Received: 22 January 2020 | Revised: 17 April 2020 | Accepted: 1 May 2020
DOI: 10.1002/sd.2073

RESEARCH ARTICLE

Sustainable Development WILEY

Interactions among Sustainable Development Goals: Knowledge for identifying multipliers and virtuous cycles

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Funding information
This research was supported by the Swiss Agency for Development and Cooperation (SDC) in the context of its support for the mandate of the Global Sustainable Development Report (GSDR) 2019

Abstract

Developed to be interconnected by design, the 17 sustainable development goals (SDGs) and their 169 targets have attracted a growing scientific community committed to exploring the systemic interactions inherent to the 2030 Agenda. Understanding which SDGs influence one another (positively or negatively) is critical to prioritize and implement policies that maximize synergies between goals while navigating trade-offs. In this way, the need for informed decision-making urgently requires knowledge of context-specific SDG interactions. Drawing on an extensive literature review (including scientific reports and scholarly articles), we collected, synthesized, and analyzed data about negative and positive interactions among SDG goals and targets. Based on this unique dataset, our analysis focused on three key elements of the resulting network of SDG interactions: First, we identified the most dominant SDGs in the network. Second, we identified systemic multipliers, defined as nodes with higher weighted amounts of outgoing than incoming influence. Third, we identified critical sub-networks of strongly interconnected SDG targets, highlighting possible virtuous cycles that could serve as concrete entry points to realize the 2030 Agenda. Building on our results, a collaborative effort to add and refine data on behalf of an open-knowledge platform could provide a solid basis for further analysis and enhanced usability in concrete contexts.

KEYWORDS

2030 Agenda, network analysis, policy coherence, science–policy interface, SDG interlinkages, social-–ecological system

1 | INTRODUCTION

SDG interactions refer to *interdependencies* between the sustainable development goals (SDGs) belonging to the 2030 Agenda for sustainable development (United Nations, 2015), whereby action toward one goal (i.e., SDG or target) impacts the performance of one or more others.

Since the early stage of their conceptualization (Griggs et al., 2013, 2014; Le Blanc, 2015), the SDGs were designed to be interconnected and indivisible, reflecting the necessarily linked challenges facing humanity: to alleviate poverty and ensure human prosperity while protecting the planet and its resources, thus balancing the three (social, economic, and environmental) dimensions of sustainable development. This integrated approach inevitably points to the need to address potential trade-offs between different goals of development.

For the international community to navigate inherent SDG trade-offs effectively and maximize synergies beneficially, it must make intentional use of the interactions between different—and potentially conflicting—goals and targets. The present study documents today's body of expert knowledge on SDG interactions by means of a systematic analysis of the current literature. Based on these data, we ask: What are central SDGs and what are important interactions between them? And which of these interactions are highly networked, given their effects on numerous SDGs? With respect to the second question, our analysis suggests certain SDGs and SDG interactions are crucial, as they can critically influence full realization of the 2030 Agenda. Drawing attention to potential risks, we reveal the positive systemic loops that dominate in the scientific literature and highlight the need to transform vicious cycles into virtuous cycles. The present article relates to and builds on the existing literature on SDG interactions in three ways.

First, many recent publications have stressed the need for sectoral integration (Biermann, Kanie, & Kim, 2017; Griggs et al., 2014; Le Blanc, 2015; Scharlemann et al., 2020; Stafford-Smith et al., 2016), for working with nexus approaches (Avellán et al., 2017; Liu et al., 2018) and considering the SDGs as interacting elements rather than a mere sum of goals, targets, and indicators (Pradhan, 2019). Additionally, authors increasingly apply concepts from formal network analysis, for example, to highlight the imperfect interconnectedness among the goals (McGowan, Stewart, Long, & Grainger, 2019) or to assess the variation of SDG interactions depending on countries' socio-economic status (Lusseau & Mancini, 2019; Pradhan, 2019). Our analysis is aligned with recent studies aiming at understanding how to best prioritize policies that realize the SDGs by exploiting positive direct and indirect effects of specifically targeted measures (Dawes, 2020; Weitz, Carlsen, Nilsson, & Skånberg, 2018). By adapting some concepts of Messerli (2000) to formal network analysis of directional interactions, we propose a methodology for identifying interconnected systemic *buffers* or *multipliers*. We further suggest alternative pathways that would maximize the leveraging potential of the 2030 Agenda, in particular by emphasizing highly connected subnetworks that could function as virtuous cycles.

Second, among existing studies on networks of SDGs, the approaches to *pre*-analysis data collection vary—in particular, two distinct departure points may be identified. In the first approach, researchers use national-level time series of SDG indicators to statistically infer positive or negative correlations between measured advances toward particular SDGs (Kroll, Warchold, & Pradhan, 2019; Lusseau & Mancini, 2019; Pradhan, Costa, Rybski, Lucht, & Kropp, 2017; Zhou & Moinuddin, 2017). The advantage of using data gathered by national statistical offices lies in that it effectively enables a disaggregation at country-level, or by socio-economic status, and potentially allows for analysis of complex, dynamic networks. However, the approach is often completed by more qualitative analyses due to the challenges and risks of inferring causal relationships between SDGs based solely on correlations between performance measures for certain indicators (Zhou & Moinuddin, 2017). In the second approach, researchers assess causal and directional interactions among SDG targets based on the judgment of experts (Allen, Metternicht, & Wiedmann, 2019; Ehrensperger, de Bremond, Providoli, & Messerli, 2019; Grace et al., 2019; McGowan et al., 2019; Weitz et al., 2018). Usually, these analysts follow the recommendations of the International Science Council to use a seven-point scale scoring system (ICSU, 2017; Nilsson, Griggs, & Visbeck, 2016), ideally reinforced with empirical evidence and explicit references to relevant literature (IPCC, 2018; Maes, Jones, Toledano, & Milligan, 2019; McCollum et al., 2018). While also employing the "ICSU score," our analysis draws on a much larger evidence base than other studies—that is, on a comprehensive sample of publications on SDG interactions as reported in relevant reports and the academic literature. Results thus represent an unprecedented effort to start synthetizing and unveiling the abundant but fragmented body of knowledge on SDG interactions.

Third, complementing previous network studies on SDGs, our approach is further distinct in that it assesses positive and negative interactions for each pair of SDG targets separately. Looking at prior analyses, we observed that assigning a mean weight to interactions—by combining positive and negative assessments—has a tendency to "dilute" understanding of the potential trade-offs. In our analysis, we chose to address positive and negative interactions separately, referring to them as "co-benefits" and "trade-offs," respectively.

Our chosen study approach aims at responding to calls for translation of factual knowledge on global phenomena into actionable implications in terms of policy, building on the normative framework provided by the SDGs. As Le Blanc (2015) states, policymaking on behalf of the 2030 Agenda must be "based on studies of the biophysical, social, and economic systems at appropriate scales".

In order to design evidence-based policy recommendations for sustainable development, we distinguish between three levels of referring to "SDG interactions": (a) interactions occurring at the policy-level pointing to conflicting worldviews and priorities; (b) interactions occurring at the level of the allocation of resources for SDG-specific actions; and (c) systemic interactions between social–ecological systems that have unintended consequences for other SDGs. If the pursuit of one SDG impacts one part of the earth system, direct and indirect interactions with other subsystems may alter the available space for achievement of other SDGs (Avellán et al., 2017; Bouma, 2014; Cowie et al., 2011; Gain, Giupponi, & Benson, 2015). For example, if agricultural production is intensified with chemical fertilizers, the additional yields can provide co-benefits in terms of local food security as well as increased trade activities. At the same time, however, excessive use of fertilizer may degrade water quality downstream and cause significant health harms within a distant community. Under business-as-usual scenarios, policymakers tend to prioritize achieving their separately considered goals, making interventions at resource level that bring about unintended effects in the social–ecological world. By contrast, pursuing policy coherence to implement the SDGs implies an inverted approach: first, seeking to understand dynamics and interactions in social–ecological systems; only then, considering their normative implications in terms of SDG governance, that is, how to allocate various capacities and financial resources. By "SDG interactions," we refer in this study to systemic level interactions (cf. Figure 1).

The remainder of this article is structured as follows. The next section on methodology explains our selection criteria for sources of information as well as our coding rules and procedure. This section also details our methods for analysis of the dominance of particular goals and interactions, for identification of the systemic role of goals, and for assessment of systemic reinforcing loops across the entire SDG network. The subsequent section on results and analysis presents an overview of the SDG interactions as well as more detailed individual findings. Finally, our concluding section summarizes the main findings, critically reflects on our approach, and suggests important avenues for further research.

2 | METHODOLOGY

2.1 | Data gathering

We undertook a systematic literature review emphasizing identification and summary of negative and positive influences of individual goals on other goals—at the target level, wherever possible, and otherwise at the SDG level. All told, we assembled and assessed a comprehensive corpus including 65 UN flagship reports and international scientific assessments as well as 112 scientific articles. Taken together, this "body of knowledge" enabled us to make evidence-based judgments of SDG interactions, which were codified, scored, and entered into a centralized database (Pham-Truffert, Rueff, & Messerli, 2019).

2.1.1 | Choice of literature

Within the corpus reviewed, the chosen global assessment reports mainly comprise major global scientific assessments (e.g., IPCC, IPBES) and a selection of flagship reports from the UN system, reflecting a variety of fields of expertise (e.g., UNCTAD, UNESCO). In addition, we extracted peer-reviewed articles based on a query search on ISI Web of Science and Scopus' databases. In order to obtain a manageable set of relevant articles, we decided to limit the selection to the papers matching the keywords "SDG" and "interaction," or very close synonyms (cf. *1. Query search* in the Appendices). In early 2018, the total number of items we exported in this manner from Web of Science and Scopus is 366. After merging the duplicates, we had still 231 publications left, and after erasing the documents comprised in the selection but with "SDG" being an acronym for something else than "Sustainable Development Goal," 176 publications were left for us to review. Out of this amount of articles we reviewed, a total of 112 actually contained SDG interactions.

While we strove for a broad selection of representative articles and reports to ensure our results reflect the current knowledge of SDG interactions among global experts, a smaller handful reports turned out to be a particularly important source of information about SDG interactions. These assessments referred explicitly to target-level

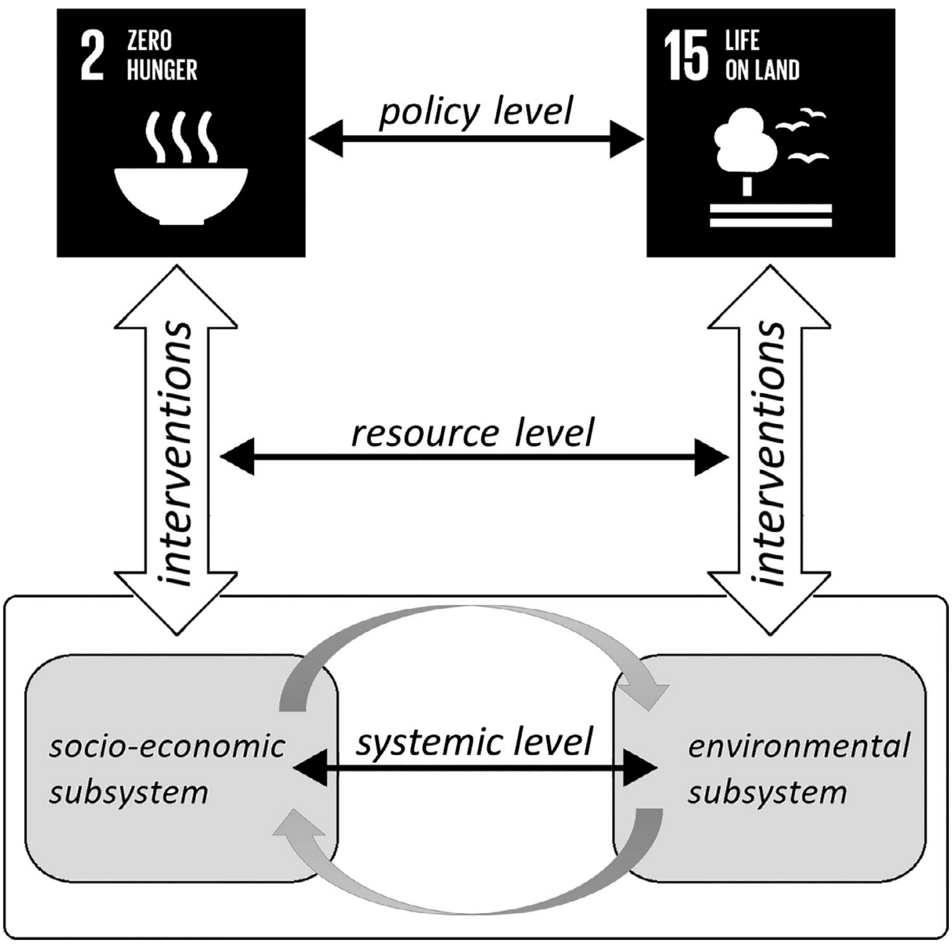

FIGURE 1 Three differentiated levels we commonly refer to by "SDG interactions": policy level, resource level, and systemic level. We focus in this study on systemic level SDG interactions

interactions, which were preliminary agreed on by experts. As a result, half of the weighted interactions we identified and were derived solely from five specific sources, namely:

- 18% from chapter 5 of *Global Warming of 1.5°C* (IPCC, 2018)
- 13% from *A Guide to SDG Interactions* (ICSU, 2017)
- 10% from *Water and Sanitation Interlinkages Across the 2030 Agenda for Sustainable Development* (UN-Water, 2016)
- 5% from *the Summary for Policymakers of the Global Assessment Report on Biodiversity and Ecosystem Services* (IPBES, 2019)
- 4% from *Connecting the Sustainable Development Goals by Their Energy Inter-Linkages* (McCollum et al., 2018)

The content we synthesized is thus especially representative of the thematic focuses of these assessments and also reflects the authors' common emphasis on "entry goal" focuses such as food (SDG 2), health (SDG 3), energy (SDG 7), and oceans (SDG 14) in ICSU (2017). Similarly, McCollum et al. (2018)—which was an important reference in the IPCC's assessment of interactions—opted to emphasize energy (SDG 7) as its entry goal. Moreover, UN-Water (2016) clearly stresses the water-related goals/targets (SDG 6). This suggests that even more comprehensive global knowledge synthesis is needed that emphasizes interactions related to other major goals—in particular poverty (SDG 1), education (SDG 4), gender equality (SDG 5), economic growth (SDG 8), innovation and infrastructure (SDG 9), inequality (SDG 10), cities (SDG 11), sustainable consumption and production (12), land and ecosystems (SDG 15), and peace and strong institutions (SDG 16)—in order to ensure more far-reaching expert agreement on all the key interactions among the full range of goals.

2.1.2 | Data coding

Building on the protocol in Nilsson et al. (2018), we codesigned and tested coding guidelines using the seven-point scale scoring framework (cf. Table 1).

Specifically, we assessed interactions at the target level whenever possible, and at more generic SDG level otherwise, considering all the 126 SDG targets that were not *Means of implementation (MoI)*—thus ignoring the "lettered" targets in the 2030 Agenda. A total of eight coders read the articles and reports and systematically filled in an MS Excel template with supporting insights on directional interactions (e.g., from target A to target B), corresponding scoring assessment, and other key information (e.g., source of reference, geographical locations, further material), following this coding procedure:

- A target level should always be preferred over a goal level entry as much as possible.
- When an interaction is mentioned in the executive summary, key messages sections, abstract, introduction, or conclusion, it should be considered.
- When an interaction is not mentioned in the above but appears in the text with concrete evidence, it should be considered.

TABLE 1 Scoring assessment of the interactions. Adapted from Nilsson et al. (2016) and ICSU (2017)

Scoring assessment	Meaning
+3: Indivisible	Inextricably linked to the achievement of another goal.
+2: Reinforcing	Aids the achievement of another goal.
+1: Enabling	Creates conditions that further another goal.
0: Consistent	No significant positive or negative interactions.
−1: Constraining	Limits options on another goal.
−2: Counteracting	Clashes with another goal.
−3: Canceling	Makes it impossible to reach another goal.

- The main text can be read "in diagonal" but looking for facts and figures (the more fact and figures that can explain interactions, the better).
- Striking facts and figures that are usable for transformations may also be entered (even if not linked to a proper interaction pair).
- If an interaction appears to have a positive and a negative effect, insert a row for each.
- Add as many rows as needed to fit all interaction directions per chapter.

For instance, we found the statement "In Tanzania the majority of the urban population […] live in slums and are, in many cases, dependent on precarious employment in the informal sector. […] Their consumption opportunities are severely constrained by low and uncertain incomes, putting their food security at risk." (Wenban-Smith, Faße, & Grote, 2016, p. 973) justified the entries of three reinforcing interactions (+2) from adequate housing and development of slums (11.1), decent work (8.5), and safe working environments (8.8), to food security (2.1).

2.1.3 | Data cleaning

A review and correction process was established by two researchers in our study team. While allowing for flexibility, coding consistency was systematically checked by going through the database row by row, with disagreements flagged to highlight potential need for revision. Striking inconsistencies between the insight and the coding decision were identified, and assigned one of following tags: (a) "SDG/target choice"; (b) "Directionality"; (c) "Other"; (d) "To delete completely." We then resolved internally all the tagged issues one by one. The resulting dataset handles positive and negative values/interactions separately. It contains 2,741 entries for positive interactions, of which 2,094 are specific to the target level; and another 543 entries for negative interactions, of which 458 are specific to the target level (see Table 2). Finally, 64 entries refer to neutral interactions (47 at target level). The latter were not further analyzed after formatting the data.

2.1.4 | Data formatting

We formatted the data to enable analysis both at the general SDG level and at the more precise target level. At the target level, we only considered data for which targets were specified. At the SDG level, we aggregated all the coded data independent of their level of precision, for example, an interaction between target 2.3 and target 1.2 would simply be coded as an interaction between SDG 2 and SDG 1. Finally, to characterize the interactions both in terms of strength of positive and negative relationships and frequency of mentions, we summed up the scores that were assigned in absolute numbers (1, 2, or 3). For instance, if an interaction between goal A and goal B was identified five times and assigned the values "−2," "−1," "+1," "+1," and "+3" across our dataset, we would first sum up the three positive interactions (+1, +1, +3) and assign a weight of five to the overall positive interactions between goal A and goal B. Second, the two negative interactions (−2, −1) would be assigned an overall weight of three. Figure 2 illustrates a sub-network of our formatted data.

2.2 | Data analysis

The analytical approach of this study moves from a generic focus—considering the full network of all interactions aggregated at the SDG level—toward a more precise target-level focus. In so doing, it draws on network analytic concepts and methods (Borgatti, Mehra, Brass, & Labianca, 2009; Steketee, Miyaoka, & Spiegelman, 2015; Wasserman & Faust, 1994). In the following, we define the network and the three measures used for analysis.

2.2.1 | Definition of network nodes and edges

In network terms, the data analyzed in this study consist of *ties* (interactions) among *nodes* (targets or SDGs) that are *signed* (positive or negative interactions), *directed* (from node A to node B; from B to A; or both), and *weighted* (interactions are not only present or absent, but also of different intensities).

Depending on the category of interaction, we observe significantly different network *density* and levels of precision. At the more precise target-level, important blind spots are revealed—that is, there are many potential interactions among targets that are either not existing in reality, or that the expert community is not reporting about. By contrast, at the aggregate SDG level, we observe a very dense network with strong interconnections between the 17 SDGs. In addition, we allow for and consider *self-loops* at the SDG level in cases where target-level interactions occur within the same SDG. For instance, an interaction between target 7.2 and target 7.1 would be deemed a self-loop for SDG 7.

TABLE 2 We identified four possible types of causal interactions

Interactions	Positive	Negative
Only interactions for which targets were specified	2,094 entries	458 entries
All the interactions aggregated at the SDG level	2,741 entries	543 entries

Note: By SDG-level interactions, we mean all target-level interactions, scaled up and considered at the SDG level; and all general interactions found in the literature for which no targets were specified to begin with.

2.2.2 | Centrality of goals

The first analytical part of this study consists of graphically representing the network of goals as a 17 × 17 cross-impact matrix (Dawes, 2020; Scharlemann et al., 2020; Weitz et al., 2018). The intersections of pairs of goals are shown as pie charts. The size of each pie chart indicates the overall weight of the interaction from A to B (sum of positive and negative weights) as well as its positive (blue) and negative (red) share.

In this matrix of directed interactions, the rows represent the influence exerted by each of the 17 SDGs, and, by contrast, the columns represent the influence received by each of the 17 SDGs. Hence, the totals per row represent the *weighted outdegree* (i.e., sum of weights of all the ties outgoing from a given SDG toward all the other SDGs); whereas the totals per column represent the *weighted indegree* (i.e., sum of weights of all the ties incoming to a given SDG from all the other SDGs). Finally, the *weighted degree* is the sum of both.

The degree centrality of a node is a straightforward measure used in SNA and defined as the number of ties belonging to a given node (Freeman, 1978). In a weighted network, the measure can also account for the weight of the ties (Opsahl, Agneessens, & Skvoretz, 2010). Hence, we define the node centrality as:

$$C_D^{W\alpha}(i),$$

where i is the node, D is its *degree* (number of ties linked to a node), and W is the weight of the ties. In our work, the weight represents the amount of knowledge supporting a given interaction. If $\alpha = 0$, we consider that the measure calculates the *degree centrality*, independently of the weights of the ties; however, if $\alpha = 1$, we obtain a *weighted degree centrality*. In this study, we apply an $\alpha = 1$, in order to account for the number of times an interaction was reported, as well as how strong the interaction is, according to the ICSU score.

2.2.3 | Systemic role of the goals

We rely on the weighted degree centrality measure described above in order to identify systemic buffers or multipliers with many / few supporting insights. In so doing, we adapted concepts from Messerli (2000) to formal network analysis and established a typology of SDGs or SDG targets that act as systemic buffers and multipliers (cf. Figure 3).

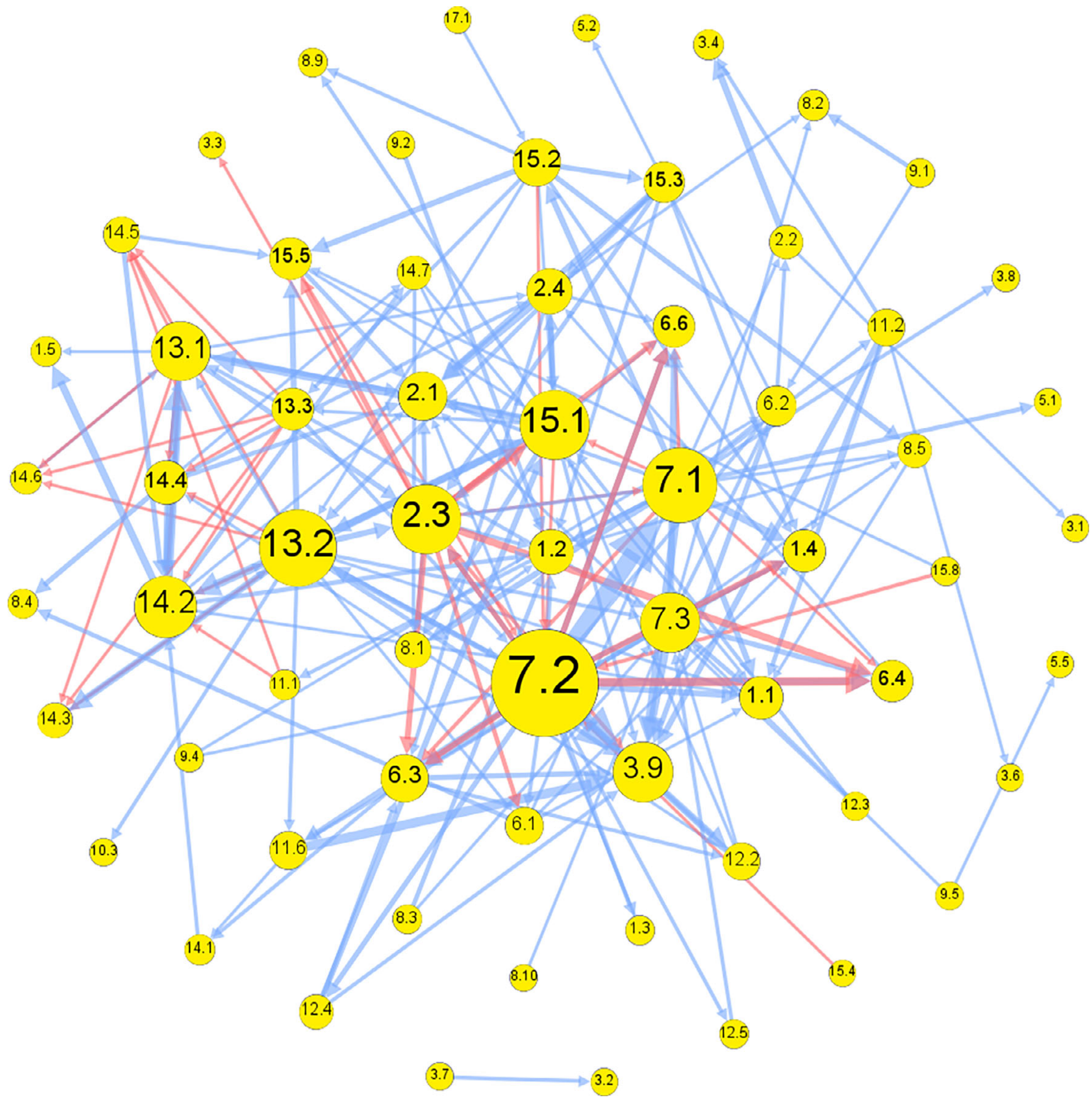

FIGURE 2 Sub-network of all positive (blue) and negative (red) target-level interactions weighted five or more. The thickness of the arrows represents the weight of the interactions [Colour figure can be viewed at wileyonlinelibrary.com]

In this way, we can identify individual SDGs as systemic "buffers" and/or "multipliers" of co-benefits (positive interactions) and trade-offs (negative interactions). This enables us to distinguish the different systemic roles of the SDGs and to classify them into four categories (cf. Table 3).

Notably, our results show interactions as central whenever the corresponding SDGs have been covered prominently in the literature. In this way, some SDGs have a higher "popularity" than others in our data, and these popular goals automatically have higher chances of exhibiting interactions with many other goals. To check whether the overall systemic roles of the SDGs differ when these "popularity effects" are eliminated, we reproduced the analysis with normalized network data in the Appendices (cf. *2. Analysis after normalization*). To this end, we down-weight the ties in the network through a normalization process. Using the *average activity normalization* proposed in Leifeld, Gruber, and Bossner (2018), we divide the interactions' weights by the mean of the popularity of the two connected nodes (i.e., SDGs) in question. The popularity of an SDG would equal the number of coded entries of interactions extending from that given SDG.

Finally, we go into more detail for two critical multipliers of trade-offs, at the target level. We analyze these critical multipliers by means of their *ego networks* defined as networks that comprise a focal "ego" node and the nodes that are directly connected to it, as well as all the ties that connect this subset of nodes (Borgatti et al., 2009).

2.2.4 | Systemic loops

The final part of our analysis deals with important target-level interactions in terms of weights and positive systemic loops that connect sub-groups of three targets. We apply a more restrictive threshold

FIGURE 3 Typology of buffers and multipliers adapted from Messerli (2000): The *x*-axis differentiates between buffers (more weight from incoming than from outgoing ties) and multipliers (more weight from the outgoing than from incoming ties). The *y*-axis differentiates the total weight of all ties of a node from low to high

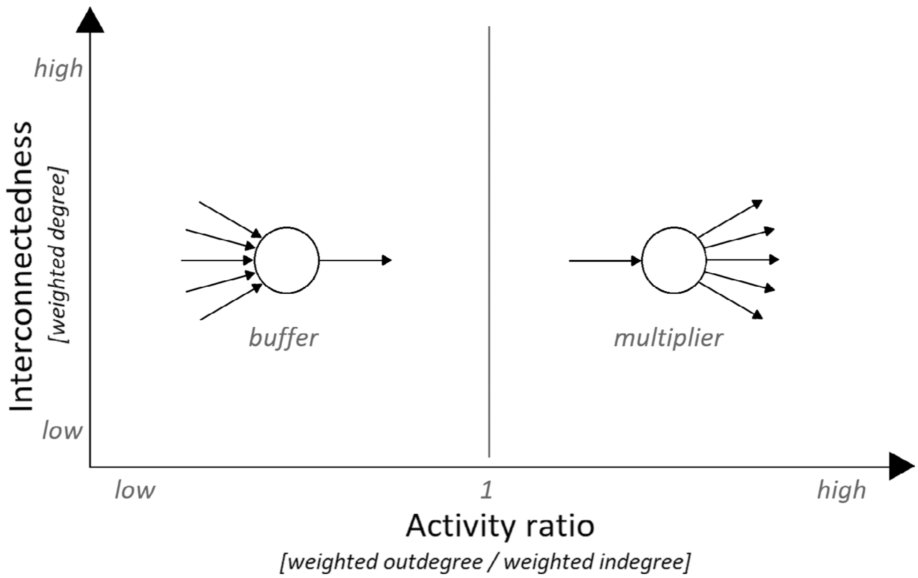

TABLE 3 Twofold systemic roles of the SDGs in terms of both co-benefits and trade-offs, revealing four categories of buffers and multipliers

Description	Simplified description
Buffers of both co-benefits and trade-offs	Buffers
Buffers of co-benefits but multipliers of trade-offs	Multipliers of trade-offs
Multipliers of both co-benefits and trade-offs	Critical multipliers
Multipliers of co-benefits and buffers of trade-offs	Multipliers of co-benefits

and consider only the interactions with a weight of five or higher. We focus on the network of targets only, in order to generate precise insights about critical synergies.

3 | RESULTS AND ANALYSIS

3.1 | Body of knowledge on SDG interactions

The matrix in Figure 4 offers an overview of data on SDG interactions, which we collected at systemic level based on our literature review. It thus shows which SDGs are interacting according to our current body of available knowledge, and—importantly—where crucial knowledge gaps remain.

Our results confirm the view of other studies that co-benefits outweigh trade-offs in terms of interaction types (Dawes, 2020; Pradhan et al., 2017; Weitz et al., 2018). Nevertheless, some interactions have significant negative-impact shares (in red). For instance, there appear to be important trade-offs between pursuit of climate (SDG 13) and ocean (SDG 14) goals, based, for example, on risks of coastal squeeze when trying to protect coasts from sea-level rise (ICSU, 2017). Further, many interactions relate to the so-called water-energy-food (WEF) nexus, a topic that was cited repeatedly in the literature. Indeed, we see that the share of negative interactions (in red) is larger between specific goals. In particular, we see that pursuit of food (SDG 2) and energy (SDG 7) goals can cause significant trade-offs with other SDGs, especially water (SDG 6) and ecosystems (SDG 15). Overall, we found that energy (29%) and food (21%) generated half of the assessed trade-offs. This relates, for instance, to competition over use of cultivable land surfaces (e.g., for biofuels or food production) as well as to land-based degradation and ecosystem pollution. Conversely, the most negatively impacted goals were those related to natural resources, with 20% of the assessed trade-offs impacting water (SDG 6), 16% impacting oceans (SDG 14), and 12% impacting terrestrial ecosystems (SDG 15).

Based on the weights of the ties, we identified the most important interactions in the network of SDGs. As seen in Figure 4, the larger the respective point at the intersection of two SDGs, the more important the respective interaction is in terms of its weight (based on the amount of available knowledge for the interaction, as well as the reported strength of the interaction based on the ICSU score). According to these criteria, the most important interactions are those between energy (SDG 7) and various other goals, including water (SDG 6), poverty (SDG 1), health (SDG 3), growth (SDG 8), and food (SDG 2). Moreover, other (A to B) interactions that rank high are between climate (SDG 13) and oceans (SDG 14), food (SDG 2) and water (SDG 6), and food (SDG 2) and health (SDG 3). Certain high-ranking interactions occur in both directions (from A to B and from B to A), such as interactions between sustainable consumption and production (SDG 12) and water (SDG 6) and interactions between land and ecosystems (SDG 15) and food (SDG 2). However, while the bidirectional interactions between sustainable consumption and production and water appear very synergistic (mostly positive interactions), the bidirectional interactions between land and food are more nuanced and asymmetrical: While land and its ecosystem services clearly sustain food systems

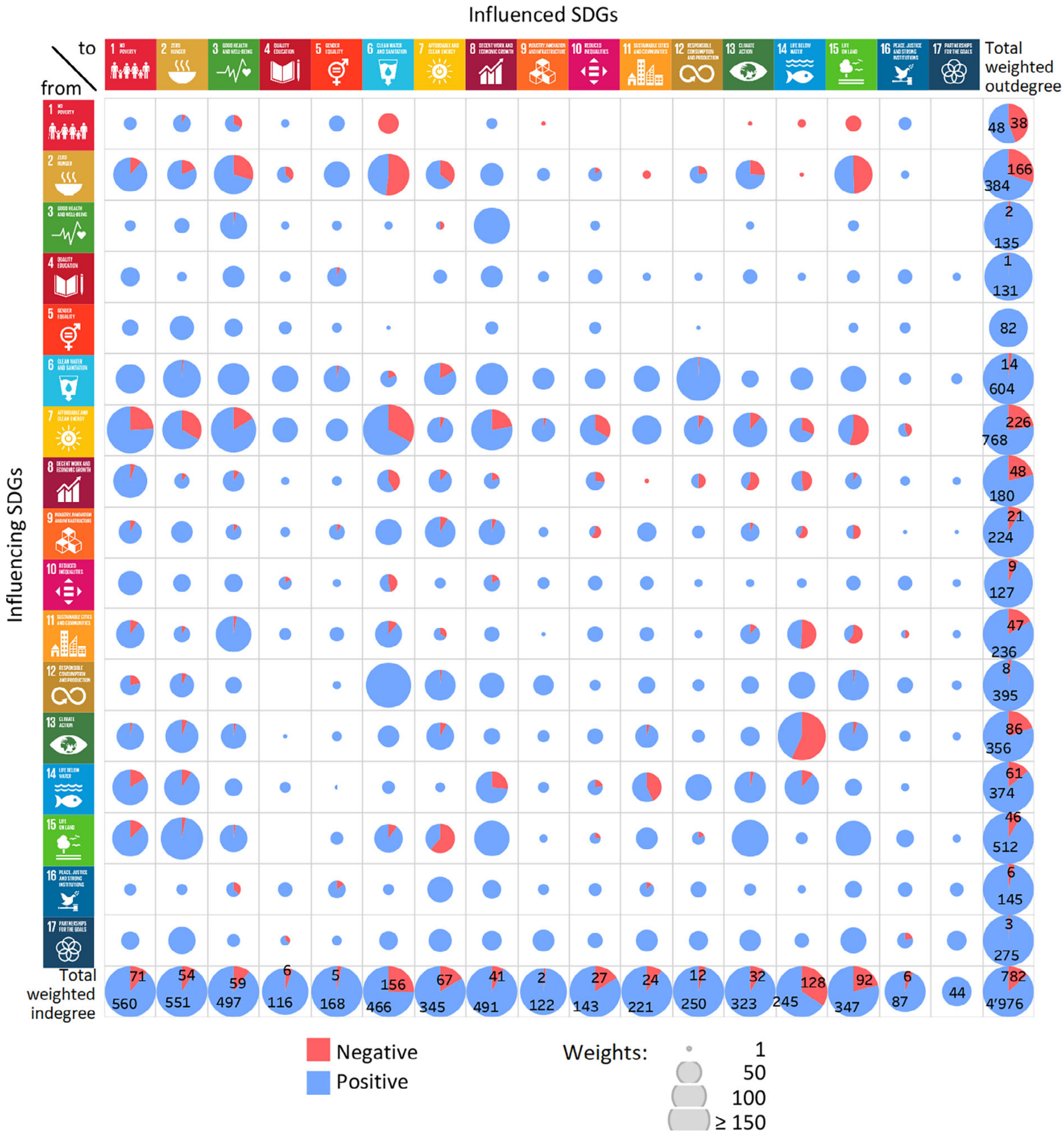

FIGURE 4 Matrix of systematically coded interactions displayed at the SDG level adapted from Pham-Truffert et al. (2019). The size of each intersection point represents the weight of the interaction or the amount of knowledge supporting the interaction [Colour figure can be viewed at wileyonlinelibrary.com]

(mostly positive interactions), food production often generates important land-related trade-offs (both positive and negative interactions).

3.2 | Systemic multipliers among the SDGs

3.2.1 | Identification of buffers and multipliers

Our results also enable classification of the SDGs from a systemic perspective that permits to draw insights in terms of SDG governance. Indeed, individual SDGs can be understood as buffers and/or multipliers of both co-benefits (positive interactions) and trade-offs (negative interactions) across the entire system. In Figure 5, the weighted degree centrality on the *y*-axis represents the “interconnectedness” of the nodes. The activity ratio on the *x*-axis represents the relationship between weighted indegree and outdegree centralities. The results indicate whether a node is predominantly *influenced* (buffer) or *influencing* (multiplier) within the system.

Our findings show that both trade-off interactions and co-benefit interactions span the whole range of roles from buffers to multipliers.

However, co-benefits generally demonstrate higher interconnectedness. As seen in Figure 5, each SDG has two potential roles (thus appearing twice in the graph)—one in terms of *trade-off* interactions (buffer or multiplier) and another in terms of *co-benefit* interactions (again, buffer or a multiplier). Their dual roles must be considered together because they have different governance implications. Only two elements—trade-offs linked to SDGs 5 and 17—do not appear in the systems view, while another—trade-offs linked to SDG 16—is situated in an ambiguous location. Indeed, the goal of gender equality (SDG 5) does not appear to generate any trade-offs—it does not exhibit any negative activity ratio. Similarly, pursuit of partnership (SDG 17) does not appear linked to trade-offs.

Goals on poverty (SDG 1), health (SDG 3), gender (SDG 5), and inequality (SDG 10) represent systemic buffers of both co-benefits and trade-offs. They are systemically more influenced than influencing, for better or worse. The results of our network analysis suggest that poverty is more often associated with co-beneficial interactions than with trade-offs. Inequality, on the other hand, tends to be negatively impacted. Health, while highly positively interconnected, also bears risks of suffering negative impacts. We could argue that these goals—SDGs 1, 3, 5, and 10—closely relate to the overarching 2030 Agenda aim of *leaving no one behind*. In that respect, they can serve as key indicators of sustainable or unsustainable development trajectories. For instance, a worsened state of public health caused by systemic dynamics related to other goals would indicate an unsustainable trajectory.

Goals that act as buffers of co-benefits but multipliers of trade-offs include those on economic growth (SDG 8) and food (SDG 2), although we saw that SDG 2 targets have differentiated roles. While tending to serve as buffers of co-benefits, they often entail tricky objectives that can cause trade-offs in other development areas. For instance, while food supply is crucial to people's livelihood, today's food systems include agricultural practices that damage soils and other resources in terms of quantity, diversity, and quality. Similarly, growth entails job opportunities; business-as-usual growth can harm other SDGs, with the traditional GDP growth measure being called into question.

Multipliers of both co-benefits and trade-offs, such as goals on energy (SDG 7), infrastructure (SDG 9), cities (SDG 11), and climate (SDG 13) can magnify impacts for better or for worst. While energy is highly interconnected and topical, associated risks of innovation, new infrastructure, and industrialization require more documentation. Our database (Pham-Truffert et al., 2019) suggests areas where caution is needed, such as industrial automation that could cause job losses (UNCTAD, 2018) or digitalization that can contribute to new addictions and mental health issues (Global Happiness Council, 2018).

Multipliers of co-benefits and buffers of trade-offs include education (SDG 4), water (SDG 6), sustainable consumption and production (SDG 12), oceans (SDG 14), ecosystems (SDG 15), peace (SDG 16), and partnerships (SDG 17). They are systemic multipliers of synergies, but are often impacted negatively by other SDGs. Indeed, results showed that these forms of natural and human capital enable co-benefits across the 2030 Agenda, while entailing relatively small risks of trade-offs.

Reproducing our systemic analysis of the SDGs after normalizing the positive and negative network data, we observed two changes (cf. *2. Analysis after normalization* in Appendices). First, SDGs 1, 3, and 8 on poverty, health, and economic growth appear more positively interconnected to the network when we eliminate the popularity effects of prominent coverage, but poverty eradication can cause significant trade-off interactions. Second, the possible systemic role of two other SDGs emerges: SDG 10 on inequality and SDG 4 on

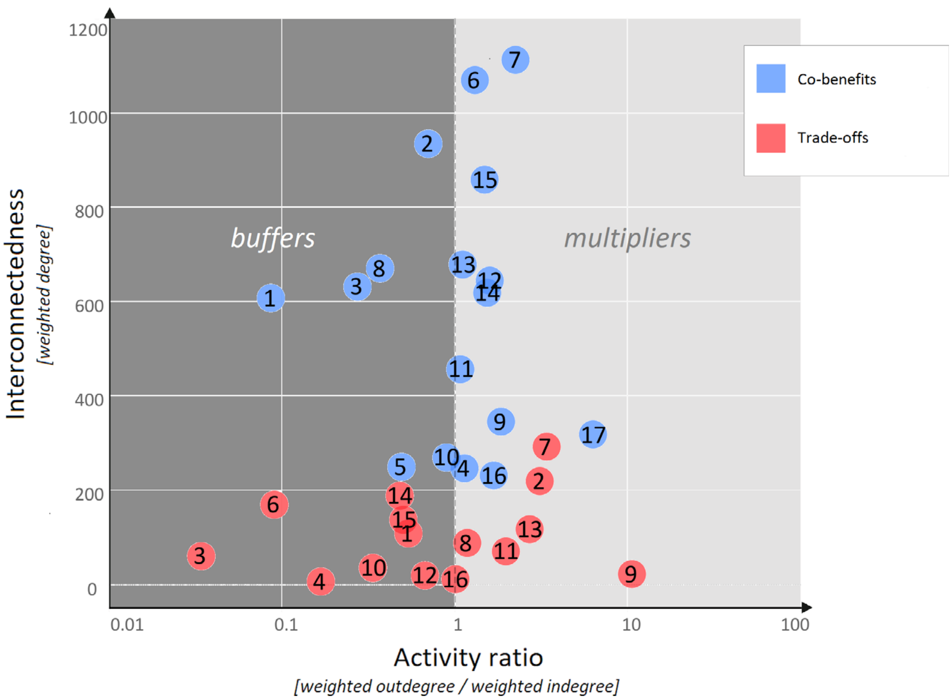

FIGURE 5 Results for SDGs acting as both systemic buffers (nodes on left side with darker background) and multipliers (nodes on right side with lighter background). The red nodes represent the trade-off interactions of each SDG; the blue nodes highlight the co-benefit interactions of each SDG [Colour figure can be viewed at wileyonlinelibrary.com]

education appear to be potential critical multipliers and SDG 16 on peace and strong institutions appears more critical as well. Nevertheless, these results are speculative, and we have opted to emphasize mainly the results of the data without normalization, as they demonstrate existing knowledge and gaps—including topics possibly neglected in the literature.

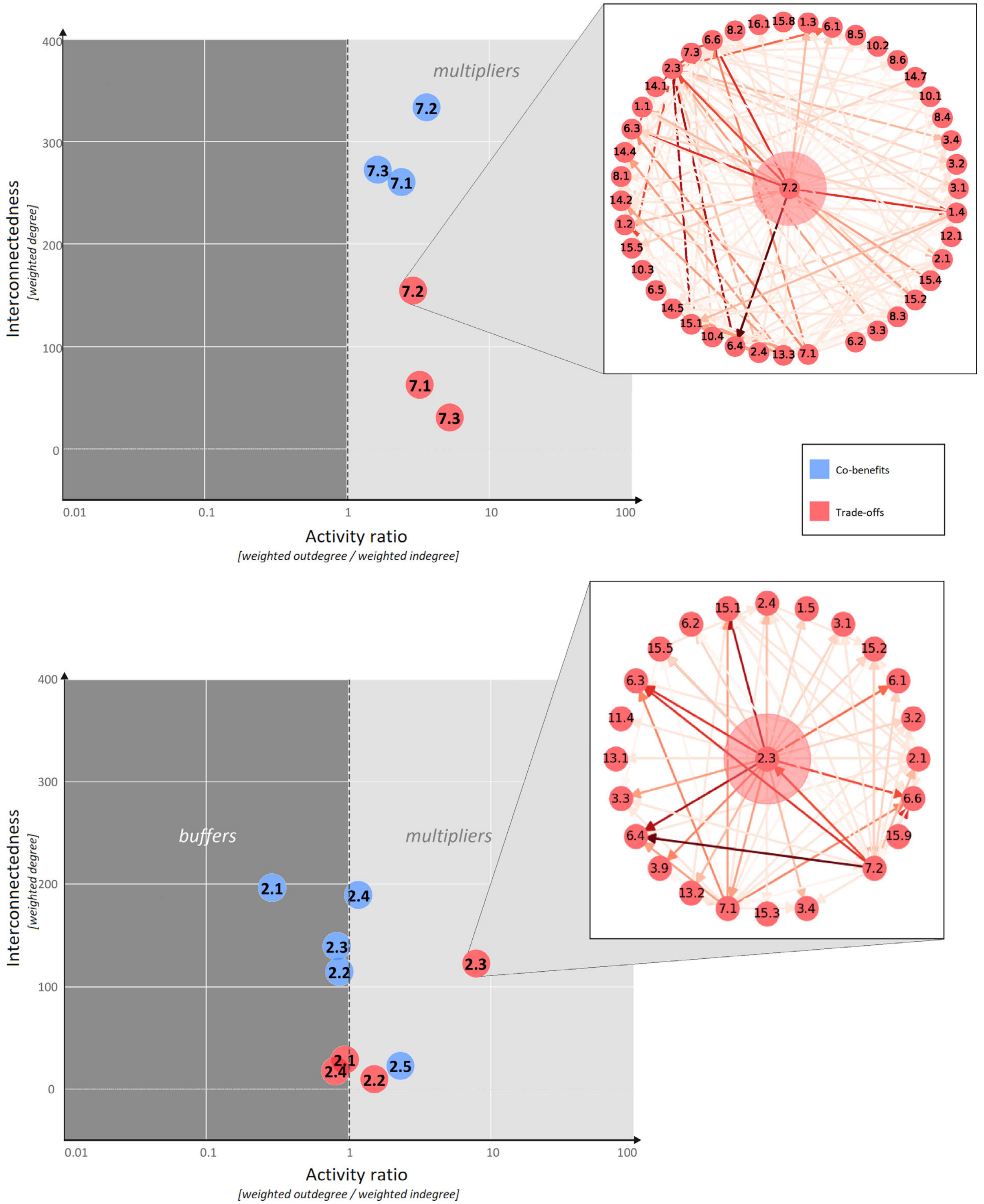

FIGURE 6 Coordinate systems at the more precise target level, filtering only for SDG targets on energy (SDG 7) and food (SDG 2)—two goals that were identified as central multipliers. Zooming in to show greater detail on potential risks makes it possible to reveal the "ego networks" of the targets on increased renewable energy (target 7.2) and agricultural productivity (target 2.3) [Colour figure can be viewed at wileyonlinelibrary.com]

3.2.2 | Focus on two central multipliers of trade-offs

We selected energy (SDG 7) and food (SDG 2) goals for a closer analysis at more precise and concrete target level. The reason for this selection is that SDGs 7 and 2 both have important negative shares of weighted out-degree centrality (226 and 116, respectively), and that they illustrate different categories of systemic roles. Thus, we reproduced our methodology, first filtering solely for energy targets, then solely for food targets (cf. Figure 6).

Our analysis reveals that energy access (7.1), expansion of renewable energy (7.2), and energy efficiency (7.3) are strong multipliers of positive and negative effects, confirming the strong systemic role of energy. However, food has a more differentiated systemic role depending on which target we focus on. Food access (2.1) appears to be a buffer whose outcome will be shaped by overall implementation of the 2030 Agenda; by contrast, increased agricultural productivity (2.3) appears to be a crucial multiplier of trade-offs across the targets: throughout the system, sustainable agriculture (2.4), and genetic diversity (2.5) are positive multipliers of co-benefits.

The two "ego networks" revealed by our analysis serve to highlight the possible negative effects of increased renewable energy (7.2) and increased agricultural productivity (2.3). We found 42 targets potentially impacted by the former and 23 by the latter. As shown in Figure 6, the interactions between targets are supported by differing levels of evidence from the literature (darker reds indicate more supporting evidence). For instance, the most recurring trade-off identified extends from the target on renewable energy (7.2) to the target on water-use efficiency (6.4) and has a weight of 13. Additionally, renewable energy can negatively impact the targets for reduced water pollution (6.3), protection of water-related ecosystems (6.6), access to resources for the poor (1.4), and increases in agricultural productivity (2.3). Finally, increases in agricultural productivity, in turn, appear likely to negatively impact various SDG targets, in particular regarding land ecosystems and their services (15.1), water resources (6.4, 6.3, 6.6, and 6.1), and health issues related to air, water, and soil pollution (3.9).

3.3 | Turning vicious into virtuous cycles

Overall, the multiplier effects we identified can be used to shape wider systems for better or worse. We now turn to sub-networks of key interactions that could serve as entry points to leverage the transformative changes needed to achieve the SDGs in the next decade (Independent Group of Scientists, 2019). There is significant potential to maximize synergies on behalf of the 2030 Agenda. Indeed, the co-benefits in our data outnumber the trade-offs, confirming the results of other studies on SDG interactions (Dawes, 2020; Pradhan et al., 2017; Weitz et al., 2018). Below, we identify the most central target-level cycles of interactions that could serve as positive self-reinforcing networks.

Applying a minimum threshold weight of five enabled us to narrow down our data to target-level sub-networks exhibiting the most supporting evidence for positive interactions, as seen in Figure 7 (darker shades of blue indicate more supporting evidence). The highest interaction weight found was 13, as seen, for example, in cycle *(c)*, showing the interaction extending from target 15.1 to target 13.1 (cf. Figure 7).

In such sub-networks, addressing one target can automatically strengthen other targets. These sub-networks represent potential virtuous cycles that could be exploited. Conversely, failure to progress on particular targets—or regressing in the opposite direction—could set in motion vicious cycles, in which failures are multiplied among the three targets.

Overall, the sub-networks illustrated in Figure 7 point to several possible entry points for "virtuous cycle"-oriented policy interventions. First, cycles *(a)* and *(b)* correspond to issues of clean and sustainable resource use for energy. Renewable energy (7.2) and energy efficiency (7.3) present opportunities to improve water quality (6.3). On the one hand, action toward reduced water pollution can support sustainable management of natural resources (12.2). On the other, action toward sustainable resource management can sustain further renewable energy production and resource efficiency. Second, cycle *(c)* corresponds to issues of sustainable agriculture and changing the food system. Here, we see that sustainable agricultural practices (2.4) can support ecosystem services (15.1), which can, in turn, enhance mitigation and adaptation to climate (13.1)—further supporting sustainable agricultural practices. Third, cycles *(d)* and *(e)* correspond to protecting natural resources. Here, we see that preserving ecosystems (15.1) serve climate policies (13.2), and such actions can support natural habitats and biodiversity (15.5). Similarly, interconnections between climate action (13.2 and 13.1) and oceans (14.2) can produce virtuous cycles.

4 | DISCUSSION

Our network analysis reveals the twofold role of the SDGs as multipliers and buffers of co-benefits and trade-offs, giving rise to various policy implications. Based on the current state of knowledge embodied in international scientific reports, UN flagship reports, and selected scientific papers, our analysis shows that SDG 1 (poverty), SDG 3 (health), SDG 5 (gender), and SDG 10 (inequality) are predominantly systemic buffers. These goals can benefit from sound implementation of the other goals of the agenda. However, if all efforts are focused on these "buffer" SDGs, the co-benefits and multiplication effects on behalf of the 2030 Agenda will be very limited from a systemic perspective. On the other hand, SDGs 2 and 8 on food and economic growth must be approached carefully, as these goals can act as multipliers of trade-offs. A rapid boost of these goals could bring about unintended side effects and hinder progress toward achievement of the overall agenda. At the same time, several goals can act as multipliers and accelerators of change, in particular SDGs 7 (energy), SDG 9 (innovation), SDG 11 (cities), and SDG 13 (climate).

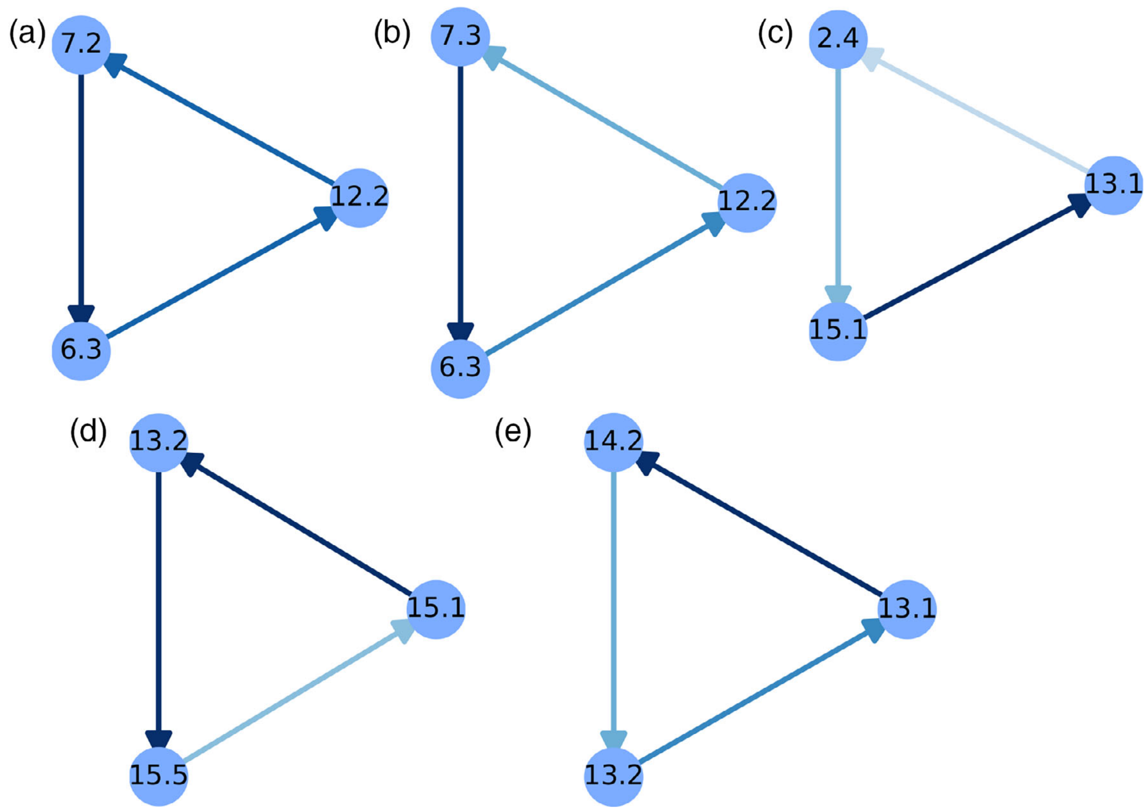

FIGURE 7 Top systemic loops of positive interactions (weighted five or more): (a) and (b) are related to the energy sector and its use of resources; (c) is related to the food system; (d) and (e) relates to protection of the environment [Colour figure can be viewed at wileyonlinelibrary.com]

However, the trade-offs and co-benefits they create may be difficult to control. Finally, several goals represent relatively "safe" multipliers of positive systemic effects, in that they create co-benefits without much risk of producing trade-offs. These are SDG 4 (education), SDG 6 (water), SDG 12 (sustainable consumption and production), SDG 14 (oceans), SDG 15 (land and ecosystems), SDG 16 (peace), and SDG 17 (partnerships).

At the more precise target-level, our analysis can help to steer policy action and prioritization toward specific targets. The "ego networks" we have identified highlight the systemic risks of attempting to achieve specific targets in isolation, in particular target 7.2 on increasing the share of renewable energy, as well as target 2.3 on increasing agricultural productivity. Our analysis also pinpoints the most crucial systemic feedback loops, namely: among clean and sustainable resource use (6.3 and 12.2) for renewable energy (7.2) and energy efficiency (7.3); sustainable agriculture (2.4) and transforming the food system into one that protects natural ecosystems (15.1) and strengthens in turns the resilience to climate-related hazards (13.1); and protecting the interlinked environmental commons, such as climate (13.1 and 13.2) and ecosystems (14.2, 15.5 and 15.1). These insights provide good entry points for policies that seek to multiply positive systemic effects of SDGs, transforming vicious cycles into positive cycles of change on behalf of the 2030 Agenda. Notably, our findings also support the models of Dawes (2020) pointing to strong reinforcing loops at the SDG level: for example, land and terrestrial ecosystems (SDG 15) and climate (SDG 13), in particular, are mutually reinforcing; further, climate (SDG 13) influences water (SDG 6), which influences energy (SDG 7), which further influences climate. Notably, in any such model, a "reinforcing" cycle could be vicious or virtuous: The transformations must be intentionally pursued to set in motion the desired co-benefits and multiplication effects.

Given the small window of time left to realize the 2030 Agenda, coherent policymaking is essential. Pursuing policy coherence means moving away from business-as-usual, narrowly focused policymaking and toward more integrated approaches (Breuer, Janetschek, & Malerba, 2019; Nilsson & Weitz, 2019). Our analysis of the interactions between SDGs highlights the risks of relying on expertise that is organized in silos, designing policies based on territorial autonomy, or pursuing development strategies determined solely by centralized authorities. The costs of ignoring these interactions could be very high (Elder, Bengtsson, & Akenji, 2016). Instead, the greatest potential for innovative pathways toward sustainable development lies in creatively and consciously managing SDG trade-offs and co-benefits, harnessing their universality and forging new partnerships. Actions toward the SDGs should adopt an integrated approach designed to minimize incoherencies and contradictions and maximize synergies on behalf of all 17 SDGs.

The data we collected and analyzed offers generic insights at mostly global level. Yet, our methodology could easily be reproduced with context or country specific data. Understanding the systemic interactions and the role of each SDG, we obtain the evidence to take better decisions on where to invest available resources and how policies—which are coherent in terms of systemic interactions—may be a way of investing limited resources much more coherently. Ultimately, policy coherence would prevent from inefficient and misspent resource allocation and counterproductive efforts.

Finally, we also understand that political debates about prioritizing certain objectives may be supported by better evidence in view of a new consensus. Such science diplomacy plays an important role when decision-makers may learn that the best way of fighting poverty may not lay in economic growth but rather in supporting social services, education, or health.

5 | CONCLUSION

The experience of coding interactions derived from a systematic literature review revealed the difficulty of identifying precise context-specific interactions capable of informing technological or governance solutions and addressing specific geographic and temporal scales. We found that the available knowledge on interactions has an inherent bias toward global perspectives and generally lacks regional or country-specific differentiation. A great deal of additional knowledge exists, but it currently remains fragmented and relatively inaccessible on behalf of the science–policy–society interface. In terms of sustainability issues, the available body of knowledge may also have a bias toward environmental rather than social perspectives. Indeed, disciplines focused on gender or health, for instance, do not appear to have undertaken assessments of SDG interactions in their studies to date.

To overcome these shortcomings, a joint initiative by the scientific community has called for creation of a knowledge platform (Nilsson et al., 2018) incorporating context-specific case studies that can inform the global policy process and support key science-based assessments, such as the Global Sustainable Development Report (GSDR). Such initiatives would increase the relevance of science for sustainable development and improve the science–policy interface (Messerli et al., 2019).

The GSDR 2019 emphasizes that context-specific knowledge is required for transformative change. Transformative change demands going beyond pursuing targets one by one, and instead maximizing the systemic, multiplying potential of the SDGs—that is, moving away from a focus on incremental, linear change and toward an emphasis on accelerated, exponential transformations. Drawing on comprehensive synthesis of existing knowledge on SDG interactions, our study points to key development areas that give rise to systemic trade-offs and highlights areas where synergies can be employed on behalf of sustainable development. Further, our methods and results have produced a useful analytical tool for identifying buffers and multipliers in a system, enabling consideration of potential trade-offs and co-benefits. Finally, our analysis highlights possible entry points for policy prioritization and leveraging transformative change (Independent Group of Scientists, 2019).

ACKNOWLEDGEMENTS

We would like to thank the following colleagues for their contribution to the systematic literature review: Tania Charlton Christensen, Jakob Fritzbøge Christensen, Renate Fleiner, Sarah Hellebek, Johan Møller Nielsen, and Alemtsehay Teklay Subhatu. We also wish to thank the communities of the European Consortium for Political Research (ECPR) and the European Conference of Social Networks (EUSN) for the great feedback we received at their respective winter schools and conferences, as well as Anu Lannen for his careful review and valuable remarks.

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How to cite this article: Pham-Truffert M, Metz F, Fischer M, Rueff H, Messerli P. Interactions among Sustainable Development Goals: Knowledge for identifying multipliers and virtuous cycles. *Sustainable Development*. 2020;1–15. https://doi.org/10.1002/sd.2073

APPENDIX A: APPENDICES

Query search

In January 2018, we extracted a set of relevant articles published since 2013 (i.e., since the preparations to the adoption of the 2030 Agenda started) from the Web of Science and Scopus' databases. We detail below the keywords we used for each database:

Query search on Web of Science:

(sdg* OR "sustainable development goal*" OR "2030 Agenda" OR "agenda 2030") AND (interaction* OR Interlinkage* OR nexus* OR interconnectedness)

Query search on Scopus:

TITLE-ABS-KEY ((sdg* OR "sustainable development goal*" OR "2030 agenda" OR "agenda 2030″) AND (interaction* OR interlinkage* OR nexus ORinterconnectedness))

TABLE A1 Popularity of each SDG, taking the positive and negative interactions separately

SDG	Positive	Negative
1	23	21
2	222	111
3	70	2
4	70	1
5	46	0
6	319	13
7	463	181
8	100	35
9	124	15
10	72	5
11	129	36
12	204	7
13	180	38
14	194	44
15	296	29
16	79	3
17	150	2

We normalize the positive and negative data separately. Finally, we provide in Figure A1 the results of our identification of buffers and multipliers after this normalization process.

Analysis after normalization

In order to test the structural changes in the network when we cancel out the popularity effects of the nodes, we applied the *average activity normalization* to our positive and negative data following the adapted from Leifeld et al. (2018):

$$\Phi_{ii'}^{\mathrm{avg}}(\omega) = \frac{\omega}{\frac{1}{2}\left(\sum_{j=1}^{n} x_{ij} + \sum_{j=1}^{n} x_{i'j}\right)}$$

where x_{kl} is the number of observed entries from node k to l.

Hence, Φ is a transformation, taking the weight of an entry from node i to node i' and dividing it by the mean of their respective popularity measures. The popularity of a node is the number of entries of interactions that depart from that node (cf. Table A1).

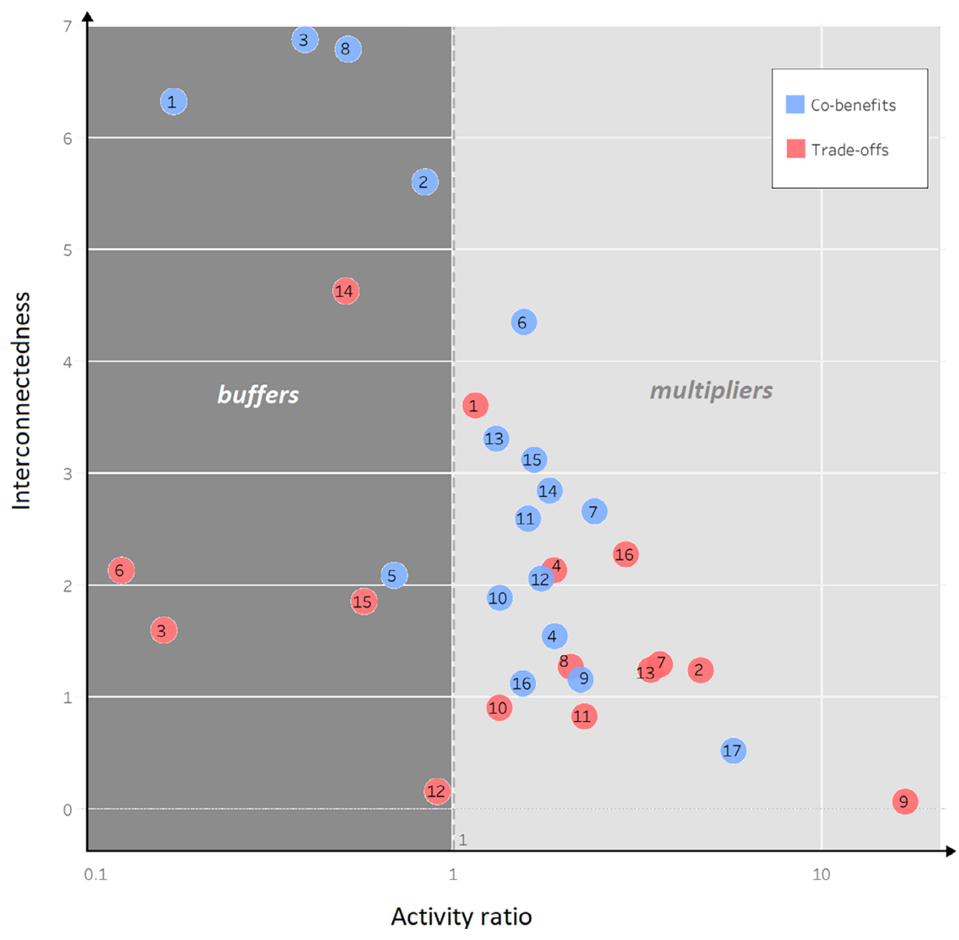

FIGURE A1 Coordinate system at SDG level after canceling out for the popularity effect using the average activity normalization proposed in Leifeld et al. (2018) [Colour figure can be viewed at wileyonlinelibrary.com]