Received: 8 July 2020 | Revised: 2 October 2020 | Accepted: 12 October 2020
DOI: 10.1002/sd.2145

RESEARCH ARTICLE

Sustainable Development WILEY

Variations in sustainable development goal interactions: Population, regional, and income disaggregation

Anne Warchold[1] | Prajal Pradhan[1] | Jürgen P. Kropp[1,2]

[1]Member of the Leibniz Association, Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany

[2]Institute for Environmental Science and Geography, University of Potsdam, Potsdam, Germany

Correspondence
Prajal Pradhan, Member of the Leibniz Association, Potsdam Institute for Climate Impact Research (PIK), P.O. Box 60 12 03, Potsdam D-14412, Germany.
Email: pradhan@pik-potsdam.de

Funding information
Bundesministerium für Bildung und Forschung, Grant/Award Number: 01DP17035; Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, Grant/Award Number: 42206-6157

Abstract

To fulfill the 2030 Agenda, the complexity of sustainable development goal (SDG) interactions needs to be disentangled. However, this understanding is currently limited. We conduct a cross-sectional correlational analysis for 2016 to understand SDG interactions under the entire development spectrum. We apply several correlation methods to classify the interaction as synergy or trade-off and characterize them according to their monotony and linearity. Simultaneously, we analyze SDG interactions considering population, location, income, and regional groups. Our findings highlight that synergies always outweigh trade-offs and linear outweigh non-linear interactions. SDG 1, 5, and 6 are associated with linear synergies, SDG 3, and 7 with non-linear synergies. SDG interactions vary according to a country's income and region along with the gender, age, and location of its population. In summary, to achieve the 2030 Agenda the detected interactions and inequalities across countries need be tracked and leveraged to "leave no one behind."

KEYWORDS

development pathways, disaggregation, inequalities, non-linearity, SDG interactions, SDGs, synergies and trade-offs

1 | INTRODUCTION

The 2030 Agenda for sustainable development constitutes a 15 years global framework to end poverty, protect the planet, and ensure prosperity for all countries—"leaving no one behind." This holistic framework is centered on a set of 17 sustainable development goals (SDGs) and 169 targets, including individual indicators, to monitor progress on the economic, social, and environmental dimensions (UN General Assembly, 2015). A harmonious development along these three sustainability dimensions will depend on the understanding of SDG interactions (Nilsson, Griggs, & Visbeck, 2016; Pradhan, Luís, Diego, Wolfgang, & Kropp, 2017). Therefore, we need to look at SDGs as a system of interacting components rather than just a collection of goals, targets, and indicators (Pradhan, 2019). Table 1 lists all SDGs and their full titles.

Multiple studies qualitatively examine SDG interactions, characterizing them as either synergies or trade-offs, often focusing on specific goals. For instance, several studies investigate interactions of SDG 6 across the 2030 Agenda (Milan, 2017; UN-Water, 2016; Velis, Conti, & Biermann, 2017) and others emphasize cross-cutting effects of "Good health and well-being" [SDG 3] (Bangert, Molyneux, Lindsay, Fitzpatrick, & Engels, 2017; Tangcharoensathien, Mills, & Palu, 2015). Similarly, Fuso Nerini et al. (2018) mapped synergies and trade-offs between SDG 7 and all other 16 goals from a global perspective. Weitz, Carlsen, Nilsson, and Skånberg (2018) conducted a qualitative case study of Sweden to illustrate priority setting for SDG implementation. Ronzon and Sanjuán (2020) analyzed quantitatively bioeconomy-related SDG interactions at the EU level for better policy coherence.

Understanding possible impeding as well as synergistic relations between SDGs is crucial for achieving the 2030 Agenda. For this, a

TABLE 1 Sustainable development goals (SDGs; UN General Assembly, 2015)

SDG	SDG description
SDG 1	End poverty in all its forms everywhere
SDG 2	End hunger, achieve food security and improved nutrition, and promote sustainable agriculture
SDG 3	Ensure healthy lives and promote well-being for all at all ages
SDG 4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
SDG 5	Achieve gender equality and empower all women and girls
SDG 6	Ensure availability and sustainable management of water and sanitation for all
SDG 7	Ensure access to affordable, reliable, sustainable, and modern energy for all
SDG 8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
SDG 9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation
SDG 10	Reduce inequality within and among countries
SDG 11	Make cities and human settlements inclusive, safe, resilient, and sustainable
SDG 12	Ensure sustainable consumption and production patterns
SDG 13	Take urgent action to combat climate change and its impacts
SDG 14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development
SDG 15	Protect, restore, and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation, and halt biodiversity loss
SDG 16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
SDG 17	Strengthen the means of implementation and revitalize the global partnership for sustainable development

holistic approach exploring the characteristics of SDG interactions is essential. In this context, several researchers address the holistic approach by using network analyses (Lusseau & Mancini, 2019; Pham-Truffert, Metz, Fischer, Rueff, & Messerli, 2020; Putra, Pradhan, & Kropp, 2020). Further works combined qualitative and quantitative modeling to detect SDG interactions (Neumann, Anderson, & Denich, 2018; Scherer et al., 2018; Tremblay, Fortier, Boucher, Riffon, & Villeneuve, 2020). Pradhan et al. (2017) provided the first quantification of synergies and trade-offs within and across SDGs by applying a data-driven longitudinal correlation analysis, accounting for all countries. Kroll, Warchold, and Pradhan (2019) projected SDG interactions until 2030, applying a cross-sectional approach. However, their work is based on the SDG index database, which is limited in the data availability and not linked to the officially adopted SDG Framework by the UN. Therefore, a holistic quantification of SDG interactions and their different characteristics at divers levels of disaggregation (e.g., population, income, and regional groups) is still missing.

Our study fills the highlighted research gap by applying a cross-sectional correlation analysis based on the official *Global SDG Indicators Database* for a holistic quantification of SDG interactions at divers levels of disaggregation. Based on this analysis, we can, on the one hand, observe how the income-level of a country, its regional location, or population groups influence SDG interactions. On the other hand, we identify existing inequalities among these disaggregations that need to be tackled for fulfilling the 2030 Agenda's pledge to "leave no one behind." Furthermore, we go beyond determining synergies and trade-offs by identifying different characteristics of SDG interactions, that is, non-linearity and monotony, based on a wide range of correlation methods. Understanding those characteristics can help identify SDG pairs with variations in the strength of interactions across the development spectrum.

2 | DATA AND METHODOLOGY

2.1 | The global SDG indicators database

This study uses the *Global SDG Indicators Database* from the United Nations Statistics Division (UN Statistics Division, 2019), which is based on the official *Global SDG indicator framework* adopted by the United Nations General Assembly (UN General Assembly, 2015). The database provides data on 171 out of 232 indicators for a total of 247 countries and areas worldwide between the years 1990 and 2019 (in some cases from 1985, status November 2019), even though indicator time-series are not available for all time steps and countries (UN Statistics Division, 2019). Our holistic analysis uses those 171 indicators, of which 54 are disaggregated in terms of population groups based on gender, age, and urban and rural distinction.

2.2 | Data preparation and processing

We take 2016 as the reference year to analyze SDG interactions because of two reasons. First, the SDGs came into effect in 2016, building on the Millennium Development Goals (MDGs), wherefore 2016 serves as a status-quo-year. Second, this year has a relatively high data availability (≈50%) compared to other years (Table S1). Still, around 50% of the data is missing for 2016. We fill this gap based on available data for the period 2010–2019 (Tables S1 and S2). To accomplish this, we take the data from the year nearest to 2016. When data is available for more than one nearest year (e.g., 2015 and 2017), we assign the average value to 2016. This procedure leads to an increase in the total available data to ≈90% (Tables S1 and S2).

2.3 | Analysis of SDG interactions

We conduct a cross-sectional correlation analysis to understand SDG interactions under the entire development spectrum for 2016 (Figure 1). This cross-sectional approach is important because the longitudinal analysis of SDG interactions applied by Pradhan et al. (2017) only compares a country's development over time. However, cross-sectional analysis enables comparison between countries across the world, covering the entire development spectrum (Kroll et al., 2019), since countries generally follow the development path of other countries (Mendelsohn et al., 2004). Before applying the correlation analyses, we assign a positive sign to indicators that are desirable to increase and a negative sign to those indicators that need a decline for meeting the SDGs (Table S3). This is explained by the fact that given the nature of an indicator, an increase or decrease in its value over time has different meanings for achieving the SDGs (Pradhan et al., 2017).

We categorize SDG interactions as synergies and trade-offs based on (anti-)correlations between pairs of SDG indicators, considering country and country-disaggregated data (Pradhan et al., 2017). These indicator pairs can belong to the same goal or two distinct goals. To ensure that the indicator pairs represent the entire development spectrum, we carry out the correlation analysis only with the pairs consisting of at least 10 data points. However, using only one correlation method can lead to undetected relations (Anscombe, 1973). This is because relations between two indicators can be monotone linear, monotone non-linear, non-monotone non-linear, or show no strong relation (Figure S1).

Looking at various correlation methods, the Pearson's product–moment correlation or simply Pearson's r measures the degree of linear dependencies between a randomly related pair of variables (x and y; Galton, 1889a, 1889b; Pearson, 1920). Spearman's ranked correlation coefficient r_s is a non-parametric measure to capture the strength of monotonic relations (Spearman, 1904). r_s is defined as the Pearson's r on ranked values, rather than the observed values. Newer correlation methods have taken a forefront in the measurements of monotone non-linear and non-monotone dependence due to the increasing realization that those are often as important, and likely more common than simple linear ones (Deebani & Kachouie, 2018; Wang et al., 2017). These include, inter alia, the maximal information coefficient (MIC; Reshef et al., 2011)—the culmination of more than 50 years of concept development of mutual information (MI; Speed, 2011). This non-parametric method captures dependencies between pairwise variables in large data sets, both functional and no functional ones (Reshef et al., 2011). Therefore, we apply several correlation methods for a holistic quantification of SDG interactions (Figures 1 and S2; Text S1).

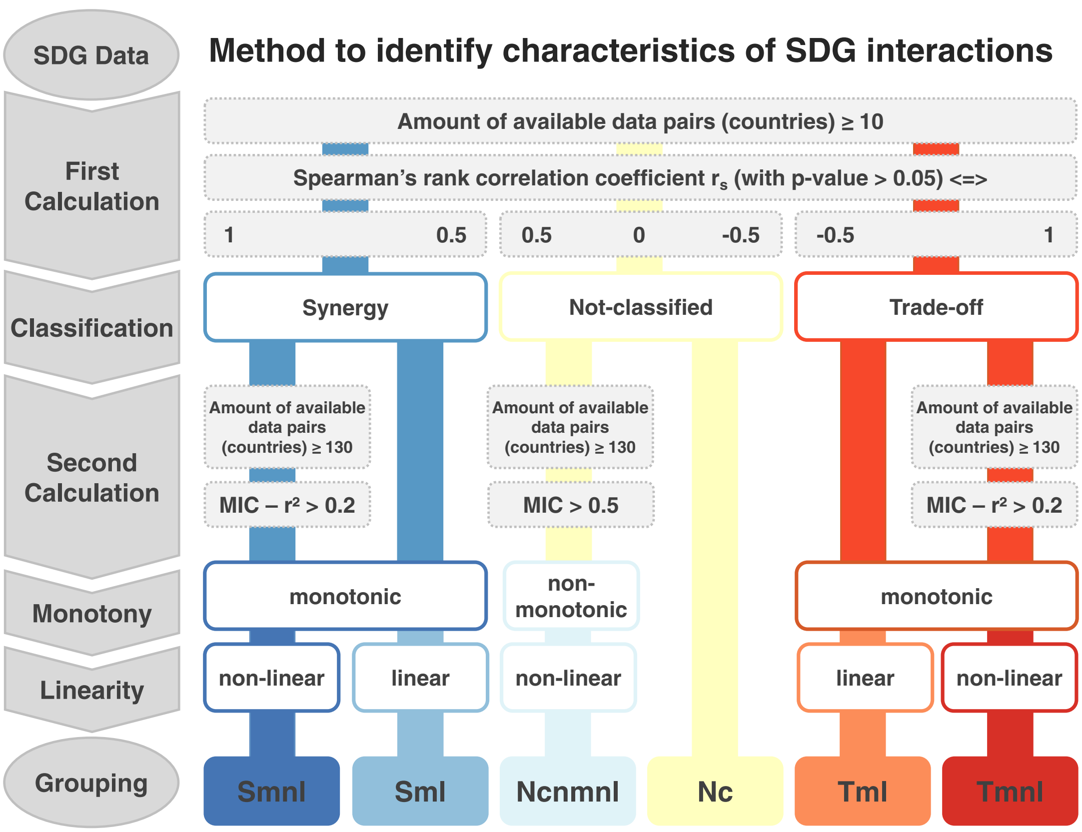

FIGURE 1 Applied method to identify characteristics of sustainable development goal (SDG) interactions. We estimate several correlation coefficients—Pearson's r, Spearman's r_s, and Maximal information coefficient (*MIC*), to categorized SDG interactions into six groups: synergy monotone non-linear interactions (Smnl), synergy monotone linear interactions (Sml), not-classified interactions (Nc), not-classified non-monotone non-linear interactions (Ncnmnl), trade-off monotone linear interactions (Tml) and trade-off monotone non-linear interactions (Tmnl) [Colour figure can be viewed at wileyonlinelibrary.com]

Initially, we estimate r_s between SDG indicators. Based on the coefficient value and the relation's direction, we define synergies and trade-offs: a plus sign indicates a positive relation (synergy), and a minus sign indicates a negative one (trade-off). To avoid over-interpretation of correlation (Hauke & Kossowski, 2011), we implement thresholds while defining synergies and trade-offs. Smarandache (2016) defines Pearson's r as weak if $r \in [-0.5, 0.5]$ and as strong or moderate relations if r exceeds this interval. Based on the comparison of r and r_s (Figure S2), we adapted these thresholds and defined an SDG interaction with $r_s \in [-0.5, 0.5]$ as "not-classified," with $r_s \in (0.5, 1]$ as "synergy" and with $r_s \in [-1, -0.5)$ as "trade-off." We also use theses thresholds to distinguish strong monotone relations (if $r_s \in [-1, -0.5)$ or $r_s \in (0.5, 1]$) from weak ones (if $r_s \in [-0.5, 0.5]$). A Spearman's ranked correlation coefficient (r_s) close to 0 implies no relation. We categorize both weak monotone relations and no relations as not-classified interactions.

Next, we distinguish linear and non-linear relations among the identified monotonic relations based on the available minimal sample size (see Text S2) and the non-linearity estimator (see Text S3). The minimal sample size is estimated using population size, margin of error, confidence level, and response distribution (Raosoft Inc., 2004). For the global analysis, we estimate the minimal sample size of 130 that varies across diverse levels of disaggregation (Tables S4–S6). Using the *MIC* and Pearson's r, Reshef et al. (2011) suggested the $MIC - r^2$ estimator to identify non-linearity. Here, a value of $MIC - r^2$ close to 0 reflects linear relations, whereby a value greater than 0.2 is considered as non-linear (Reshef et al., 2011).

Lastly, we distinguish non-monotonic non-linear relations across the not-classified ones from weak monotone relations. We do this based on the available minimal sample size and the value of *MIC* (Figure 1). The non-monotonic relations are considered non-linear when the minimal sample size is met, and the value for *MIC* is greater than 0.5. We chose this threshold based on Reshef et al. (2011), showing robustness of *MIC* to detect non-monotonic relationships, despite noises. This also corresponds with the results of our correlation comparison (see Text S1 and Figure S2). By applying the above-described correlation methods, we holistically quantify SDG interactions into six types (Figure 1):

- Smnl: synergy monotone non-linear interaction,
- Sml: synergy monotone linear interaction,
- Ncnmnl: not-classified non-monotone non-linear interaction,
- Nc: not-classified interaction,
- Tml: trade-off monotone linear interaction, and
- Tmnl: trade-off monotone non-linear interaction.

2.4 | Variation in SDG interactions

We apply the above-described method not only at the global scale but also at divers levels of disaggregation, namely population, income, and regional groups (detailed information on all levels of disaggregation are provided in Text S4). The *Global SDG Indicators Database* provides data for the population disaggregation: gender, age, and urban and rural, to monitor the 2030 Agenda's pledge to "leave no one behind." These disaggregated data enables to track population groups left behind while a country is making progress on an average. Therefore, we make use of the disaggregated data to understand variation in SDG interactions across these groups globally. Eight out of 17 SDGs consist of disaggregated data usable for our analysis (Table S4). Therefore, we only consider interactions within and across these eight SDGs for our analysis.

Besides this global analysis, we also carry out the cross-sectional analysis among country groups based on income and region to understand variation in SDG interactions across different development spectra for 2016. For this, we use the World Bank Atlas' four income groups (World Bank Group, 2018), that is, low-income countries (LIC), lower-middle-income countries (LMIC), upper-middle-income countries (UMIC), and high-income countries (HIC), to identify SDG interactions across income groups (Figure S3). SDG interactions could also vary due to differences in social and environmental factors across the world. We attempt to capture this variation determined by world regions based on the United Nations Regional Groups (UN, 2018): Western World, Latin America, Asia-Pacific, and Africa (Figure S4). By capturing these variations of SDG interactions, we also distinguish similarities from differences among the income and regional groups (for mythological details see Text S5).

3 | RESULTS

3.1 | Interactions within SDGs

Globally, we observe varying shares of synergies and trade-offs but also linear and non-linear relations within SDGs (Figure 2, left). However, most intra-goal interactions are not-classified and, therefore, do not mutually interfere. Within all 17 goals, synergies (an average sum of Sml and Smnl interactions of 35.1%) outweigh trade-offs (an average sum of Tml and Tmnl interactions of 5.8%). This result implies that the indicators are more coherent than conflicting within the same goal, which is a positive starting point to implement the 2030 Agenda. Additionally, we observe more linear (an average sum of Sml and Tml interactions of 35.2%) than non-linear relations (an average sum of Smnl and Tmnl interactions of 5.7%). We do not detect any Ncnmnl interactions within SDGs.

Within SDG 1, 5, and 6, we observe Sml interactions for more than 50% of all data pairs. These linear synergies indicate broad compatibility, where progress in one indicator is proportionally associated with the advancement of another one within the same goal. This compatibility also holds for Smnl interactions. SDG 3, 12, and 14 have notables share of Smnl interactions (≈10–30%). These non-linear synergies reflect the disproportionate improvement of one indicator by a change of another. Hence, non-linearity compared to linearity shows the possibility of variations in progress rate for the SDGs after reaching specific thresholds. An example of the Smnl interactions is

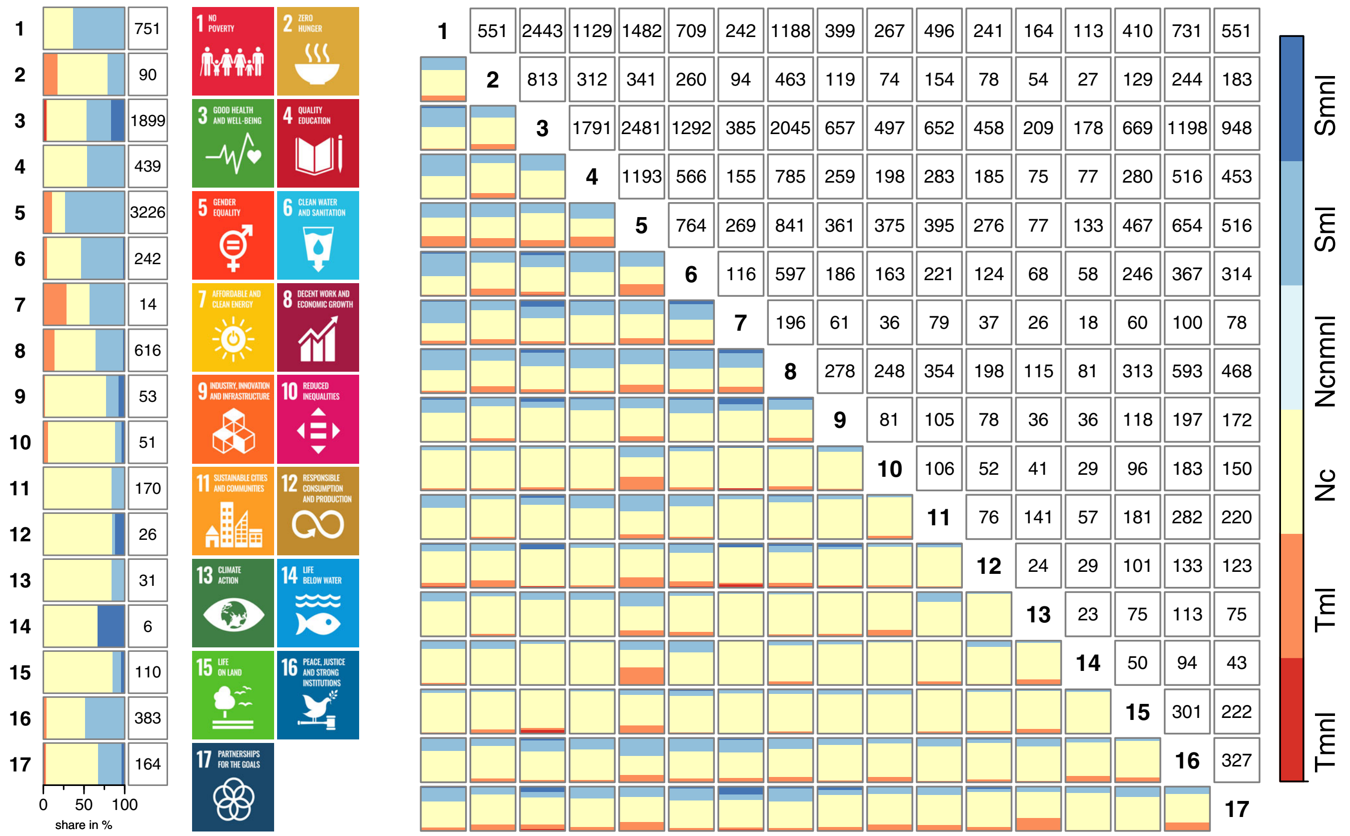

FIGURE 2 Detected interactions within (left) and across (right) sustainable development goals (SDGs) globally in 2016. The color bar represents the six groups of SDG interactions: synergy monotone non-linear interactions (Smnl), synergy monotone linear interactions (Sml), not-classified interactions (Nc), not-classified non-monotone non-linear interactions (Ncnmnl), trade-off monotone linear interactions (Tml) and trade-off monotone non-linear interactions (Tmnl). The numbers in the boxes represents the number of data pairs used for the analysis. The SDGs are represented with the numbers in the left, in the diagonal and the icons [Colour figure can be viewed at wileyonlinelibrary.com]

disproportional relation between non-communicable diseases (NCDs) [Indicator 3.4.1] and the “maternal mortality ratio” [Indicator 3.1.1] (Figure 3a). From this relation, we can infer that investments in the prevention of NCDs, for example, addressing tobacco use, unhealthy diets including alcohol use and physical inactivity, reduce women's vulnerability not only to NCDs but also to ensure maternal health. According to Kapur (2015), the prevention and control of NCDs, particularly diabetes, obesity, and hypertension, improve maternal health and pregnancy outcomes drastically. Furthermore, this non-linear synergy indicates the necessity to invest in prevention measures at the right place because outcomes vary across the globe due to inequalities.

Within SDG 2, 5, 7, and 8, we observe substantial shares of Tml interactions (10–30%). These linear trade-offs reflect interactions where progress in one indicator is proportionally creating an obstacle in fulfilling another indicator and vice versa. We also identify non-linear trade-offs within some SDGs, for example, a small share of Tmnl interactions within SDG 3 (≈4%).

Some SDGs also consist of both a substantial share of synergies and trade-offs (Figure 2, left)—for example, SDG 5 and 7. In SDG 5, these impeding intra-goal interactions can arise due to the gender-disaggregation of indicators. For example, when more women hold positions in leadership and managerial roles [Indicators 5.5.1, 5.5.2], men might indirectly spend more time on unpaid domestic and care work [Indicator 5.4.1]. Therefore, the changed distribution of responsibilities at work and home can cause those impeding SDG 5 interactions. This trade-off can be tackled by valuing unpaid domestic and care work.

3.2 | Interactions across SDGs

SDG interactions widely vary across goals (Figure 2, right). Nc interactions (70.2%) largely outweigh synergies (an average sum of Sml and Smnl interactions of 21.7%) and trade-offs (an average sum of Tml and Tmnl interactions of 8.1%). The linear relations (an average sum of Sml and Tml interactions of 26.6%) prevail the non-linear ones (an average sum of Smnl and Tmnl interactions of 3.2%). Ncnmnl interactions do not appear across SDGs.

SDG 1, 4, 5, and 6 have high shares of Sml interactions across most other SDGs with average shares greater than 25%. Our analysis highlights synergies between SDG 6 and the social dimensions of the 2030 Agenda, as expressed by SDG 1–5 with shares of 40–60%. For example, improved access to safe water [Targets 6.1, 6.2] in homes,

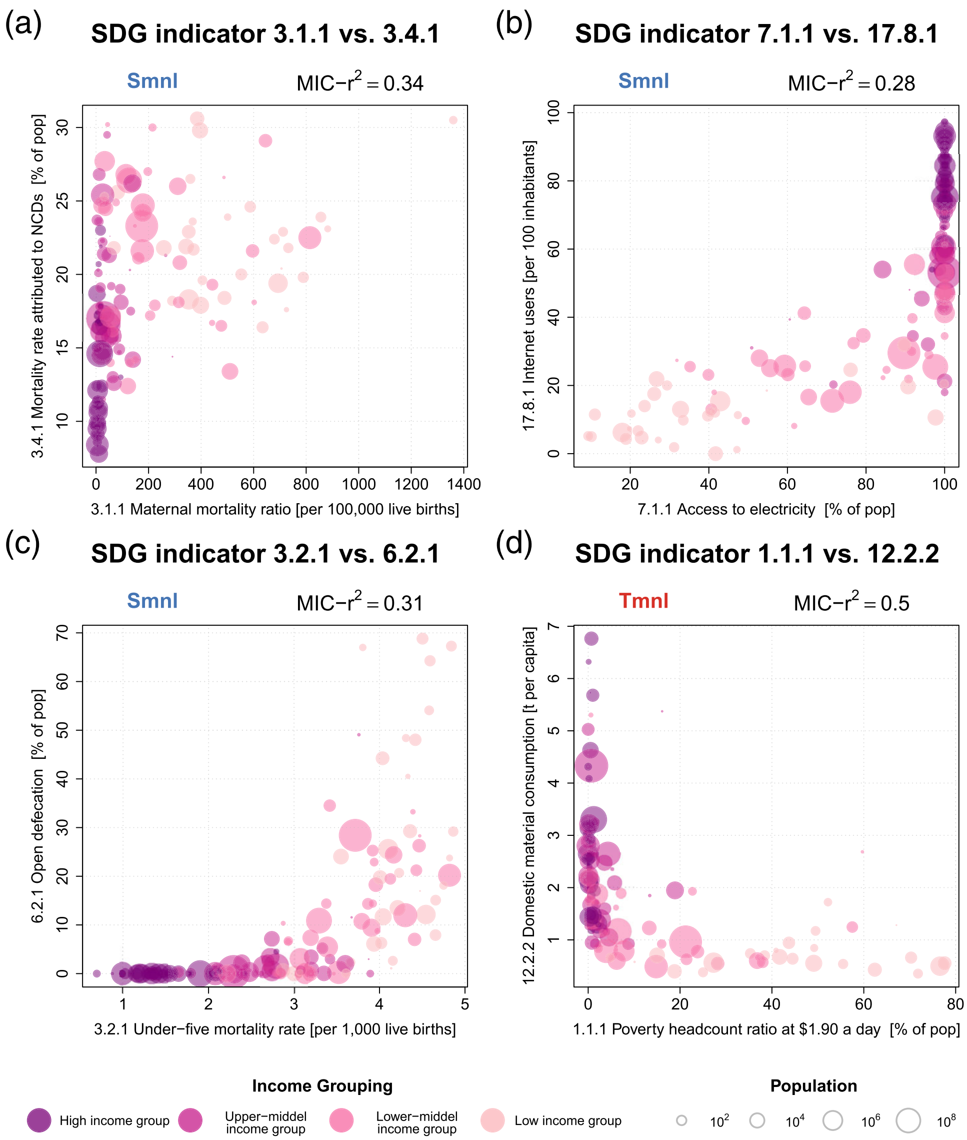

FIGURE 3 Examples of synergy monotone non-linear interactions (Smnl) (a–c) and trade-off monotone non-linear interactions (Tmnl) (d) globally in 2016. The four different colors underline the four income-based groups. The size of each colored dot highlights the country's population size for the reference year 2016. The non-linearity estimator is calculated via the maximal correlation coefficient (MIC) minus squared Pearson's *r* being more than 0.2 [Colour figure can be viewed at wileyonlinelibrary.com]

health-care facilities, and schools will directly support several targets on nutrition and health [Targets 2.2, 3.1–3.3, 3.9], education [Targets 4.1, 4.2, 4.3] and gender equality [Targets 4.5, 5.2, 5.5]. Additionally, the lives of women and girls are significantly improved by better drinking water services [Indicator 6.1.1] because it saves them time spent collecting water from distant sources, thus reducing the time spent on unpaid domestic and care work [Indicator 5.4.1] (UN-Water, 2016).

We predominantly observe Smnl interactions for SDG 3 and 7 with an average share of >5% across all other SDGs. The SDG pair 7 and 17 has the largest share of Smnl interactions (18%). Figure 3b illustrates an example of non-linear synergies in this SDG pair that shows—with a marginal increase in the "proportion of the population with access to electricity" [Indicator 7.1.1], the "proportion of individuals using the internet" [Indicator 17.8.1] can grow disproportional across countries. This non-linear synergy with Indicator 7.1.1 also holds for the "fixed internet broadband subscriptions per 100 inhabitants" [Indicator 17.6.2]. These results elucidate an effective way of exploiting potential synergies for internet connectivity with marginal investments in electricity.

Figure 3c highlights another strong Smnl interaction whereby a decrease of the "proportion of population practicing open defecation" [Indicator 6.2.1] leads to a decline of the "under-five mortality rate" [Indicator 3.2.1]. This non-linear synergy is an outcome of inequalities across the world. HIC have a high density of sanitation services and low under-five mortality rates, whereas LIC exhibit a lower density of sanitation services and higher under-five mortality rates. Through this inequality, it is clear that LIC need capacity building on clean sanitation solutions, resulting in synergistic effects on improved children's health. This non-linear synergy highlights that a marginal increase in the density of basic sanitation services can drastically decrease under-five mortality rates. This is an example of how the understanding of SDG interactions can be leveraged to achieve the 2030 Agenda.

SDG 2, 5, and 17 exhibit comparatively a high share of linear trade-offs (Tml interactions of 10–20%) across all other SDGs. These goals are currently in conflict with most other SDGs, antagonizing sustainable development due to various reasons. For example, trade-offs associated with SDG 5 are mainly due to the gender-disaggregation of indicators, reflecting differences between the population groups.

Similarly, SDG 3 and 12 exhibit most non-linear trade-offs (Tmnl interactions of 3%) across SDGs. Specifically, the "domestic material consumption (DMC)" [Indicator 12.2.2] is attributed to a relatively high amount of Tmnl interactions across SDGs. The SDG pair 7 and 12 has the largest share of Tmnl interactions (8%). An example of non-linear trade-offs in this SDG pair is growing DMC with increased electricity accessibility [Indicator 7.1.1]. Similarly, another example is the relation between "proportion of population below the international poverty line of US$1.90 per day" [Indicator 1.1.1] and DMC (Figure 3d). For achieving the 2030 Agenda, poverty needs to be eliminated, and DMC should be limited to a sustainable level. However, DMC currently increases with economic growth that is required to eliminate poverty. Therefore, the growing DMC must be reconciled with all dimensions of the 2030 Agenda. Responsible consumption and production are considered as the bottleneck for sustainable development (Pradhan et al., 2017). Tackling these trade-offs will broadly depend on technology and policy changes but also on rethinking the demanding behaviors of society worldwide (Haraguchi & Kitaoka, 2015).

3.3 | SDG interactions among population groups

SDG interactions vary among population groups (Figure 4 and Table S5). Mainly, we observe a high share of synergies (mainly Sml interactions) for female, younger, and rural populations in comparison to male, elderly, and urban populations, respectively (Figure 4 and Table S5). Additionally, SDG interactions for female, younger, and rural population depict low or negligible shares of trade-offs (mainly Tml interactions). Consequently, the progress of an SDG indicator will in general foster progress in another SDG indicator for these population groups.

For example, interactions of SDG 4 with other SDGs show mostly higher shares of synergies for female than male population due to various reasons. For example, young women, especially those from poor households, face unequal education opportunities compared to the male population. This causes a chain of drawbacks in women's life affecting health [SDG 3], employment [SDG 8], social security [SDG 16] as well as other determinants, creating negative dependencies. Therefore, ensuring women's education has more leveraging effects in attaining the 2030 Agenda by fixing the current disadvantaged position for females.

Similarly, the reduction of poverty [SDG 1] has high shares of synergies within the younger population, whereas the elderly population exhibits instead of Nc relations (Figure 4). Poverty is linked to unsustainable agriculture, causing hunger and malnutrition. Particularly in early childhood, this is related to compromised cognitive and physical performance [SDG 3], which undermines the education [SDG 4], productivity, and future earnings [SDG 8] of those affected (Baye, 2017). In the end, poverty is linked to a chain of negative effects the young population is without assistance not able to escape from.

Moreover, people living in rural areas are far more likely to be affected by poverty than people in urban areas. The most pressuring reason is a multi-dimensional lack of water- and electricity-related infrastructures. Accordingly, the rural population shows higher shares of synergies than the urban population for SDG 1, 6, and 7 (Figure 4). On the one hand, domestic water for drinking and sanitation is a basic need indivisible for the achievement of numerous other SDGs. On the other hand, in increasingly interconnected societies and technology-enabled economies, digital exclusion impedes the rural population significantly from fully participating in their country's economy, society, and political system. Leveraging these observed synergies could, therefore, contribute to inclusive and sustainable rural development.

The above-described results imply that the female, younger, and rural population groups have a good starting point for successfully implementing the 2030 Agenda. But in reality, these population groups still have disadvantaged positions in most countries. Under the current development paths, they are more vulnerable to and affected by adverse situations such as poverty [SDG 1], discrimination [SDG 5], violence [SDG 5 and 16], and health problems [SDG 3]. These population groups also have few years of education [SDG 4], consequently face economic disadvantages [SDG 8], and suffer from inadequate infrastructure [SDG 6 and 7]. In some cases, intersections between these population groups exist. For example, rural females or younger females could especially be affected by these adverse situations. Therefore, breaking away the current disadvantaged positions for these population groups—by leveraging the presented SDG synergies—can fulfill the 2030 Agenda's pledge to "leave no one behind."

3.4 | SDG interactions among income groups

Among the income groups, SDG interactions vary strongly between synergies and trade-offs and marginally between linear and non-linear relations (Figures S5 and S6; Table S6). HIC show the lowest shares of synergies (an average sum of Sml and Smnl interactions of 29.3%) and trade-offs (an average sum of Tml and Tmnl interactions of 17.3%; Table S6). In contrast, LIC have, on the one hand, the highest shares of synergies (an average sum of Sml and Smnl interactions of 45%) and trade-offs (an average sum of Tml and Tmnl interactions of 22%) and, on the other hand, exhibits the highest shares of non-linear SDG interactions. UMIC and LMIC are ranked between these two income groups. Consequently, a high share of synergies reflects a good start to implement the 2030 Agenda in LIC. However, the share of trade-offs also highlights the need for transforming the current development paths to achieve the SDGs.

Some SDG pairs show similarities in synergies and trade-offs among the income groups (Figure 5a). For example, interactions within SDG 5, 6, and 8 consist mainly of synergies (sum of Sml and Smnl interactions >50%; Figure 5a—left). Similarly, the SDG pairs 2 and

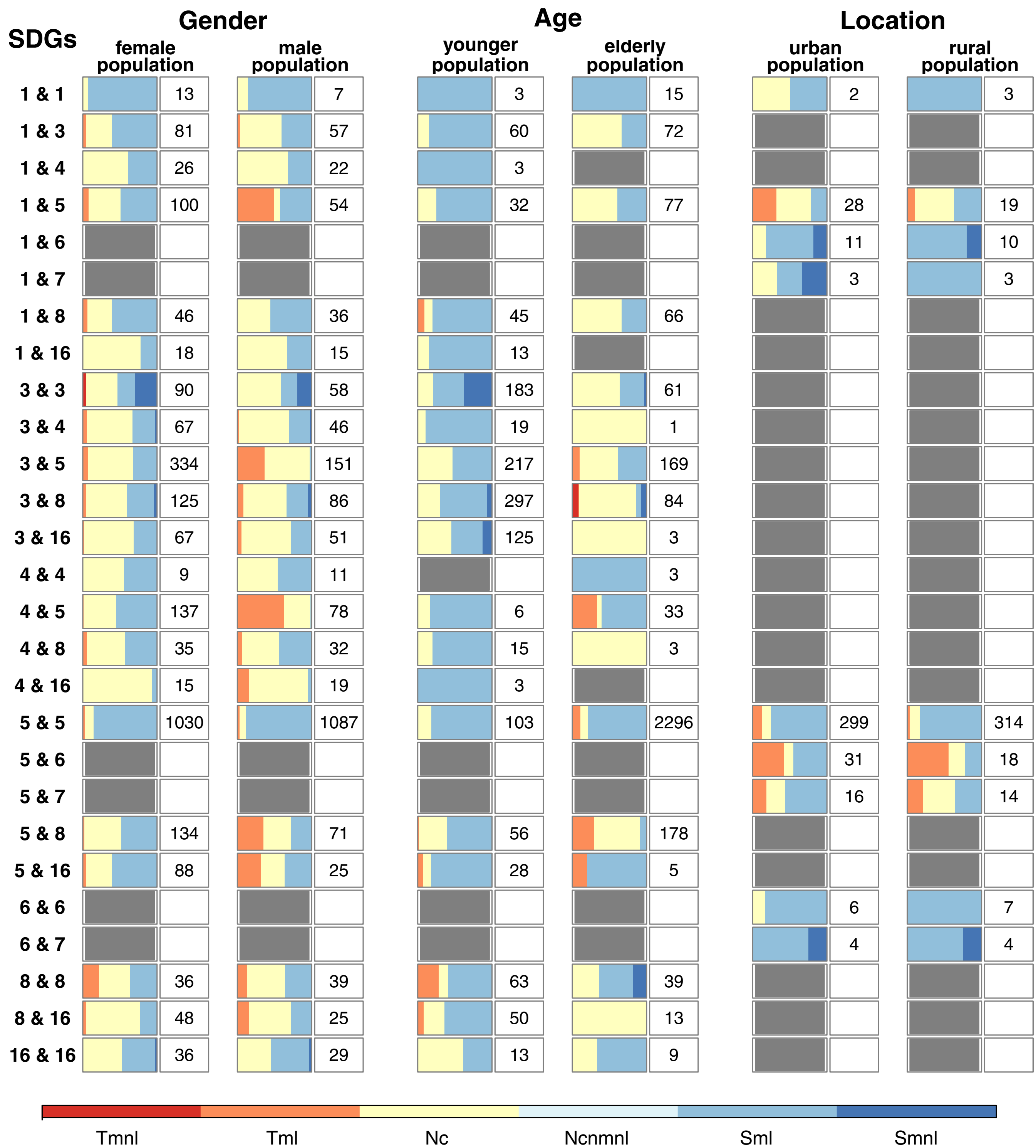

FIGURE 4 Detected interactions within and across gender-, age- and geographical-disaggregated sustainable development goals (SDGs) in 2016. The color bar represents the shares of monotone non-linear synergies (Smnl—dark blue), monotone linear synergies (Sml—blue), not-classifieds (Nc—yellow), non-monotone non-linear not-classifieds (Ncnmnl—light blue), monotone linear trade-offs (Tml—orange) and monotone non-linear trade-offs (Tmnl—dark red). The gray bar depicts insufficient data for the analysis. The numbers in the boxes represents the number of data pairs used for the analysis. The numbers in left hand side of the figures represents the SDG pairs [Colour figure can be viewed at wileyonlinelibrary.com]

10, 3 and 15, and 5 and 16 are examples, showing trade-offs for all the income groups (Figure 5a—right). Here, the observed trade-offs between SDG 2 and 10 seem counter-intuitive. This impeding interaction comes, for example, from negative correlations of "Prevalence of stunting" [Indicator 2.2.1] and "Food price volatility" [Indicator 2.c.1] with "Proportion of tariff lines applied to imports from least

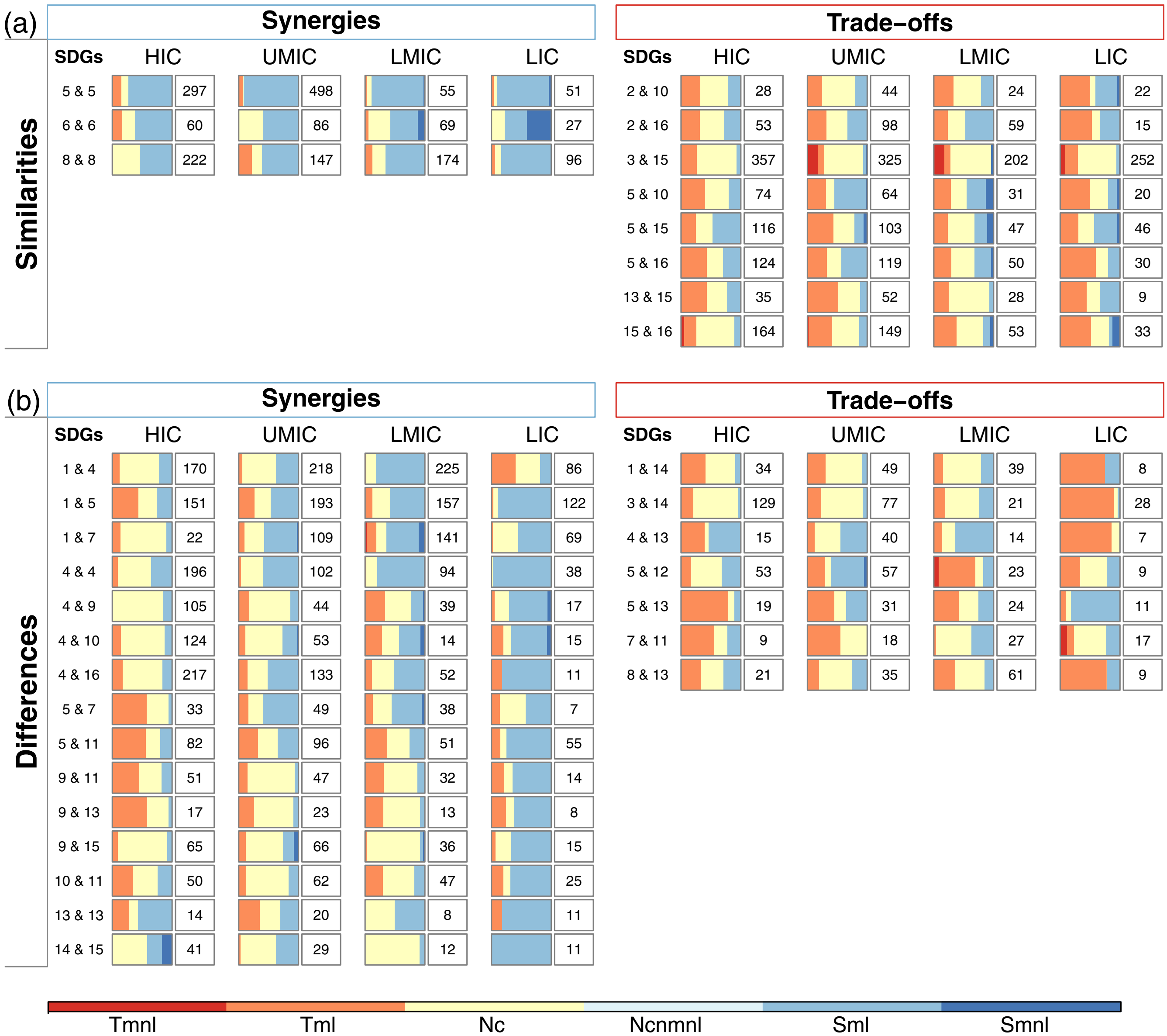

FIGURE 5 Detected similarities (a) and differences (b) of sustainable development goal (SDG) interaction among the four income groups—low-income countries (LIC), lower-middle-income countries (LMIC), upper-middle income-countries (UMIC), and high-income countries (HIC)—in 2016. The color bar represents the six groups of SDG interactions: synergy monotone non-linear interactions (Smnl), synergy monotone linear interactions (Sml), not-classified interactions (Nc), not-classified non-monotone non-linear interactions (Ncnmnl), trade-off monotone linear interactions (Tml) and trade-off monotone non-linear interactions (Tmnl). The numbers in the boxes represents the number of data pairs used for the analysis. The numbers in left hand side of the figures represents the SDG pairs. The methodology for detected similarities and differences across SDG interactions is given in Text S5 [Colour figure can be viewed at wileyonlinelibrary.com]

developed countries and developing countries with zero-tariff" [Indicator 10.a.1] for LIC. Adjaye-Gbewonyo, Vollmer, Avendano, and Harttgen (2019) state that government assistance to tradable agriculture, such as reduced taxation, is associated with small but significant improvements in child nutritional status. This support for agriculture, indicated by positive rates of assistance, sometimes occurs in the form of trade protection such as through import tariffs or export subsidies. In the short run, this support can lead to increased consumer food prices, affecting food security, nutritional status, and poverty. In the case of HIC, we instead observe negative correlations, for example, between "Proportion of local breeds for which sufficient genetic resources are stored for reconstitution (%)" [Indicator 2.5.2] and "Return on assets (%)" [Indicator 10.5.1]. These similar interactions reflect the needs of sustainable transformations in all countries, regardless of their incomes.

We also observe differences among the income groups for some SDG pairs (Figure 5b), mainly for SDG 1, 4, and 9. The SDG pair 1 and 7 is an example of the variation in synergies (Figure 5b—left). For this SDG pair, three income groups, except HIC, have mostly synergies (60–75%). A reason for these synergies is attributed to the observed positive correlations of poverty reduction and social protection [Targets 1.1–1.3] with universal access to affordable, reliable, and modern energy services [Target 7.1]. Within these income groups, the marginal effort to improve electricity access would drastically reduce poverty. This poverty reduction is also indirectly linked with the strengthening of living standards through the provision of basic services, including health-care, education, water, and sanitation [SDG 2–4, 6, 9] and building resilient rural and urban livelihoods [SDG 1 and 11] as results of improved electricity access (Fuso Nerini et al., 2018). The SDG pair 4 and 10 is another example of the variation in synergies. For LIC, this pair has mostly synergies (share of Sml and Smnl interactions of 56.25 and 6.25%, respectively), which is limited (share of Sml interactions of 12%) for HIC. This high share of synergies in LIC also reflects the leveraging potential of economic growth for achieving SDGs, however, with reduced effects after reaching certain income levels.

Similarly, some SDG pairs have variations in trade-offs among the income groups (Figure 5b—right). The SDG pair 1 and 14 is an example where trade-offs are higher in LIC than in other income groups. These trade-offs in LIC can be explained by the Environmental Kuznets Curve (EKC) that increases environmental pollution with economic growth until a certain income level is reached. However, the existing EKC needs to be broken away for a harmonious development along the three sustainability dimensions.

3.5 | SDG interactions among regional groups

Similar to the income groups, SDG interactions range from synergies to trade-offs and a small extent, from linear and non-linear relations among the regions (Figure S7 and S8; Table S7). Latin America shows the highest shares of synergies (an average sum of Sml and Smnl interactions of 45.5%) and trade-offs (an average of Tml interactions of 28.1%; Table S7). In contrast, Africa has the lowest shares of both synergies (an average sum of Sml and Smnl of 36.5%) and trade-offs (an average sum of Tml and Tmnl interactions of 17.8%) but exhibits the highest shares of non-linear SDG interactions (Table S7). For the Western World and Asia-Pacific, shares of SDG interactions vary between Latin America and Africa. A high share of synergies in all regions can be interpreted as a good start to implement the 2030 Agenda but only with sustainable transformations of the current development paths. This is because the trade-offs are also substantial across the regions.

Interactions between some SDG pairs show mostly synergies or trade-offs among the regions (Figure 6a). In contrast to the income groups, the regions have a larger number of similarities than differences in SDG interactions. For example, the SDG pairs 1 and 13, 1 and 11, and 4 and 10 have more than 50% shares of synergies (sum of Sml and Smnl interactions) among the regions (Figure 6a—left) while the SDG pairs 2 and 5, 5 and 13, and 14 and 16 have substantial trade-offs (Figure 6a—right). Here, the counter-intuitive trade-off between SDG 2 and 5 occurs due to negative correlation of the "Prevalence of undernourishment (%)" [Indicator 2.1.1] in Latin America and "Food insecurity" [Indicator 2.1.1] in the Western World with "Proportion of time spent on unpaid domestic chores and care work, by sex, age, and location (%)" [Indicator 5.4.1]. On the one hand, Indicator 5.4.1 occurs due to the high levels of disaggregation far more often in our analysis than other indicators. On the other hand, women's unpaid work in agriculture seems to harm household nutrition through reduced time for care work, causing seasonal energy deficits. Longer working hours or increases work intensity can have detrimental effects on their health [SDG 3] and, consecutively, on their ability to care for their children—impairing child- and household nutrition [SDG 2] (Komatsu, Malapit, & Theis, 2018).

Differences in synergistic SDG interactions among the regions are mainly attributed to SDG 1 (Figure 6b—left). The SDG pair 1 and 16 is an example. We observe strong positive relations between different targets on poverty reduction [Targets 1.1–1.5] and the support towards a peaceful and inclusive society with strong institutions [SDG 16], especially in Latin America (Sml interactions >80%). This SDG pair also has a high share of synergies (≈45%) in Asia-Pacific and Africa but a low share (≈25%) in the Western World. In general, poverty can be reduced by increasing social (family disruption), mental (heterogeneity), and income stability (Pridemore, 2002). These stability components are reflected in SDG 16 by the following indicators, among others—the number of victims of homicide [Indicator 16.1.1] and sexual violence [Indicator 16.1.3], and building competent authorities for all [Indicator 16.3.1]. Therefore, these differences in the share of synergies can be due to variations in the stability among the regions. For example, Latin America has the highest homicide rate (Roser & Ritchie, 2020).

Some SDG pairs also have differences in impeding SDG interactions among the regions (Figure 6b—right). For example, the SDG pairs 9 and 13 and 12 and 13 show a large share of trade-offs for Latin America in comparison to other regions. These trade-offs might be associated with adverse environmental impacts of increased economic, mainly industrial, activities in the region. Similarly, the SDG pair 1 and 14 also exhibits a high share of trade-offs in Latin America and Africa. These trade-offs reflect that poverty reductions can have environmental externalities due to increasing accessibility to basic services (e.g., clean energy, safe water, and health care systems) that could have environmental costs under the current development paths. For achieving the 2030 Agenda, these trade-offs should be tackled by transforming the current ways of natural resource use by energy, manufacturing, and human systems to minimize the adverse environmental impacts (Fuso Nerini et al., 2018).

4 | DISCUSSION

We characterize, for the first time, variations in SDG interactions by applying a wide range of correlation methods for different groups, beyond the global analysis. Our study offers several novel contributions to SDG research.

First, although synergies outweigh trade-offs, our cross-sectional analysis highlights that most SDG interactions are non-classifieds

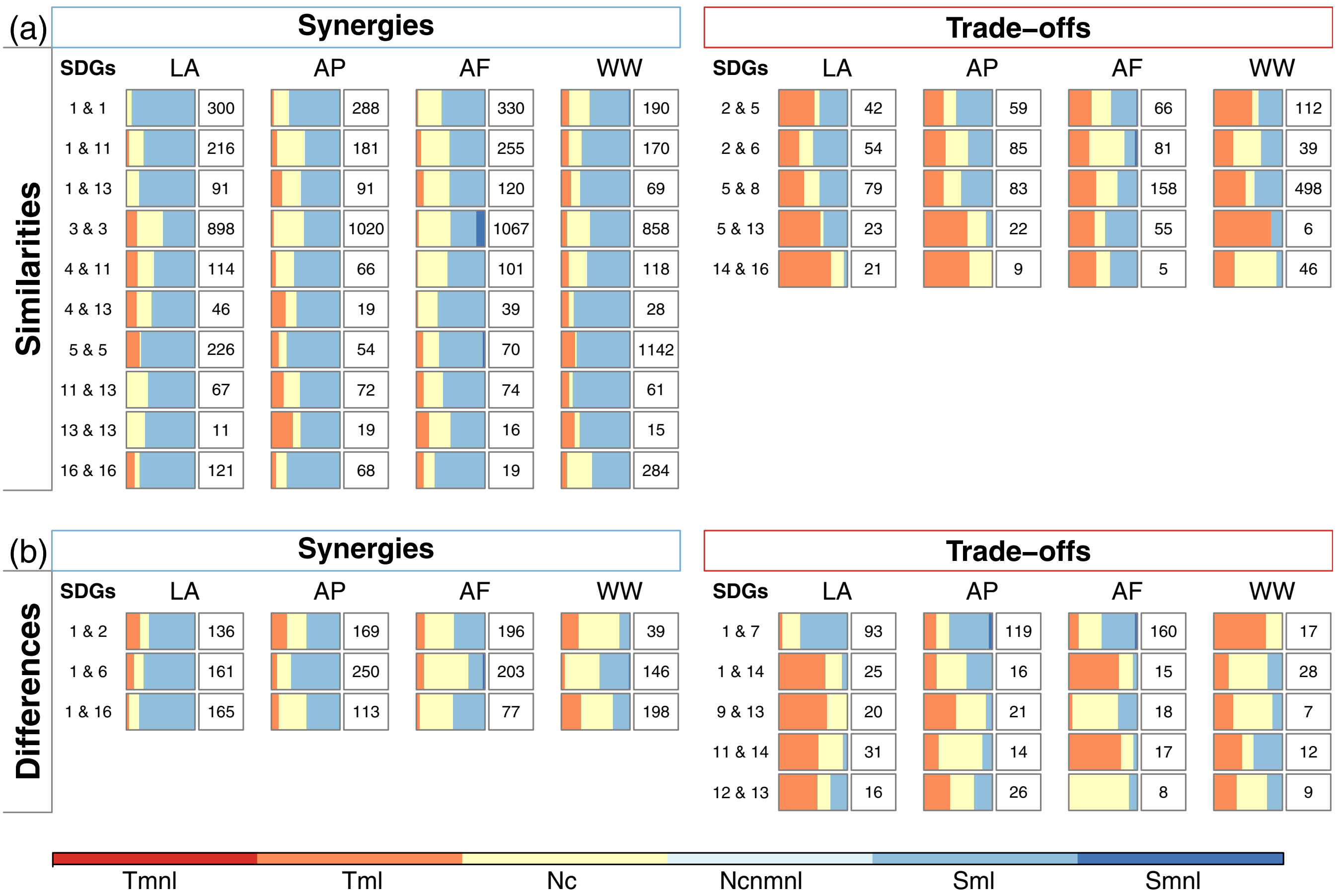

FIGURE 6 Detected similarities (a) and differences (b) of sustainable development goal (SDG) interaction among the four regional groups—Western World (WW), Latin America (LA), Asia-Pacific (AP), and Africa (AF)—in 2016. The color bar represents the shares of monotone non-linear synergies (Smnl—dark blue), monotone linear synergies (Sml—blue), not-classifieds (Nc—yellow), non-monotone non-linear not-classifieds (Ncnmnl—light blue), monotone linear trade-offs (Tml—orange) and monotone non-linear trade-offs (Tmnl—dark red). The numbers in the boxes represents the number of data pairs used for the analysis. The numbers in left hand side of the figures represents the SDG pairs. The methodology for detected similarities and differences across SDG interactions is given in Text S5 [Colour figure can be viewed at wileyonlinelibrary.com]

(i.e., no strong relation). This finding is in contrast to many studies that reported a larger share of synergies than trade-offs among SDGs (Dawes, 2020; Pradhan et al., 2017; Weitz et al., 2018). We observe a large share of non-classifieds because we consider the entire development spectrum to investigate SDG interactions in one year. Previous studies either applied longitudinal analysis, comparing a country's development over time (Pradhan et al., 2017) or using qualitative analysis that focuses only on positive and negative interactions. Similar to this study, Kroll et al. (2019) investigated SDG interactions by applying a cross-sectional analysis of the SDG Index data. However, our study is based on the *Global SDG Indicators Database* that consists of a broader set of data than the SDG Index data. For example, for 2016, the SDG Index Data provides 79 indicators (Sachs, Schmidt-Traub, Kroll, Durand-Delacre, & Teksoz, 2016), whereas we use 171 SDG indicators. This leads, on the one hand, to a more considerable amount of insufficient data on the part of Kroll et al. (2019), and, on the other hand, to a different distribution of synergies, trade-offs, and not-classified interactions. This aspect emphasizes the importance of a holistic SDG database in order to obtain comparable results from the scientific SDG community.

The identified large shares of Nc interactions reflect variations in development paths and inequalities across the countries because synergies are mostly observed when a country's development is compared over time (Pradhan et al., 2017). We highlight that socially oriented SDGs currently show more variations in interactions (synergies, trade-offs, linear and non-linear relations) than environmentally and economically oriented SDGs, globally. This variation implies that countries worldwide are more likely to follow the social development paths of other countries than environmental and economic paths. However, if we examine the income and regional groups, the interactions between all 17 SDGs are more pronounced. Consequently, countries tend to follow the transition paths of other countries within the same group in all sustainable dimensions. For the successful implementation of the 2030 Agenda, the development paths of countries need to be aligned, maximizing synergies and minimizing trade-offs. The synergies provide leveraging opportunities for fulfilling the

SDGs while the trade-offs highlight the need for sustainable transformation of the current development paths that focus on economic growth to generate human welfare at the expense of environmental sustainability (Sen, 1983).

Second, we detect, for the first time, (non-)linearity or (non-) monotony on SDG interactions besides synergies and trade-offs. So far, previous studies have not looked at these characteristics of SDG interactions. Our holistic analysis of SDG interactions reveals that linear relations outweigh non-linear ones and detects no non-monotone interactions, thereby providing new insights for the successful implementation of the 2030 Agenda. These linear relations indicate that progress in an SDG is proportionally associated with the advancement of (i.e., in case of synergies) or creating an obstacle in the fulfillment of another SDG (i.e., in case of trade-offs). However, the non-linear relations reflect disproportionate improvement or obstacle in achieving an SDG by progress in another one, showing complex SDG interactions.

From the cross-sectional perspective, non-linearity exemplifies that countries have different progress segments for specific SDG interactions. These interactions can, in some instances, be beneficial and in other, can hinder the SDG progress. Within each segment, the SDG progress can be linear. However, considering the whole spectrum, the slope, and thereby the strength of the SDG interaction changes over the different segments. Having that knowledge of SDG interactions' non-linearity enables investigating why certain countries follow a similar logic within the segments. Second, it could be explored why there are segments and possible constraints in SDG development. And lastly, why countries change their behavior after crossing one segment. Non-linear SDG interactions might occur because countries struggle to meet the competing demands of international initiatives. The reasoning behind can be the additional income- or regional-orientated constraints of countries. This is indicated by our results exhibiting less non-linear SDG interactions within those groups than globally.

Third, our analysis of SDG interactions across the population groups reveals that fulfilling the 2030 Agenda's pledge to "leave no one behind" plays a crucial role in leveraging achievements of SDGs. This is because female, younger, and rural populations have mostly synergistic SDG interactions compared to male, elderly, and urban populations. Currently, female, younger, and rural populations have disadvantaged positions and limited opportunities in many countries. Breaking away these disadvantaged positions is an additional step towards the successful implementation of the 2030 Agenda. For this, we need to better understand barriers certain population groups are facing and systematically dismantle these barriers that leave people behind. As a result, inequalities among the population groups need to be tackled from their roots leaving no one behind for sustainable development. Akuraju, Pradhan, Haase, Kropp, and Rybski (2020) also argue in a similar direction for sustainable cities saying "cities should be sustainable and efficient regardless of their sizes, tackling the existing inequalities among cities."

Fourth, we highlight that SDG interactions vary across income and regional groups. We observe higher shares of synergies and trade-offs and lower shares of not-classified interactions across these groups than our global analysis. The high shares of synergies provide leveraging opportunities for achieving SDGs. However, a substantial share of trade-offs among all the income and regional groups also emphasize the need for sustainable transformation instead of following the current development paths for making the 2030 Agenda a success. Our finding also reflects substantial inequalities among income and regional groups than within these groups. These inequalities might be due to similar features within and large differences among the groups. For example, countries within an income group can have similar economic features, whereas countries within a region can have similar socio-cultural, economic, political, and environmental features.

Among the income groups, we observe the highest shares of synergies and trade-offs in LIC. Lusseau and Mancini (2019) also reported that most SDGs have synergistic interactions for LIC, but they did not observe goals exhibiting trade-offs that we identified. This difference would be due to deviations in the applied SDG databases. Lusseau and Mancini (2019) used the World Bank database instead of the official *Global SDG Indicators Database*. However, Lusseau and Mancini (2019), and our analysis reveal that SDG 12 is impeding the progress of other goals, mainly in HIC. Kroll et al. (2019) also reported similar variations in SDG interactions across income groups. Comparing continents, our analysis highlights that efforts towards achieving an SDG in Africa are least likely to impede progress in other SDGs relative to other regions. This is because we observe the lowest shares of trade-offs for Africa. In contrast, Latin America has the highest shares of trade-offs but with the highest shares of synergies.

Our study also consists of potential limitations. First, by applying a cross-sectional approach, we identify the current SDG interactions instead of future ones. Additionally, interaction among some SDGs might be more prominent with time delay. For example, it is well-known that returns to investment in education take time (Psacharopoulos & Patrinos, 2018). Our current analysis does not account for such time-lag and does not capture the full spectrum of potential synergies and trade-offs. Nevertheless, we can find SDG interactions that occur in the short run. Furthermore, the global analysis addresses rather specific SDG aspects since the majority of interactions are not-classified. Therefore, we conducted our analysis not only globally but at divers levels. Nonetheless, the current SDG interactions provide new insights for the successful implementation of the 2030 Agenda. On the one hand, we identify synergies that can be leveraged and trade-offs that need to be resolved. On the other hand, we show that especially economic and environmental SDG aspects need to be tackled at the income and regional level. Second, the identified SDG interactions are based on the currently available data for 171 out of 232 SDG indicators. Although the availability of SDG data is improving, so far, data is not provided for all the indicators. This data availability issue can generate biased results. We attempt to tackle this biasedness by investigating SDG interactions in a relative (i.e., share of synergies and trade-offs) instead of an absolute term. Third, the applied correlation analysis does not imply causality (de Siqueira Santos, Takahashi, Nakata, & Fujita, 2013). Therefore, identified interactions could also be related to other factors linked with SDG indicators. Nevertheless, the correlation is a necessary but not sufficient condition for a causal relation. We apply several correlation methods to holistically characterize SDG interactions, which is a step forward towards the identification of causal relations. Additionally, we explain and interpret causal relations for some indicators based on existing studies. Fourth, our study is restricted by using thresholds, although they are useful and practicable to differentiate linear and non-linear relations effectively. Mainly, low data availability for some income and regional groups would lead to false detection of characteristics of SDG interactions in terms of (non-)linearity. To tackle this limitation, we obtain four world regions by summing up the United Nations Regional Groups. Nevertheless, since the fulfillment of all methodological conditions, including thresholds and the data availability varies across all SDG indicators, there might be further undetected associations. These limitations need to be addressed in further investigations.

Overall, our study holistically investigates characteristics of SDG interactions and highlights that some SDGs can have complex non-linear interactions. By doing so, we provide new insights for the successful implementation of the 2030 Agenda by identifying goals with potential economic, social, or environmental trade-offs not only at a global scale but also for population, income, and regional groups. Defining proper strategies to achieve certain SDG requires not only understanding of potential synergies and trade-offs but also the characteristics (i.e., linearity or non-linearity) of the interactions.

Development is generally not a linear process. This might also hold for meeting SDGs. For achieving the 2030 Agenda, rapid progress towards SDGs is required following non-linear paths. A continuation of the current trends in many countries would not be enough to meet SDGs by 2030 (Nature, 2020; Sachs, Schmidt-Traub, Kroll, Lafortune, & Fuller, 2019). Knowledge about interfering non-linear SDG interactions can be essential to prevent countries from rapidly following negative development trends. It also allows delaying the adverse effects of one indicator on another. Contrarily, non-linearity enables for a rapid push for synergistic progress or to examine why countries only improve gradually. These results can consequently have a beneficial implication for global institutions. According to the explained non-linearity, policy-makers could adjust the international initiatives towards a more nuanced target setting at the population, income and, regional level. Moreover, our results imply that countries can identify innovative SDG solutions by building partnerships within those groups through peer-to-peer learning. This partnership could be more strengthened during the UN High-level Political Forum on Sustainable Development, where countries meet annually to review and discuss the follow-up of their status on SDGs. Also, in the light of the current COVID-19 pandemic and its adverse impacts on SDG implementation, exponential progress is required for achieving the 2030 Agenda for sustainable transformation in the remaining 10 years. Additionally, filing the current data gaps is crucial for not only monitoring the progress made in SDG implementation but also to have an enriched understanding of SDG interactions. Policy-makers, investors, and other stakeholders can then use these results to manage the benefits and risks of achieving the various goals and targets for their areas of interest.

ACKNOWLEDGEMENTS

A. Warchold and P. Pradhan acknowledges funding from the German Federal Ministry of Education and Research (BMBF) for the SUSFOOD project (grant agreement No. 01DP17035) and the German Federal Ministry for the Environment, Nature Conservation, Building, and Nuclear Safety for the Sustainable Amazonian Landscapes project (42206-6157). The funders had no role in the design, data collection and analysis, decision to publish, or preparation of the study. Open access funding enabled and organized by Projekt DEAL.

CONFLICT OF 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.

ORCID

Anne Warchold https://orcid.org/0000-0002-0280-2758
Prajal Pradhan https://orcid.org/0000-0003-0491-5489
Jürgen P. Kropp https://orcid.org/0000-0001-7791-3420

REFERENCES

Adjaye-Gbewonyo, K., Vollmer, S., Avendano, M., & Harttgen, K. (2019). Agricultural trade policies and child nutrition in low- and middle-income countries: a cross-national analysis. *Globalization and Health*, *15*(1), http://dx.doi.org/10.1186/s12992-019-0463-0.

Akuraju, V., Pradhan, P., Haase, D., Kropp, J. P., & Rybski, D. (2020). Relating SDG11 indicators and urban scaling – An exploratory study. *Sustainable Cities and Society*, *52*, http://dx.doi.org/10.1016/j.scs.2019.101853.

Anscombe, F. J. (1973). Graphs in statistical analysis. *The American Statistician*, *27*(1), 17. http://dx.doi.org/10.2307/2682899.

Bangert, M., Molyneux, D. H., Lindsay, S. W., Fitzpatrick, C., & Engels, D. (2017). The cross-cutting contribution of the end of neglected tropical diseases to the sustainable development goals. *Infectious Diseases of Poverty*, *6*(1), http://dx.doi.org/10.1186/s40249-017-0288-0.

Baye, K. (2017). The Sustainable Development Goals cannot be achieved without improving maternal and child nutrition. *Journal of Public Health Policy*, *38*(1), 137–145. http://dx.doi.org/10.1057/s41271-016-0043-y.

Dawes, J. H. P. (2020). Are the Sustainable Development Goals self-consistent and mutually achievable?. *Sustainable Development*, *28*(1), 101–117. http://dx.doi.org/10.1002/sd.1975.

de Siqueira Santos, S., Takahashi, D. Y., Nakata, A., & Fujita, A. (2014). A comparative study of statistical methods used to identify dependencies between gene expression signals. *Briefings in Bioinformatics*, *15*(6), 906–918. http://dx.doi.org/10.1093/bib/bbt051.

Deebani, W., & Kachouie, N. N. (2018). Ensemble Correlation Coefficient. *International Symposium on Artificial Intelligence and Mathematics (ISAIM)*, 1–7.

Fuso Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., … Mulugetta, Y. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, *3*(1), 10–15. http://dx.doi.org/10.1038/s41560-017-0036-5.

Galton, F. (1889a). I. Co-relations and their measurement, chiefly from anthropometric data. *Proceedings of the Royal Society of London*, *45* (273–279), 135–145. http://dx.doi.org/10.1098/rspl.1888.0082.

Galton, F. (1889b). Natural inheritance. *Publications of the American Statistical Association*, *1*, 331–334.

Haraguchi, N., & Kitaoka, K. (2015). Industrialization in the 2030 Agenda for Sustainable Development. *Development*, *58*(4), 452–462. http://dx.doi.org/10.1057/s41301-016-0052-y.

Hauke, J., & Kossowski, T. (2011). Comparison of values of Pearson's and Spearman's correlation coefficients on the same sets of data. *Quaestiones Geographicae*, *30*(2), 87–93. http://dx.doi.org/10.2478/v10117-011-0021-1.

Kapur, A. (2015). Links between maternal health and NCDs. *Best Practice & Research Clinical Obstetrics & Gynaecology*, *29*(1), 32–42. http://dx.doi.org/10.1016/j.bpobgyn.2014.04.016.

Komatsu, H., Malapit, H. J. L., & Theis, S. (2018). Does women's time in domestic work and agriculture affect women's and children's dietary diversity? Evidence from Bangladesh, Nepal, Cambodia, Ghana, and Mozambique. *Food Policy*, *79*, 256–270. http://dx.doi.org/10.1016/j.foodpol.2018.07.002.

Kroll, C., Warchold, A., & Pradhan, P. (2019). Sustainable Development Goals (SDGs): Are we successful in turning trade-offs into synergies?. *Palgrave Communications*, *5*(1), http://dx.doi.org/10.1057/s41599-019-0335-5.

Lusseau, D., & Mancini, F. (2019). Income-based variation in Sustainable Development Goal interaction networks. *Nature Sustainability*, *2*(3), 242–247. http://dx.doi.org/10.1038/s41893-019-0231-4.

Mendelsohn, R., Dinar, A., Basist, A., Kurukulasuriya, P., Ihsan Ajwad, M., Kogan, F., & Williams, C. (2004). Cross-Sectional Analyses of Climate Change Impacts. *Policy Research Working Paper, World Bank, Washington, D.C., No. 3350*, https://openknowledge.worldbank.org/handle/10986/14172.

Meyer, M. (1904). The proof and measurement of association between two things. *Psychological Bulletin*, *1*(10), 363–363. http://dx.doi.org/10.1037/h0065390.

Milan, B. F. (2017). Clean water and sanitation for all: interactions with other sustainable development goals. *Sustainable Water Resources Management*, *3*(4), 479–489. http://dx.doi.org/10.1007/s40899-017-0117-4.

Nature (2020). Get the Sustainable Development Goals back on track. *Nature*, *577*(7788), 7–8. http://dx.doi.org/10.1038/d41586-019-03907-4.

Neumann, K., Anderson, C., & Denich, M. (2018). Participatory, explorative, qualitative modeling: application of the iMODELER software to assess trade-offs among the SDGs. *Economics: The Open-Access, Open-Assessment E-Journal*, http://dx.doi.org/10.5018/economics-ejournal.ja.2018-25.

Nilsson, M., Griggs, D., & Visbeck, M. (2016). Policy: Map the interactions between Sustainable Development Goals. *Nature*, *534*(7607), 320–322. http://dx.doi.org/10.1038/534320a.

Pearson, K. (1920). Notes on the history of correlation. *Biometrika*, *13*(1), 25–45.

Pham-Truffert, M., Metz, F., Fischer, M., Rueff, H., & Messerli, P. (2020). Interactions among Sustainable Development Goals: Knowledge for identifying multipliers and virtuous cycles. *Sustainable Development*, *28*(5), 1236–1250. http://dx.doi.org/10.1002/sd.2073.

Pradhan, P. (2019). Antagonists to meeting the 2030 Agenda. *Nature Sustainability*, *2*(3), 171–172. http://dx.doi.org/10.1038/s41893-019-0248-8.

Pradhan, P., Costa, L., Rybski, D., Lucht, W., & Kropp, J. P. (2017). A Systematic Study of Sustainable Development Goal (SDG) Interactions. *Earth's Future*, *5*(11), 1169–1179. http://dx.doi.org/10.1002/2017ef000632.

Pridemore, W. A. (2002). What we know about social structure and homicide: A review of the theoretical and empirical literature. *Violence and Victims*, *17*(2), 127–156. http://dx.doi.org/10.1891/vivi.17.2.127.33651.

Psacharopoulos, G., & Patrinos, H. A. (2018). Returns to investment in education: a decennial review of the global literature. *Education Economics*, *26*(5), 445–458. http://dx.doi.org/10.1080/09645292.2018.1484426.

Putra, M. P. I. F., Pradhan, P., & Kropp, J. P. (2020). A systematic analysis of Water-Energy-Food security nexus: A South Asian case study. *Science of The Total Environment*, *728*, 138451. http://dx.doi.org/10.1016/j.scitotenv.2020.138451.

Raosoft Inc. (2004) Sample size calculator. Retrieved from http://www.raosoft.com/samplesize.html

Reshef, D. N., Reshef, Y. A., Finucane, H. K., Grossman, S. R., McVean, G., Turnbaugh, P. J., … Sabeti, P. C. (2011). Detecting Novel Associations in Large Data Sets. *Science*, *334*(6062), 1518–1524. http://dx.doi.org/10.1126/science.1205438.

Ronzon, T., & Sanjuán, A. I. (2020). Friends or foes? A compatibility assessment of bioeconomy-related Sustainable Development Goals for European policy coherence. *Journal of Cleaner Production*, *254*, 119832. http://dx.doi.org/10.1016/j.jclepro.2019.119832.

Roser, M., & Ritchie, H. (2020). Homicides. *Our World in Data*. Retrieved from Https://ourworldindata.org/homicides

Sachs, J., Schmidt-Traub, G., Kroll, C., Durand-Delacre, D., & Teksoz, K. (2016). An SDG index and dashboards—Global report. Tech. Rep., Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York.

Sachs, J., Schmidt-Traub, G., Kroll, C., Lafortune, G., & Fuller, G. (2019). Sustainable development report 2019: Transformations to achieve the sustainable development goals. Tech. rep., Bertelsmann Stiftung and Sustainable Development Solutions Network (SDSN), New York.

Scherer, L., Behrens, P., de Koning, A., Heijungs, R., Sprecher, B., & Tukker, A. (2018). Trade-offs between social and environmental Sustainable Development Goals. *Environmental Science & Policy*, *90*, 65–72. http://dx.doi.org/10.1016/j.envsci.2018.10.002.

Sen, A. (1983). Development: Which Way Now?. *The Economic Journal*, *93* (372), 745. http://dx.doi.org/10.2307/2232744.

Smarandache, F. (2016). Alternatives to Pearson's and Spearman's correlation coefficients. *SSRN Electronic Journal*, 1–9. http://dx.doi.org/10.2139/ssrn.2725499.

Speed, T. (2011). A Correlation for the 21st Century. *Science*, *334*(6062), 1502–1503. http://dx.doi.org/10.1126/science.1215894.

Tangcharoensathien, V., Mills, A., & Palu, T. (2015). Accelerating health equity: the key role of universal health coverage in the Sustainable Development Goals. *BMC Medicine*, *13*(1), http://dx.doi.org/10.1186/s12916-015-0342-3.

Tremblay, D., Fortier, F., Boucher, J.-F., Riffon, O., & Villeneuve, C. (2020). Sustainable development goal interactions: An analysis based on the five pillars of the 2030 agenda. *Sustainable Development*, 1–13. http://dx.doi.org/10.1002/sd.2107.

UN. (2018). United Nations regional groups of member states. Retrieved from http://www.un.org/depts/DGACM/RegionalGroups.shtml

UN General Assembly. (2015). Resolution adopted by the General Assembly on 25 September 2015: 70/1. Transforming our world: The 2030 Agenda for Sustainable Development.

UN Statistics Division. (2019). SDG indicators. United Nations Global SDG Database. Retrieved from https://unstats.un.org/sdgs/indicators/database/

UN-Water (2016). *Water and Sanitation Interlinkages across the 2030 Agenda for Sustainable Development* (pp. 1–48). Geneva: UN Water.

Velis, M., Conti, K. I., & Biermann, F. (2017). Groundwater and human development: synergies and trade-offs within the context of the sustainable development goals. *Sustainability Science*, *12*(6), 1007–1017. http://dx.doi.org/10.1007/s11625-017-0490-9.

Wang, Y., Li, Y., Liu, X., Pu, W., Wang, X., Wang, J., … Jin, L. (2017). Bagging Nearest-Neighbor Prediction independence Test: an efficient method for nonlinear dependence of two continuous variables. *Scientific Reports*, *7*(1), 1–12. http://dx.doi.org/10.1038/s41598-017-12783-9.

Weitz, N., Carlsen, H., Nilsson, M., & Skånberg, K. (2018). Towards systemic and contextual priority setting for implementing the 2030 Agenda. *Sustainability Science*, *13*(2), 531–548. http://dx.doi.org/10.1007/s11625-017-0470-0.

World Bank Group. (2018). Data: World Bank Country and Lending Groups.

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

How to cite this article: Warchold A, Pradhan P, Kropp JP. Variations in sustainable development goal interactions: Population, regional, and income disaggregation. *Sustainable Development*. 2021;29:285–299. https://doi.org/10.1002/sd.2145