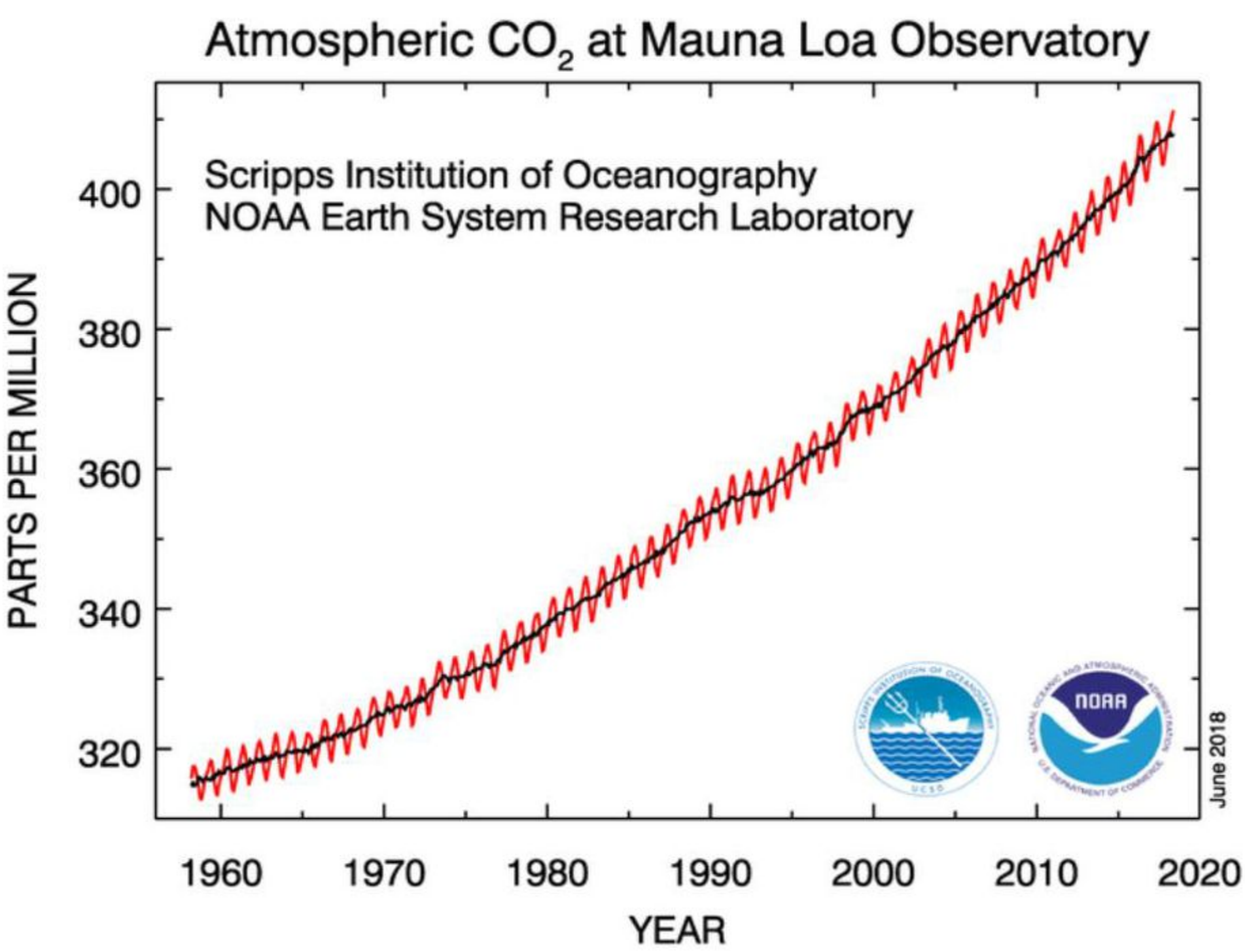
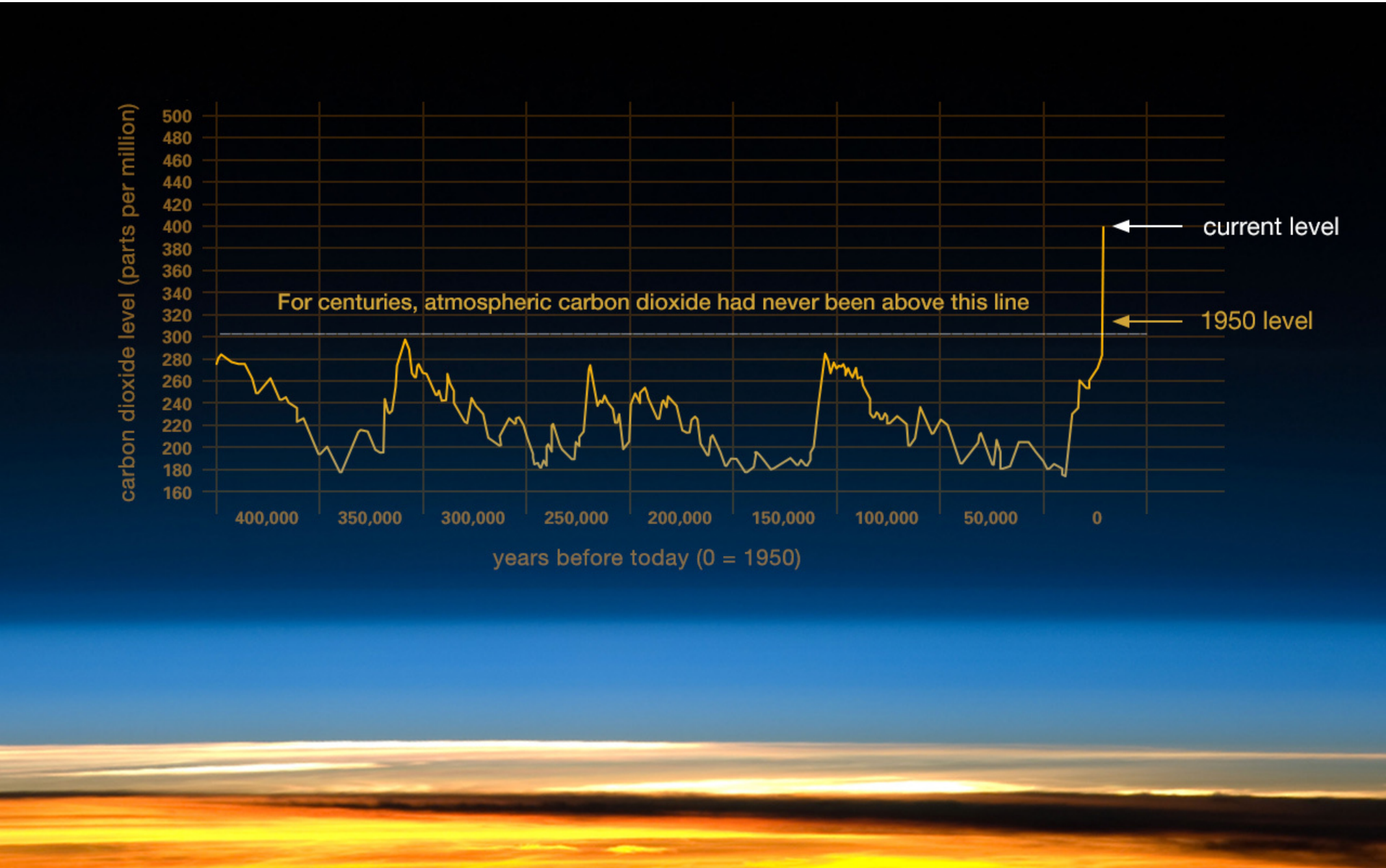
A Mathematical Model of National Sustainability: Where the World is Heading

Yannis A. Phillis
Technical University of Crete, Greece


Atmospheric CO_2 at Mauna Loa Observatory
Scripps Institution of Oceanography
NOAA Earth System Research Laboratory
PARTS PER MILLION
400
380
360
340
320
1960
1970
1980
1990
2000
2010
2020
YEAR
June 2018


carbon dioxide level (parts per million)
500
480
460
440
420
400
380
360
340
320
300
280
260
240
220
200
180
160
For centuries, atmospheric carbon dioxide had never been above this line
current level
1950 level
400,000
350,000
300,000
250,000
200,000
150,000
100,000
50,000
0
years before today (0 = 1950)

252 million years ago the Permian-Triasic extinction occurred

96% of marine species and

70% land vertebrates became extinct.

Cause:

Ocean hypoxia due to climate warming.

Cause:

Tremendous volcanic activity in the Siberian Traps released enormous quantities of CO_2 and CH_4

The importance of national sustainability and its assessment cannot be overstated nowadays.

It is also clear that this type of sustainability cannot be focused only on some narrow aspect of social or environmental performance.

Instead, it should encompass a holistic viewpoint of ecological, social, and economic components.

Two major categories of sustainability assessment models:

Basic.

They consider particular aspects of sustainability

Barometers of sustainability.

They are aggregated sustainability approaches

First category:

- Pressure-State-Response (PSR) framework of OECD
- Ecological footprint
- Green GDP

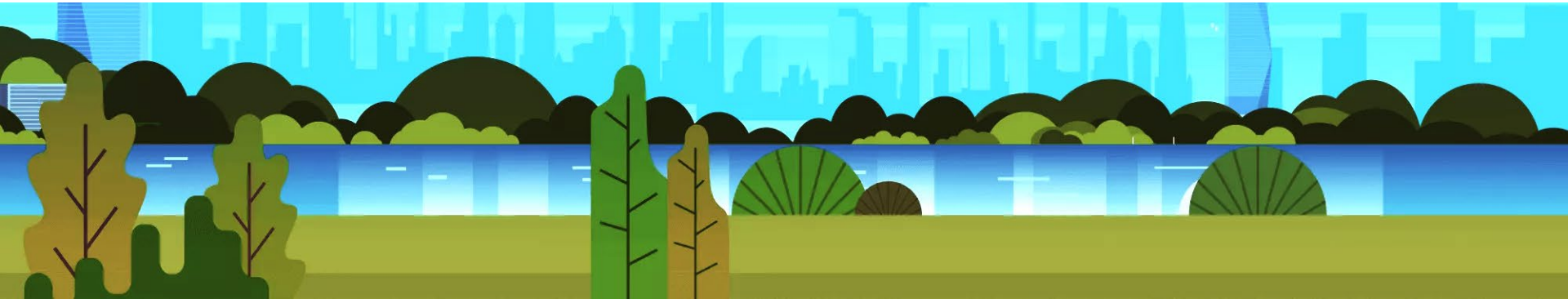
  (it quantifies the environmental impact of economic growth)

2nd category:
Environmental Performance Index (EPI)
It is based on
24 indicators across ten facets of environmental health:

1. air quality
2. water and sanitation
3. heavy metals
4. biodiversity and habitat
5. forests
6. fisheries
7. climate and energy
8. air pollution
9. water resources
10. agriculture

The Sustainable Society Index (SSI) is based on 21 environmental and social indicators aggregated into 7 main categories:

1. basic needs
2. personal development and health
3. well-balanced society
4. natural resources
5. climate and energy
6. transition
7. economy



Individual indicators are normalized and aggregated using a geometric average to generate a score for each category.

Better Life Index proposed by OECD is an interactive web-based tool that compares well-being across countries based on 11 topics:

1. community
2. education
3. environment
4. civic engagement
5. health
6. housing
7. income
8. jobs
9. life satisfaction
10. safety
11. work-life balance

Normalized indicators are aggregated using equal weights to generate an overall score for each topic.

No overall index is given.

Instead,

users obtain their own index

based on their weighting preferences.

Human Development Index (HDI) developed by the United Nations Development Program.

HDI is calculated using a geometric mean of country scores on 3 major dimensions:

1. **longevity**
2. **access to knowledge**
3. **standard of living**

Other sustainability assessment approaches include:

- the Genuine Progress Indicator (GPI)
- the Index for Sustainable Economic Welfare
- the Legatum Prosperity Index
- the Living Planet Index

SAFE, compared to the previous approaches has the following major advantages:

- it is nonlinear
- the model uses fuzzy logic to handle the vagueness of sustainability
- SAFE is a holistic approach of environmental and social aspects
- the incorporated sensitivity analysis identifies the most important indicators
- the model takes into account past performance

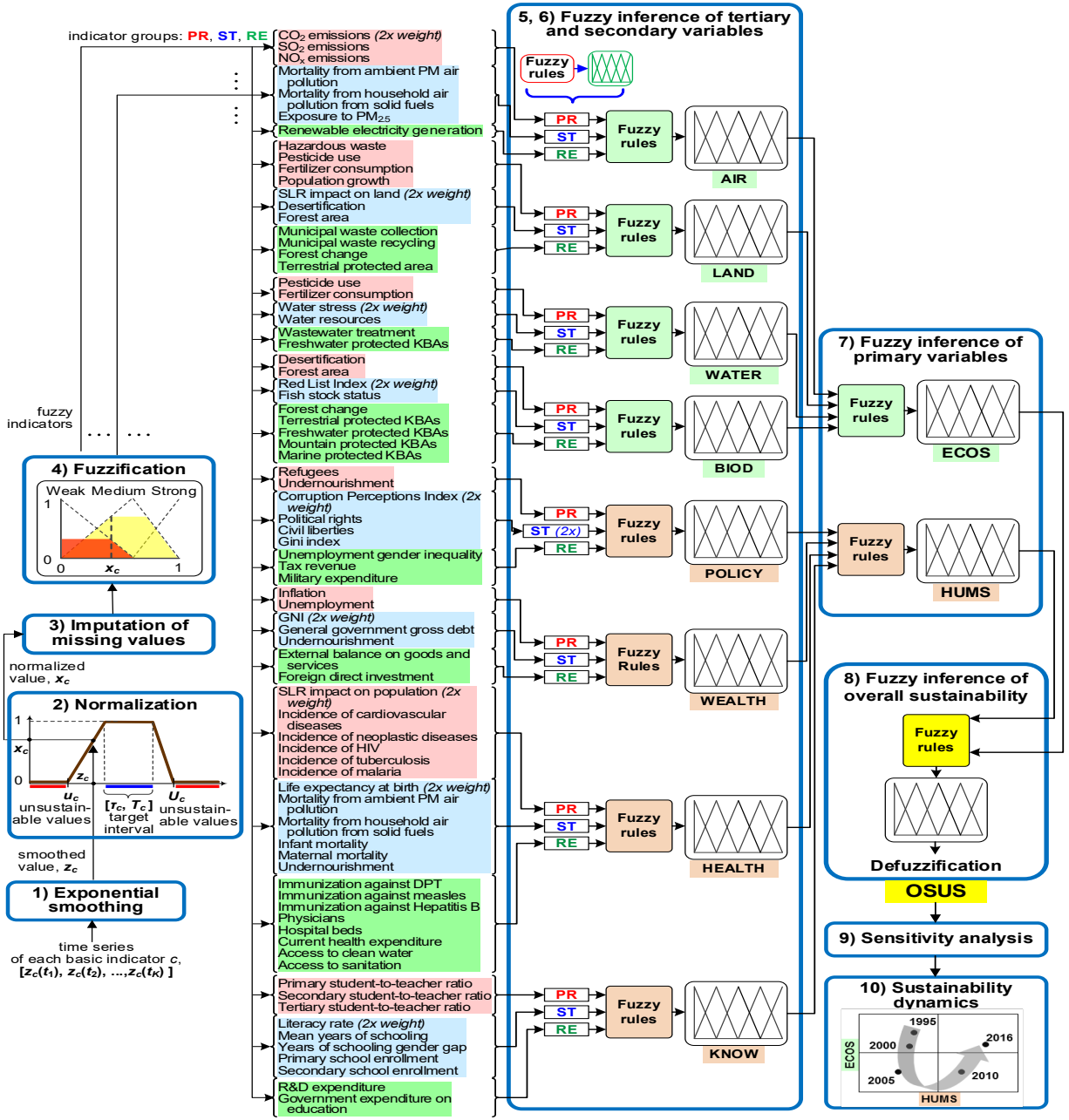


Fig. 1
Computational steps of the SAFE model

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
AIR	PR	Carbon dioxide (CO_2) emissions (tons per capita per year)	SB	T=5.2 (EU[b] target[c]), U=19.75 (97.5th percentile of all countries)
AIR	PR	SO_2 emissions (kg per capita per year)	SB	T=3.06 (min of EU14[d] countries), U=99.24 (97.5th percentile of all countries)
AIR	PR	NO_x emissions (kg per capita per year)	SB	T=13.57 (min of EU14 countries), U=60.70 (97.5th percentile of all countries)
AIR	ST	Mortality from ambient particulate matter (PM) air pollution (deaths per 100,000 population per year)	SB	T=0 (min possible), U=125.5 (max of all countries)
AIR	ST	Mortality from household air pollution from solid fuels (deaths per 100,000 population per year)	SB	T=0 (min possible), U=123.9 (max of all countries)
AIR	ST	$PM_{2.5}$ air pollution (average annual exposure to PM less than 2.5 microns in diameter in $\mu g/m^3$)	SB	T=10 [World Health Organization guideline (WHO, 2006, p.9)], U=87.45 (97.5th percentile of all countries)
AIR	RE	Renewable electricity generation (% of total electricity generation)	LB	u=0 (min of all countries), τ=100 (max possible)
LAND	PR	Hazardous waste (kg generated per capita per year)	SB	T=0 (min possible), U=818.4 (max of EU14)
LAND	PR	Pesticide use (tons per hectare of arable land per year)	SB	T=4.393 (average of EU14), U=9.979 (max of EU14)
LAND	PR	Fertilizer consumption (kg per hectare of arable land per year)	SB	T=172.8 (average of EU14 excluding Ireland), U=316.7 (max of EU14 excluding Ireland)
LAND	PR	Population growth (annual % rate)	SB	T=0 (only nonpositive growth rates can be sustainable), U=2.293 (max of EU)
LAND	ST	Sea level rise (SLR) impact on land (% of land where elevation is lower that 3 m)	SB	T=0 (min possible), U=25 (one quarter of the total land)

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
LAND	ST	Desertification (annual increase of terrestrial barren land as a percentage of total land area)	SB	T=0 (no increase or net reduction), U=0.006183 (97.5th percentile of all countries)
LAND	ST	Forest area (% of the total forest area in 1990)	LB	u=24.55 (min of all countries), τ=109.99 (average of EU)
LAND	RE	Municipal waste collection (% of population served by municipal waste collection)	LB	u=0 (min possible), τ=100 (max possible)
LAND	RE	Municipal waste recycling (% of the municipal waste collected which is recycled)	LB	u=0 (min possible), τ=26.63 (average of EU14)
LAND	RE	Forest change (annual trend component of forest area time series, expressed as a percentage of the total area)	LB	u=0 (a negative trend is unsustainable), τ=0.6777 (97.5th percentile of all countries)
LAND	RE	Terrestrial protected area (% of total land area)	LB	u=0.23 (min of all countries), τ=53.86 (max of all countries)
WATER	PR	Pesticide use; see above		
WATER	PR	Fertilizer consumption; see above		
WATER	ST	Water stress (freshwater withdrawals percent of total resources net of quantities required to sustain freshwater and estuarine ecosystems)	SB	T=25 and U=75 [Food and Agriculture Organization of the United Nations target levels (FAO, 2017))
WATER	ST	Water resources (maximum theoretical yearly amount of water available in m^3 per capita)	LB	u=1,000 (value for South Africa), τ=50,000 (a rounded 90th percentile)
WATER	RE	Wastewater treatment (% of population connected to wastewater treatment plants)	LB	u=2.760 (2.5th percentile), τ=97.105 (average of EU14)

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
WATER	RE	Freshwater protected Key Biodiversity Areas (KBAs) (% of total freshwater KBAs)	LB	u=0 (min possible), τ=100 (max possible)
BIOD	PR	Desertification; see above		
BIOD	PR	Forest area; see above		
BIOD	ST	Red List Index (RLI) (a measure in [0, 1] of the distance from extinction of all species in a country)	LB	u=0.6543 (2.5th percentile), τ=1 (max possible)
BIOD	ST	Fish stock status (% of fish catch classified as either over-exploited or collapsed)	SB	T=0 (min possible), U=100 (max possible)
BIOD	RE	Forest change (trend component of forest area time series, % of total area; 1990-2015)	LB	Trend component of forest area time series; u=0% (only a positive trend is sustainable) τ=0.63% (97.5th percentile of all countries)
BIOD	RE	Terrestrial protected KBAs (% of total terrestrial KBAs)	LB	u=0 (min possible), τ=100 (max possible)
BIOD	RE	Mountain protected KBAs (% of total mountain KBAs)	LB	u=0 (min possible), τ=100 (max possible)
BIOD	RE	Marine protected KBAs (% of total marine KBAs)	LB	u=0 (min possible), τ=100 (max possible)
POLICY	PR	Refugees (number of refugees from a country per 100,000 population of that country)	SB	T=250 and U=1000 [according to the P-assessment function of Fig. 10 in Bossel (1999)]
POLICY	PR	Undernourishment (% of population)	SB	T=2.5 (min of all countries), U=61.8 (max of all countries)

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
POLICY	ST	Corruption Perceptions Index (CPI) (value in [0, 100], 0 representing the most corrupt and 100 the least corrupt country)	SB	T=30 (values below 30 correspond to extremely corrupt countries), U=80 (lower value for least corrupt countries)
POLICY	ST	Political rights (seven-category scale, 1 representing the most free and 7 the least free countries)	SB	T=1 (min of all countries), U=3 (most developing countries range over [3,7], 3 being their best value)
POLICY	ST	Civil liberties (seven-category scale, 1 representing the most free and 7 the least free countries)	SB	T=1 (min of all countries), U=3 (most developing countries range over [3,7], 3 being their best value)
POLICY	ST	Gini index (value in [0, 100], 0 representing perfect equality and 100 perfect inequality)	SB	T=29.2 (max of Scandinavian countries[e]), U=50 (countries with a higher Gini index exhibit weak social cohesion)
POLICY	RE	Tax revenue (% of GDP)	LB	u=11.24 (min of EU14), τ=22.78 (average of EU14)
POLICY	RE	Unemployment gender inequality (absolute difference between % unemployment rates for female and male labor force)	SB	T=0 (min possible), U=8.232 (max of EU14)
POLICY	RE	Military expenditure (% of GDP)	SB	T=1.263 (average of EU14), U=21.166 (max of all countries)
WEALTH	PR	Inflation (GDP implicit deflator annual % growth rate)	SB	T=0.9653 (average of EU14), U=112.8 (max of all countries excluding 1.5% outliers)
WEALTH	PR	Unemployment (% of total labor force)	NB	u=0.7927 (3.5th percentile), τ=4, T=7, and U=12 (set by experts)
WEALTH	ST	Gross national income (GNI) (per capita constant 2011 international $)	LB	υ=17,688 (min of EU), τ=41,689 (max of EU14)

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
WEALTH	ST	General government gross debt (% of GDP)	SB	T=73.49 (average of EU14 excluding Greece and Italy), 130.35 (97.5th percentile)
WEALTH	ST	Undernourishment; see above	SB	
WEALTH	RE	External balance on goods and services (% of GDP)	LB	υ=–79.740 (min of all countries), τ=7.109 (average of EU14)
WEALTH	RE	Foreign direct investment (% of GDP)	LB	υ=–32.9 (min of all countries), τ=11.01 (average of EU14)
HEALTH	PR	Sea level rise (SLR) impact on population (estimate of the percentage population living in 3 m or lower elevation coastal zones in 2100)	SB	T=0 (min possible), U=20 (one-fifth of the total population in 2100)
HEALTH	PR	Incidence of cardiovascular diseases (number of new cases each year per 100,000 population)	SB	T=0 (min possible), U=3313 (max of all countries)
HEALTH	PR	Incidence of neoplastic diseases (number of new cases each year per 100,000 population)	SB	T=0 (min possible), U=2040 (max of all countries)
HEALTH	PR	Incidence of HIV (number of new cases each year per 100,000 population aged 15-49)	SB	T=0 (min possible), U=30 [threshold of the upper category of HIV incidence rates according to the US Centers for Disease Control and Prevention (CDC, 2017)]
HEALTH	PR	Incidence of tuberculosis (number of new cases each year per 100,000 population)	SB	T=0 (min possible), U=597.6 (max of all countries)
HEALTH	PR	Incidence of malaria (number of new cases each year per 100,000 population)	SB	T=0 (min possible), U=0.01107 (median value of all countries)
HEALTH	ST	Mortality from ambient PM air pollution; see above		
HEALTH	ST	Mortality from household air pollution from solid fuels; see above		

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
HEALTH	ST	Infant mortality (deaths per 1,000 live births per year)	SB	T=2.525 (average of Scandinavian countries), U=68.3 (97.5th percentile)
HEALTH	ST	Maternal mortality (deaths per 100,000 live births per year)	SB	T=6.5 (average of Scandinavian countries), U=725.5 (95th percentile)
HEALTH	ST	Life expectancy at birth (years)	LB	u=51.84 (min of all countries), τ=81.81 (average of Scandinavian countries)
HEALTH	ST	Undernourishment; see above		
HEALTH	RE	DPT (diphtheria-pertussis-tetanus) immunization (% of population)	LB	u=87 (min of EU14), τ=100 (maximum possible)
HEALTH	RE	Measles immunization (% of population)	LB	u=89 (min of EU14), τ=100 (maximum possible)
HEALTH	RE	Hepatitis B immunization (% of population)	LB	u=76 (min of EU14), τ=100 (maximum possible)
HEALTH	RE	Physicians (per 1,000 population)	LB	u=0.01869 (min of all countries), τ=3.86156 (average of Scandinavian countries)
HEALTH	RE	Hospital beds (per 1,000 population)	LB	u=0.1930 (min of all countries), τ=3.3923 (average of Scandinavian countries)
HEALTH	RE	Current health expenditure (% of GDP)	LB	u=2.484 (min of all countries), τ=10.19 (average of Scandinavian countries)
HEALTH	RE	Access to safe water (% of population)	LB	u=41.09 (2.5th percentile), τ=100 (max possible)
HEALTH	RE	Access to sanitation (% of population)	LB	u=13.04 (2.5th percentile), τ=100 (max possible)
KNOW	PR	Primary student-to-teacher ratio	SB	T=12.15 (average of EU14), U=62.88 (99th percentile)

Indicators and normalization parameters

Component		Indicator (units)	Type[a]	Thresholds
KNOW	PR	Secondary student-to-teacher ratio	SB	T=11.51 (average of EU14), U=41.1 (max of all countries)
KNOW	PR	Tertiary student-to-teacher ratio	SB	T=15.27 (average of EU14), U=58.3 (99th percentile)
KNOW	ST	Literacy rate (% of population aged 15 and above)	LB	u=15.46 (min of all countries), τ=100 (max possible)
KNOW	ST	Expected years of schooling (years)	LB	u=5.398 (min of all countries), τ=17.359 (average of EU14)
KNOW	ST	Years of schooling gender gap (gender deviation per cent of expected years of schooling)	SB	T=0 (min possible), U=50 (a subjective threshold: weaker gender has half the expected number of schooling years)
KNOW	ST	Primary school enrollment (% of children of official school age)	LB	u=28.17 (min of all countries), τ=97.36 (average of EU14)
KNOW	ST	Secondary school enrollment (% of children of official school age)	LB	u=8.29 (min of all countries), τ=94.40 (average of EU14)
KNOW	RE	Research and development (R&D) expenditure (% of GDP)	LB	u=0.03672 (1st percentile), τ=0.4233 (average of Australia, Canada, Japan, Norway, and USA)
KNOW	RE	Government expenditure on education (% of GDP)	LB	u=1.094 (1st percentile), τ=4.627 (average of Australia, Canada, Japan, Norway, and USA)

[a] SB (smaller is better), LB (larger is better), NB (nominal is best)
[b] EU: 28 European Union member countries
[c] The target value T=5.2 is the ratio of the expected CO_2 emissions and the projected population of EU in 2030. The emissions target corresponds to EU's Intended Nationally Determined Contribution under the 2015 Paris Agreement for a 40% reduction of the 1990 levels of GHG emissions by 2030, assuming an equal reduction for CO_2.
[d] EU14: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Italy, Luxembourg, Netherlands, Portugal, Ireland, Spain and Sweden
[e] Scandinavian countries: Denmark, Finland , Norway, and Sweden (in the numerical results Iceland is included in the group of Scandinavian countries)

Exponential smoothing

indicator values $z_c(t_1)$, $z_c(t_2)$, …, $z_c(t_K)$

years t_1, t_2, …, t_K

level and trend estimates L_k and T_k

Holt-Winters algorithm

→ estimate of $z_c(t_k)$ in previous year t_{k-1}:

$$y_k = L_{k-1} + T_{k-1}(t_k - t_{k-1})$$

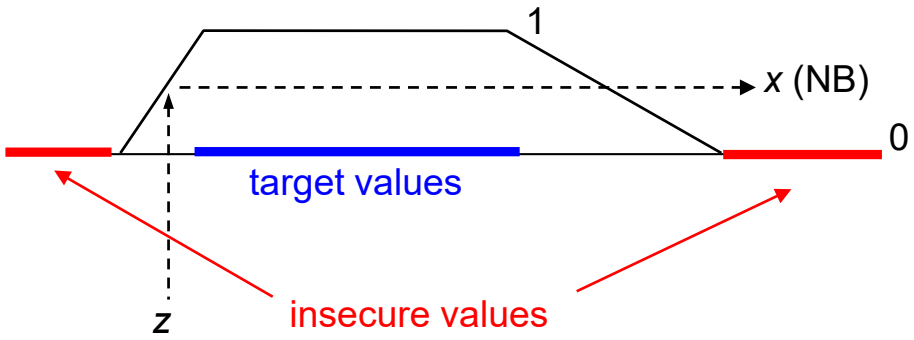
→ error: $e_k = z_c(t_k) - y_k$

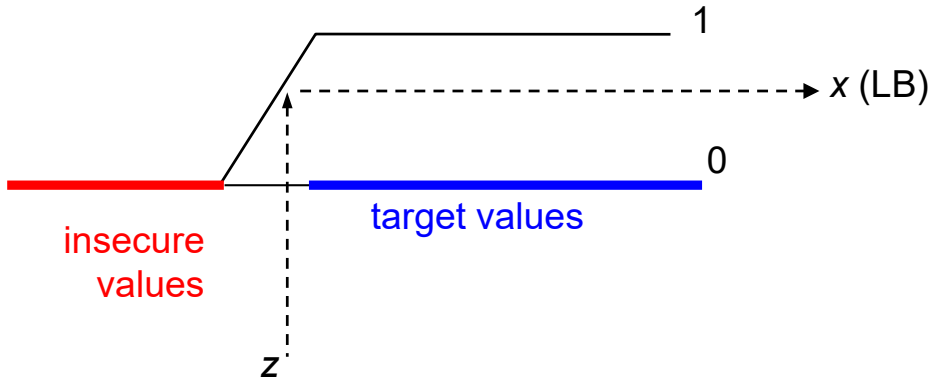
→ level update: $L_k = y_k + \alpha e_k$

→ trend update: $T_k = T_{k-1} + \gamma \alpha e_k$

where $L_0 = T_0 = T_1 = 0$ and α and γ are parameters in [0, 1] chosen so that the sum of squared errors is minimized.

Normalization


1
x (NB)
0
target values
insecure values
z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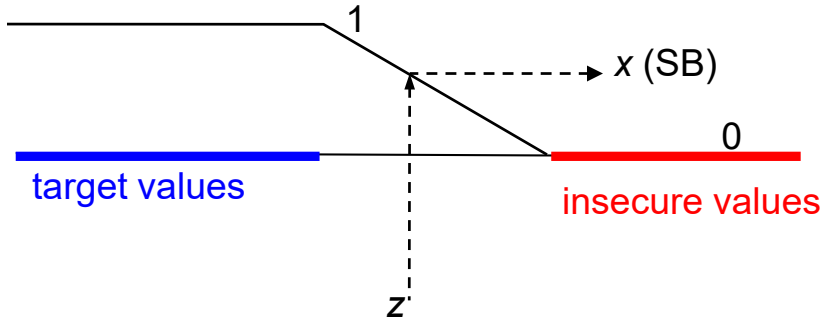
0
target values
insecure
values
z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x (SB)
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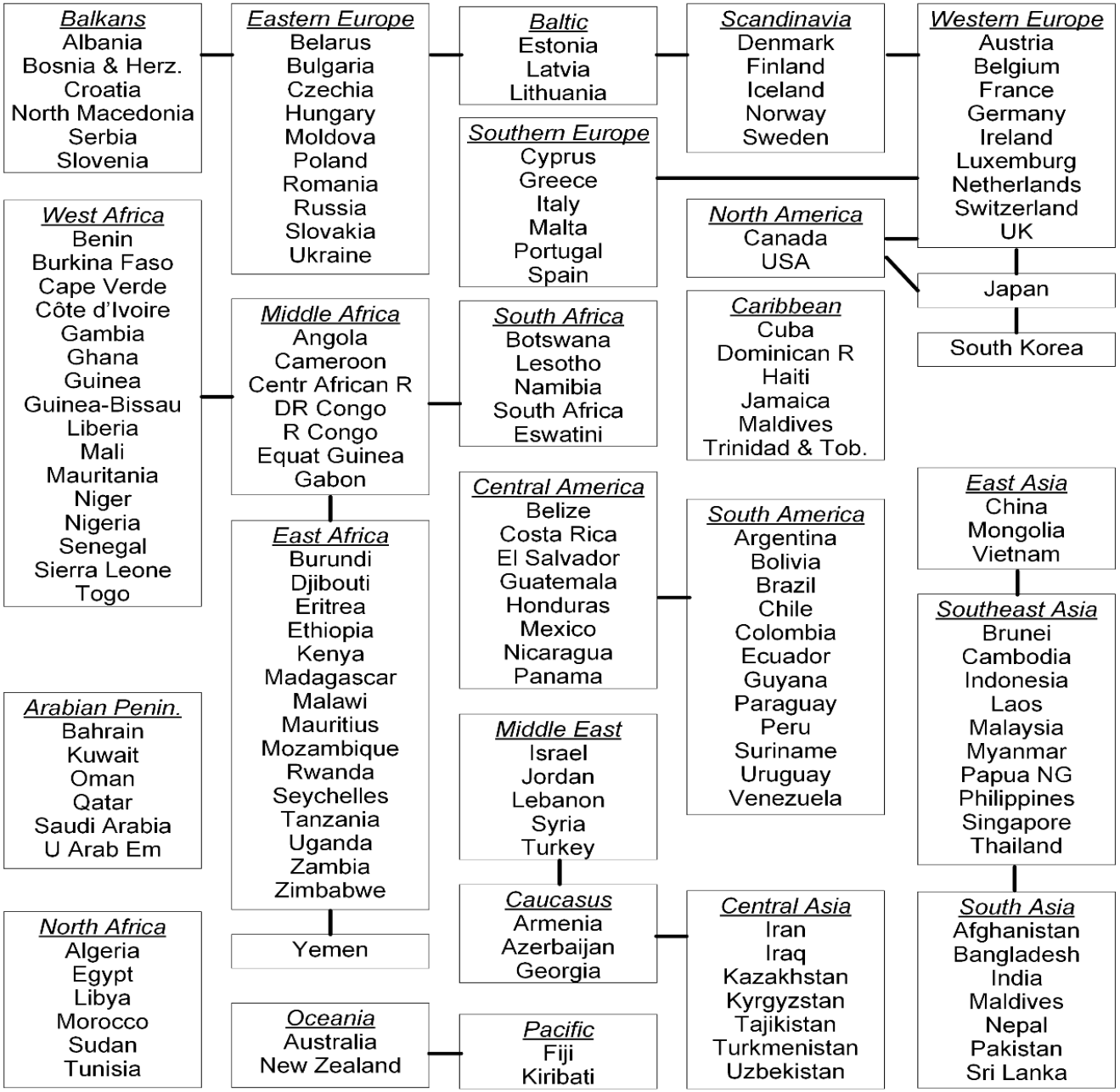
Imputation of Missing Indicators

Fig. 3. Geo-economic similarities: high (boxes) and moderate (lines)



Suppose that a missing indicator belongs to component g (g=AIR, …, KNOW). For two countries i and j let Cijg denote the collection of all indicators of component g which are available for both countries and |Cijg| the set cardinality. A Euclidean distance dijg is defined by

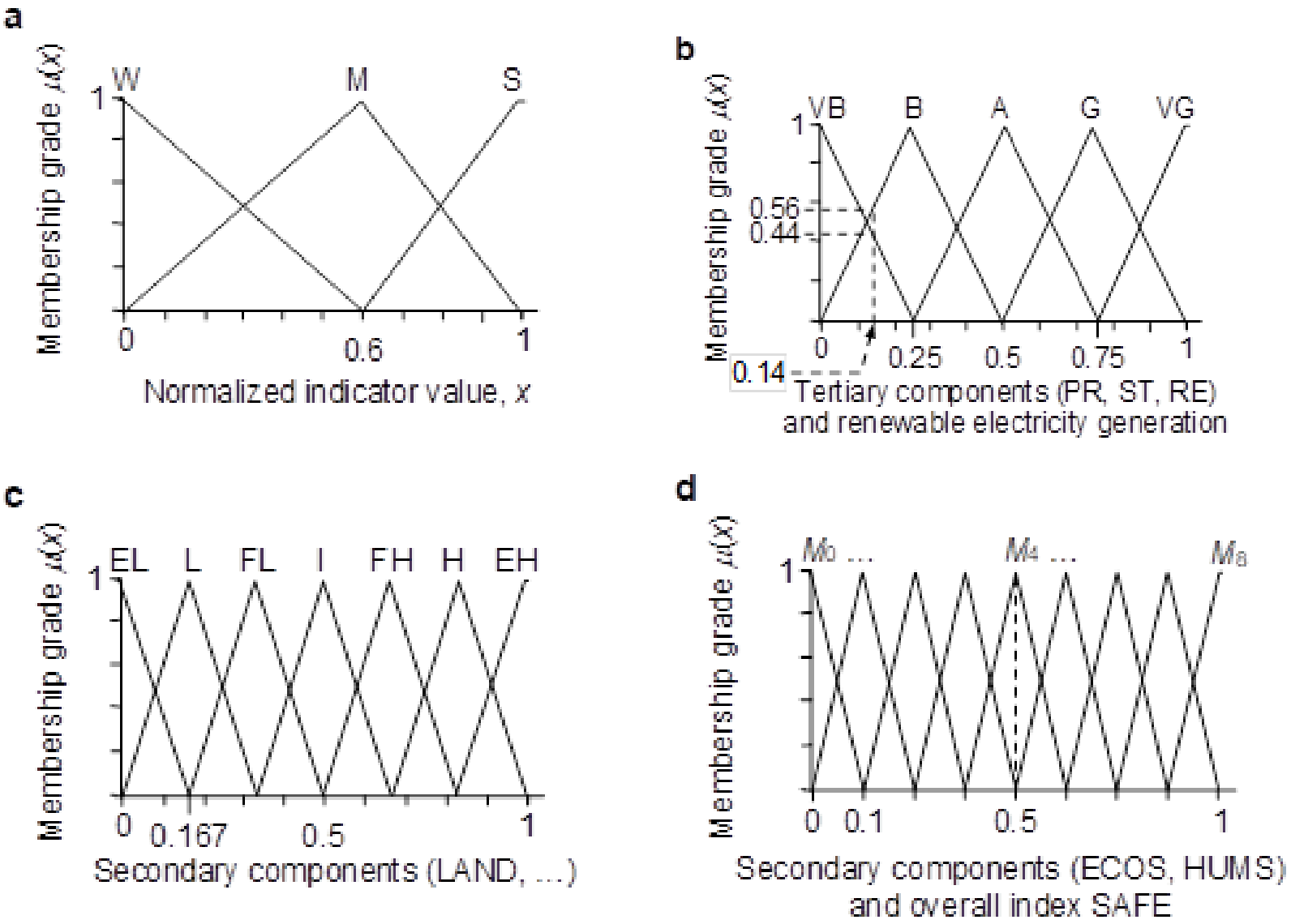
$$d_{ijg} = \begin{cases} \sqrt{\frac{1}{|C_{ijg}|} \sum_{\sigma \in C_{ijg}} (x_{\sigma i} - x_{\sigma j})^2} & |C_{ijg}| > 0 \\ 1 & |C_{ijg}| = 0 \end{cases}$$

where $x_{\sigma i}$ and $x_{\sigma j}$ are the normalized values of indicator σ for countries *i* and *j*.

When no component *g* indicator is jointly available for *i* and *j*, d_{ijg} assumes the maximum value 1.

Fuzzification

Fig. 4. Fuzzy sets and corresponding membership functions $\mu(x)$



Rule Bases

Fuzzy Inference and Defuzzification

Rule *j*: if (input 1 is $L_{1,j}$) and … and (input *n* is $L_{n,j}$), then (output 0 is $L_{0,j}$)

the firing strength of rule j is given by

$$\mu_{0,j} = \mu_{1,j}\mu_{2,j}\cdots\mu_{n,j}$$

If *different* rules assign the *same* fuzzy set *L* to the output

$$\mu_{0,L} = \sum_{j:L_{0,j}=L} \mu_{0,j} = \sum_{j:L_{0,j}=L} \prod_{i=1}^{n} \mu_{i,j}$$

Height defuzzification method:

$$x_0 = \frac{\sum_{\substack{\text{all fuzzy sets } L \\ \text{of the output}}} y_L \mu_{0,L}}{\sum_{\substack{\text{all fuzzy sets } L \\ \text{of the output}}} \mu_{0,L}}$$

Sensitivity Analysis

$$\Delta_c = \mathrm{SAFE}(x_1, \ldots x_c + \varepsilon, \ldots) - \mathrm{SAFE}(x_1, \ldots x_c, \ldots)$$

$$S_c = \Delta_c (1 - x_c)$$

$$\Delta_{cv} = \mathrm{SAFE}(x_1, \ldots x_c + \varepsilon, \ldots x_v + \varepsilon, \ldots) - \mathrm{SAFE}(x_1, \ldots x_c, \ldots x_v, \ldots)$$

and

$$S_{cv} = \Delta_{cv} (1 - x_c)(1 - x_v)$$

Results

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
1	Denmark	0.8691	0.8900	0.7434	19	SLR impact on land area	SLR impact on land area, Immunization against Hepatitis B
2	Sweden	0.8623	0.9157	0.7312	13	Forest change	Forest change, Renewable electricity generation
3	Norway	0.8606	0.8995	0.7321	3	Forest change	Forest change, Freshwater protected KBAs
4	Switzerland	0.8545	0.9540	0.6944	12	Renewable electricity generation	Renewable electricity generation, Forest change
5	Austria	0.8284	0.8849	0.6996	6	Forest change	Forest change, Red List Index
6	Finland	0.8179	0.8729	0.6942	6	Renewable electricity generation	Renewable electricity generation, Forest change
7	Netherlands	0.8076	0.9538	0.5918	10	Pesticide use	Pesticide use, Renewable electricity generation
8	UK	0.8019	0.8735	0.6767	17	Renewable electricity generation	Renewable electricity generation, Forest change
9	France	0.7977	0.8033	0.7365	8	Renewable electricity generation	Renewable electricity generation, Unemployment
10	Slovenia	0.7972	0.8494	0.6843	26	Renewable electricity generation	Renewable electricity generation, Forest change
11	Iceland	0.7970	0.8720	0.6729	4	Freshwater protected KBAs	Freshwater protected KBAs, Forest change

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
12	Germany	0.7945	0.9040	0.6431	18	Renewable electricity generation	Renewable electricity generation, Forest change
13	Ireland	0.7923	0.8928	0.6521	6	Fertilizer consumption	Fertilizer consumption, Renewable electricity generation
14	Poland	0.7840	0.8264	0.6805	26	Renewable electricity generation	Renewable electricity generation, Water resources
15	Hungary	0.7835	0.7924	0.7236	23	Incidence of cardiovascular diseases	Incidence of cardiovascular diseases, Renewable electricity generation
16	Slovakia	0.7817	0.7969	0.7092	17	Corruption Perceptions Index	Corruption Perceptions Index, Renewable electricity generation
17	Lithuania	0.7787	0.7808	0.7399	23	Tax revenue	Tax revenue, Forest change
18	Czechia	0.7735	0.8101	0.6739	12	Renewable electricity generation	Renewable electricity generation, Forest change
19	Portugal	0.7544	0.7944	0.6394	9	Renewable electricity generation	Renewable electricity generation, Forest change
20	Latvia	0.7529	0.7430	0.7448	18	Renewable electricity generation	Renewable electricity generation, Forest change
21	Australia	0.7520	0.8962	0.5158	3	Renewable electricity generation	Renewable electricity generation, Forest change
22	Croatia	0.7519	0.7112	0.7499	24	Forest change	Forest change, Unemployment

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
23	Estonia	0.7519	0.8364	0.6269	19	Renewable electricity generation	Renewable electricity generation, Forest change
24	Spain	0.7511	0.7623	0.6559	10	Tax revenue	Tax revenue, Unemployment
25	Luxembourg	0.7468	0.9230	0.4975	16	Pesticide use	Pesticide use, Forest change
26	Belgium	0.7457	0.8721	0.5210	18	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
27	Italy	0.7457	0.7546	0.6458	19	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment
28	Uruguay	0.7414	0.8051	0.6104	3	Pesticide use	Pesticide use, Freshwater protected KBAs
29	New Zealand	0.7355	0.8768	0.4883	–15	Freshwater protected KBAs	Fertilizer consumption, Red List Index
30	Malta	0.7326	0.8602	0.5033	31	Corruption Perceptions Index	Corruption Perceptions Index, Pesticide use
31	Canada	0.7322	0.8435	0.5550	0	Tax revenue	Tax revenue, Desertification
32	USA	0.7179	0.8313	0.5337	–2	Renewable electricity generation	Renewable electricity generation, Gini index
33	Greece	0.7142	0.6693	0.6946	12	Renewable electricity generation	Renewable electricity generation, Unemployment

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
34	Japan	0.7119	0.8360	0.5099	12	Renewable electricity generation	Renewable electricity generation, Pesticide use
35	Cyprus	0.7113	0.7948	0.5647	11	Renewable electricity generation	Renewable electricity generation, Pesticide use
36	Romania	0.7102	0.6932	0.6624	15	Corruption Perceptions Index	Corruption Perceptions Index, GNI
37	Costa Rica	0.7054	0.7370	0.5899	20	Pesticide use	Pesticide use, Fertilizer consumption
38	Bulgaria	0.7052	0.6983	0.6428	16	Corruption Perceptions Index	Corruption Perceptions Index, GNI
39	Belarus	0.6797	0.6752	0.6314	9	Unemployment	Unemployment, GNI
40	Chile	0.6712	0.7734	0.5275	1	Fertilizer consumption	Fertilizer consumption, Pesticide use
41	Russia	0.6501	0.6746	0.5633	5	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
42	Turkey	0.6476	0.6639	0.5721	10	Renewable electricity generation	Renewable electricity generation, Fish stock status
43	Albania	0.6468	0.6040	0.6500	5	Wastewater treatment	Wastewater treatment, Forest change
44	Brunei	0.6457	0.7180	0.5275	–3	Renewable electricity generation	Renewable electricity generation, CO_2 emissions

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
45	Cuba	0.6426	0.7342	0.5196	–1	Red List Index	Red List Index, Renewable electricity generation
46	Peru	0.6390	0.6010	0.6387	2	Renewable electricity generation	Forest change, Red List Index
47	Brazil	0.6388	0.6139	0.6365	4	Freshwater protected KBAs	Freshwater protected KBAs, Forest change
48	Morocco	0.6374	0.6367	0.6175	21	GNI	GNI, Corruption Perceptions Index
49	Venezuela	0.6355	0.5782	0.6404	2	Forest change	Forest change, Fish stock status
50	Moldova	0.6354	0.6368	0.6069	3	GNI	GNI, Political rights
51	Mexico	0.6346	0.6671	0.5297	3	Renewable electricity generation	Renewable electricity generation, Red List Index
52	Mongolia	0.6346	0.6471	0.5552	36	Renewable electricity generation	Renewable electricity generation, GNI
53	Argentina	0.6338	0.6926	0.5161	17	Forest area	Forest area, Forest change
54	Azerbaijan	0.6330	0.6499	0.5413	29	Renewable electricity generation	Renewable electricity generation, Political rights
55	Tunisia	0.6325	0.6533	0.5336	3	Renewable electricity generation	Renewable electricity generation, Forest change

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
56	Serbia	0.6314	0.6517	0.5349	18	Renewable electricity generation	Renewable electricity generation, Unemployment
57	Thailand	0.6299	0.6131	0.6220	–5	Renewable electricity generation	Renewable electricity generation, Forest change
58	Ghana	0.6298	0.5608	0.6351	4	Wastewater treatment	Wastewater treatment, Forest change
59	Fiji	0.6289	0.6429	0.5288	–16	Red List Index	Red List Index, GNI
60	FYR Macedonia	0.6265	0.6210	0.6064	4	Unemployment	Unemployment, GNI
61	Kyrgyzstan	0.6264	0.6278	0.5638	0	GNI	GNI, Political rights
62	Paraguay	0.6257	0.6051	0.6162	15	Forest change	Forest change, GNI
63	Namibia	0.6254	0.5015	0.6838	14	Gini index	Gini index, Unemployment
64	Gabon	0.6249	0.4900	0.7335	20	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment gender inequality
65	Ukraine	0.6230	0.6167	0.5836	3	Political rights	Political rights, Corruption Perceptions Index
66	Malaysia	0.6225	0.6971	0.4920	–1	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
67	Ecuador	0.6219	0.6304	0.5129	10	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
68	Georgia	0.6218	0.6007	0.6083	2	Mortality from ambient PM pollution	Mortality from ambient PM pollution, Forest change
69	Dominican R	0.6211	0.5163	0.6265	0	Renewable electricity generation	Renewable electricity generation, Water resources
70	Cape Verde	0.6199	0.6006	0.5968	5	Freshwater protected KBAs	Freshwater protected KBAs, GNI
71	Israel	0.6173	0.8074	0.3619	–2	Renewable electricity generation	Renewable electricity generation, Pesticide use
72	South Korea	0.6171	0.7939	0.3709	30	Renewable electricity generation	Renewable electricity generation, Pesticide use
73	Nicaragua	0.6158	0.5220	0.6153	30	Red List Index	Red List Index, Forest change
74	Panama	0.6158	0.5929	0.5876	7	Red List Index	Red List Index, Forest change
75	Guyana	0.6143	0.5128	0.6166	0	Forest change	Forest change, Wastewater treatment
76	Suriname	0.6112	0.5748	0.5905	11	Renewable electricity generation	Pesticide use, Forest change
77	Bolivia	0.6110	0.5337	0.6061	24	Forest change	Forest change, Pesticide use

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
78	Singapore	0.6091	0.7200	0.4391	–2	Renewable electricity generation	Renewable electricity generation, Political rights
79	Mauritius	0.6069	0.6853	0.4653	3	Renewable electricity generation	Renewable electricity generation, Red List Index
80	Philippines	0.6065	0.4977	0.6157	–3	Renewable electricity generation	Renewable electricity generation, Red List Index
81	Kiribati	0.6061	0.6202	0.4869	–14	Pesticide use	Pesticide use, Freshwater protected KBAs
82	Kazakhstan	0.6060	0.6404	0.4803	35	Renewable electricity generation	Renewable electricity generation, Forest change
83	Zimbabwe	0.5984	0.5044	0.6002	24	Red List Index	Red List Index, Forest change
84	Sri Lanka	0.5963	0.5721	0.5575	4	Red List Index	Red List Index, Corruption Perceptions Index
85	Armenia	0.5957	0.5887	0.5277	9	Corruption Perceptions Index	Unemployment, GNI
86	Honduras	0.5952	0.5861	0.5312	–3	R&D expenditure	R&D expenditure, GNI
87	Tajikistan	0.5899	0.5855	0.5171	25	GNI	GNI, Corruption Perceptions Index
88	Colombia	0.5897	0.5677	0.5483	–3	Pesticide use	Pesticide use, Fertilizer consumption

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
89	El Salvador	0.5895	0.5746	0.5369	10	Renewable electricity generation	Corruption Perceptions Index, GNI
90	Bosnia and Herzegovina	0.5893	0.5806	0.5284	14	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
91	Vietnam	0.5869	0.5750	0.5307	–6	Fertilizer consumption	Fertilizer consumption, Corruption Perceptions Index
92	Botswana	0.5818	0.5745	0.5183	11	Renewable electricity generation	Renewable electricity generation, Forest change
93	Saudi Arabia	0.5811	0.6871	0.4143	1	Renewable electricity generation	Renewable electricity generation, Tax revenue
94	Burkina Faso	0.5780	0.4642	0.6146	46	Corruption Perceptions Index	Corruption Perceptions Index, GNI
95	Lao PDR	0.5752	0.4486	0.6337	40	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment
96	Congo R.	0.5735	0.3897	0.6997	15	Wastewater treatment	Tax revenue, GNI
97	Jordan	0.5710	0.6075	0.4644	11	Renewable electricity generation	Renewable electricity generation, Water stress
98	Algeria	0.5706	0.5606	0.5196	9	Renewable electricity generation	Renewable electricity generation, Political rights
99	Nepal	0.5695	0.5015	0.5728	41	Freshwater protected KBAs	Freshwater protected KBAs, Forest change

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
100	Togo	0.5665	0.4444	0.6226	50	Red List Index	GNI, Life expectancy at birth
101	Senegal	0.5660	0.5539	0.5218	33	GNI	GNI, Renewable electricity generation
102	Kenya	0.5646	0.4549	0.6109	11	Tax revenue	Unemployment, GNI
103	Eq Guinea	0.5622	0.4334	0.6338	32	R&D expenditure	R&D expenditure, GNI
104	Turkmenistan	0.5616	0.6432	0.4275	17	Renewable electricity generation	Renewable electricity generation, Water stress
105	Maldives	0.5594	0.6750	0.3928	12	SLR impact on land area	SLR impact on land area, Pesticide use
106	Kuwait	0.5548	0.6785	0.3780	40	Renewable electricity generation	Renewable electricity generation, Tax revenue
107	Indonesia	0.5533	0.5547	0.5035	–4	Renewable electricity generation	Renewable electricity generation, GNI
108	Iran	0.5522	0.5679	0.4857	–3	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
109	China	0.5505	0.6333	0.4218	–5	Renewable electricity generation	Renewable electricity generation, Pesticide use
110	Lesotho	0.5472	0.4203	0.6282	7	Unemployment	Unemployment, GNI

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
111	Côte d'Ivoire	0.5437	0.4260	0.6192	9	Undernourishment	GNI, Life expectancy at birth
112	Uzbekistan	0.5431	0.6406	0.4084	15	Renewable electricity generation	Renewable electricity generation, Water stress
113	Benin	0.5395	0.4754	0.5643	41	Mortality from household air pollution	Renewable electricity generation, Forest change
114	Seychelles	0.5389	0.6102	0.4287	–3	Freshwater protected KBAs	Freshwater protected KBAs, Fertilizer consumption
115	Malawi	0.5352	0.4692	0.5661	14	Freshwater protected KBAs	Freshwater protected KBAs, GNI
116	Jamaica	0.5319	0.5556	0.4766	20	Renewable electricity generation	Unemployment, GNI
117	Zambia	0.5319	0.4096	0.6230	37	Government expenditure on education	Government expenditure on education, GNI
118	Qatar	0.5300	0.7225	0.3075	3	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
119	Cambodia	0.5219	0.4419	0.5796	5	Undernourishment	Forest change, Corruption Perceptions Index
120	Belize	0.5218	0.5767	0.4451	–7	Red List Index	Fertilizer consumption, Corruption Perceptions Index
121	Trinidad and Tobago	0.5216	0.6322	0.3912	8	Pesticide use	Pesticide use, Fertilizer consumption

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
122	Rwanda	0.5210	0.4009	0.6205	38	Political rights	Political rights, Civil liberties
123	South Africa	0.5208	0.5378	0.4833	10	Renewable electricity generation	Renewable electricity generation, Unemployment
124	Lebanon	0.5187	0.5688	0.4494	0	Corruption Perceptions Index	Corruption Perceptions Index, Fertilizer consumption
125	Cameroon	0.5169	0.4466	0.5701	32	Red List Index	Red List Index, GNI
126	Mali	0.5124	0.4512	0.5604	40	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
127	Eswatini	0.5092	0.4923	0.5171	–13	Renewable electricity generation	Renewable electricity generation, Unemployment
128	Sierra Leone	0.5076	0.3641	0.6449	31	Corruption Perceptions Index	Corruption Perceptions Index, Renewable electricity generation
129	India	0.5030	0.5398	0.4629	8	Renewable electricity generation	Renewable electricity generation, Red List Index
130	Libya	0.4893	0.5601	0.4290	–4	Renewable electricity generation	Renewable electricity generation, Water stress
131	Liberia	0.4890	0.3657	0.6228	27	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
132	Ethiopia	0.4872	0.4189	0.5663	14	Freshwater protected KBAs	Freshwater protected KBAs, Corruption Perceptions Index

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
133	Egypt	0.4841	0.5367	0.4469	–4	Freshwater protected KBAs	Renewable electricity generation, Corruption Perceptions Index
134	Djibouti	0.4814	0.4859	0.4947	17	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs
135	Tanzania	0.4795	0.4660	0.5126	2	Red List Index	Red List Index, Corruption Perceptions Index
136	Bahrain	0.4788	0.6357	0.3427	25	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
137	Nigeria	0.4783	0.4460	0.5312	3	Renewable electricity generation	Renewable electricity generation, GNI
138	Bahamas	0.4684	0.6601	0.3081	5	Freshwater protected KBAs	Freshwater protected KBAs, SLR impact on land area
139	U Arab Em	0.4647	0.6559	0.3088	–21	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
140	Papua NG	0.4593	0.4548	0.5040	–25	Freshwater protected KBAs	Freshwater protected KBAs, GNI
141	Mozambique	0.4551	0.3260	0.6284	21	Life expectancy at birth	Unemployment, GNI
142	Madagascar	0.4537	0.3611	0.5860	7	Corruption Perceptions Index	Corruption Perceptions Index, GNI
143	Guinea	0.4495	0.3279	0.6178	15	Corruption Perceptions Index	Corruption Perceptions Index, GNI

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
144	Gambia	0.4493	0.3442	0.5965	0	Corruption Perceptions Index	Corruption Perceptions Index, GNI
145	Oman	0.4476	0.6380	0.3086	–25	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
146	Bangladesh	0.4455	0.4933	0.4467	10	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
147	Burundi	0.4407	0.3179	0.6167	42	Corruption Perceptions Index	Corruption Perceptions Index, Refugees
148	Uganda	0.4393	0.3960	0.5372	14	Red List Index	Red List Index, Corruption Perceptions Index
149	Myanmar	0.4355	0.3651	0.5556	–5	Corruption Perceptions Index	Corruption Perceptions Index, Forest change
150	Guatemala	0.4295	0.4959	0.4285	0	Red List Index	Red List Index, Pesticide use
151	Angola	0.4290	0.4036	0.5183	22	Renewable electricity generation	Desertification, Corruption Perceptions Index
152	Pakistan	0.4080	0.4262	0.4530	5	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
153	Niger	0.4048	0.3986	0.4901	11	Unemployment	Unemployment, GNI
154	Congo DR	0.4039	0.2819	0.6067	2	Corruption Perceptions Index	Corruption Perceptions Index, Inflation

Country rankings, assessments, and most important indicators

	Country	SAFE	HUMS	ECOS	δx %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
155	Iraq	0.3956	0.4242	0.4291	4	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
156	Yemen	0.3858	0.3638	0.4879	21	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment
157	Guinea-Bissau	0.3827	0.2861	0.5289	–7	Renewable electricity generation	Renewable electricity generation, GNI
158	Chad	0.3794	0.3111	0.5083	7	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
159	C African R	0.3754	0.2048	0.6207	–3	Wastewater treatment	Wastewater treatment, Forest change
160	Eritrea	0.3746	0.2750	0.5032	12	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs
161	Sudan	0.3721	0.2565	0.5071	6	Freshwater protected KBAs	Freshwater protected KBAs, Corruption Perceptions Index
162	Haiti	0.3640	0.2808	0.4875	–15	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs
163	Mauritania	0.3590	0.2762	0.4808	8	Freshwater protected KBAs	Renewable electricity generation, Desertification
164	Afghanistan	0.3368	0.2549	0.4625	34	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs

The largest improvements in SAFE are seen in:

- Togo
- Burkina Faso
- Burundi

The strongest declines in SAFE are seen in:

- Papua New Guinea
- Oman
- United Arab Emirates

South Korea has a relatively low ranking
because four indicators have zero scores:

- pesticide use
- forest change
- incidence of malaria
- and freshwater resources

renewable electricity generation is close to zero.

Interestingly,
renewable electricity generation has
the highest potential of improving sustainability of South Korea,
a result that would not be straightforward
without the application of sensitivity analysis.

	Regions	SAFE	HUMS	ECOS	Weakest secondary component
NA	North America	0.725	0.837	0.544	BIOD (0.385)
EC	Europe and Central Asia	0.722	0.756	0.627	AIR (0.583)
LA	Latin America and the Caribbean	0.596	0.601	0.544	BIOD (0.441)
EA	East Asia and Pacific	0.604	0.633	0.520	BIOD (0.458)
ME	Middle East and North Africa	0.533	0.613	0.436	WATER (0.349)
SA	South Asia	0.488	0.495	0.478	POLICY (0.333)
SS	Sub-Saharan Africa	0.503	0.423	0.576	HEALTH (0.336)
	Europe				
EU	European Union	0.773	0.820	0.662	AIR (0.576)
EU14	EU14 countries	0.788	0.850	0.653	AIR (0.615)
Sc	Scandinavian countries	0.841	0.890	0.715	LAND (0.643)
	Income groups				
HO	High income OECD	0.767	0.843	0.625	AIR (0.58)
HN	High income non-OECD	0.600	0.700	0.468	AIR (0.431)
UM	Upper middle income	0.599	0.603	0.545	POLICY (0.431)
LM	Lower middle income	0.546	0.510	0.553	POLICY (0.402)
LI	Low income	0.470	0.386	0.565	POLICY (0.313)

Table 3.
SAFE components by region and economy

SAFE	HDI	EPI	SSI Human Wellbeing	SSI Economic Wellbeing	SSI Environmental Wellbeing
Denmark	Norway	Switzerland	Finland	Norway	Burundi
Sweden	Switzerland	France	Germany	Switzerland	Togo
Norway	Australia	Denmark	Netherlands	Estonia	Lesotho
Switzerland	Ireland	Malta	Iceland	Sweden	C African R
Austria	Germany	Sweden	Norway	Czechia	Uganda
Finland	Iceland	UK	Sweden	Luxembourg	Ethiopia
Netherlands	Sweden	Luxembourg	Slovenia	Denmark	Rwanda
UK	Hong Kong	Austria	Belgium	Australia	Malawi
France	Singapore	Ecuador	Denmark	Lithuania	Gambia
Slovenia	Netherlands	Malaysia	Ireland	U Arab Em	Guinea
Kendall's tau with SAFE	0.61	0.62	0.64	0.41	-0.30

Table 4.
Top 10 countries in several national sustainability ranking approaches

Dynamic aspects of SAFE over 1995-2016

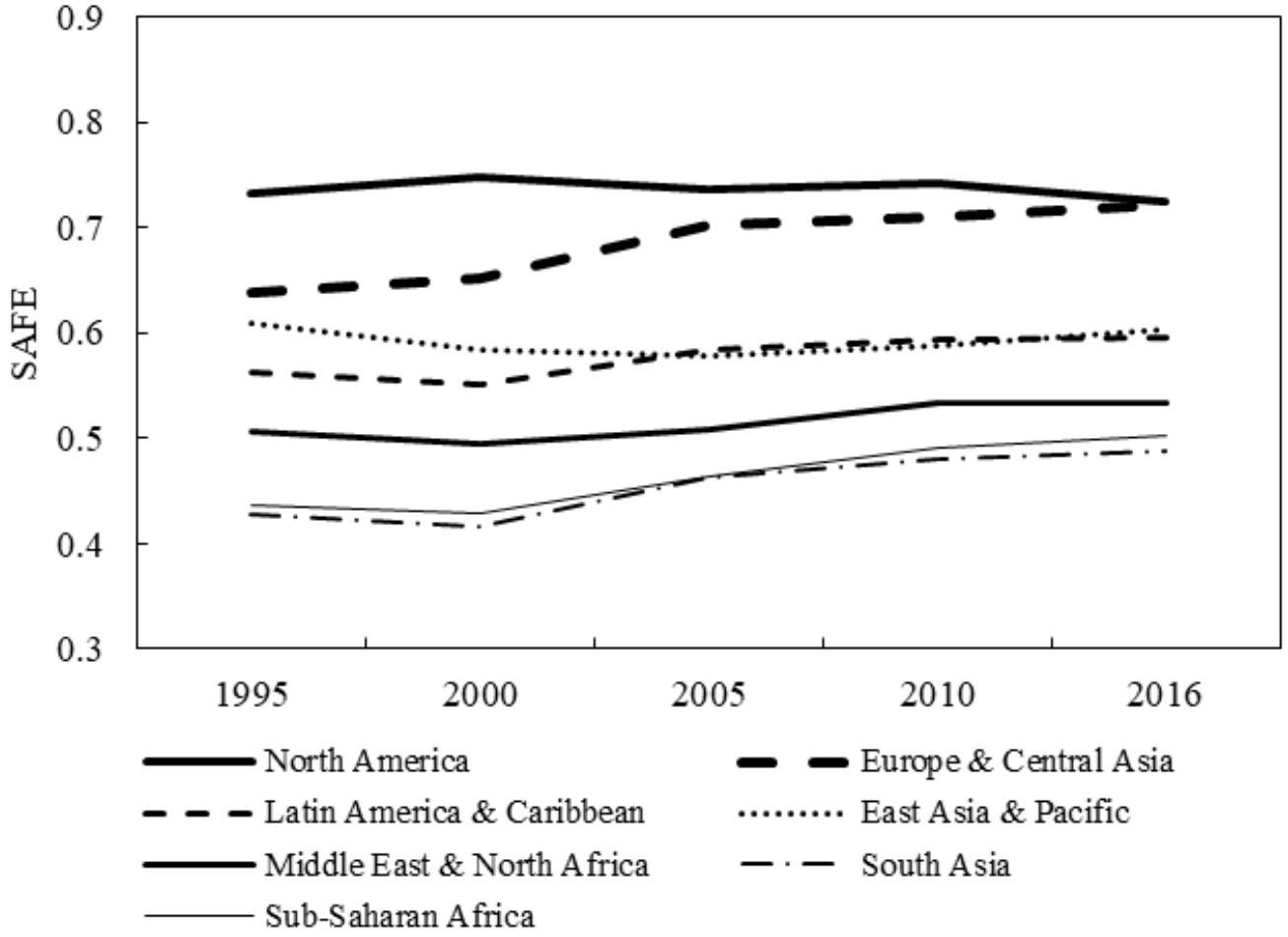


Fig. 5.
SAFE results by geographical region between 1995 and 2016

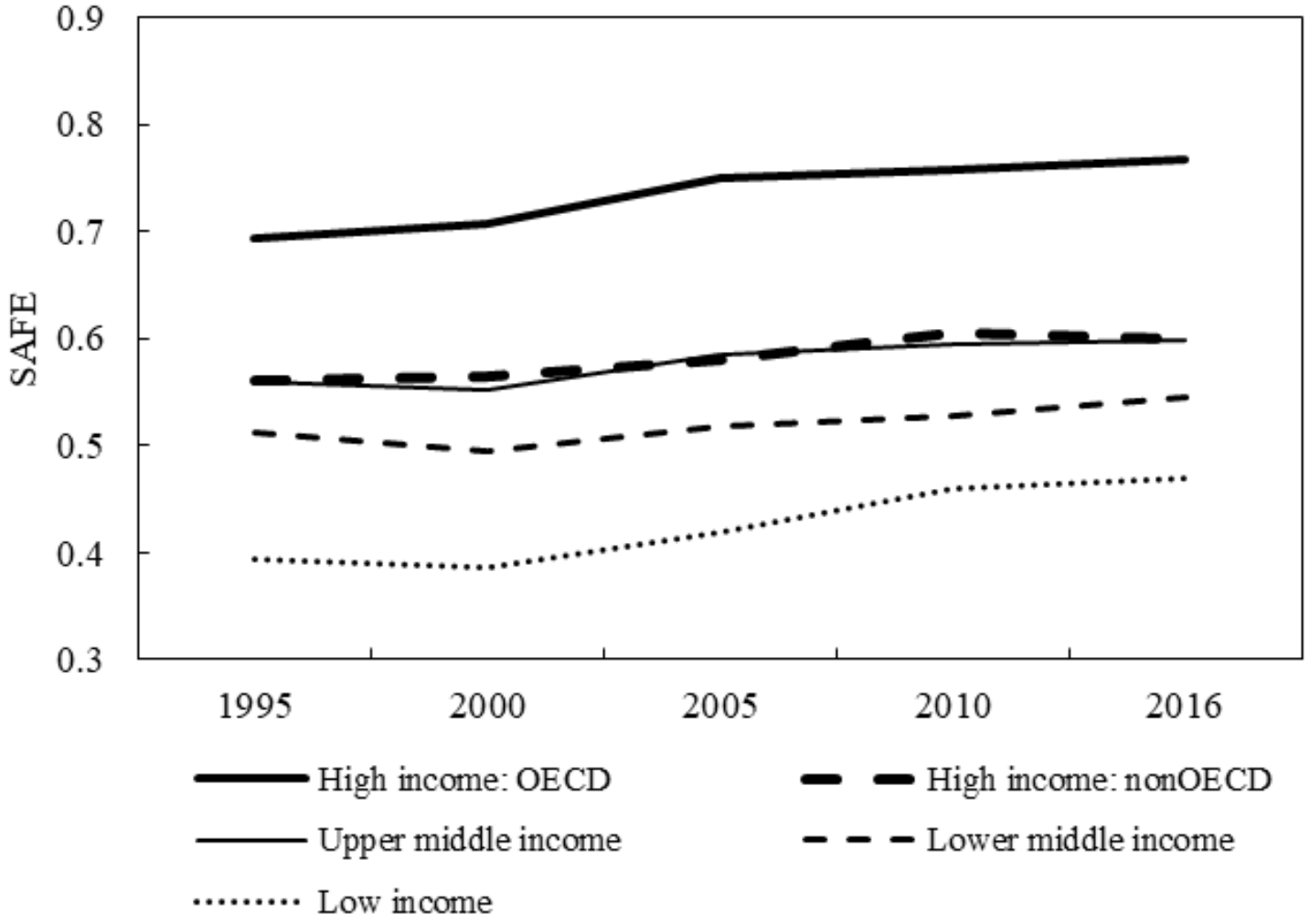
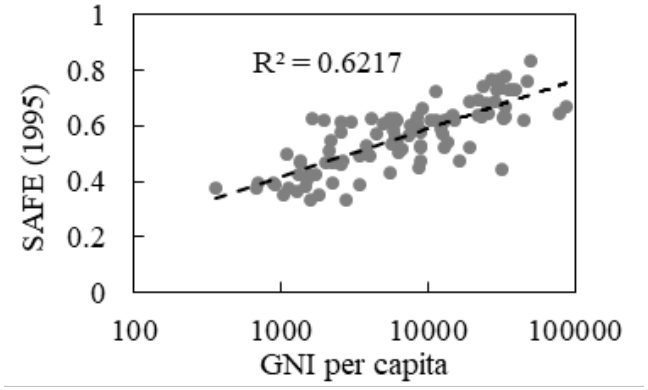
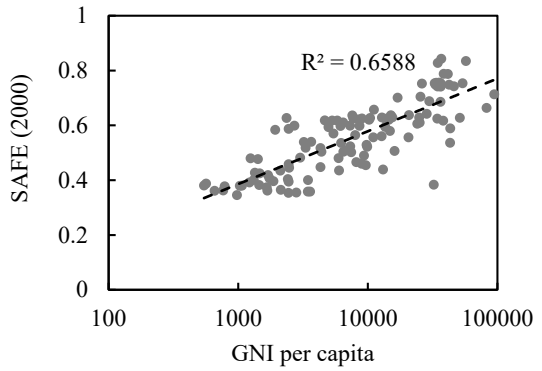
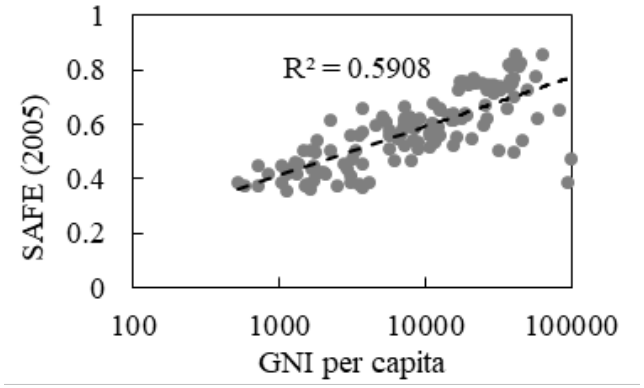
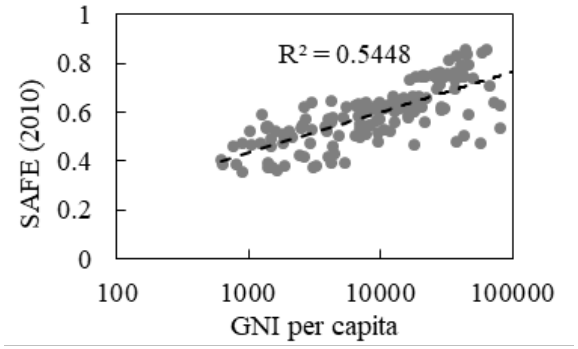


Fig. 6.
SAFE results by income group between 1995 and 2016









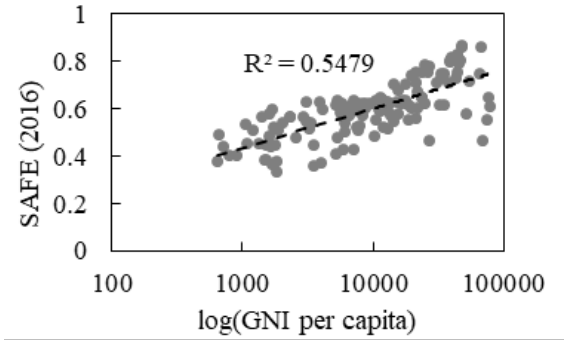


Fig. 7.
Correlations between wealth and SAFE

Fig. 8 shows the human and ecological sustainability performance across regions.

To avoid arbitrary thresholds for high and low performance, data have been standardized around their means:

$$H_r' = \frac{H_r - \bar{H}}{\sqrt{\sum_r (H_r - \bar{H})^2}} \quad \text{and} \quad E_r' = \frac{E_r - \bar{E}}{\sqrt{\sum_r (E_r - \bar{E})^2}}$$

H_r' and E_r' are the standardized HUMS and ECOS scores of region r, H_r and E_r are their raw HUMS and ECOS scores, and $\bar{H}$ and $\bar{E}$ are the average HUMS and ECOS scores of all regions.

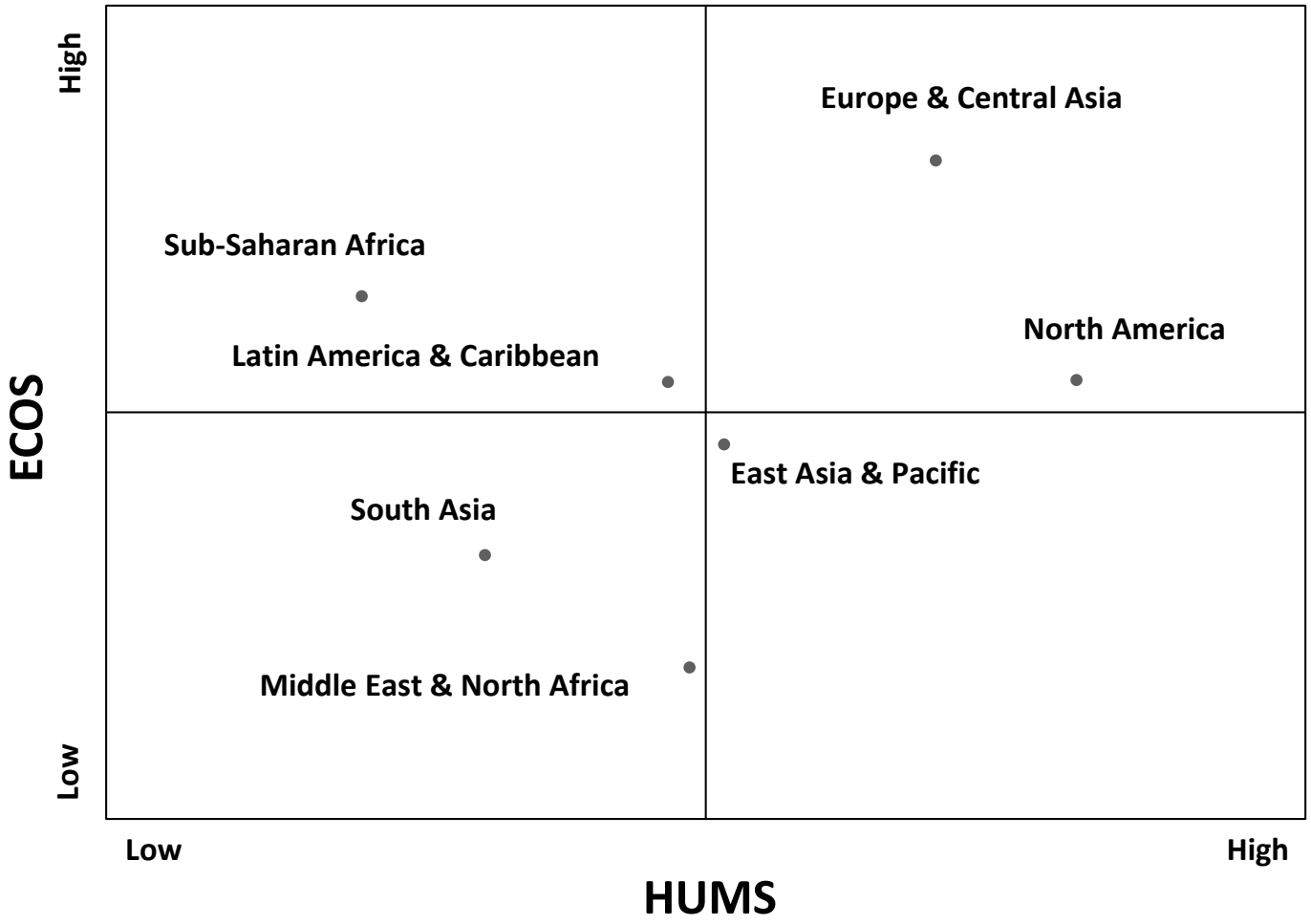


Fig. 8.
Relative ECOS/HUMS diagrams for 2016

Evolution of sustainability over time
Via maps of ECOS vs. HUMS
Fig. 8.

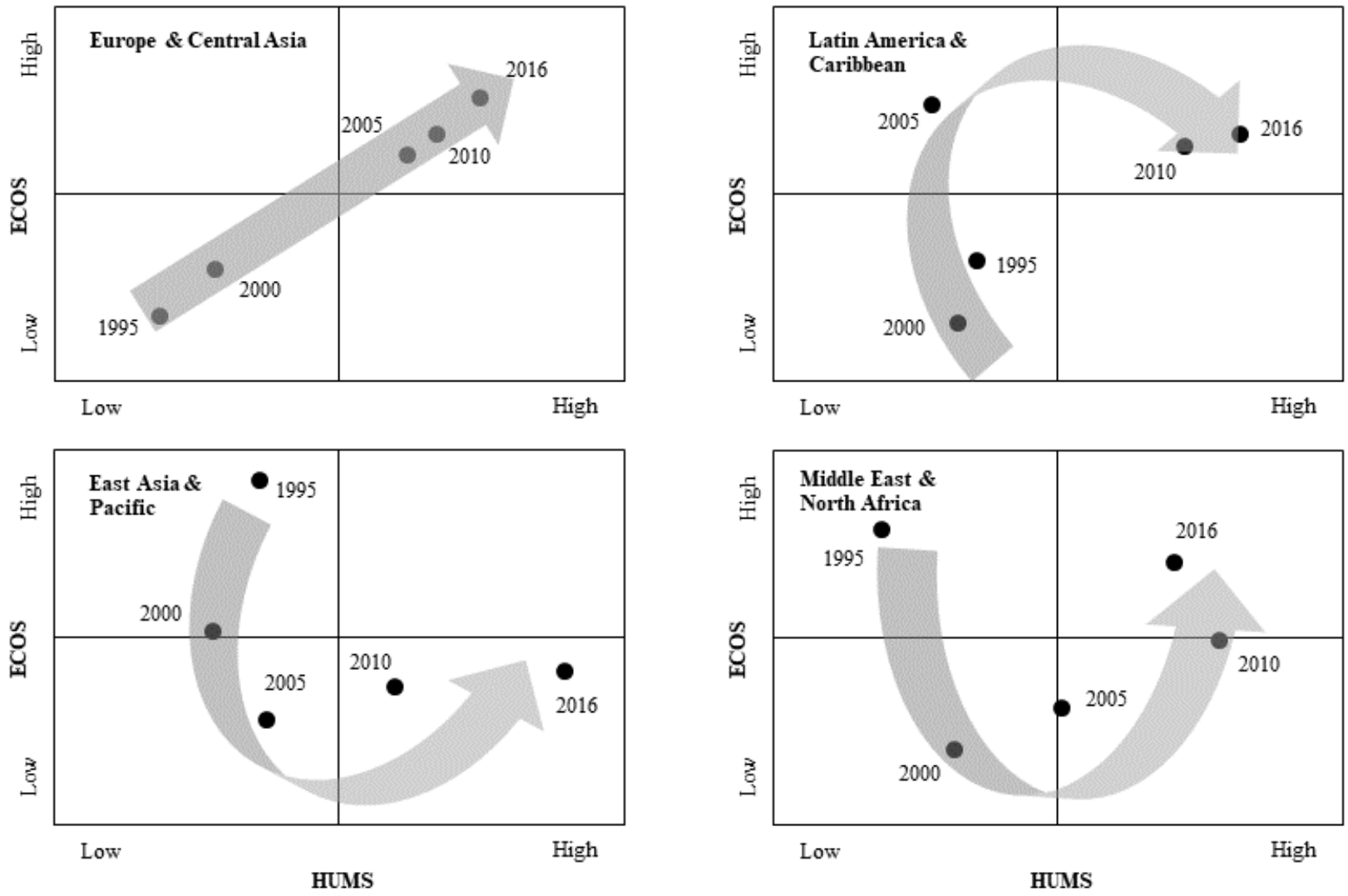


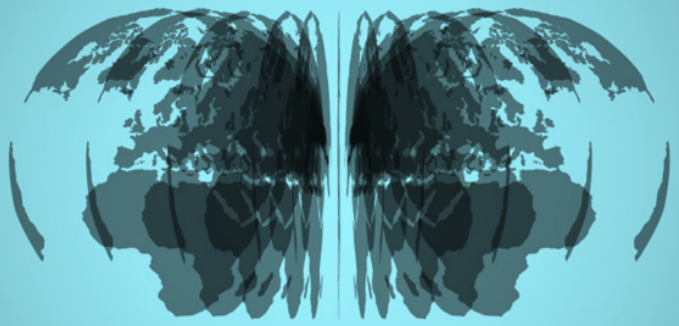
Fig. 9.
Relative dynamic ECOS/HUMS diagrams of selected geographical regions

Concluding Remarks

Worldwide,

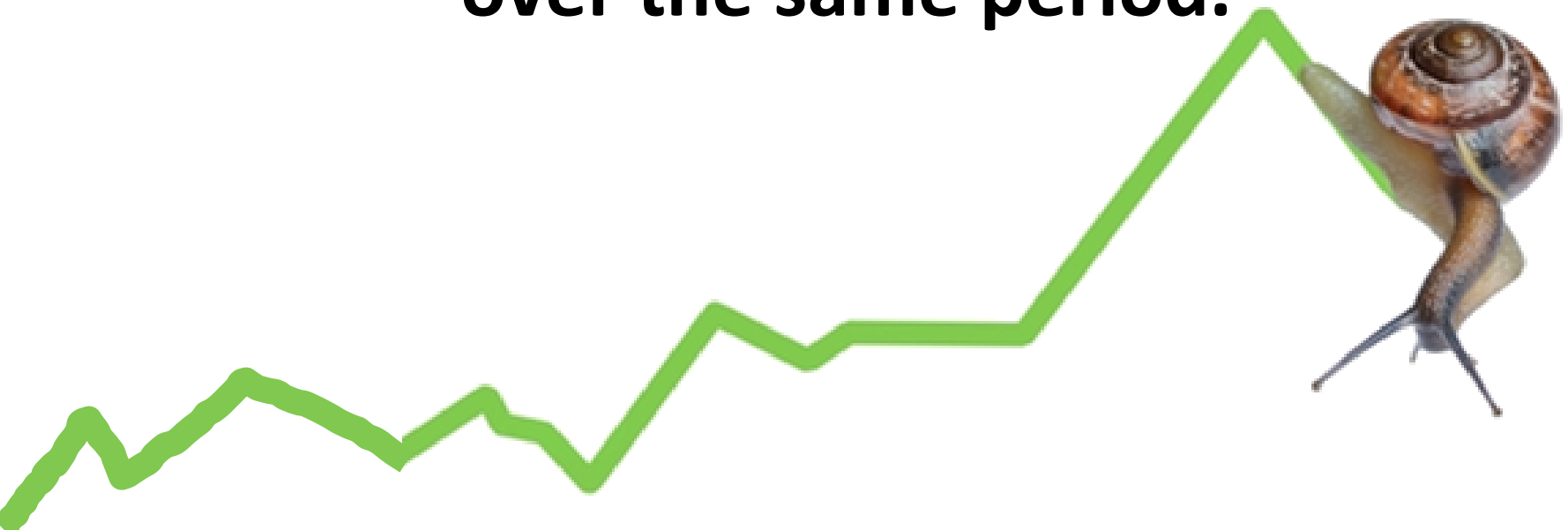
renewable energy generation, corruption, forest change, GNI, and threatened species (RLI) are the most prominent indicators,

while in developed countries CO_2 emissions appear first.



An interesting finding is
that progress towards sustainability
worldwide
in the last 25 years is rather modest.

North America regressed slightly
over the same period.



SAFE is a global model of sustainability
it is easily modified
to incorporate new knowledge and data,
and aids decision making
with its sensitivity analysis module.

This is a joint project with professors: Vasilis S Kouikoglou and Vangelis Grigoroudis

Thank you
for your attention