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Ecosystem Services Trade-off: the Nexus of Water, Food and Ecological Conservation

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Background

Bonn2011 Conference
The Water, Energy and Food Security Nexus
Solutions for the Green Economy
16–18 November 2011

Bonn2011 has provided a first platform for consideration of the close interlinkages of water, energy and food (WEF) security and the benefits of a nexus perspective.

- About 0.9 billion people lack access to safe drinking water
- 2.6 billion people lack access to adequate sanitation
- 1.3 billion people lack access to electricity
- 2.7 billion have no access to modern and healthy forms of cooking
- close to 1 billion people are undernourished

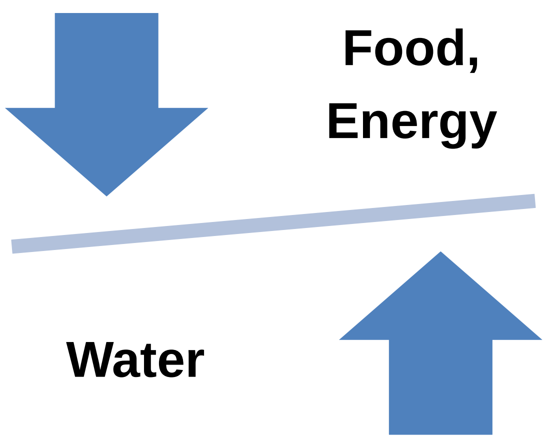
Challenge

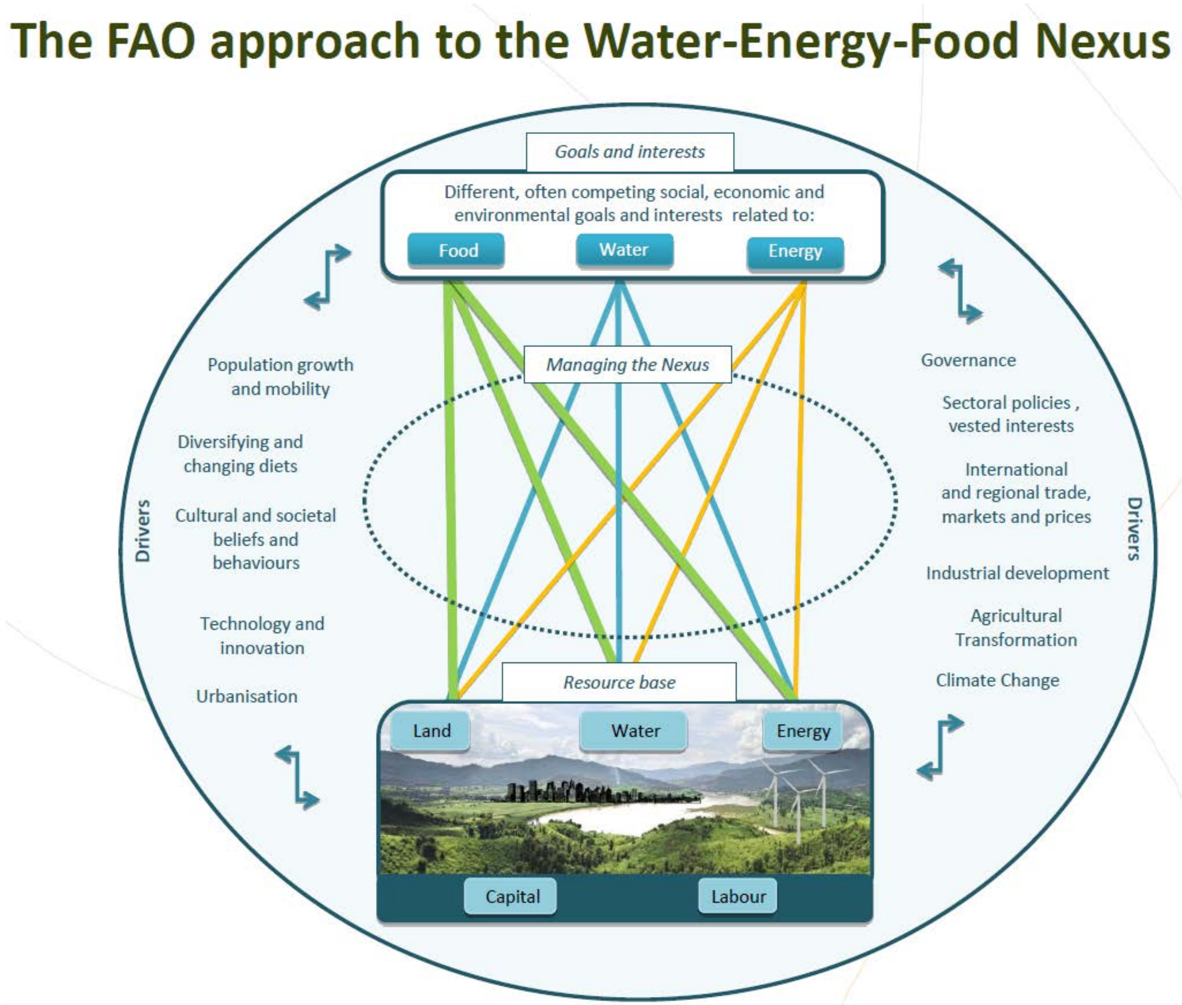
Water, energy, and food sectors are interconnected in important ways, and actions in one sector may either help or harm the other two. Disconnected approaches and silo thinking are more likely to make matters worse.

Water-Energy-Food Nexus: 60% more food by 2050 – mostly from yield increase – hence a lot more energy, 40% more water and 40% more energy in 2030 (FAO)

Tradeoff

- Balance different uses of ecosystem resources (energy, water, land, soil and socio-economic factors)

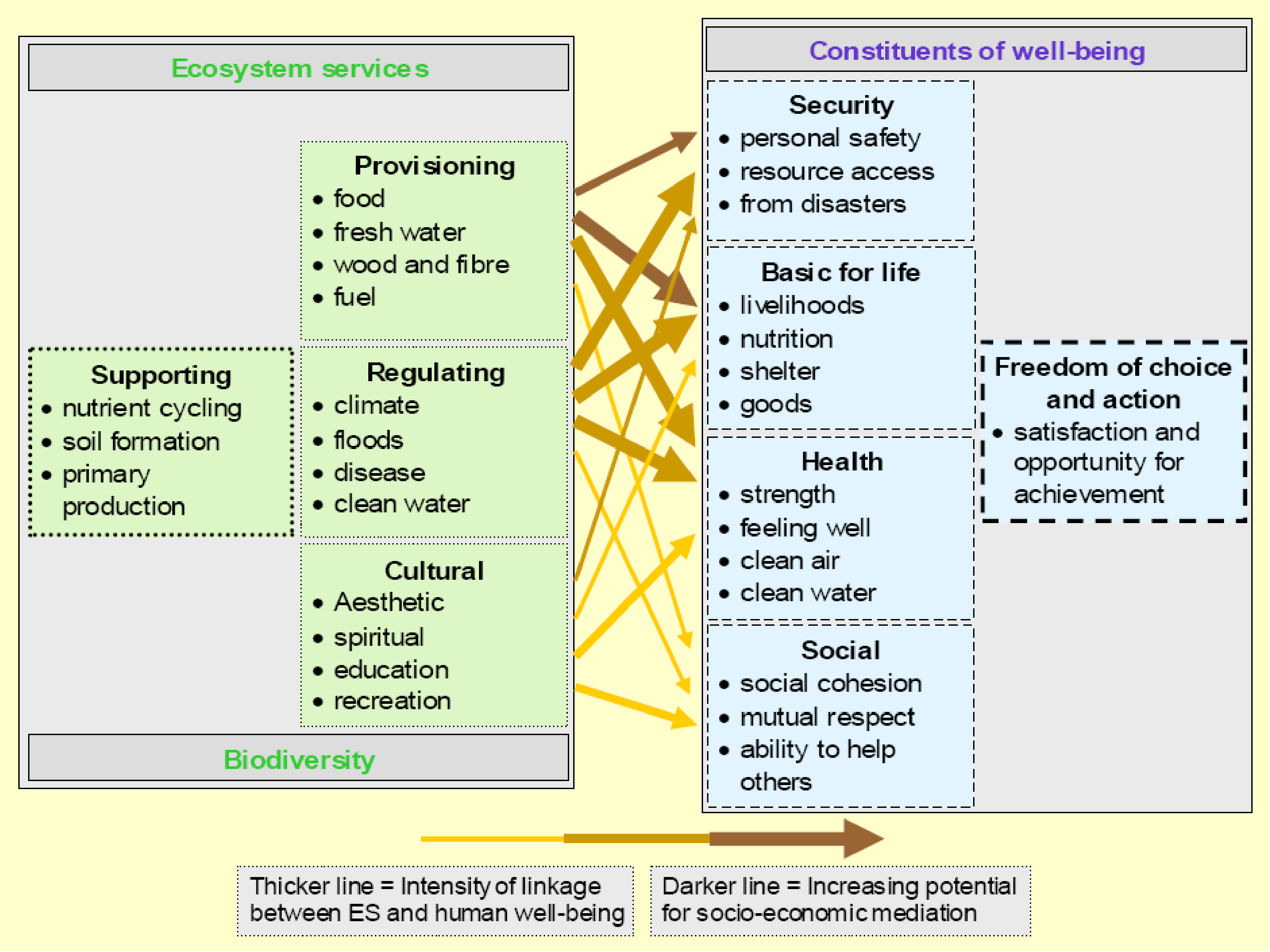




Ecosystem services and human wellbeing

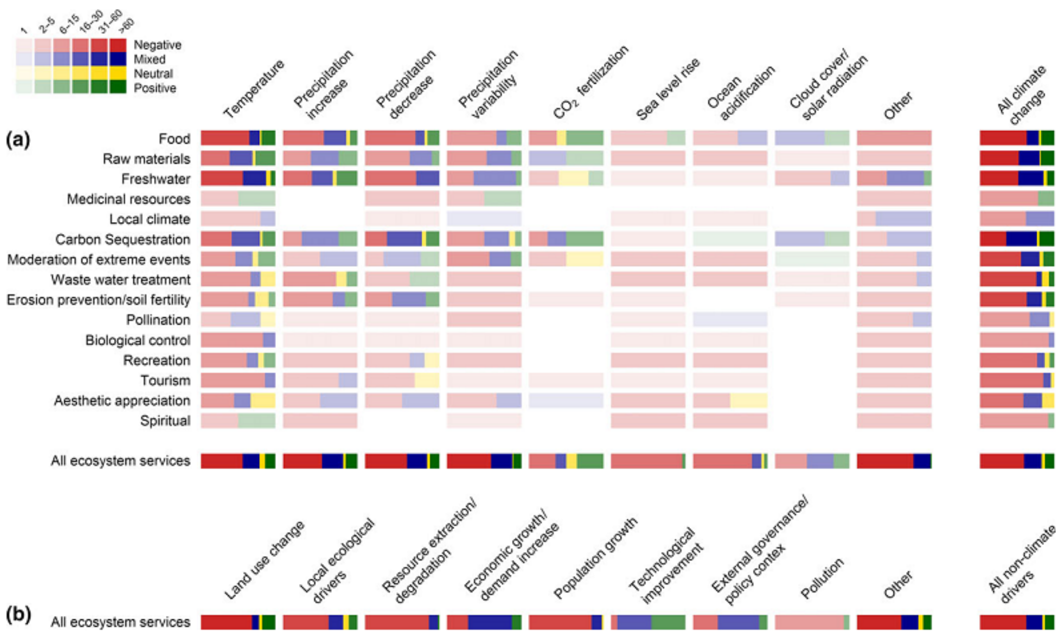
Ecosystem services: The benefits humans obtain from ecosystems.

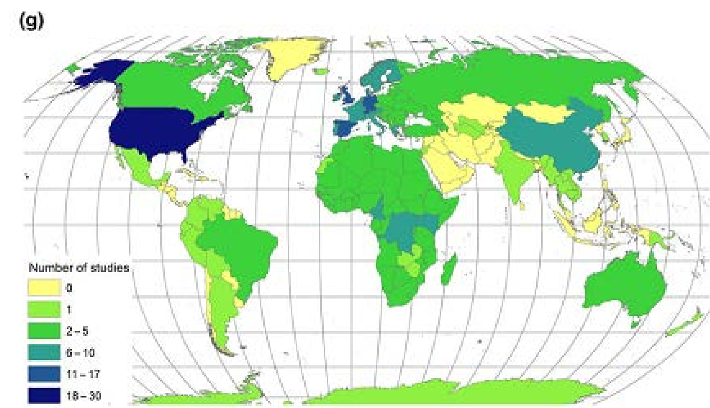
(MEA 2005)



Climate change and ES

- ➢ Global change has significantly affected global ecosystem services



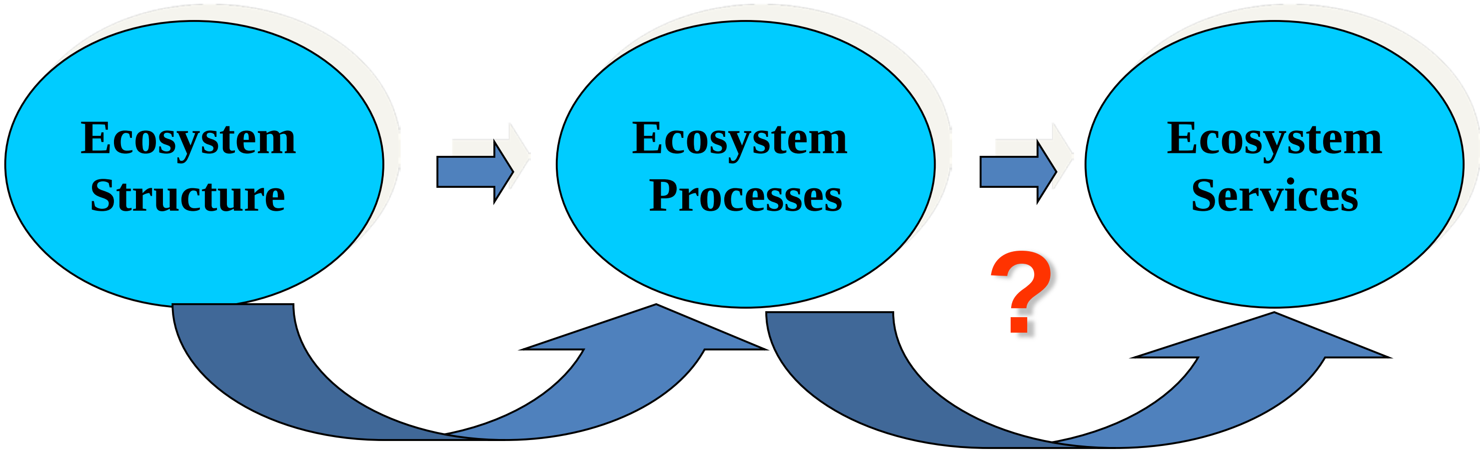


Runting et al., Global Change Biology, 2016

Climate change and land use have a negative impact on most ecosystem services；
Global change has become an important challenge for the sustainable development of human society.

Key topics of Ecosystem Services

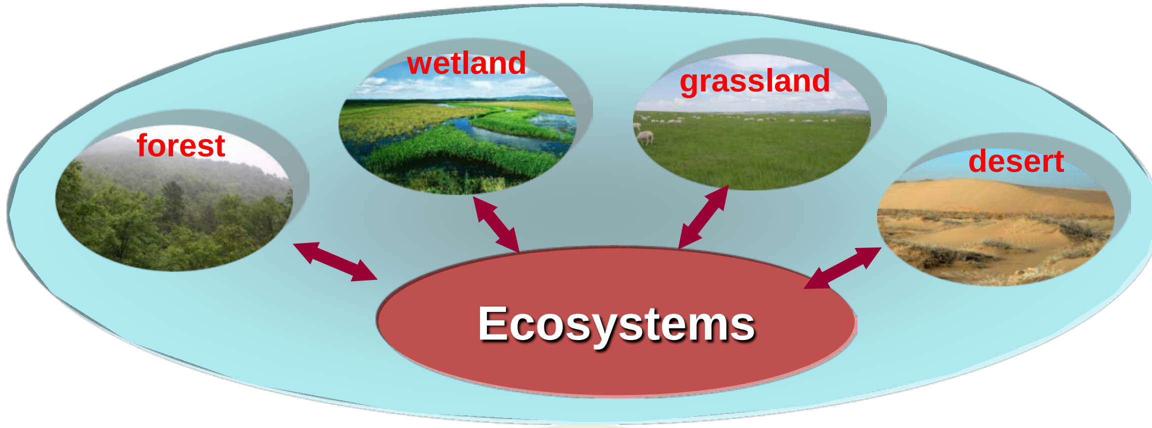
- Ecosystem processes and services



- Understanding relationships among multiple ecosystem services

- Regional integration of ecosystem services

Ecosystem Processes and Services



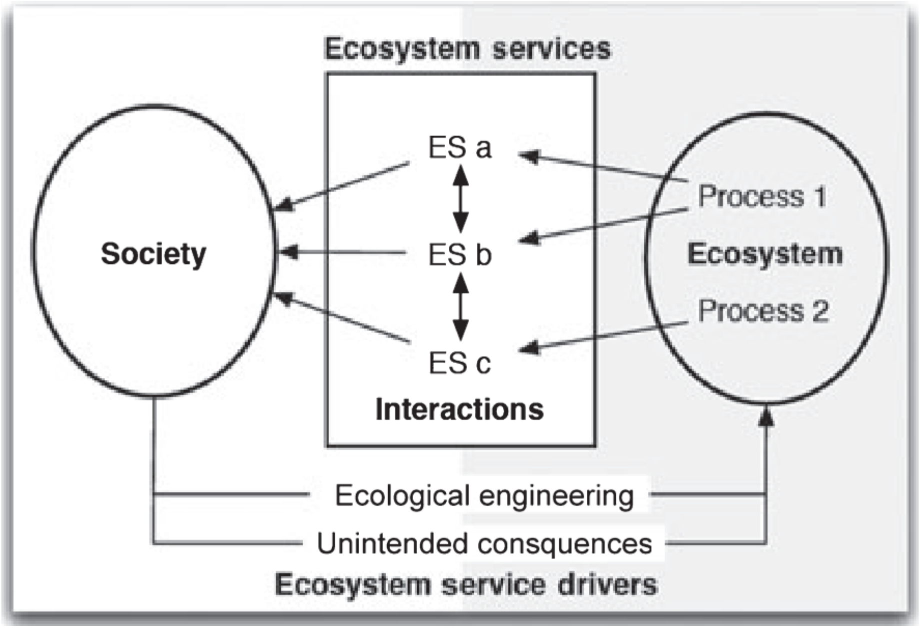
Ecosystem services	Research	Focus	Target
■ Water conservation and hydrological regulation ■ Soil conservation, ■ Carbon sequestration	▪ Generation and regulation ▪ mechanism of ecosystem services	▪ Impact of ecosystem structure and process changes onto ecosystem services ▪ Interactions between supporting services and regulation services ▪ Models on process	To reveal the interactions between ecosystem structure-process and ecosystem services

Based on long-term ecosystem monitoring and experiment

Basis for interrelations within ES

Ecosystem services are interrelated due to:

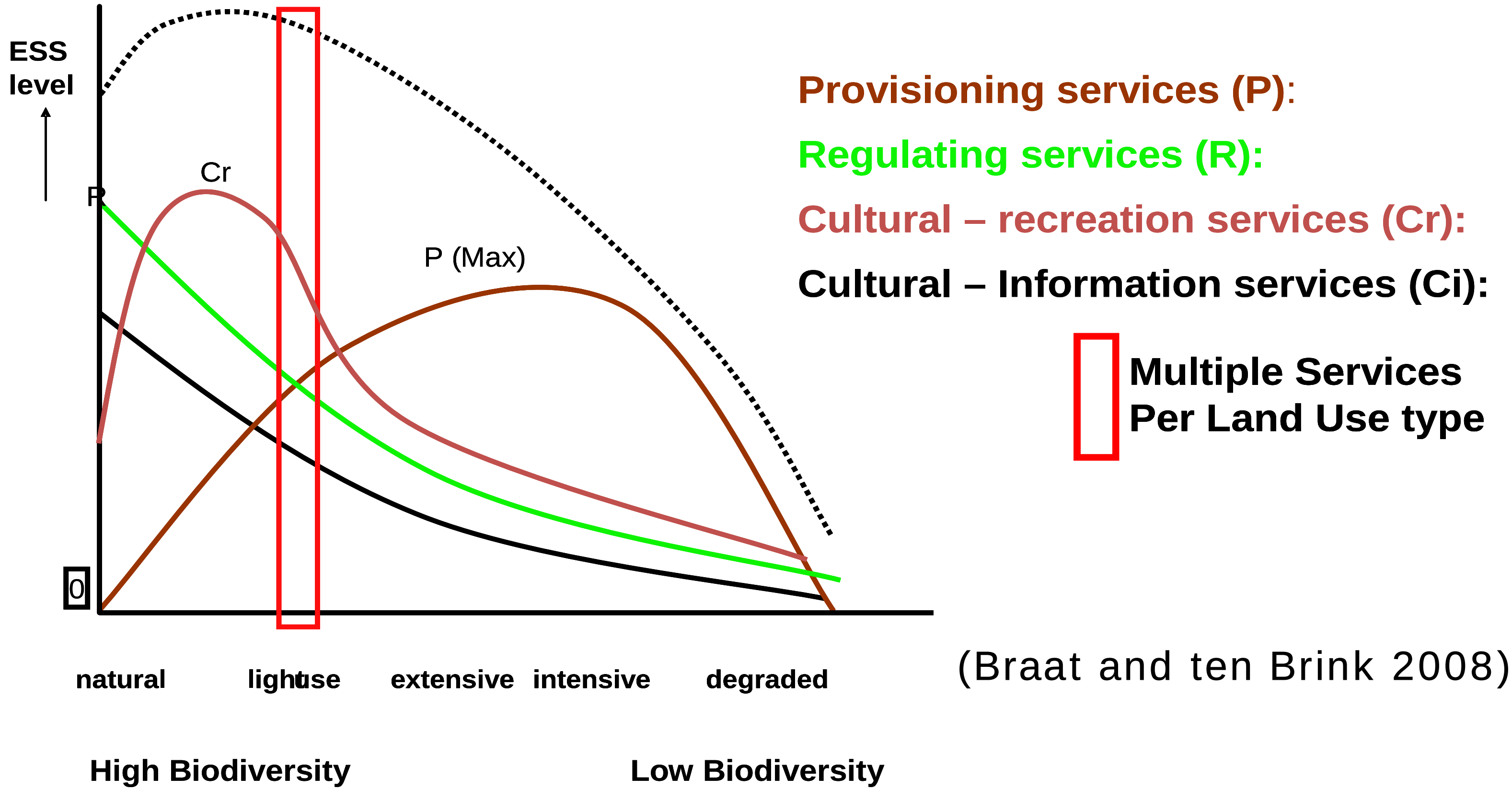
1. effects of common driver;
2. interrelation between ecosystem services.



Trade-off

Synergy

Land use is crucial for ecosystem service

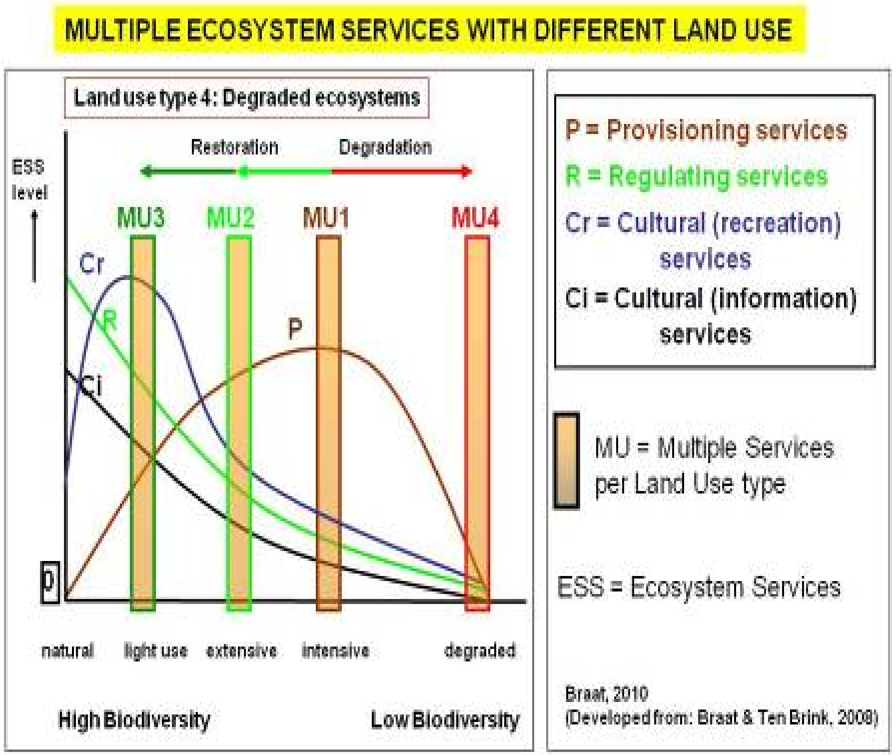


(Braat and ten Brink 2008)

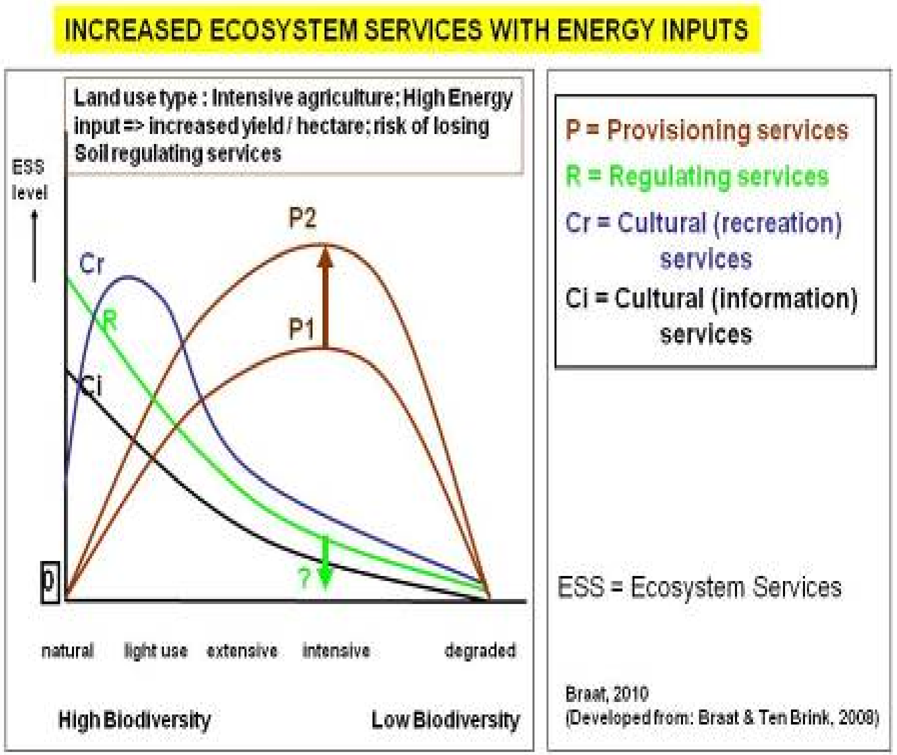
- **Regulating and cultural services are very often correlated with high biodiversity**
- **There is often a conflict between provisioning services and regulating and cultural services.**

Management of ecosystem services

•Restoration



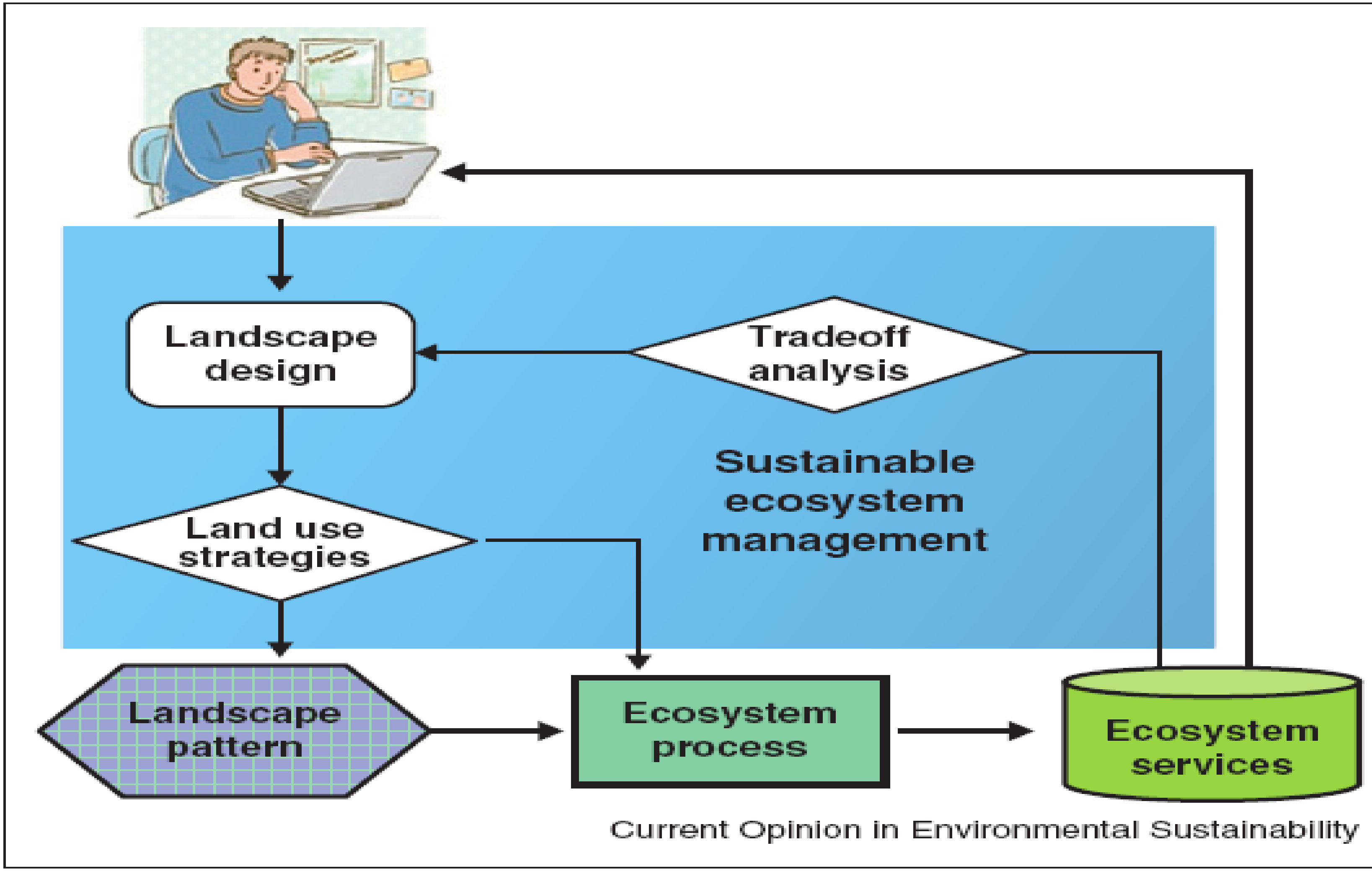
•Increased inputs



(Braat and ten Brink 2008)

Land use change

- Biogeochemical, Hydrological cycles change;
- ecological processes and ecosystem services.

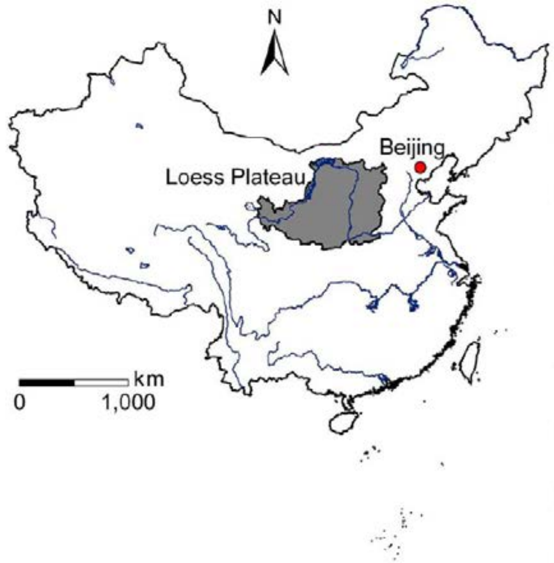


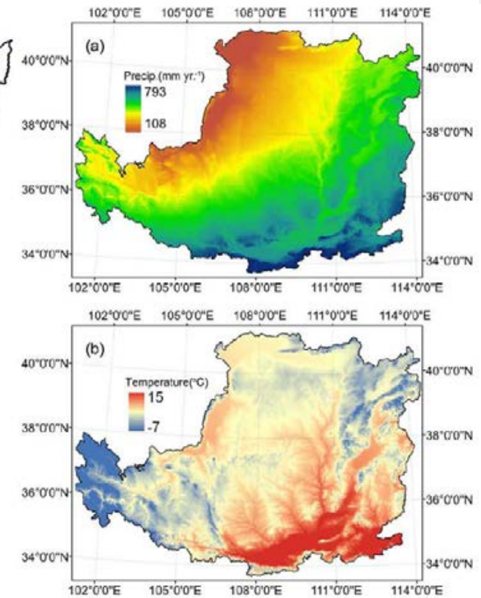
Linking landscape pattern –ecosystem process-ecosystem Services and landscape design

(Fu et al., *Current Opinion in Environmental Sustainability* , 2013)

Study Area—Loess Plateau

- **Located in northern China with an area of over 600 thousand Km^2**
- **Semi-arid area with water shortage problem**
- **Diversified landforms**
- **Soil erosion severe**

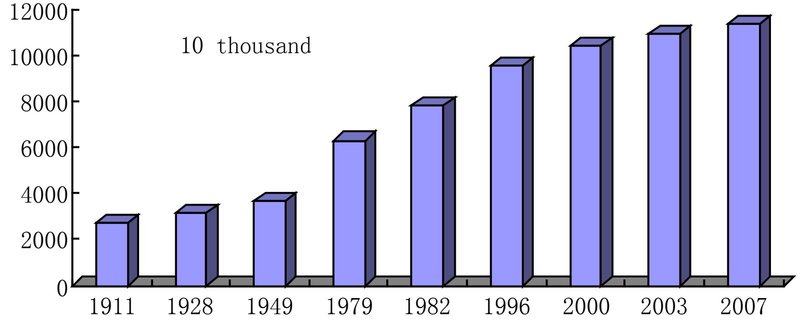




Human-nature relationship and ecosystem management

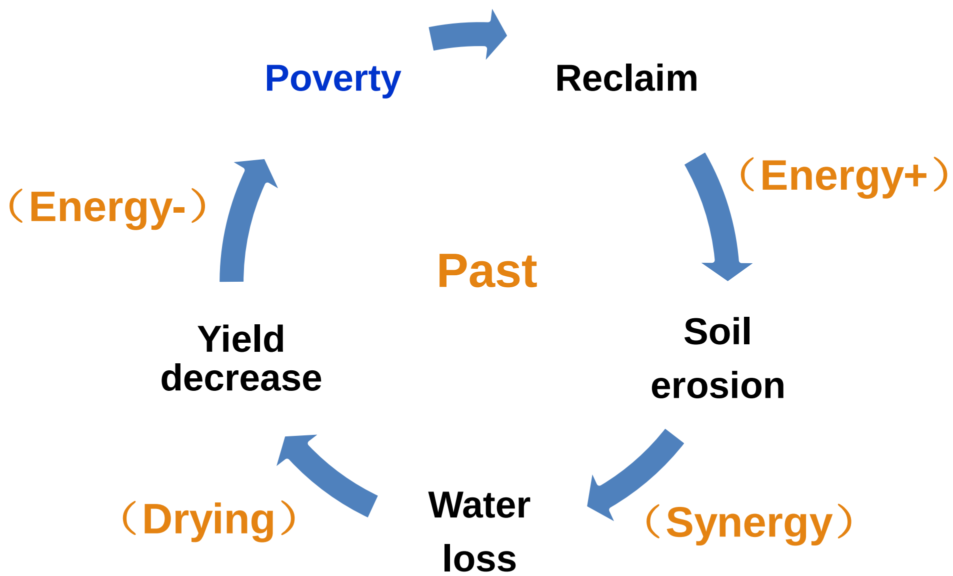
- Population increased
- Supporting 8.5% Chinese people with 6.7% of the territory

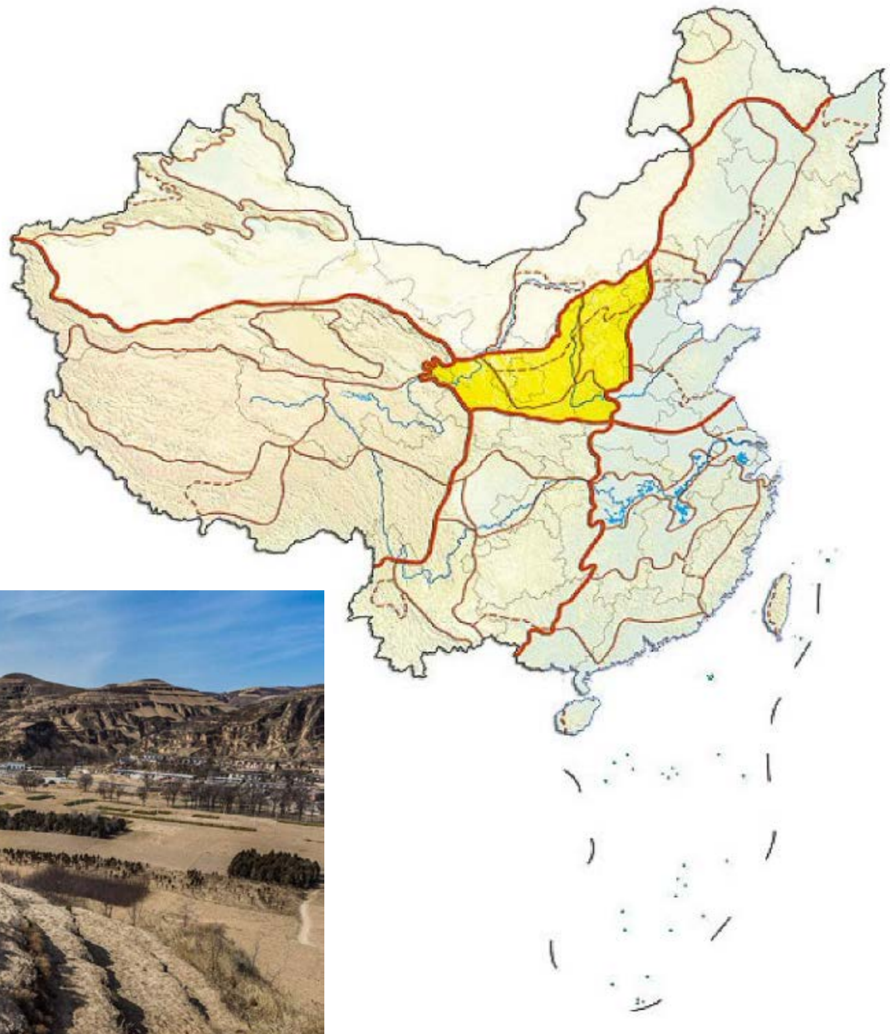
Population increase



- Agricultural development and soil water conservation have been the focus of ecosystem management since 1949
- 1980’s some ecosystem restoration projects have been done. Grain to Green Programme have been implemented since 1999

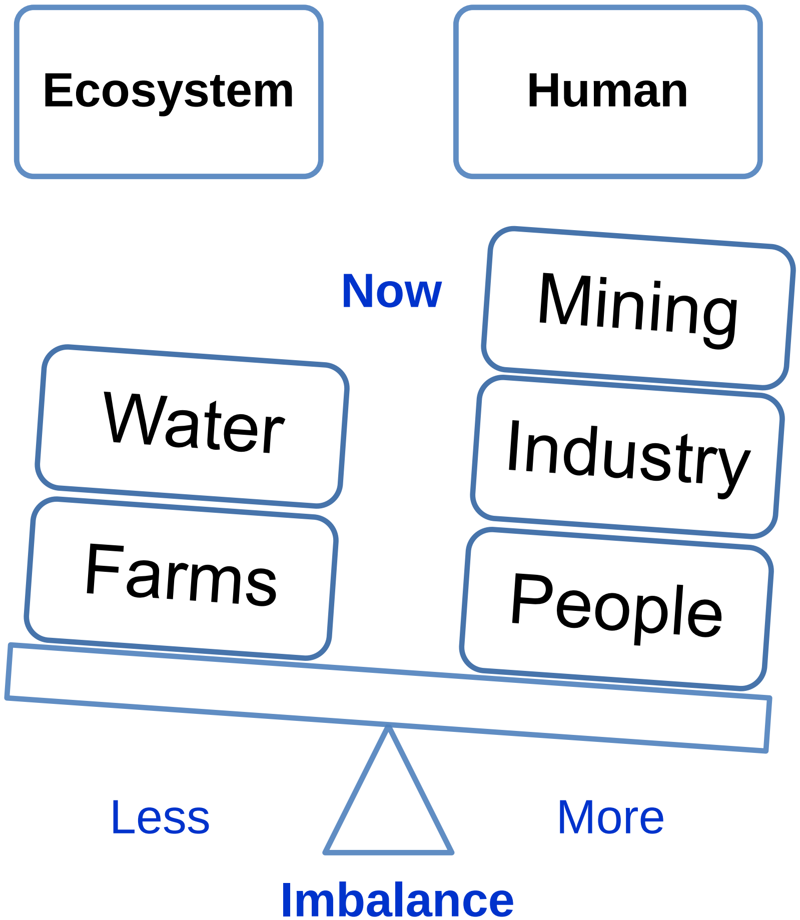
Tradeoff in Loess Plateau





Current situation of LP

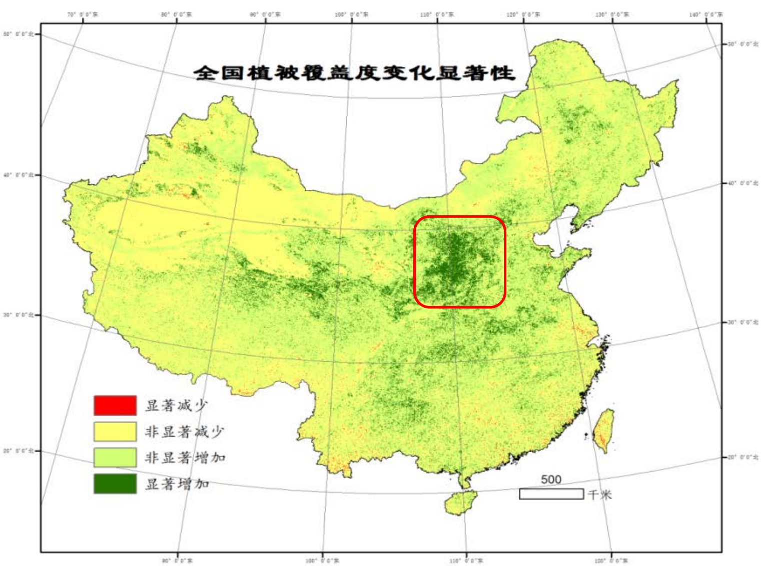
- Most of the poor are famers
- Small-scale farming cannot alleviate poverty but cost much water
- Mining for fossil energy may pollute the soil and water
- Urbanization with increasing people requires water, energy and food

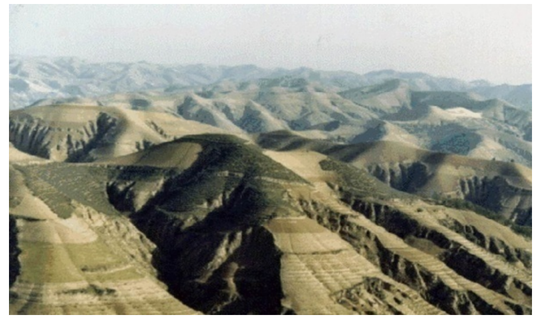


Mission

- Understanding the Water, Food and Ecological Conservation nexus tradeoffs in LP
- Identifying the balancing thresholds in the nexus
- Developing models to simulate the WF and Ecological conservation
- Evaluating the nexus sustainability in different scenarios
- Finding the adaption way to both alleviate poverty and protect the environment

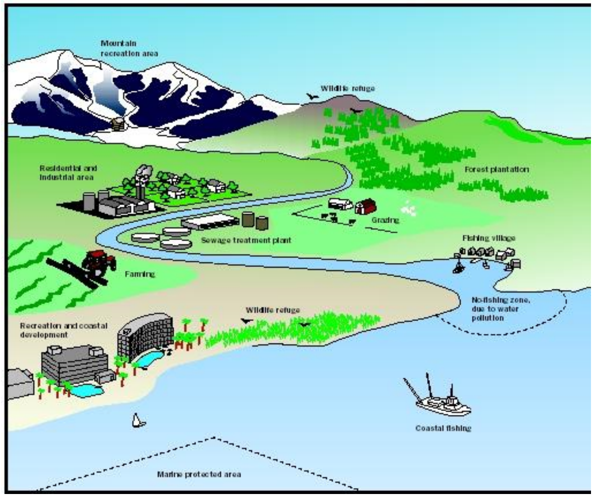
Landscape and land use Change in the Loess Plateau





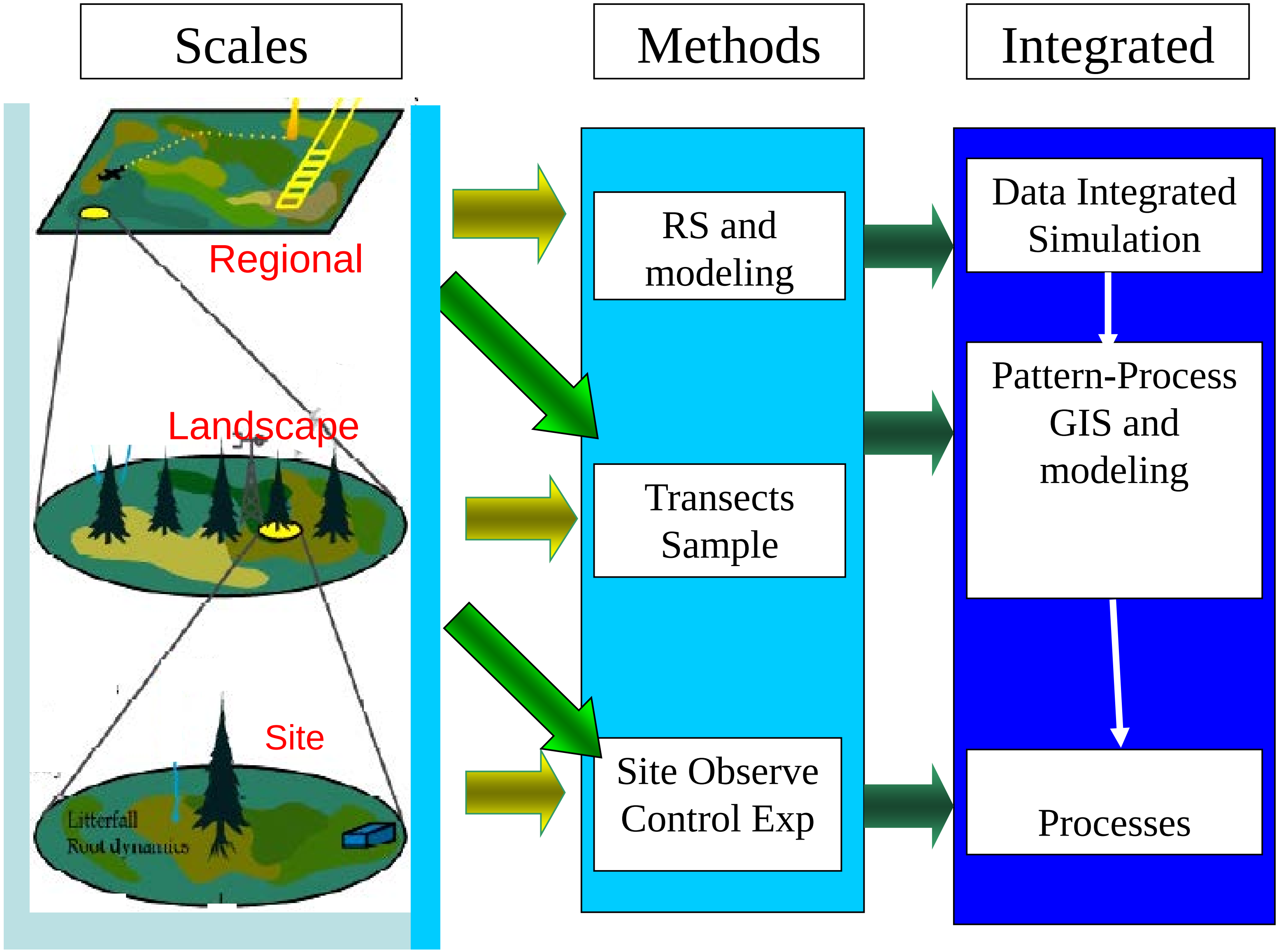
Change of Vegetation Coverage is biggest in the Loess Plateau from 2000 to 2010

What Happen ?



Land Cover Change **Ecosystem Services**

Methods



Scales
Methods
Integrated
Regional
Landscape
Site
Litterfall
Root dynamics
RS and modeling
Transects Sample
Site Observe Control Exp
Data Integrated Simulation
Pattern-Process GIS and modeling
Processes

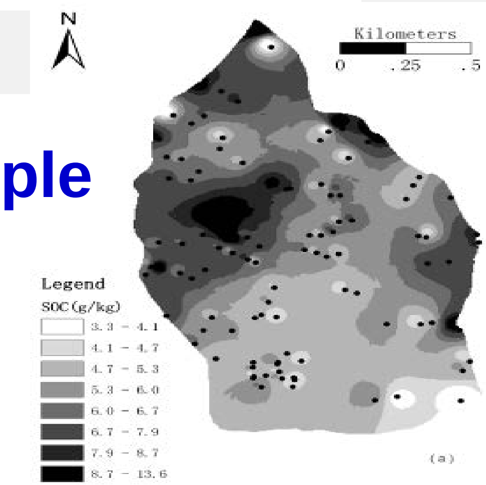
Measurement and Investigation

Plot

Compare

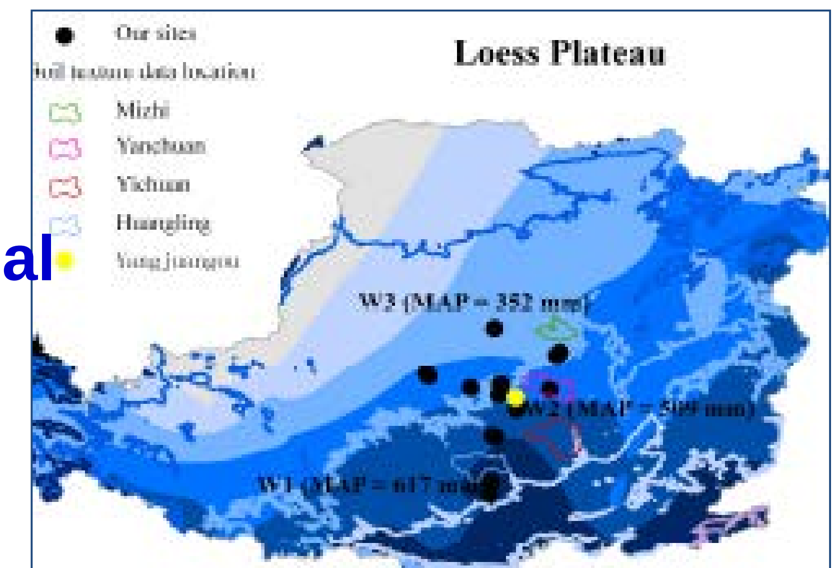
Catchment

Sample

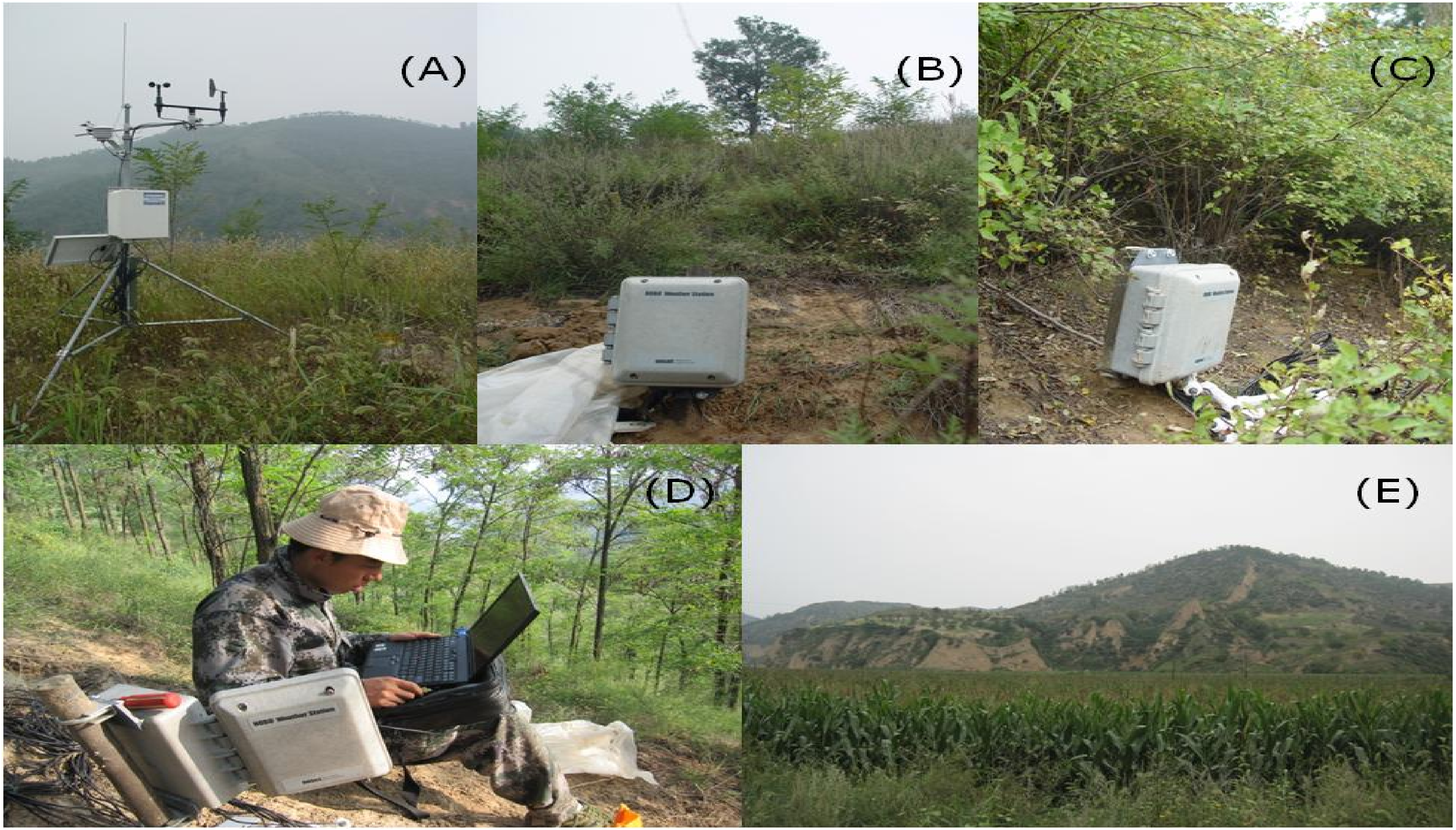


Transect

Regional



Soil Moisture Dynamics in plot scale



Wang, Fu et al, *HESS*, 2012

◆ Plantation Forestry ET Observation

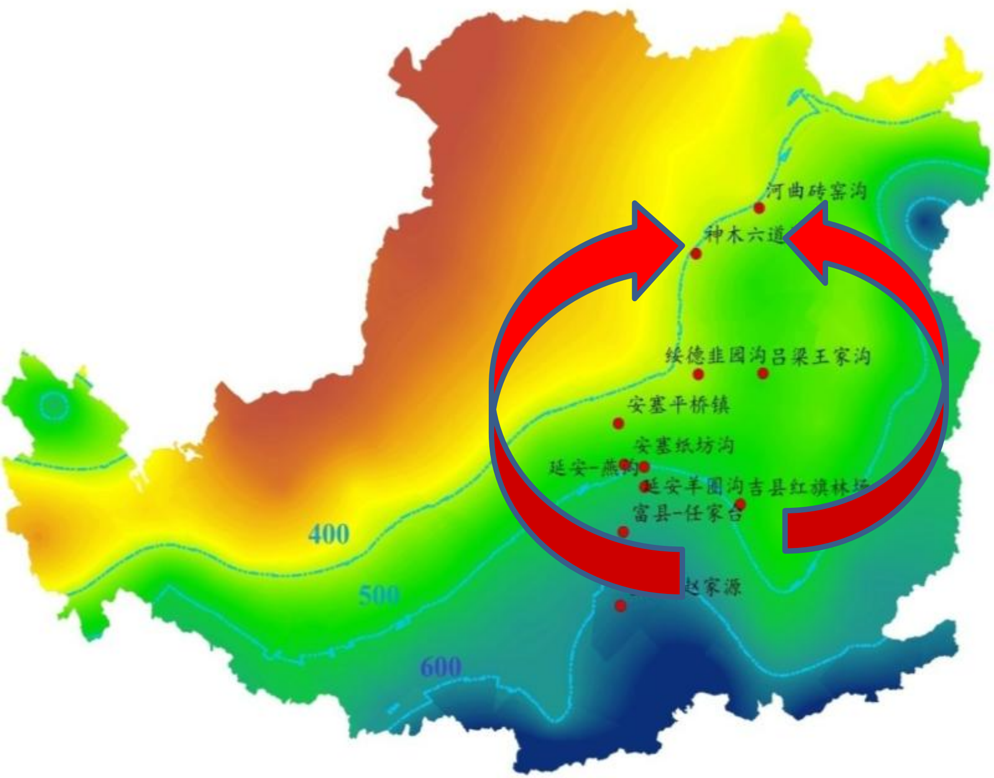
Plot 4 (15年/23º/E)

Plot 1 (>30年/22º/NW)

Plot 3 (25年/23º/E)

Plot 2 (25年/24º/S)

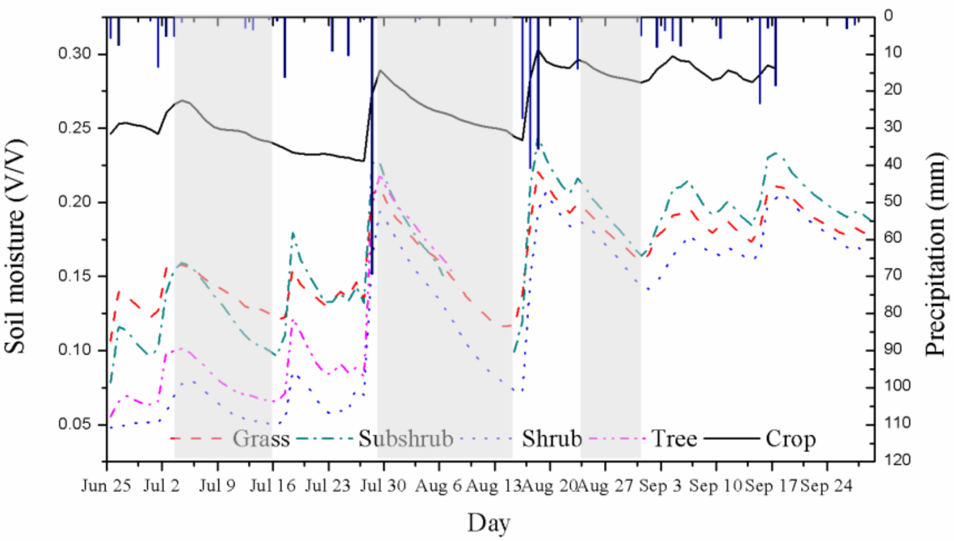
N-S Transect Survey

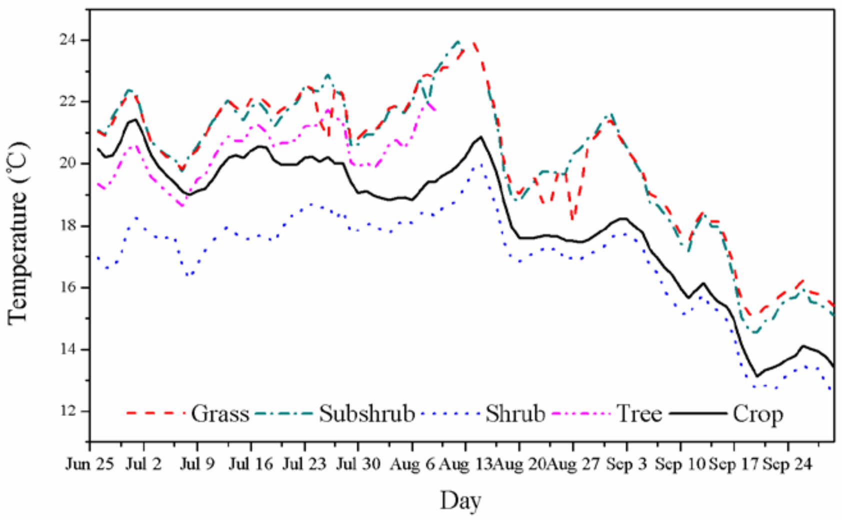


共计11个流域，51块样地

样带	地点	年均降雨 (mm)	样地类型
陕西样带	宜君（赵家塬）	~709	刺槐、辽东栎、狼牙刺、撂荒地、坡耕地
	富县（任家台）	~561	刺槐、油松、狼牙刺、坡耕地
	延安（燕沟）	~558	刺槐、沙棘、丁香
	延安（羊圈沟）	~535	刺槐、沙棘、撂荒地、坡耕地
	安塞（平桥镇）	~460	刺槐、沙棘、撂荒地、坡耕地 **
	安塞（纸坊沟）	~550	刺槐、柠条、撂荒地、坡耕地
	绥德（韭园沟）	~410	刺槐、油松、撂荒地、坡耕地
	神木（六道沟）	~430	刺槐、油松、柠条、撂荒地
山西样带	吉县（马连滩）	~522.8	刺槐、油松、黄刺玫、苹果园、耕地
	吕梁（王家沟）	~461.5	刺槐、柠条、撂荒地、坡耕地
	河曲（砖窑沟）	~447	刺槐、柠条、撂荒地、坡耕地

Dynamics of the mean soil moisture and temperature

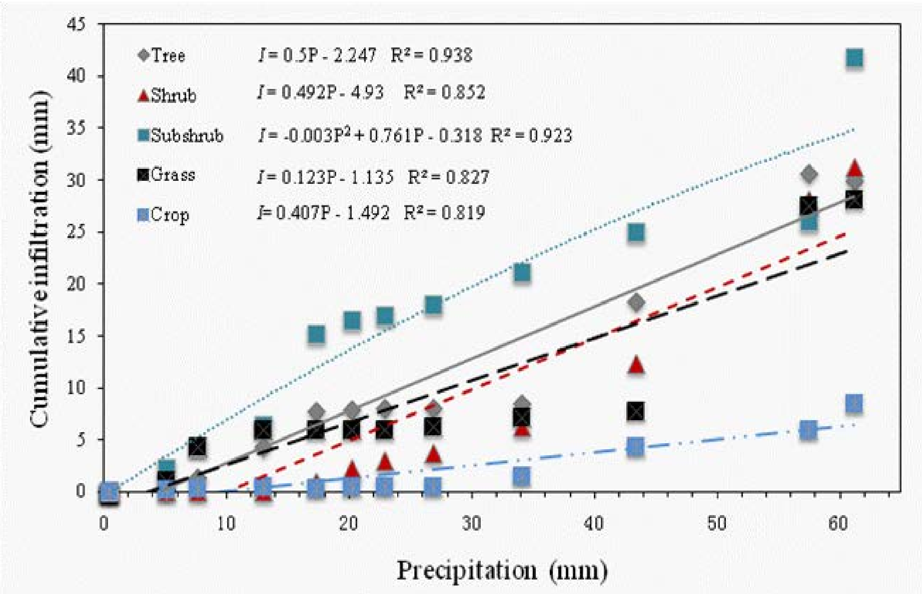


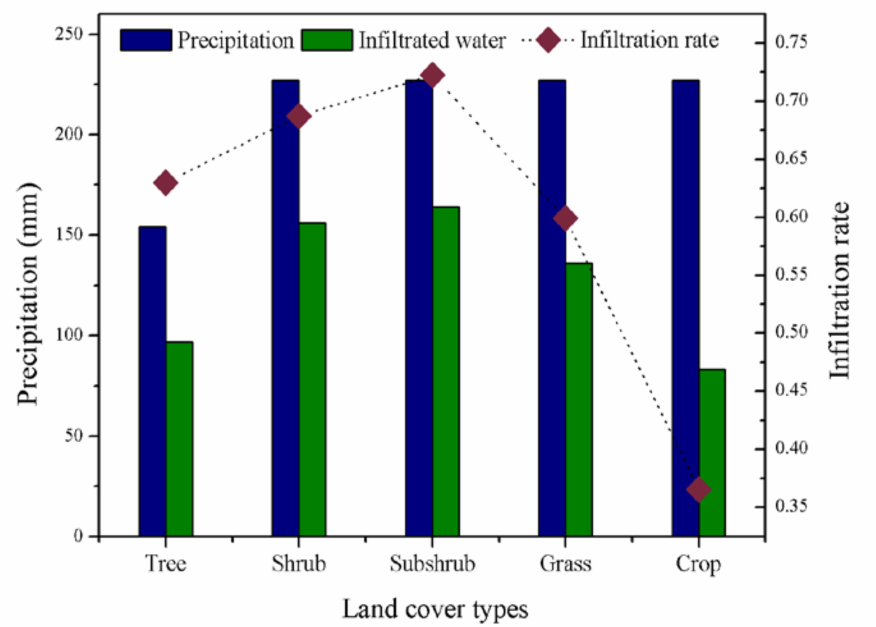


- The mean soil moisture can be ordered as crop>grass>subshrub>tree>shrub ;
- This relationship displayed time stability;
- Soil moisture increasing and temperature decreasing throughout the observation period .

Wang, Fu* et al, *Catena*, 2013

Precipitation and cumulative infiltration



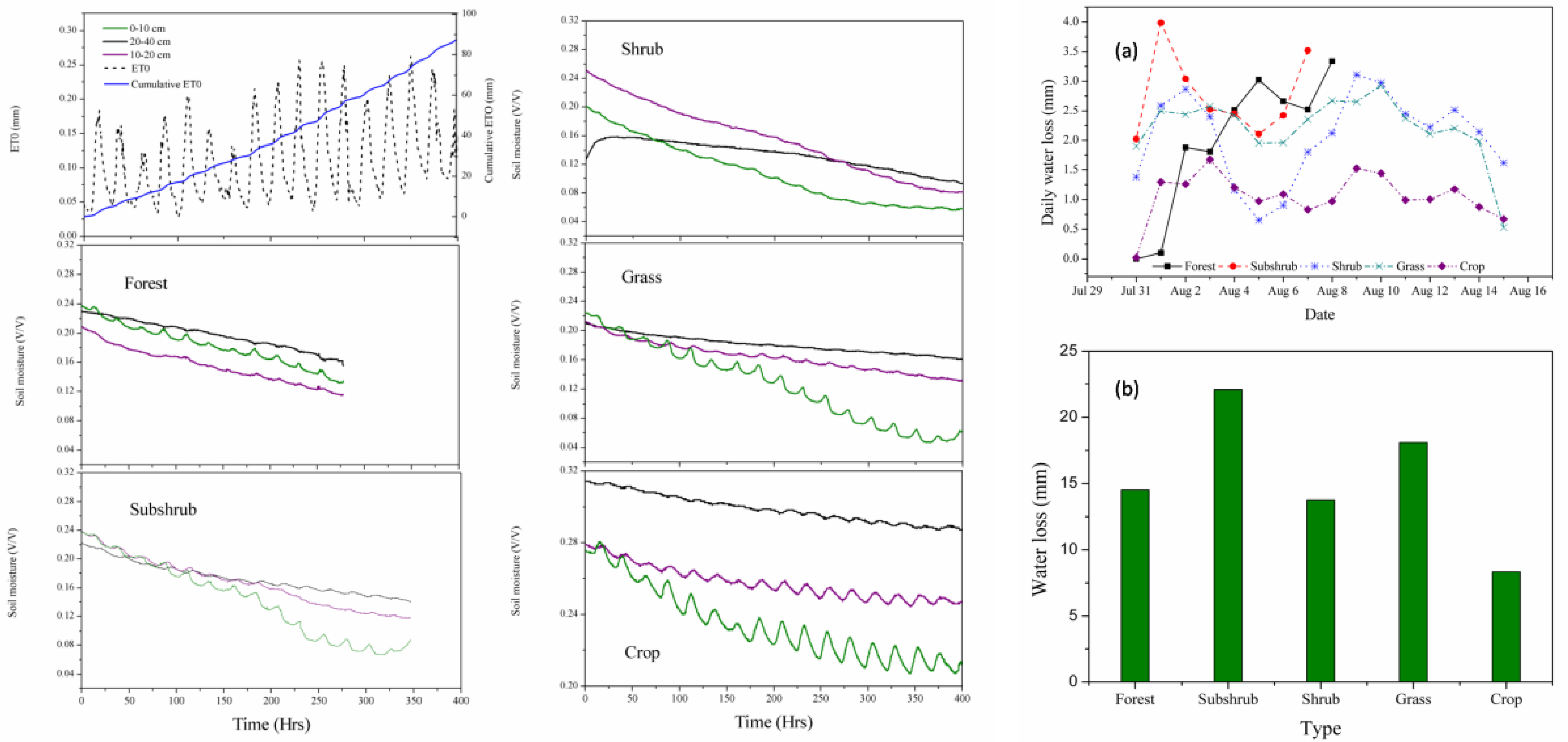


- Subshrub site showed the highest total infiltration rate, 72%;
- Followed by grass site, approximately69%;
- The tree site had an infiltration rate was approximately 64%;
- The shrub site had an infiltration rate was approximately 60%;
- The crop site had the lowest infiltration rate was approximately 37%.

Wang, Fu* et al, *Catena*, 2013

Soil moisture decrease process

Relative wet period



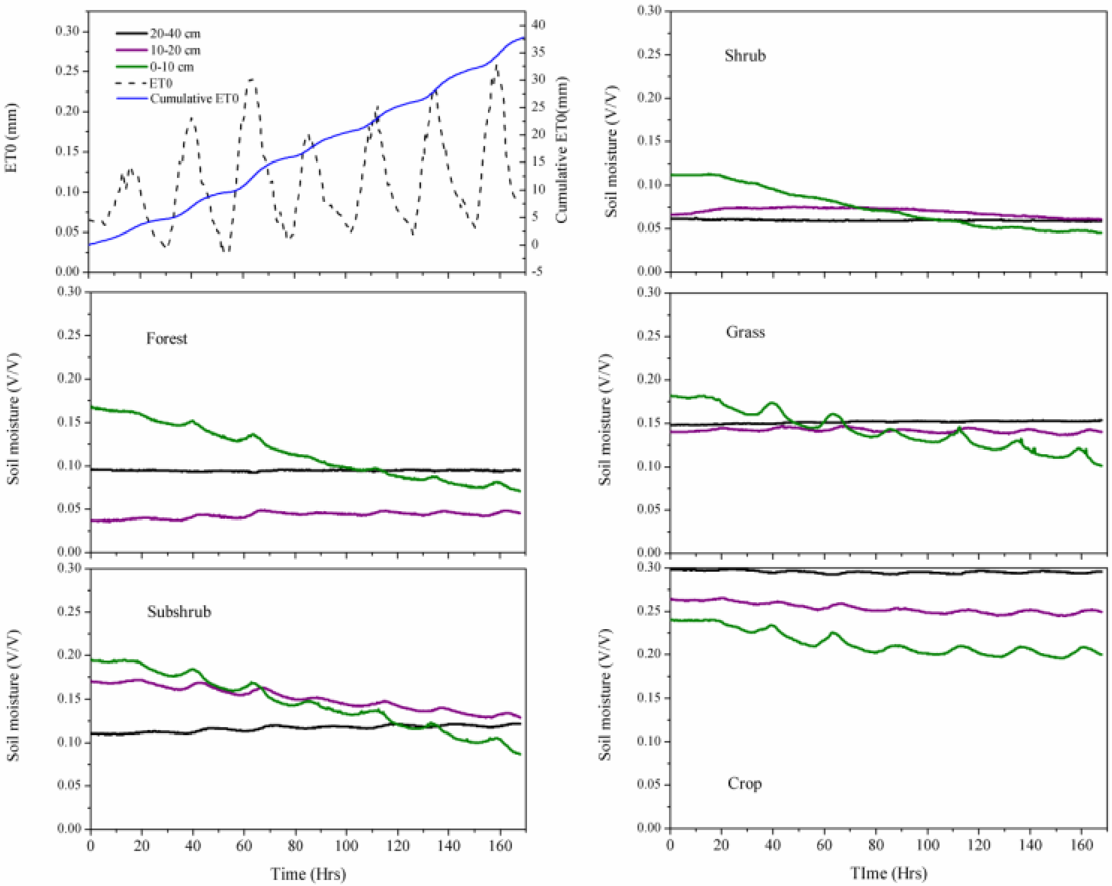
- Average daily water losses for subshrub and grass were 2.3 and 2.2mm;
- Corn showed the lowest average daily water loss of 1mm;
- The forest and shrub sites presented an intermediate level, 1.7 and 1.8mm.

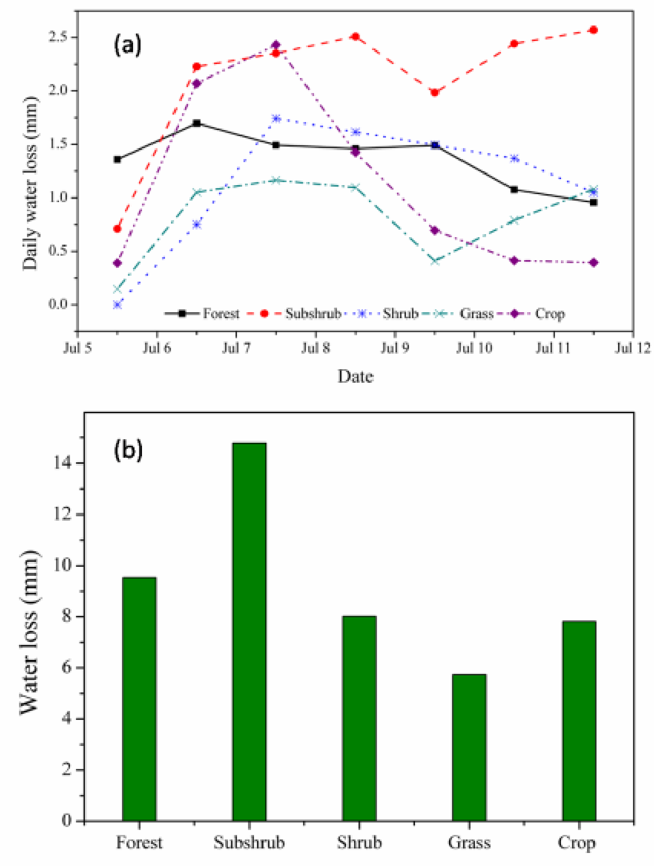
Wang, Fu* et al, *HESS*, 2012

Soil moisture decrease process

Relative dry period

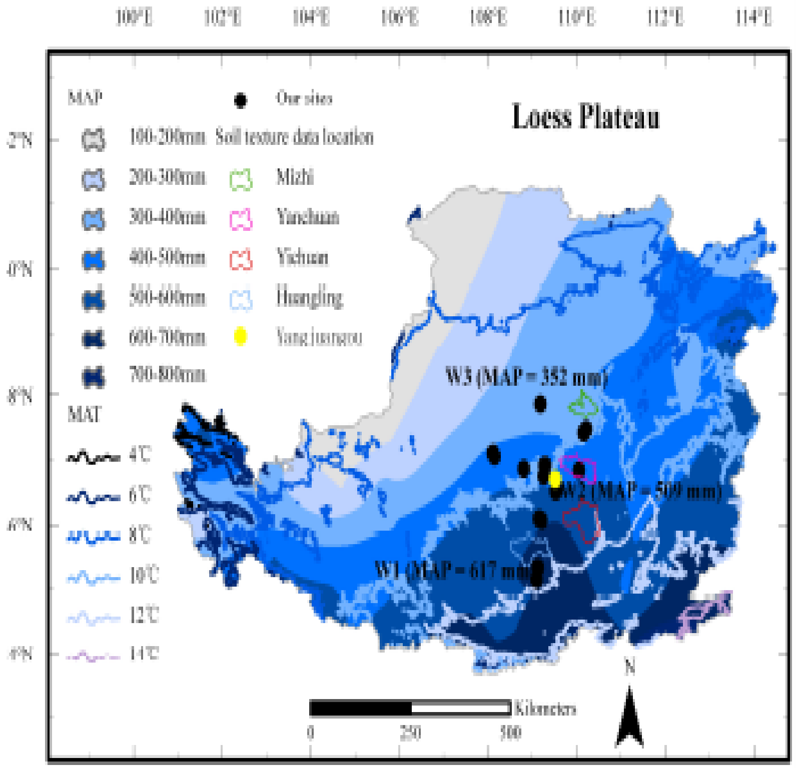
Wang, Fu et al, HESS, 2012

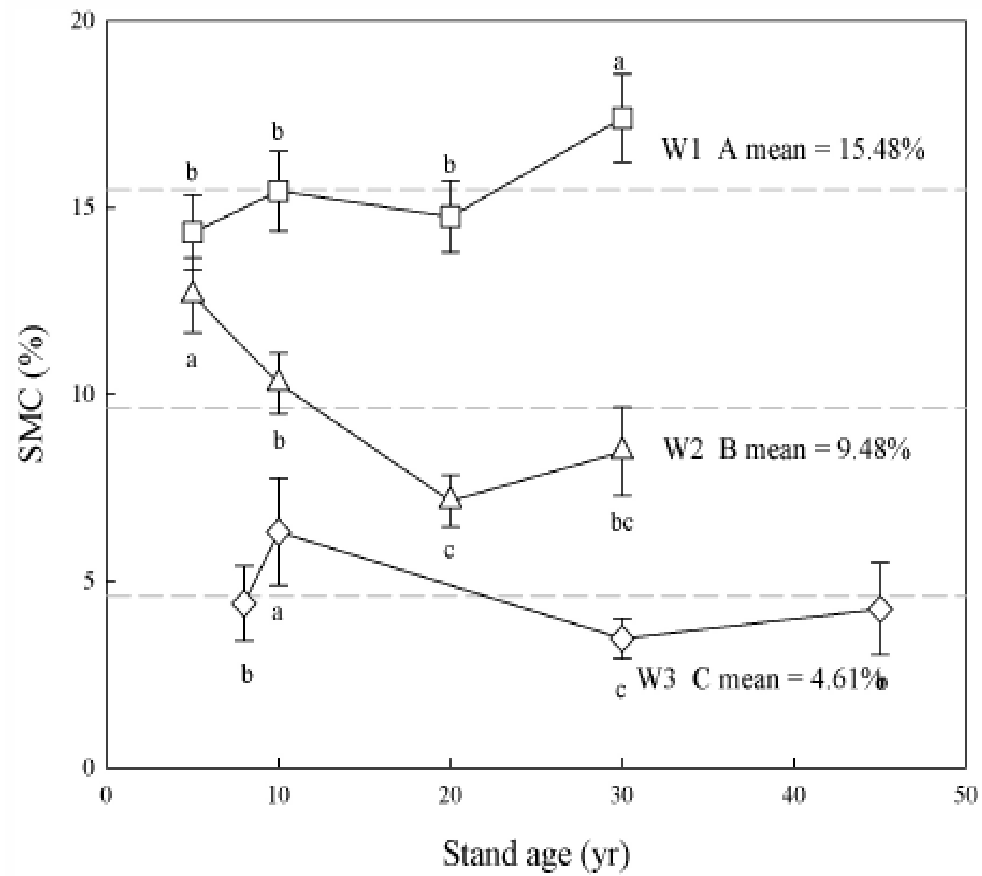




- The daily ET trends of the forests and shrub sites were similar and were more stable than those of the other types;
- The higher initial soil moisture content resulted greater post-rainfall water loss under subshrub and grass sites.

Soil Moisture Change

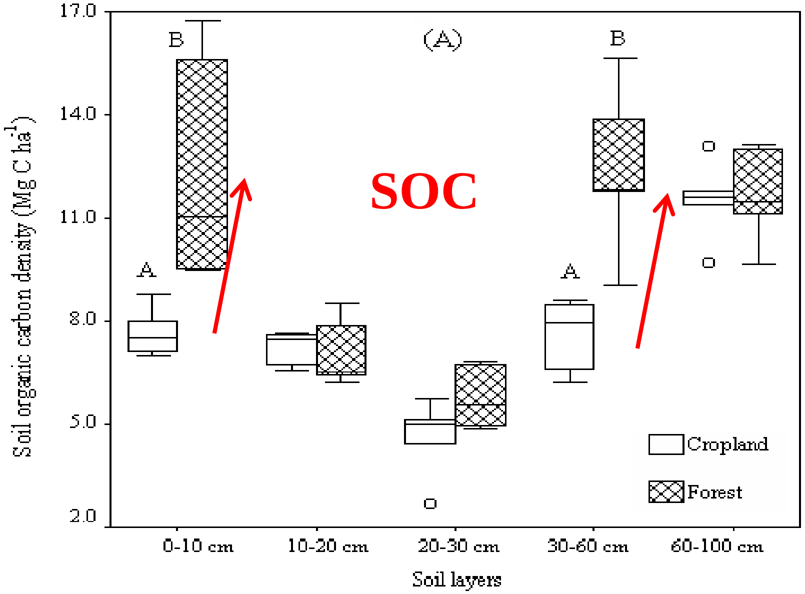


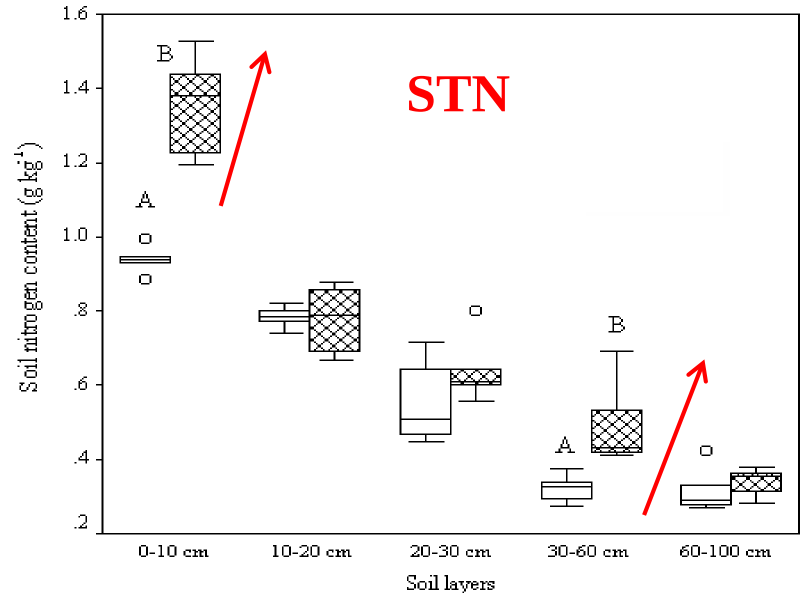


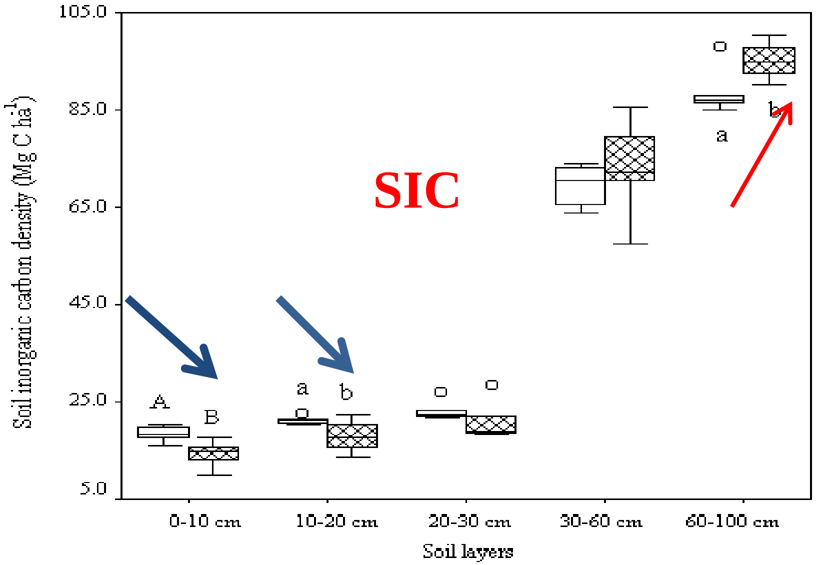
- **Soil moisture under black locust forestry**

Jin, Fu* et al, *HESS*, 2011

Soil C Sequestration

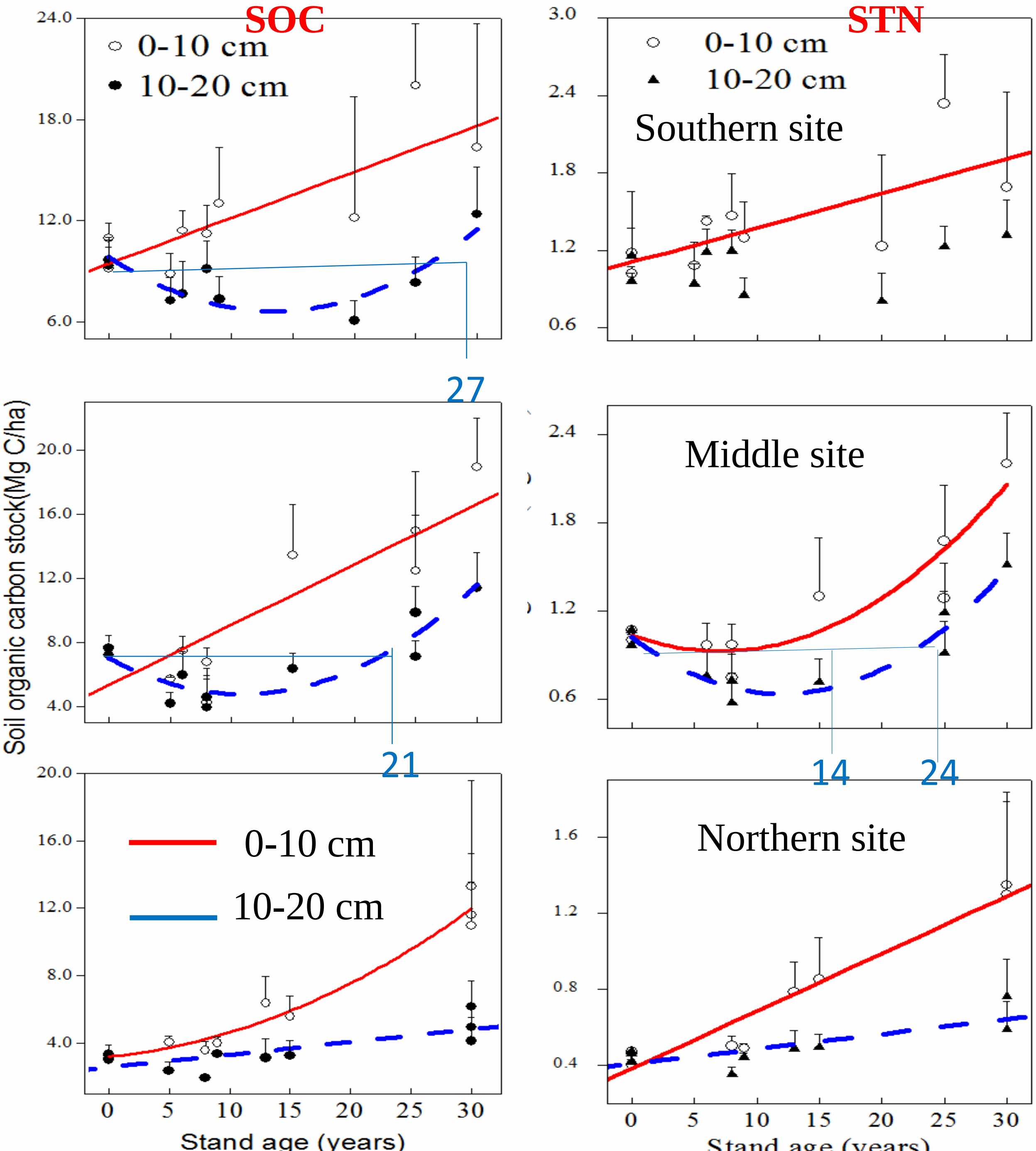






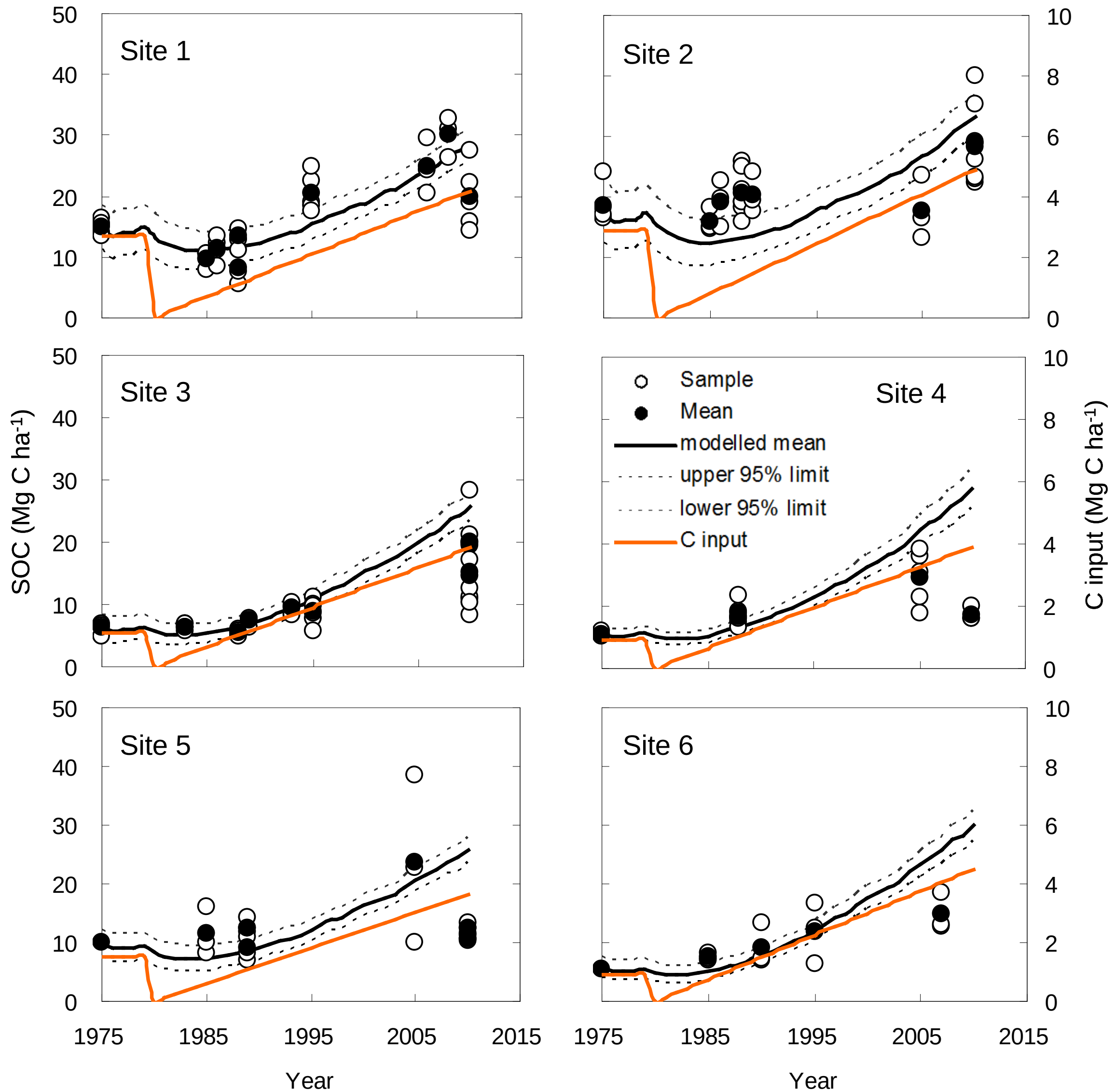
- **Soil can accumulate OC in both topsoil and subsoil in relative short time after afforestation.**
- **Soil N content in the top/subsoil changed in synchronicity with SOC during afforestation.**
- **Afforestation redistributed SIC along soil depth without affecting SIC pool.**

Chang, Fu* et al, Catena, 2012



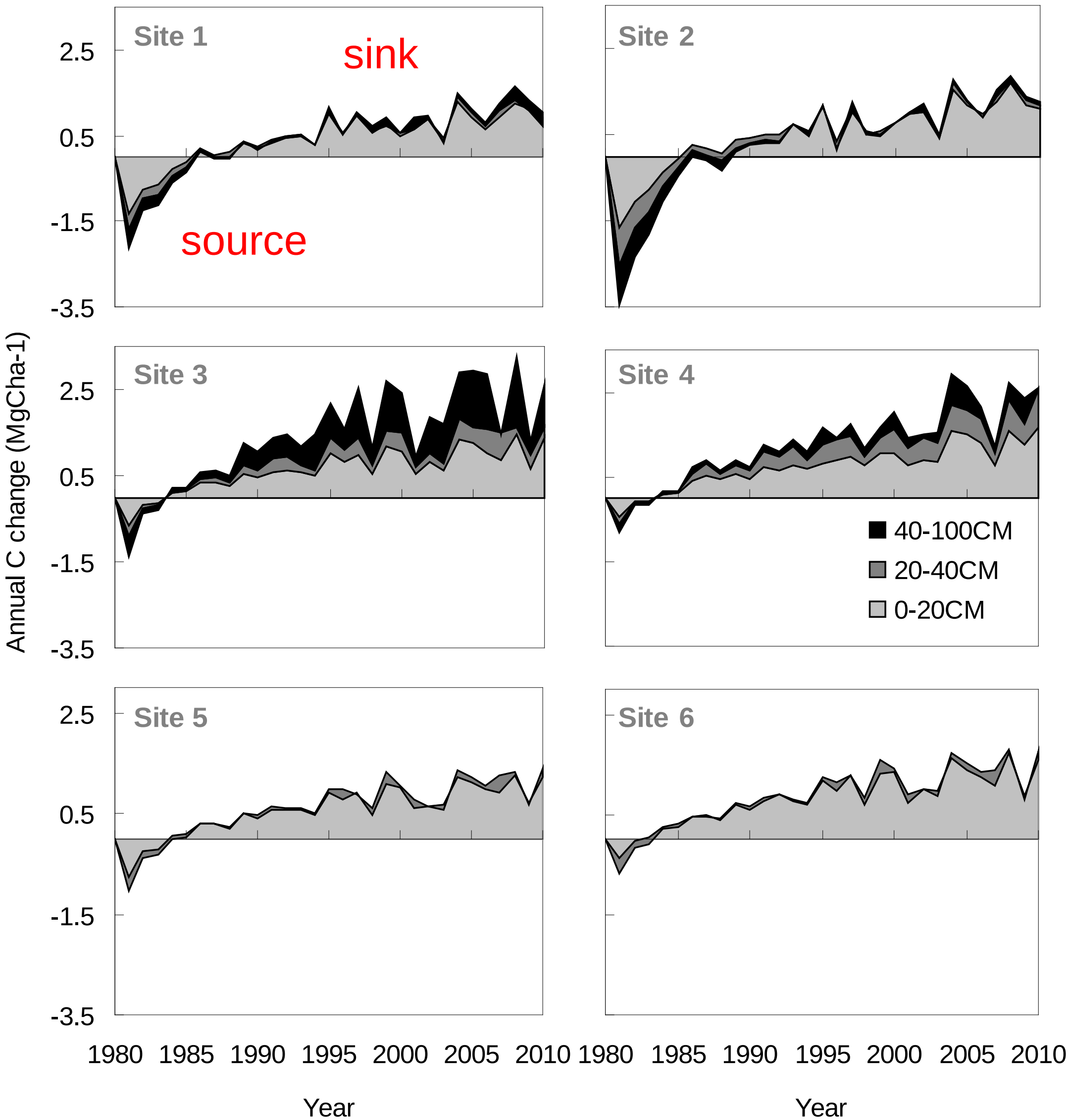
- **Strong evidence to support that the initial decline in SOC and STN occurred in subsurface soil layers after afforestation of fertile cropland, but neither in the uppermost layer nor in the infertile cropland .**

Lu et al, *Biogeosciences*, 2013



SOC dynamics from 1975-2010 (0-20 cm soil depth)

- ✓In general, the modeled SOC fit well with the measurements.
- ✓The SOC dynamics was mainly following that of litter input.
- ✓SOC decreased in the first a few years and then increased.



Simulated SOC Change from 1980 to 2010

✓ The soils turned from C sources to C sinks after about 3-8 years of afforestation.

✓ The changes of SOC in the 0-20 cm contributed the highest proportion to the total changes in the 0-100 cm of soil depth.

Multiple Ecosystem Services of Plantations

Storage of soil organic carbon (SOC)

Storage of soil total nitrogen (STN)

Soil water storage (SWC)

Aboveground biomass (AGB)

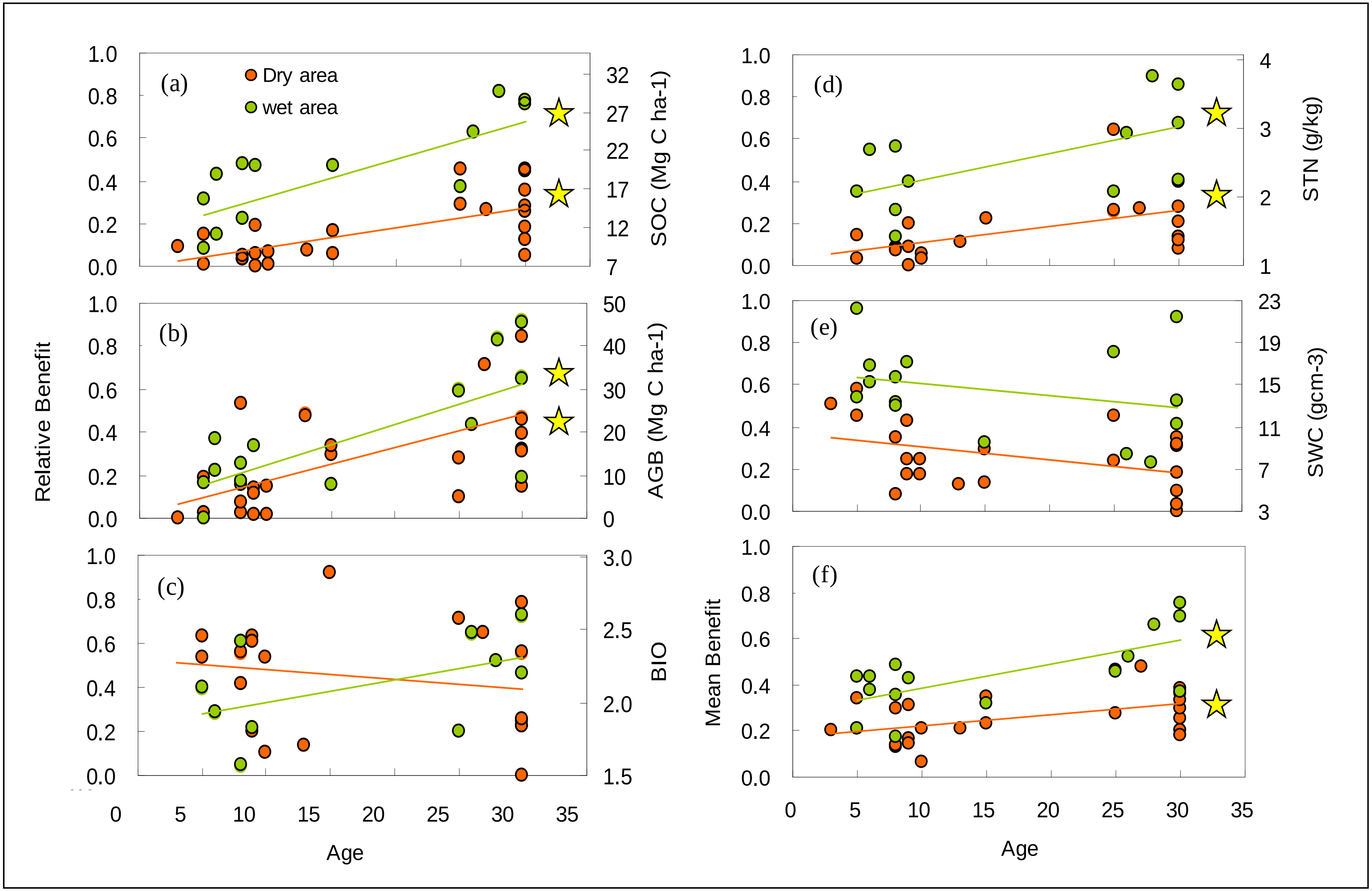
Erosion control

Runoff

Understory vegetation diversity (BIO)

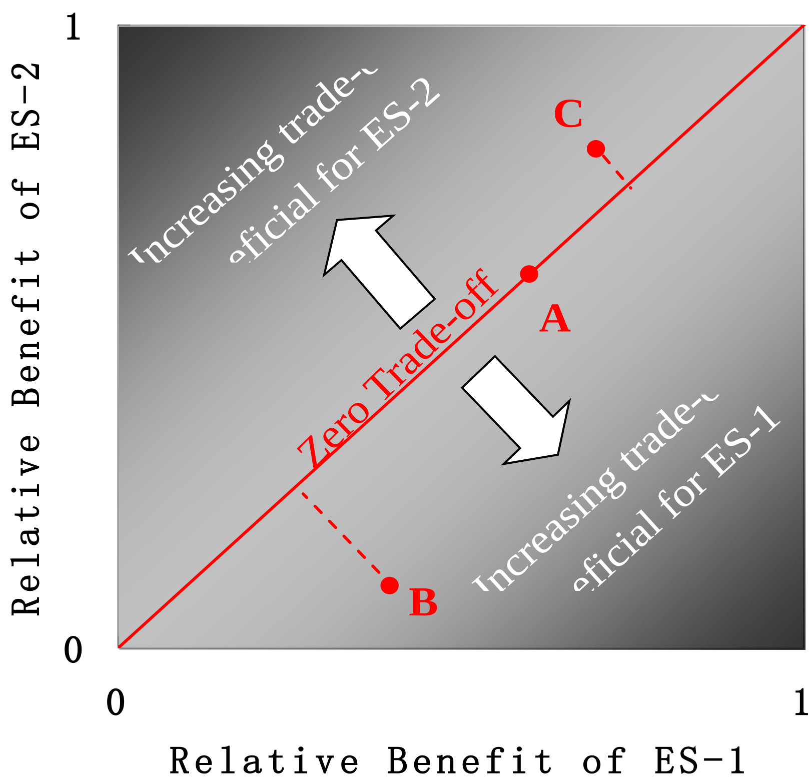
Others

Temporal Changes of ESs



Lu and Fu*et al, *Landscape Ecology*, 2014

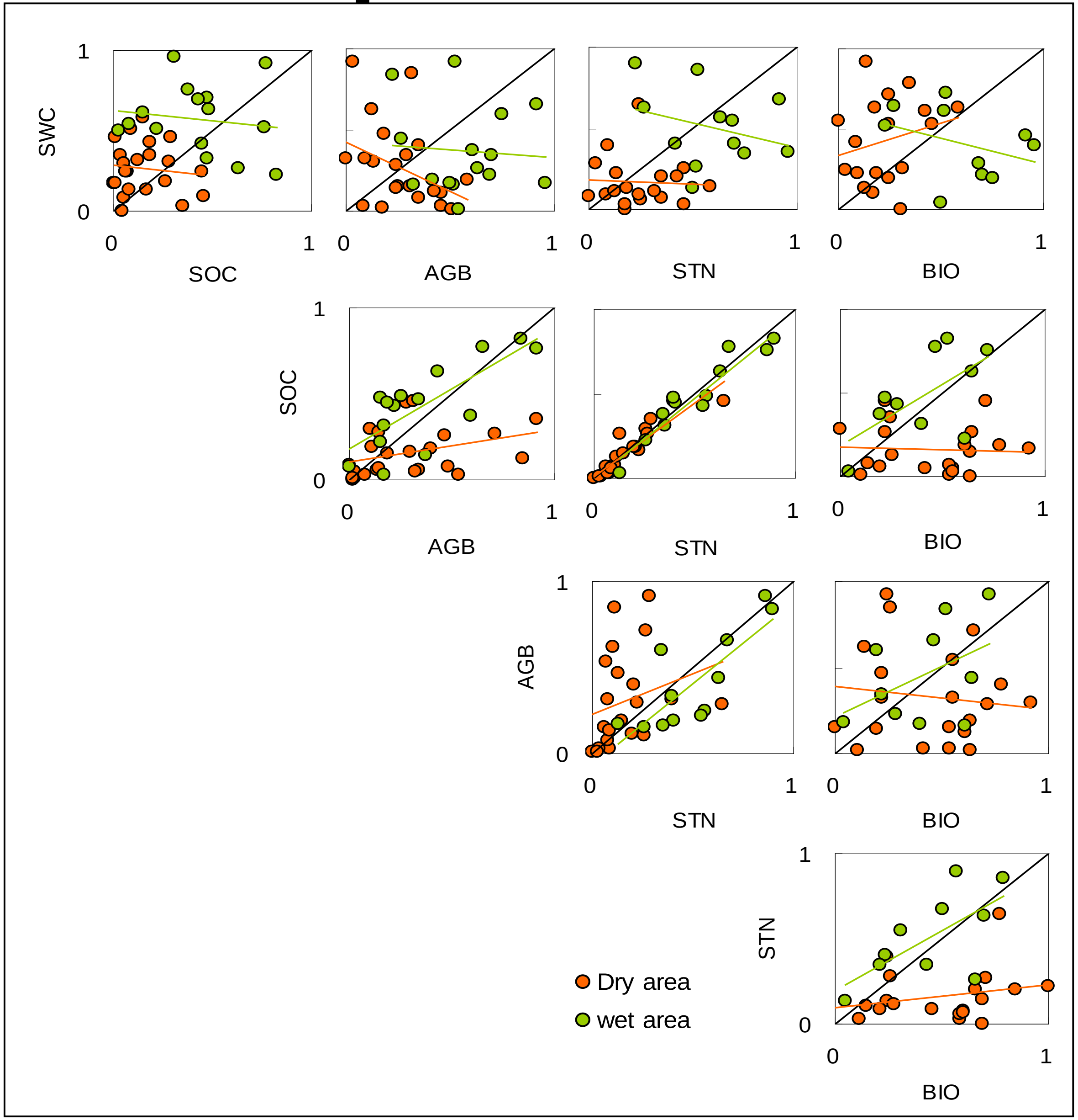
A Method to Quantify the Trade-offs among ESs



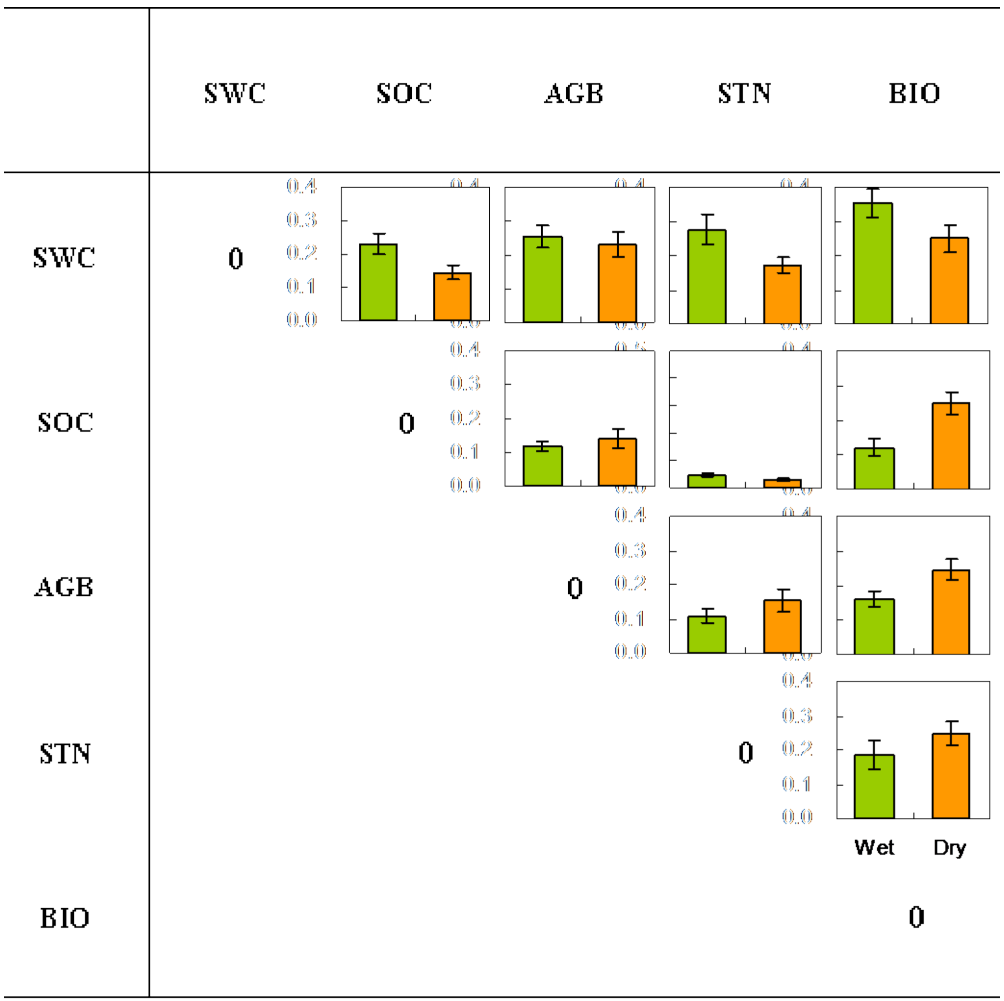
A diagram of trade-off between two ESs. The figure is modified from Bradford and D’ Amato (2012)

- Data standardization, scale from 0-1.
- Calculating root mean squared error (RMSE) between two or more ESs.
- RMSE represents the distance from the coordinate from a pair of ESs to the 1:1 line (in two dimesion), where the two ESs are equal (trade-off = 0).
- Trade-off: B>C>A

Relationship between ESs



Trade-off plots of paired ESs – Quantitative Measures



- The trade-offs between SWC and other ESs were relatively large.
- The trade-offs between BIO and other ESs were relatively large.
- The trade-off was largest between SWC & BIO, and smallest between SOC & STN.
- The SWC-related trade-offs were larger under wet conditions . But others were larger under dry conditions.

Y-axis represents trade-off value (RMSE), scale: 0–0.4

Trade off of ES in regional scale

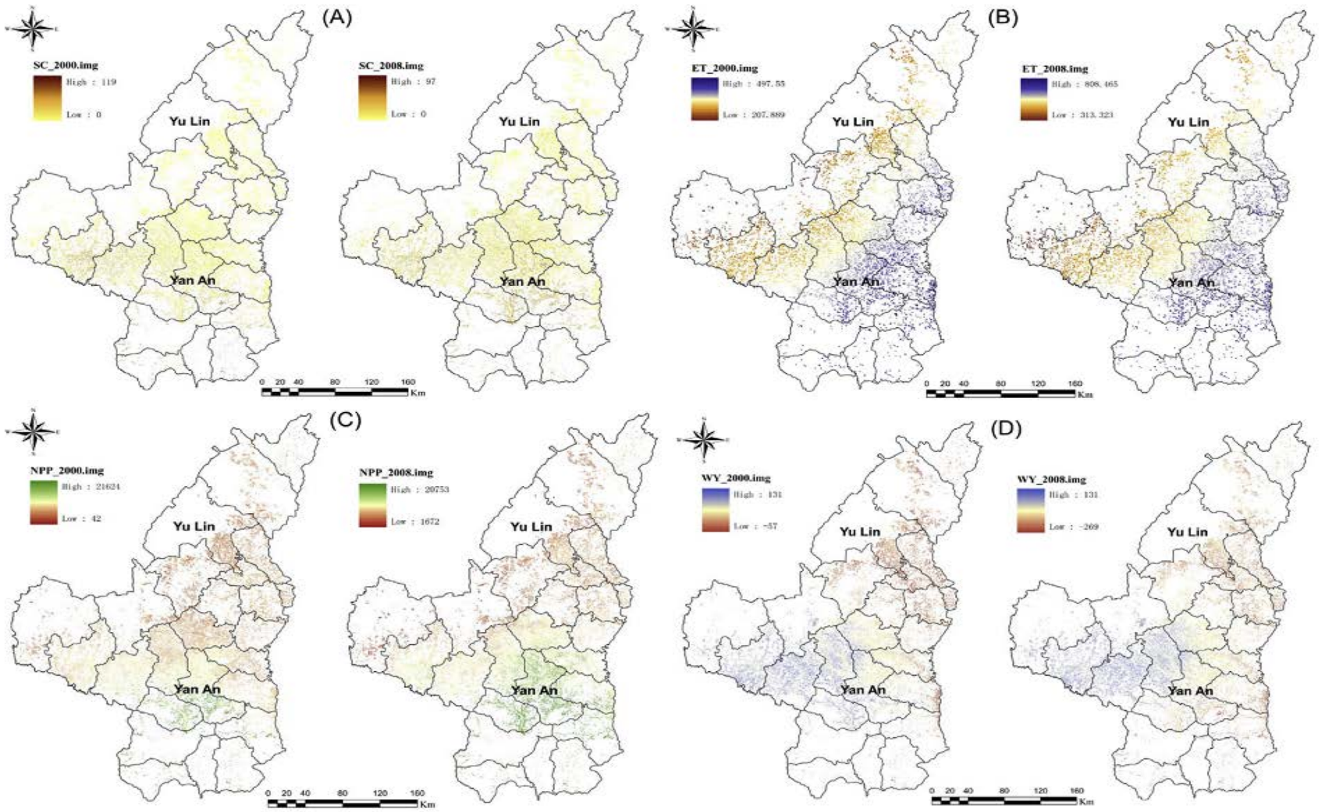
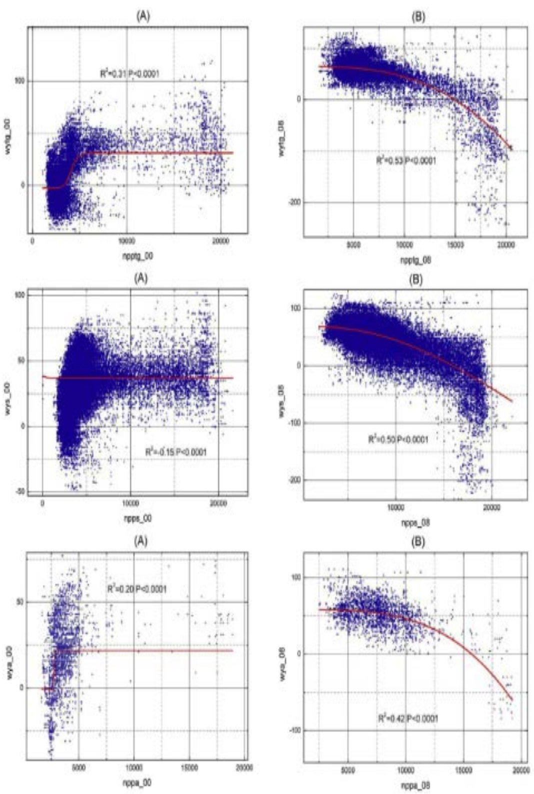


Fig. 2. Maps of ecosystem services in the GFGP plots with resolution of 90 m. (A) Soil conservation service supply (t km^{-2} a^{-1}). (B) The amount of evapotranspiration (mm). (C) Net primary productivity (g carbon m^{-2} $month^{-1}$) to regulate climate and gas. (D) The volume of water yield (mm).

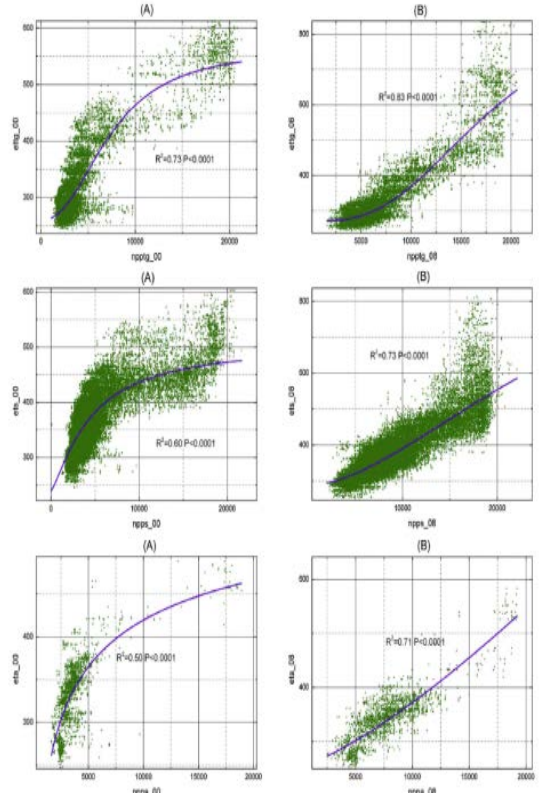
ES Mapping

Jia and Fu* et al, *Ecological Indicators*, 2014

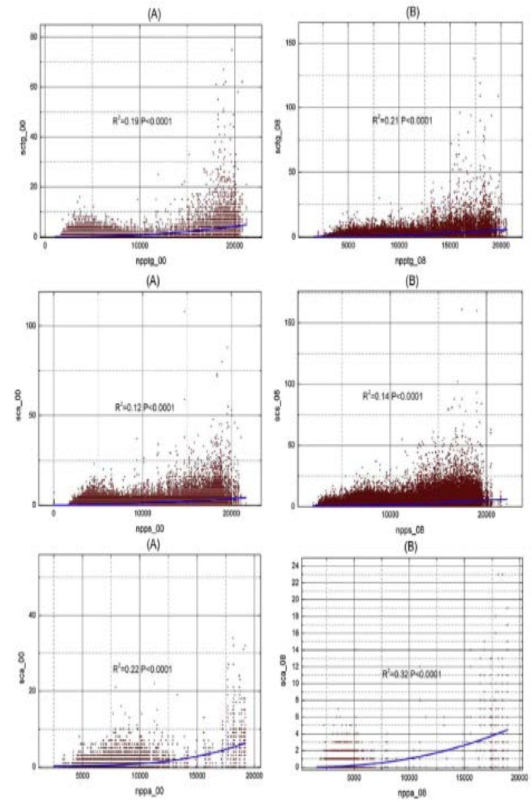
Trade off of ES in regional scale



NPP and water yield



NPP and water regulation



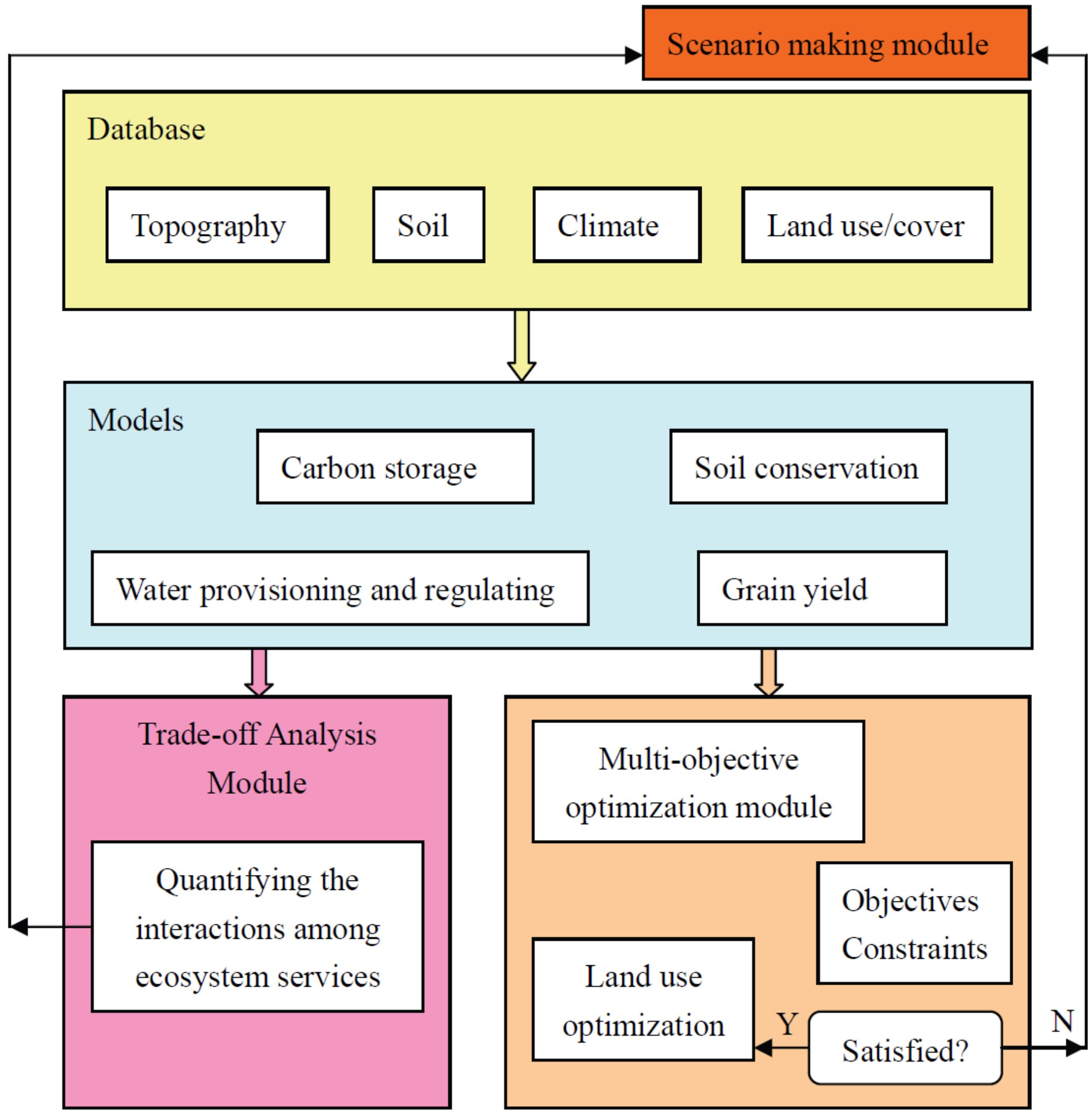
NPP and soil sonservation

Jia and Fu et al, Ecological Indicators, 2014*

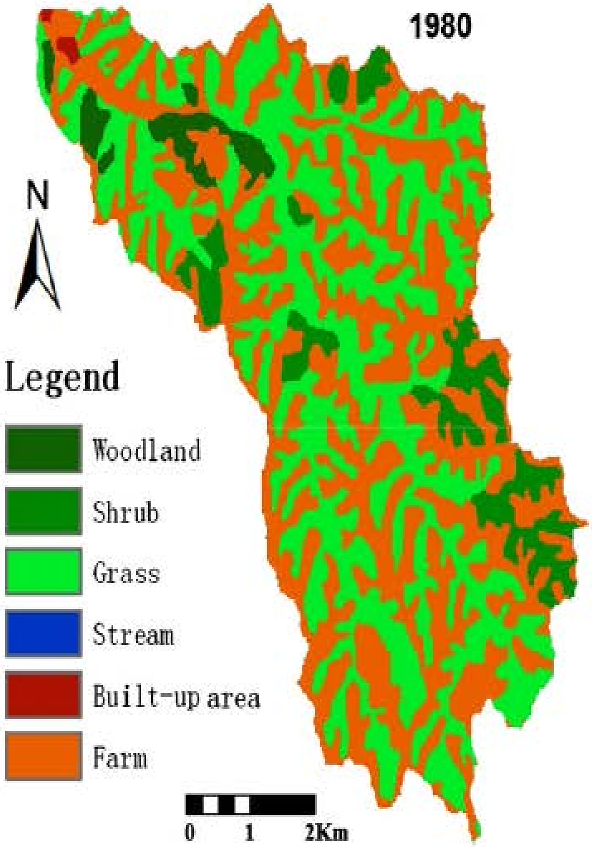
Integrated ES Modeling System

Based on landscape pattern and ecosystem service relations, ES scaling and spatial heterogeneity, we developed an integrated regional ES assessment and modeling system

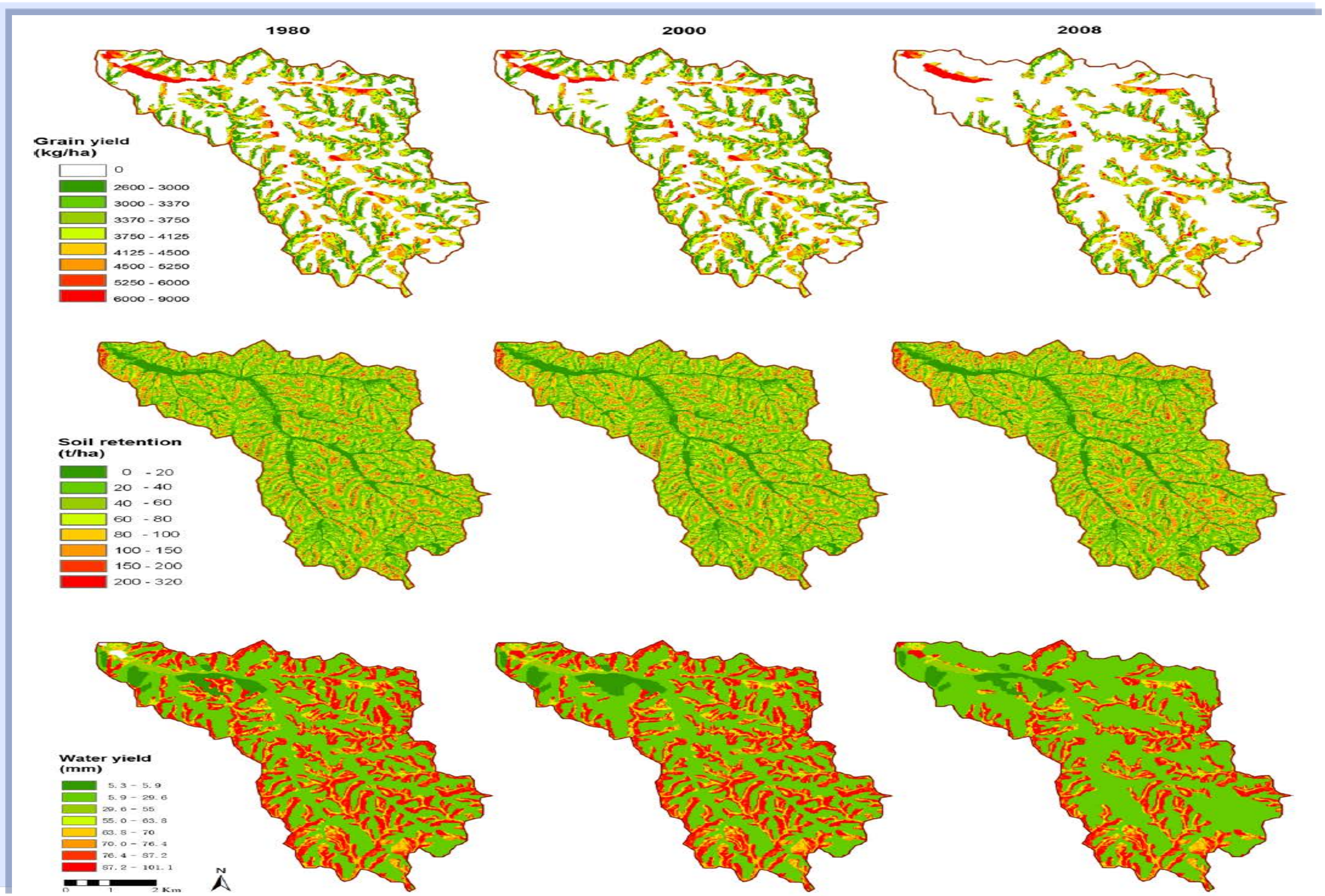
Hu, Fu* et al, *Landscape Ecology* 2015



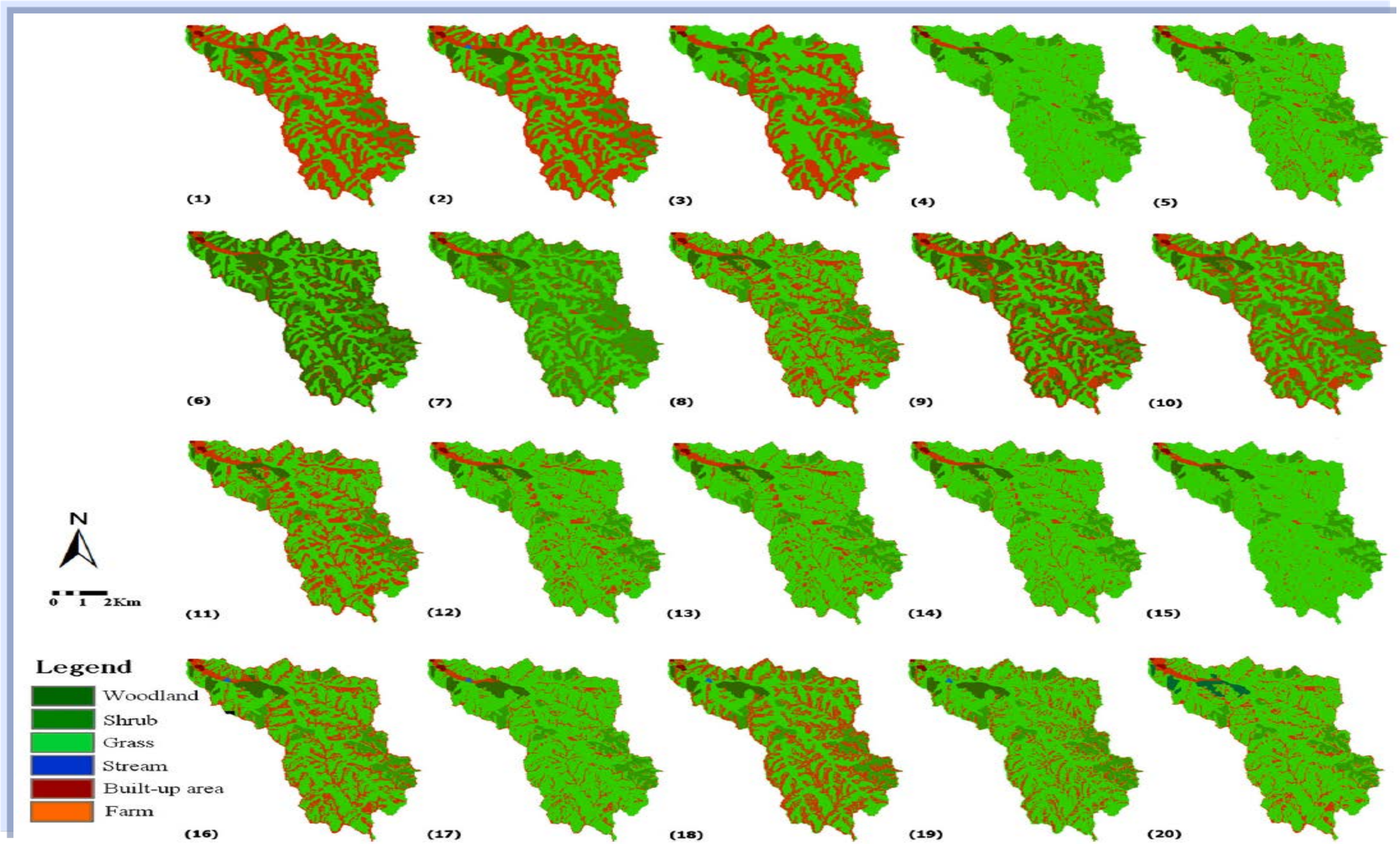
Land use change



Ecosystem services change



Scenarios analysis



One of the optimized solutions

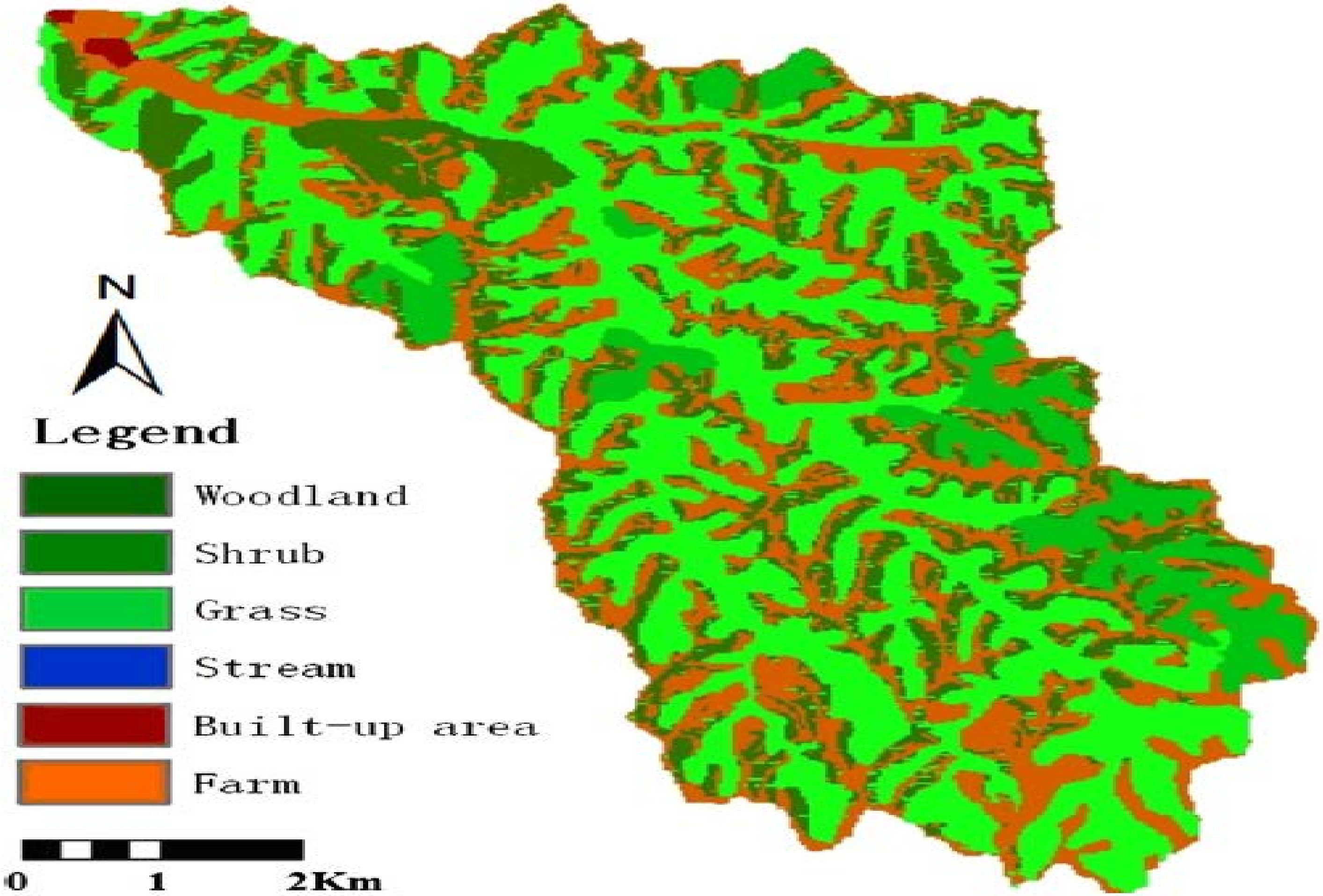
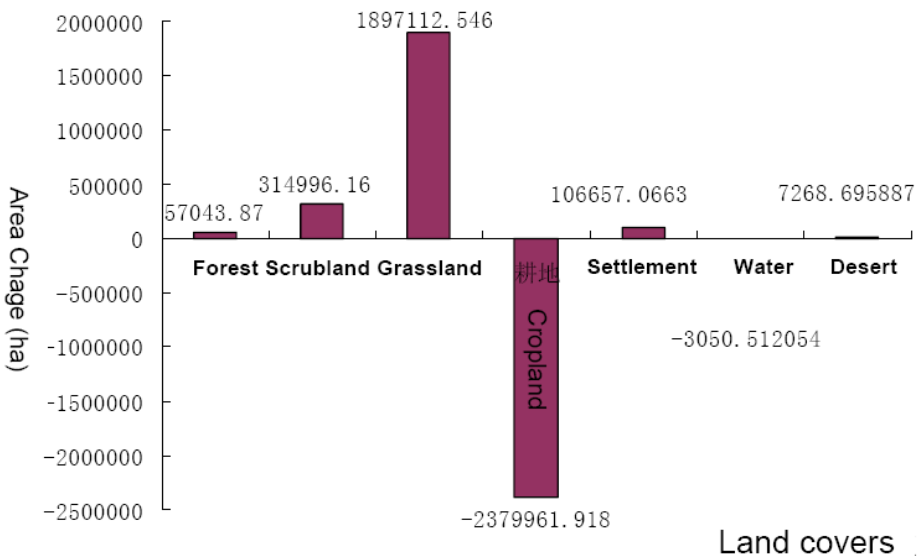
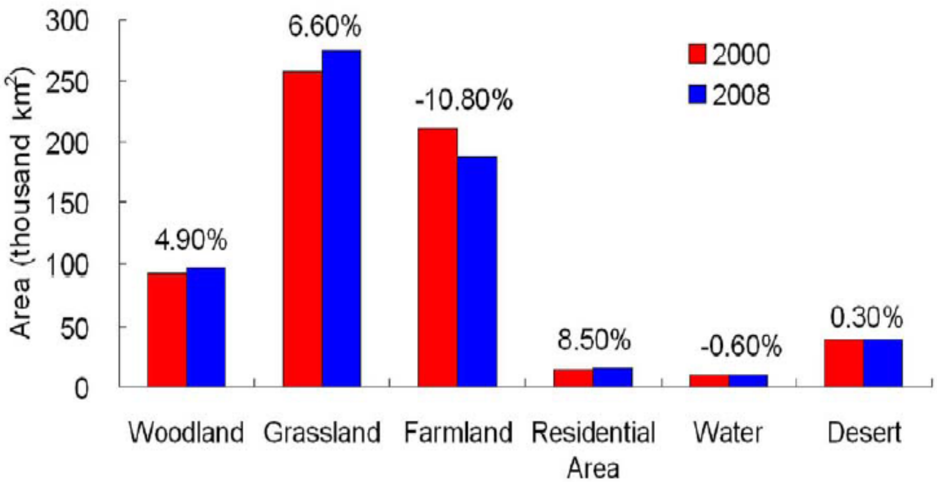
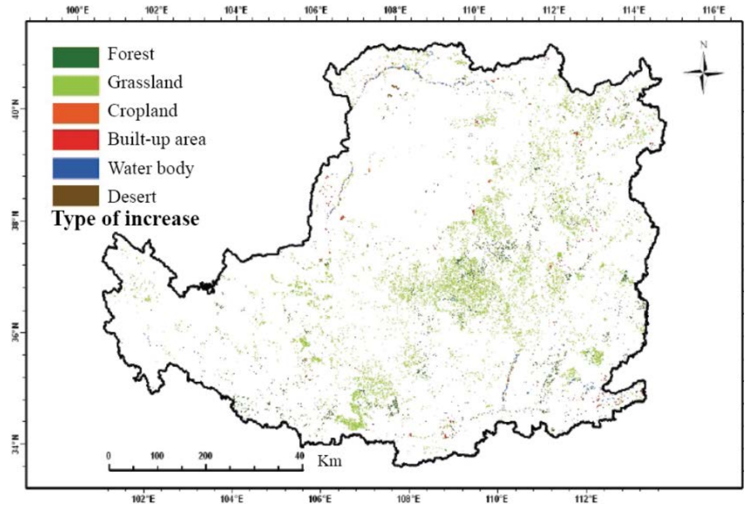


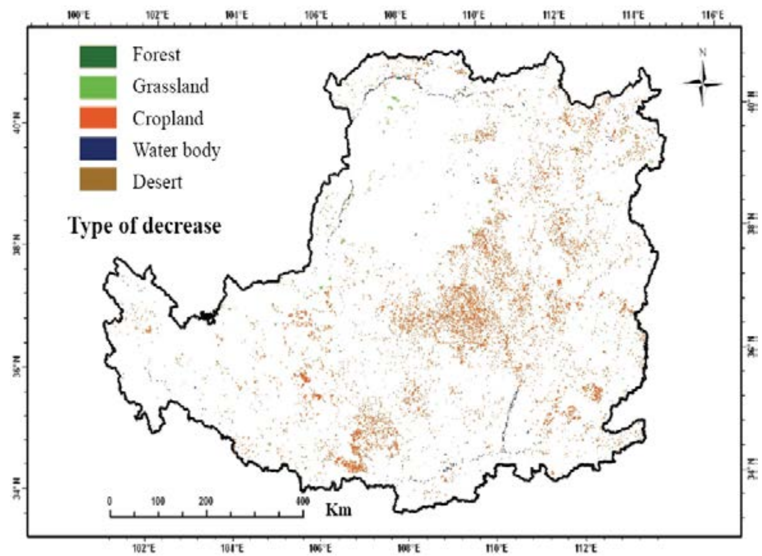
Fig. 8 Land use map for one of the optimized solutions

Land cover change 2000-2008









Lu, Fu* et al, *PlosOne*, 2012

Water Yield

A General Monthly Arid-Semiarid Evapotranspiration Model

ET = k1 +k2* PET*PPT+K3* PET*LAI + K4*PPT *LAI

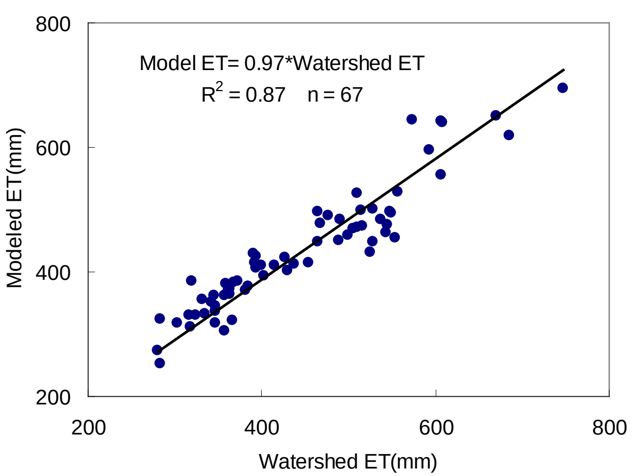
R^2 =0.82

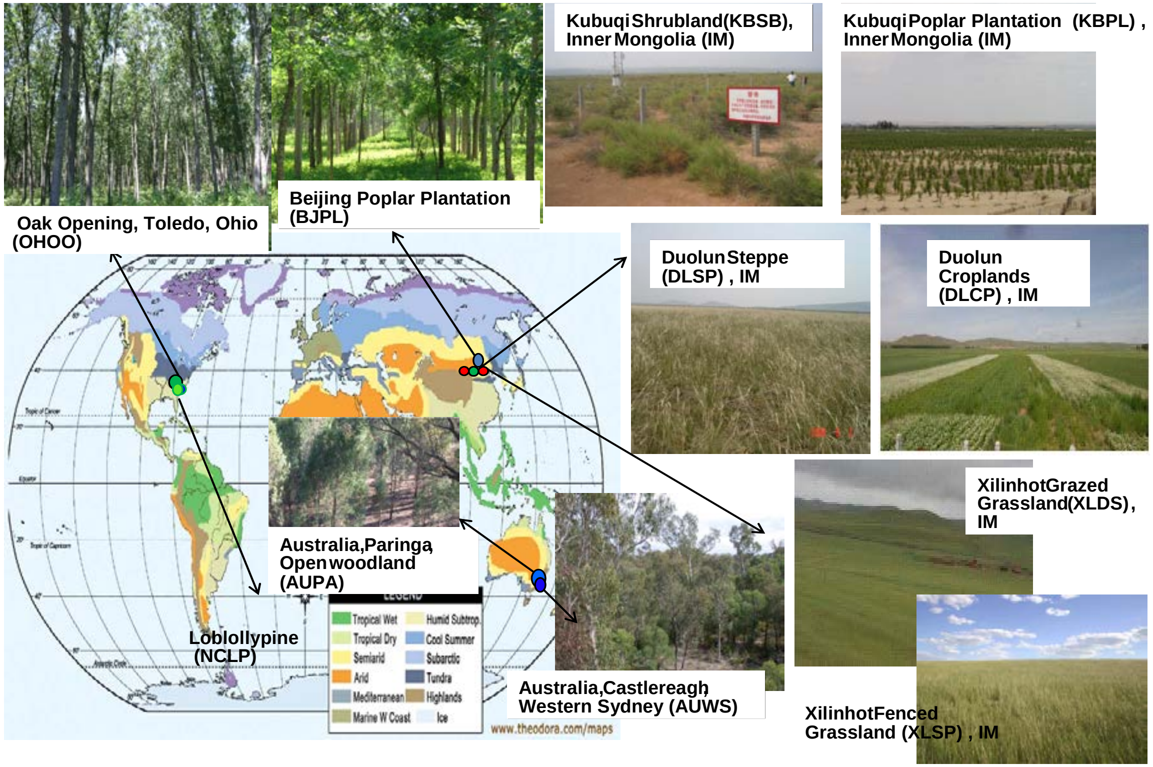
RMSE =15mm

PET*PPT:70.5%

PET*LAI:4.0%

PPT*LAI:7.3%

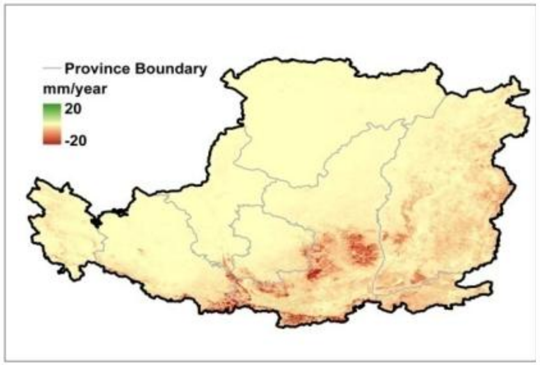




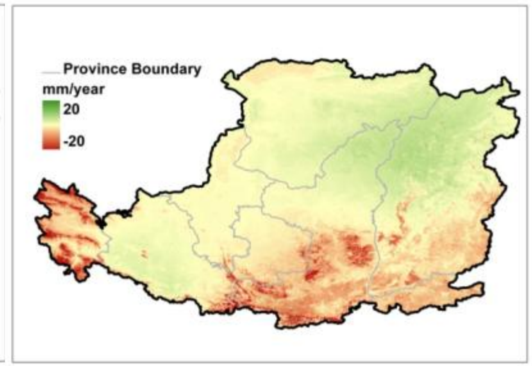
Feng et al, *HESS*, 2012

Water Yield

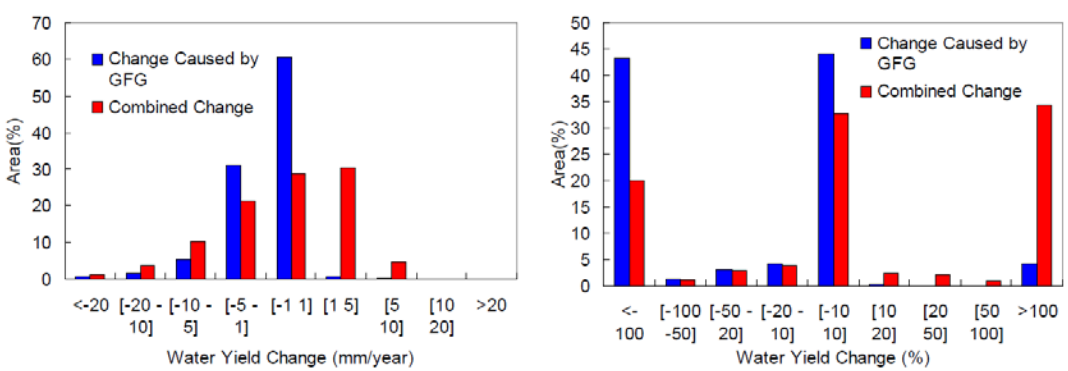
Spatial and temporal variability of water yield and the driving forces



Effects of land cover change only



Effects of land cover change + climate variability



Temporal variability of water yield

- **Due to ecological restoration, about 38% of the study region experienced a decrease in water yield during 2000-2008 within a range of 1–48 mm per year.**
- **Due to the combined water yield responses to ecological restoration and climate variability, about 37% of the study area saw a decrease in water yield within a range of 1–54 mm per year. About 35% of the study areas have experienced an increase in water yield with a range of 1-10 mm per year**
- **Mean annual water yield across the region decreased during 2000-2008 except in 2000 and 2001 when a slight increase in water yield. The restored ecosystems appeared to be stabilized three years after the implementation of the GFG project.**

Feng et al, *HESS*, 2012

Soil Conservation

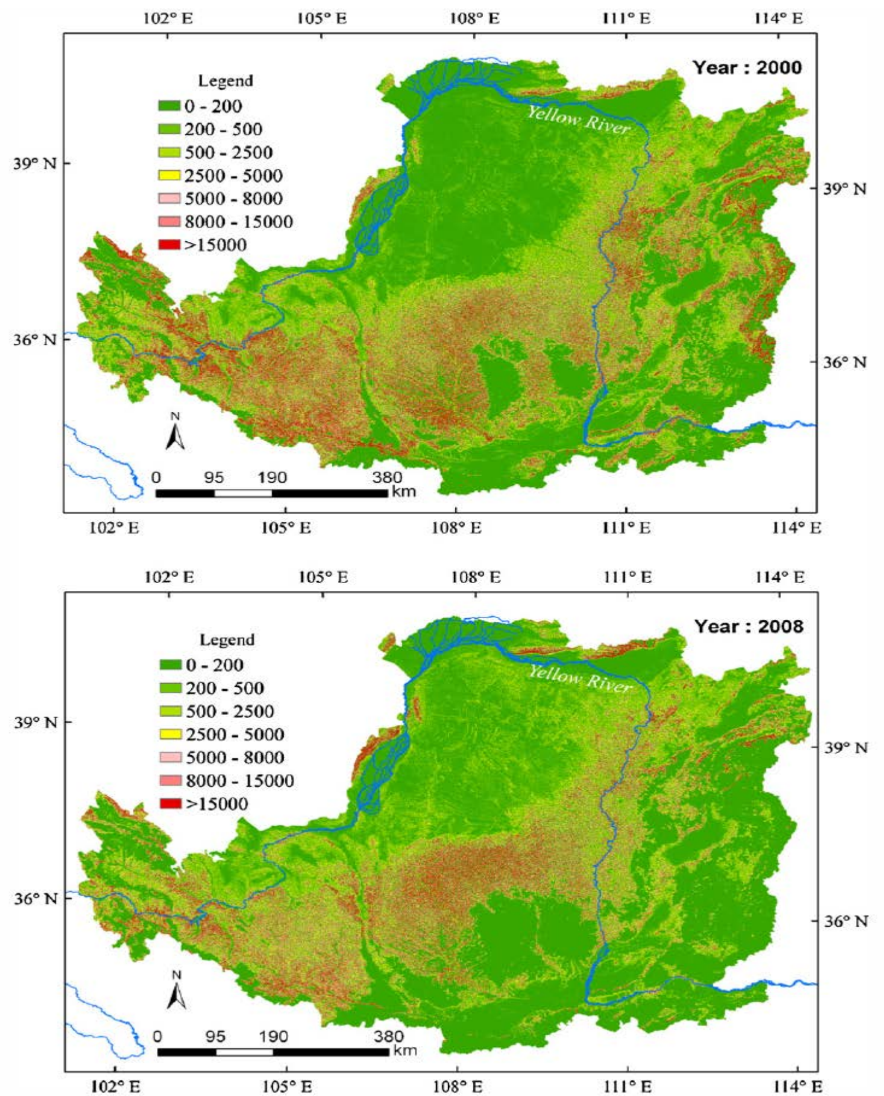
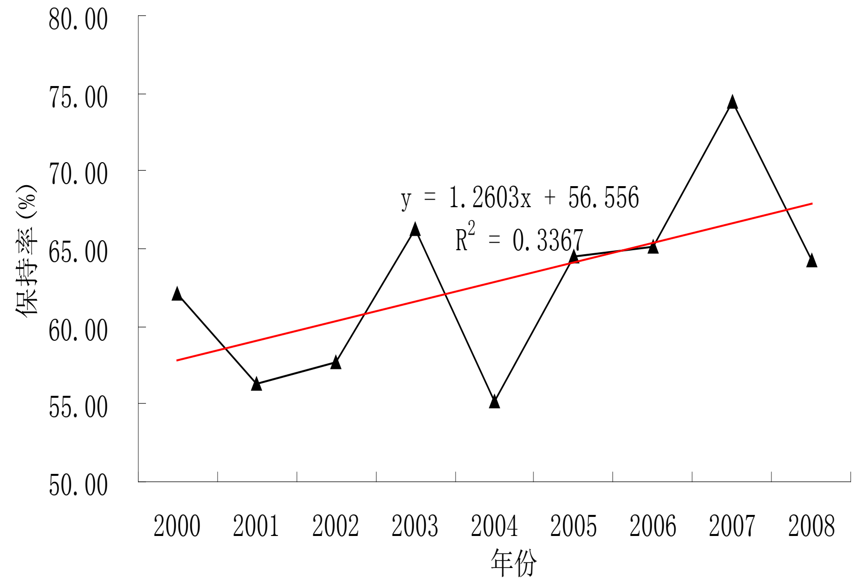


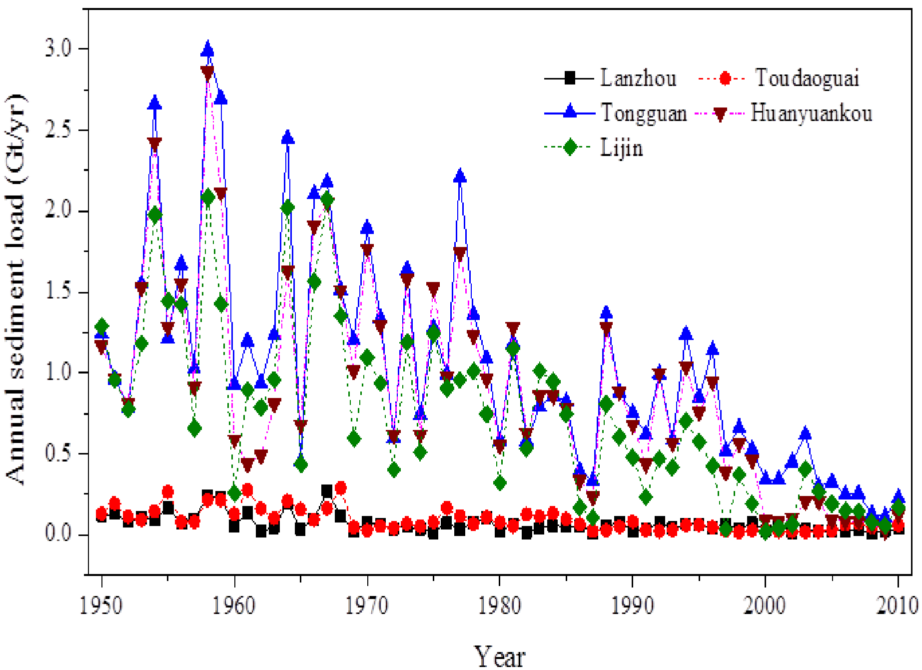
Fig. 5. Spatial distribution of estimated soil loss (t km^{-2} yr^{-1}) in 2000 and 2008.

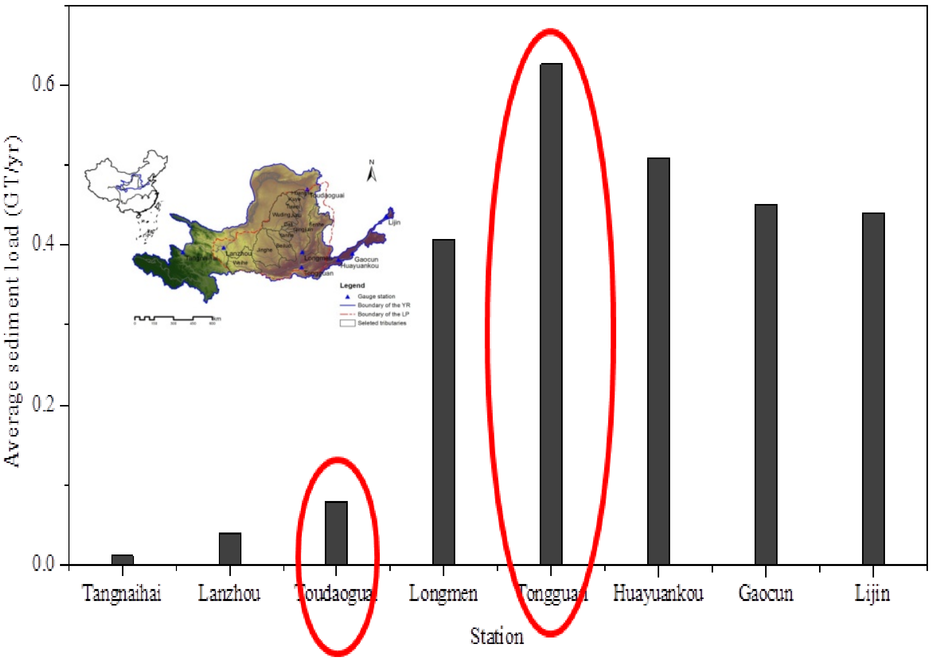


- Average retention rate is 63.3%
- During 2000-2008, the soil retention amounted to 0.15 billion tons annually

Fu et. al, *Ecological Complexity,* 2011

Dynamics of runoff and sediment





- Sediment delivery of the Yellow River decreased significantly decreased by 81% in the last 60 yrs to about 0.3 billion tons annually

Wang, Fu et al, 2016, Nature Geoscience*

Developed attribution method for ecosystem service change

LETTERS
PUBLISHED ONLINE: 30 NOVEMBER 2015 | DOI: 10.1038/NGEO2602
nature geoscience

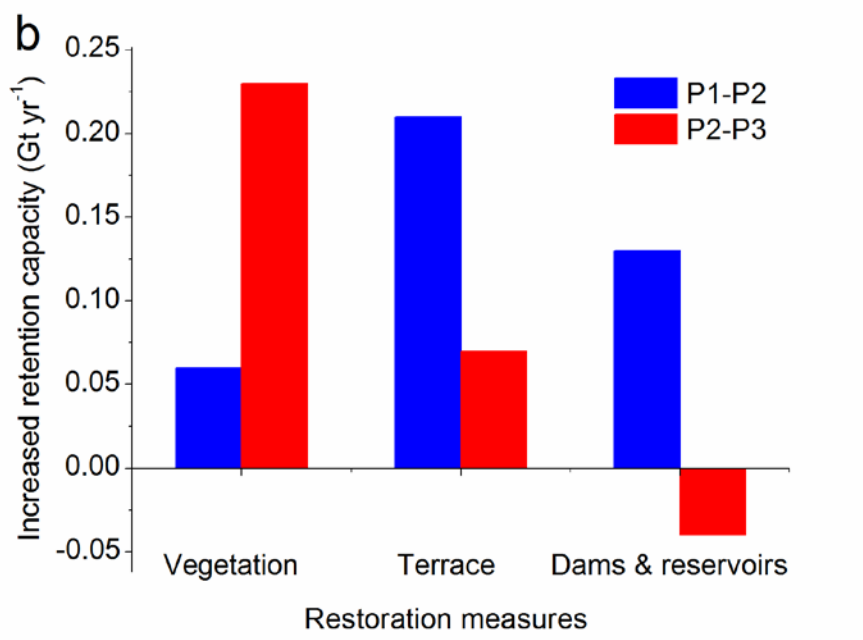
Reduced sediment transport in the Yellow River due to anthropogenic changes

Shuai Wang[1,2], Bojie Fu[1,2*], Shilong Piao[3,4], Yihe Lü[1,2], Philippe Ciais[5], Xiaoming Feng[1,2] and Yafeng Wang[1,2]

$$S=P\left(\frac{R}{P}\right)\left(\frac{S}{R}\right)=Prs \quad (1)$$

We then define the proportional change rate of a quantity $X(t)$ as $r(X)=X^{-1}\mathrm{d}X/\mathrm{d}t$. Because $((\mathrm{d}S/\mathrm{d}t)/S)=((\mathrm{d}(Prs)/\mathrm{d}t)/Prs)=((\mathrm{d}P/\mathrm{d}t)/P)+((\mathrm{d}r/\mathrm{d}t)/r)+((\mathrm{d}s/\mathrm{d}t)/s)$, the counterpart of the sediment identity for proportional change rates can be rewritten as

$$r(S)=r(P)+r(r)+r(s) \quad (2)$$

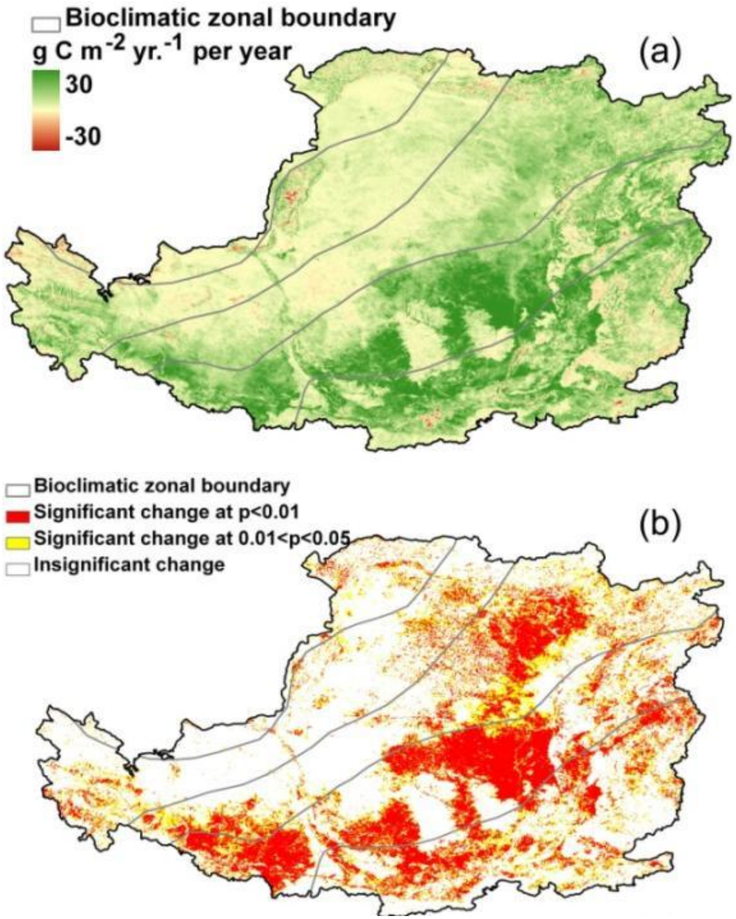


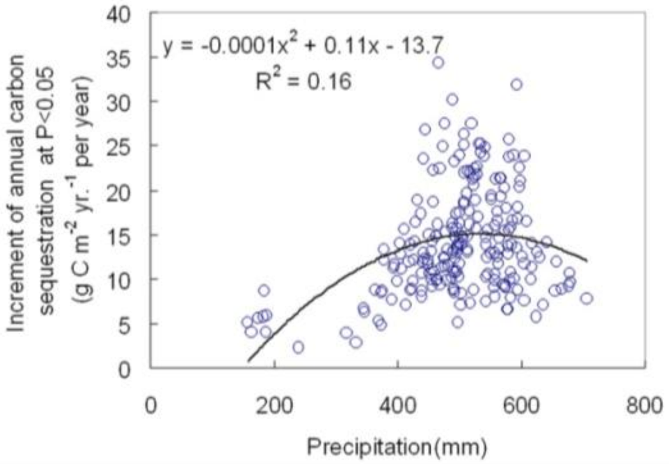
- Before the 1990s,landscape engineering measures (e.g., dam & terrace cropland building) were the main reason for sediment reduction (54%)
- Since 2000, vegetation restoration has been the main contributor for sediment reduction (57%)

Wang, Fu et al, 2016, Nature Geoscience*

Carbon Sequestration

Carbon sequestration by plant growth：CASA NPP+land cover map



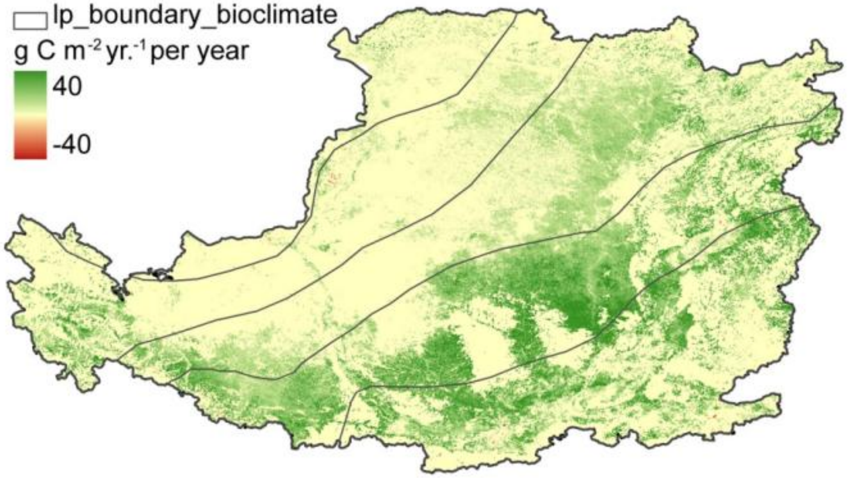


- ➢The total annual NPP increased from 0.170 Pg C in 2000 to 0.217 Pg C in 2008: a significant rate of 9.4 g C m^2 per year (P<0.01).
- ➢Spatial variaed: Significant increase of annual NPP (P<0.05) occured in 37% of the Loess Plateau area
- ➢The highest increment occurred in the area with annul precipitation 500mm

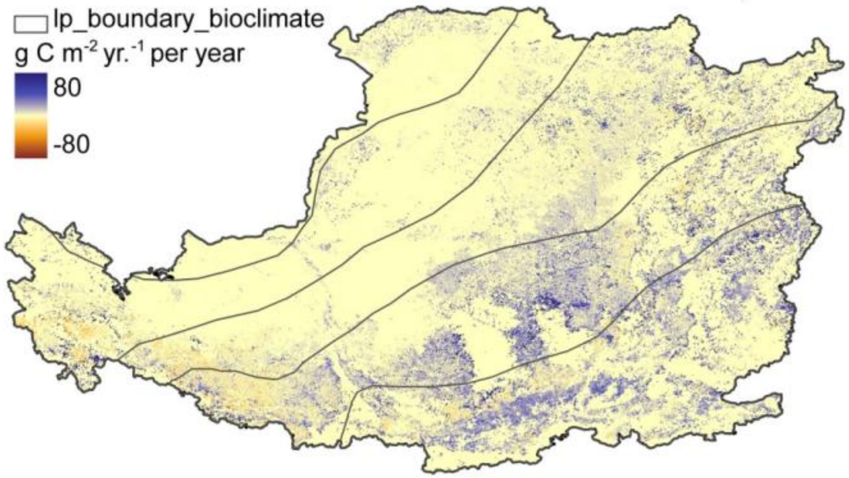
Feng and Fu* et al, *SR*, 2013

Carbon Sequestration

NEP and soil carbon- NPP derived ecosystem process model CENTURY



Trend of NEP (2000-2008)

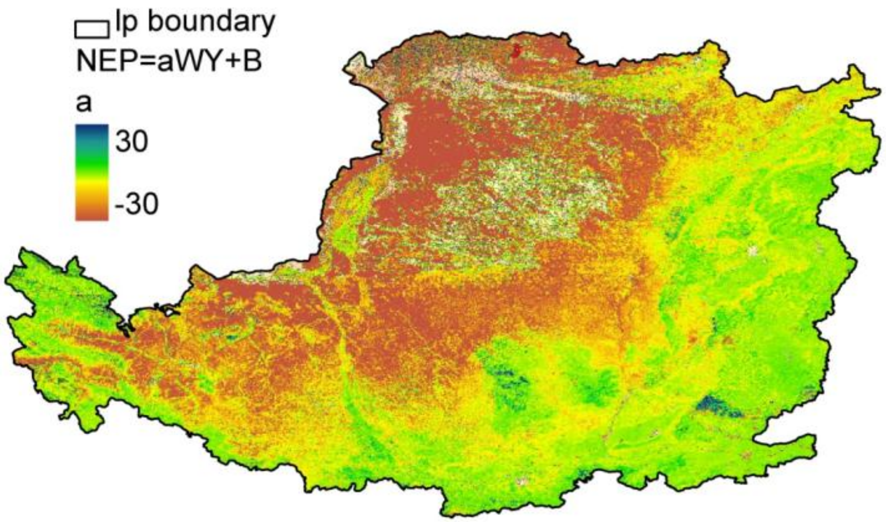


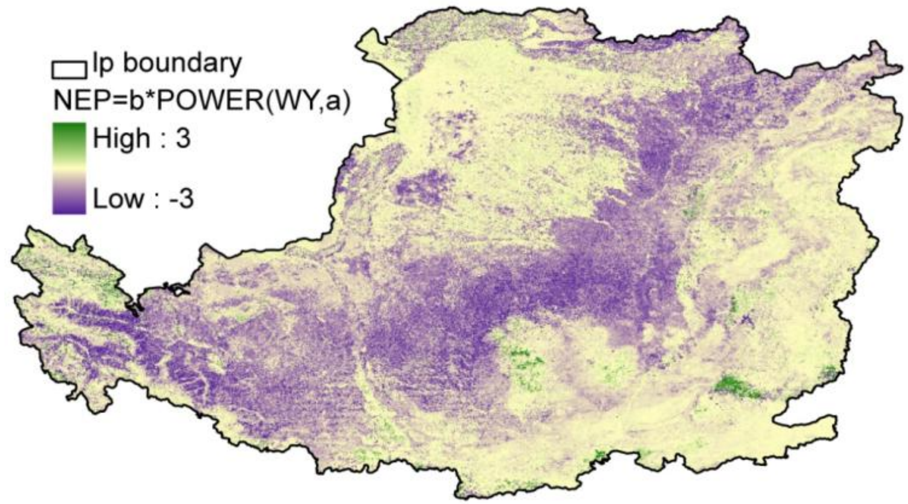
Trend of soil carbon (2000-2008)

- **The Loess Plateau ecosystem had shifted from a net carbon source in 2000 (-0.011 Pg C) to a net carbon sink in 2008(0.108 Pg).**
- **A total of 96.1 Tg of additional carbon had been sequestered, This sequestration of carbon is equivalent to 6.4% of China's total fossil fuel carbon dioxide emissions in 2006.**
- **No significant trend of soil carbon during 2000-2008. Soil carbon storage usually lag behind that of aboveground productivity**

Feng and Fu* et al, *SR*, 2013

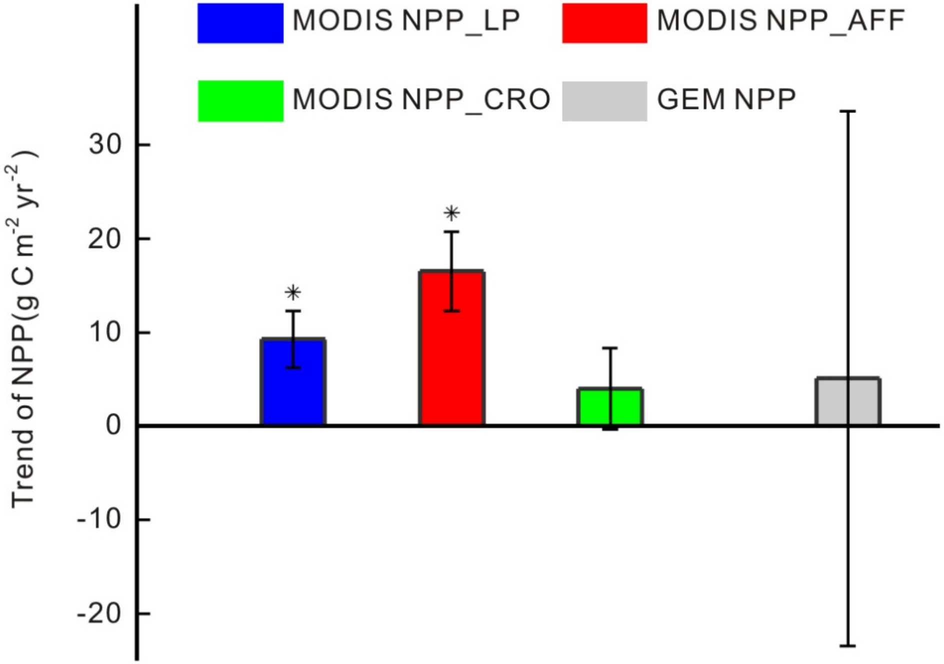
The Tradeoff Relationship Between Carbon Sequestration and Water Yield

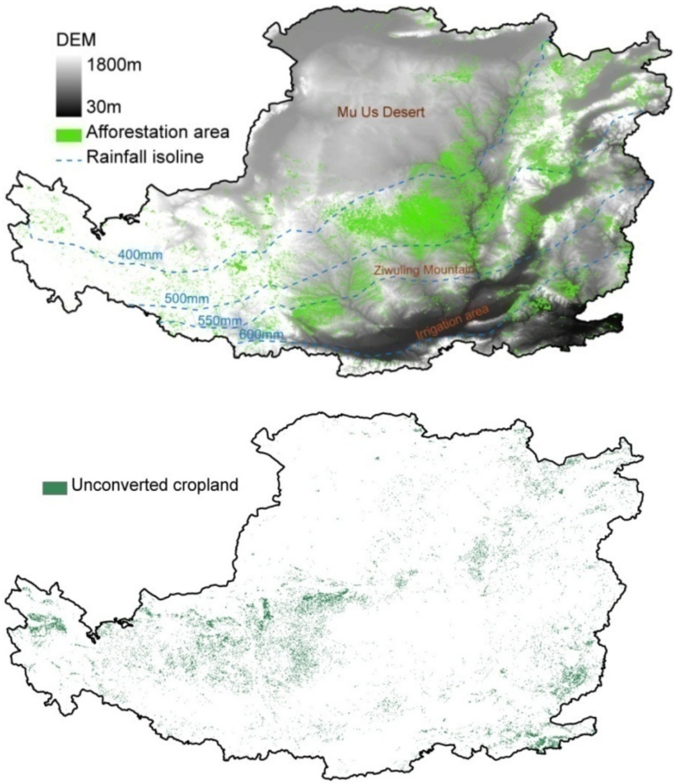




- **The gain of carbon sequestration was at the cost of water yield in arid and semiarid area of Loess Plateau.**
- **However, the gain of carbon sequestration increased as water yield declined allometrically (a power function fitted best) in the restored area.**

Trend of NPP



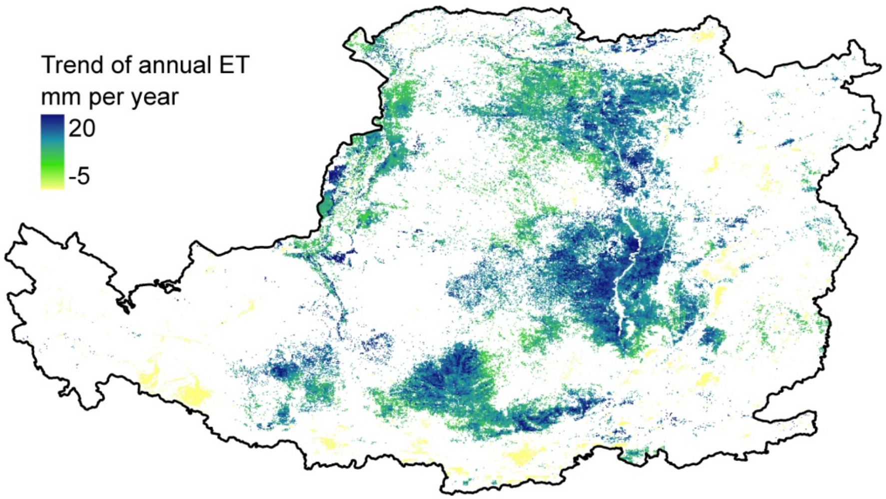


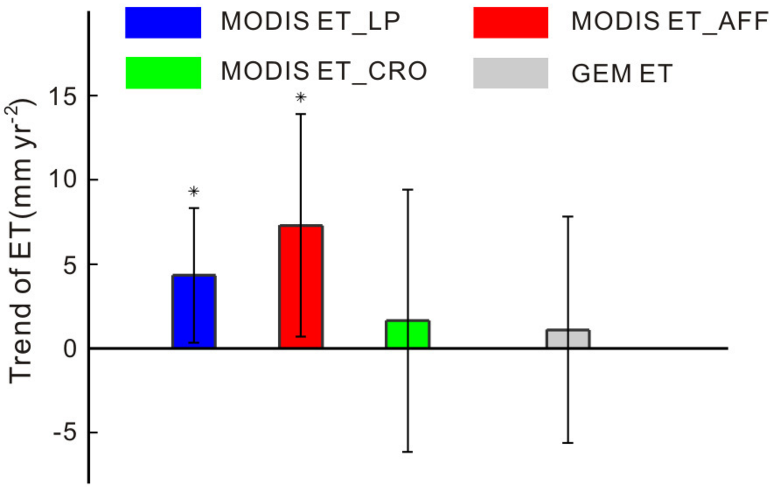
➢Annual NPP estimated from the models without reforestation does not show any significant trend, supporting attribution of the observed NPP increase to this land use change

Feng and Fu* et al, *Nature Climate Change*, 2016

Trend of ET

ETWatch ET





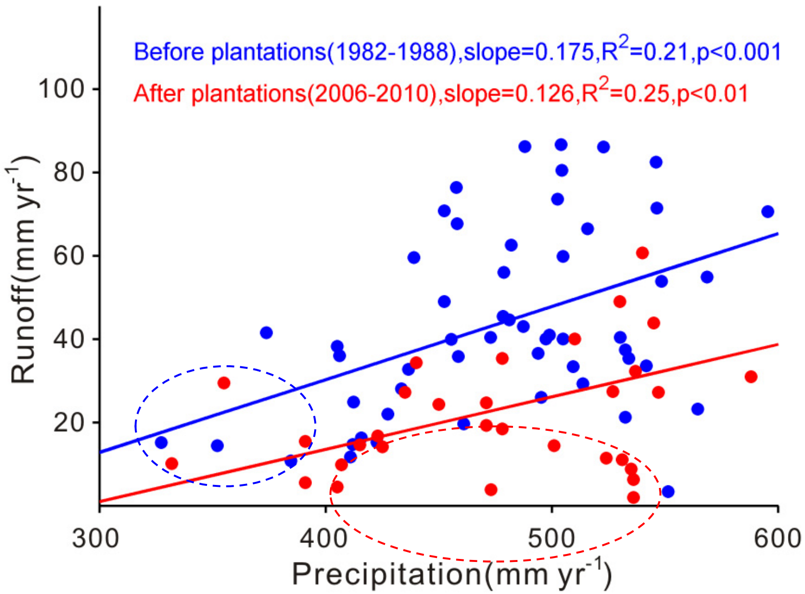
➢The sub-regional areas of ET increases are also found to coincide with plantation areas.

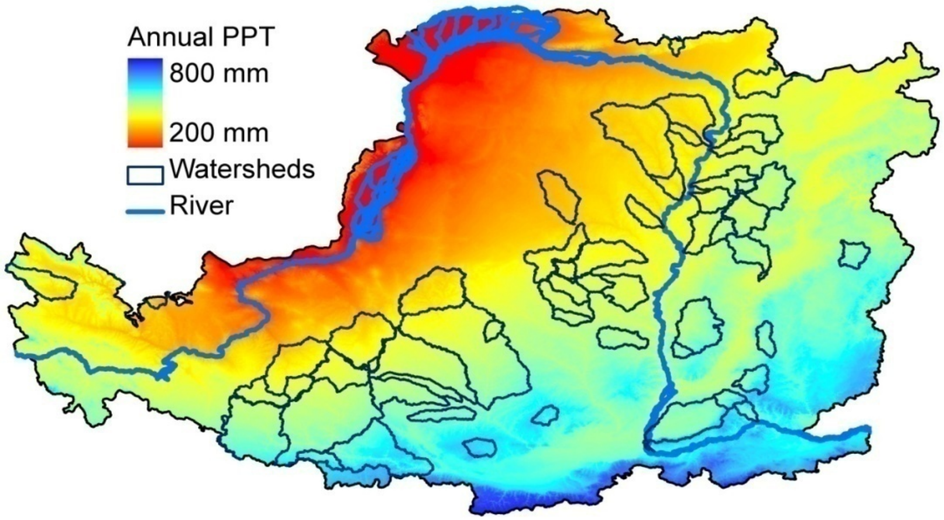
➢ Annual ET estimated from the models without reforestation does not show any significant trend, supporting attribution of the observed ET increase to this land use change

Feng and Fu* et al, *Nature Climate Change*, 2016

Trend of ET and Runoff Change

Observed runoff of 55 catchments





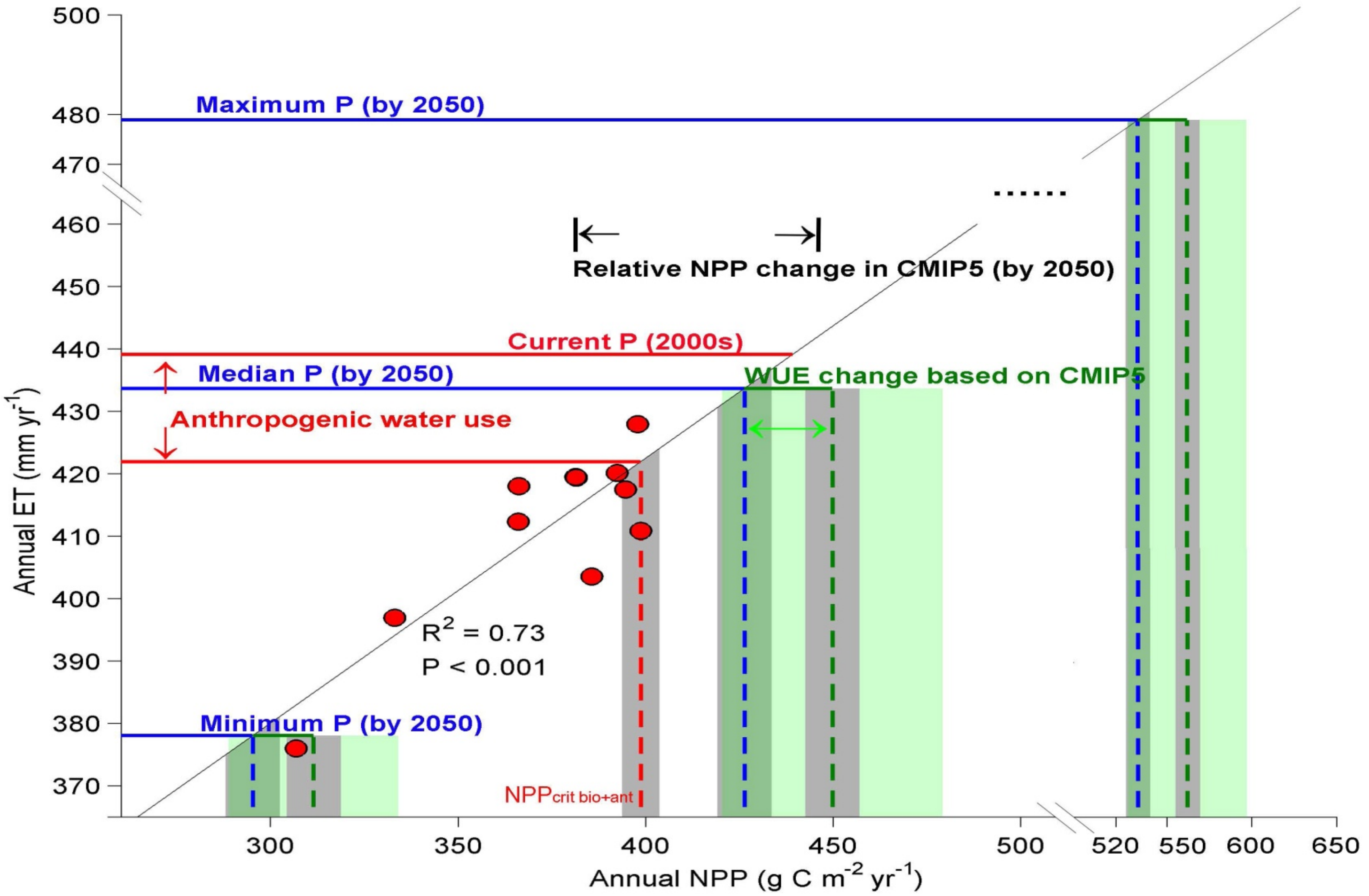
➢The spatial distribution of runoff between catchments has also been modified by the different fractions of afforested land

lowest runoff in the driest watersheds before GFGP.

lowest runoff in watersheds with precipitation of 400-550 mm yr^{-1}

Feng and Fu* et al, *Nature CC*, 2016

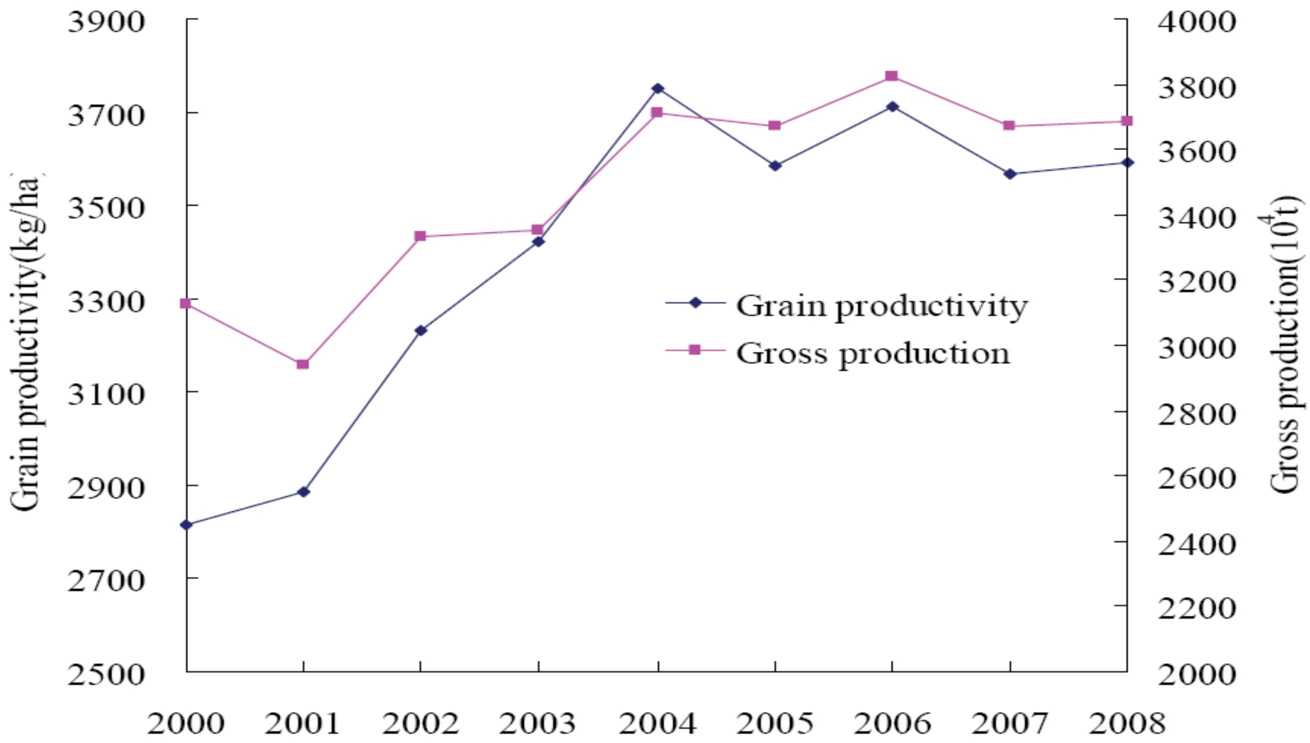
Integration ET NPP and Water Use



➢**NPPs predicted by the CMIP5 under the RCP2.6 climate scenario, is approaching water sustainable use limits**

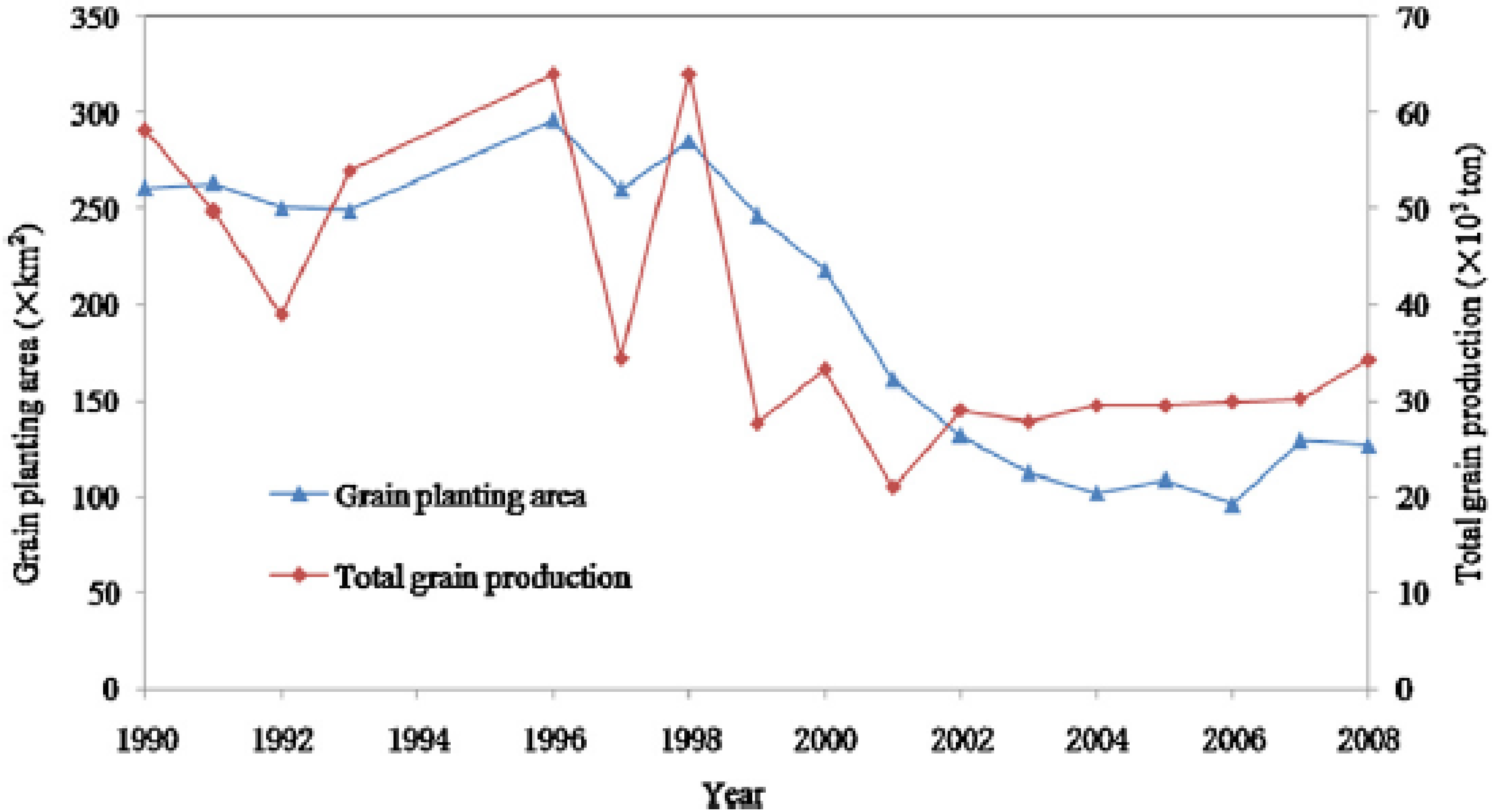
Feng and Fu* et al, *Nature Climate Change*, 2016

Grain production



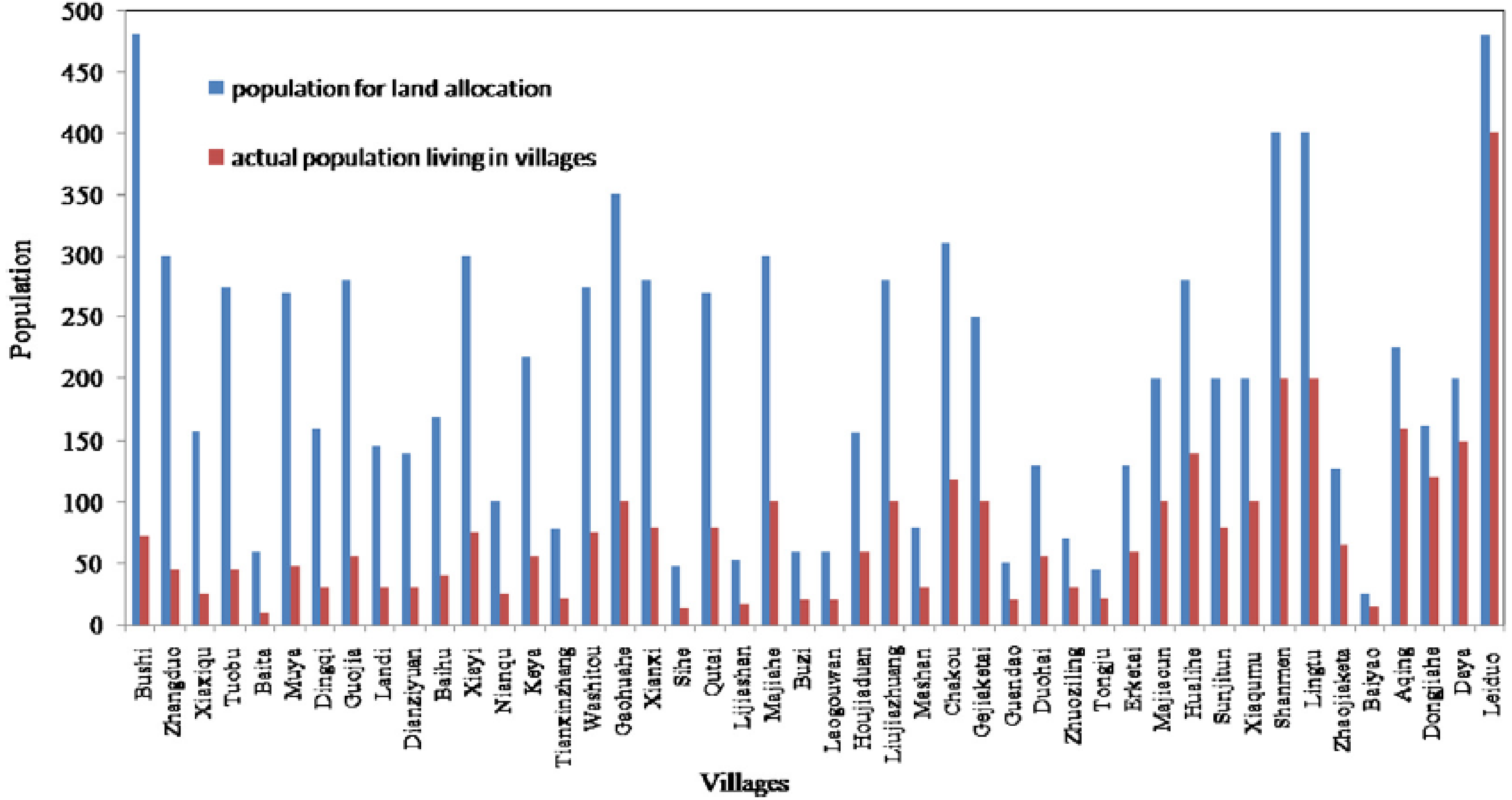
- Decrease of cropland area
- Increase of unit area production
- Total production changed from decrease to increase

Cropland areas and grain production in Yanchang County



Zeng and Fu* et al, *Land use policy*, 2014

Population in Yanchang in 2012



Zeng and Fu* et al, *Land use policy*, 2014

Trade-offs and synergies among ecosystem services

- Positive on soil conservation, carbon sequestration, NPP Vs. negative on surface runoff
- Gain on ecosystems can be realized along with the improvement of agricultural production and social economic well off
- Trade-offs and synergies of ES may vary according to scales and geographic location

Summary

- The loess plateau is ecologically vulnerable with tense man-land relationship
- Soil and water conservation as well as local development are the focus of present ecosystem management
- The regional ecosystems and their services have been significantly improved at regional scale since 2000
- To further improve ES, science and policy need to be integrated as two important elements.

Conclusions

- **Linking FW and Eco-conservation provide the scientific base for ecosystem restoration**
- **Understanding relationships among multiple ecosystem services (FWE) lead to ecosystem services optimization and management.**
- **Ecosystem services modeling is an integrated approach to support land use management.**
- **Multidisciplinary in holistic approach, resolving nexus FWE.**

Thanks !