A fuzzy approach to sustainability I: A time-series analysis of the Sustainable Development Goals

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We use a t-measure derived from fuzzy logic to evaluate progress towards the 2030 Agenda for Sustainable Development adopted by the United Nations Member States. In this first of a two-part series, we evaluate the 17 individual Sustainable Development Goals by applying the t-measure to a set of indicators. We examine the distribution and characteristics of the scores for each Goal and note trends over time, highlight outlier countries, and evaluate progress in each Goal area. In the second part, we will consider worldwide progress toward the Goals as a whole.

Keywords: Sustainable Development Goals; fuzzy mathematics

1. Introduction

In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development, a blueprint for responsible economic, social, and environmental development.[1] The agenda focuses on the eradication of poverty and other deprivations while improving health and education and spurring economic growth in a way that addresses climate change and preserves the world's oceans and forests. It is centered in 17 Sustainable Development Goals (SDGs), such as Goal 1 (No Poverty), dedicated to "ending poverty in all its forms everywhere". The UN Secretary-General issues an annual SDG Progress Report prepared by the U.N. Department of Economic and Social Affairs summarizing countries' progress in the Goal areas.[2] Beginning in 2019 and repeating every 4 years, an independent group of scientists appointed by the Secretary-General produces the Global Sustainable Development Report, which weighs the evidence, analyzes the challenges facing global sustainable development, and, where appropriate, recommends solutions.[3]

We reexamine countries' progress in the Goals using a measure inspired by fuzzy math and perform a time series analysis to study trends over the last two decades. This new approach reveals different patterns from the more traditional methods

used in the SPR, and it highlights a number of intriguing positive and negative trends worthy of further consideration.

Techniques from fuzzy math have previously been used in a variety of ways to analyze the Goals, both to address the Goals as a whole and to examine progress towards specific targets or in specific regions.[4,5]

Outline

In Section 2, we discuss the dataset, our data processing, and a new measure inspired by fuzzy math. We apply this measure to study progress in the individual Sustainable Development Goals from the 2030 Agenda: we assign a Goal t-score to each country and describe the distribution of t-scores across the world, along with trends over the period from 2000 to 2022. In Section 3, we focus on the Goals related to eliminating deprivation in all its forms and ensuring access to necessary resources. In Section 4, we focus on the Goals related to eliminating inequality and ensuring fair and just access to resources and opportunities as well as the institutions necessary for continued development and care of the world. In Section 5, we focus on the Goals related to protecting the environment and ensuring continued presence of a healthy world.

2. Data and Calculations

2.1. *The 2022 SDG Progress Report Dataset*

The SPR 2022 is based on Global SDG Indicators Database, a dataset collected from over 200 countries and territories.[6] The 2030 Agenda defined 169 targets for the 17 Goals.[1] For example, Goal 1 (No Poverty) lists 7 targets, ranging from targets like

> Target 1.1: By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day.

and

> Target 1.5: By 2030, build the resilience of the poor and those in vulnerable situations and reduce their exposure and vulnerability to climate-related extreme events and other economic, social and environmental shocks and disasters.

Progress towards each target is tracked using a set of indicators called the Global Indicator Framework developed by the Inter-Agency and Expert Group on Sustainable Development Goal Indicators, approved by the UN Statistical Commission, and adopted by the General Assembly.[7] Target 1.1 is assessed using a single indicator,

> Indicator 1.1.1: Proportion of the population living below the in-

ternational poverty line by sex, age, employment status and geo-
graphical location (urban/rural).

In contrast, Target 1.5 is assessed using 4 indicators, such as

Indicator 1.5.4: Proportion of local governments that adopt and im-
plement local disaster risk reduction strategies in line with national
disaster risk reduction strategies.

The indicators are scored from 0 (representing the worst possible outcome, defined
as the 2.5th percentile of the distribution) to 100 (the ideal, target value for 2030).
They are divided into three tiers based on level of methodological development and
availability of data; as of 2022, there were 231 indicators in the Global Framework,
148 well-defined and regularly available at the country level and another 77 well-
defined but not regularly collected, as well as an additional 6 with components from
both tiers. Currently, there are no indicators in the third tier, those for which there
is not a consensus on a well-developed definition.[8]

To study these indicators, the dataset includes 95 variables for 163 countries, as
well as composite variables for 8 regional and 4 income categories (and partial data
for an additional 30 countries and 1 region; we omit these, as did the SPR 2022
when it assigned index scores):[6]

Regional Category	Income Category			
	Low	Lower-Middle	Upper-Middle	High
Eastern Europe and Central Asia	1	4	15	3
East and South Asia		13	4	2
Latin American and the Caribbean		6	13	3
Middle East and North Africa	2	5	3	6
Oceania		1	1	
Organization for Economic Cooperation and Development (OECD)			4	34
Sub-Saharan Africa	21	17	5	

The variables are intended to describe the indicators in the Global Framework, but
worldwide data collection practices (or lack thereof) have affected the data available,
and COVID-19 has further impeded recent data collection efforts. For example, for
Goal 1 (No Poverty) Target 1.1 (Eradicate extreme poverty ... people living on less
than $1.25/day), there are 2 variables: *poverty headcount ratio at $1.90/day,* and
poverty headcount ratio at $3.20/day, but there are no separate variables available
on a worldwide scale to address the other 12 indicators. Where possible, the UN
Statistics Division has imputed data for the purpose of calculating regional/income
category scores or index scores, but it has not reported the imputed data for the
individual country. It has also imputed historical data where possible (many of the
variables were available since 2017 but were imputed for earlier years), and these
are included in the dataset.

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In addition to individual variables reflecting the indicators, the dataset includes a combined score for each case (country, region, or income category) for each Goal (the average of the available variable scores) as well as an index score (the average of the Goal scores).[6]

The dataset[6] is regularly updated. We use the version promulgated with the 2022 SDG Progress Report.[2]

2.2. *The t-measure and t-scores*

Fuzzy math extends the concepts of set intersection and union by replacing them with minima and maxima of functions. A prominent tool in fuzzy logic is the Gödel *t*-norm, the minimum function of a set, which is the fuzzy version of conjunction. We employ a measure inspired by the *t*-norm and first introduced as a way to combine scores of multiple variables into a single Goal score:[9] if a set S has values from the interval $[0, 100]$, we define

$$t(S) = \begin{cases} \max\{s : s \in S\} & \text{if all } s < 50 \\ \min\{s : s \in S\} & \text{if all } s > 50 \\ 50 & \text{else} \end{cases}$$

For example, to score a country's progress on Goal 3 (Good Health and Well-Being), the 2030 Agenda lists 13 targets and the Global Indicator Framework 27 indicators. The dataset contains 17 variables, which are scores between 0 and 100, whose values it averages to generate an overall score for Goal 3. The *t*-measure gives us an alternate way to combine these 17 variables into one Goal score: if all the variables are lower (i.e., below 50), it will record the highest; if all are higher (above 50), it will return the lowest; if the set is mixed, containing some below 50 and some above, it will return a placeholder value of 50.

For a country doing well in a particular area, this *t*-measure detects a lagging variable and shows an area in which is perhaps especially challenging or where extra work is needed or which stands out in some other way. On the other hand, for a country doing poorly in the same area, this measure will identify the highest variable, highlighting perhaps a recent emphasis item or positive accomplishment of a country otherwise struggling in this area. In either case, one may contemplate the advantage to the international community of increased attention to such a situation. A score of 50 provides less detailed information but does still identify either of two important situations, both of which we will see; this score may occur for a country with contradictory variables (as in the case of Goal 2 below), or it may have a set of variables which is moving together and transitioning from low to high (as in Goal 3) or vice versa.

Additionally, the *t*-measure is a particularly useful tool for time-series analysis as it is more sensitive to movement than a mean. If only a single variable moves, a mean will respond sluggishly, especially in cases with more variables (and this seems likely to become more common in future years as the data collection improves and

the dataset expands to address the Global Indicator Framework more fully), but a t-measure will respond more immediately. In many cases, for arithmetic reasons, a variable seeing a disproportionate amount of movement is more likely to be or to become closer to the mean, that is, it is actually the leading variable (for poorly performing areas) or lagging one (for well performing areas), in which case the t-measure will detect its movement.

2.3. *The index t-score*

The SDG Progress Report of 2022 calculated a composite index score for each country by averaging the Goal scores; it does not weight the Goals individually as the authors did not find a consensus among experts from different epistemic communities. We follow that practice in the second part of this article series[10] and will generate the index t-score, an unweighted average of the t-scores. (Note: we considered applying the t-measure again to the set of t-scores, but it suppressed too much information and resulted in an excess of 50s.)

2.4. *Time-series analysis*

To examine trends over time, we perform a linear regression for the t-scores. We calculate the correlation coefficient for each regression to assess how strongly the data match the trend, i.e., how consistent the trend is over time. We considered a score to show a positive (respectively, negative) trend if its regression slope was at least 0.1 (respectively, -0.1) and its correlation was moderately strong, that is, had correlation coefficient of at least 0.6 (respectively, -0.6). For countries not showing such positive or negative trends over time, this regression and correlation coefficient may be misleading or unhelpful, so we calculate instead the standard deviation in scores over time. The Appendix of the second half of this paper lists 2022 index t-scores for all countries, along with their index rank and either the slope and correlation (for countries with significant trends) or variance.[10]

2.5. *Data processing*

Where the dataset is missing data and the UN Statistical Division has chosen not to publish its imputed data, we have imputed our own. Unless otherwise noted, we have imputed on the basis of region and income category, while the UN imputed on the basis of region only. Imputing on the basis of region alone would have its advantages: it would increase sample size, therefore improving data quality, while the subsequent averaging of variable scores would suppress the effects of outliers anyway and move any erroneous scores towards the norm. Since we will be using methods from fuzzy math, however, we will rely heavily on finding extrema rather than means (in particular, our t-scores will rely on finding the element of a set closest to the middle value of 50 or recording whether a variable crosses 50). We do not profit from additional samples near the norm, and the t-score is easily thrown

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off by one extra sample past the extremum. The data are often widely spread across income categories, so we find it more useful to examine smaller collections of more tightly spaced data points grouped by income category.

Details of data imputation are given when discussing the relevant Goals below. Some countries lacked most or all variables for a particular Goal. Specifically, 11 of 163 (6.7%) of countries lacked both variables for Goal 1 (No Poverty), 16 of 163 (9.8%) lacked both variables for Goal 10 (Reduced Inequalities), and 42 of 163 (25.8%) most or all variables for Goal 14 (Life below Water). We have omitted these countries from trend analysis for the relevant Goals. For the purpose of calculating and index score, we have imputed these data from the average for region/income category (or, if sufficient data were not available for that income category in that region, we have used the adjacent income category). In some other cases, countries lacked individual variables. If we consider these unlikely to have altered the outcome of any calculation, we have merely omitted them and continued with the analysis. In a few cases, we suspect the missing data could have altered a country's score in some Goal, in which case we have omitted the country from trend analysis of that Goal and imputed the missing from the region/income category (or adjacent income category) for the purpose of calculating index scores. For example, we have been able to estimate the missing variables with some confidence for Somalia and Turkmenistan for Goal 4 (Quality Education) and Chad for Goal 7 (Affordable and Clean Energy); in contrast, a number of countries lacked possibly significant variables in Goals 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities), and 12 (Responsible Consumption and Production), and their variables showed unpredictable enough behavior that imputing the missing data comes with some loss of confidence.

3. The Goals: Eliminating Deprivation

We describe here the distributions and trends of the t-scores for the first 16 Goals and examine the patterns in the variables which these scores highlight for us. Checking the t-scores gives us a novel entry into the dataset and directs us immediately to these interesting patterns. We list the scores in order, although we consider Goals 3 and 5 to be especially intriguing.
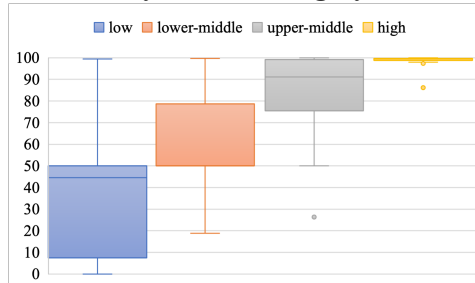
Goal 1 (No Poverty)

Goal 1 concerns eliminating poverty. There are 7 listed targets in the 2030 Agenda and currently 13 indicators in the Global Indicator Framework; however, as of 2022, the dataset contains only 2 variables, both measurements of population living in poverty using two different thresholds.

By definition, the variables were not independent, and the t-score does not highlight information which is noticeably distinct from a traditional mean, i.e., t-scores resemble the traditional Goal score. That said, analyzing the t-scores for this Goal facilitates our analysis of later Goals related to income.

There were 152 countries with sufficient data to include in the trend analysis. As shown in the box plot and as is intuitively reasonable, the t-score is positively associated to income category; e.g., in 2022, all high-income countries except 3 outliers received a t-score of at least 97.5. The middle 50% of upper-middle-income countries were distributed from 72.9 to 98.2, with Venezuela an outlier (it moved into the

Distribution of 2022 Goal 1 t-scores by income category

30s during this period). In fact, 61 of the countries (40.1%) were at or above 90 the entire time period from 2000 to 2022, including all high-income countries except Barbados, the rest being upper-middle-income countries. On the other hand, the middle 50% of lower-middle-income countries ranged from a t-score of 50.0 to 80.1, and low-income from 4.0 to 50.0; 17 of the countries (11.2%) were below 50 the entire time, all in sub-Saharan Africa and 14 in the low-income category, the other 3 lower-middle-income.

We graph the trends for these countries in the histogram. A smooth upward trend appeared in 39.5% of countries, or 60 of 152: their t-score was at least moderately strongly associated to time (correlation coefficient of at least 0.6), and linear regression produced a slope of at least 0.1, and up to 1.7, with an outlier of China at 2.8 (which

Proportion of countries with a trend in Goal 1 t-scores (points/year)
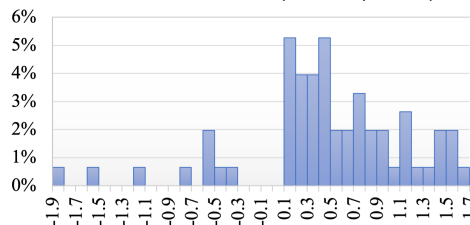
is omitted from the histogram for legibility). At the same time, 9 of 152 (5.9%) of countries showed a negative trend of at least -0.1, with outliers of Venezuela, South Sudan, and Angola (at slopes of -1.9, -1.6, and -1.2, respectively). All three of these were stable until a sharp drop-off occurred over a brief period of time. It is outside the scope of this paper to comment on causality, but the political and social changes in these countries over this time period have been well-studied.

Both variable scores were missing for 11 countries. This Goal is associated to income category and, more weakly, to region. When one or more other countries in the same region and income category received ratings in these variables, we have averaged their data to impute the missing data; when not possible, we have imputed the missing data from the region and adjacent income category. We have omitted these countries from the trend analysis for Goal 1; they are Afghanistan, Bahrain, Brunei, Cuba, Kuwait, Oman, Qatar, Saudi Arabia, Syria, Yemen, and Zimbabwe.

Goal 2 (Zero Hunger)

Food health and security are addressed by 14 indicators in the Global Indicator Framework, for which there are 9 variables in the dataset, including undernourishment, stunting, wasting, and obesity.

No variables were pairwise correlated, even those which seem intuitively related; for example, see the scatterplot for 2022 scores of wasting (underweight) and stunting (underheight), which are only weakly correlated (coefficient of 0.389).

Association of 2022 Goal 2 variables

The t-scores almost uniformly recorded values of 50. The only exceptions were Uzbekistan (which received strong scores in the other variables but weaker scores in trophic index, the energy intensiveness of food sources) and Sudan and South Sudan (which we omit because of missing data - see below). While applying this t-score does not differentiate between countries or record progress in individual variables as the traditional Goal score would, it strongly attests to the on-going worldwide issues related to a healthy and responsible diet.

There were 73 cases where a country lacked data in a variable for the entire period. None could have altered the t-scores as they were already 50 except for Sudan (which measured 49.2 for 2000-2001 until its leading variable, undernourishment, climbed above 50) and South Sudan (which lacked 3 variables; its leading variable in 2000 was stunting, at 27.9, but trophic index climbed through it and reached 47.7 by 2022). The regional income category average for both (low-income, sub-Saharan Africa) for the obesity variable started at 97.8 in 2000 and slowly sank to 87.1 in 2022, so it is likely the missing variable would have affected the t-score significantly for South Sudan. We have omitted both countries from analysis of this Goal but have imputed their scores from the regional and income category average for the purpose of creating their index t-scores.

Goal 3 (Good Health and Well-Being)

The Global Indicator Framework includes 28 indicators which are addressed by 17 variables in the dataset.

Most variables trended gently upwards or stayed stable from 2000 to 2022. There were not strong associations between individual variables, although most were positively associated to income category, although the data were widely spread (see box plot): for example, the middle 50% for neonatal mortality ranged from 21.1 to 46.6 for low-income, 40.2 to 76.4 for lower-middle-income, 75.0 to 92.2 for upper-middle-income, and 94.1 to 98.4 for high-income countries. We did not discover any widespread associations between variables and region category beyond those which arose from the association between region and income category.
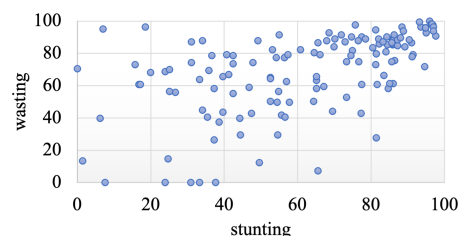
Of the 163 countries in the dataset, 139 (85.3%) began in 2000 with t-scores of 50, reflecting a mixed variable set (some above 50, some below). Only Cameroon began with all variables below 50, but its top variables (TB and deaths due to household air pollution) climbed sufficiently that the t-score stabilized at 50 during the period. The re-

Distribution of 2022 Goal 3 variables by income category

maining countries, primarily high-income, started 2000 spread out from 50 up to 67.3 (Australia), and all showed significant positive regression slopes of at least 0.3 (Sweden, Canada, and the United Kingdom all exceeded a slope of 1.0, the last two ending above 80).

This example shows us how the t-score may perform on a larger set of more diverse variables. As was the case for Goal 2, it does not distinguish between countries with a t-score of 50, that is, whose variables as a group were in transition between lower and higher scores for the entire period. Instead, it highlights achievements in those countries which moved out of this transition phase. For example, Singapore began with all variables above 65 except for neonatal mortality, which was rated 38.6 in 2000 but climbed to 76.7 by 2022. This change is muted by the calculation of the mean in a traditional score, but it is strongly identified by the extremum in the t-score. Similarly, Austria was rated near 70 or higher in all areas except access to health care, which climbed from 45.0 to 70.9, and vaccinations, which climbed from 57.6 to 74.6. In Canada, Sweden, and the United Kingdom, access to health care was the lowest variable by at least 10 points, and its improvement over the course of the time period was reflected by significant growth in the t-score.

In all, 48 of 163 countries (29.4%) displayed positive trends in their Goal 3 t-scores, ranging up to a regression slope of 1.4 for Singapore.
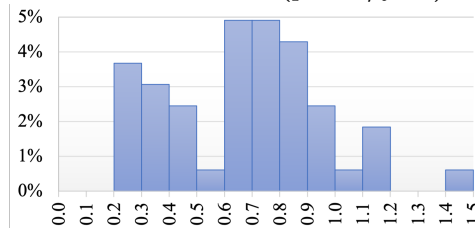
Of this Goal's variables, a "subjective well-being" score was missing for 5 countries, but it would not have changed the outcome as these countries all scored a 50 because of other vari-

Proportion of countries with a trend in Goal 3 t-scores (points/year)

ables. The percentage of births attended by health care personnel was missing for

another 5 countries, but these were all OECD and high-income; in comparable countries, this variable was not one of the lower ones, so it is unlikely to have affected the t-scores and we have included all of these countries.

Goal 4 (Quality Education)

The dataset includes 4 variables for the 11 indicators from the Global Framework, literacy and 3 measures of participation in education (which were only weakly correlated to one another).
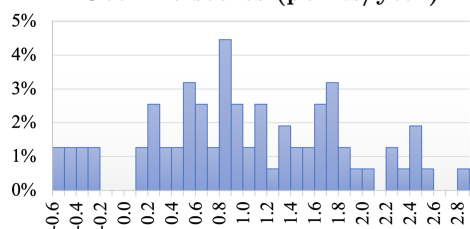
The t-scores were positively associated to income category: for low-income countries, the middle 50% lay between 47.0 and 50.0, while lower-middle- and upper-middle-income countries in the ranges 50.0-74.2 and 50.0-84.4, respectively, and high-income countries fell between 86.9 and 96.2. The participation variables were inconsistent between countries across all groups, although they usually trended in unison;

Distribution of 2022 Goal 4 t-scores by income category

85 of 157 (54.1%) recorded a t-score of 50 at some point during the time period, usually reflecting a transition in the variables as a group from lower scores to higher scores.
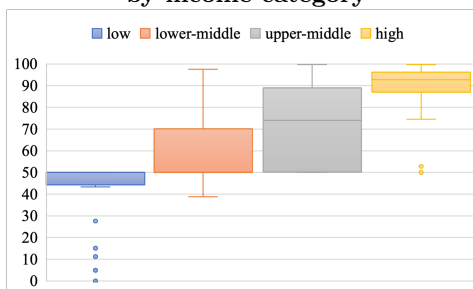
In 67 of 157 (42.7%), the t-score showed a positive trend; the strongest improvements came from countries such as Burkina Faso (an increase from 0 in 2000 to 50 in 2022, a regression slope of 2.9, the highest in the group), where the variables improved as a group and the t-score tracked the movement of the leading variable. Another group

Proportion of countries with a trend in Goal 4 t-scores (points/year)

with less pronounced positive trends began at or near 50 and climbed as a single lagging variable caught up; e.g., Albania climbed from 50 to 91.1 (a slope of 2.6, the second-highest in the set) when its lagging indicator, participation in early education, climbed from 29.4 to 95.5. At the other extreme, 9 of 157 countries (5.7%) saw negative trends, all of which started above 50 and traced a drop in the lowest variable, usually one of the participation measures; the most extreme was Macedonia with a slope of -1.2, which we have omitted from the histogram for readability.

Somalia was missing data for all variables, and Turkmenistan for all except literacy (which was stable at 99.6; among other countries with very high literacy, it was rarely the determining factor for the t-score). We have imputed both based on the averages for their region/income category. China, Japan, Lebanon, and Haiti

were missing one or more of the participation scores, which may have affected the calculated t-scores, and we have chosen not to impute these data points as the variables in general were widely distributed. We have omitted these 6 countries from the trend analysis. An additional 35 variables were missing for other countries but seem unlikely to have changed the t-score significantly (e.g., if the score was already near 50, or if the missing score were literacy in a high-income country where it routinely scored higher than the other variables).

Goal 6 (Clean Water and Sanitation)

This Goal is represented by 5 variables for the 13 indicators in the framework.

Three of the 5 variables were associated positively to income, 1 negatively, and 1 not at all. The variables were generally widely spread.

A full 135 of 163 of countries (82.8%) received t-scores of 50 for the entire period, showing that the variables were contradictory and widely spread. Additionally, they were highly

Distribution of 2022 Goal 6 variables by income category

stable. Only 4 of 163 countries (2.5%) showed a trend with moderately strong confidence, all positive, Japan at 0.2, Eswatini at 0.3, Spain at 0.5, and Germany at 0.8. Eswatini was the only one to start below 50; most of its scores were low and stable over the period, but its highest, sanitation, climbed steeply from 42.9 to 60.5 and therefore was recorded by an increase in the t-score to 50 from 2009 on. The other three saw an improvement in their lagging variable, stress on freshwater resources.

One country lacked data for stress on water reserves and 11 for water imports, but these t-scores were already set at 50.

Goal 7 (Affordable and Clean Energy)

The dataset contains 4 variables for the 6 indicators in the Global Framework.

Electricity access and clean cooking fuel were positively associated to income, renewable energy moderately negatively associated, and clean electricity production not associated (except that the low-income category was more widely spread than the others: the middle 50% spread from 19.6 to 90.3, whereas the other categories spread from the 60s/70s into the 80s).

**Distribution of 2022 Goal 7 variables by income category**
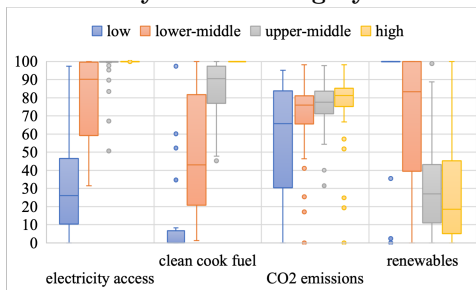
No countries ever t-scored below 50, and 18 of 150 (12.0%) were above 50 at least half the time period, which included 4 above 70 the entire time. The prevalence of 50 as a t-score reflects two characteristics: first, there was significant instability in some countries, for example, Uruguay vacillated twice between around 60 and the 90s as its renewable score varied; second, the variables were highly inconsistent in many countries, for example, higher income countries had generally higher ratings for electricity access and lower ratings for renewable energy, while lower income countries were the opposite.

Of 150 countries, 16 (10.7%) had positive trends, led by Tajikistan with a regression slope of 1.7; of these, the high-income countries' increases were driven by renewable improvements, while the others were driven by access improvements.

Renewable energy data was missing for 13 countries of the 163 countries in the dataset (8.0%); these may well have affected indicators as the renewable score negatively associated to income, while several of the other indicators were positively associated. We have imputed data for these countries and omitted them from trend analysis.

**Proportion of countries with a trend in Goal 7 t-scores (points/year)**
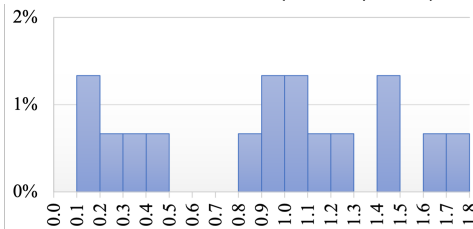
Goal 8 (Decent Work and Economic Growth)

The 16 indicators in the Global Framework are reflected by 6 variables.

The t-norm highlights the vagaries of economic growth as 108 of 162 countries (66.7%) were t-scored at 50 the entire time, and few of the others showed trends. Two of 162 (1.2%) had negative trends, Spain at -0.2 (whose regression slope traced its lagging variable, unemployment) and Korea at -1.1 (whose lagging variable was labor rights). Another 23 of 162 countries (14.2%) trended positively, with an outlier of Poland at 1.0, also due to unemployment. Unemployment was the most common lagging variable, especially among high- and upper-middle-income countries, and the instability in the t-scores for Goal 8 reflects its variability.

Proportion of countries with a trend in Goal 8 t-scores (points/year)
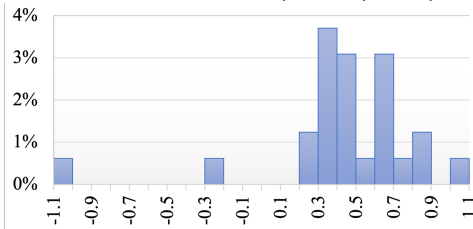
There were 71 country/variable pairings without data. No t-scores would have been affected except possibly for Cuba's; it was missing scores for 3 variables which were regionally rather unstable but sometimes lower than the variables scored for Cuba, which were all relatively high. We have imputed these data points and have omitted Cuba from the trend analysis.

Goal 9 (Industry, Innovation, and Infrastructure)

There are 6 variables reflected in the dataset (for the 12 indicators from the Global Indicator Framework) ranging from rates of internet and mobile broadband usage to trade and transportation infrastructure and assorted measures of research. Internet and mobile broadband usage were moderately strongly correlated (with a coefficient of 0.704), while the number of research publications was moderately strong correlated to R&D expenditure (0.646), internet usage (0.608), and quality of transportation infrastructure (0.623); transportation infrastructure and R&D expenditures were almost as well correlated at 0.597.
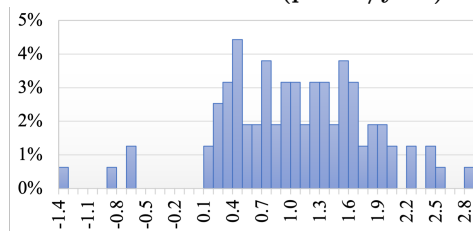
In 2000, 62 of 158 (39.2%) of countries received a t-score of 50, reflecting strongly mixed variables, although 19 of 158 (12.0%) had climbed above 50 by 2022, primarily members of OECD. The remaining countries all began below 50, and 34 of 158 (21.5%) remained below 50 for the entire period.

Over half of the countries (85 of 158, or 53.8%) showed positive trends, ranging from 0.1 to Namibia at 2.9, most of these very strongly correlated (coefficient above 0.8). Somalia remained below 10 and Angola below 35, while 69 of 158 (43.7%), most of which were low-income or lower-middle-income, began below 50 and climbed most or all the

Proportion of countries with a trend in Goal 9 t-scores (points/year)

way to 50, while the remaining 15 of 158 (9.5%) started at 50 and climbed higher, all high-income OECD countries. Only 4 countries showed negative trends, Madagascar, Malawi, Niger, and Democratic Republic of the Congo, all at or below 50 and all with sudden and sharp decreases in their strongest variable, trade and transportation infrastructure; again, it is outside the scope of this article to discuss the social and political developments in these countries, but the t-norm highlights here significant trends in the their statuses and their impact on global sustainability. The remaining countries consisted of 52 of 158 (32.9%) with small regression slope (between -0.1 and 0.1), only one of which, the Central African Republic, had variance over 20; and 16 of 158 (9.8%) with greater magnitude slope but low correlation, and these showed more significant correlation (except for 2, all above 20). Most of these showed two or more distinct areas, for example, the most variable were Sierra Leone (variance of 229.4), which was below 1 until it jumped to 41.0 in 2012, stayed there through 2016, then dropped to the teens, both due to changing scores in trade and transportation infrastructure. Similarly, Djibouti, with variance of 140, was stable at 33.3 until it dropped to 7.4 in 2011 due to a sharp change in the score for trade and transportation infrastructure, then internet and mobile broadband usage slowly climbed up past 50.

The t-score highlights the difficulty in assessing Goal 9: the variables are quite different and track an assortment of sometimes contradictory behaviors; in partic-

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ular, mobile broadband and/or internet usage started low in almost all countries
and rose sharply over this period. For low- and lower-income countries, the t-score
began low but rose, sometimes up to 50, explained by the fact that trade and trans-
port infrastructure was often the highest rating initially and climbed slowly, but
mobile broadband and/or internet usage climbed and sometimes surpassed infras-
tructure. Most upper-middle-income and high-income countries outside the OECD
saw the t-score steady at 50 because infrastructure and university quality were
both quite high, but measures of research and innovation lagged below 50, conceal-
ing the movement of individual variables. In contrast, for members of the OECD,
the t-score often started at 50 and climbed sharply as the only lagging variables,
mobile broadband and internet usage, caught up with the other variables.

Trade and transportation infrastructure was missing data for 5 countries and
R&D expenditures for 18; we estimate this would not have affected the later t-scores
significantly, although it may have affected some of the earlier scores and therefore
trend recognition for the low- and lower-middle-income countries. We have imputed
this data. If it changed the t-scores in more than half the time period, we have
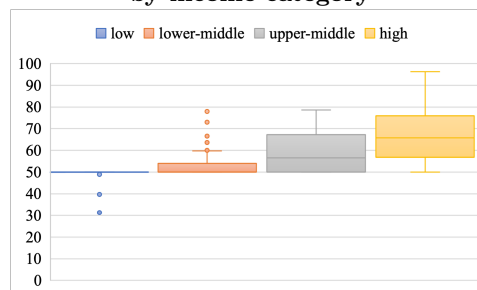omitted the countries from the trend analysis.

Goal 11 (Sustainable Cities and Communities)

This area is documented in the dataset using 4 variables for the 14 indicators listed
in the Global Framework.

The t-score was associated to in-
come, as were all four variables (al-
though they were only weakly corre-
lated to one another). As of 2022, as
seen in the box plot, all low-income
countries other than outliers were t-
scored at 50, and lower-middle income's
75th percentile was 53.6, while upper-
middle-income's was 66.5 and high-
income's 76.3.

**Distribution of 2022 Goal 11 t-scores
by income category**

A t-score of 50 was recorded for at
least half of the period for 70 of 154 countries (45.5%), reflecting the fact that
public transportation lagged other variables. Only 2 countries (2.5%) were always
below 50, with Afghanistan trending gently upwards (regression slope of 0.4, al-
though the correlation coefficient was only 0.543), while the Central African Repub-
lic trended negatively (-0.8). Afghanistan's t-score first tracked its leading variable,
public transportation, which climbed somewhat unsteadily from 34.1 in 2000 to 43.8
in 2017, when it sharply reversed track, and diminished below particulate pollution,
which had slowly climbed from 27.7 to 39.7. This is a case of a t-score switching
variables when a leading variable reversed course. The Central African Republic's
t-score tracked access to improved piped water through 2005, as it was steadily

decreasing from 48.1 in 2000 (it ended at 27.9 in 2022), which was surpassed by particulate pollution score which slowly climbed from 41.8 in 2000 to 44.7 in 2011, then also reversed course and dropped to 31.3. This is an example of the t-score switching between a pair of closely spaced variables.

A full 15 of the 154 (9.7%) showed negative trends, the worst of which were Japan and Colombia at -0.9, both due to decreases in the scores for public transportation, while 33 of 154 (21.4%) trended positively, most notably the Netherlands, Czech Republic, and Kyrgyz Republic at 1.8, 1.6, and 1.4, respectively, again all due to improve-

Proportion of countries with a trend in Goal 11 t-scores (points/year)

ments in the public transportation score; most changes in the t-score for Goal 11 were driven by public transportation.

No data were available for slums for 28 countries, piped improved water for 14, and transportation for 5. Some of these will not have affected the t-score because it was already between 40 and 60. When examining trend data, we have omitted the countries where the imputed data may have changed the t-scores. For each variable, we have imputed by region and income category when possible (with the exception of Lebanon - we have omitted Iraq from consideration as its slum score decreased dramatically in 2005 after the beginning of the Iraq War). When sufficient data was not available (for slums in Middle East/North Africa high-income, East/South Asia high-income, and Oceania lower-middle-income), we have imputed from the adjacent income category in the same region; we made this choice because we visually determined that the slum variable scores present in the dataset were more strongly correlated to region than to income category. This may be due to local cultural differences and government safety nets having a larger impact on slums than economic factors. Neither Oceania country contained transportation data, so we have used the global income category averages. When imputed data changed the t-score from the previously present data, we have omitted the country from trend analysis. This included Barbados, Bhutan, Brunei, Fiji, Malaysia, Mauritius, Papua New Guinea (which, without the imputed data, recorded the worst negative trend of -1.3), Singapore, Sri Lanka, and Turkmenistan.

4. The Goals: Equal Access and Justice

Goal 5 (Gender Equality)

This Goal was another with limited data available: for the 14 indicators for evaluating 9 targets, 4 variables are listed in the dataset.

Only 4 of 161 countries (2.5%) were below 50 the entire time (Yemen, Pakistan, Mauritania, and Somalia), while only 10 of 161 (6.2%) were above the entire time, reflecting contradictory variables.
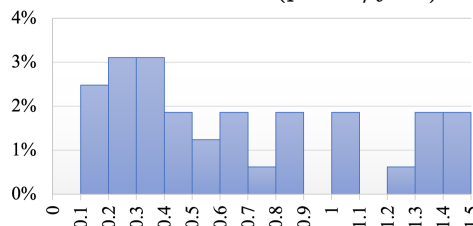
16   *M. Doig, D. S. Malik*
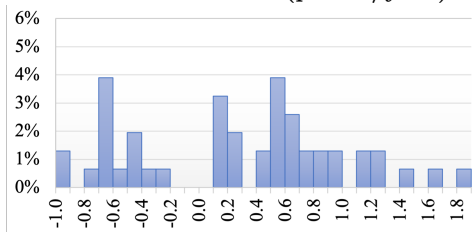
Approximately a quarter (36 of 161, 22.4%) had noticeable trends, all of them positive, ranging up to 1.5 for Namibia, which climbed from 50 to 76.2 as the number of women in parliament out-climbed several other variables. A positive trend often tracked improvement in one or more variables, not a movement of all the variables as

Proportion of countries with a trend in Goal 5 *t*-scores (points/year)

a group, although the number of women in parliament was often the lowest variable and so responsible for the improvement.

A few countries were missing data, 15 for access to family planning, and 3 for equal access to education for men and women; as many of these *t*-scores were near or at 50, this should not have affected the *t*-scores, except possibly for Djibouti (which lacked data on equality of educational access, one of the higher scores across sub-Saharan Africa) and Iceland (which lacked information on access to family planning - if it tracked with the OECD high-income average, this would have lowered its *t*-score by up to 10 points for approximately half the time period). We have imputed the missing variables for Djibouti and Iceland from their regional and income category averages and have omitted them from trend analysis.

Goal 10 (Reduced Inequalities)

Very little information is currently available in the dataset for Goal 10, only 2 variables for the 14 identified indicators.

The two variables present are measures of income inequality and were very strongly correlated to one another (coefficient of 0.687) and so, like Goal 1's measures of poverty, Goal 10's measures of income inequality do not profit significantly from using the *t*-score. The GINI is symmetrically distributed, centered at 70, whereas the Palma has median at 58.5 and is skewed to the left with a heavy concentration at 0; as a result, the *t*-score for Goal 10 is symmetrically distributed around about 50 but with a taller than expected peak at 50.

Just over a tenth (16 of 147, or 10.9%) saw negative trends as bad as -1.6 for Sao Tome and Principe, including 8 from sub-Saharan Africa and 7 from OECD, while 55 of 147 (37.4%) trended positively, up to a regression slope of 1.8 for Portugal.

Proportion of countries with a trend in Goal 10 *t*-scores (points/year)

Both measures were missing for 16 countries, and we have imputed these using the averages for their region and income category (or, for East/South Asia high-income and Eastern Europe/Central Asia for low-income, the adjacent income
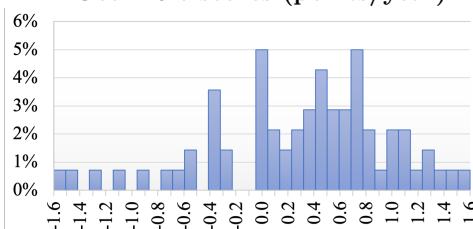
category). An additional 1 country lacked a GINI score only and 6 a Palma score only, and we have imputed these using an income category specific linear regression between the two variables. We have omitted the countries with no variables from the trend analysis but included the countries with one variable as our imputation has produced a *t*-score which still tracks the trend of the other variable and so does demonstrate at least some of the behavior of the variables for the given country.
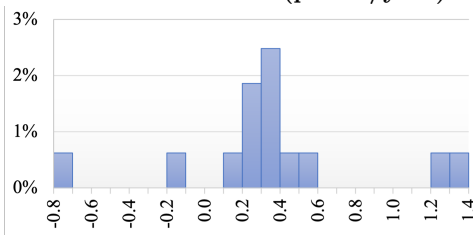
Goal 16 (Peace, Justice, and Strong Institutions)

This is an umbrella Goal focusing on building peaceful and sustainable societies with strong, inclusive, and accountable institutions. The dataset includes 10 variables out of 24 indicators from the Global Indicator Framework.

Of 161 countries, 139 (86.3%) recorded a score of 50 for most or all of the period, which reflects the fact that the individual variables do not demonstrate consistent movement between countries. Most countries saw mixed positive and negative movement in several variables which combined into a negative trend in only Canada

Proportion of countries with a trend in Goal 16 *t*-scores (points/year)

(-0.8) and Barbados (-0.2), both due to decreases in scores for percentage of prisoners who were held without a sentence, and a positive trend in 12 of 161 (7.5%) countries, most notably Japan and Estonia at a regression slope of 1.3, both due to strong improvements in perception of personal safety (which was the lagging variable and the mode of improvement in most of the countries with positive trends).

There are 168 missing country/variable combinations; no country was missing more than three. We imputed the missing variables, which may have affected the *t*-scores for Fiji and Qatar, so we omit them from the trend analysis.

Goal 17 (Partnership for the Goals)

This Goal addresses countries' active pursuit of sustainable development, strengthening means of implementation internally and pursuing international partnerships which will are necessary for an interconnected world to meet the Agenda 2030. For 24 indicators in the Global Framework, there are 5 variables in the dataset. We have omitted 2 due to data concerns (see below).

Distribution of 2022 Goal 17 variables by income category

Only 3 of 156 countries (1.9%) ever *t*-scored below 50, the UAE, Lebanon, and Panama. Lebanon was stable at 45.3
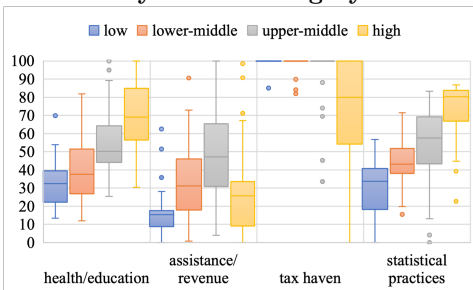
with a leading variable of its rating as a tax haven. Panama was relatively stable in the upper 40s, reflecting a set of variables below 50 which did not change (led by tax haven, at 47.0) and one variable which vacillated between 47.6 and 62.9, government expenditures on health and education. The UAE saw the highest trend in the set, 0.9, when its leading variable (development assistance provided to other countries) climbed from 30 to 100, and then dropped, but was passed by a new leading variable (quality of statistics collection) at 46.2. Another 24 countries (15.4%) climbed above 50 at some point, and their lagging variables varied. For example, there were 3 (1.9%) which broke 70: Germany started at 50 and climbed to 71.2 following an improvement in its lagging variable, development assistance provided to other countries; Sweden was constant at 73.4 with a lagging variable of its rating as a tax haven; Norway climbed from 71.8 to 86.8 following improvement in its lagging variable, a rating of statistical collection practices.

In all, only 8 of 156 countries (5.1%) had consistent and definite trends (correlation coefficient of at least 0.6), all of them positive, half of them because of increased government expenditures on health and education.

Note that two of the variables came in a pair: official development assistance provided to other countries (only listed for high-income countries) and government revenue excluding grants (not listed for high-income countries). There were 50 cases of a country missing a variable (aside from these exclusions); we have imputed them from the region/income (or adjacent income) category or, in the case of development assistance for high-income countries in both Latin America and the Caribbean and East and South Asia, where we could not use the adjacent income category, we have used the world average. Exactly 7 of these countries may have resulted in changes to the t-scores, so we have omitted them from trend analysis.

5. The Goals: Care for the Environment

Goal 12 (Responsible Consumption and Production)

Goal 12 is covered in the dataset by 7 variables for 13 indicators.

This Goal was negatively associated to income: 49 of 159 countries (30.8%) scored a 50 at some point, primarily high-income countries, and the rest were higher; by 2022, all high-income countries were ranked 50 (except for the outlier, Chile), the middle 50% of upper-middle-income countries fell between 57.0 and 70.4, and the middle

Distribution of 2022 Goal 12 t-scores by income category

50% of lower-middle-income and low-income fell into the range of 75.6-90.6 and 79.4-90.9, respectively.
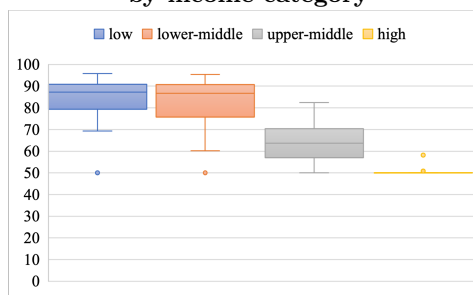
On the other hand, 59 of 159 (37.1%) showed a negative trends as bad as -0.3, with outliers of South Sudan, Paraguay, and Chad at -0.6, -0.6, and -2.1, respectively. In these three cases, the t-score tracked scores for reactive nitrogen emitted during production; this was one of the most common lagging variables, along with electronic waste. There were no countries with positive trends.

Proportion of countries with a trend in Goal 12 t-scores (points/year)
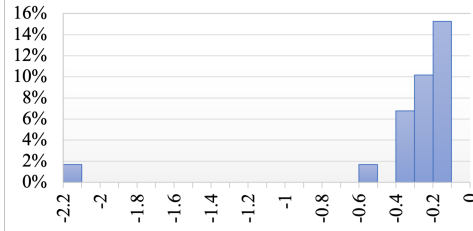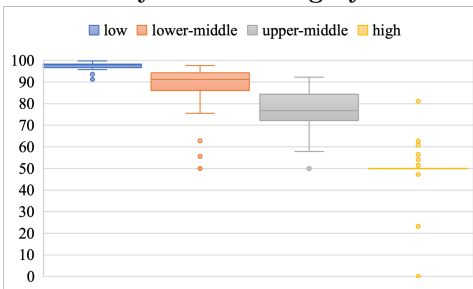

The dataset lacked data for 44 combinations of country/variable. Most omissions are unlikely to have affected the t-score: in particular, exports of plastic waste were routinely scored poorly only for countries in the high-income category (the medians for the four categories from low- to high-income were, respectively, 99.7, 99.1, 97.1, and 59.7). The scores for electronic waste and SO_2 emissions from production likewise showed a strong correlation to income category, and their omissions seem unlikely to have affected t-scores for most countries. We have imputed data for the missing variables by region and income category and have observed only four countries where this may have introduced error, which we have therefore omitted from the trend analysis: Bangladesh, Bhutan, Cuba, and Haiti.

Goal 13 (Climate Action)

The dataset tracks 3 variables for 8 indicators from the Global Indicator Framework, all related to CO_2 production.

The t-score was negatively associated to income category, as demonstrated in the box plot for the 2022 t-scores. Only 4 of 158 (%) countries were below 50 the entire time, Qatar (which scored 0 every year), Brunei (which started at 31.1 and sank unevenly to 0), UAE (which started at 1.9 and climbed to 24.0), and Australia (which started at 1.0 and climbed slowly to 23.2); the latter three all tracked the leading vari-

Distribution of 2022 Goal 13 t-scores by income category

able, CO_2 emissions from fossil fuel combustion and cement production. Another 42 out of 158 (%) were scored at or just below 50 for at least half the period, most of them OECD. The median t-score for low-income countries stayed above 97.3 the entire time, and the median for lower-middle-income between 90.3 and 93.7, with the middle 50% of countries between 86.2 and 94.8 by 2022. For upper-middle-income countries, the median stayed between 76.7 and 79.9 with the rest of the countries grouped relatively closely, e.g., in 2022, the middle 50% were between 70.5 and 84.9.

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For high-income countries, only outliers were ever observably far from 50, primarily because many had decent scores for CO_2 production from exports while they had poor scores from imports or fossil fuel and cement production.

Some 21 of 158 countries (13.3%) had positive trends, including countries from a mix of regions and income categories; the most significant were the UAE at 1.0 and Botswana at 1.2, which climbed from 53.3 to 73.3 due to improvements in CO_2 emissions from imports. An additional 30 countries showed negative trends, the worst being China at -1.2 and Brunei at -1.8, most from fossil fuel or cement production emissions.

Proportion of countries with a trend in Goal 13 t-scores (points/year)
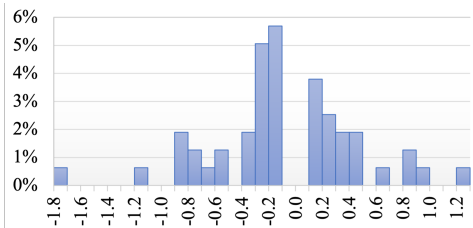
There were 21 countries missing one or two variables, which have been imputed from region and income category (or adjacent income category when required). Many of these seem extremely unlikely to have affected t-scores; several individual countries showed another variable near 50, thus reducing the impact that a new variable could have, while several large groups of countries were missing one variable routinely farther from 50 than others present, for example, CO_2 emissions from imports for low- and lower-middle-income countries and emissions from exports for all except high-income countries were unlikely to have been the leading or lagging variable. The countries where the imputation may have affected the t-score and have been omitted from the trend analysis are Barbados, Fiji, the Maldives, Montenegro, and Trinidad and Tobago.

Goal 14 (Life below Water)

The dataset addresses marine ecosystem health with 6 variables for 10 indicators.

Of 123 countries, 111 (90.2%) recorded t-scores of 50 over the entire period, reflecting that all variables were spread except threats to biodiversity from imports.

No countries exhibited a negative trend, and 5 of 123 (4.0%) had a positive trend, all starting at or near 50 and climbing: Suriname at 1.3, Namibia at 0.9, Australia at 0.4, and Norway and Finland at 0.3. The variation in t-score

Distribution of 2022 Goal 14 variables by income category
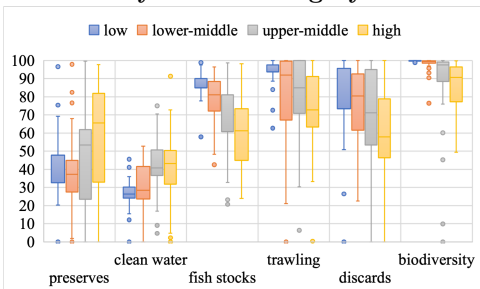
behavior emphasizes the uncorrelated nature of this set of variables: Suriname had a strongly lagging variable of discards in the fishing industry, which rose from 0 to 71.1 (scores for marine contamination also climbed, but not as dramatically; all

other variables were above 70 the entire time). Namibia's lagging variable was marine area under preservation, which rose from 22.5 to 83.0, far surpassing its next lowest variable, fish caught by trawling, which was relatively constant around 60. Australia's variables were more variable and contradictory: its t-score initially rose after its lagging variable, discards in the fishing industry, rose from 0 (it ended at 57.2) and surpassed its second lagging variable, marine area under preservation, which climbed from 43.2 to 64.6; simultaneously, the score for maintaining sustainable levels of fish stocks dropped from 81.5 into the 40s and then recovered to 57.2. Both Norway's and Finland's t-scores tracked their lagging variable, marine area under preservation, which rose from 33.4 to 55.1 for Norway and 52.0 to 60.7 for Finland; at the same time, the other, higher variables also moved, including a drop in marine contamination, but this went undetected by the t-score for Norway and barely halted the climb of the t-score for Finland at 58.1.

Significant data were missing for 42 countries out of 163 total in the dataset (25.8%): 2 have no data for any of the 6 variables, 33 only for threats to marine biodiversity embodied in imports, and 7 more for threats to biodiversity embodied in imports and contamination of marine waters under national jurisdiction. With the exception of Ethiopia, they are all either mostly or totally landlocked. (There are additional missing variables for more countries, but none would have affected any of the t-scores.) We choose not to assign a t-score to these countries as this would skew the index t-scores: the top 10 countries would then include the Kyrgyz Republic, Tajikistan, Nepal, and Bhutan, all without coastlines but with a t-score in Goal 14 near 100. Instead, we have imputed the missing data from regional and income (or adjacent income) categories as usual and omitted them from trend analysis. This is a suboptimal solution as the presence of coastline should have at least as strong a link to marine activities as regional or income characteristics. That said, we make this choice because it is the same one the UN has made for its Goals - if insufficient data are available to provide a Goal score for a country, the index score was calculated using the regional Goal score in its place.

Goal 15 (Life on Land)

The land version of Goal 14, this Goal refers to terrestrial ecosystem health, which is documented by 5 variables for 14 indicators.

There were not strong associations between any two of the variables, except for terrestrial and freshwater areas under preservation, which were moderately correlated. Income category has a positive association to deforestation and a negative association to threats to

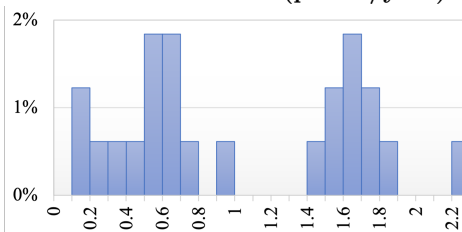**Distribution of 2022 Goal 15 variables by income category**
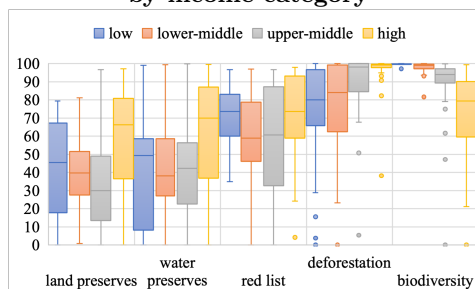
biodiversity embodied in imports. The remaining 3 variables are widely spread across all income categories and do not show an association. We did not observe an association between region and any of the variables which may be separated from the association to income category.

No countries received a t-score under 50 at any time, though 123 of 163 (8.0%) were stable at 50 over the entire period, and another 26 of 163 (16.0%) started at 50 and climbed higher. Outliers were the Central African Republic, stable at 74.2, and Denmark, stable at 83.2. In all, 23 of 163 (14.1%) had an improvement significant enough to be

Proportion of countries with a trend in Goal 15 t-scores (points/year)

termed a positive trend, ranging up to 1.9 for Bulgaria with an outlier of Namibia at 2.2. Many countries saw improvements in areas under preservation, although some of these improvements were offset by falls in forested area and red-listed species.

There are 29 missing country/variable combinations. None should affect the t-scores as it is either already 50, or the missing variables are routinely higher than the present ones.

6. Conclusion

There are many ways to analyze world progress towards the Sustainable Development Goals of the 2030 Agenda for Sustainable Development adopted by the UN Member States. The min/max emphasis of the t-score inspired by fuzzy math highlights different types of behavior from a traditional mean: for a country excelling in some goal area, it identifies the lagging or worst variable; for a country struggling in that goal area, it identifies the strongest performing variable; for a country with mixed variables, it records a transition or mixed score. The t-score can be especially enlightening when performing a time series analysis because they track the variable score closest to the middle, that is, they can identify a case where a country's variables move away from the extremes and toward the mean, whether the variables move as a group or an outstanding variable moves away from the others.

We saw that, worldwide, countries showed positive performance in the goals related to access to resources, although the current trends suggest some difficulty meeting the targets by 2030. All countries performed very strongly with respect to poverty (Goal 1). In 2000, t-scores of 50 predominated in hunger, health, education, water and sanitation, energy, work, and cities and communities (Goals 2-4, 6-9, and 11), but all except hunger showed a marked improvement over the time period.

The goals relating to equality and justice were more mixed. Gender equality, income equality, and justice were all dominated by 50s as well in 2000, but the first two saw significant improvement by 2022, and the last saw improvement in a few countries.

The goals related to environment and climate showed more concerning trends, and 3 of the 4 were negatively associated to income category, which is concerning since the income situation of most countries is steadily improving. Consumption and climate action (Goals 12 and 13) both showed high t-scores with averages well above 50, but both also showed a mix of negative and positive trends in different countries. Of the two goals related to ecosystem health (Goals 14 and 15), t-scores of 50 dominated very strongly for saltwater areas over the entire period, while freshwater and land areas were assigned much higher and fairly stable t-scores.

Acknowledgements

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