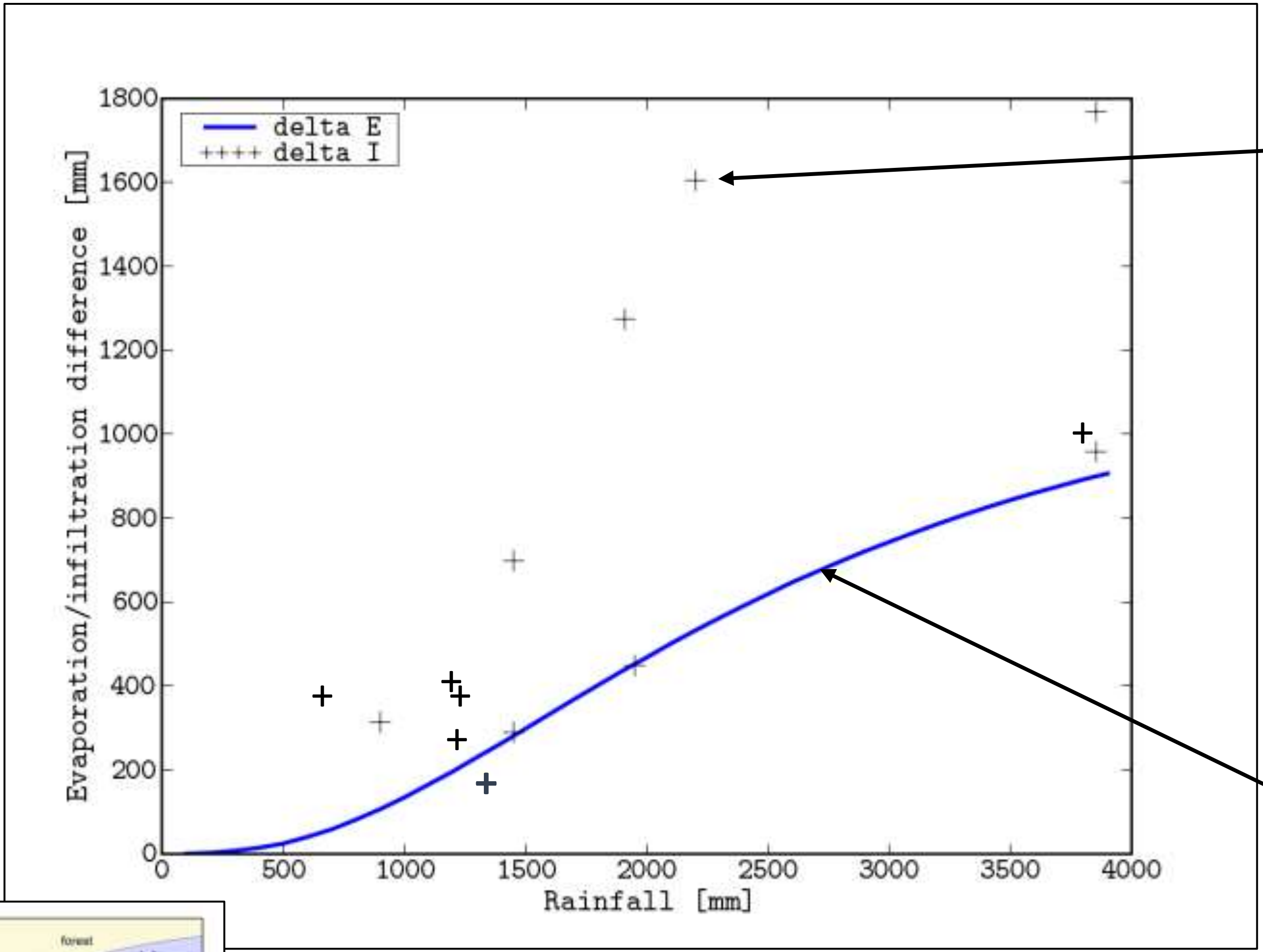
The *balance of the changes in ET <u>and</u> infiltration* after forestation (= 'trade-off') determines the net impact on groundwater recharge and baseflow (modified by soil depth / soil water storage opportunity).

Soil hydrological recovery after forestation



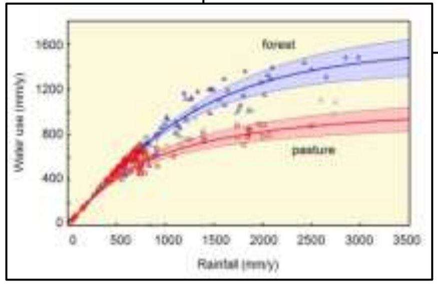
- Rebuilding of infiltration capacity may well require one to two decades…
- ***Repeated disturbance (fire, grazing, litter harvesting) may be fatal…***

(Some) hope for the tree lovers that baseflows may be boosted…



Water gain by increased infiltration (observed, as reductions in stormflow).

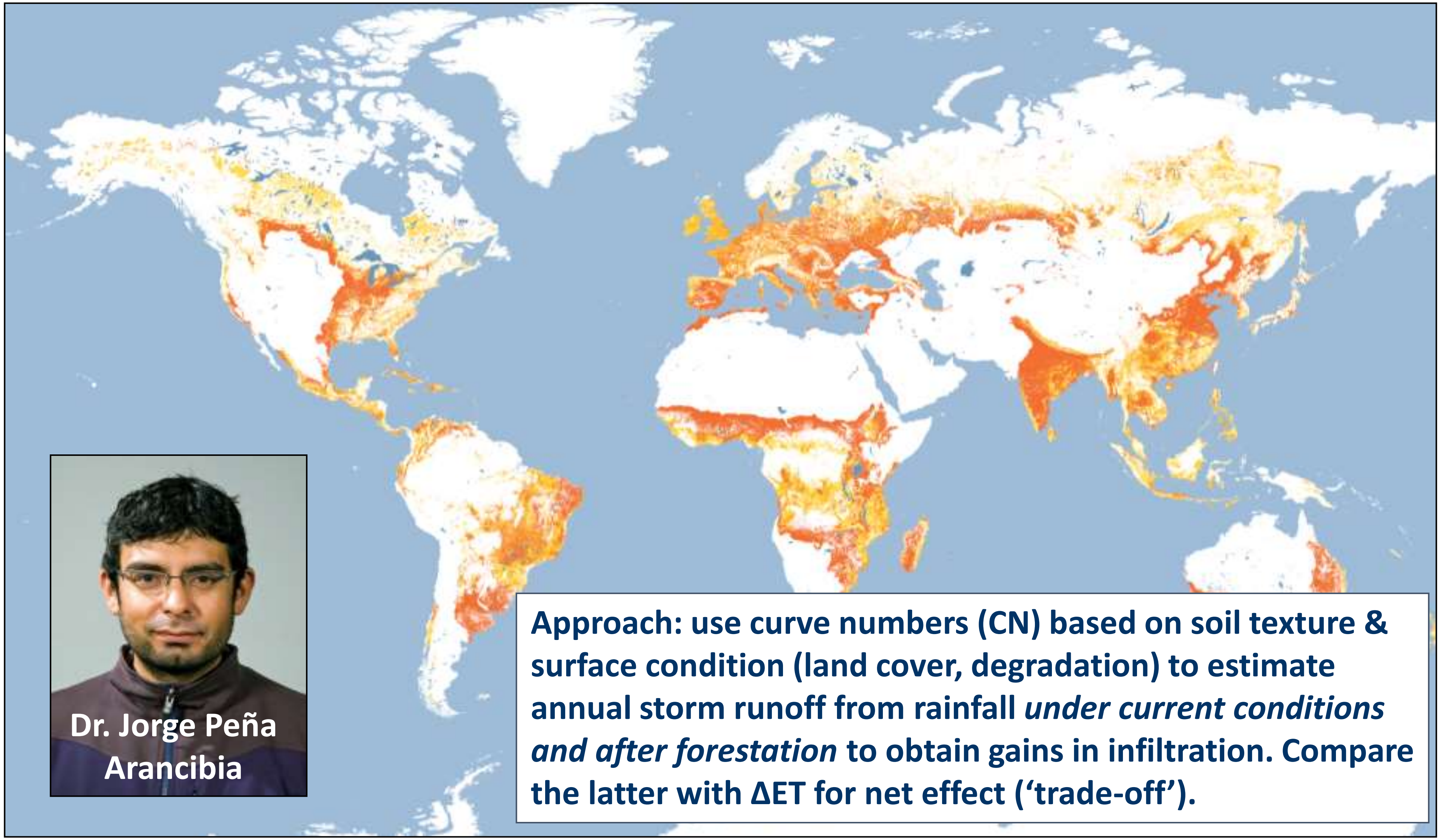
Extra water lost to ET after tree planting / forestation (generic Zhang curves).



Updated from Bruijnzeel (2008)

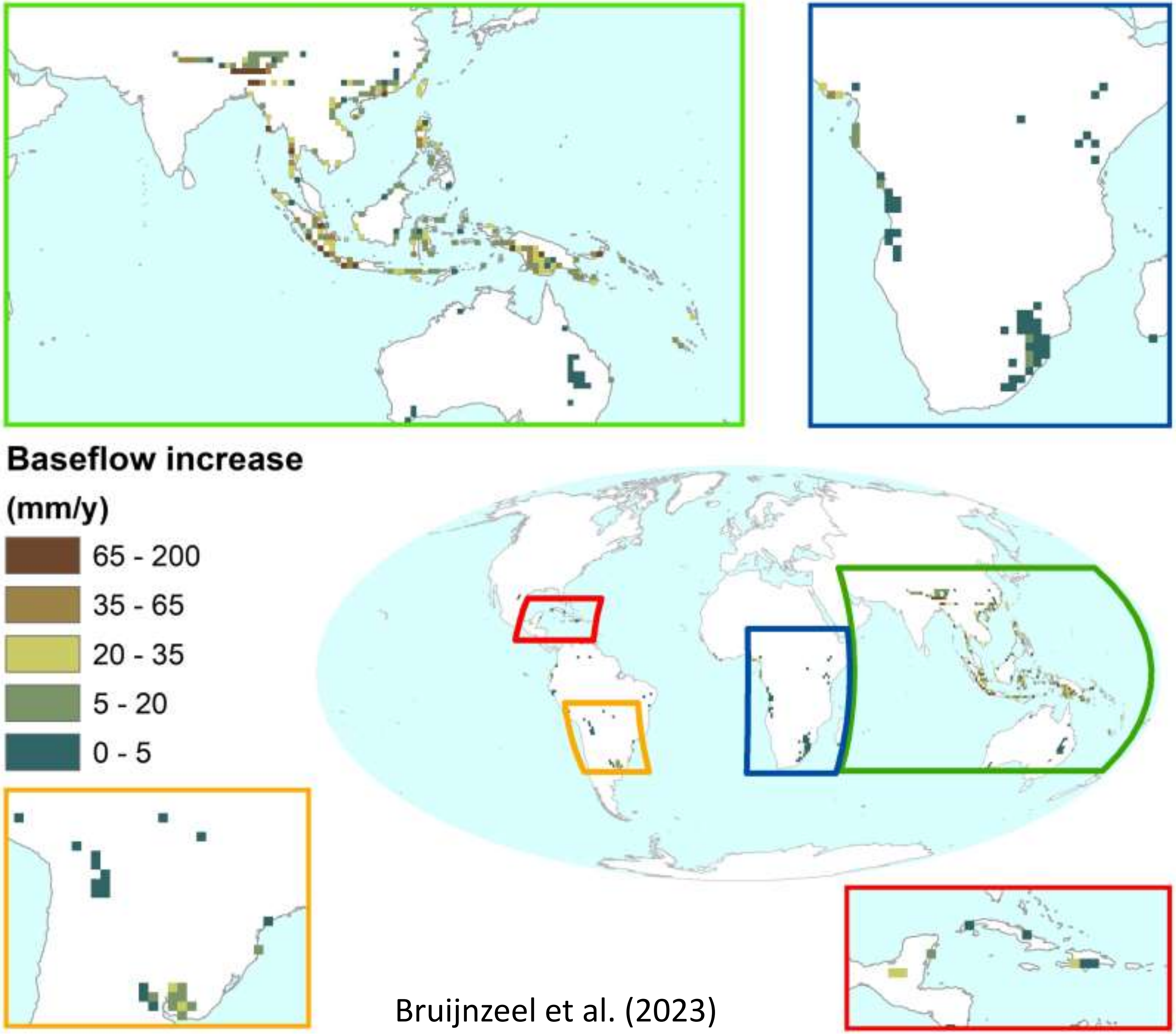
More than 2 billion hectare of degraded land world-wide for re-greening:

where might we expect improved baseflows?



Approach: use curve numbers (CN) based on soil texture & surface condition (land cover, degradation) to estimate annual storm runoff from rainfall *under current conditions and after forestation* to obtain gains in infiltration. Compare the latter with ΔET for net effect ('trade-off').

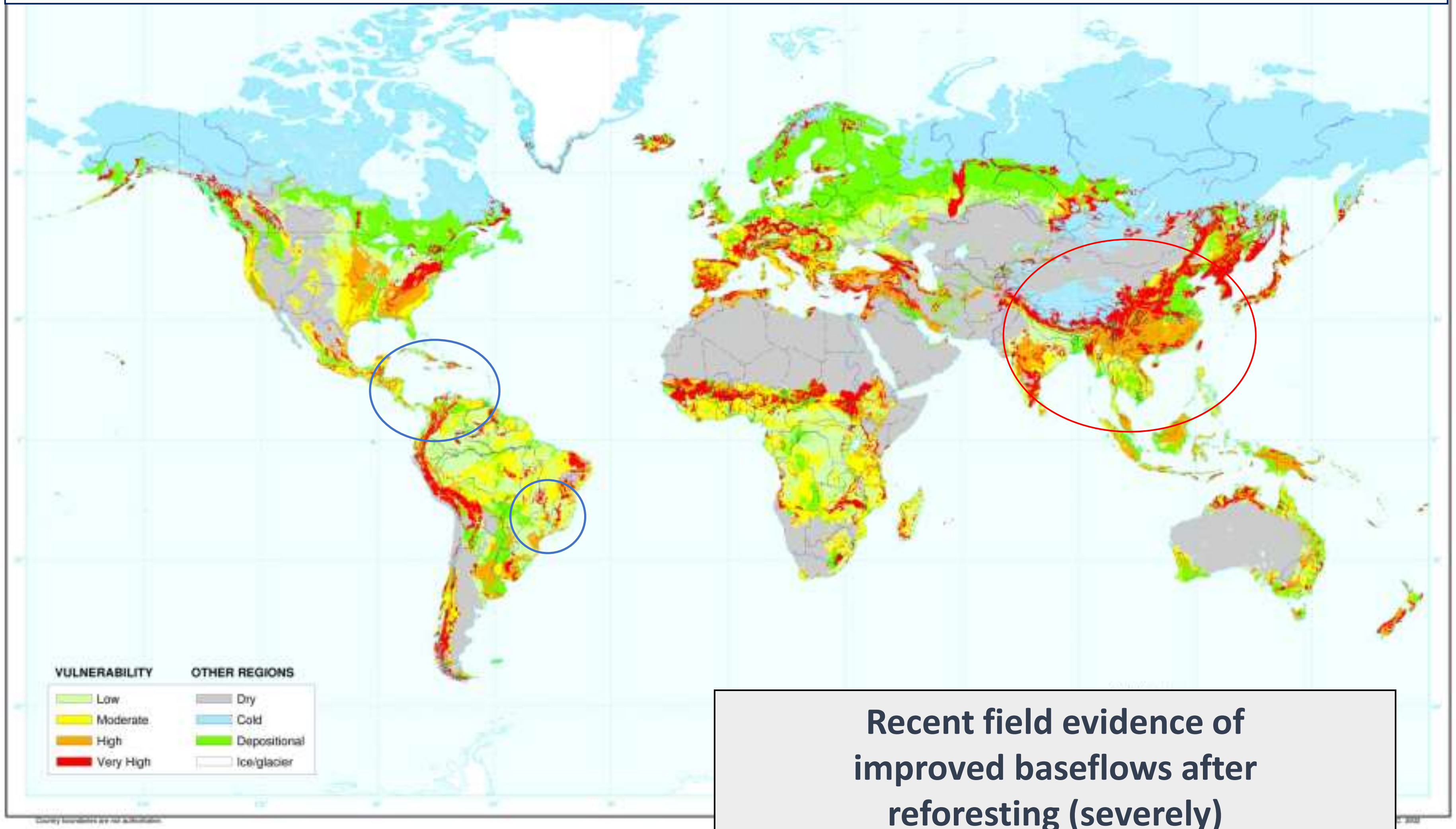
SOURCE: **WRI**, FLR, TEEB



Bruijnzeel et al. (2023)

Predicted 'bright spots' of increased baseflow following forestation coincide with areas of high seasonal rainfall, deep soils and advanced initial soil degradation.

Are the model predictions supported by field evidence?

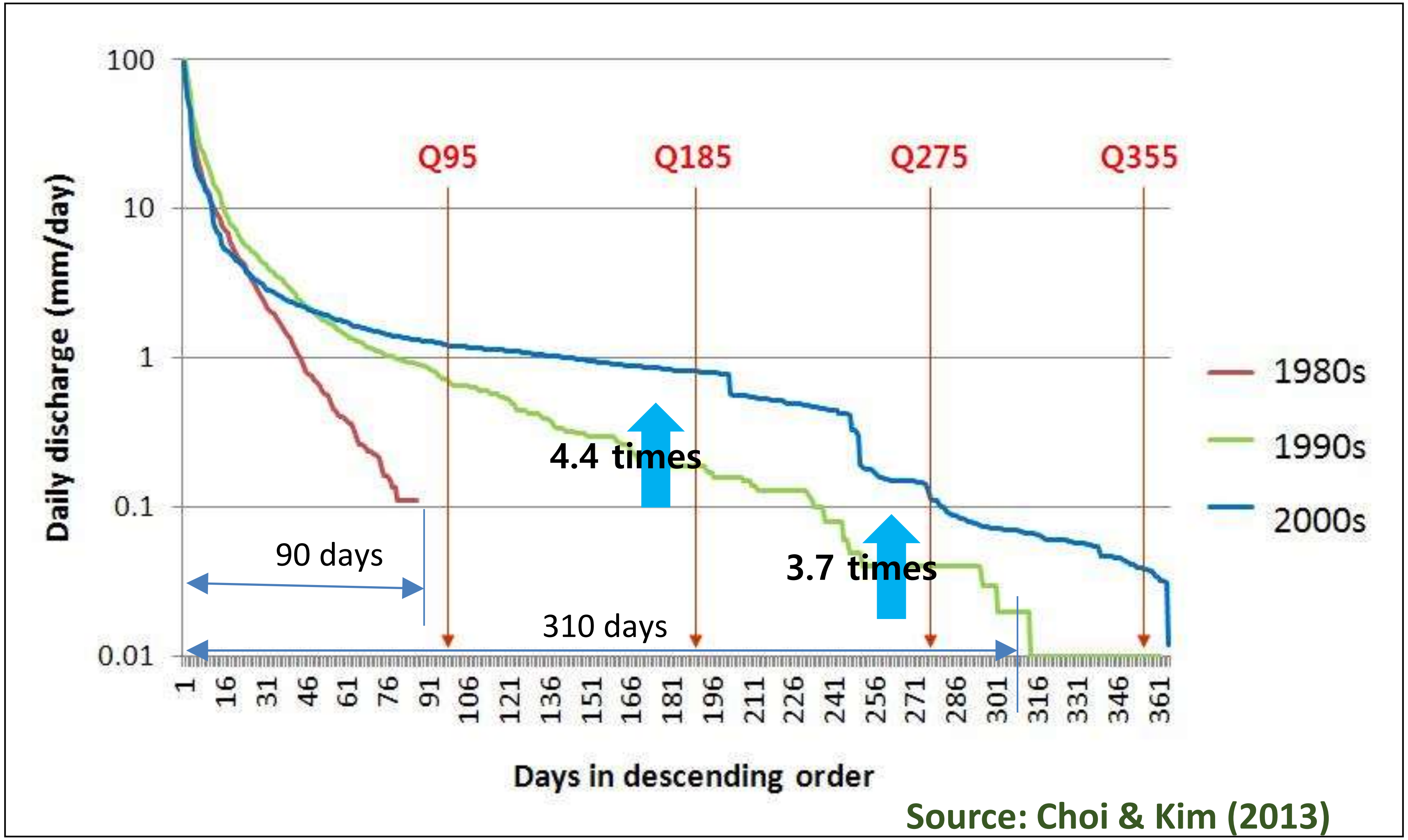


Recent field evidence of improved baseflows after reforesting (severely) degraded land in (S)E Asia:
S Korea, SW India, Philippines, P.R. China

Vegetation development in Yangjoo, S Korea, 1975 - 2005

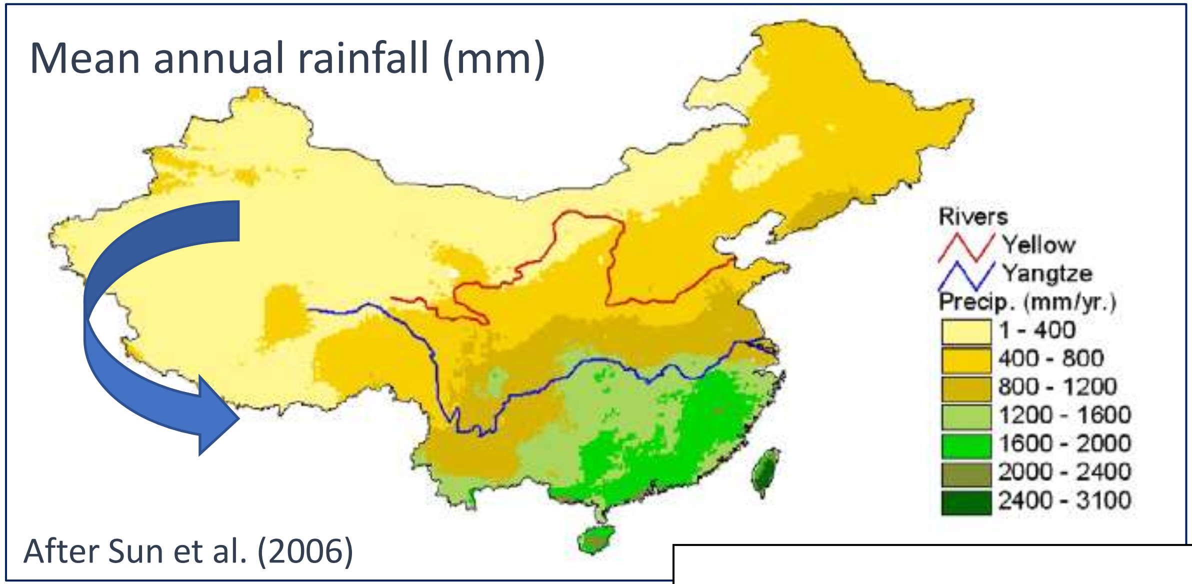
Source: Choi & Kim (2013)

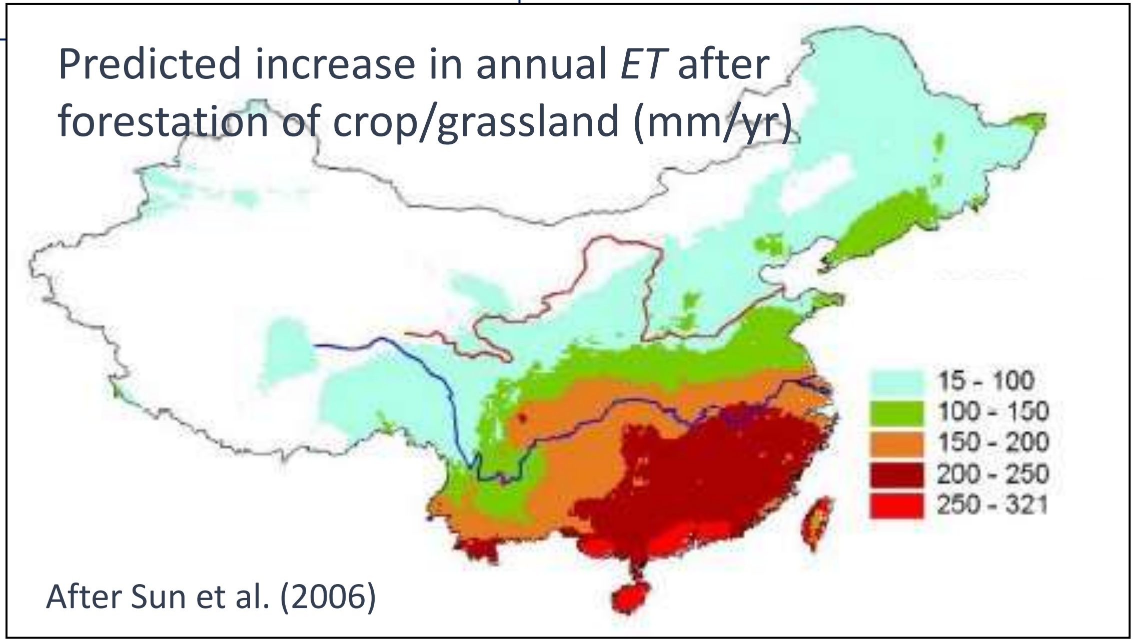
Improved flow duration: Yangjoo, South Korea



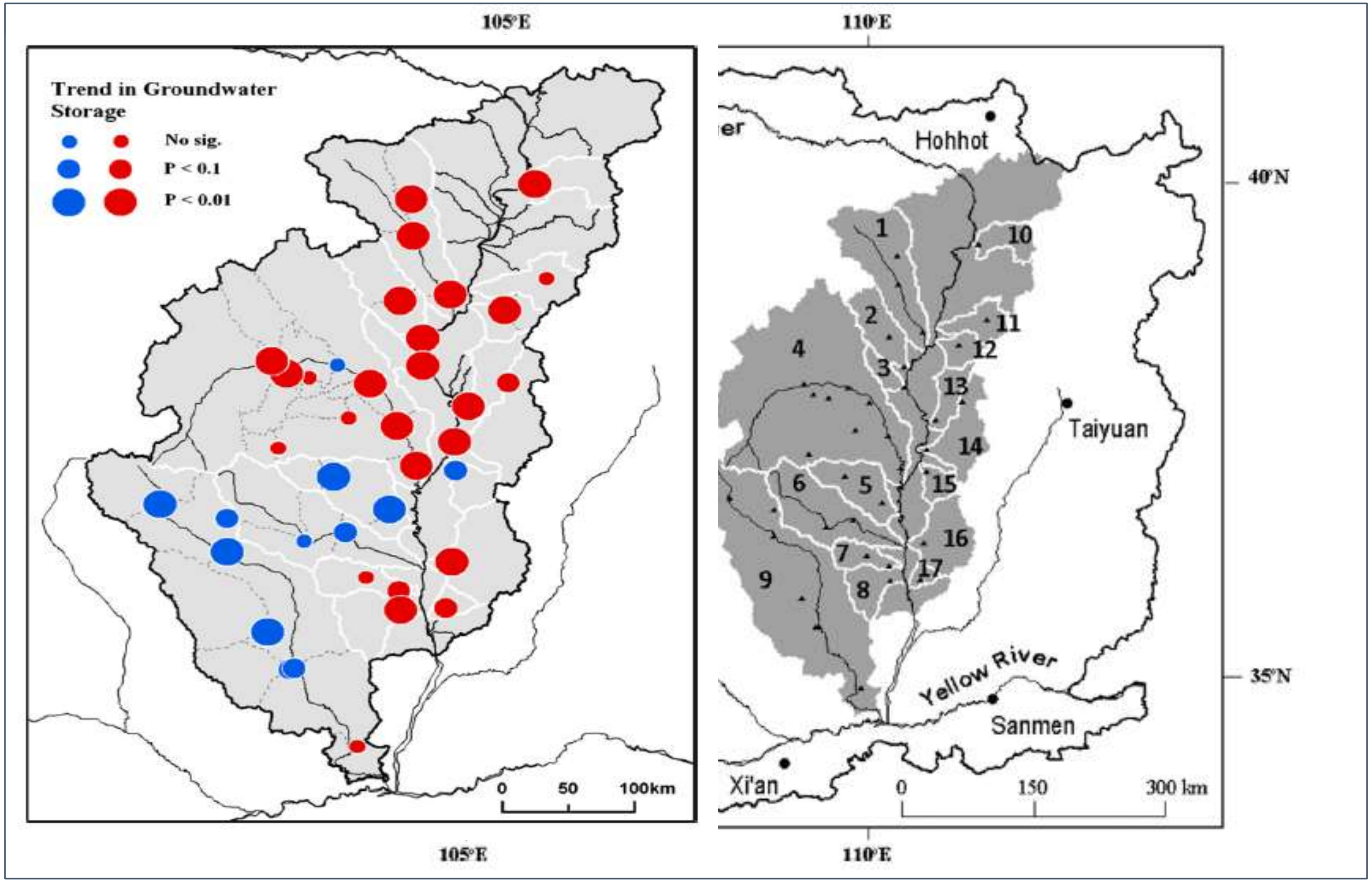
Improvements in low flows with time as vegetation matures

Potential for positive trade-off after forestation greatest in SE China?



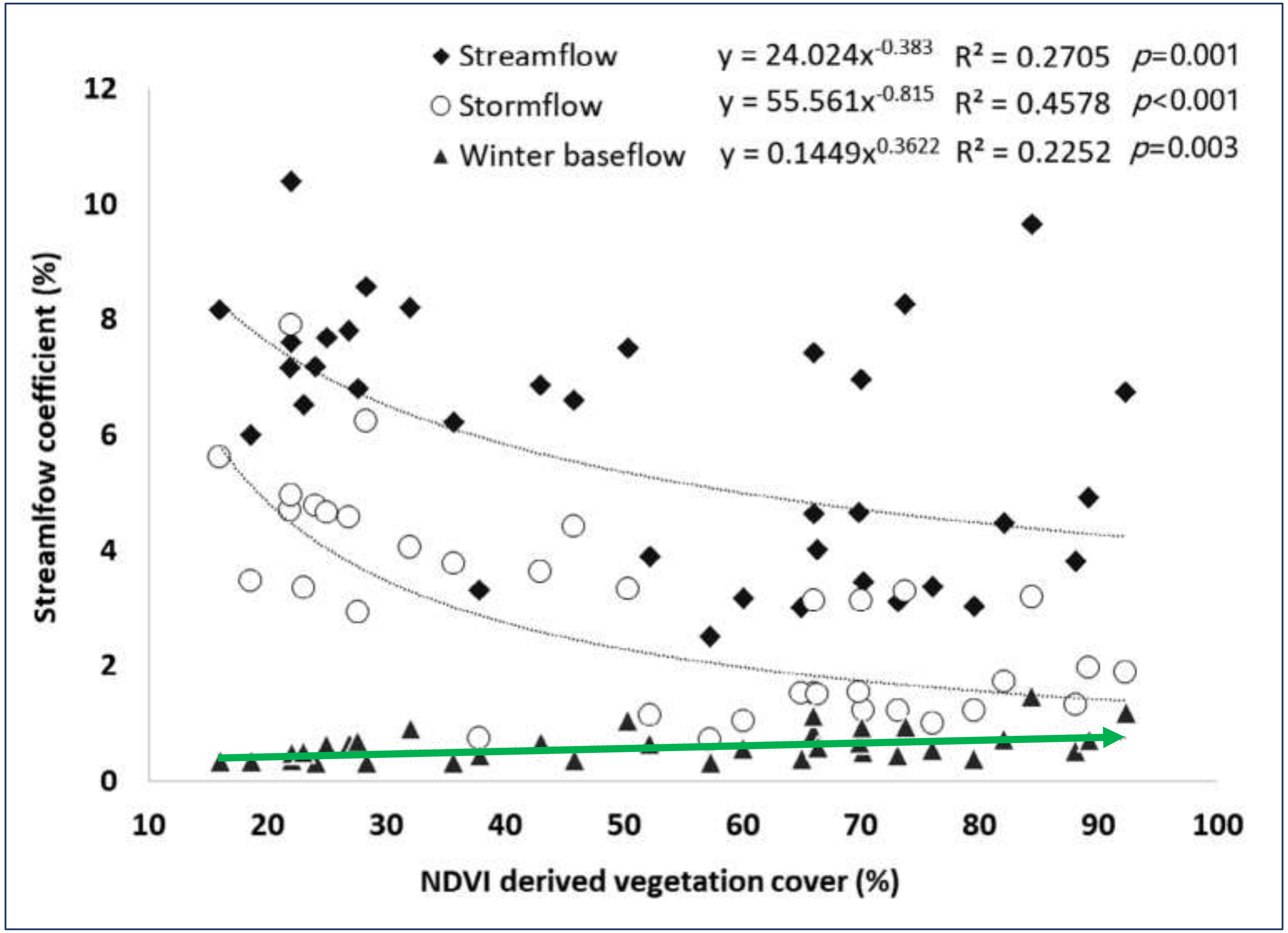


Positive trends in groundwater storage & baseflow for large catchments on the Southern Loess Plateau



Gao et al. (2015)

Declining total water yield does not always imply reduced baseflow…

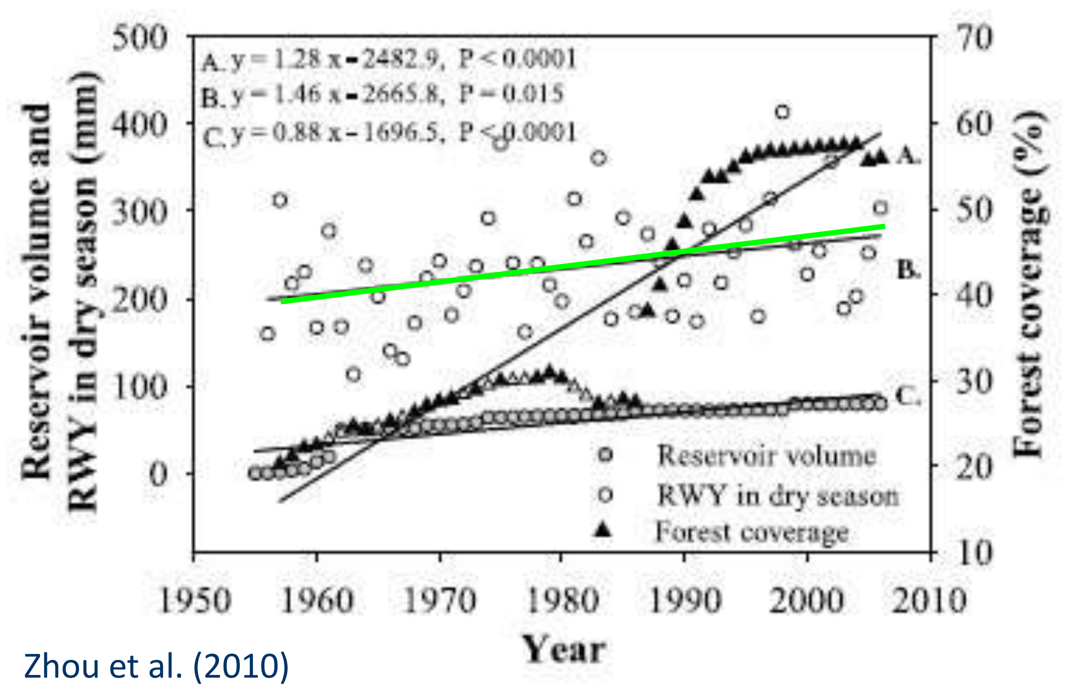


XP Zhang et al. (2022)

Beiluo River Basin, South-Central Loess Plateau

Declining water yield after afforestation on the Loess Plateau mostly reflects reductions in storm runoff, while winter baseflow *for large river basins* is seen to increase with cover…

Positive impact of large-scale reforestation on baseflow in humid SE China (Guangdong): boosted infiltration or reservoir operation?



Zhou et al. (2010)

Tropical forestation and flows: what can be achieved?

- Undisturbed forest and well-managed grassland maintain baseflows best.
- **Higher flow peaks and lower dry-season flows possible following advanced soil degradation.**
- **Surface degradation** is widespread, but **insufficiently represented in experiments** and ‘scientific’ reviews.
- **Adding trees to deforested landscapes will reduce baseflow, unless infiltration capacity (macropores) are improved sufficiently to overcome extra water use**.

Tropical forestation and flows: what can be achieved? - 2

- **Positive trade-off** between changes in plant water use and infiltration after reforesting *degraded* land is feasible.
- **Predicted baseflow increases greatest in highly degraded areas with high rainfall excess and deep soils.**
- Given the risk of reduced streamflow after planting trees / natural regrowth, **agroforestry may be preferred in densely populated seasonal climates?**

Outlook: Explore real-world conditions…

- Intensify research outside mature, undisturbed forests.
- More focus required on water dynamics of secondary forests, exotic invaders, and agroforestry systems as well as *restoration of degraded land* (time sequences).

XIE XIE NIN!

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