Sustainability Challenges for the Social-Environmental Systems across the Asian Drylands Belt
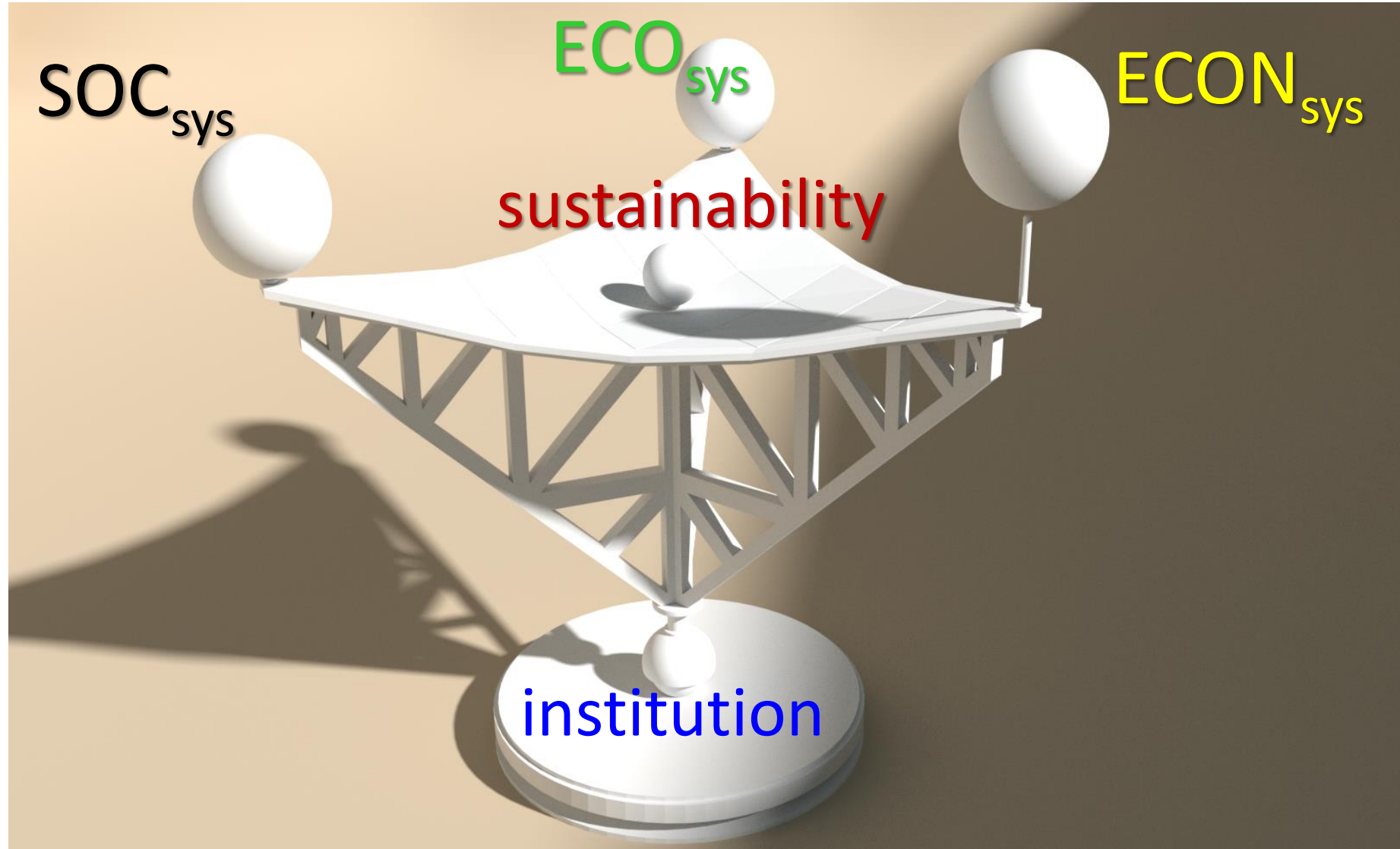
Jiquan Chen

Co-Authors: Ranjeet John, Garik Gutman, Changliang Shao, Geoffrey M. Henebry, Pasha Groisman, Zutao Ouyang, Elizabeth A. Mack, Gang Dong, Ginger R.H. Allington, David P. Roy, Amber L. Pearson, Peilei Fan, Gabriela Shirkey, Li Tian, Maira Kussainova, Fangyuan Zhao, David E. Reed, Martin Kappas, Michael Abraha, Dan Brown, Jiaguo Qi, Jing Yuan, Yaoqi Zhang, Ochirbat Batkhishig, Amartuvshin Amarjargal, Hogeun Park, and **more**

Landscape Ecology & Ecosystem Science
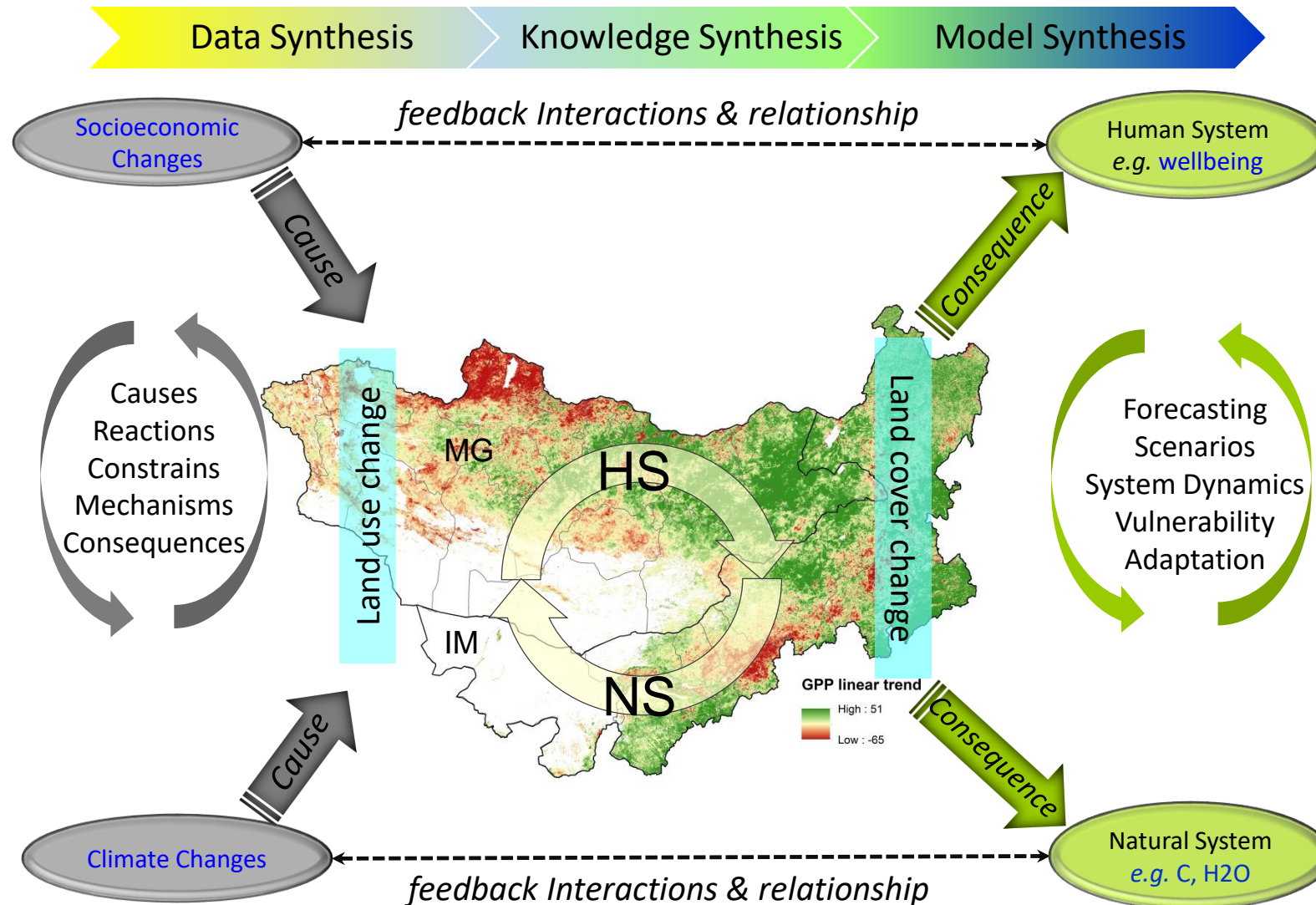Michigan State University
Email: jqchen@msu.edu

Feb. 8, 2023
Geo873-001, MSU

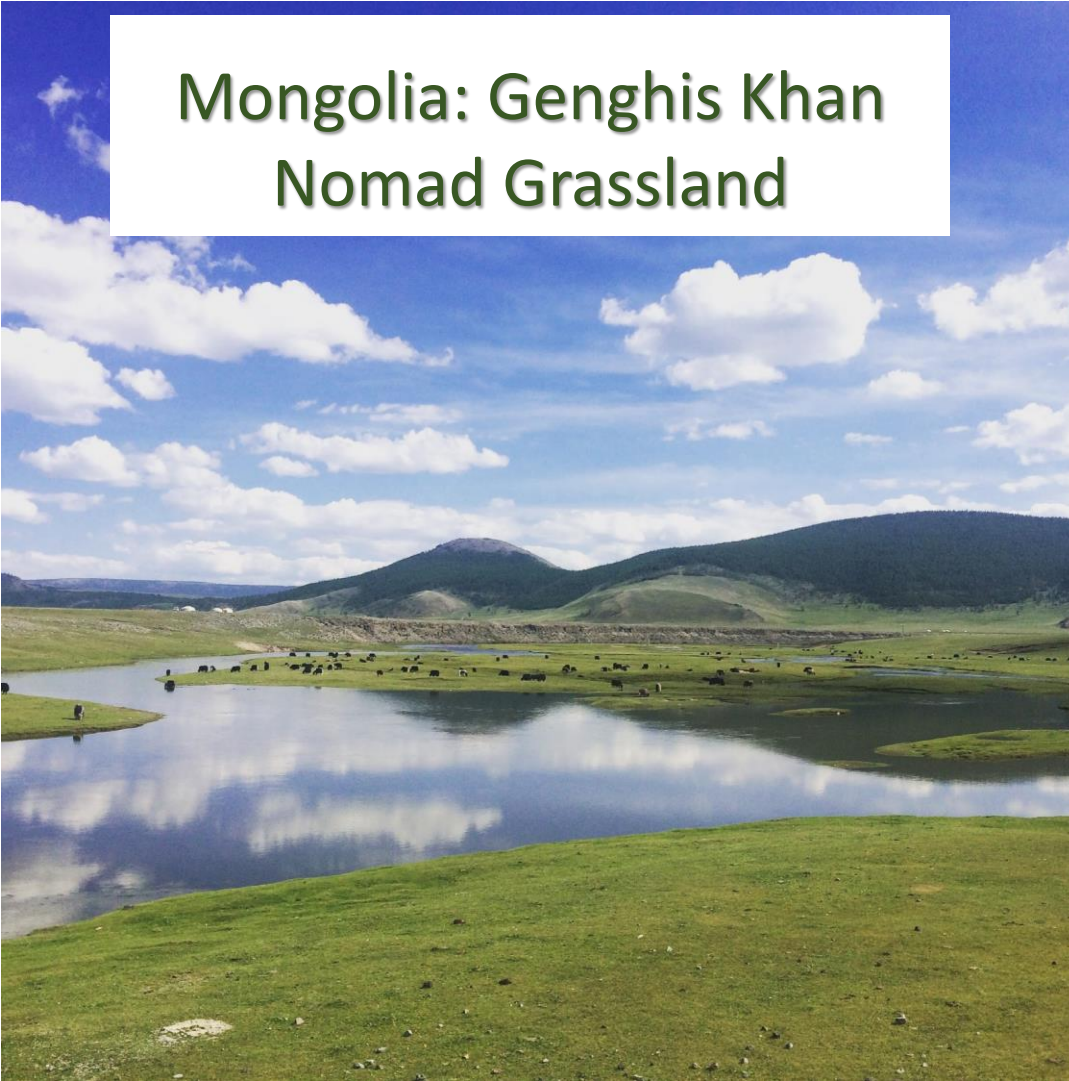# Sustainability: 3 Pillars & Institution Foundation

Chen et al. 2021

Social-Ecological Systems (SES)

Understanding the drivers, mechanisms, and consequences of socioeconomic & physical changes on the functional changes of the human system (HS) and natural systems (NS)
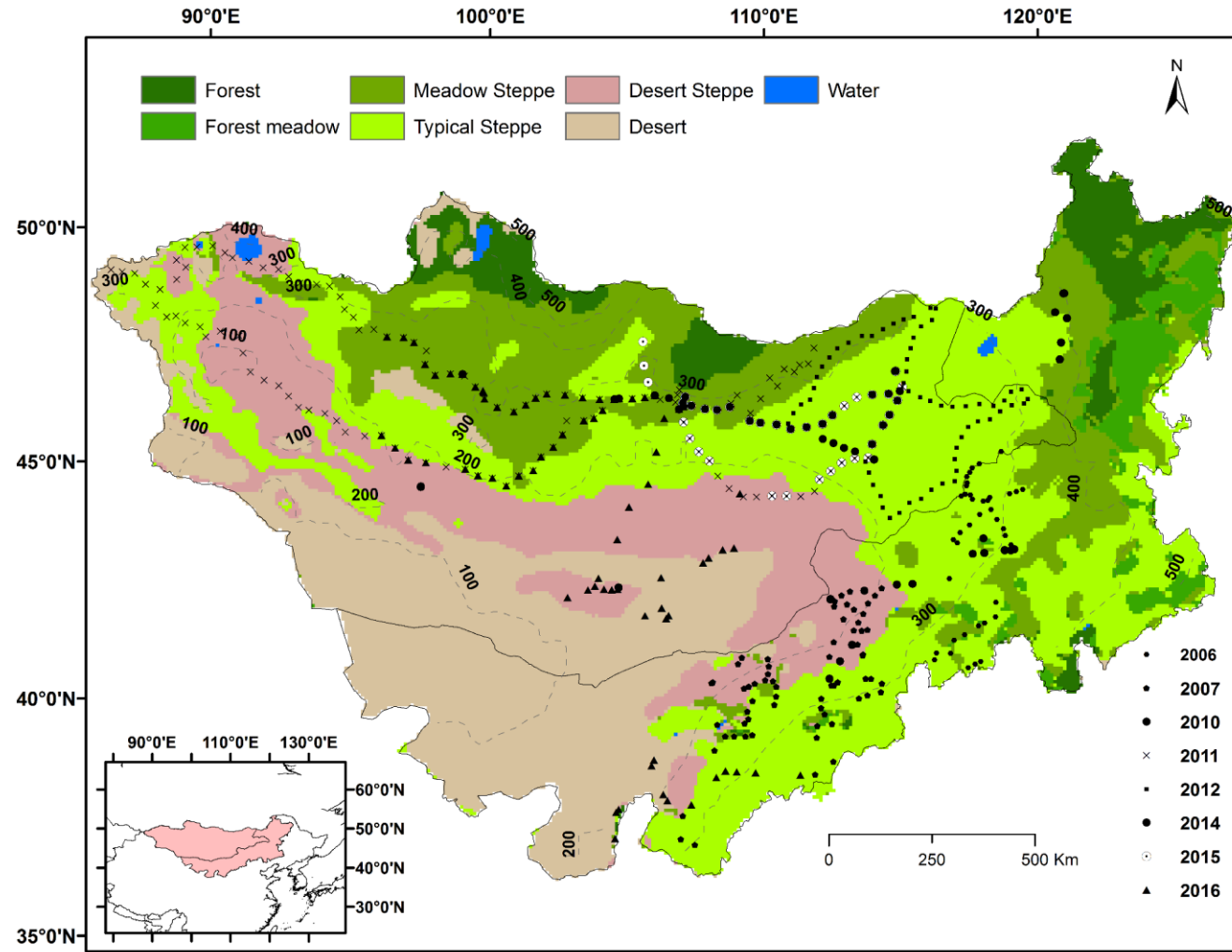
Lessons from the Mongolian Plateau

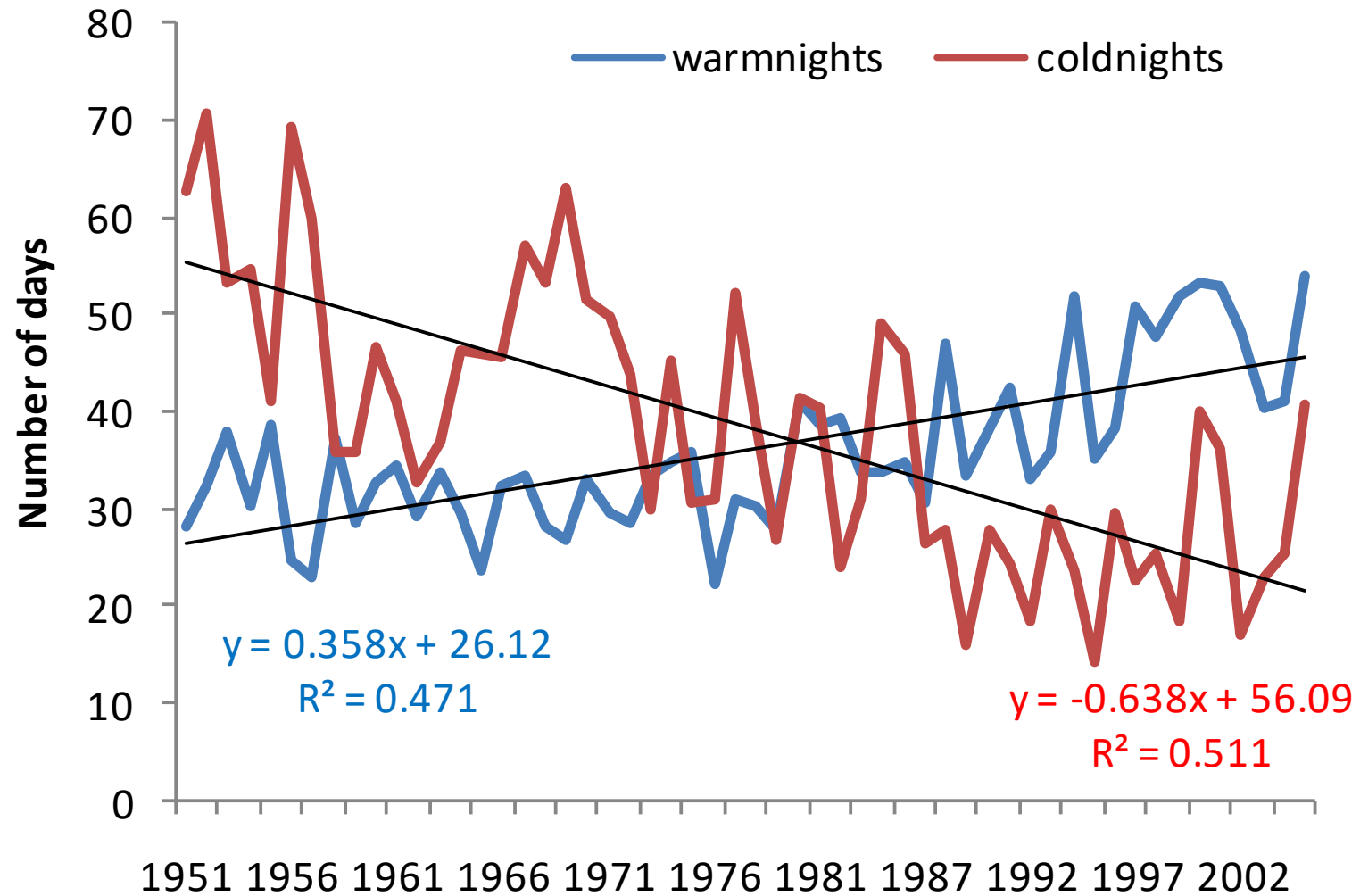Mongolia: Genghis Khan
Nomad Grassland

Vegetation type map of the Mongolian plateau overlaid with isohyets (dashed lines) derived from CRU TS323 mean annual precipitation (1981-2014)
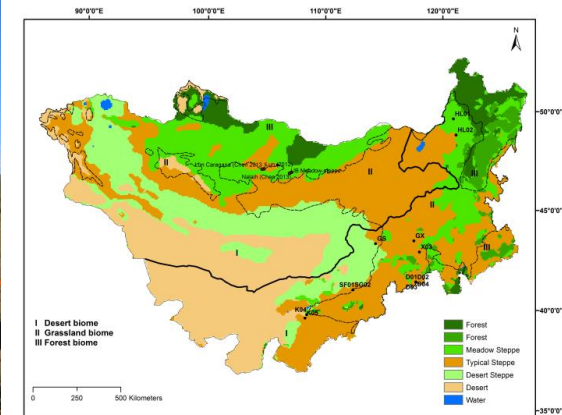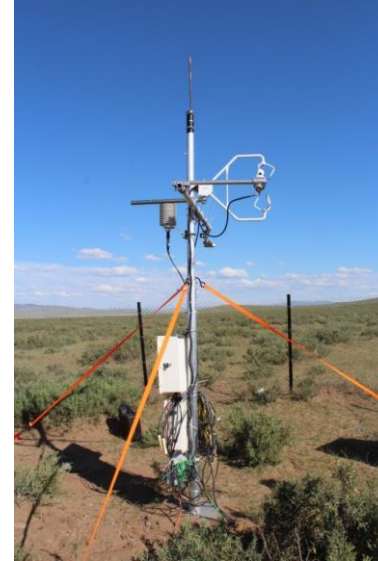
Regional trend of warm nights and cold nights

Lu et al. 2009.

Direct measurements of CO$_2$ and H$_2$O through eddy-covariance towers on the Mongolian Plateau

# Changes in livestock, policy, and climate in IM & MG

Qi et al. (2012)

Challenges

1) Central to the concept of the coupled natural and human (CNH) system, humans and nature are organized into interacting sub-systems of a cohesive whole at multiple spatial and temporal scales.

2) Quantitative linkages between the elements between the human and natural systems are rare!

The Asian Drylands Belt (ADB)

- 22 political Entities (PEs) in 17 countries
- 15.4 million km^2, 10.3% of the global land area
- Three sub-regions: the Middle East (ME), Central Asia (CA), and the East Asia (EA)
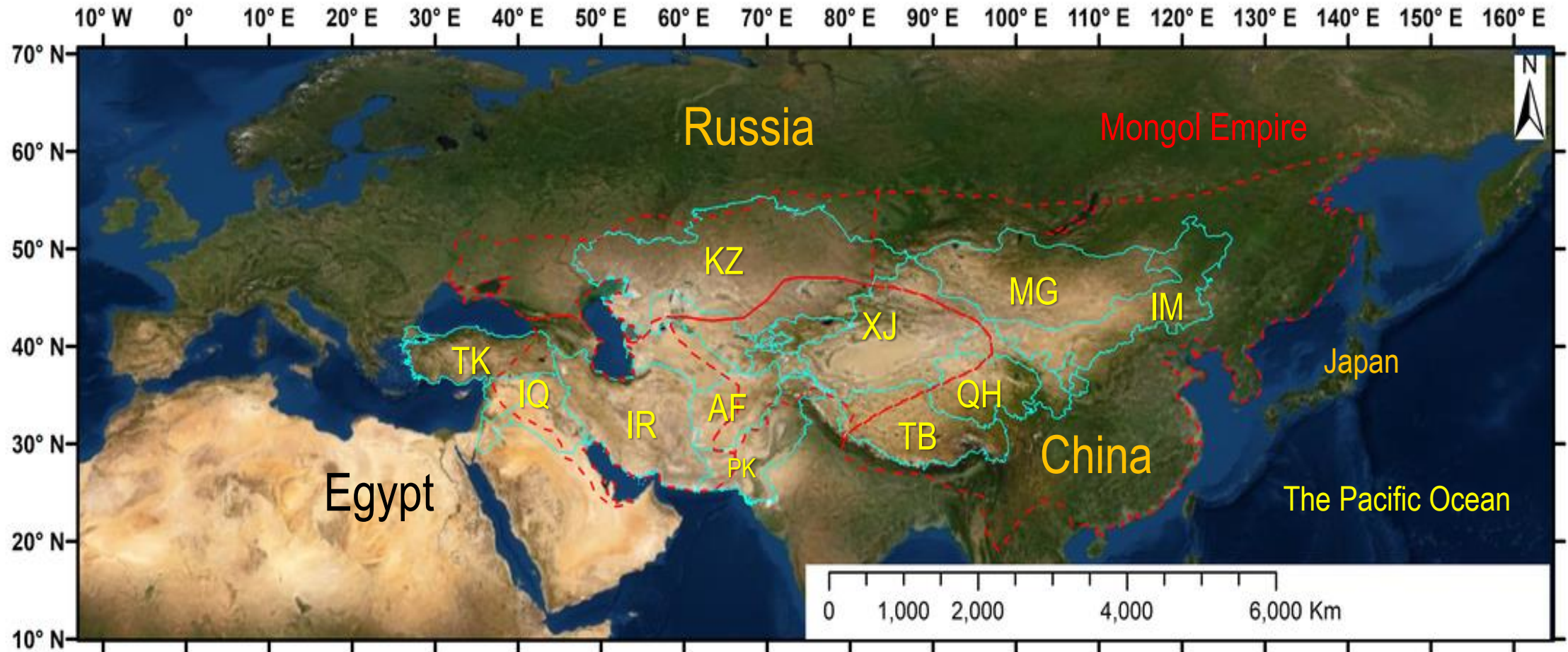
Nomad Societies

The Mongol Empire was the only authority that completely controlled the region during 13th and 14th century
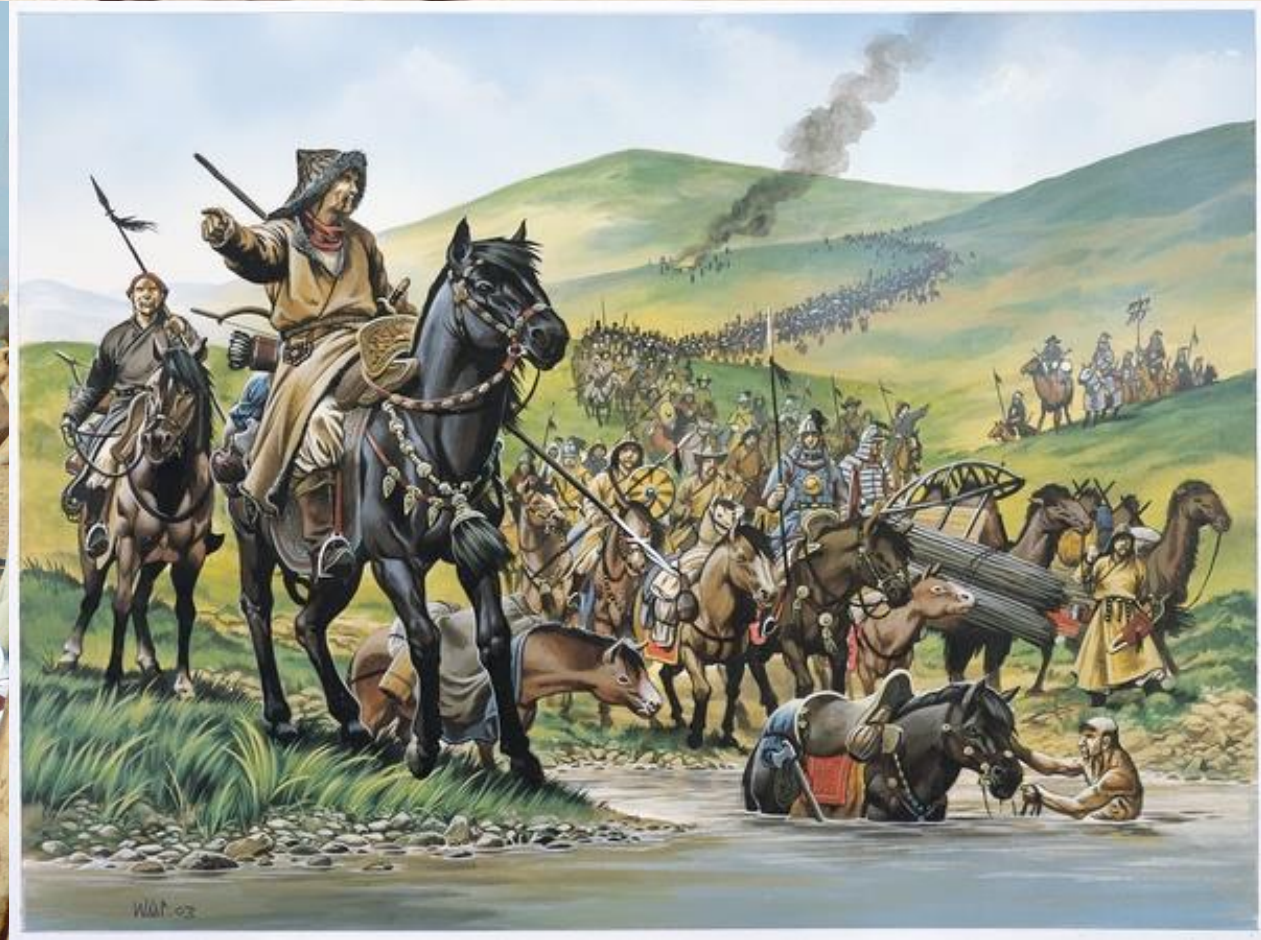
First Persian Empire (522 BC to 486 BC)

THE PERSIAN EMPIRE (CA. 538-332 B.C.E.)

Alexander's Empire (336–323 BC)

(https://en.wikipedia.org/wiki/Alexander_the_Great#Conquest_of_the_Persian_Empire)

The Roman Empire (27 BC – AD 476)

The Roman Empire in 117 AD

Senatorial provinces
Imperial provinces
Client states

Parthian Empire (Arsacid Empire) (247 BC to 224 AD)

Sassanian Empire (aka, the Iranian dynasty) (224 - 651 AD)

Islamic Movement (622 - 750 AD): Umayyad Dynasty (661 – 750), Abbasid Dynasty (750 – 1258)
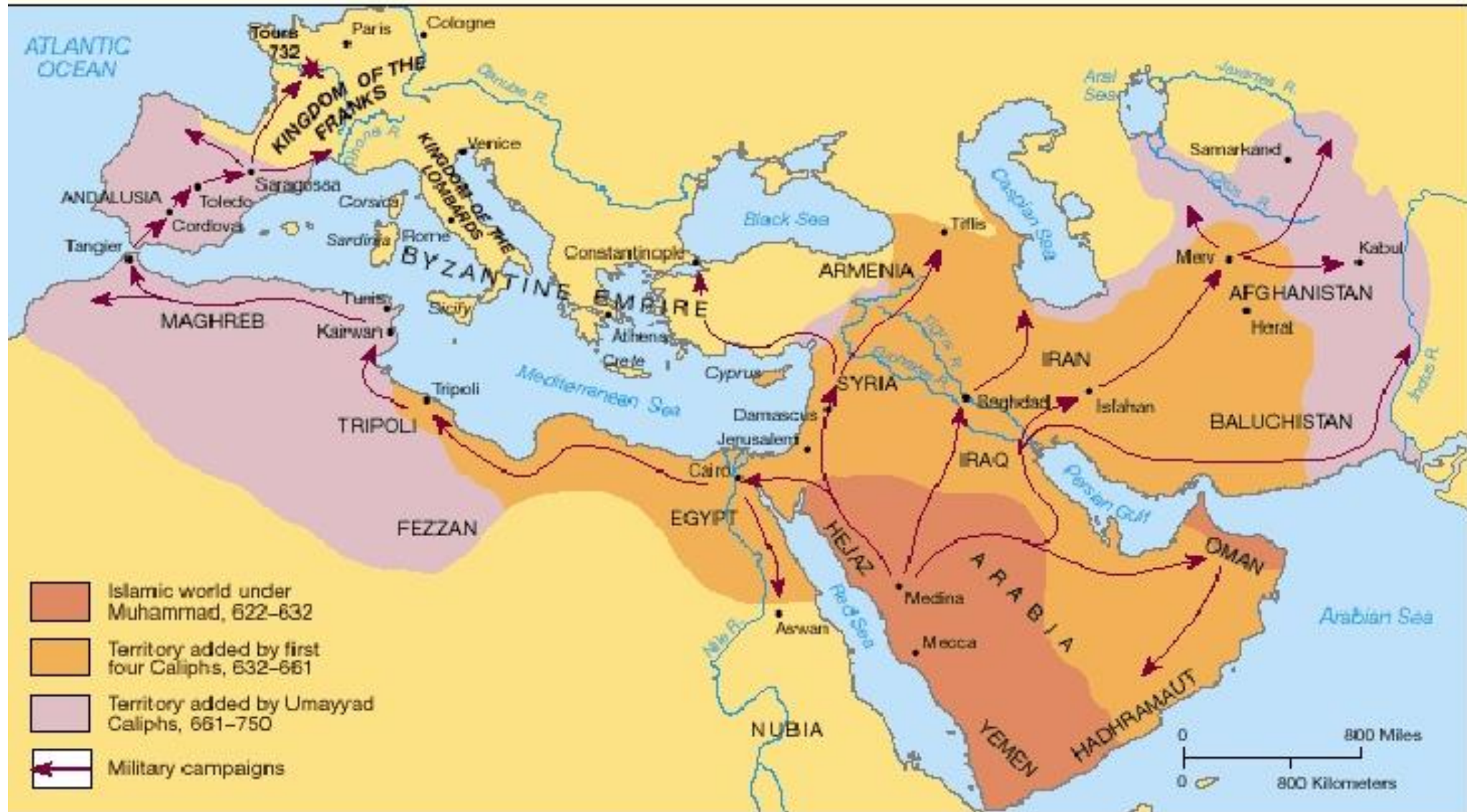
Mongol Empire (1206–1294 AD)

1206

The Ilkhanate Empire (in 1345 AD)

SOUTHWEST ASIA
AFTER THE COLLAPSE
OF THE ILKHANATE, 1345

Timurid Empire (1370-1857?)

SOUTHWEST ASIA
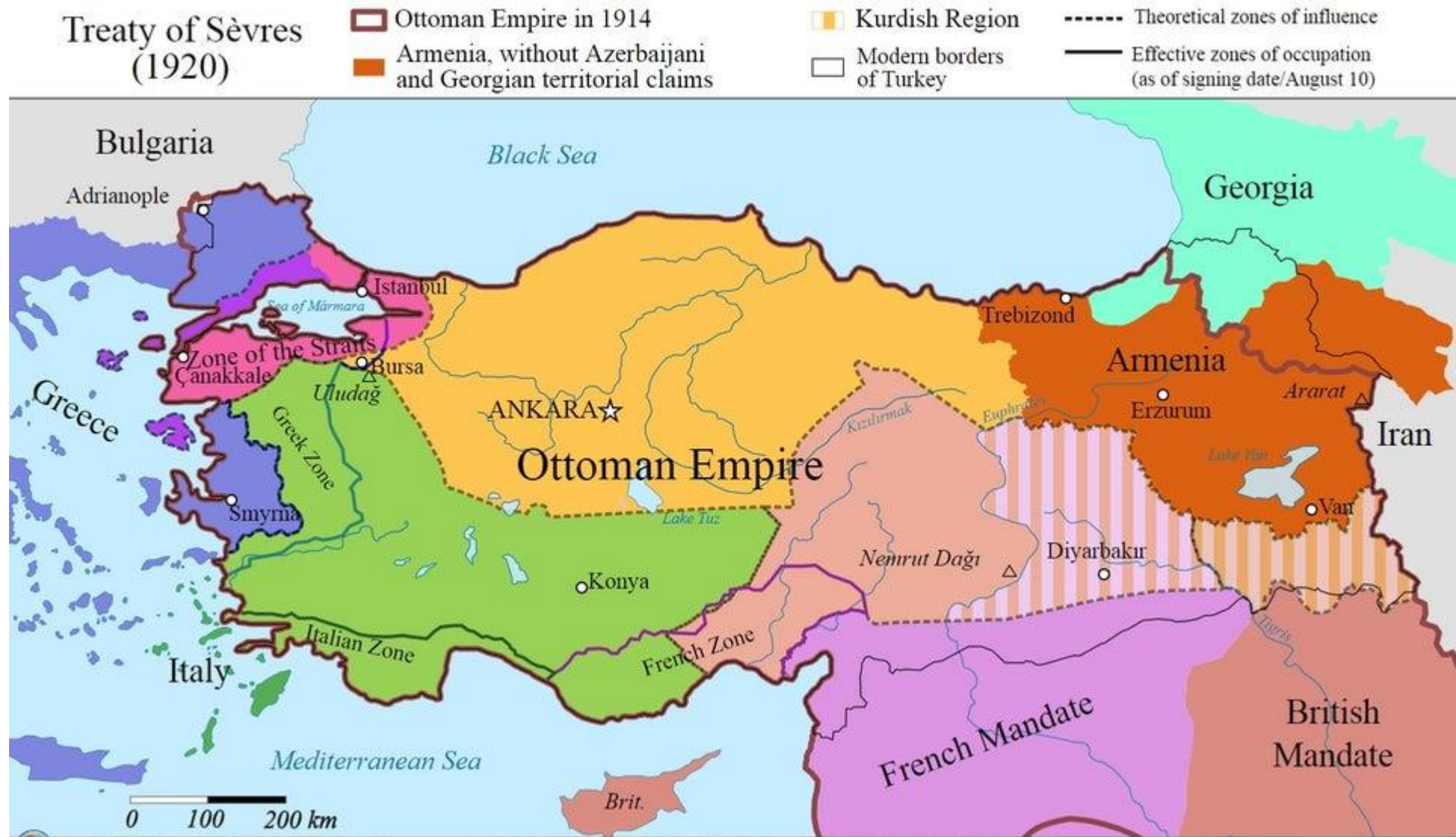AFTER THE COLLAPSE
OF THE ILKHANATE, 1345

Ottoman Empire (14th and early 20th centuries)

The Most Extensive Boundaries of the Ottoman Empire

Partitioned Ottoman Empire During the Treaty of Sèvres (1920)

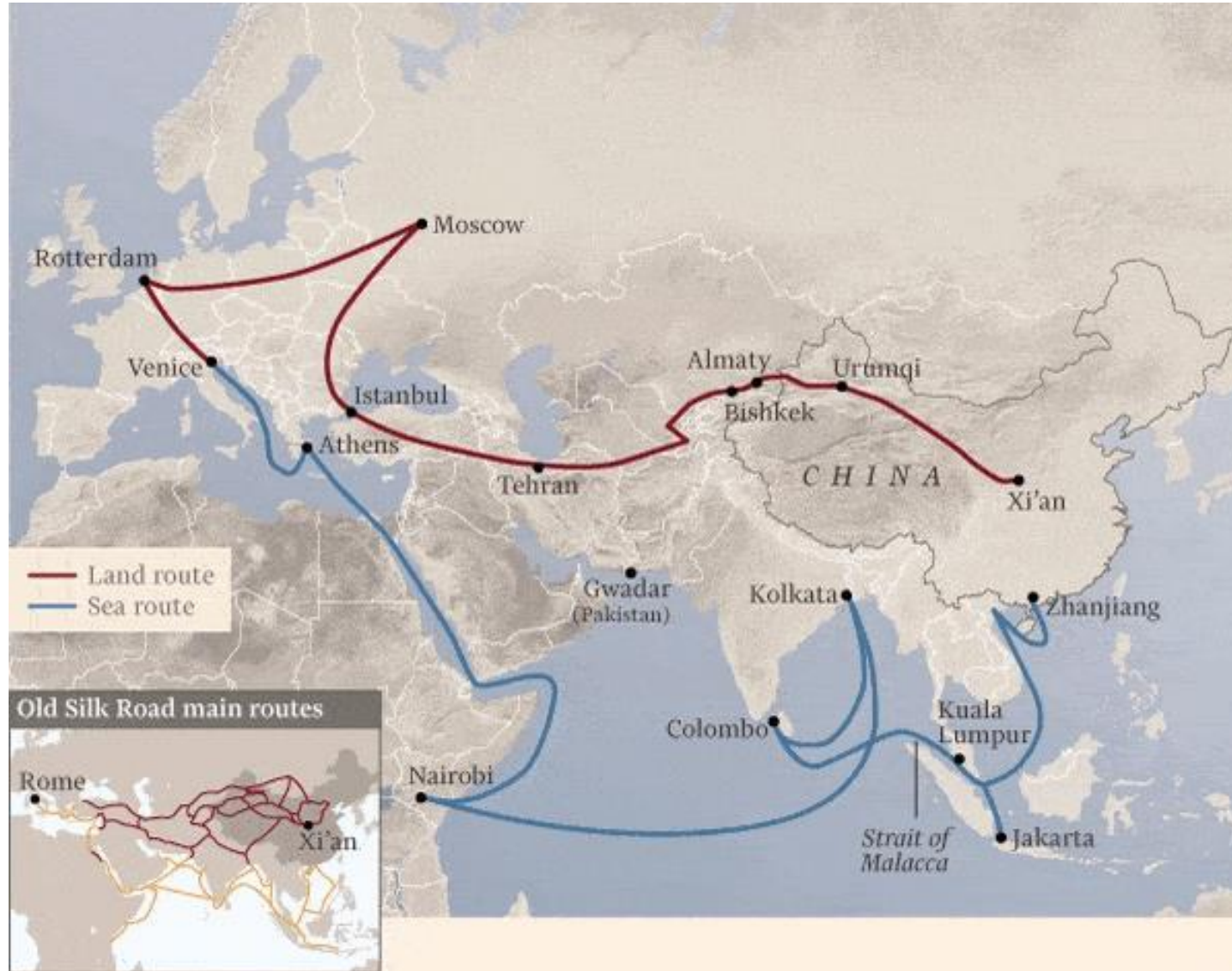# Russian Empires (1721–1917 AD)

The third-largest empire in history

Chinese Empires (200 BC – present)

https://www.youtube.com/watch?v=zdHkY3XYHKA

China's Great Game: Road to a new empire

Sources: NDRC; Commerce ministry; Digital Silk Road Project; IMF

ADB: the terrestrial routes connecting East Asia and Southeast Asia with East Africa, West Asia and Southern Europe

Major routes of Human Migration & the Silk Road (Chen et al. 2020)

A battle ground between the west (Europe) and east (China) for ~1500 years
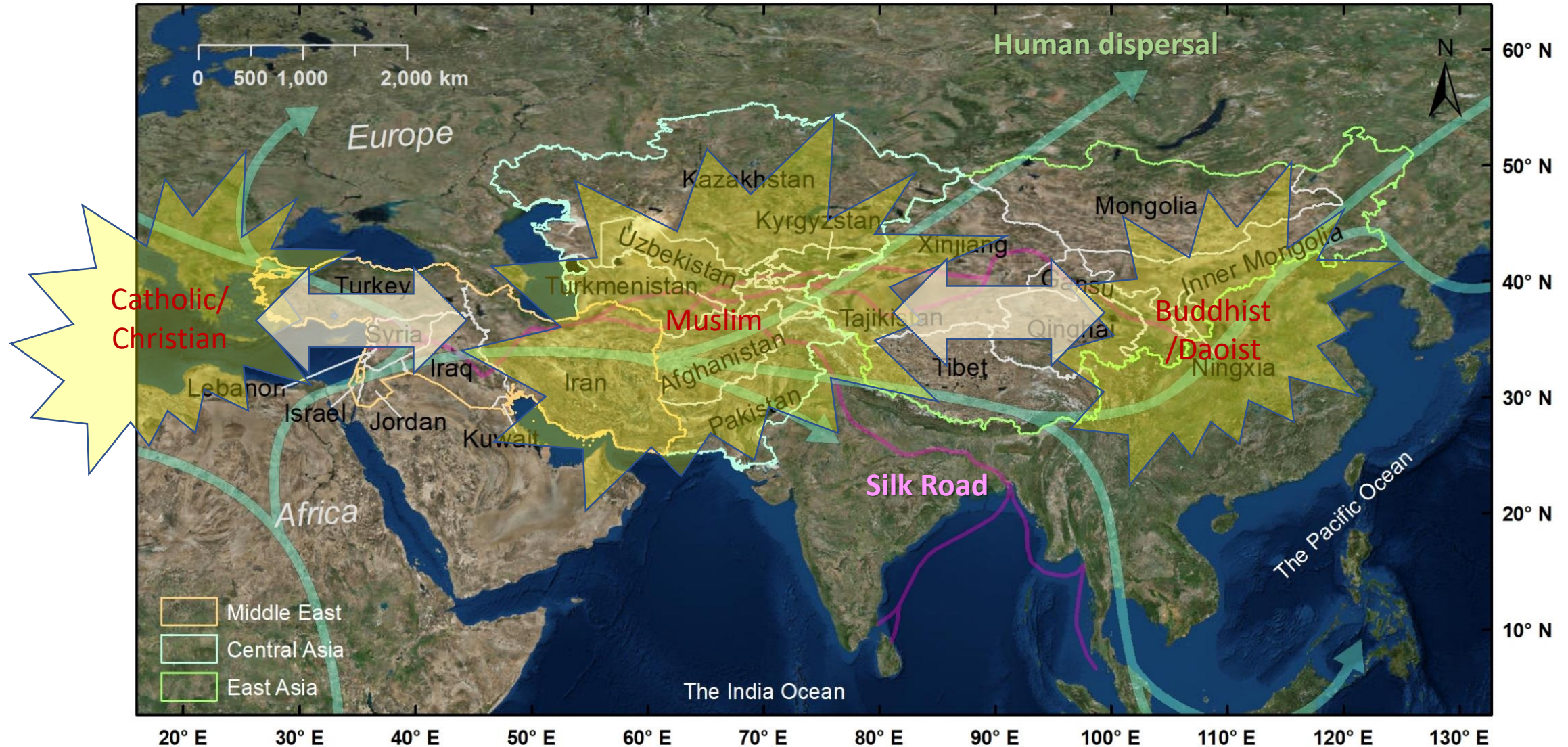
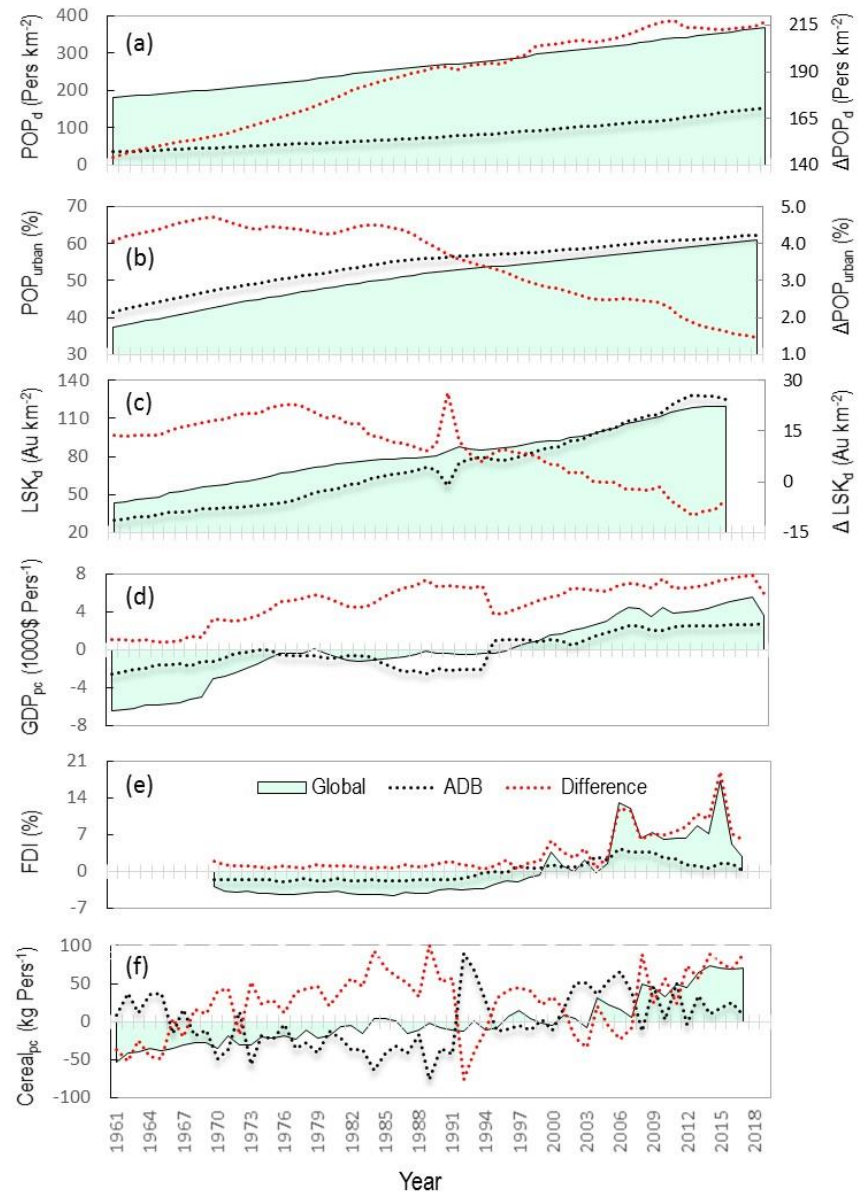Change in anomalies of land surface air temperature (°C) (i.e., differences from the long-term mean) for global land and ADB region during 1880-2000 (Data: https://www.ncdc.noaa.gov/cag/).

A much higher rate of warming than the average global warming, especially since 1980s
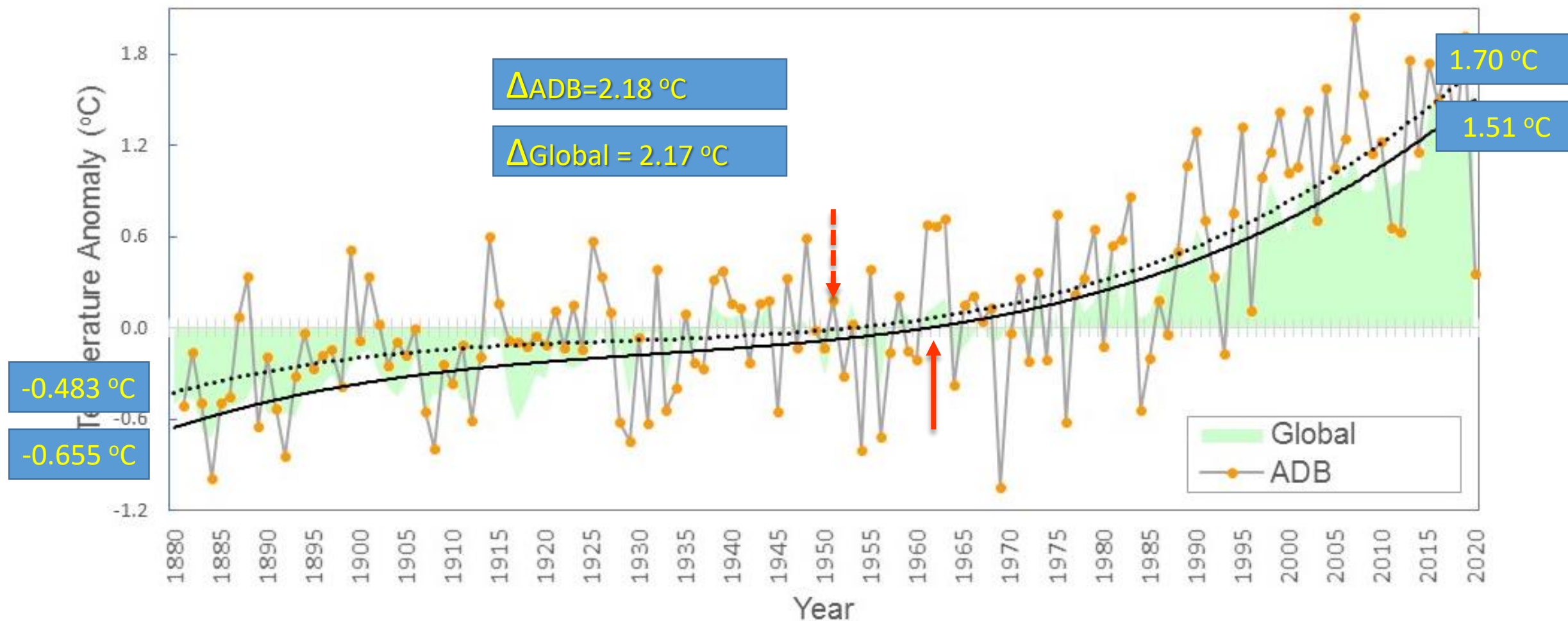
Long-term changes in six social and economic indicators (mean, anomalies and the differences between the ADB and the world

Spatial Variability: not homogeneous and with hotspots
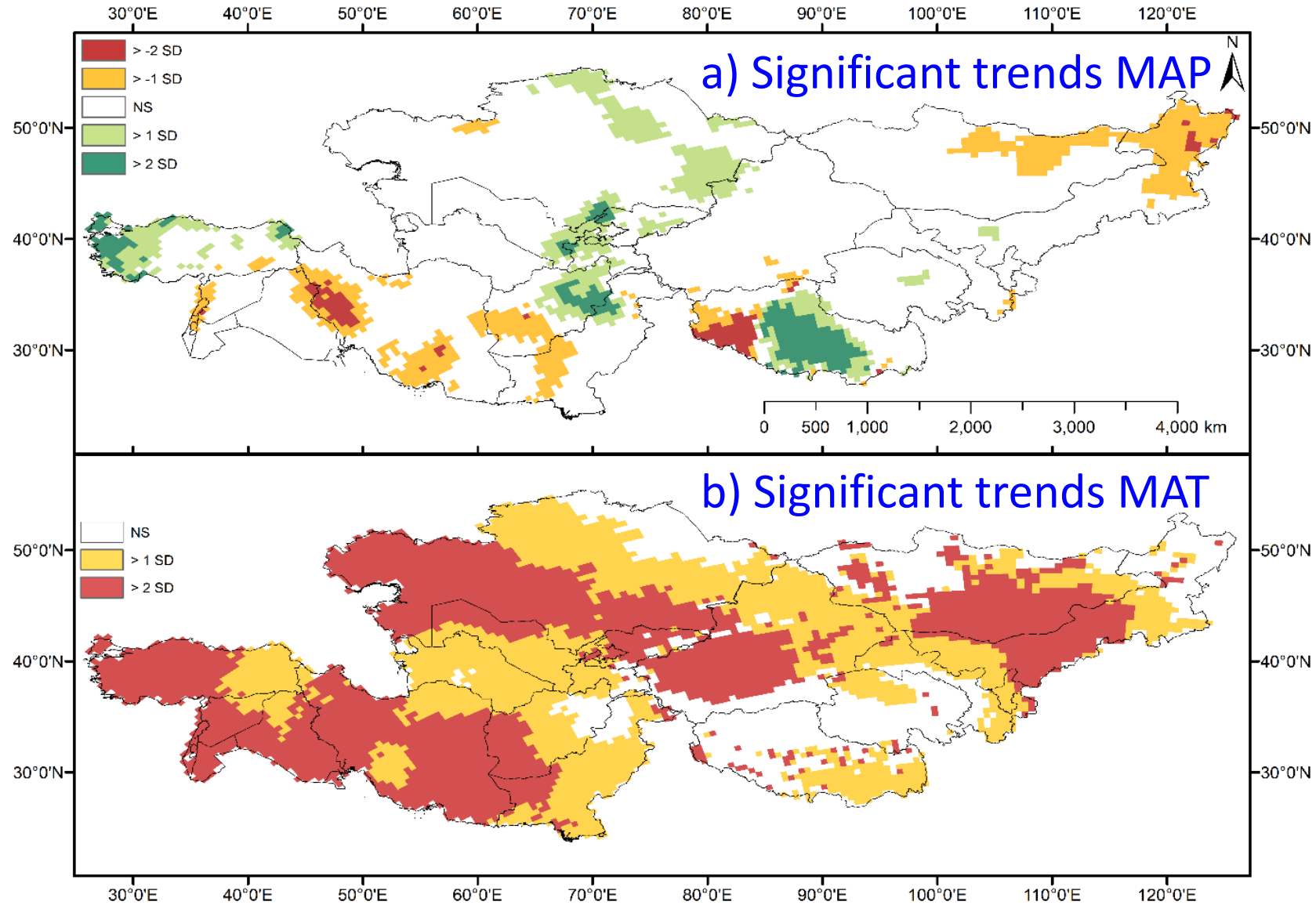
a) Significant trends MAP

Legend:
- > -2 SD
- > -1 SD
- NS
- > 1 SD
- > 2 SD

Scale: 0 500 1,000 2,000 3,000 4,000 km

b) Significant trends MAT

Legend:
- NS
- > 1 SD
- > 2 SD

Long-term changes in six social and economic indicators (mean, anomalies and the differences between the ADB and the world
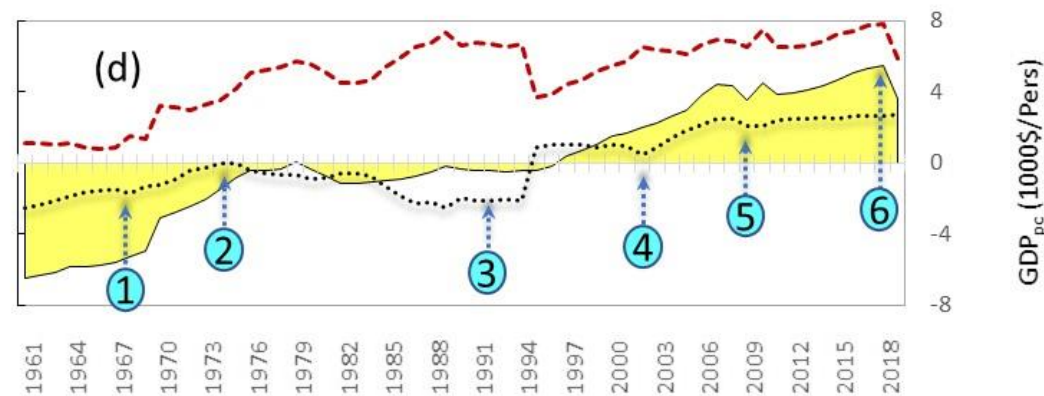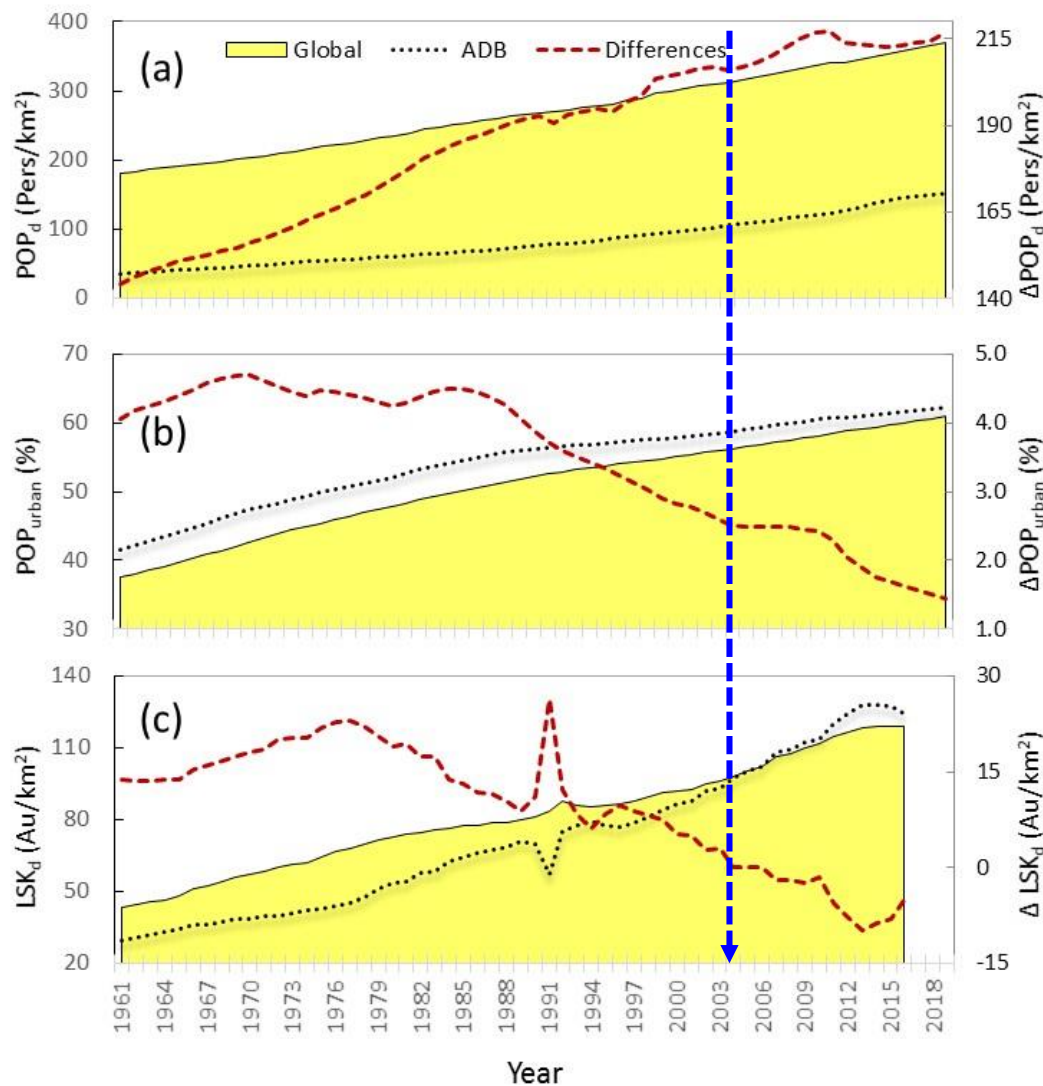
- Population density in ADB region has been low and continue being lower than the global average
- Urban population has been surprisingly higher in ADB
- Regardless of nomad tradition, livestock density has been lower until 2006.
- GDP per capital of ADB has been lower; its long-term anomalies has been lower than the global averages, with a quite stable period during 1970-1990
- Recent geopolitical conflicts cause immediate, and some lasting, consequences.
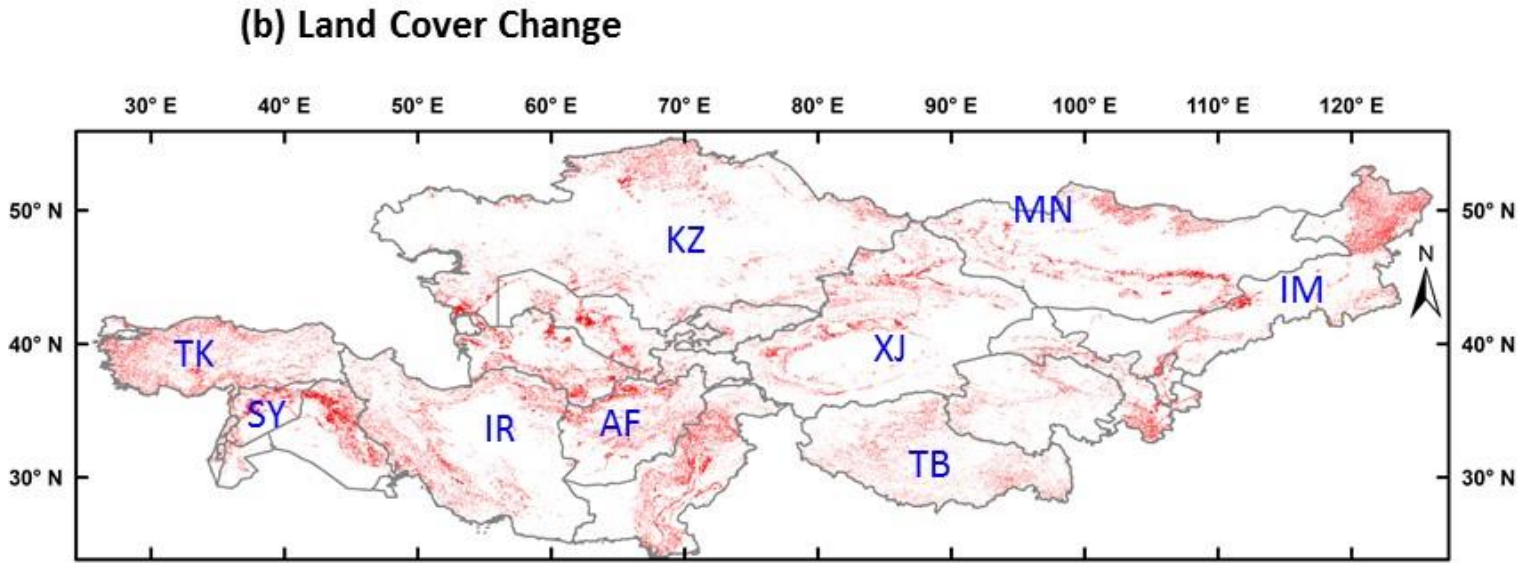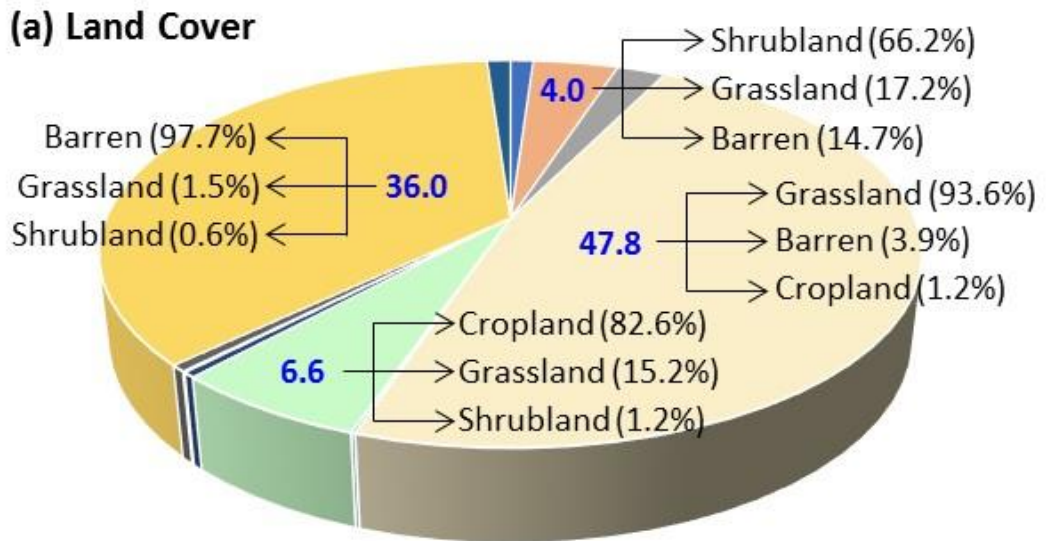
Land cover and land use changes across the ADB

Barrens: 41.2%
Grassland: 37.3%   85.7%
Shrubland: 7.2%

Cropland: 9.8%

Forest: <1%

Forest | Savanna | Wetland | Urban | Water
Shrubland | Grassland | Cropland | Barren
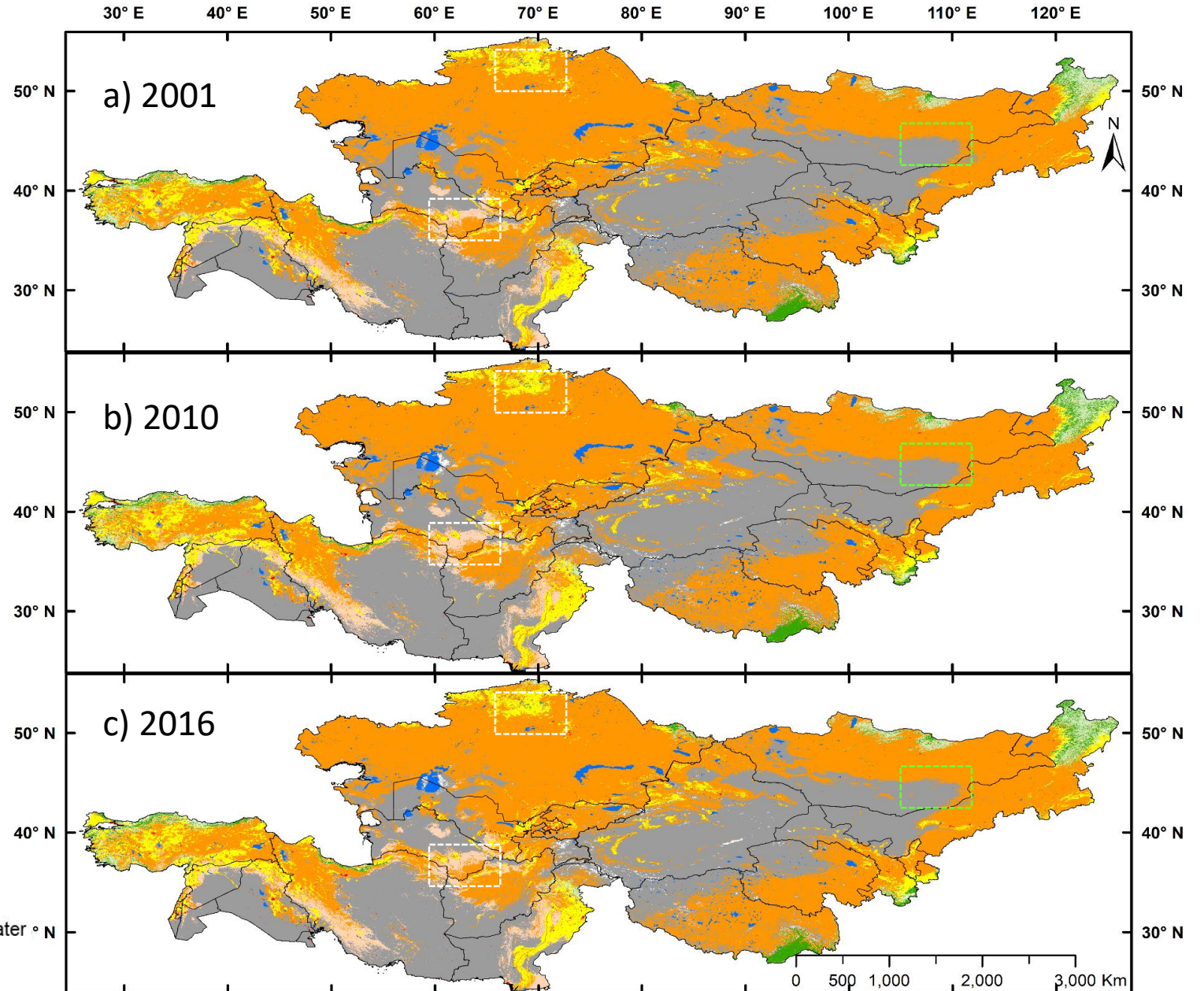
Land cover and land use changes across the ADB. (a) Composition of land cover for the ADB in 2019 (MODIS MCD12Q1) and major cover changes and (b) LCC from 2001 to 2019. Detailed statistics are provided in table S3.

(a) Land Cover

Shrubland (66.2%)
Grassland (17.2%)
Barren (14.7%)
4.0

Barren (97.7%)
Grassland (1.5%)
Shrubland (0.6%)
36.0

Grassland (93.6%)
Barren (3.9%)
Cropland (1.2%)
47.8

Cropland (82.6%)
Grassland (15.2%)
Shrubland (1.2%)
6.6

(b) Land Cover Change

SES Challenges:

Integrating the interactive dynamics and underlying connections of system properties, i.e., coupled dynamics of **SOCsys**, **ECONsys** and **ECOsys**

- **GDP per capital; HANPP (Mg C/person), etc.**

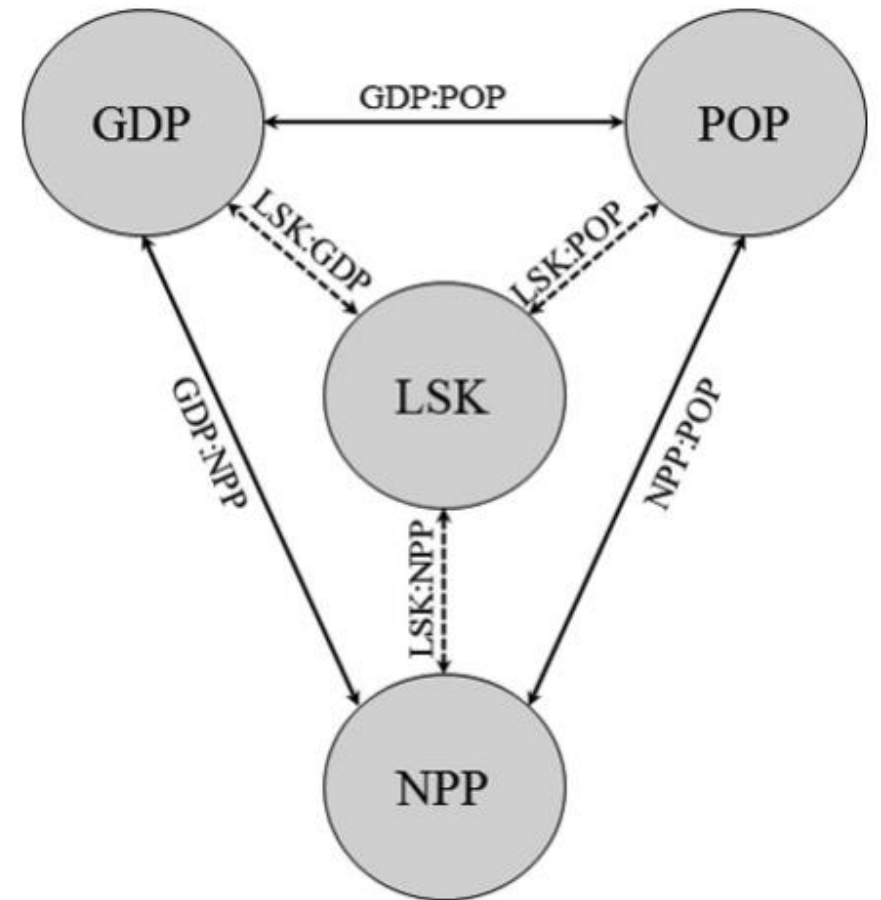- **LSK/NPP; GDP/NPP; LSK/ET?**

Here are some empirical evidences!

Figure 1. The working framework connecting the dots representing social, economic, and ecosystem functions and land use. The quantitative measure for each dot is population (POP), gross domestic product (GDP), net primary productivity (NPP) of ecosystems, and livestock (LSK), respectively. We focus on the changes in ratios between any two measures in Inner Mongolia (IM) and Mongolia (MG) between 1981 and 2010.

Changes in Livestock density (LSK$_d$) with GDP per capita (GDP$_d$) (a) and ET (b) in KaZ and MG. Each data point represents the provincial means in 2016
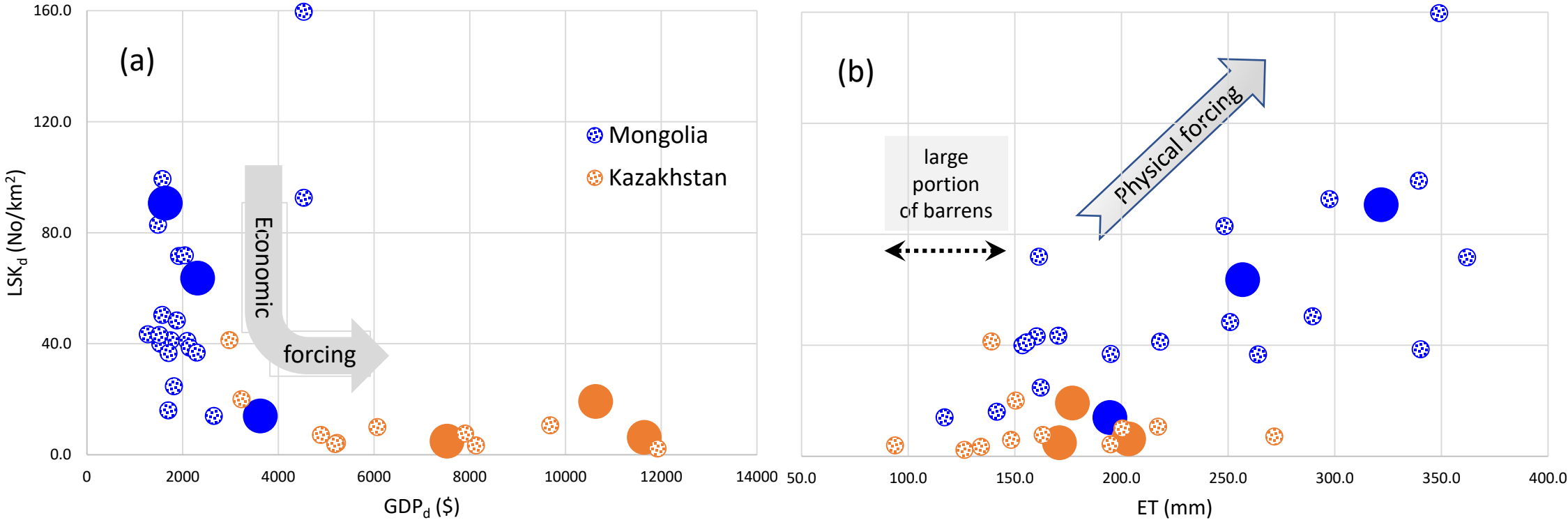
Interrelationships among SES indicators

1) Are society functions dependent of natural functions (e.g., Fig. d-f)?

2) Would population/economic increases affect ecosystem function and agricultural productions?

3) What are the differences among ADB countries?

4) Others?
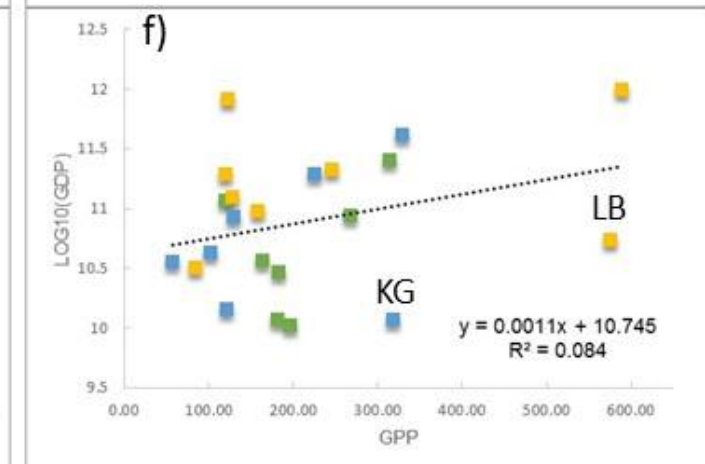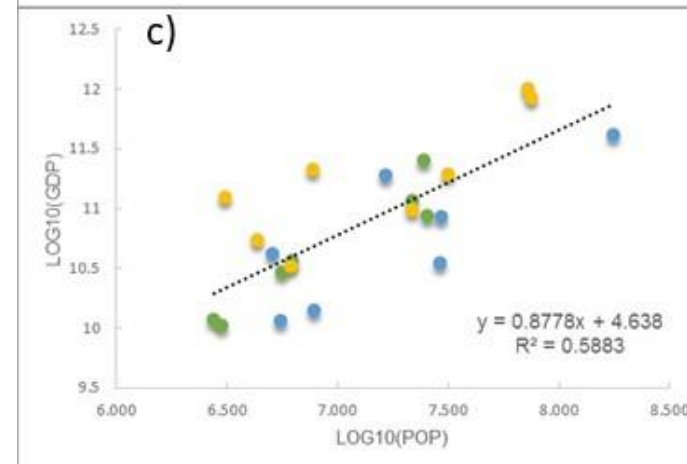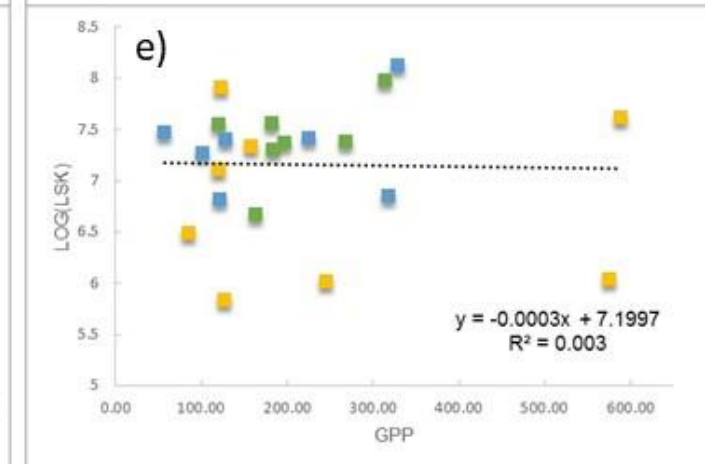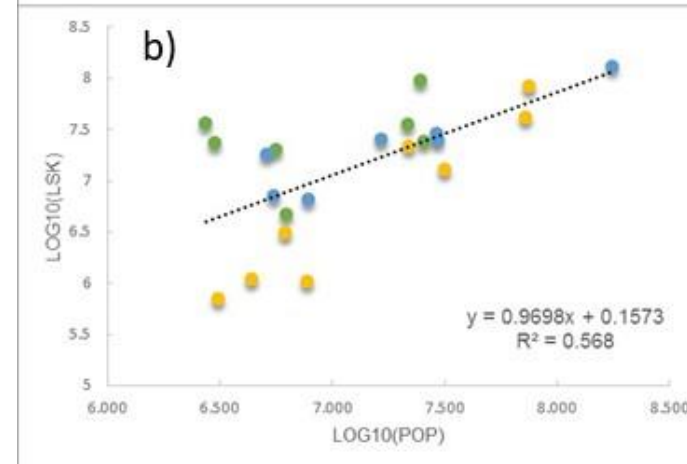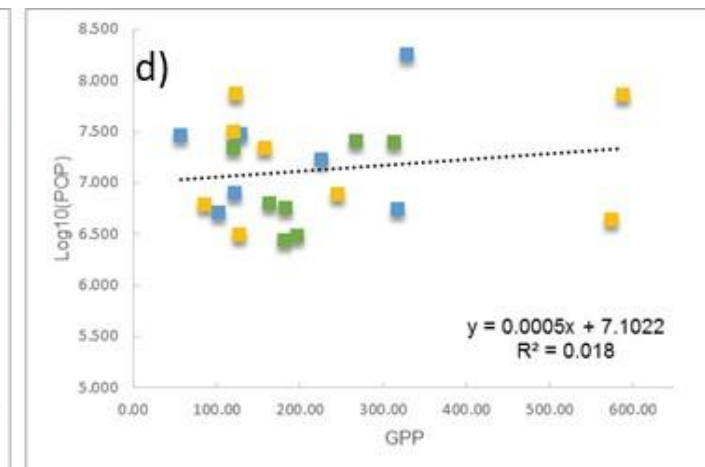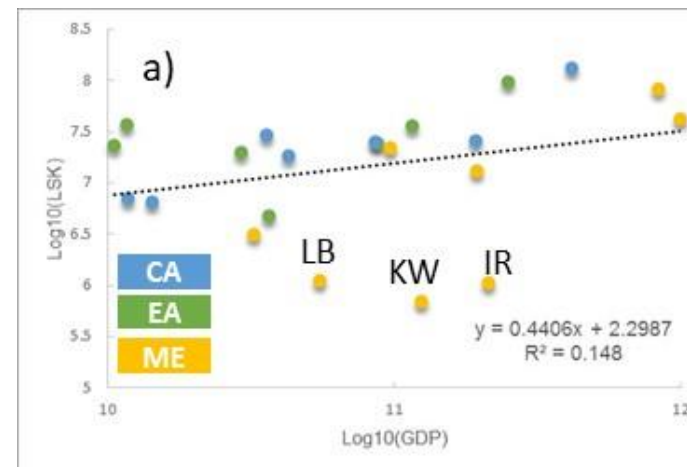
The interdependency at regional level
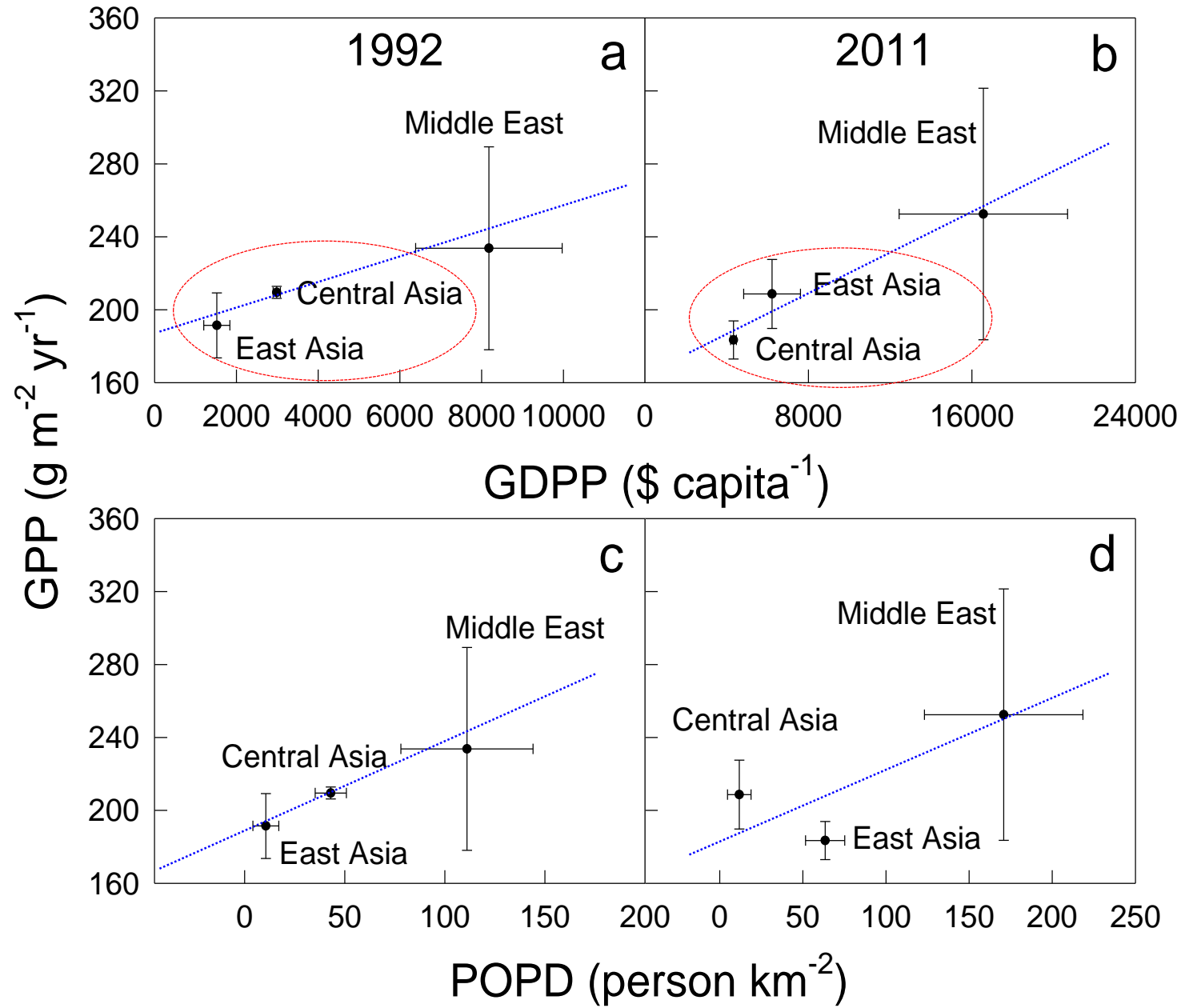
The interdependency at regional level

Empirical relationships between economic (GDP$_{pc}$) and social (LEI) measures with GPP for the ADB region using annual PE data of 1992-2016
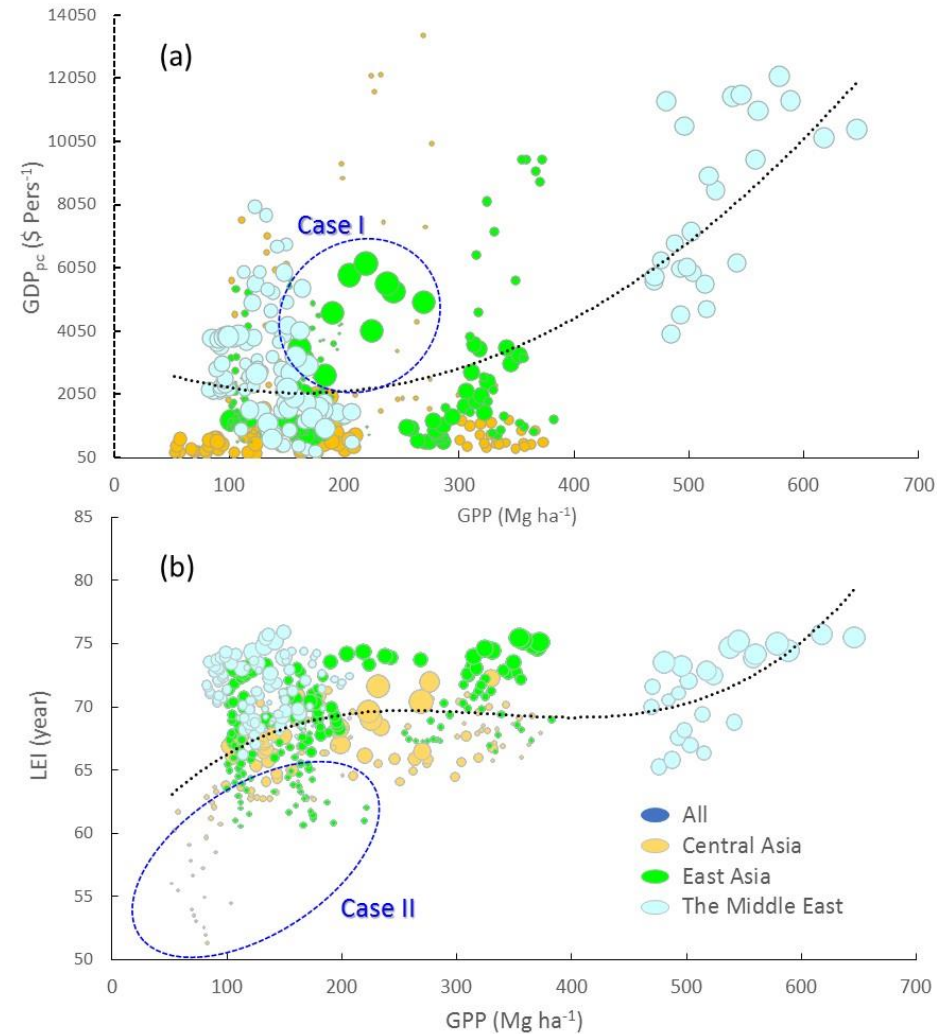
The interdependency at regional level

Empirical relationships of LSK density (LSK$_d$) with (a) GDP per capita (GDP$_{pc}$) and (b) ET in 2016 using the provincial annual statistics of three countries. The dashed lines represent the trending of the three countries with a power function.
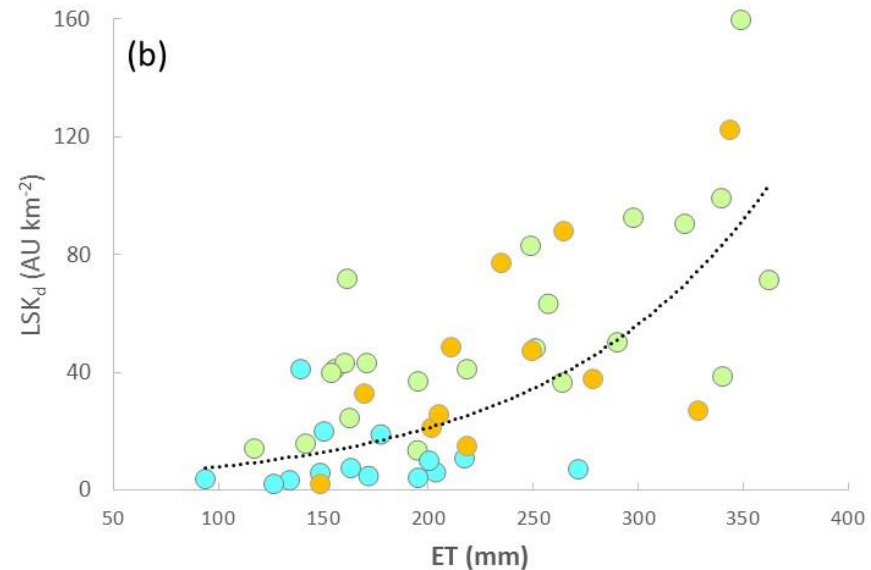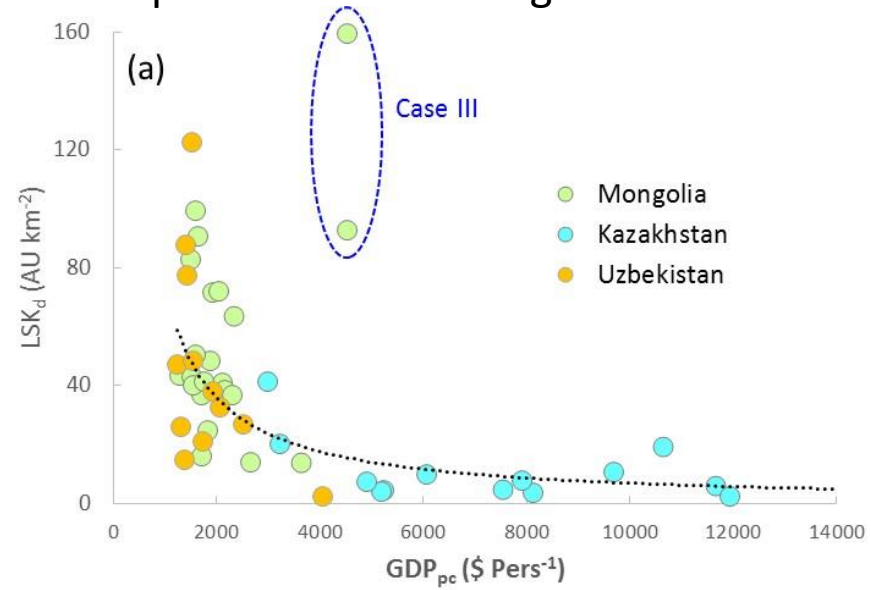
The interdependency at regional level

Amount of land (%) that experienced changes in cover type during 2000-2020 based on the MODIS cover type products. Cyan, green, and yellow represent PEs from the Middle East, Central Asia and East Asia, respectively. Standard deviations (SD) during 1992-2016 were calculated by grouping the PEs into high LCC (>9.1%) and low (≤9.1%) groups, with an overall average of 9.1% (vertical line in the left bar plot).
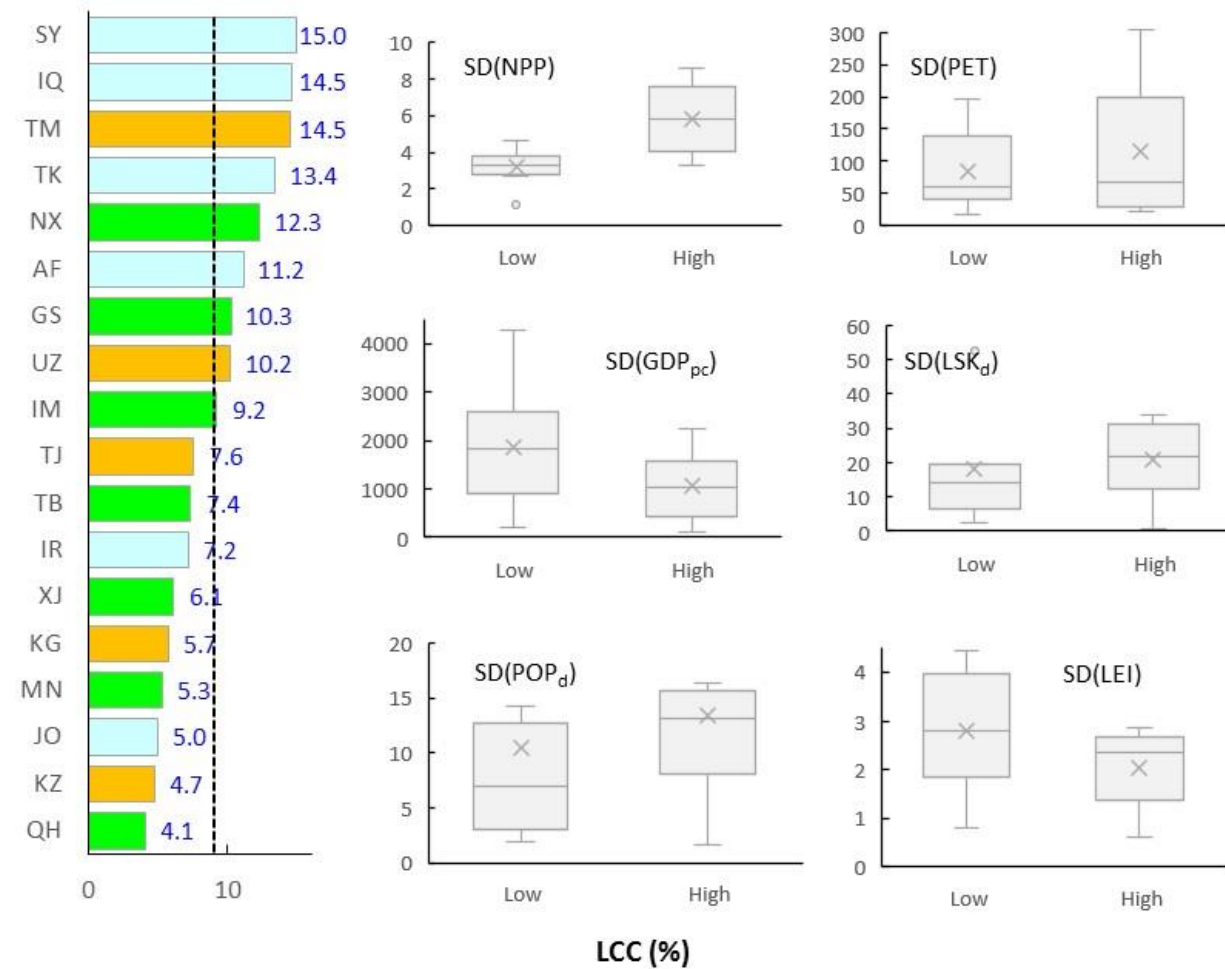
Integrated SES metric: a single metric for integrating SES function:

$$SES_{m1} = \left[\frac{\sqrt{GDP \cdot (A \cdot NPP)}}{POP} \right] \cdot \frac{1}{ET^{\kappa/2}}$$

Where

1) GDP: Gross Domestic Production ($)

2) NPP: Net Primary Production (Mg C.ha^{-}yr^{-1})

3) POP: Population Size (person)

4) WUE: Ecosystem Water Use Efficiency (NPP:ET)

5) A: Land Area of the SES (km^{-2})

6) A·NPP: Total NPP of the SES (Mg C. year^{-1})

1) The unit of NPP can be converted to $ yr^{-1} based on monetary valuations of ecosystem services, resulting in SES_{m1} with a unit of $ yr^{-1} pers^{-1} mm^{-1}.

2) Thus, SES_{m1} can be interpreted as water use efficiency of SES performance. When energy consumption replaces ET, SES_{m1} becomes a measure of energy use efficiency.

Chen et al. 2021

Admirably, many metrics have been developed in each discipline

SOC$_{sys}$

- Population size
- Life expectancy Index
- Education Index
- Health Index
- Years of Schooling
- Prisoner Population
- Crime Rate
- Unemployment Rate
- Poverty Index
- Urban Population
- Literacy rate
- Labor Force
- Net Immigration Rate
- Family Size
- Sex Ratio
- Age structure
- Birth/Death Rate
- …

ECO$_{sys}$

- Gross Primary Production (GPP)
- Net Ecosystem production
- Evapotranspiration (ET)
- Carbon Sequestration strength
- Ecosystem Respiration
- Global Warming Potentials
- Biomass
- Livestock
- Grain production
- Time Volume
- Canopy height/cover
- Stand Density
- Number of Species
- Leaf Area Index
- Diversity Indices
- Soil Water, N, P,
- Water Retention
- …

ECON$_{sys}$

- Gross domestic production
- 2nd and 3rd Industrial Production
- Gross Capital Formation
- Health Expenditure
- Steel Production
- Consumer Index
- Energy Consumption
- Ag. Livestock, Forestry Production
- Income Index
- Import/Export
- Remittance
- CO_2 Emission
- Foreign direct investment
- Inflation
- Military Expenditure
- External Debt Stocks
- Domestic Credit
- …

Here introduce the new SESometric: SES$_{m1}$

Note: IMoSES is used in the final publication (Chen et al. 2021)

1) The term $\frac{(NPP \cdot A)}{POP}$ is called HANPP.

2) The four forms (Eqs. 1-4) are different

3) The term $\sqrt{GDP \cdot (A \cdot NPP)}$ can be interprete[d]
   a measure of total SES production; it depends [on A]
   whereas $\frac{\sqrt{GDP \cdot (A \cdot NPP)}}{POP}$ is an indicator of SES
   production per capita.

$$SES_{m1}^2 = \left[\frac{GDP}{POP} \cdot \frac{(NPP \cdot A)}{POP}\right] \cdot \frac{1}{ET^K}$$

$$= \frac{GDP}{POP} \cdot \frac{1}{POP/A} \cdot \frac{NPP}{ET^K}$$

$$= \frac{GDPpc}{POPd} \cdot WUE \qquad \text{when } \kappa = 1$$

$$= \left[\frac{\sqrt{GDP \cdot (A \cdot NPP)}}{POP}\right]^2 \cdot \frac{1}{ET^K}$$
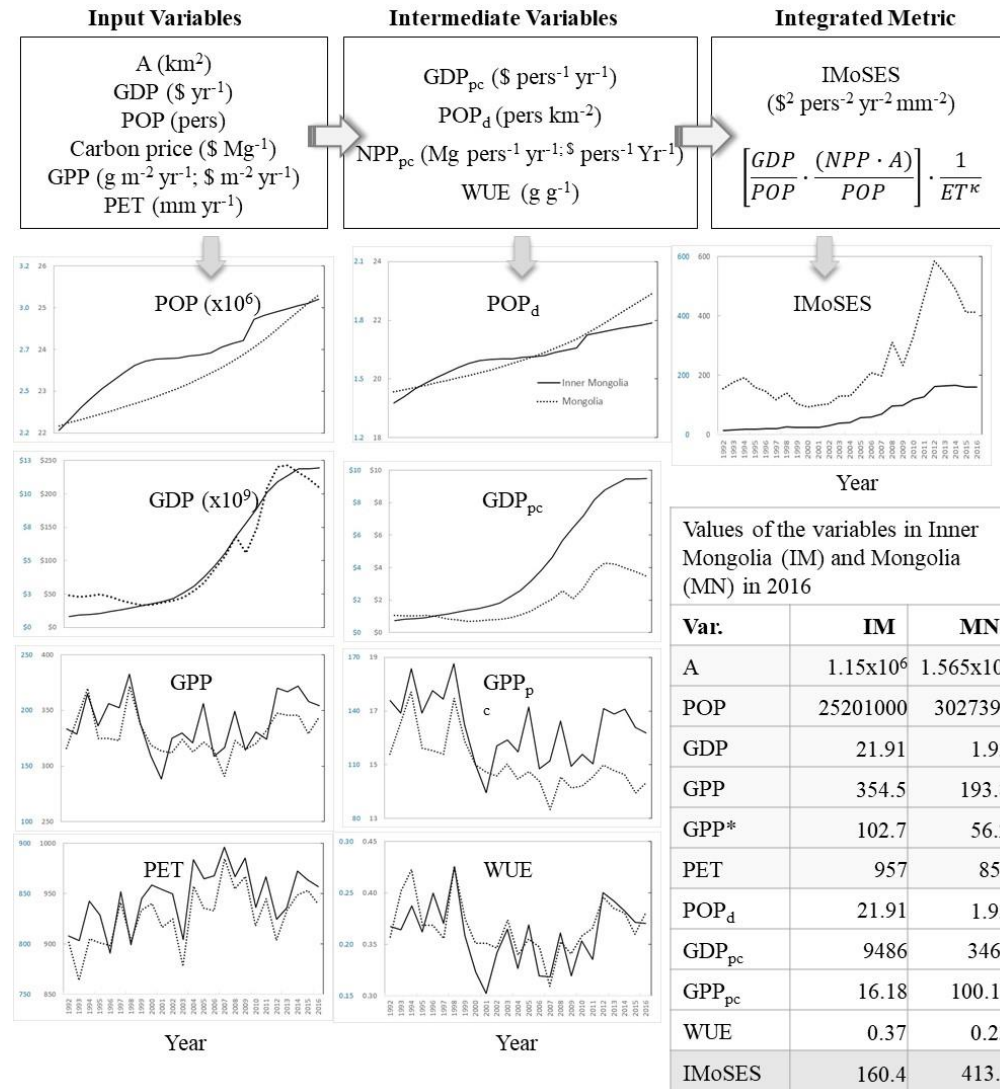
$$SES_{m1} = \left[\frac{\sqrt{GDP \cdot (A \cdot NPP)}}{POP}\right] \cdot \frac{1}{ET^{K/2}}$$

We used public data sources during 1992-2016 to calculate SES_{m1} and to make cross-entity comparisons between SES_{m1} and other metrics in natural and social sciences.

SI-1. Variable names and data sources for SES_{m1} calculations and verifications. GDP in 2020 USD is deflated to constant 2011 dollars using the consumer price index (CPI) from the Bureau of Labors Statistics. Daily carbon price is available. We used the average carbon price of 9.966 Euro per ton of CO_2 and currency exchange rate of $0.7875 per Euro during 2009-2020 due to a lack of price data before 26 October 2009. Livestock was converted to animal unit (Au) equivalents following conversion from livestock to sheep by the FAO (http://www.fao.org/3/y4176e/y4176e04.htm)
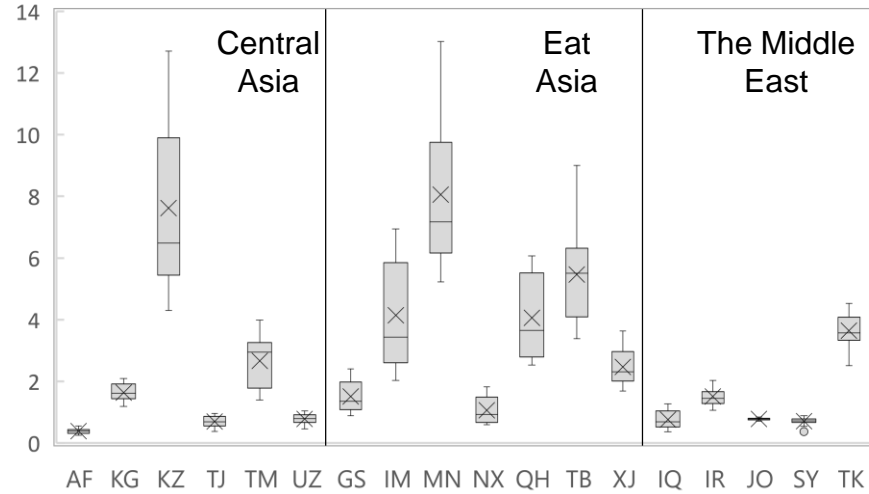
Variable (unit)	Source	Webpage
Political Entity (PE) level (1992–2016)		
NPP (g m^{-2} yr^{-1})	AVHHR	http://glcf.umd.edu/data/glopem/
NPP (g m^{-2} yr^{-1})		https://earthdata.nasa.gov/
PET (mm)	CRU@UEA	http://www.cru.uea.ac.uk/data
GDP ($)	SNA of UN	https://unstats.un.org/unsd/snaama/Basic
POP (pers)	UN	https://population.un.org/wpp/Download/Standard
PDSI (-10, 10)	CRU@UEA	http://www.cru.uea.ac.uk/data
LSK (Au km^{-2})	FAOSTAT	http://www.fao.org/faostat/en/#data/QA
HDI (0-1)	WB	https://datacatalog.worldbank.org/
SDI (0-1)	SDI Team	https://www.sustainabledevelopmentindex.org/
LEI (yr)	WB	https://datacatalog.worldbank.org/
CO_2 & N_2O emission	WB	https://datacatalog.worldbank.org/
Prefecture level (2016)		
NPP (g m^{-2} yr^{-1})	MOD17A3	https://earthdata.nasa.gov/
ET (mm)	MOD16A3	https://earthdata.nasa.gov/
GDP ($)	Yearbooks	https://unstats.un.org/unsd/snaama/Basic
POP (n)	Yearbooks	http://data.stats.gov.cn/easyquery.htm?cn=E0103
LSK (Au)	Yearbooks	http://data.stats.gov.cn/easyquery.htm?cn=E0103
Others		
Temperature (^{o}C)	CRU4.04	https://crudata.uea.ac.uk/cru/data/hrg/
Precipitation (mm)	CRU4.40	https://crudata.uea.ac.uk/cru/data/hrg/
Carbon Price ($ Ton CO_2)	Markets Insider	https://markets.businessinsider.com/

Calculations of the intermediate variables and IMoSES from six input variables for Inner Mongolia (IM) and Mongolia (MN) to illustrate the changes of input variables, intermediate variables and IMoSES. Because of the large differences between the two jurisdictions, independent vertical axes are used for MN (leftmost labels, blue) and IM (rightmost labels, grey). The vertical axes are scaled for easy visualization of the changes over time.
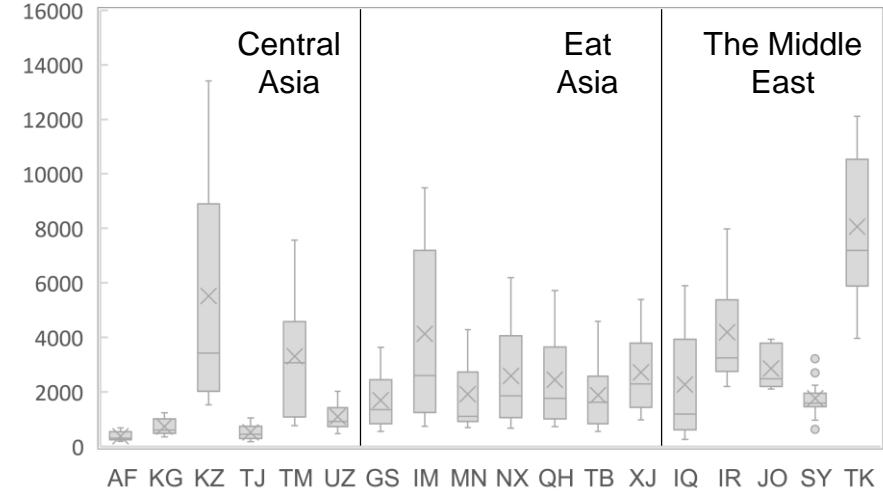

Input Variables	Intermediate Variables	Integrated Metric
A (km²) GDP ($ yr⁻¹) POP (pers) Carbon price ($ Mg⁻¹) GPP (g m⁻² yr⁻¹; $ m⁻² yr⁻¹) PET (mm yr⁻¹)	GDP_{pc} ($ pers⁻¹ yr⁻¹) POP_d (pers km⁻²) NPP_{pc} (Mg pers⁻¹ yr⁻¹; $ pers⁻¹ Yr⁻¹) WUE (g g⁻¹)	IMoSES ($^2 pers⁻² yr⁻² mm⁻²) $$\left[\frac{GDP}{POP} \cdot \frac{(NPP \cdot A)}{POP}\right] \cdot \frac{1}{ET^\kappa}$$

Values of the variables in Inner Mongolia (IM) and Mongolia (MN) in 2016

Var.	IM	MN
A	1.15x10⁶	1.565x10⁶
POP	25201000	3027398
GDP	21.91	1.93
GPP	354.5	193.8
GPP*	102.7	56.2
PET	957	853
POP_d	21.91	1.93
GDP_{pc}	9486	3463
GPP_{pc}	16.18	100.17
WUE	0.37	0.23
IMoSES	160.4	413.0

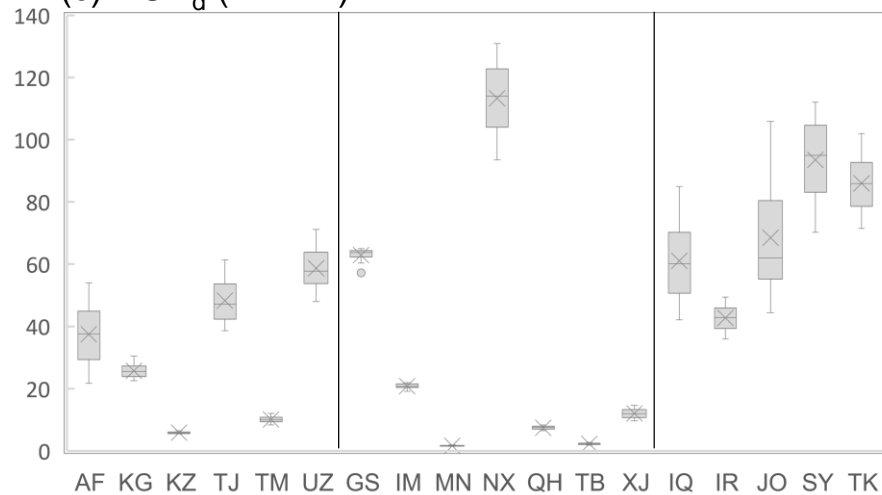# Boxplots of SES$_{m1}$ & its three components during 1992–2016

(a) SES$_{m1}$ ($ yr^{-1} pers^{-1} mm^{-1})

(b) GDP$_{pc}$ ($ pers^{-1})
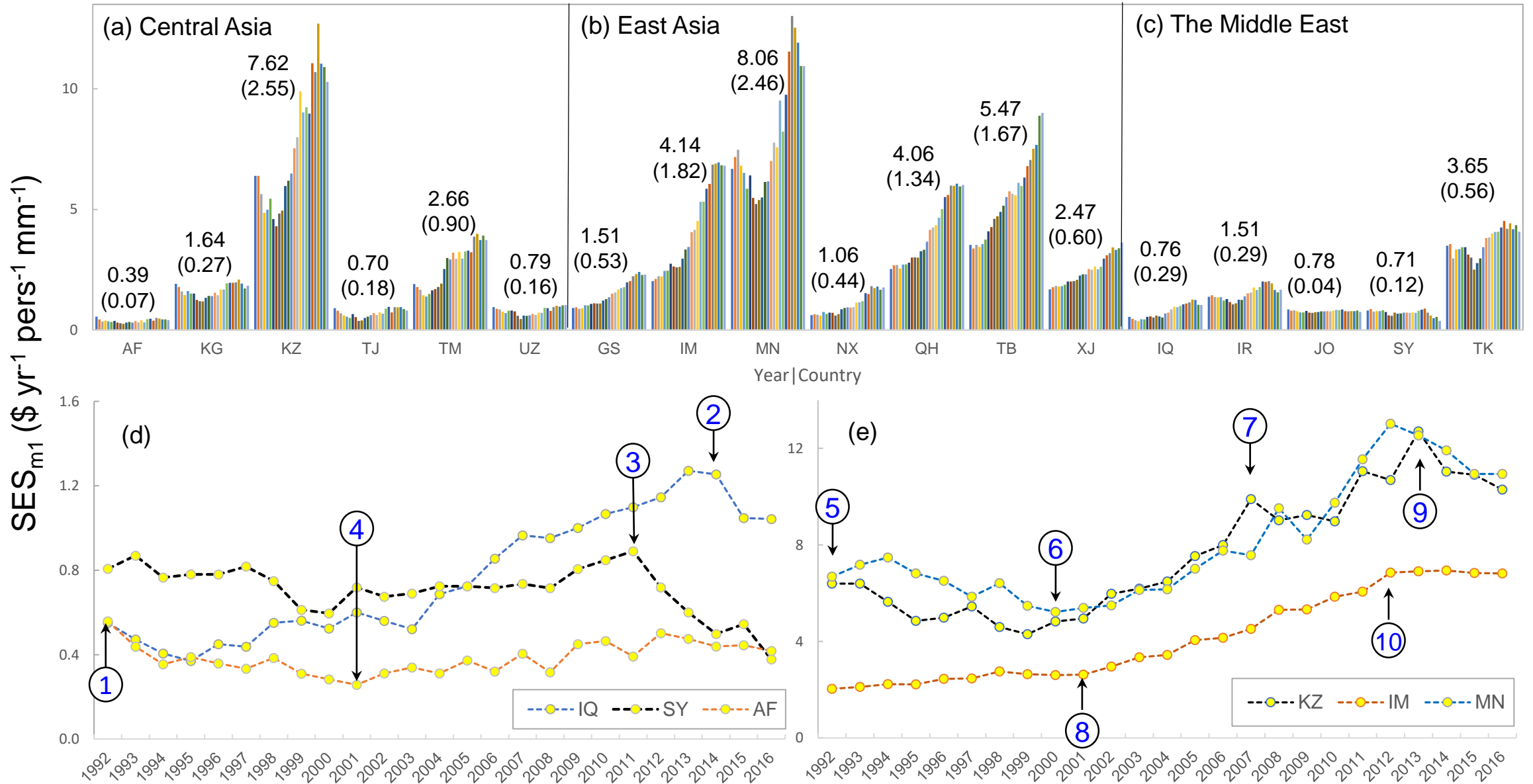
(c) POP$_d$ (N km^{-2})

(d) HANPP (Ton pers^{-1})

Central Asia   Eat Asia   The Middle East

AF KG KZ TJ TM UZ GS IM MN NX QH TB XJ IQ IR JO SY TK

Chen et al. 2021
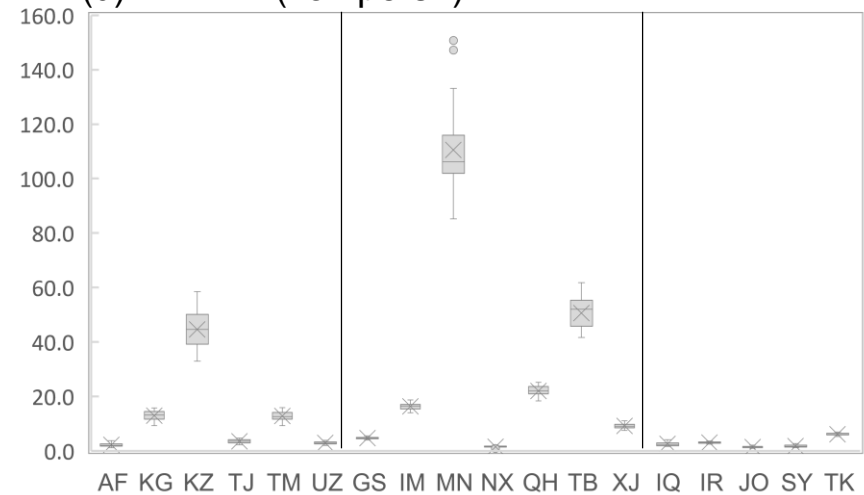
Changes in SES$_{m1}$ during 1992-2016 across the ADB
Pivotal Roles of Institutional Changes

Distributions of SES_{m1} with Palmer Drought Severity Index (PDSI) and Human Development Index (HDI) for the 18 political entities

- The strong correlations with PDSI indicate that SES_{m1} changes with environmental conditions, similar to the idea behind the environmental Kuznets curve.

- The observed decrease in LSK_d with SES_{m1} indicates the potential constraints of SES performance on livestock development.

Chen et al. 2021
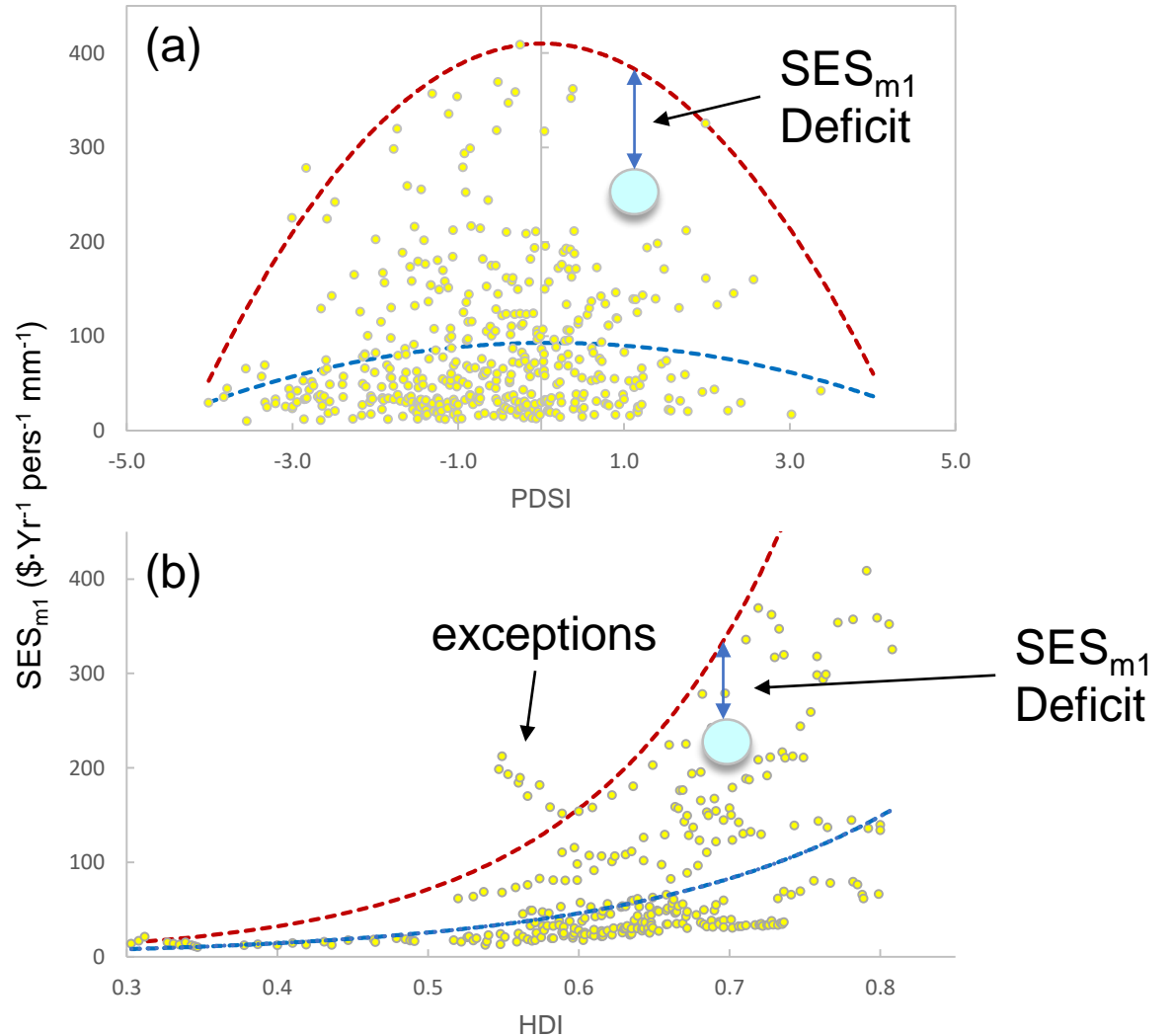
It appears that

- The SES_{m1} is a product of GDP_{pc} and HANPP, rather than the linear sum of three components;

- Proposed SES_{m1} addresses the lack of environmental regulatory function that is missing in the HDI;

- In-depth investigations are needed to explore how well SES_{m1} aligns with other indicators;

- The relationship between SES_{m1} and other social indicators would increase understanding of the alignment between GDP and social aspects that together encapsulate the idea of economic development;

- From a global perspective, it would be important to identify countries with similar SES_{m1} trajectories, which are indicative of similar dynamics among the three pillars.

Sustainability Index (SI) of the 22 political entities in 1992, 2001, 2011
(2016 was included in Chen et al. 2021)

SI
- 0.00 - 0.10
- 0.11 - 0.20
- 0.21 - 0.30
- 0.31 - 0.40
- 0.41 - 0.50
- 0.51 - 0.60

(a) 1992

(b) 2001

(c) 2011

LEI
GDP$_P$
GPP$_P$
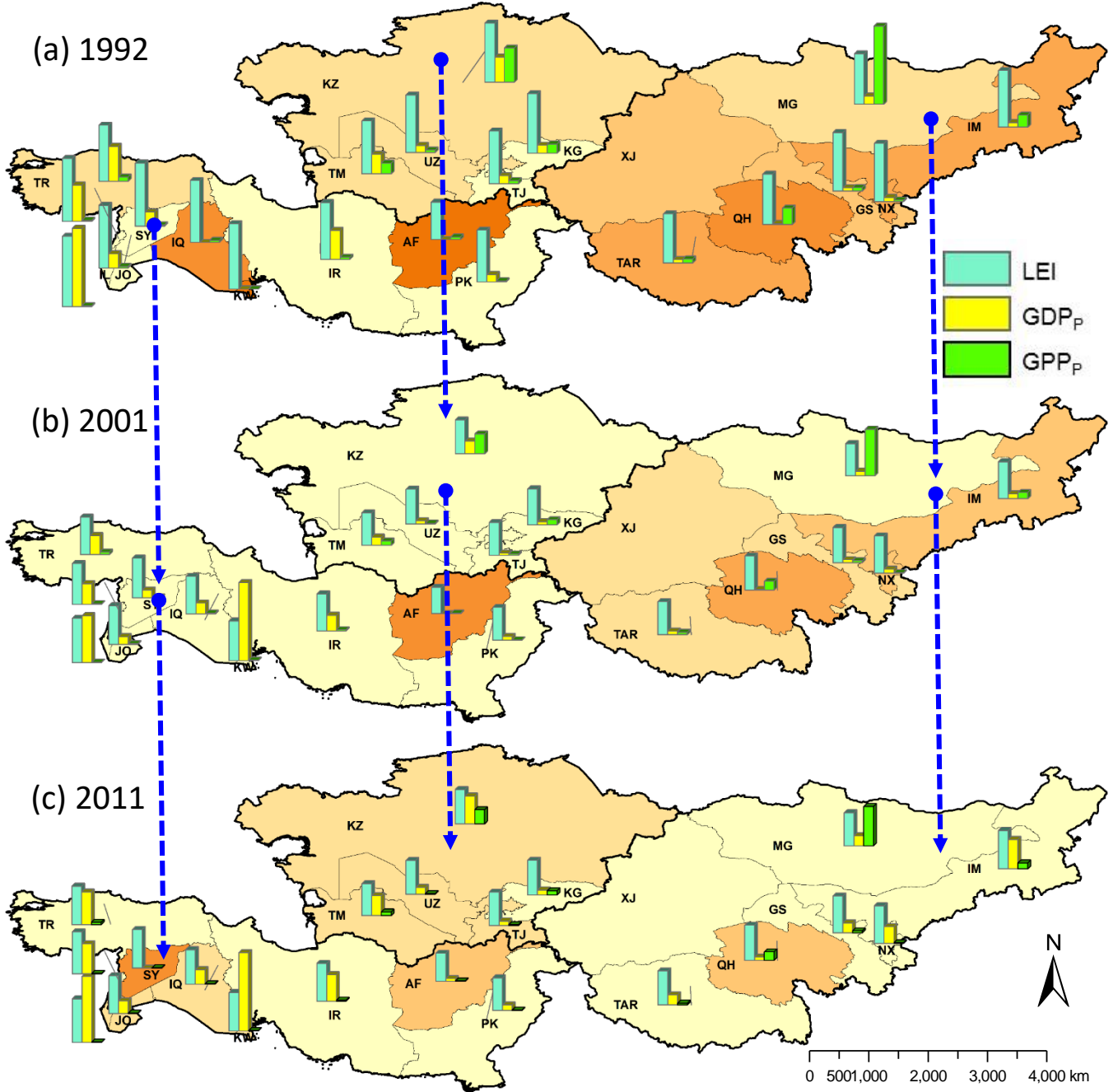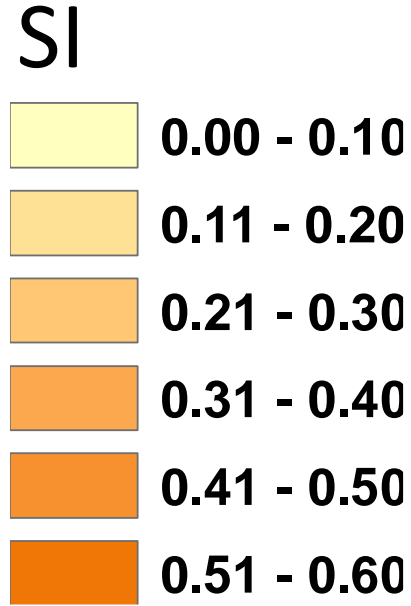
The results are updated for 2020 for next MS!

0 500 1,000 2,000 3,000 4,000 km

In Sum, the major challenges for the sustainability of ADB SES include:

1) Reduced water quantity and quality under warming, drying, and escalating extreme events

2) Continued, if not intensifying, geopolitical conflicts

3) Volatile, uncertain, and shifting socioeconomic structures

4) Intensification and shifts in land use for land cover change

5) Globalization and cross-country influences

Conceptual framework illustrating the research approaches for SES. The entangled elements of *EcoSys, SocSys* and *EconSys* are driven by changes in global climate, market, technology, informational technology, *etc.* for modeling the SES dynamics. Institutional structure and shift are proposed as the foundation for understanding the complex interactions among the nodes of the three pillars, with LCC mediating the interactions and feedback among three pillars.

Chen et al. 2022. ERL
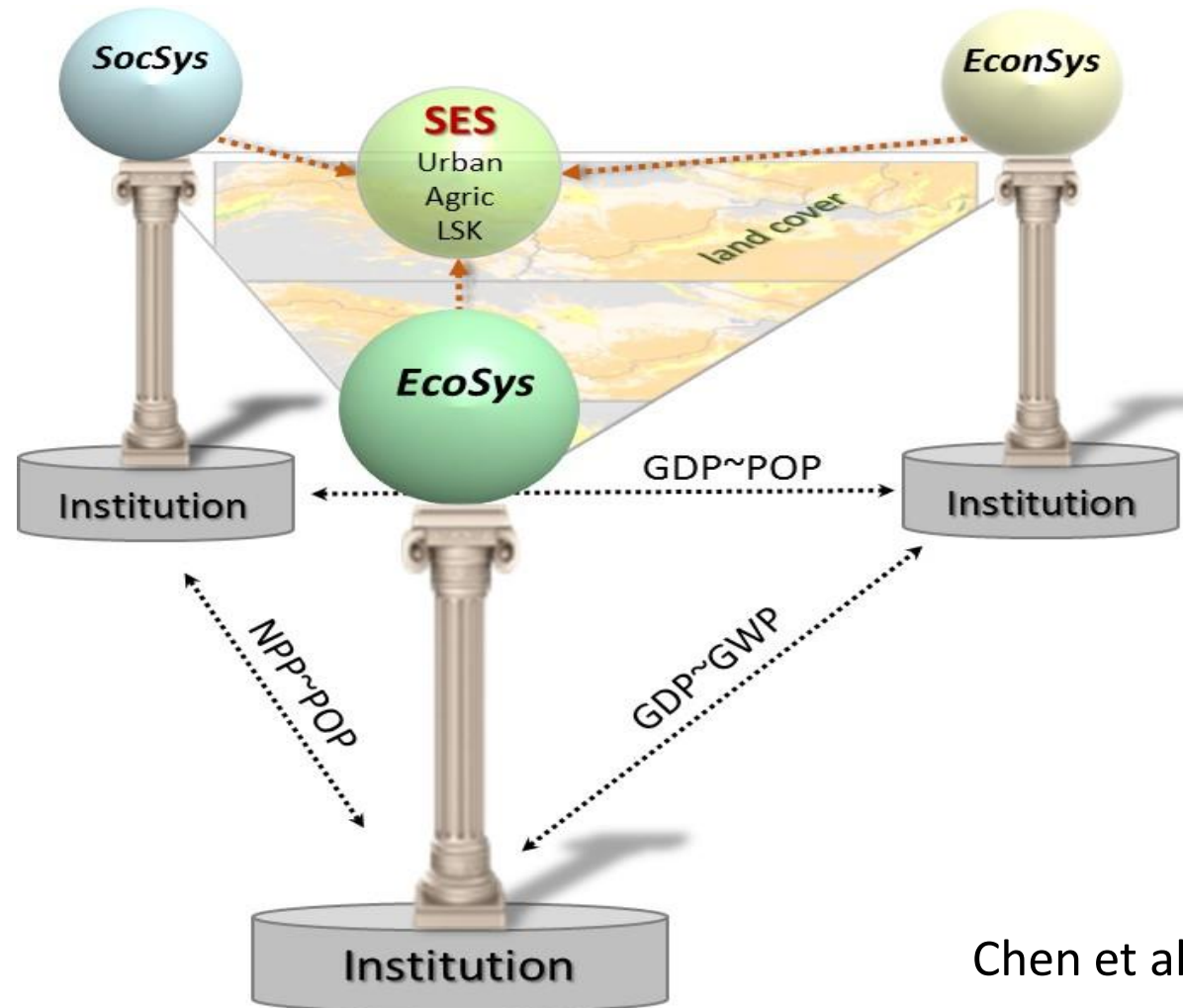
Each management option is accompanied with some expectations and many surprises

1) <u>Jafar tricked by Aladdin</u>: the power fighting for the lamp between evil and people continues throughout;
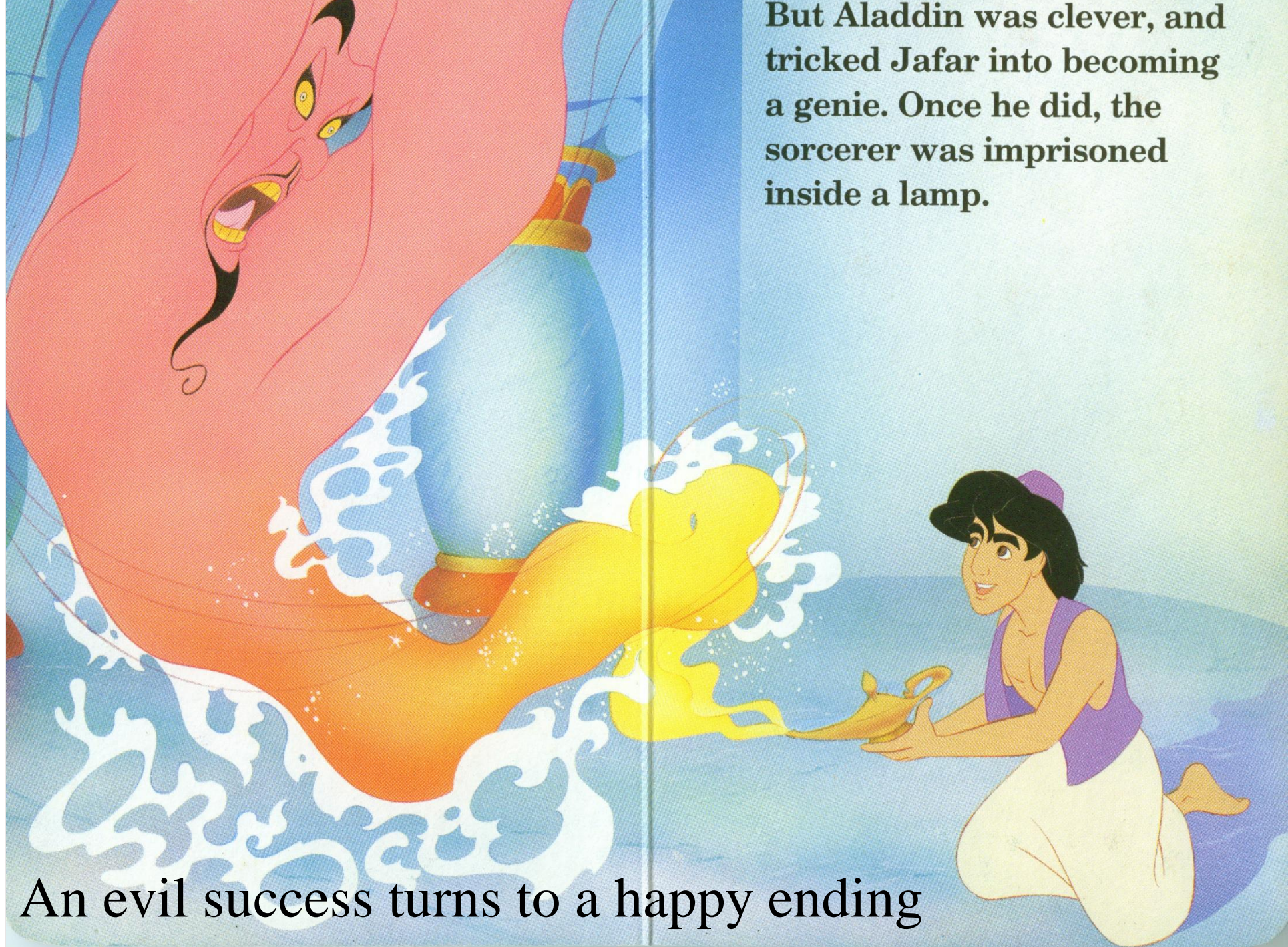
Meanwhile, Jafar and his parrot, Iago, plotted to steal the lamp.

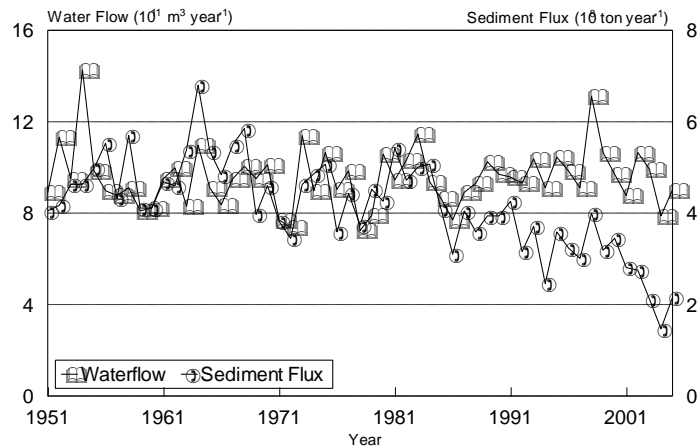With the genie's magic, the evil sorcerer would be all-powerful!
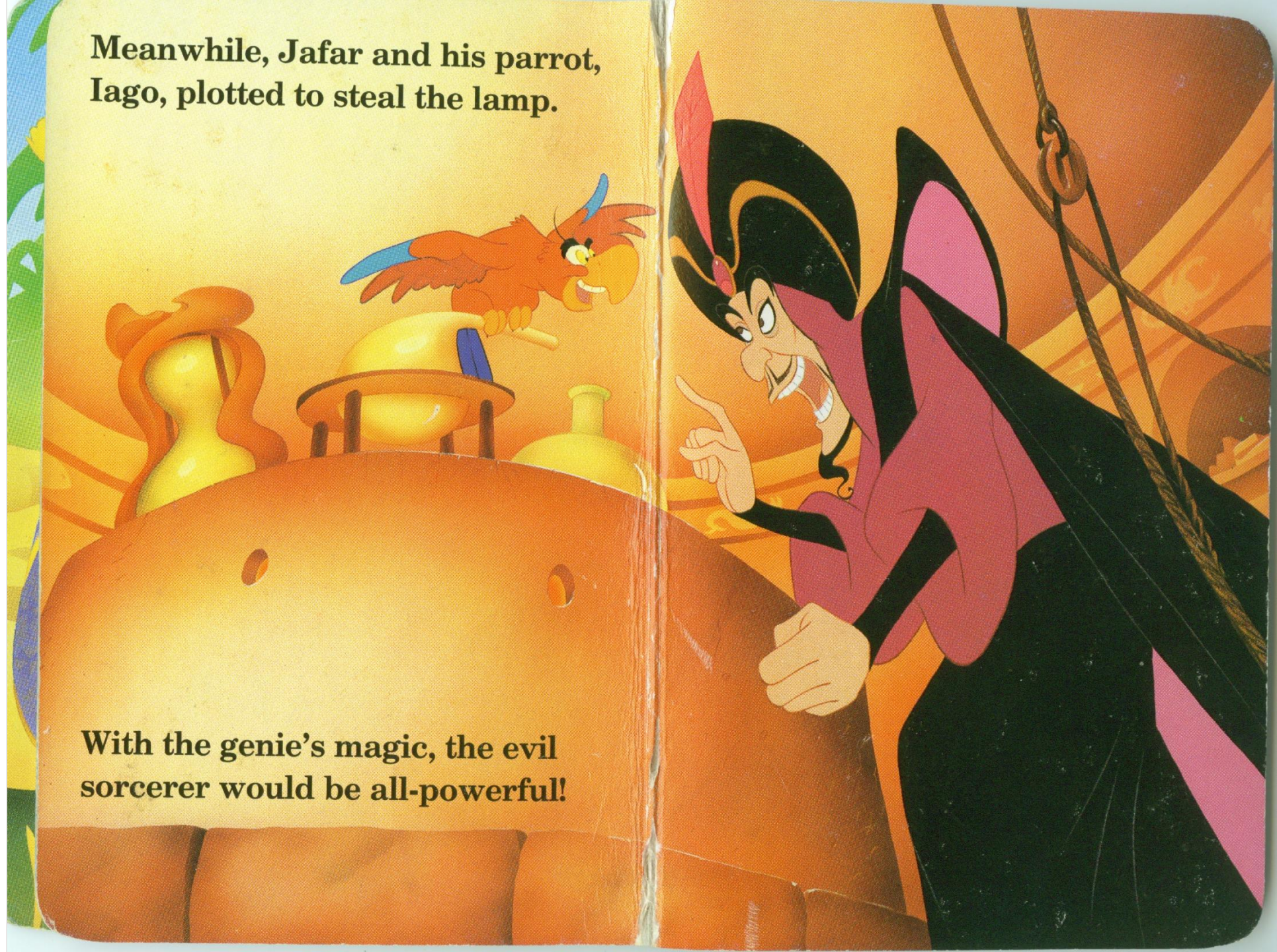
But Aladdin was clever, and tricked Jafar into becoming a genie. Once he did, the sorcerer was imprisoned inside a lamp.
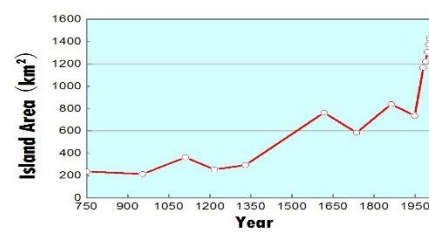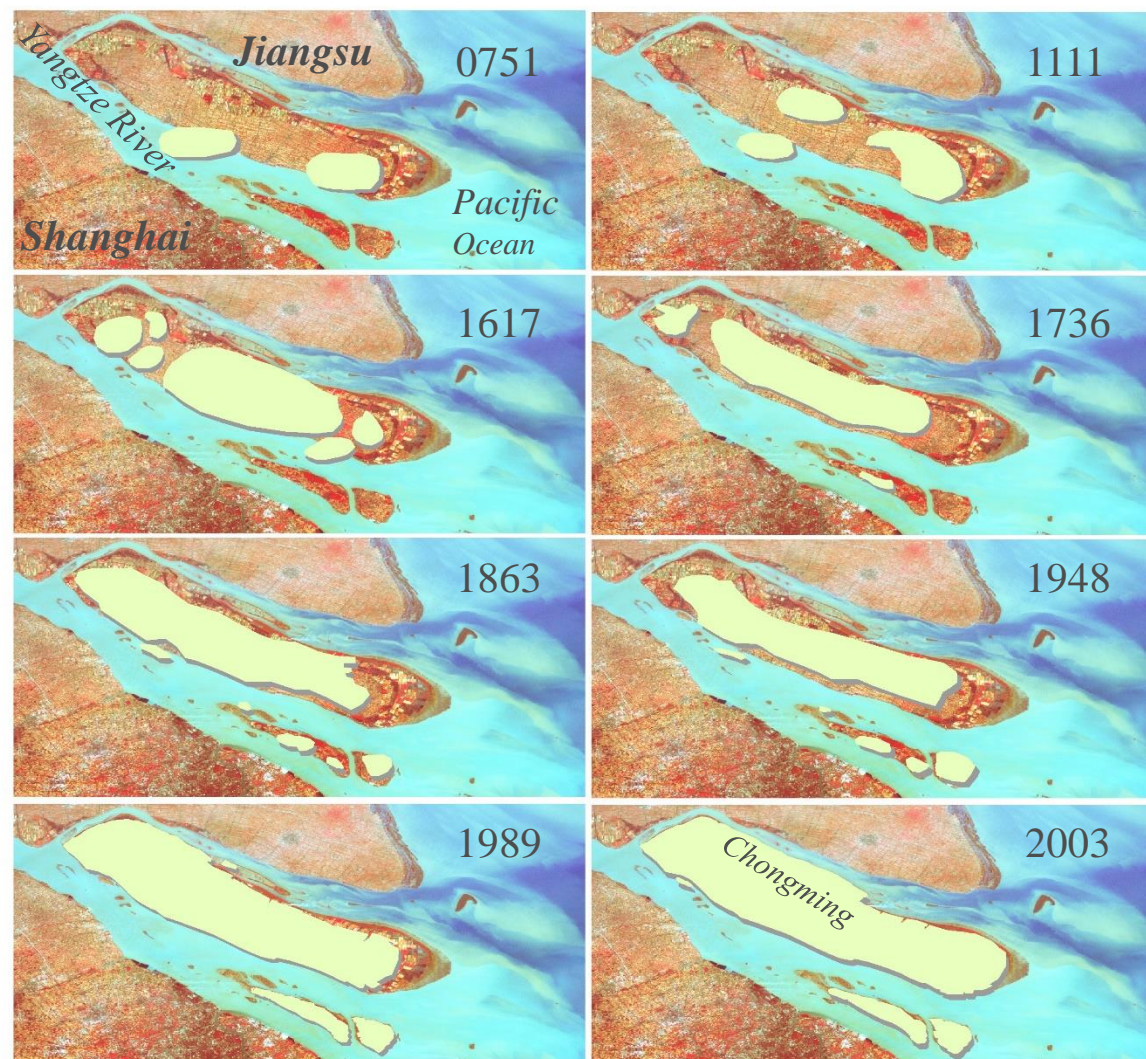
An evil success turns to a happy ending

Growing islands
(120/year) were
measured because of
large amount of
sediments carried down
from >2000 km polluted
Yangtze River.

The island has been growing

Chen et al. 2008

Invasive *Spartina* on coastal islands of eastern China.

It provides a powerful filtering function clean water from heavily polluted Yangtze River and higher carbon sequestration;

But native species lose their habitats

Policy-Driven Migration in Mongolia

Abandoned village in Inner Mongolia, China