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SAFE 2019: Updates and new sustainability findings worldwide

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ABSTRACT

SAFE (Sustainability Assessment by Fuzzy Evaluation) is updated with data starting at 1990 and reaching 2016. Older versions of the model have been refined to remove outdated indicators and incorporate new ones. Also new modules were added to expose various dynamic features of sustainability worldwide. In all 69 time series of basic indicators are used to generate various intermediate sustainability indices and finally an overall index for 164 countries which are ranked accordingly. Data are manipulated statistically to introduce memory, then normalized in [0, 1], and finally passed through a sequential fuzzy reasoning system to obtain the SAFE sustainability index. A sensitivity analysis reveals those indicators with the highest potential of improving sustainability. Most countries have made a modest progress towards sustainability over 1990–2016. Interestingly, North America shows a small decline. Another counterintuitive result is the relatively low ranking of advanced countries such as South Korea, a fact explained satisfactorily by the model. Finally, there is a high correlation of the SAFE index and per capita income which implies that sustainability is predicated on a reasonably high economic level.

1. Introduction

A number of sustainability assessment approaches serve as definitions and measurement schemes for this concept. According to Grigoroudis et al. (2012), there are two major categories of sustainability assessment models:

- Basic. They consider particular aspects of sustainability or examine the physical relation between society and nature.
- Barometers of sustainability. They are aggregated sustainability approaches based on ecological, social, or economic indicators that lead to rankings of countries.

The Pressure-State-Response framework of the Organisation for Economic Co-operation and Development (OECD, 1991), the ecological footprint (see for example Ewing et al., 2010), and the green GDP (Gross Domestic Product) (Boyd, 2007) belong to the first category.

The Environmental Performance Index (EPI) is a typical example of barometer based on 24 indicators across ten facets of environmental health: air quality, water and sanitation, heavy metals, biodiversity and habitat, forests, fisheries, climate and energy, air pollution, water resources, and agriculture (Wendling et al., 2018). EPI is computed as a weighted average of indicators for 180 countries (Hsu et al., 2013).

The Sustainable Society Index (SSI) is based on the definition of sustainability of the Brundtland Commission (van de Kerk and Manuel, 2016) and covers 21 environmental and social indicators aggregated into 7 main categories: basic needs, personal development and health, well-balanced society, natural resources, climate and energy, transition, and economy. These components are further aggregated into 3 wellbeing dimensions: human, environmental, and economic wellbeing. Individual indicators are normalized and aggregated using a geometric average scheme to generate a score for each category and finally each dimension.

In a different context, the Better Life Index proposed by OECD is an interactive web-based tool that compares well-being across countries based on 11 topics: community, education, environment, civic engagement, health, housing, income, jobs, life satisfaction, safety, and work-life balance. Normalized indicators are aggregated using equal weights to generate an overall score for each topic (OECD, 2014). No overall index is given. Instead, users obtain their own index based on their weighting preferences.

The Commitment to Development Index (CDI) is published annually since 2003 by the Center for Global Development. CDI ranks countries according to their policies that benefit people living in poorer nations (Robinson et al., 2018). The index reviews the level of support given to poor countries to realize prosperity, good governance, and security. It is composed of 7 major components: aid, trade, finance, migration, environment, security, and technology together with a large set of indicators.

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Indicators are normalized into a score with mean 5 and standard deviation 1. Then they are weighted by the inverse of the standard deviations and provide the aggregated CDI score using equal weights.

Another important barometer is the Human Development Index (HDI) developed by the United Nations Development Program (UNDP, 2018). It provides a standard of human well-being and is used to measure the impact of economic policies on the quality of life. HDI is calculated using a geometric mean of country scores on 3 major dimensions of human development: longevity, access to knowledge, and standard of living.

Other sustainability assessment approaches include the Genuine Progress Indicator (Redefining Progress, 1995), the Index for Sustainable Economic Welfare (Daly and Cobb, 1989), the Legatum Prosperity Index (Legatum Institute, 2018), the Living Planet Index (McRae et al., 2016), and the Bertelsmann Transformation Index (Bertelsmann Stiftung, 2016). Reviews of sustainability assessment indices may be found in Neumayer (2000), Lawn (2003), and Grigoroudis et al. (2012).

The main aim of this paper is to present an updated and revised version of the SAFE (Sustainability Assessment by Fuzzy Evaluation) model. Using fuzzy logic, SAFE can handle quantitative, qualitative or mixed sustainability information and provide overall and partial sustainability measures. SAFE is a hierarchical, fuzzy rule-based system, which aggregates basic indicators of sustainability into a single numerical value for the overall sustainability of a country. Compared to the previous sustainability evaluation approaches, SAFE has the following major advantages:

- The model uses fuzzy logic which is a convenient approach to handle such a vague and complex concept as sustainability.
- SAFE is a holistic approach that uses a balanced representation of environmental and social aspects, therefore it can evaluate country sustainability considering both its human and ecological dimensions.
- The incorporated sensitivity analysis identifies the most important indicators or combination of indicators affecting national sustainability the most.
- The model takes into account past performance, since past environmental and social pressures have significant cumulative effects.

Several extensions of SAFE have enriched the initial work by Phillis and Andriantiatsaholiniaina (2001), by introducing sensitivity analysis (Andriantiatsaholiniaina et al., 2004), ensuring monotonic inference in conjunction with exponential smoothing (Kouloumpis et al., 2008), and adding imputation (Phillis et al., 2011; Grigoroudis et al., 2014).

SAFE 2019 introduces the following improvements over older versions:

1. Outdated indicators were removed in favor of others reflecting present reality. For example, sea level rise impact on land and population due to climate change as well as immunization against hepatitis B and undernourishment are four new indicators for which data now exist. Additionally, great weights have been assigned to such indicators as greenhouse gases emissions and renewable energy adoption, given the urgency of climate change. All modules of SAFE (normalization, imputation, rule bases, and membership functions) are modified appropriately.
2. The imputation procedure was improved, thus achieving smaller errors by 25% compared to old versions. The root mean squared error now stands at 0.19.
3. The number of ranked countries has gone up to 164 from 128 previously, thanks to data availability by authoritative organizations.
4. The dynamics of sustainability is exposed by (a) showing its variation over 1995–2016, (b) graphing its evolution by geographical area and income level, and (c) showing patterns and relationships between human/social and environmental components of sustainability.
5. Comparisons of SAFE with other existing ranking models are provided.
6. In addition to first order, second order sensitivity is performed which can easily be expanded further, thus identifying synergistic relations among indicators.

The remainder of this paper is organized as follows. Section 2 presents the sustainability indicators used in this study and an overview of the SAFE model, including the different computations steps (exponential smoothing, normalization, imputation, fuzzification/defuzzification, and sensitivity analysis). Section 3 presents the results of the SAFE model. Finally, Section 4 summarizes results and gives an overview of the strengths and weaknesses of the model.

2. Materials and methods

2.1. The SAFE model of national sustainability

SAFE estimates the sustainability of countries using environmental and socioeconomic indicators. The overall sustainability (SAFE) of a country comprises two primary components: ecological sustainability (ECOS) and human sustainability (HUMS). ECOS has four secondary components: air quality (AIR), land integrity (LAND), water quality (WATER), and biodiversity (BIOD). The components of HUMS are: political aspects (POLICY), economic welfare (WEALTH), health (HEALTH), and education (KNOW). We adopt the Pressure-State-Response indicators' classification of OECD (1991) to evaluate each secondary component. Pressure (PR) assesses the negative impacts of human activities, state (ST) describes the prevailing conditions, and response (RE) summarizes the actions taken to improve the state of the corresponding secondary component. Tertiary components are functions of one or more indicators which are the raw inputs of the model. The indicator datasets consist of time series typically spanning from 1990 through 2016, depending on the availability of data for each country.

The sequence of data processing of SAFE is depicted in Fig. 1 and outlined below:

1) Each indicator time series is first transformed into a single value via exponential smoothing.
2) The smoothed indicators are normalized on the scale 0–1 using thresholds, u_c, τ_c, T_c, and U_c, deemed as endpoints of unsustainable and sustainable indicator regions.
3) Missing indicators are replaced by appropriate cluster averages.
4) Normalized indicators are transformed into fuzzy linguistic terms.
5) By using a hierarchy of fuzzy rule-based inference processes the fuzzy indicators are successively aggregated into tertiary variables, secondary variables, primary variables, and the overall sustainability index, SAFE, which is then defuzzified into the 0–1 scale.
9) A sensitivity analysis identifies the indicators with the highest potential to improve the sustainability of each country.
10) Steps 1–9 are repeated to yield a graphical representation of the evolution of SAFE, ECOS and HUMS.

All basic indicators are shown in Table 1; columns "Type" and "Thresholds" are discussed in Section 2.3. The indicator assumptions are given in Appendix A and data sources in Appendix E.

In the next sections we describe the model and its improvements over previous versions.

2.2. Exponential smoothing

Indicator data are available as time series of annual averages or totals. Each time series records the progress of a country towards a particular aspect of sustainability. Using time series for each indicator, rather than the most recent value, combined with a statistical smoothing

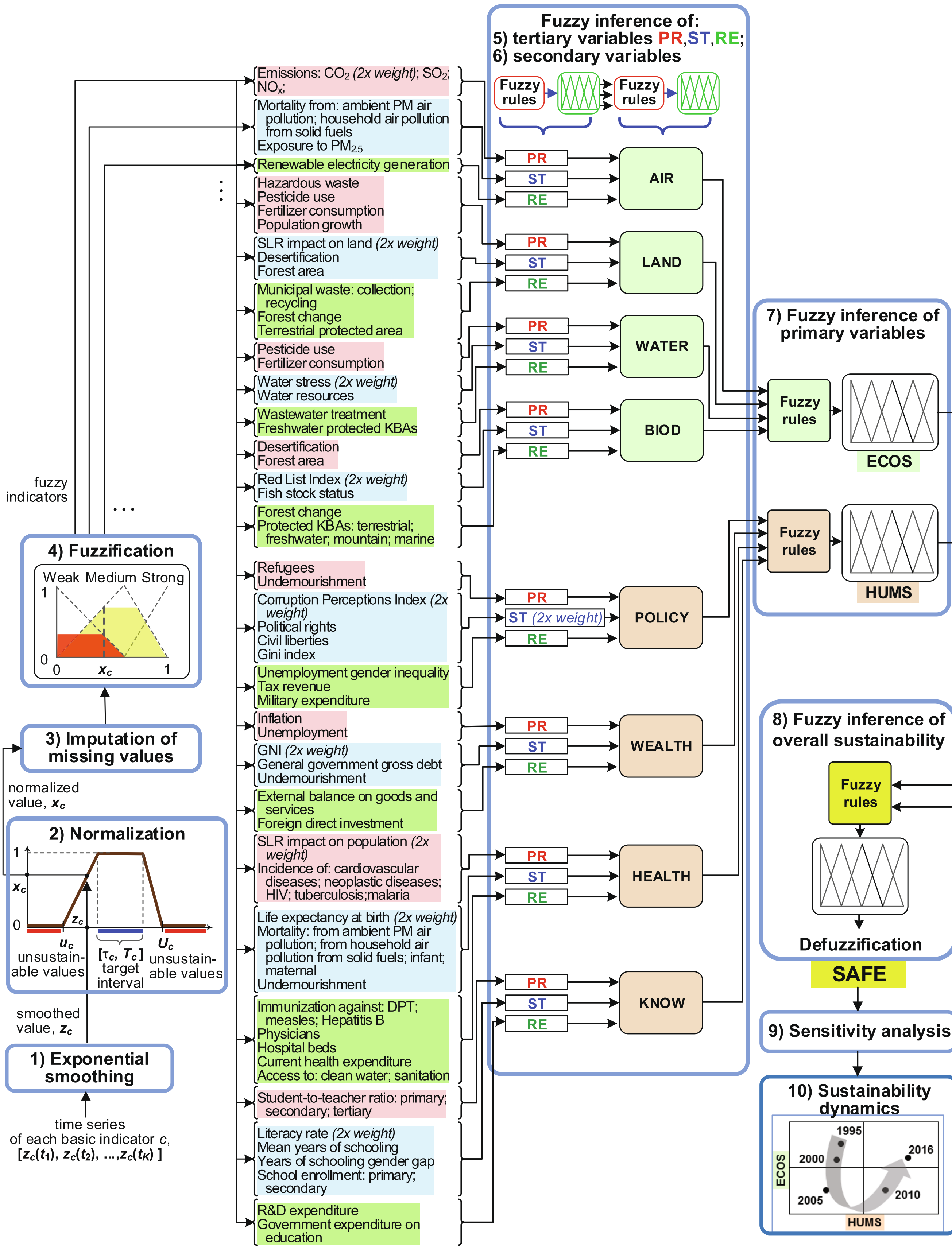

Fig. 1. Computational steps of the SAFE model.

Table 1
Indicators and normalization parameters.

Component		Indicator (units)	Type[a]	Thresholds[a]
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 μm in diameter in μg/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), $\tau = 100$ (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)
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), $\tau = 109.99$ (average of EU)
LAND	RE	Municipal waste collection (% of population served by municipal waste collection)	LB	$u = 0$ (min possible), $\tau = 100$ (max possible)
LAND	RE	Municipal waste recycling (% of the municipal waste collected which is recycled)	LB	$u = 0$ (min possible), $\tau = 26.63$ (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), $\tau = 0.6777$ (97.5th percentile of all countries)
LAND	RE	Terrestrial protected area (% of total land area)	LB	$u = 0.23$ (min of all countries), $\tau = 53.86$ (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), $\tau = 50{,}000$ (a rounded 90th percentile)
WATER	RE	Wastewater treatment (% of population connected to wastewater treatment plants)	LB	$u = 2.760$ (2.5th percentile), $\tau = 97.105$ (average of EU14)
WATER	RE	Freshwater protected Key Biodiversity Areas (KBAs) (% of total freshwater KBAs)	LB	$u = 0$ (min possible), $\tau = 100$ (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), $\tau = 1$ (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) $\tau = 0.63\%$ (97.5th percentile of all countries)
BIOD	RE	Terrestrial protected KBAs (% of total terrestrial KBAs)	LB	$u = 0$ (min possible), $\tau = 100$ (max possible)
BIOD	RE	Mountain protected KBAs (% of total mountain KBAs)	LB	$u = 0$ (min possible), $\tau = 100$ (max possible)
BIOD	RE	Marine protected KBAs (% of total marine KBAs)	LB	$u = 0$ (min possible), $\tau = 100$ (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)
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), $\tau = 22.78$ (average of EU14)
POLICY	RE	Unemployment gender inequality (absolute	SB	$T = 0$ (min possible), $U = 8.232$ (max of EU14)

(*continued on next page*)

Table 1 (*continued*)

Component		Indicator (units)	Type[a]	Thresholds[a]
		difference between % unemployment rates for female and male labor force)		
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), $\tau = 4$, $T = 7$, and $U = 12$ (set by experts)
WEALTH	ST	Gross national income (GNI) (per capita constant 2011 international $)	LB	$\upsilon = 17{,}688$ (min of EU), $\tau = 41{,}689$ (max of EU14)
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	$\upsilon = -79.740$ (min of all countries), $\tau = 7.109$ (average of EU14)
WEALTH	RE	Foreign direct investment (% of GDP)	LB	$\upsilon = -32.9$ (min of all countries), $\tau = 11.01$ (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		
HEALTH	ST	Infant mortality (deaths per 1000 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), $\tau = 81.81$ (average of Scandinavian countries)
HEALTH	ST	Undernourishment; see above		
HEALTH	RE	DPT (diphtheria-pertussis-tetanus) immunization (% of population)	LB	$u = 87$ (min of EU14), $\tau = 100$ (maximum possible)
HEALTH	RE	Measles immunization (% of population)	LB	$u = 89$ (min of EU14), $\tau = 100$ (maximum possible)
HEALTH	RE	Hepatitis B immunization (% of population)	LB	$u = 76$ (min of EU14), $\tau = 100$ (maximum possible)
HEALTH	RE	Physicians (per 1000 population)	LB	$u = 0.01869$ (min of all countries), $\tau = 3.86156$ (average of Scandinavian countries)
HEALTH	RE	Hospital beds (per 1000 population)	LB	$u = 0.1930$ (min of all countries), $\tau = 3.3923$ (average of Scandinavian countries)
HEALTH	RE	Current health expenditure (% of GDP)	LB	$u = 2.484$ (min of all countries), $\tau = 10.19$ (average of Scandinavian countries)
HEALTH	RE	Access to safe water (% of population)	LB	$u = 41.09$ (2.5th percentile), $\tau = 100$ (max possible)
HEALTH	RE	Access to sanitation (% of population)	LB	$u = 13.04$ (2.5th percentile), $\tau = 100$ (max possible)
KNOW	PR	Primary student-to-teacher ratio	SB	$T = 12.15$ (average of EU14), $U = 62.88$ (99th percentile)
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), $\tau = 100$ (max possible)
KNOW	ST	Expected years of schooling (years)	LB	$u = 5.398$ (min of all countries), $\tau = 17.359$ (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 enrolment (% of children of official school age)	LB	$u = 28.17$ (min of all countries), $\tau = 97.36$ (average of EU14)
KNOW	ST	Secondary school enrolment (% of children of official school age)	LB	$u = 8.29$ (min of all countries), $\tau = 94.40$ (average of EU14)
KNOW	RE	Research and development (R&D) expenditure (% of GDP)	LB	$u = 0.03672$ (1st percentile), $\tau = 0.4233$ (average of Australia, Canada, Japan, Norway, and USA)
KNOW	RE	Government expenditure on education (% of GDP)	LB	$u = 1.094$ (1st percentile), $\tau = 4.627$ (average of Australia, Canada, Japan, Norway, and USA)

[a] SB: smaller is better; LB: larger is better; NB: nominal is best; indicator thresholds: u, τ, T, U (see Section 2.3).
[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).

method allows for dealing with temporal variations, measurement or reporting errors, outliers, and missing values. Past and recent indicator data are weighted via exponential smoothing and summarized into two values, the level and the trend, which estimate the current state and the annual change of the indicator respectively. The model uses the level component for 67 indicators and the trend component to estimate forest change and desertification. For each country and indicator, two exponential smoothing algorithms described in Phillis et al. (2018) are applied; the final smoothed indicator value is set equal to the (level or trend) estimate of the algorithm that yields the smallest root mean squared error (RMSE).

2.3. Normalization

To facilitate the synthesis of an overall sustainability measure, we rescale all smoothed indicators from their physical domains into a common interval [0, 1] representing a range from the lowest to the highest levels of sustainability. For each indicator, we define either two or four reference thresholds, $u < \tau \leq T < U$, specified according to scientific knowledge, international regulations and agreements, or just common sense. Values lower than u or larger than U represent absolute

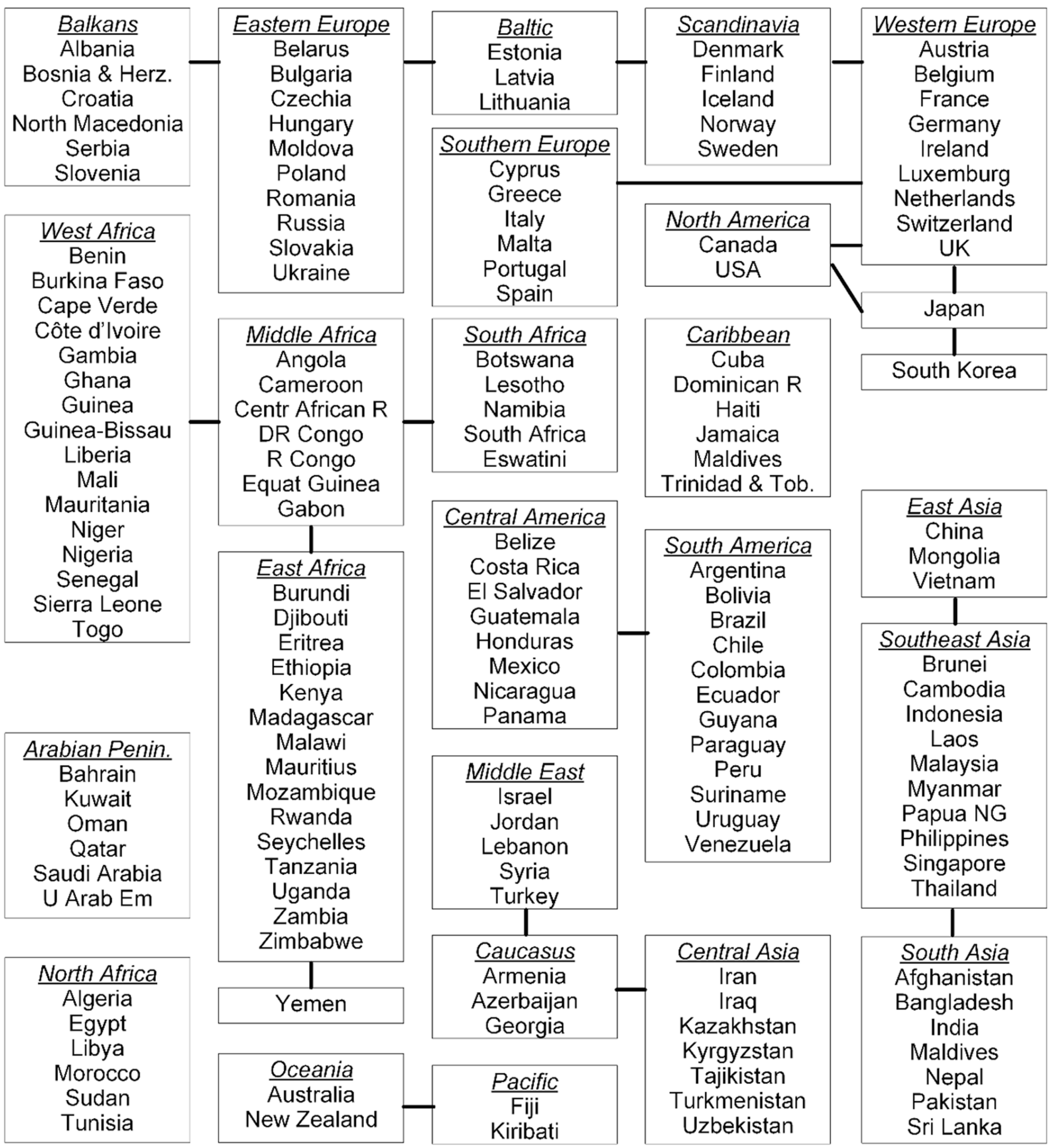

Fig. 2. Geo-economic similarities: high (boxes) and moderate (lines).

unsustainability and are assigned the normalized value 0. The interval $[\tau, T]$ represents the range of target or sustainable values, which are assigned the normalized value 1.

If a smoothed indicator value z is between two successive thresholds, it is assigned a normalized value by linear interpolation as follows:

$$x = \begin{cases} 0 & z \leqslant u \\ \dfrac{z-u}{\tau-u} & u < z < \tau \\ 1 & \tau \leqslant z \leqslant T \\ \dfrac{U-z}{U-T} & T < z < U \\ 0 & U \leqslant z \end{cases} \quad (1)$$

For some indicators, larger values lead to a higher sustainability (larger is better, LB), and for others, such as pollutant emissions smaller values are more sustainable (smaller is better, SB). For unemployment (% of jobless labor force), neither LB nor SB is appropriate, but a range of values (nominal is best, NB) containing the unemployment rates of Germany (about 4%) and Sweden and Canada (7%). The normalization type and thresholds for each indicator are registered in Table 1.

2.4. Imputation of missing indicators

At least one indicator is not available for 159 of 164 countries and, overall, 810 values are missing out of a total of 11,316 inputs. The missing values are filled in with averages of available indicators of other countries selected on the basis of geo-economic similarity and indicator proximity criteria.

Geo-economic similarity is defined in Fig. 2 where highly similar countries are placed in the same box while moderately similar countries are in different but connected boxes. The figure follows mainly the United Nations Statistics Division geoscheme classification of geographical subregions (UNSD, 1999), with some exceptions. For example, Yemen is a low income country, more similar to Eastern African countries than to its neighbors in the Arabian Peninsula.

Indicator similarity is a second criterion for selecting data donor countries. Suppose that a missing indicator belongs to component g (g = AIR, …, KNOW). For two countries i and j let C_{ijg} denote the collection of all indicators of component g which are available for both countries and $|C_{ijg}|$ the set cardinality. A Euclidean distance d_{ijg} is defined by

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

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.

If a given country is missing an indicator, its value is imputed by averaging the corresponding values of other countries having high similarity and Euclidean distance below a certain threshold θ. If no such countries exist, other similarity-distance combinations are tried involving moderately similar countries and/or a larger threshold $\Theta > \theta$. Details on the imputation procedure with $\theta = 0.1$ and $\Theta = 0.2$ are provided in Phillis et al. (2011). We improve that algorithm by choosing the optimal pair (θ, Θ) for each country with the aid of a statistical procedure known as leave-one-out cross-validation. The parameter space $\{(\theta, \Theta), \theta \in [0, 1], \Theta \in (\theta, 1]\}$ is replaced by a finite grid of points. The algorithm of Phillis et al. (2011) is recursively applied over the available indicators, rather than the missing ones, and imputed values with corresponding imputation errors are computed for every candidate (θ, Θ) pair. The optimal pair for each country is chosen according to minimum RMSE.

The parameter pair used in Phillis et al. (2011) returned a country average of 0.26 for RMSE and 0.16 for the mean absolute error (MAE). Using the optimal pair by the search procedure described above resulted in smaller errors, namely, RMSE = 0.19 and MAE = 0.12.

Finally, the following modifications are made to the data after the imputation procedure:

- Fifty percent of the current terrestrial land is under 3 m in elevation in the Netherlands. The corresponding land and population impact indicators are both assigned a normalized value of zero. However, these indicators are omitted because the Netherlands has already taken measures against flooding by building dikes and reclaiming land for agriculture.
- Forty-three countries either lack or have EEZs smaller than 1% of their total areas. For these countries, fish stock status and marine protected KBAs are not imputed and are omitted from the analysis.
- Mountain protected KBAs are not reported for 36 countries, thirteen of which have highest peaks lower than 650 m; for these countries mountain protected KBAs are omitted from the analysis.
- Finally, the missing data on literacy rate for 25 developed countries are filled in with ones, the most sustainable values.

2.5. Fuzzification

The interval [0, 1] of normalized values is divided into pairwise overlapping segments representing various levels of sustainability. Each level is described by a fuzzy set and a membership function on the corresponding segment. Any value in [0, 1] belongs to one or more fuzzy sets with certain membership grades. Four types of fuzzy partitions are defined in the interval [0, 1] as shown in Fig. 3.

Indicators are assigned to three fuzzy sets: *Weak* (W), *Medium* (M), and *Strong* (S). The tertiary components (PR, ST, and RE) are represented with five fuzzy sets: *Very Bad* (VB), *Bad* (B), *Average* (A), *Good* (G), and *Very Good* (VG). Renewable electricity generation is handled as a tertiary component because it is the sole input for RE(AIR). For the secondary components (LAND, WATER, etc.) we use seven fuzzy sets: *Extremely Low* (EL), *Low* (L), *Fairly Low* (FL), *Intermediate* (I), *Fairly High* (FH), *High* (H), and *Extremely High* (EH). Primary components ECOS and HUMS and the overall sustainability SAFE have nine fuzzy sets labeled M_0, …, M_8. The first fuzzy set of each partition (i.e., W, VB, EL, and M_0) corresponds to the lowest sustainability level and the last set (S, VG, EH, and M_8) corresponds to the highest level.

For example, 14% of the electricity in Estonia is generated from renewable and hydroelectric sources. The normalization parameters for the renewable electricity generation indicator are (Table 1) $u = 0\%$ and $t = 100\%$; hence, the normalized value for Estonia is 0.14. As shown in Fig. 3b, this value is VB with membership grade $\mu_{VB}(0.14) = (0.25–0.14)/(0.25–0) = 0.44$, B with grade $\mu_B(0.14) = (0.14–0)/(0.25–0) = 0.56$, and A, G or VG with zero grades. In a similar manner we transform each numerical input into one or several fuzzy sets.

2.6. Multistage fuzzy inference and sustainability assessment

The model aggregates indicators of sustainability into more composite variables using several fuzzy systems and, finally, generates an overall sustainability index.

Each fuzzy system comprises four entities: a set of fuzzy inputs, a fuzzy output, a set of rules, and an inference process. For a fuzzy system with inputs $i = 1, …, n$ and output 0, a rule has the form

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

where $L_{i,j}$ is the fuzzy set of input i and $L_{0,j}$ the corresponding fuzzy set of the output. All rule premises are formulated as logical conjunctions (*and*). Details on the rule bases of SAFE and their representation are given in Appendix B.1. The rules are *monotonic* in the sense that if two rules, say, j and k have the same premises except for input's i fuzzy set $L_{i,j}$ being more sustainable than $L_{i,k}$, then the output fuzzy set $L_{0,j}$ is at least as sustainable as $L_{0,k}$.

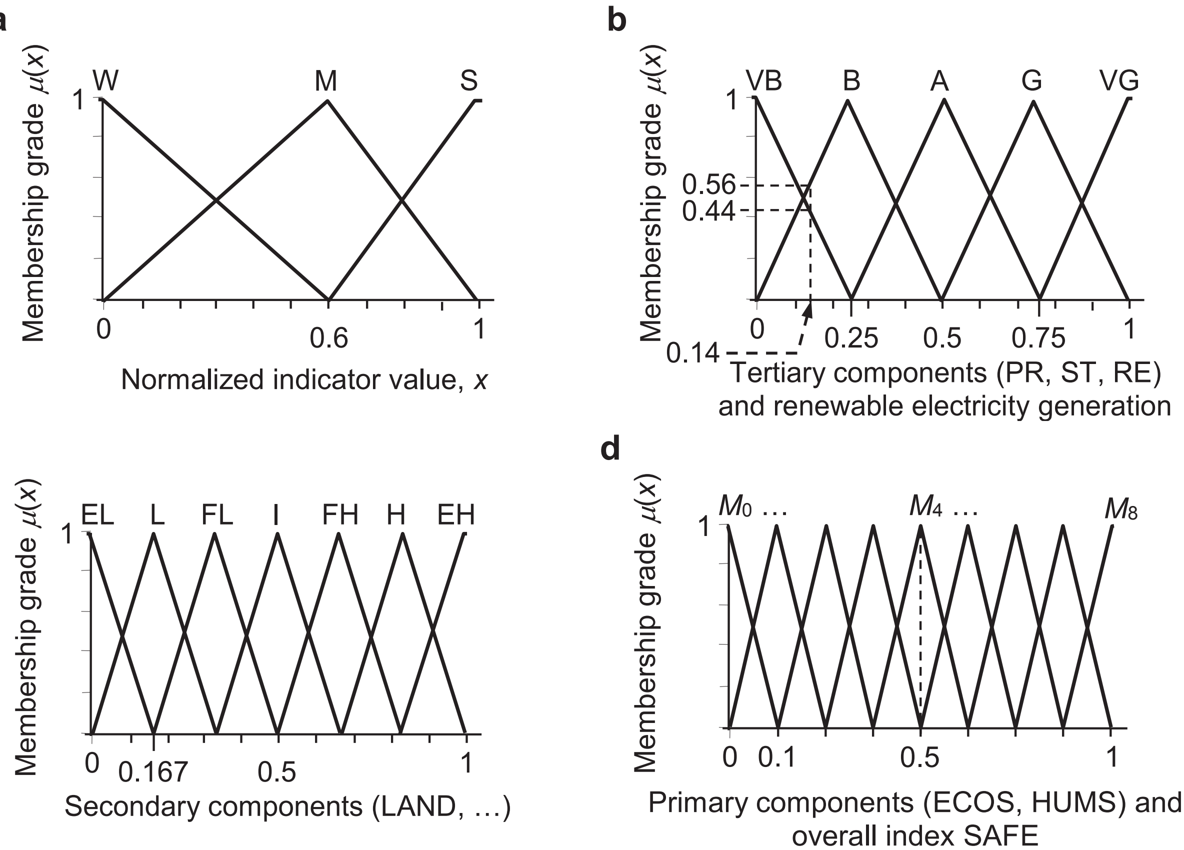

Fig. 3. Fuzzy sets and corresponding membership functions $\mu(x)$.

Fuzzy inference generates the membership grade of the output variable to its prescribed fuzzy sets, using all the rules of the rule base. This is done in two steps. First, the membership grade of the output of each rule is set equal to the product of the input membership grades. Thus, for Rule j we have

$$\mu_{0,j} = \mu_{1,j} \dots \mu_{n,j} \tag{3}$$

where $\mu_{i,j}$ is the membership grade of input i to the fuzzy set $L_{i,j}$. Appendix B.2 presents an approach for dealing with missing inputs. Second, if several rules have the same output fuzzy set L, i.e., $L_{0,j} = L$, then the overall membership grade of the output to L is given by the sum of the individual membership grades:

$$\mu_{0,L} = \sum_{j:\ L_{0,j}=L} \mu_{0,j} \tag{4}$$

If the output is an input to a subsequent rule base, then a similar inference process is carried out using another rule base and so on until all composite fuzzy variables are evaluated.

The final step is to transform fuzzy outputs into crisp values. This is necessary for ranking the countries on the basis of some high-level composite variable or the overall index SAFE. To each fuzzy set L of Fig. 3 we assign a typical sustainability value $y_L \in [0, 1]$. In the model, y_L is such that $\mu_L(y_L) = 1$. Thus, for the fuzzy sets M_0, …, M_8, in Fig. 3d, we have $y_0 = 0$, $y_1 = 0.125$, …, and $y_8 = 1$. A crisp value $x_0 \in [0, 1]$ for any output is computed using the *height defuzzification* method:

$$x_0 = \frac{\sum_{\text{all fuzzy sets } L \text{ of the output}} y_L \mu_{0,L}}{\sum_{\text{all fuzzy sets } L \text{ of the output}} \mu_{0,L}} \tag{5}$$

The use of monotonic rules, product-sum inference, triangular or trapezoid membership functions, and height defuzzification ensures that the value of SAFE increases whenever an indicator is improved. These four conditions are sufficient for the monotonicity of any hierarchical fuzzy inference system (Kouikoglou and Phillis, 2009).

2.7. Sensitivity analysis

Sensitivity analysis is an important module of SAFE as it completes the analytical part with the normative one. SAFE first provides rankings for countries and then guides decision makers towards the most important indicators that have the highest potential of sustainability improvement. This information is crucial when limited resources are prioritized to achieve maximum sustainability gains.

Let x_i, $i = 1,2,\dots,69$ be the normalized input variables and the final sustainability index SAFE(x_1,…,x_{68}). An indicator variable x_c is perturbed by $\varepsilon > 0$. The first order difference is

$$\Delta_c = SAFE(x_1, \dots x_c + \varepsilon, \dots) - - SAFE(x_1, \dots x_c, \dots) \tag{6}$$

which, by monotonicity, is the rate of sustainability improvement. However, ranking indicators according to Δ_c is problematic because the ranking would be biased in favor of components with few inputs and does not account for inputs far from sustainable. Instead, inputs are ranked according to

$$S_c = \Delta_c(1 - x_c) \tag{7}$$

where $1 - x_c$ is the distance of x_c from a fully sustainable value. For further explanations about the rationale of the expression above see Phillis et al. (2011). If resources are available for the improvement of two inputs simultaneously the relevant expressions become

Δ_{cv} = SAFE(x_1,…$x_c + \varepsilon$,…$x_v + \varepsilon$,…)–SAFE(x_1,…x_c,…x_v,…)

and

$$S_{cv} = \Delta_{cv}(1 - -x_c)(1 - -x_v) \tag{8}$$

The extension to higher dimensions is obvious.

2.8. Sustainability Comparisons and dynamics

To identify the most important indicators to improve sustainability for groups of countries, we compute the frequency for each indicator to be among the top three most influential ones in any member of the group. The frequency of indicator c is given by

$$\frac{1}{3}\frac{\left(\begin{array}{c}\text{number of times } S_c \text{ is among the three}\\ \text{largest gradients for all group members}\end{array}\right)}{(\text{number of member countries in the group})}100\% \tag{9}$$

The model permits exploring the dynamics of the SAFE index over any time span, here 1995–2016. By specifying a year t less than 2016, all indicator time series are automatically truncated to t, omitting the data from $t+1$ on. Normalization thresholds that depend on data (percentages, max, min, percentiles, or indicator values of specific countries), are adjusted accordingly. The calculations outlined in the previous sections generate the composite sustainability variables and the overall index for that year.

Finally, to show graphically the human and ecological sustainability performance across regions we use the expressions

$$H_r^{'} = \frac{H_r - \overline{H}}{\sqrt{\sum_r \left(H_r - \overline{H}\right)^2}} \text{ and } E_r^{'} = \frac{E_r - \overline{E}}{\sqrt{\sum_r \left(E_r - \overline{E}\right)^2}} \tag{10}$$

where H_r' and E_r' are the standardized HUMS and ECOS scores of region r, respectively, H_r and E_r are the raw HUMS and ECOS scores, and $\overline{H}$ and $\overline{E}$ are the average HUMS and ECOS scores of all regions. Thus data have been standardized around their means and the problem of selecting arbitrary thresholds for high and low performances is avoided.

3. Results and discussion

Table 2 shows the ranking of countries by SAFE based on the complete 1990–2016 time series. The top 30 places of the list are occupied by Scandinavia and other European countries, Australia, Uruguay, and New Zealand. The least sustainable countries in the list are Afghanistan, Haiti, and Mauritania. Sub-Saharan countries take more than half of the lowest 30 places.

The SAFE index was also calculated for partial data starting at 1990 and ending at various years before 2016. The "Δ %" column shows the percentage change of the overall SAFE index from 1995 to 2016. The largest improvements in SAFE are seen in Togo and Burkina Faso and the worst declines in Oman and Kiribati.

Table 2 also shows the indicators with largest first and second-order sensitivities for each country. These are computed by introducing perturbations $\varepsilon = 0.01$ to indicators c or pairs of indicators (c, v), one at a time, and iteratively running the model to compute S_c and S_{cv}. In general, the most influential indicator according to the first-order sensitivity analysis is also in the important pair of second-order perturbations. In 20 countries, however, the second-order analysis reveals some synergistic relations among indicators that cannot be captured by S_c alone. For example, the first-order sensitivity analysis points to GNI as the most influential factor for improving Hungary's sustainability, whereas a second-order analysis identifies the pair of renewable electricity generation and incidence of cardiovascular diseases. It is worth noting that, since SAFE is nonlinear, first and second order sensitivity analysis might not contain common indicators.

A few somewhat counter intuitive results appear such as the relatively low ranking of South Korea. A close look at the detailed results revealed that South Korea has the second weakest WATER component and the eighth weakest overall environmental sustainability (ECOS) of all 164 countries. Five indicators of South Korea have zero scores, namely, pesticide use, fertilizer consumption, forest change, freshwater resources, and incidence of malaria. 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.

POLICY and KNOW have the largest correlation coefficients with SAFE ($R = 0.85$), followed by HEALTH ($R = 0.71$), WEALTH ($R = 0.64$), and LAND ($R = 0.55$). BIOD and WATER are moderately correlated with SAFE (R = 0.49, 0.40) and AIR is weakly correlated (R = 0.16). However, AIR contains the most influential indicator in improving the sustainability of most countries as can be deduced from the ubiquity of renewable electricity generation in the last two columns of Table 2.

Table 3 shows the country averages by region and economic group. Scandinavian countries and members of the European Union and the OECD have the highest overall sustainability scores. Low-income, South Asian, and Sub-Saharan countries have the lowest scores for most components with health-related and political issues having the weakest sustainability levels. Water sustainability has the lowest levels in the Middle East and North Africa. Air quality has the lowest score relative to the other secondary components in developed countries and biodiversity sustainability has relative low levels in various regions irrespective of economic development: North America, Latin America, the Caribbean, East Asia, and the Pacific region.

The indicators with the highest potential to improve sustainability in European, North American, Scandinavian, and other high-income countries are CO_2 emissions, renewable electricity generation, and forest change (Appendix Table D.1). Renewable electricity generation is also a frequent influential indicator in all other groups and regions except for low-income countries where corruption is the main impediment to sustainable development. RLI of threatened species together with renewable electricity emerge in South Asia and Latin America. Finally the most frequent important indicator among the 164 countries is renewable electricity generation followed by corruption, GNI, forest change, and RLI.

Table 4 compares SAFE with some of the sustainability ranking approaches reviewed in the introduction. The results are based on the relative rankings of countries that are common with those of SAFE. HDI, EPI, and the human and economic dimensions of SSI have four to six countries among the top 10 in common with SAFE and Jaccard similarity indices (Eq. (C.2)) from 0.25 to 0.43. SAFE is strongly correlated with HDI, EPI, and the human dimensions of SSI, with Kendall τ higher than 0.60 as per Eq. (C.1); it is moderately correlated with the economic dimension of SSI. The environmental dimension of SSI has a narrow scope and differs completely from all other approaches in its top 10 list (Jaccard index 0 and $\tau = -0.30$).

Next we look at certain dynamic aspects of SAFE over 1995–2016. We applied the model to five sets of time series ending in the years 1995, 2000, 2005, 2010 and 2016, and estimated past values for all sustainability indicators and components. Fig. 4a shows the progress towards sustainability of seven world regions. All regions on average show modest sustainability progress with the exception of North America and East Asia & Pacific which suffer a slight decline.

Another side of sustainability is viewed in Fig. 4b where countries are grouped according to income level. Again, all groups have made modest progress over time in line with income gains. Further analysis shows that HUMS is the main component that causes the small improvements in the SAFE score.

Fig. 4 shows no dramatic sustainability changes over 1995–2016. This is due to small overall changes of the indicators in this rather short time frame. SAFE is quite sensitive to indicator value differentials. We tested SAFE for 2016 but now all indicators were incremented by 0.01. Average SAFE score over all countries improved by 0.011 with a maximum increase of 0.023 for countries with ample room for improvement and minimum of 0.002 for countries with little room for improvement. For an increase of 0.05 in all indicators the corresponding numbers of SAFE were: average 0.049, maximum 0.107, and minimum 0.006. Similar results were obtained for indicator increments of 0.10.

Table 2
Country rankings; overall (SAFE), ecological (ECOS), and human (HUMS) sustainability indices; percentage change of SAFE from 1995 to 2016 (Δ %); and most important indicators.

	Country	SAFE	HUMS	ECOS	Δ %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
1	Denmark	0.8691	0.8888	0.7434	18	SLR impact on land area	SLR impact on land area, Immunization against Hepatitis B
2	Sweden	0.8618	0.9124	0.7312	12	Forest change	Forest change, Renewable electricity generation
3	Norway	0.8578	0.8808	0.7321	4	Forest change	Forest change, Freshwater protected KBAs
4	Switzerland	0.8387	0.9184	0.6944	11	Renewable electricity generation	Renewable electricity generation, Forest change
5	Austria	0.8284	0.8848	0.6996	5	Forest change	Forest change, Red List Index
6	Finland	0.8189	0.8748	0.6942	5	Renewable electricity generation	Renewable electricity generation, Forest change
7	Slovenia	0.8067	0.8692	0.6843	28	Renewable electricity generation	Renewable electricity generation, Forest change
8	Netherlands	0.8044	0.9492	0.5919	9	Renewable electricity generation	Renewable electricity generation, Pesticide use
9	Slovakia	0.8043	0.8341	0.7056	19	Renewable electricity generation	Renewable electricity generation, Forest change
10	UK	0.8041	0.8780	0.6767	13	Renewable electricity generation	Renewable electricity generation, Forest change
11	France	0.8039	0.8103	0.7365	7	Renewable electricity generation	Renewable electricity generation, Unemployment
12	Lithuania	0.8033	0.8080	0.7399	27	Tax revenue	Tax revenue, Forest change
13	Iceland	0.7970	0.8720	0.6729	3	Freshwater protected KBAs	Freshwater protected KBAs, Forest change
14	Germany	0.7943	0.9038	0.6431	15	Renewable electricity generation	Renewable electricity generation, Forest change
15	Poland	0.7927	0.8457	0.6805	27	Renewable electricity generation	Renewable electricity generation, Water resources
16	Hungary	0.7903	0.8011	0.7236	24	GNI	Renewable electricity generation, Incidence of cardiovascular diseases
17	Ireland	0.7903	0.8901	0.6521	6	Fertilizer consumption	Fertilizer consumption, Renewable electricity generation
18	Czechia	0.7858	0.8410	0.6739	12	Renewable electricity generation	Renewable electricity generation, Forest change
19	Portugal	0.7597	0.8290	0.6394	6	Renewable electricity generation	Renewable electricity generation, Forest change
20	Latvia	0.7583	0.7537	0.7448	19	Renewable electricity generation	Renewable electricity generation, Forest change
21	Estonia	0.7567	0.8596	0.6269	20	Renewable electricity generation	Renewable electricity generation, Forest change
22	Spain	0.7552	0.7747	0.6559	3	Tax revenue	Tax revenue, Unemployment
23	Croatia	0.7529	0.7225	0.7499	23	Forest change	Forest change, Unemployment
24	Australia	0.7517	0.8944	0.5158	1	Renewable electricity generation	Renewable electricity generation, Forest change
25	Italy	0.7516	0.7673	0.6481	19	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment
26	Belgium	0.7455	0.8721	0.5190	16	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
27	Malta	0.7446	0.8738	0.5033	26	Pesticide use	Pesticide use, Forest change
28	Uruguay	0.7432	0.8151	0.6113	2	Pesticide use	Pesticide use, Freshwater protected KBAs
29	Luxembourg	0.7424	0.8903	0.4975	18	Forest change	Forest change, Pesticide use
30	New Zealand	0.7385	0.8929	0.4883	−15	Red List Index	Red List Index, Fertilizer consumption
31	Canada	0.7322	0.8435	0.5550	−2	Tax revenue	Tax revenue, Desertification
32	Greece	0.7248	0.6930	0.6946	11	Renewable electricity generation	Renewable electricity generation, Unemployment
33	Cyprus	0.7210	0.8148	0.5647	7	Renewable electricity generation	Renewable electricity generation, Unemployment
34	Romania	0.7194	0.7064	0.6624	16	Corruption Perceptions Index	Corruption Perceptions Index, Immunization against measles
35	Japan	0.7175	0.8426	0.5099	12	Renewable electricity generation	Renewable electricity generation, Pesticide use
36	USA	0.7129	0.8243	0.5337	0	Renewable electricity generation	Renewable electricity generation, Gini index
37	Bulgaria	0.7107	0.7051	0.6428	17	Corruption Perceptions Index	Corruption Perceptions Index, Mortality from ambient PM pollution
38	Costa Rica	0.7054	0.7370	0.5899	20	Pesticide use	Pesticide use, Fertilizer consumption
39	Belarus	0.6794	0.6760	0.6297	9	Unemployment	Unemployment, GNI
40	Chile	0.6757	0.7795	0.5275	1	Fertilizer consumption	Fertilizer consumption, Pesticide use
41	Turkey	0.6609	0.6838	0.5761	12	Renewable electricity generation	Renewable electricity generation, Fish stock status
42	Russia	0.6602	0.6944	0.5633	6	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
43	Brunei	0.6482	0.7045	0.5365	2	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
44	Albania	0.6459	0.6040	0.6489	5	Wastewater treatment	Wastewater treatment, Forest change
45	Cuba	0.6428	0.7349	0.5196	−1	Red List Index	Red List Index, Renewable electricity generation
46	Peru	0.6396	0.6010	0.6397	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	Mexico	0.6366	0.6748	0.5297	2	Renewable electricity generation	Renewable electricity generation, Red List Index
50	Moldova	0.6366	0.6368	0.6175	3	GNI	GNI, Political rights
51	Venezuela	0.6363	0.5822	0.6404	2	Forest change	Forest change, Fish stock status
52	Thailand	0.6360	0.6131	0.6320	−5	Renewable electricity generation	Renewable electricity generation, Forest change
53	Argentina	0.6356	0.6992	0.5175	15	Forest area	Forest area, Forest change
54	Mongolia	0.6345	0.6471	0.5548	34	Renewable electricity generation	Renewable electricity generation, GNI
55	Azerbaijan	0.6330	0.6499	0.5413	28	Renewable electricity generation	Renewable electricity generation, Political rights
56	Tunisia	0.6318	0.6507	0.5336	2	Renewable electricity generation	Renewable electricity generation, Forest change
57	Serbia	0.6314	0.6517	0.5349	2	Renewable electricity generation	Renewable electricity generation, Unemployment
58	Ghana	0.6298	0.5608	0.6351	3	Wastewater treatment	Wastewater treatment, Forest change
59	Paraguay	0.6274	0.6052	0.6211	15	Forest change	Forest change, Freshwater protected KBAs
60	North Macedonia	0.6265	0.6210	0.6064	4	Unemployment	Unemployment, GNI
61	Kyrgyzstan	0.6264	0.6278	0.5638	−1	GNI	GNI, Political rights
62	Malaysia	0.6262	0.7230	0.4906	−1	Renewable electricity generation	Renewable electricity generation, Red List Index
63	Namibia	0.6254	0.5015	0.6838	14	Gini index	Gini index, Unemployment
64	Gabon	0.6252	0.4895	0.7359	14	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment gender inequality
65	Israel	0.6245	0.8404	0.3619	−2	Renewable electricity generation	Renewable electricity generation, Pesticide use
66	Singapore	0.6240	0.6913	0.4973	0	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
67	Dominican R	0.6229	0.5236	0.6292	0	Renewable electricity generation	Renewable electricity generation, Water resources
68	Ukraine	0.6229	0.6167	0.5829	3	Political rights	Political rights, Corruption Perceptions Index
69	Cape Verde	0.6226	0.6006	0.6097	5	Renewable electricity generation	Renewable electricity generation, GNI
70	Fiji	0.6226	0.6222	0.5473	−19	GNI	GNI, Red List Index

(continued on next page)

Table 2 (*continued*)

	Country	SAFE	HUMS	ECOS	Δ %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
71	South Korea	0.6223	0.8106	0.3709	30	Renewable electricity generation	Renewable electricity generation, Pesticide use
72	Ecuador	0.6219	0.6304	0.5129	11	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
73	Georgia	0.6218	0.6007	0.6083	2	Mortality from ambient PM pollution	Mortality from ambient PM pollution, Forest change
74	Panama	0.6184	0.5945	0.5962	14	Red List Index	Forest change, Gini index
75	Guyana	0.6162	0.5284	0.6152	−1	Forest change	Forest change, Wastewater treatment
76	Nicaragua	0.6158	0.5220	0.6153	32	Red List Index	Red List Index, Forest change
77	Philippines	0.6125	0.4977	0.6241	−2	Red List Index	Red List Index, GNI
78	Suriname	0.6122	0.5763	0.5918	5	Renewable electricity generation	Pesticide use, Forest change
79	Kazakhstan	0.6112	0.6458	0.4847	34	Renewable electricity generation	Renewable electricity generation, Forest change
80	Bolivia	0.6099	0.5341	0.6045	23	Forest change	Forest change, Pesticide use
81	Mauritius	0.6099	0.6957	0.4653	5	Renewable electricity generation	Pesticide use, Red List Index
82	Sri Lanka	0.6038	0.5721	0.5747	7	Red List Index	Red List Index, Forest change
83	Bosnia and Herzegovina	0.5989	0.5933	0.5284	15	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
84	Zimbabwe	0.5978	0.5024	0.6002	27	Red List Index	Red List Index, Forest change
85	Armenia	0.5957	0.5887	0.5277	8	Corruption Perceptions Index	Unemployment, GNI
86	Honduras	0.5952	0.5861	0.5312	−2	R&D expenditure	R&D expenditure, GNI
87	Seychelles	0.5940	0.6566	0.4600	2	Freshwater protected KBAs	Freshwater protected KBAs, Fertilizer consumption
88	Colombia	0.5918	0.5677	0.5529	1	Red List Index	Pesticide use, Fertilizer consumption
89	El Salvador	0.5895	0.5746	0.5369	13	Renewable electricity generation	Corruption Perceptions Index, GNI
90	Vietnam	0.5839	0.5703	0.5321	−7	Corruption Perceptions Index	Corruption Perceptions Index, GNI
91	Botswana	0.5818	0.5745	0.5183	11	Renewable electricity generation	Renewable electricity generation, Forest change
92	Nepal	0.5811	0.5015	0.5853	41	Freshwater protected KBAs	Freshwater protected KBAs, Forest change
93	Eq Guinea	0.5788	0.4491	0.6381	39	R&D expenditure	R&D expenditure, Government expenditure on education
94	Lao PDR	0.5784	0.4486	0.6401	40	Corruption Perceptions Index	Corruption Perceptions Index, GNI
95	Burkina Faso	0.5780	0.4642	0.6146	48	Corruption Perceptions Index	Corruption Perceptions Index, GNI
96	Kiribati	0.5769	0.5867	0.4903	−22	Pesticide use	Corruption Perceptions Index, GNI
97	Congo R.	0.5764	0.3941	0.6997	15	Wastewater treatment	Tax revenue, GNI
98	Tajikistan	0.5751	0.5708	0.5129	16	Corruption Perceptions Index	Corruption Perceptions Index, GNI
99	Jordan	0.5745	0.6075	0.4680	10	Renewable electricity generation	Renewable electricity generation, Water stress
100	Algeria	0.5706	0.5606	0.5196	7	Renewable electricity generation	Renewable electricity generation, Political rights
101	Senegal	0.5704	0.5539	0.5293	34	Renewable electricity generation	Renewable electricity generation, GNI
102	Iran	0.5696	0.5784	0.4948	−1	Corruption Perceptions Index	Corruption Perceptions Index, Renewable electricity generation
103	Saudi Arabia	0.5692	0.6822	0.4011	−5	Renewable electricity generation	Renewable electricity generation, Tax revenue
104	Indonesia	0.5681	0.5547	0.5260	−2	Renewable electricity generation	Renewable electricity generation, GNI
105	Togo	0.5659	0.4444	0.6217	50	Red List Index	Red List Index, GNI
106	Kenya	0.5646	0.4549	0.6110	15	Tax revenue	Unemployment, GNI
107	Turkmenistan	0.5598	0.6348	0.4316	17	Renewable electricity generation	Renewable electricity generation, Water stress
108	Maldives	0.5558	0.6922	0.3671	−4	Renewable electricity generation	Renewable electricity generation, SLR impact on land area
109	China	0.5532	0.6333	0.4248	−5	Renewable electricity generation	Pesticide use, Fertilizer consumption
110	Malawi	0.5527	0.4692	0.5836	19	Freshwater protected KBAs	Freshwater protected KBAs, GNI
111	Trinidad and Tobago	0.5509	0.6694	0.3912	12	Pesticide use	Pesticide use, Fertilizer consumption
112	Uzbekistan	0.5493	0.6405	0.4156	16	Renewable electricity generation	Renewable electricity generation, Water stress
113	Côte d'Ivoire	0.5486	0.4311	0.6193	8	Undernourishment	Renewable electricity generation, GNI
114	Lesotho	0.5472	0.4203	0.6282	6	Unemployment	Unemployment, GNI
115	Benin	0.5395	0.4754	0.5643	40	Mortality from household air pollution	Renewable electricity generation, Forest change
116	Sierra Leone	0.5340	0.3827	0.6548	35	Corruption Perceptions Index	Corruption Perceptions Index, Renewable electricity generation
117	Cambodia	0.5331	0.4419	0.5910	3	Undernourishment	Corruption Perceptions Index, Unemployment
118	Jamaica	0.5326	0.5556	0.4774	19	Renewable electricity generation	Unemployment, GNI
119	Zambia	0.5320	0.4096	0.6230	37	Government expenditure on education	Government expenditure on education, GNI
120	Kuwait	0.5293	0.6518	0.3784	29	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
121	Libya	0.5285	0.5994	0.4290	5	Renewable electricity generation	Renewable electricity generation, Water stress
122	Lebanon	0.5222	0.5688	0.4531	−3	Corruption Perceptions Index	Corruption Perceptions Index, Fertilizer consumption
123	India	0.5216	0.5398	0.4819	3	Renewable electricity generation	Renewable electricity generation, GNI
124	Rwanda	0.5210	0.4009	0.6205	38	Political rights	Political rights, Civil liberties
125	South Africa	0.5208	0.5378	0.4833	10	Renewable electricity generation	Renewable electricity generation, Unemployment
126	Cameroon	0.5169	0.4466	0.5701	32	Red List Index	Red List Index, GNI
127	Mali	0.5138	0.4512	0.5618	43	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
128	Swaziland	0.5092	0.4923	0.5171	−13	Renewable electricity generation	Renewable electricity generation, Unemployment
129	Belize	0.5086	0.6182	0.3897	−11	Fertilizer consumption	Fertilizer consumption, Renewable electricity generation
130	U Arab Em	0.5002	0.6506	0.3502	−18	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
131	Papua NG	0.4973	0.4589	0.5381	−20	Freshwater protected KBAs	Freshwater protected KBAs, Renewable electricity generation
132	Bahamas	0.4938	0.6859	0.3088	9	Freshwater protected KBAs	Freshwater protected KBAs, SLR impact on land area
133	Liberia	0.4915	0.3680	0.6230	27	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
134	Ethiopia	0.4873	0.4189	0.5665	17	Freshwater protected KBAs	Freshwater protected KBAs, Corruption Perceptions Index
135	Egypt	0.4841	0.5367	0.4469	−4	Freshwater protected KBAs	Renewable electricity generation, Corruption Perceptions Index
136	Bahrain	0.4817	0.6378	0.3438	15	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
137	Nigeria	0.4814	0.4494	0.5311	1	Renewable electricity generation	Renewable electricity generation, GNI
138	Tanzania	0.4795	0.4660	0.5127	2	Red List Index	Red List Index, Corruption Perceptions Index
139	Djibouti	0.4780	0.4823	0.4947	18	Renewable electricity generation	Renewable electricity generation, Literacy rate
140	Qatar	0.4689	0.6606	0.3082	−17	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
141	Angola	0.4563	0.4359	0.5183	29	Renewable electricity generation	Desertification, GNI

(*continued on next page*)

Table 2 (*continued*)

	Country	SAFE	HUMS	ECOS	Δ %	Most influential indicator (arg max S_c)	Most influential pair of indicators (arg max S_{cv})
142	Mozambique	0.4552	0.3260	0.6286	20	Life expectancy at birth	Unemployment, GNI
143	Madagascar	0.4537	0.3611	0.5860	7	Corruption Perceptions Index	Corruption Perceptions Index, GNI
144	Guinea	0.4523	0.3260	0.6250	15	Corruption Perceptions Index	Corruption Perceptions Index, GNI
145	Gambia	0.4520	0.3448	0.5995	1	Corruption Perceptions Index	Corruption Perceptions Index, GNI
146	Oman	0.4519	0.6427	0.3090	−27	Renewable electricity generation	Renewable electricity generation, CO_2 emissions
147	Myanmar	0.4484	0.3651	0.5719	3	Corruption Perceptions Index	Corruption Perceptions Index, Forest change
148	Burundi	0.4407	0.3179	0.6167	42	Corruption Perceptions Index	Corruption Perceptions Index, Refugees
149	Uganda	0.4393	0.3960	0.5372	8	Red List Index	Red List Index, Corruption Perceptions Index
150	Bangladesh	0.4365	0.4900	0.4388	4	Renewable electricity generation	Renewable electricity generation, Fertilizer consumption
151	Guatemala	0.4295	0.4959	0.4285	6	Red List Index	Red List Index, Pesticide use
152	Pakistan	0.4134	0.4262	0.4642	7	Corruption Perceptions Index	Corruption Perceptions Index, Political rights
153	Chad	0.4126	0.3256	0.5614	16	Life expectancy at birth	Life expectancy at birth, Corruption Perceptions Index
154	Niger	0.4048	0.3982	0.4908	9	Unemployment	Unemployment, GNI
155	Congo DR	0.4039	0.2819	0.6067	2	Corruption Perceptions Index	Corruption Perceptions Index, Inflation
156	Iraq	0.3957	0.4242	0.4294	−1	Renewable electricity generation	Renewable electricity generation, Corruption Perceptions Index
157	Guinea-Bissau	0.3934	0.3180	0.5334	−5	Renewable electricity generation	Renewable electricity generation, Forest change
158	Yemen	0.3862	0.3648	0.4879	22	Corruption Perceptions Index	Corruption Perceptions Index, Unemployment
159	C African R	0.3830	0.2295	0.6297	−2	Wastewater treatment	Wastewater treatment, Forest change
160	Eritrea	0.3747	0.2750	0.5037	11	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs
161	Sudan	0.3664	0.2427	0.5071	−6	Corruption Perceptions Index	Corruption Perceptions Index, Refugees
162	Mauritania	0.3643	0.2840	0.4863	10	Freshwater protected KBAs	Desertification, Corruption Perceptions Index
163	Haiti	0.3640	0.2808	0.4875	−8	Renewable electricity generation	Renewable electricity generation, Freshwater protected KBAs
164	Afghanistan	0.3621	0.2461	0.5036	45	Corruption Perceptions Index	Corruption Perceptions Index, Freshwater protected KBAs

Table 3
SAFE components by region and economy.

	Regions	SAFE	HUMS	ECOS	Weakest secondary component
NA	North America	0.723	0.834	0.544	BIOD (0.385)
EC	Europe and Central Asia	0.725	0.761	0.628	AIR (0.583)
LA	Latin America and the Caribbean	0.598	0.607	0.542	BIOD (0.44)
EA	East Asia and Pacific	0.609	0.632	0.531	BIOD (0.458)
ME	Middle East and North Africa	0.534	0.613	0.438	WATER (0.352)
SA	South Asia	0.496	0.495	0.488	POLICY (0.333)
SS	Sub-Saharan Africa	0.508	0.428	0.580	HEALTH (0.336)
Europe					
EU	European Union	0.779	0.830	0.662	AIR (0.576)
EU14	EU14 countries	0.789	0.853	0.653	AIR (0.615)
Sc	Scandinavian countries	0.841	0.886	0.715	LAND (0.643)
Income groups					
HO	High income OECD	0.770	0.849	0.625	AIR (0.58)
HN	High income non-OECD	0.607	0.703	0.476	AIR (0.433)
UM	Upper middle income	0.602	0.608	0.545	POLICY (0.43)
LM	Lower middle income	0.549	0.509	0.558	POLICY (0.402)
LI	Low income	0.475	0.388	0.571	POLICY (0.311)

Given that over time some indicators improve and others deteriorate, Fig. 4 reflects small net overall indicator improvement for selected regions.

Fig. 5 elucidates the statistical connection between income and SAFE for the year 2016. Similar connections can be established for the years 1995, 2000, 2005, and 2010. A logarithmic relation is observed between SAFE scores and GNI per capita for all these years (R^2 varies from 0.509 to 0.660). This logarithmic relation implies that the connection between GNI per capita (income) and overall sustainability is not proportional but decreases as income increases.

Using the results of Table 3, we show graphically in Fig. 6 the human and ecological sustainability performance across regions according to Eq. (10).

It is important to note that this is a relative diagram since each sustainability score is compared to the scores of the other regions. The performance map of Fig. 6 categorizes regions according to their average HUMS and ECOS scores based on 2016 data:

a. Europe and Central Asia have relatively high human and ecological sustainability.
b. Latin America, Caribbean, East Asia, and the Pacific are close to the origin of the axes since their HUMS and ECOS scores are close to the average of all regions.
c. Sub-Saharan Africa has a rather high ECOS score but its HUMS is low.

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

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
Slovenia	Sweden	Luxembourg	Slovenia	Denmark	Rwanda
Netherlands	Singapore	Austria	Belgium	Australia	Malawi
Slovakia	Netherlands	Ireland	Denmark	Lithuania	Gambia
UK	Denmark	Finland	Ireland	U Arab Em	Guinea
Top-10 Jaccard coefficient with SAFE	0.25	0.43	0.43	0.25	0
Kendall τ with SAFE	0.61	0.63	0.65	0.41	–0.30
(number of common countries)	(164)	(163)	(149)	(149)	(149)

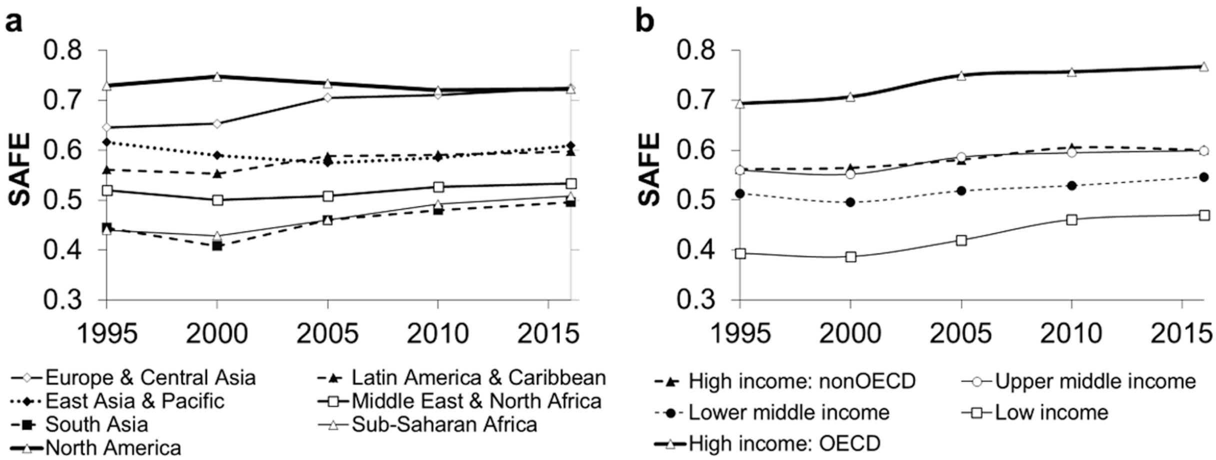

Fig. 4. Evolution of country group average SAFE indices for geographical regions and income groups between 1995 and 2016.

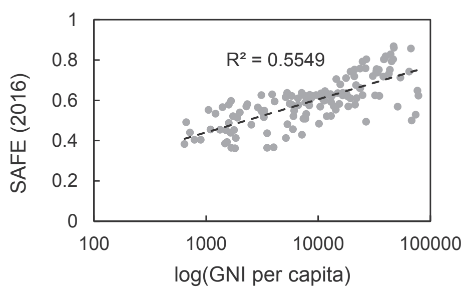

Fig. 5. Correlation between income and SAFE.

d. Middle East and North Africa have the lowest ecological sustainability performance, while their human sustainability score is close to the average of all countries.
e. North America has the highest human sustainability performance, while its ecological sustainability score is close to the average of all regions.
f. South Asia has relatively low human and ecological sustainability scores.

The evolution of sustainability over time is also exposed through a series of dynamic performance maps of ECOS vs. HUMS for selected regions as shown in Fig. 7. Now the standardized scores are restricted to the temporal variations of a particular region and are calculated using the regional average over time rather than $\overline{H}$ and $\overline{E}$. The main findings of Fig. 7 are summarized as follows:

a. Europe and Central Asia show a steady progress towards higher sustainability.
b. Latin America and Caribbean follow a clockwise path, starting from the lower-left quadrant (low HUMS/low ECOS) and ending at the upper-right quadrant (high HUMS/high ECOS), thus exhibiting a modest improvement of overall sustainability over time.
c. In contrast, a counter clockwise path is observed in East Asia and Pacific starting from the upper-right quadrant (low HUMS/high ECOS) and ending at the lower-right quadrant (high HUMS/low ECOS). These countries managed to improve their HUMS scores but

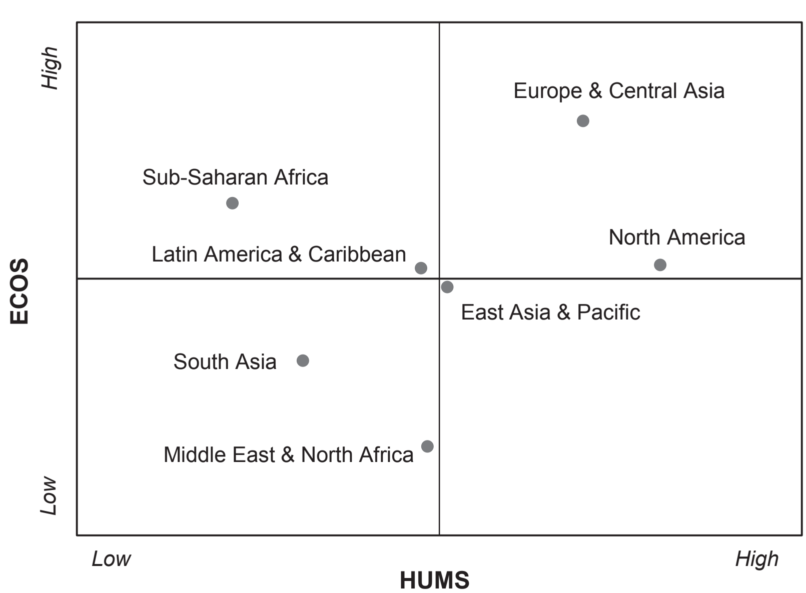

Fig. 6. Relative ECOS/HUMS diagrams for 2016.

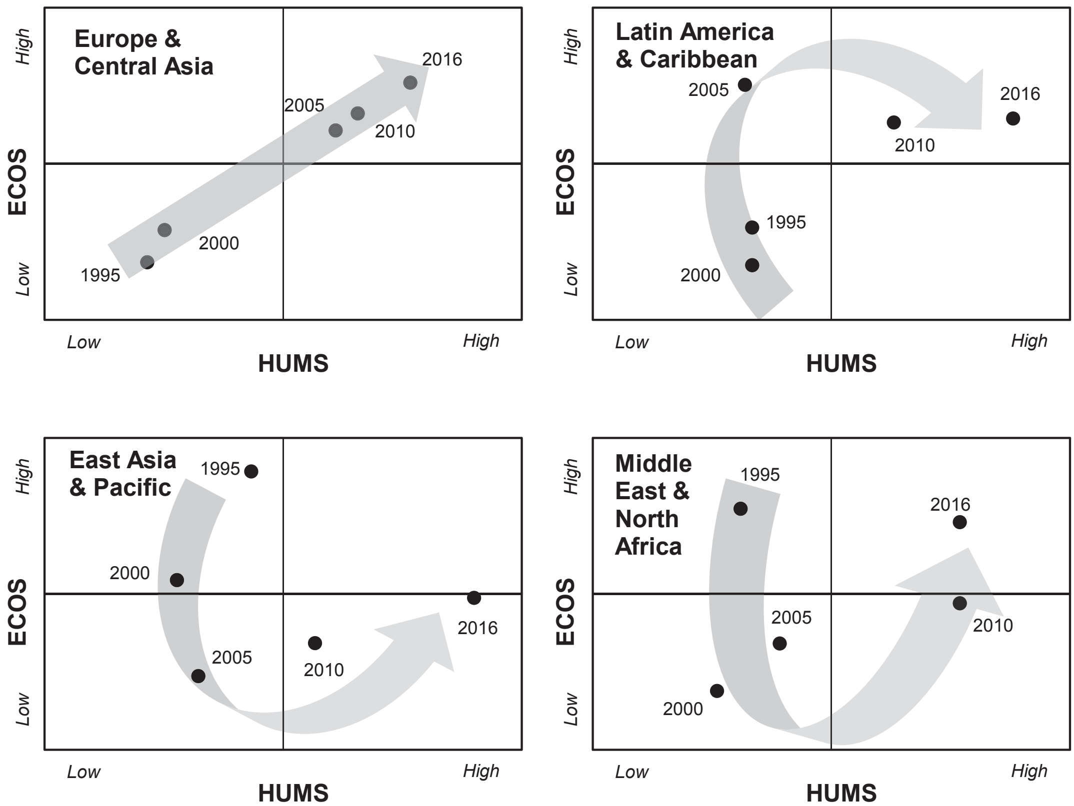

Fig. 7. Relative dynamic ECOS/HUMS diagrams for selected geographical regions.

their ECOS performance has been weakened over the examined period.

d. A similar counter clockwise path is observed in the Middle East and North Africa, a trajectory that results in a drop and then modest sustainability gains.

Figs. 6 and 7 reflect sustainability standing and evolution for groups of countries via available data. It should be stressed that data change over time and are heavily influenced by the environmental and sociopolitical conditions as well as the history of each region. For example, in the Middle East and North Africa ECOS deteriorates over 1995–2005 and then it improves until 2016 almost at the 1995 level, while HUMS initially remains about constant and then, after 2005, it takes off rather sharply. Northwestern Africa experienced a severe and prolonged drought in 1999–2002 which affected its environment and rainfed agriculture negatively (Masih et al., 2014). A severe drought also struck the Middle East in 1998–2001 (Bazza et al., 2018) with similar effects. Unfortunately, due to the civil war in Syria, no publicly available data exist about this country, which would have shown a very poor performance in both ECOS and HUMS. Thus the improvement of HUMS in the Middle East and North Africa is an average with Syria absent.

The opposite trend appears to be happening in Latin America and the Caribbean, where ECOS initially improves and then HUMS follows. Here one should take notice of the political situation in this region which became more democratic after 1995 when most dictatorships had collapsed. This democratic change, which continues to the day, was not without stagnation and regression. It, however, resulted in a net improvement of HUMS.

It should be stressed that improvement of one component does not necessarily imply improvement or deterioration of the other. For, example, in contrast to the previous cases, Europe and Central Asia exhibit a steady improvement of both. Indeed, Europe enjoys a very high standard of living coupled with strict environmental laws and enforcement. The bottom line is that the sociopolitical and environmental history of a region plays a very important role in its sustainability dynamics.

4. Conclusions

SAFE was updated for the fourth time to include the latest developments regarding sustainability. Of 164 ranked countries most of the top places were taken by developed countries while the bottom rungs were occupied by developing ones. A sensitivity analysis exposed those indicators with the highest potential of improving sustainability. 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. Indeed, it is well established that climate change, poverty, and species extinction are at the forefront of global problems threatening the global wellbeing.

The conclusion is that progress towards sustainability worldwide in the last 25 years is rather modest. Interestingly, North America regressed slightly over the same period. This counterintuitive finding was enabled by SAFE. Other counterintuitive results such as the relatively lower ranking of South Korea are discussed in the results section.

A shortcoming of SAFE is its subjectivity and emulation of human thinking via fuzzy logic. However, in the absence of a rigorous mathematical definition of sustainability, SAFE adopts an efficient way to model the multitude of facets of sustainability, environmental and social. In reality, SAFE serves as a definition and assessment tool simultaneously. Additionally, it should be stated that certain parameters of sustainability are only amenable to verbal descriptions and “computation with words” as the inventor of fuzzy logic, Lotfi Zadeh wrote (Zadeh, 1996). Corruption, political rights, and human liberties are some cases in point.

The SAFE index is composite and thus it generates an average measure of sustainability standing. One has to go backwards by means of sensitivity analysis to obtain a more detailed a picture. A careful analysis of the most sensitive indicators gives a finer idea of the intricacies of sustainability for a given country, in a sense, moving from the forest to trees. Other existing models of sustainability compute weighted averages of indicators with fixed weights. Most do not perform sensitivity analysis. SAFE is a global model that encompasses sustainability from a multitude of sides, it is flexible in that it is easily modified to incorporate new knowledge and data, and aids decision making with its sensitivity analysis module.

CRediT authorship contribution statement

Evangelos Grigoroudis: Methodology, Formal analysis, Investigation. **Vassilis S. Kouikoglou:** Methodology, Formal analysis, Software, Investigation, Writing - original draft. **Yannis A. Phillis:** Conceptualization, Methodology, Writing - original draft.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2020.107072.

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