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Mobilizing the transformative power of the research system for achieving the Sustainable Development Goals[1]

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Abstract

This paper addresses the important question of how national research systems can support the implementation of the United Nations 17 sustainable development goals (SDGs) set out in the 2030 agenda. Much attention on this topic has so far coalesced around understanding and measuring possible synergies and trade-offs that emerge in the SDGs. We contribute to this discussion by arguing that it is necessary to move from a focus on system interaction towards system transformation. A conceptual approach is presented based on the notion that research that "builds bridges" between science and technology and the social and environmental pillars of sustainable development can more fully support simultaneous achievement of the SDGs and thus be transformational. This proposition is put to the test empirically through a study of the Mexican research system using methods from bibliometrics and social network analysis. Our results can help to provide a diagnostic of how research systems are approaching SDGs and where potential exists for transformative research.

Key Words: Sustainable Development Goals, Mexico, Poverty, Inequality, Social Network Analysis, Triad, Co-bibliography, Transformation.

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Introduction SDGs

The 17 Sustainable Development Goals (SDGs) set out in the United Nations 2030 Agenda create a space to stimulate thinking and action about long-term changes in our economy and society. Therefore, the SDGs should not been seen as a set of individual goals, they represent a truly new ambition that is flagged in the strapline of Agenda 2030: *Transforming our World*.[2] As the 2016 International Council for Science and the International Social Science Council *Review of Targets for the Sustainable Development Goals* states, there is a need for the formulation of an overarching goal to develop interlinking targets and a compelling narrative of development.

The new transformative agenda invites a deep reflection about the choices and directions for investments in the research system since these may drive the change processes. This is the main question we address in this paper: how to unlock the transformative potential of research for addressing the SDGs? To answer such a question means not only going beyond an analysis of individual goals, but also engaging in a discussion about what sorts of interactions are taking place in the research system, between which areas and what type of research is more likely to be a catalytic for transformations. This echoes wider calls for new policy framings for science, technology and innovation research based on transformative innovation by a number of authors (see for example Schot and Steinmueller, 2018: Steward 2012; Weber and Rohracher 2012, Diericks and Steward, 2019). As (Lundin and Schwaag, 2018) have noted, transformative innovation has a strong fit with the principles of the SDGs and indeed we build on this notion, that to be consistent with the SDGs, publicly funded R&D investments should consider the nexus between different areas of research and build bridges between SDG related-research. Our approach will assist in doing this.

The paper is structured as follows. First we engage with the different narratives regarding the role of the research systems and in particular science and technology, in mobilizing the potentially transformative power of the SDGs. We emphasize that whilst discussion about measurement has rightly been on systems, synergies and trade-offs, transformative processes require opening up of innovation systems to research at the nexus between different SDGs and interactions between science, technology, social science and governance forms. We then take up the challenge of developing a methodology for evaluating SDGs that is consistent with this new narrative. This is done by using triad analysis and bibliographic coupling to help identify different cognitive communities that are present in journal publications from the Web of Science (WoS) and SciELO databases, (English and Spanish/Portuguese languages respectively). An important characteristic of our approach is that rather than establishing ex-ante where goal interaction might take place by, for example asking experts, we take a more grounded approach that identifies where bridges are built between different areas of research. This can help to identify where potential synergies and trade-offs exist in meeting SDG goals.

Finally, we present an empirical study of the Mexican research system using this method. First, although we find that in Mexico there has been considerable increase in investment in SDG-related research activity over the past twelve years, much of this has been concentrated in a small number of more technical related SDGs rather than in addressing social challenges. We do nevertheless find some pockets of nexus-type research that bring together different SDGs and could lay the basis for new areas of public investment in Mexico. We also find important nexuses between health, water and agriculture and between education and human rights. These could be important agendas for development.

[2] See https://sustainabledevelopment.un.org/post2015/transformingourworld.

Measuring the SDGs: From interaction to transformations

Empirical studies of progress on SDGs stress that a key area of research is to understand the interlinkages between SDG goals (Allen, Metternicht and Wiedmann, 2018; Nilsson *et al.*, 2018). The emphasis on goal interaction responds in large part to the limitations of relying uniquely on single goal indicator-based systems that are not sufficient as decision support systems because of their inability to provide adequate insights on possible synergies and trade-offs. In particular, discussions around the nexus of, for example, water, energy and food or climate change, poverty and cities emphasizes the integration of goals across sectors and systems analysis, although as (Timko *et al.*, 2018) suggests, a deeper understanding of the complex dynamics of these nexuses is still required.

Future SDG research agendas therefore involve making extra efforts to improve the quality of data, explore new sets of metrics and use these to provide indicators of progress that may help to construct impact assessment of certain policies. Currently, the main methodologies used for measuring SDGs range from narrow single goal measures, such as that used by the influential Sustainable Development Report dashboard (https://dashboards.sdgindex.org/#/) to rank the "progress" of countries on SDGs, to methods that look for system dynamics (Muff, Kapalka and Dyllick, 2017; Schmidt-Traub *et al.*, 2017; Weitz *et al.*, 2018) and include tools such as bench marking and indicator based assessments used in National Country Reviews (VNRs) by the Organisation for Economic Cooperation and Development (2016), the United Nations Development Group (2016) and the United Nations Division for Sustainable Development (2017). The general trend for models inspired by systems thinking (Le Blanc, 2015; Nilsson *et al.*, 2018) is to involve the identification of clusters of interconnected targets and integrated models (McCollum, Krey and Riahi, 2011; Le Blanc, 2015).

And yet, beyond the complexities of measuring synergies, trade-offs and systemic properties at different scales, it is important that those involved in gathering evidence and monitoring progress of SDG compliance not lose sight of the *transformative* ambition that these SDGs represented when developed. Thus, whilst interactions can be defined in terms of negative or positive feedback loops (Nilsson *et al.*, 2018), a broader challenge exists of developing a methodology to enable a grasp of where research is taking place (or could take place) that can support the transformational change inherent in the SDG ambition and the leverage points required to enable this to happen (Abson *et al.*, 2017). This involves the development of an analytical framework that adds more dynamic interconnectivity between different types of goals and feedbacks associated with transformational change.

Drawing upon sustainability transitions research, we assume that such transformational impacts are generated through socio-technical system change, created in participatory and inclusive processes by a wider group of actors, including universities and research centres, governments, firms and civil society. Transforming socio-technical systems therefore consists of establishing new alignments between scientific and technological solutions, user preferences, cultural perceptions, industry strategies and policy measures, that provision for certain needs, such as healthcare, food, mobility and energy (Grin, Rotmans and Schot, 2010; Markard, Raven and Truffer, 2012). A public policy built on principles of transformative change that transcend single goals in relation to science, technology and innovation and social sciences, so that the social and environmental consequences of the use of STI are incorporated.

We sidestep some of the debates between different forms of disciplinarity research, for our emphasis is closer to what (Cornell *et al.*, 2013) argues is the need to "open up" knowledge systems for achieving transitions social transformations. This means that effective societal responses to persistent problems of unsustainability requires open knowledge systems which can help scientific practices to orient towards social arenas. Thus the ability of academic disciplines to understand and interact with specialisms from a wide range of other specialisms is critical[3].

We therefore propose a new approach to measuring and diagnosing the contribution of research systems towards the 17 SDGs. This is done by breaking down the SDGs into three types: A first type is SDGs which we refer to as "socio-technical systems" that provide systemic services such as cities (SDG 11), clean energy (SDG 7), health and wellbeing (SDG 3), zero hunger (SDG 2) (which is related to agriculture) (SDG 2) and clean water (SDG 6). Sociotechnical systems are critical for society and encompass systems of production, distribution and consumption[4]. Underpinning these systems are networks of producers, suppliers and users, but also expectations about cultures and how we interact with nature. However, the link between socio-technical system development and "directionalities" is a critical feature of transformative thinking and not only a technical driven process. It involves constructing sustainable futures and connecting these to specific socio-technical change development trajectories. These futures are expressed in quite specific directionalities or transversal directions as captured in SDGs no poverty (SDG 1); gender equality (SDG 5); decent work and economic growth (SDG 8); reduced inequalities (SDG10); responsible production and consumption (SDG 8) and Climate Action (SDG 13). Finally, transformational impact requires wider participation which assumes specific governance and political conditions in which societies can discuss, negotiate and navigate different trajectories of development. These are exemplified in SDG 16 on Peace, Justice and Strong Institutions and SDG 17 on inclusive partnerships[5]. The three categories of SDGs outlined above can therefore be distinguished in the following way:

1. SDGs which cover specific or a wider range of socio-technical systems or application areas.
2. SDGs which emphasizes 'transversal directions' or directionality.
3. SDGs which focus on structural transformation in governance conditions.

From this it is possible to propose a new view on how to group the SDGs based on a transformative change perspective as outlined in figure 1 below. This framework emphasizes how public policy in its various framings (including R&D spending) can address SDGs including and in particular on building

[3] It is possible to introduce more information on organisations and authors and their agency. However, this is beyond the scope of this paper. Our focus is on analysing interactions between SDGs rather than the organizations embedded in the research. Therefore, we only discussed three networks methods: co-words, co-citation and co-bibliography

[4] The transitions literature has made the distinction between sectoral systems of innovation that focusses on supplier side technological systems and socio-technical systems that more clearly incorporates users and the relationship between actors and institutions in system change (Geels, 2004). We suggest a socio technical systems approach is a useful mechanism to understand transformations as proposed by the SDGs.

[5] Aggregating SDG goals into these three analytical categories can be problematic since features of all three categories can often be found in the numerous targets associated with each goal. However, rather breaking up the goals into the 150 different targets, a careful inspection of each goal and targets shows that a dominant approach exists when addressing each goal. For example, sociotechnical systems focuses on systems in which technological and social elements are deeply intertwined. Directionalities by contrast are social and environmental goals which guide the mode of sociotechnical systems. SDG2 (zero hunger) is composed of eight targets. 2.1 and 2.2 are related to social and environmental goals, target 2.3, 2.4, 2.5 are about food production (double the agricultural productivity, ensure sustainable food production systems, maintain the genetic diversity of seeds). Targets a, b and c on the other hand are related to framework conditions and sociotechnical systems (rural infrastructure, world agricultural markets and functioning of food commodity market). Therefore there is a tendency to focus on transforming food production system and we therefore consider it related to a sociotechnical system.

Likewise, Life Under Water (SDG 14) is in socio technical systems since it refers predominantly to the fishing system, whilst life on land (SDG 15) is placed in directionality because it refers primarily to bio-diversity loss.

relational capabilities through investments in activities that generate interaction between different goals. In particular, building interaction between socio technical systems, transversal directions (or directionality) and governance conditions may generate synergies and the creation of spaces, visions, coalitions and deep learning for transformative change.

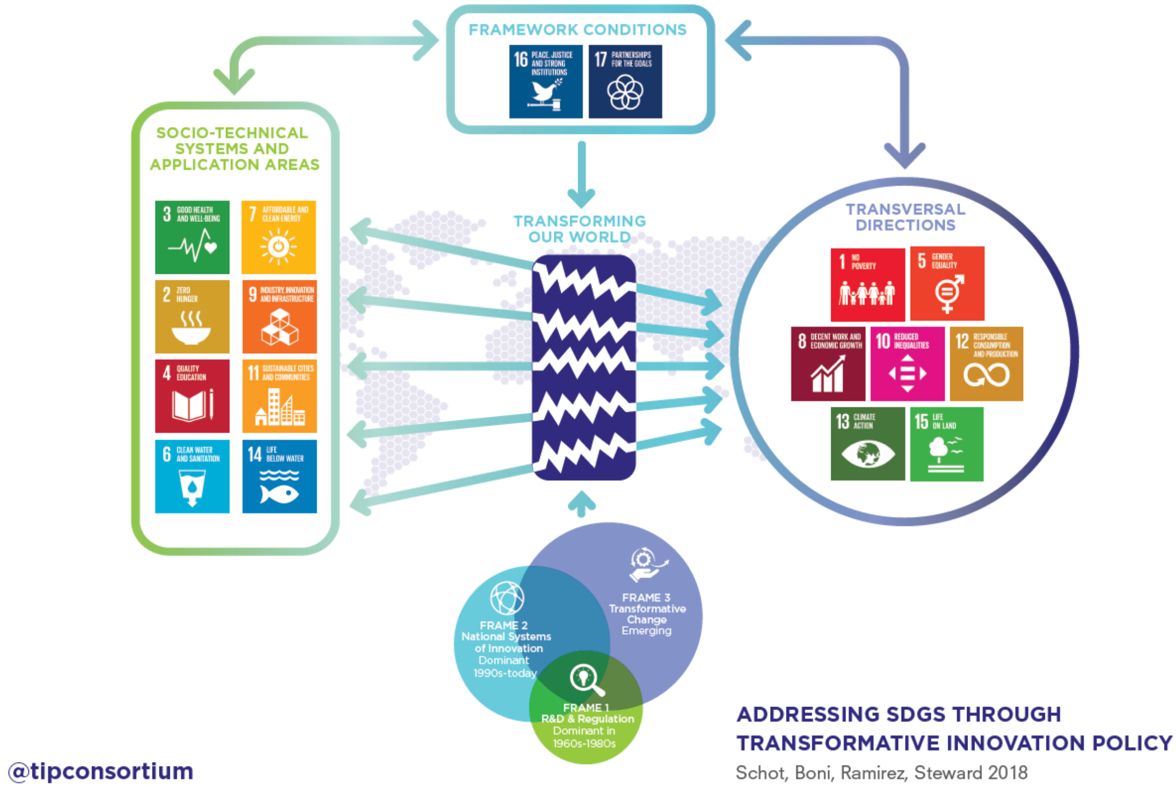


Figure 1. Addressing SDGs through Transformative Innovation Policy.

Evaluating the capability of an innovation system to address the SDGs

Our empirical study analyses how the Mexican research system has contributed to the SDGs, although particular emphasis is placed on finding evidence of research that has the potential to support transformative activities. We focus on citation indices because these have been used widely as an indicator of knowledge output, knowledge diffusion and to measure collaborations around particular agendas (Garfield, 2006; Rafols, Porter and Leydesdorff, 2010; Bornmann, 2013) both in the natural and social sciences.

Following figure 1, our method relies on knowledge integration around specific topics. For this purpose "maps of knowledge" are commonly used to understand the relationship between different types of knowledge and/or disciplines (Rafols, Porter and Leydesdorff, 2010; Grauwin and Jensen, 2011). Social network analyse (SNA) is commonly used to visualise and develop specific measures of knowledge integration (Shiffrin and Börner, 2004; Wagner and Leydesdorff, 2005; Leydesdorff, 2007; Rafols and Meyer, 2010) and from this, maps of knowledge have been frequently developed using four different approaches: Co-word-similarity (co-keywords), bibliographic coupling (co-bibliography), collaboration (co-authors and co-affiliations) and co-publication coupling (heterogeneous maps) (Shiffrin and Börner, 2004; Rafols and Meyer, 2010; Rafols, Porter and Leydesdorff, 2010; Grauwin and Jensen, 2011). These analyses are used to evaluate clustering around specific terms, topics, themes, disciplines, areas of knowledge and collaborations. Moreover, by introducing time series analysis it is possible to analyse changes of topics through time in order to understand transformation in the science interests (Brandes and Corman, 2003).

For our purposes, we are interested in representing SDGs as composed of different socio technical systems and directionalities that illustrate contrasting societal needs or demands. There are a number of alternatives that can be followed. For instance, Ciarli and Rafols (2017) used co-word similarity to analyse the relationship between research priorities, technological trajectories and societal needs. In their study, the change of topics associated with rice research over time helped to understand the changing research trajectories and priorities on rice research. However, this approach might have problems when used in SDG contexts since it is undertaken in a specific discipline, in this case agriculture. SDG topics, by contrast, are composed of different socio technical systems and directionalities that are built on different knowledge areas. Therefore, this methodology may not have enough resolution to evaluate different disciplines.

Consequently, we turn to bibliographic coupling. This has the advantage that it can be used as a measure to identify knowledge communities (cognitive distance between articles). This methodology identifies groups of cohesive communities (Blondel *et al.*, 2008) based on groups of articles that have a significant number of common references (see Louvain network modularity optimization for detailed explanation; De Meo *et al.*, 2011; Grauwin and Jensen, 2011; Nakamura *et al.*, 2019). We base this approach on Nakamura, Pendlebury, Schnell, & Szomszor, (2019)'s method to identify SDG research communities which provides a unique background view of SDGs knowledge production[6] Within this, bibliographic coupling is an established method to evaluate SDGs in bibliometric databases and permits evaluation of key relationships between SDG topics. However, this was not used for labelling bibliometric sources since it is possible that some SDG topics will be underestimated, for example poverty and inequality[7], because they search topics tend to be all linked to the word "sustainability". An alternative and unique "thesaurus" was therefore constructed to allow us to identify bibliometric sources that are strongly related to SDGs topics (see methods and analysis).

Two complementary methods are undertaken. The first evaluates interconnectivity between groups of three articles based on their SDGs in the co-bibliography network. These are groups of three connected nodes that are called triads in social network analysis jargon. The second approach involves analysing cognitive communities that are formed by grouping common topics. These provide complementary but different lenses with which to analyse the nature of connectivity of research. With respect to triad analysis, the approach taken is to find the most common triads in the network (Burgin, 2018). Then, using Triad Census Distributions (TCDs) (Aarstad, 2013) approach it is possible to determine the most common relationships between our three SDG categories. This is considered a more "bottom-up" approach to looking at SDGs than for example the use of more common words, because it looks for high levels of interconnectivity. Thus triads generate circuits (a key features of communities). Triads are also more resilient in a network structure since a break in one connection doesn't isolate other nodes as would be the case in dyads. Referring back to figure 1, we can use triad

[6] Other methods for constructing the dataset were considered, for example the "keywords" approach used in the Green Book (2018) by Colciencias. However, this had some drawbacks, including large range of key words for each SDG (SDG 10 has around 42 key keywords compared to SDG 11 with more than 200) which could be because of the high correlation between the number of key words used and the number of bibliometric sources detected per SDG. This could led to an overestimate (or underestimate) of SDG bibliometric sources.

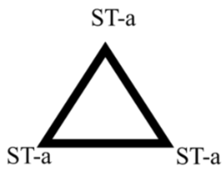
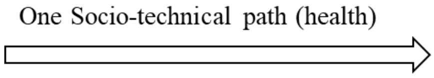
[7] Nakamura, Pendlebury, Schnell, & Szomszor, (2019) method labels bibliometric sources that search only "sustainable development" in the title, abstract, key words and bibliography.

analysis to detect connections between different forms of SDGs. This leads to distribution of cognitive relationships in 21 types of triads.

<table>
<tr><td>Triad Types</td><td colspan="2">Illustrative example</td></tr>
<tr><td>1. These Triads are composed of just one SDG which can come from sociotechnical systems, Transversal directionalities and framework conditions.

One category:

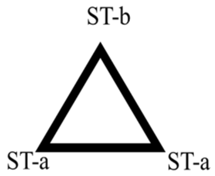
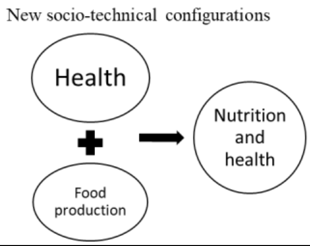
ST-ST-ST-1
TD-TD-TD-1
FC-FC-FC-1</td><td>one category

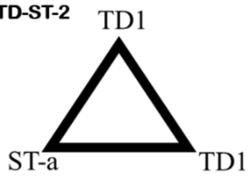
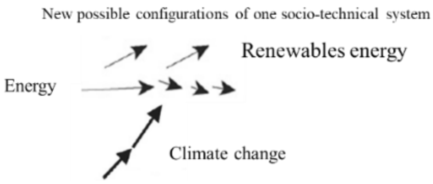
ST-ST- ST-1

</td><td>
</td></tr>
<tr><td rowspan="2">2. These triads are composed of two SDGs which can be come from one or two SDGs categories:

One category:

ST-ST- ST-2
TD-TD-TD-2
FC-FC-FC-2

Two categories:

ST-ST-TD-2
TD-TD-SD-2
ST-ST-FC-2
TD-TD-FC-2
FC-FC-ST-2
FC-FC-TD-2</td><td>one category
ST-ST- ST-2

</td><td>
</td></tr>
<tr><td>Two categories

TD-TD-ST-2

</td><td>
</td></tr>
<tr><td rowspan="3">3. These triads are composed by three SDGs which can be come from one, two or three different SDGs categories.

one category:

ST-ST-ST-3
TD-TD-TD-3

Two categories:

ST-ST-TD-3
TD-TD-SD-3
ST-ST-FC-3
TD-TD-FC-3
FC-FC-SD-3
FCFC-TD-3

Three categories:

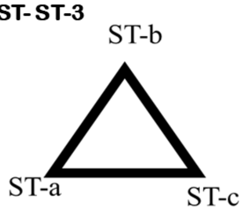
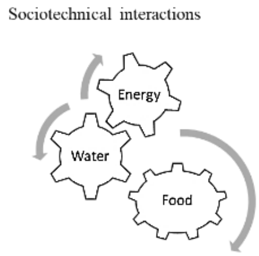
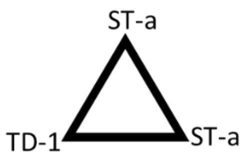
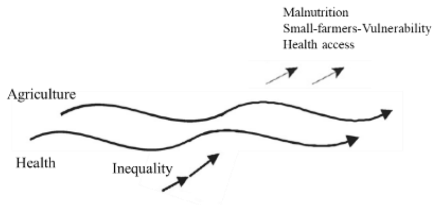
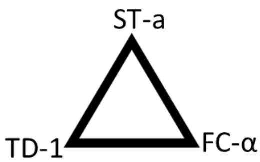
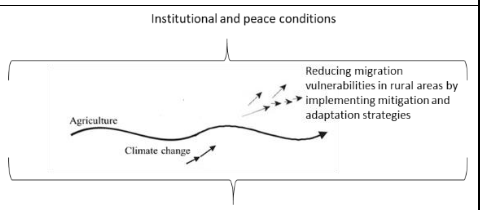
ST-TD-FC-3</td><td>one category
ST-ST- ST-3

</td><td>
</td></tr>
<tr><td>Two categories
ST-ST-TD-3

</td><td>
</td></tr>
<tr><td>Three categories
ST-TD- FC-3

</td><td>
</td></tr>
</table>

Table 1. Triads types according to transformative innovation perspective of Social Development Goals. Note: ST: Socio-technical System; TD: Transversal Directionalities and FC: Framework Conditions.

We propose three categories of triads as detailed in table 1. Firstly, triads that are made up of just one SDG (e.g. health). These may produce new knowledge but are more likely to remain within narrower cognitive boundaries. The second group includes triads that combine knowledge about two SDGs. They can be made up by SDGs from one or two SDGs categories. This category may support more complex interaction between SDGs, for instance, knowledge that combines two socio-technical systems such as food and health, might support socio-technical interactions such as nutrition and health. Triads might also combine SDGs from two different categories. An example identified in this research could be papers by (Feng, Krueger and Oppenheimer, 2010; Beuchelt and Badstue, 2013) on conservation agriculture, that integrated knowledge about food production with knowledge about inequality. This research framework could lead to new pathways in the production and consumption of food that help to address inequality.

The final group includes triads that combine three different SDGs and can be come from all three categories. For instance, the nexus project https://www.water-energy-food.org/resources/projects/) between energy, water and food in developmental contexts address configurations relevant to produce alignments between sociotechnical systems that address disruptive technologies. A second example could be directionality triads which combine social and ecological goals (e.g. climate change, inequality and life on land leading to research on the social impact of biodiversity loss). These configurations could contribute to opening up debates that combine social and ecological challenges. The last example is research that combines climate change and human migration such as by (Arbour, 2018). Human migration is strongly related to sociotechnical systems SDGs (health, education and cities), transversal directionalities SDGs (gender equality, labour condition, inequality and climate change) and framework conditions SDGs (inclusive institutions, justice access and peace). In summary, we can identify triads that group knowledge production (in terms of journal articles) around networks of SDG-related research. This allows us to look not only at diversity of research, but captures in more detail efforts to orient science more clearly toward social and *environmental goals.*

Methods and data analysis

Co-bibliography networks are composed of nodes (bibliometric data sources), ties (bibliography) and attributes (SDGs) and the connectivity between the attributes of the articles (17 SDGs). Bibliometric data was gathered related to SDGs in Web of Science (124,368 sources), a comprehensive English language database of research publication and SciELO Citation Index (41,599 sources)[8] a Spanish and Portuguese language database of scholar publications[9]. A data set with 1,162 search items related to SDGs was generated and a preliminary data base with 884 search items was produced using goals, targets and indicators of 2030 agenda. Those items were searched in every bibliometric data source's abstract, key words and title. The detail of data generating process is laid out in figure 2.

[8] The query was CU=Mexico* in WoS, and AD= Mexico* in SciELO, and we took information from 2006 to 2017.

[9] The analysis based on these databases will provide some contrasting results, therefore it is important to point out differences in how these databases are made up. According to (Velez-Cuartas G: Lucio-Arias, D: Leydersdoff, 2016), WoS prioritizes more "high end" journals and international visibility, whilst Scielo is focussed on encouraging regional circulation and desire to reflect strong social content. WoS has more collaboration with Europe and North America, but also collaboration of Latin American countries (LAC) with peers from the North dominates scientific communications where LAC participate. South- south collaboration is much more strongly expressed in SciELO and collaboration with Europe is concentrated in Spain and Portugal. WoS also has strong influence of biomedical and natural sciences, SciELO public health, agriculture and social science.

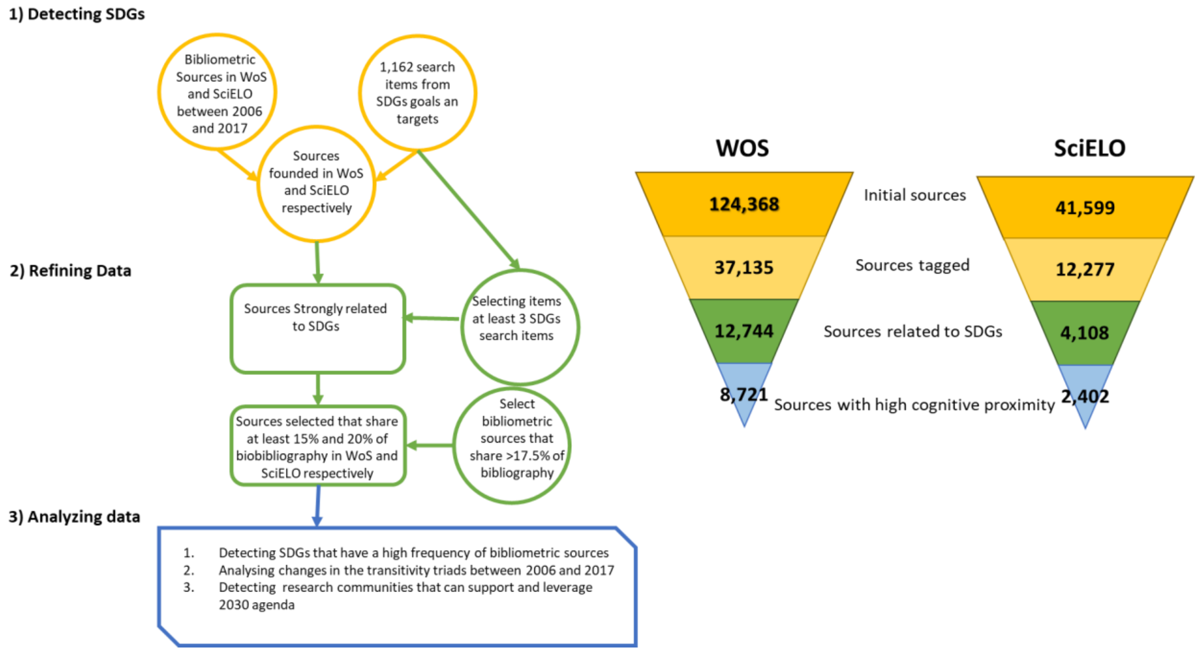


Figure 2. Analysis of steps with bibliometric database. **a)** Process of data cleaning, depuration and analysis. **b)** Number or bibliometric sources remaining after each step of processing.

As outlined in figure 2, a number of steps were taken to edit the database. The first involved sifting out terms not related to SDGs, a first trawl allowed us to detect 37,135 and 12,277 sources in WoS and SciELO and respectively. However, there were also some items that would not be considered to have a social or environmental sustainability perspective, for example "economic growth" on its own. A more careful analysis of the words chosen for inclusion was therefore undertaken, particularly around SDG goals 8, 9 and 17. Here it was decided to include only words which have some normative association with sustainable futures whether social or environmental in the article search items. For instance, in SDG 8, we only considered bibliometric sources related to economic issues that also contain sustainability and/or directionality topics. The result is that our dataset and results will be biased towards references that include social or sustainable objectives and will therefore underplay some SDGs[10]. Secondly, it was also important to reduce the correlations between the number of items per SDG and the number of articles detected in every SDG[11]. Therefore, the number of search items in every SDG was limited to between 60 and 76.

Thirdly, search items within each paper were categorized into three different groups. A first group of 242 search items exist (based on key SDG words) that are always together, such as "climate change" or "clean energy". A second group consisted of 702 topics that mix two terms that are not always together such as "economic" and "sustainability". A third group then consisted of 218 items composed of more than two words (but which did not appear in the second group, for example "public access", but were important to include because they represent the sense of the SDGs. This was done by adding an extra word from the SDG target, for example by adding "transport" to find a paper with "public access transport". To reduce the effect of detecting articles not relate to SDG topics, the frequency of words found in every bibliometric source was evaluated to determine the minimum search items to be considered. We took bibliometric sources that appear a minimum of three times in each article (for example "climate change" three times). We did not consider this rule for the third category (218 items)

[10] Some key words from the bibliometric sources were added in the search items that reflect "researchers jargon" such as "ecosystems restauration" or "climate resilience".
[11] It was reduced the person correlation from 0.7236 to 0.1256.

since it will be difficult to find three examples all together. The result was to reduce the number of bibliometric sources to 12,744 in WoS and 4,108 SciELO.[12]

Finally, in terms of determining the relevant SDG for each article, there are a number of options. For example, it can be determined according to the frequency of search items found in every goal. However, this will not help if three different search items are found one time and indeed, we found that in many cases, it was not possible to determine the most "relevant" SDG because that bibliometric source could be related to different SDGs (e.g. Reynolds and Borlaug, 2006; Delgado-Ramos, 2018). Therefore, selecting the most frequent SDGs would lead to a loss of key aspects of the diversity of the system. Two rules were therefore developed to choose the SDGs in every bibliometric source. First, one SDGs was considered when the frequency of search items found in one SDG is greater than 60% of the total search items found in a bibliometric source. Where this criteria was not met we considered as many SDG goals until the sum of the frequency of SDGs search items were equal to 75% of the search items in that bibliometric source. This was done to avoid selecting SDGs that were not very relevant for that article. Due to the fact that some articles may have more than one attribute (SDGs), it was necessary to multiply one node as many times as number of attributes (SDGs) for undertaking the Triad Census Distribution analysis.

Evaluating SDGs in Mexico

Mexico was chosen for the empirical analysis. This was in part because of the familiarity of the researchers with the national science and technology funding agency and because Mexico is an important economy in Latin America with one of the highest investments in science and innovation (CONACYT, 2017) in the region, and with a significant number of actors working in the science and technology system. A cursory analysis of existing studies of Mexico and SDGs shows a somewhat mixed picture. Data using indices proposed by Schmidt-Traub *et al.* (2017) show some improvements in gender equality, clean water and sanitation, sustainable cities and communities, responsible consumption and production, climate action and partnerships. In addition, according to the Gap Frame indicators, air quality, primary education enrolment, adult literacy rate, access to electricity, energy intensity, freedom of assembly and freedom of movement are approaching "ideal" category (http://gapframe.org/by-region/central-america/mexico/). Nevertheless, Mexico's National Review (VNRs) also showed that the most important areas that need transformation include gender violence, inequality, poverty, air pollution in big cities, reduction of carbon emissions and labour conditions in rural areas (Federal Government Mexico, 2018). The contrasting results suggest some possible gaps between some indicators and policy maker perspective about SDGs capacities, priorities and implementation.

In terms of investment in the overall system, according to General Report on the State of Science, Technology and Innovation, (2017) the National Expenditure on Science, Technology and Innovation (GERD) increased from 97,703 to 108,404 million (Mexican) pesos between 2010 and 2015, subsequently falling by 10.37% to 2017. In addition, CONACYT, the science and technology funding agency reported that the number of researchers funded by the National Researcher System rose from 10,189 to 27,186 between 2004 to 2017 (CONACYT, 2016, 2017). During this period the number of scientific publications increased significantly from 8,526 to 22,063 bibliometric sources per year between 2006 to 2017 (figure 3). In terms of our measure of publications related to SDGs, these increased from 377 to 1721 bibliometric sources per year between 2006 and 2017, an increase from

[12] It is worth noting that 100 bibliometric sources were evaluated and only one article not related to SDGs was found.

4.42% to 7.80% (figure 3). These broad descriptive figures suggest an important increase in SDG-related activity output during the period. The next section lays out and discusses the results highlighted in the methodological above proposition.

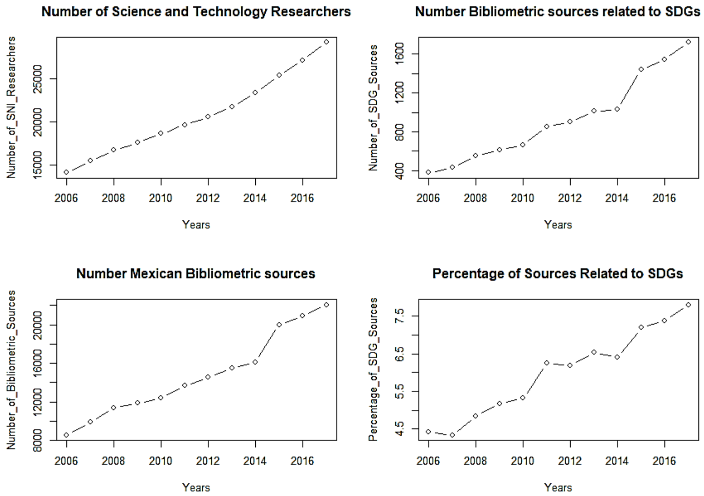


Figure 3. The graphs shows the increase in the number of recognized researchers in the national innovation system (NIS), the number of sources related to SDGs, the number of Mexican publication and the percentage of sources related to SDGs between 2006 to 2016. The information related to the number of NIS researchers associated was collected from the General Report on the State of Science, Technology and Innovation (2016, 2017). The bibliometric information was collected from Web of Science and SciELO citation Index (information downloaded at 15th July 2018). The number of SDG articles was calculated using our strategy for detecting SDGs bibliometric source.

Analysis of SDG interconnectivity trends [13]

In this section we evaluate key aspects of knowledge production related to specific SDGs (Figure 4). Here we see that publications related to SDG 3 (health), 6 (clean water), 9 (innovation and infrastructure) and 12 (responsible production and consumption) have the highest frequency of bibliometric sources, while SDG 1 (poverty) and 10 (reduced inequalities) have the lowest. Research using the word "inequality" has not increased at all in the period in question. The difference between the highest and lowest areas of research is significant, suggesting important imbalances in the SDG-related research in Mexico.

[13] Detection of bibliographic communities was undertaken following the method of Grauwin and Jensen, (2011) that takes the weight of ties between nodes (deep bibliography). This methodology applies bibliographic coupling (BC) similarity between two bibliometric sources i and j to normalize the number of references that every bibliometric source has (Kessler, 1963), and Louvain modularity algorithm to find communities of bibliometric sources (knowledge communities) that share a large number of references (Grauwin and Jensen, 2011; Duncan and Pascucci, 2017). This approach also focusses on modularity maximization that allows one to detect well defined communities (strong cognitive relationships). In addition, it is necessary to detect a cut point where the number of reference is strong enough, and the modularity clustering has a high value (around 7.0) (Newman and Girvan, 2004; Grauwin and Jensen, 2011). It was decided that 40 would be the cut off point between 0 and 1 (Grauwin and Jensen, 2011) to detect the "best" point to evaluate SDGs communities. As a result, a co-bibliography network was selected with 8,721 in WoS (modularity=0.916, cut point=0.15) and 2,402 in SciELO (Modularity=0.7631, and cut point=0.20) in the great component.

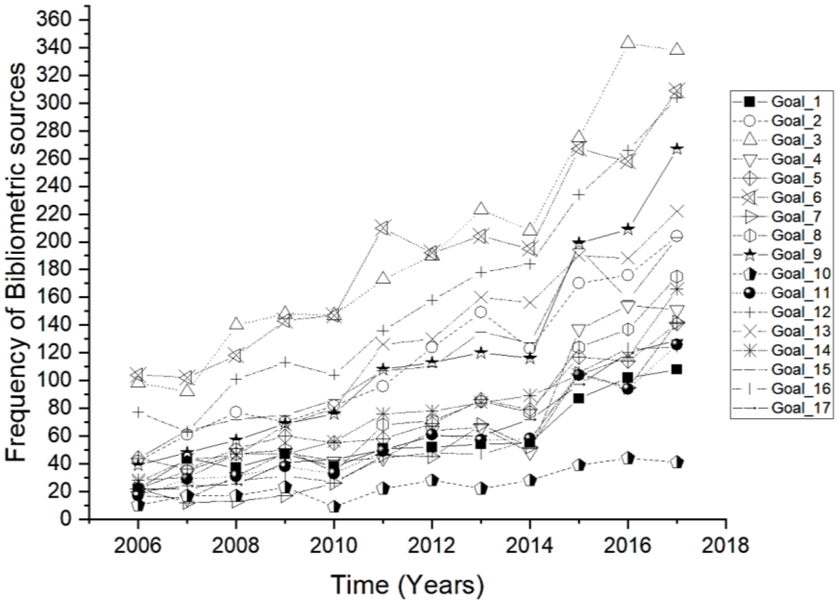


Figure 4. The line graph shows the frequency of bibliometric sources from 2006 to 2017. This frequency is calculated from Web of Science and SciELO Citation Index information.

However, as outlined earlier, the focus of our methodology lies in the nature of interconnectivity and research agendas that exist between researchers working on different SDGs. This will allow us to see where emergent processes of knowledge networks might be occurring. For this purpose, we first evaluate key relationships using Transitivity Triad Census Distribution method. In this instance we are measuring cross interconnectivity between SDGs. Figure 5 (i) based on Web of Science shows that the category socio-technical systems based on single SDGs (STSTST-1) is the most dominant category (number 14) of triad and the two most common triads are SDG3 (health) and SDG6 (water). The second most common triads are represented by two SDGs, 6 (water) and 12 (responsible production and consumption). In terms of directionalities, triads formed of single SDGs, 13 (climate action) and 12 (responsible production consumption) are the most dominant. SciELO (5ii) shows a different pattern. The most frequent triads are related to SDG3 (health), SDG 8 (labour conditions), SDG9 (infrastructure and innovation), SDG 4 (education) and SDG12 (responsible production and consumption). In both SciELO and WoS SDG1 (poverty) and SDG10 (inequality) are not present in the dominant triads[14]. Framework condition triads are hardly visible in WoS and more frequent in SciELO. These contrasting results are significant. Research published in WoS is a great deal more specialised in single SDG functions than in SciELO.

[14] TDTDTD-1 refers to transversal direction triads with just one SDG. TDTDTD2- 2 refers to transversal directions triads with two SDGs and so on. The most common triads are with just one SDG in WoS. Scielo has a more cross-disciplinary pattern.

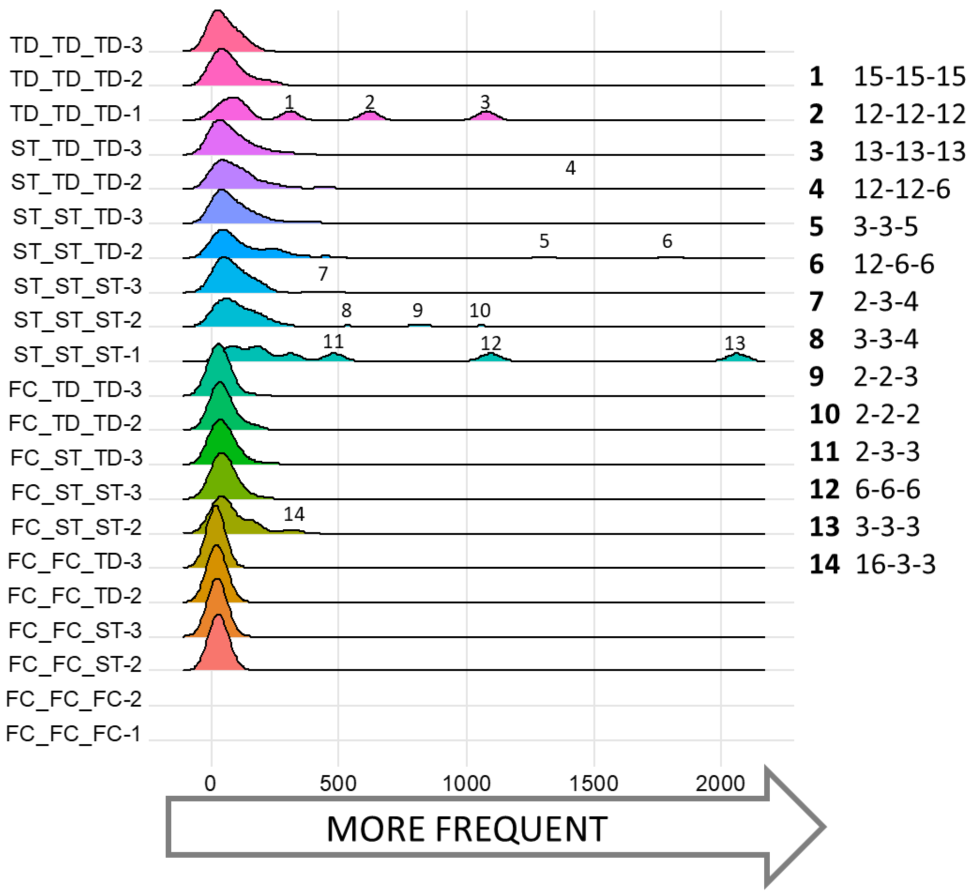


Figure 5 (i): Triad analysis in WoS

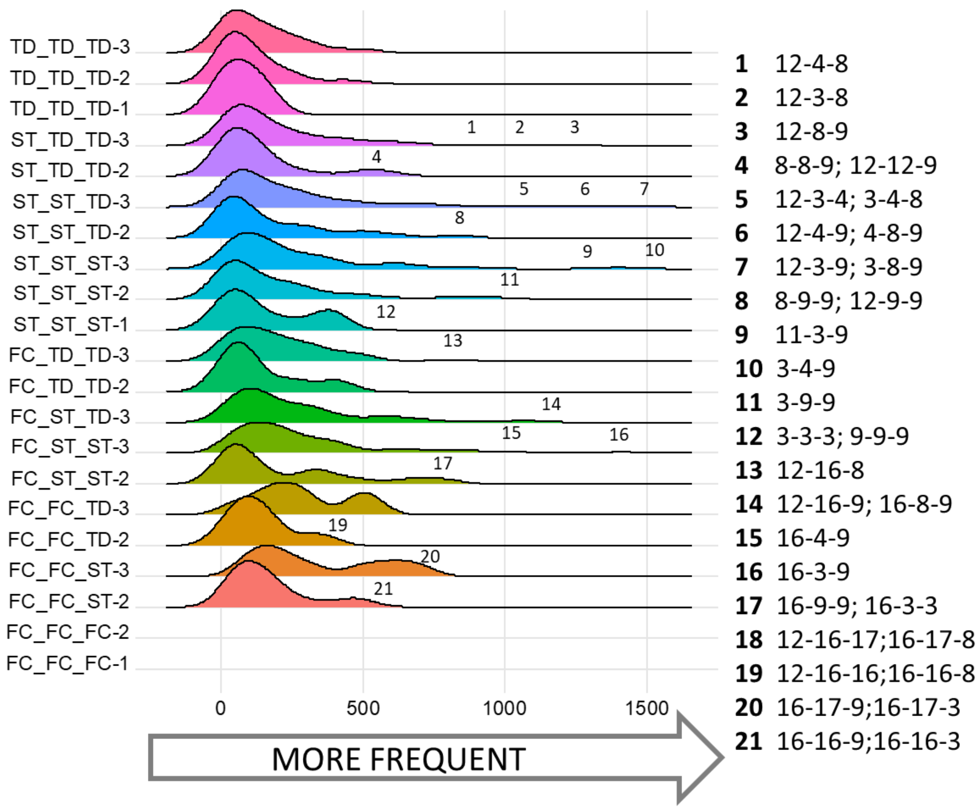


Figure 5 (ii) Triad analysis in Scielo

Figure 5(i) and (ii). Analysis of triads through socio technical systems and transversal directions. The figure shows the consolidation of the network from 2006 to 2017. ST: Socio-technical System; TD: Transversal Directionalities. The details of the 10 triads are shown in table 1

Figures 6 (i) and (ii) below and time windows in appendix 1 also shows the results of triad analysis, but here we graphically emphasize connectivity patterns between socio technical systems and directionalities. Counting the number of SDGs in each triad (represented by the size of circle) we see that in the WoS knowledge network, SDG 6 (clean water), SDG 3 (health), and 9 (industry, innovation and infrastructure) were the most frequent "socio technical" SDGs, while SDG 12 (responsible consumption and production) was by far the most dominant "transversal direction" SDG over the time period. The same pattern appears in terms of connectivity between socio technical systems and directionalities, represented by the top (most connectivity) to bottom (least connectivity), although SDG 2 (zero hunger), associated with agriculture, appears highly dominant. Given their significance for social and environmental sustainability, appendix 1 shows some important detail on SDG 1 (poverty), SDG 10 (inequality) and SDG 13 (climate change). This shows that in WoS time-window (2006-2008), SDG 1 (poverty) and 10 (inequality) builds relationships with each other and with SDG 2 (zero hunger), SDG 3 (health), SDG 9 (Industry, innovation and infrastructure) and SDG 17 (global partnerships). But in subsequent years, research into poverty and inequality drop out of the triads altogether[15]. SDG 13 (climate change) has a different pattern. Although SDG 13 is a constant feature of research, much of this is done separately and in isolation from other SDGs. Therefore it appears as a cohesive research group, but poorly connected with other researcher in other topics.

The SciELO knowledge network in figure 6 (ii) shows a higher diversity composition of triads than WoS. Although SDGs 3 (health), 6 (water), 9 (innovation and infrastructure) and 12 (responsible consumption and production) are also dominant, other SDGs appear in building transitivity triads. Appendix 1 shows that SDG 4 (education), 7 (clean energy) and 11 (sustainable cities) build transitivity triads with SDG 3 (health), 5 (gender) and 9 (innovation and infrastructure). Appendix 1 also show important connections between framework conditions related to peace and justice (SDG 16) in SciELO, building triads with SDGs 3 (health) and 4 (education) (2006-2008), with SDG 3 (health) and SDG 8 (labour conditions) (2007-2009). Research on SDG1 (poverty) consistently builds networks with health (SDG 3). On the other hand, SDG 10 (inequality) is completely absent. Weak connectivity is also a feature of SDG 13 (climate change). Summarising, we find that the most dominant triad patterns in WoS are concentrated in socio-technical systems section of figure 1, and within this specialised in health and water. The SciELO database has a broader and more diverse connectivity reflecting a more applied pattern of research with potential for connections between goals. Some SDGs such as inequality (SDG 10) are very weakly represented overall.

[15] The reasons for the drop in research in poverty and inequality would in itself be an interesting topic of investigation

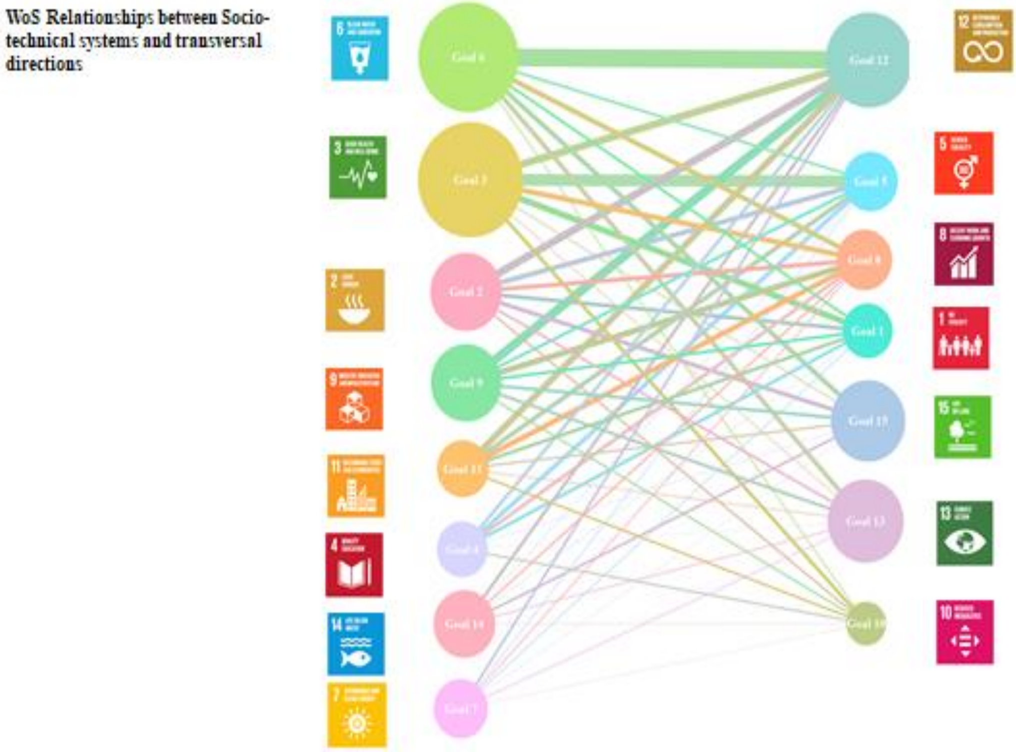


Figure 6(i): WoS relationships between socio technical systems and transversal directions

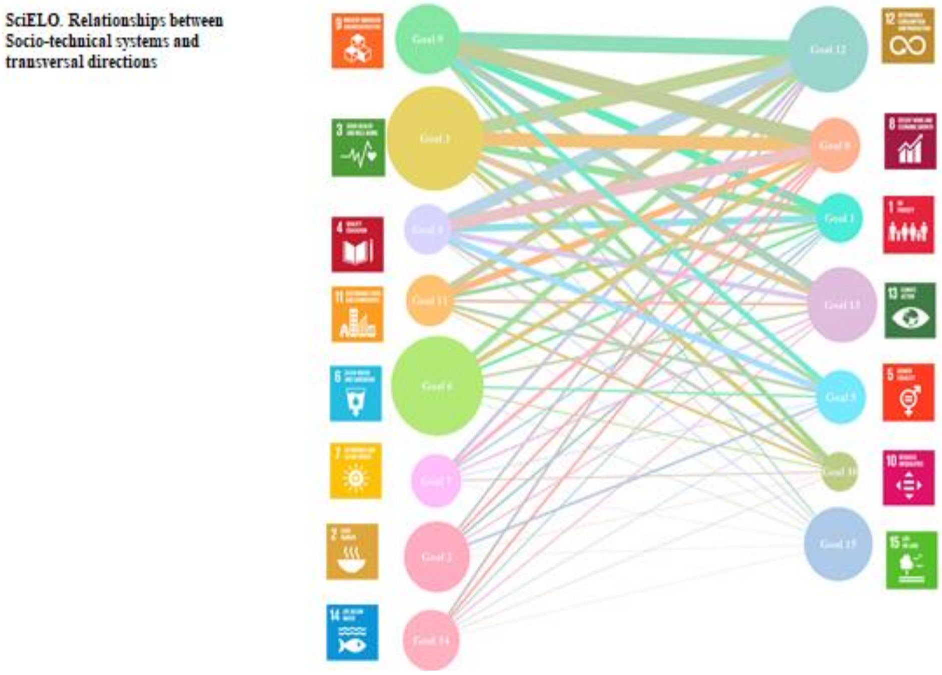


Figure 6 (ii): SciELO relationship between socio technical systems and transversal directions

Detecting key areas in Knowledge communities

Triad analysis identified overarching views of how SDGs are linked in publications. This section uses a different but complementary analytical lens to study potentially transformative research. Here we focus on the topics being researched by "knowledge communities", which we define as the articles that share significant proportions of their bibliographies. This analysis allows us to observe the topics in which groups of researchers are working on and how this relates to our earlier analysis of SDGs. The communities were built by relating every article to SDGs and secondly, evaluating research topics (semantic words) to detect "key communities". Analysis of these communities allows us to identify in more detail how different SDGs connect in the system as whole and secondly to identify specific research agendas that are prioritized within the research system and to what extent these combine different types of SDGs. For this purpose, we evaluated the consolidated co-bibliography networks in the 12 years (2006-2017). As previously described, the WoS co-bibliography network is composed of 8,721 nodes. This produces 17,919 edges in the grand component (i.e. only taking into account nodes linked to a main network) whereas SciELO network has 2,402 nodes and 7,945 edges. We set the number of articles required to be considered a community as at least 10 articles. Based on this analysis, it was possible to detect 106 researcher communities in WoS and 41 in SciELO.

We then take a more detailed look at the actual communities and their topics, which is illustrated in figures 7(i) and (ii). Every colour in the maps represents a cluster of research communities that is summarised by its label. We detected eight main research community groups in WoS and five in SciELO (classification undertaken according to Johnson cluster similarity where communities were organized according to the frequency of SDGs bibliometric sources).

The eight communities on WoS consist of two communities working on health: 1) health care system (non-communicable and communicable diseases): 2) Public health strategies related to reduce vulnerabilities such as water, air pollution or malnutrition. There are three communities working on water: 6) development of sustainable technologies to reduce the contamination of water from agriculture (production and consumption), 7) interactions between water, agriculture and energy (e.g. debate about biofuels and the possible impacts in agriculture and water) and 8) research that focuses on developing technologies for water treatment. Finally there are three communities working on other aspects of sustainability: Community 5) working on planetary boundaries (represented by SDGs 13,14,15) where conservation and regeneration of ecosystems are the main strategies to address ecosystem degradation, community 4) on climate change scenarios and possible strategies for mitigation and adaptation and a smaller community 3) on research related to photovoltaic energy.

It is significant that some communities are much more diverse in terms of SDGs than others and therefore conduct research in a different manner. Communities 1 (health care), 8 (water) and 3 (solar energy materials) work on just one socio technical SDG and can therefore be regarded as more disciplinary. Community 4 on climate change also just works on SDG 13. By contrast, community 2, also on health combines health quality, natural resources (water and air quality) and social problems (vulnerability and malnutrition). Community 7 also has an important nexus between water, agriculture and energy (biotechnology).

For SciELO (figure 7ii), the network can be grouped into five communities working on 1) sustainable development and innovation in cities, (2) health and social vulnerabilities, 3) education strategies to address human rights in vulnerable communities, 4) conservation strategies to address climate change mitigation and adaptation and 5) production and consumption strategies to manage water and agriculture systems. Each community works across different SDGs. Community 3 working on education and human rights is worthy of highlighting because it combines SDGs from socio technical systems, directionalities and framework conditions. SDGs from sociotechnical systems such as hydrology (SDG6) and agroecology (SDG2) are most important, but SDG 5 (education) and 16 human rights) work with SDG 10 (inequality) and 1 (poverty). Thus analysis of cognitive communities provides an important alternative picture of SDG activity in Mexico that facilitates a more fine grained and enriched understanding of how different SDG related topics embrace complex problems.

A more in-depth analysis of some of the publications that make up these different research communities allows us to observe some differences in how communities are constructed. We take the example of communities working on water quality. In figure 7 (i) community 8 is narrowly technological and incorporates papers only in SDG 6. An analysis of these papers shows that the problem of water contamination is addressed by building artificial wetlands and wastewater treatment plants to reduce environmental impacts (e.g. Durán-de-Bazúa, Guido-Zárate, Huanosta, Padrón-López, & Rodríguez-Monroy, 2008; Zurita, White, Zurita, & White, 2014) from wastewater in industry and households. There is no mention of other SDGs, for example 11 (cities), 2 (zero hunger) or SDG12 (consumption) which might have broadened this to the use of water infrastructure for different types of users and engaged with discussions about consumption behaviour (rather than just filters). A second approach to water quality is community 7 that focuses on SDG 6 (clean water) to produce positives impacts in SDG 2 (agriculture). So this looks at the effect of one socio technical systems on another (Cortés-Jiménez et al., 2007; Delgado-Ramos, 2018). Community 6 on the other hand groups papers that are working on cleaning contaminated water in a more complex way by aligning social and political aspects related to water demands and social vulnerabilities in rivers in Mexico, see for example (Navar, 2011). This research open up a discussion about unsustainable practices, climate change impact in water supply, and conservation and restoration strategies to avoid flooding (Corral-Verdugo & Pinheiro, 2006; Saldaña-Fabela, Díaz-Pardo, & Gutiérrez-Hernández, 2011). This connects SDGs 6, 12, 13, 15. Embracing greater complexity in research that builds bridges between different types of SDGs can help to open up ways of thinking about common problems that are more sensitive to societal needs.

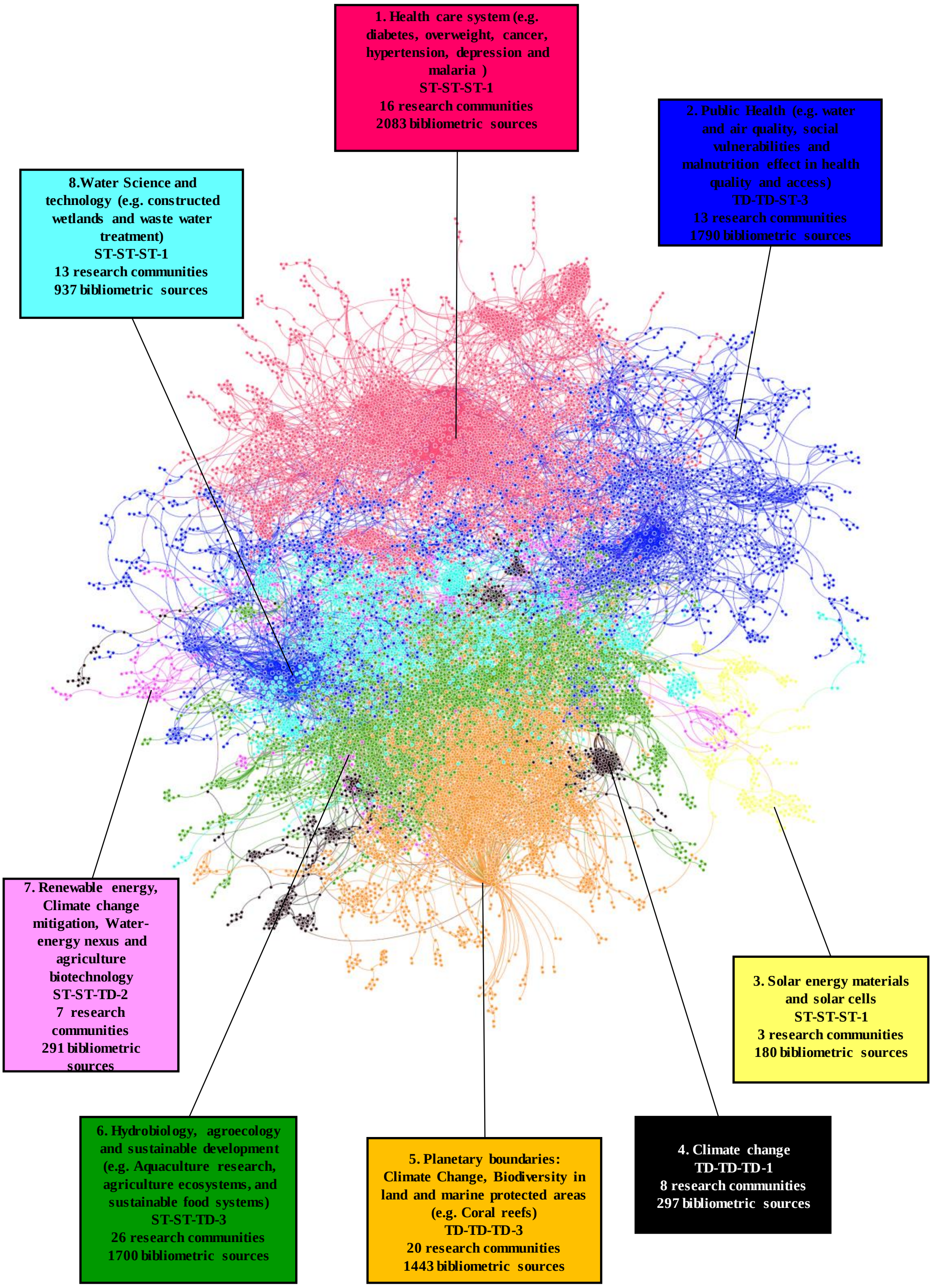


Figure 7 (i) Web of Science knowledge network.

The parameters of plotting were Force atlas 2 (tolerance 1.0, approximation 1.2 and gravity 0.001. The principal network measures are: Average Degree: 4.109; Network Diameter: 31; Modularity: 0.959; Average Clustering: 0.336 and Average path Length 10.036. Every Square shows the main topics of the cluster, the most common type of triads, the number of research communities and the number of bibliometric sources. It was graphed using Gephi 0.92.

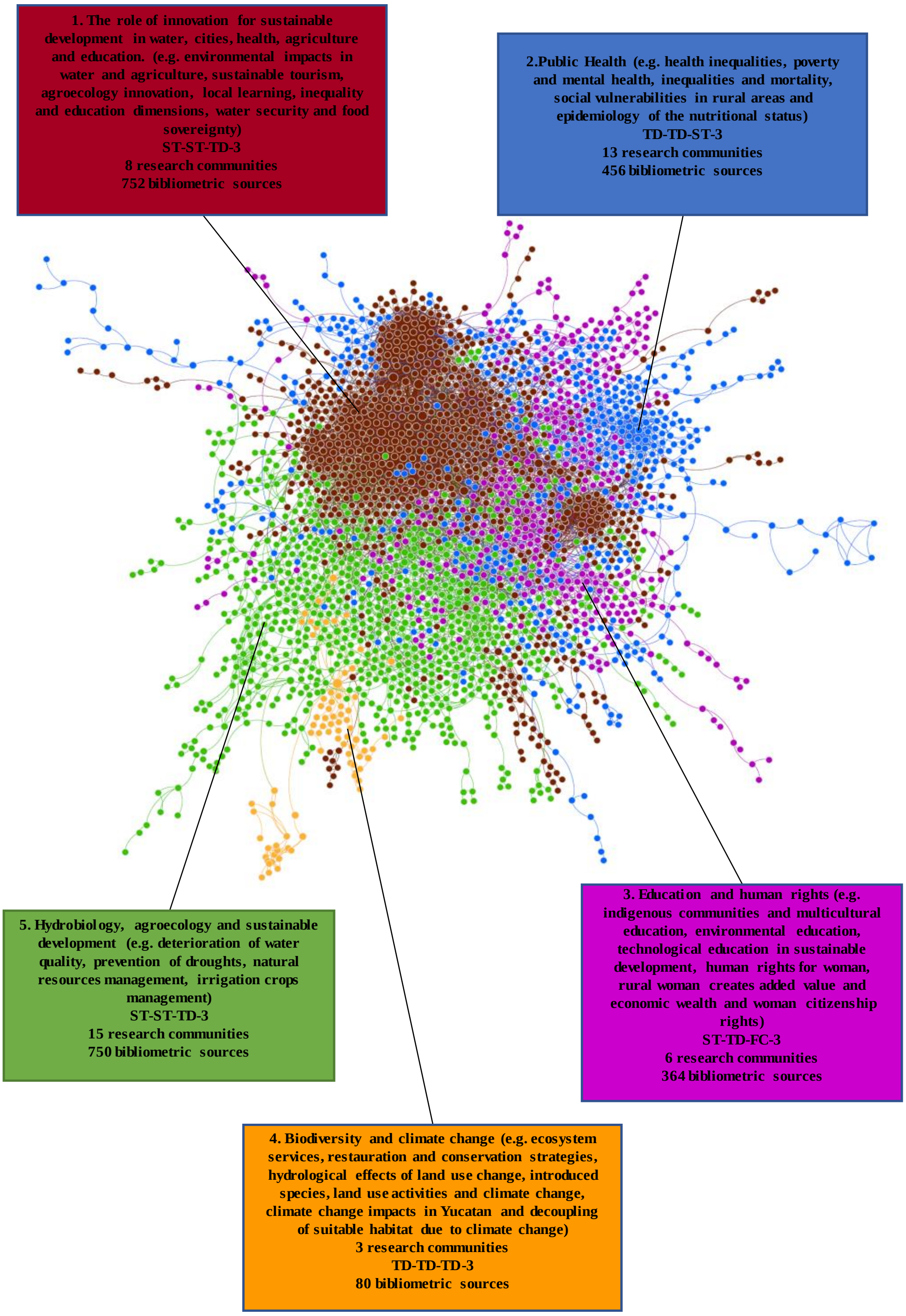


Figure 7 (ii) SciELO knowledge network.

The parameters of plotting were Force atlas 2 (tolerance 1.0, approximation 1.2 and gravity 0.01. The principal network measures were: Average Degree: 6.241; Network Diameter: 22; Modularity: 0.798; Average Clustering: 0.324 and Average path Length 6.529. Every Square shows the main topics of the cluster, the most common type of triads, the number of research communities and the number of bibliometric sources. It was graphed using Gephi 0.92.

Conclusions

The sustainable development goals can motivate some useful questions about whether, to what extent and how research systems are helping to build a knowledge base to construct sustainable futures. We have proposed that investment in research that links sociotechnical systems and directionality related SDGs may help to advance an agenda of transformative change that is required to successfully address different SDGs. The use of bibliometric methods to provide a diagnostic that identifies different types of connections can be a useful tool towards this end, although any empirical generalisations need to be cognisant of the specificities of the databases being used, as became clear through comparison of WoS and SciELO.

Tthree additional arenas for contribution are discussion. Firstly, both WoS and SciELO databases show that over a 12 year period there has been a considerable increase in research and publications in SDG related areas in Mexico although, particularly in WoS, much of the production of knowledge revolves around four SDGs associated with health, water, infrastructure and responsible production and consumption (see figure 5i). A first interpretation of these results would suggest that social priorities are being addressed predominantly from technical and indeed disciplinary perspectives. Where links between socio technical systems and directionality appear they take place predominantly with SDG 12 (responsible production and consumption). It is significant that two areas of chronic and prolonged problems - poverty and inequality - are under-represented. The wider point is that the research system is unlikely to have strong transformational impact in terms of strategies to reduce some of the most enduring problems of social exclusion and planetary degradation if investment in poverty, inequality and biodiversity continues to be underinvested.

However, the use of triads and cognitive communities as a methods uncovered that some SDGs that do not appear strongly represented, (including social the environmental goals), are working alongside other science SDGs in nexus-type relationships. Indeed, SDGs 3, 6, 12 in fact appear as enablers for the integration of other SDGs. Furthermore, we detected the key role of education and human rights to integrate poverty and inequality agendas, as well agriculture and water to integrate climate change and biodiversity. This discussion sheds light on a second arena of contribution, which is with regard to methodologies for the measurement of SDG interaction and transformations. As discussed earlier, an important preoccupation exists around ex-ante identification of the synergies and trade-offs between SDGs. Some approaches, for example (Nerini *et al.*, 2017), address these by bringing in experts whilst Nilsson et al. (2018) propose engaging with policy makers, stakeholders and researchers consultation through dyad analysis. However, ex-ante understanding of all the possible interactions across different contexts is likely to be a difficult task. A more grounded empirical approach such as that suggested in this paper could significantly add value to existing approaches.

Thirdly, in terms of the direction of SDG research, Randers et al. (2018) propose four main strategies to achieve SDGs. They argue that limiting oneself to economic approaches, or addressing the 17 goals simultaneously, is unlikely to be enough to achieve the 2030 agenda. Therefore, they make four main recommendations. A focus on the acceleration of renewable energy growth: transitions to sustainable agriculture; active inequality reduction; and encouraging investment in education for all. Our analysis of the SciELO database also suggest that in a Mexican context, education and human rights need to be linked to inequality and poverty. Our results from WoS also suggest that it could be relevant to include water quality technologies as a nexus to address transitions in energy and agriculture. Furthermore, that reducing social vulnerabilities and encouraging the conservation of planetary boundaries could have a positive impact in good health and wellbeing.

Finally, in terms of future research, our approach chimes with Cornell et al. (2013), who emphasize the importance of learning from knowledge production to address sustainability. However, they also suggest that bibliometric analysis on its own might be rather limited to evaluate impact of knowledge. Thus it is necessary to include knowledge production with experimentation to learn about synergies and trade-offs. In this regard, we suggest that knowledge communities and triads might be relevant approaches to plan experiments and strengthen transformative niches. This paper can thus help to open up a discussion about new policy framings for science, technology and innovation policies for transformations and accelerate SDGs inspired approaches.

As a final reflection, it is clear that embracing the transformative potential of the SDGs will require systems of innovation with the capacity to absorb more complex interactions. Research of this nature is already taking place – see for example nexus project (Bazilian et al., 2011; https://www.water-energy-food.org/resources/projects/). Our approach and results can help to make this type of work more visible and make connections with the current literature about SDGs from transformative innovation approaches.

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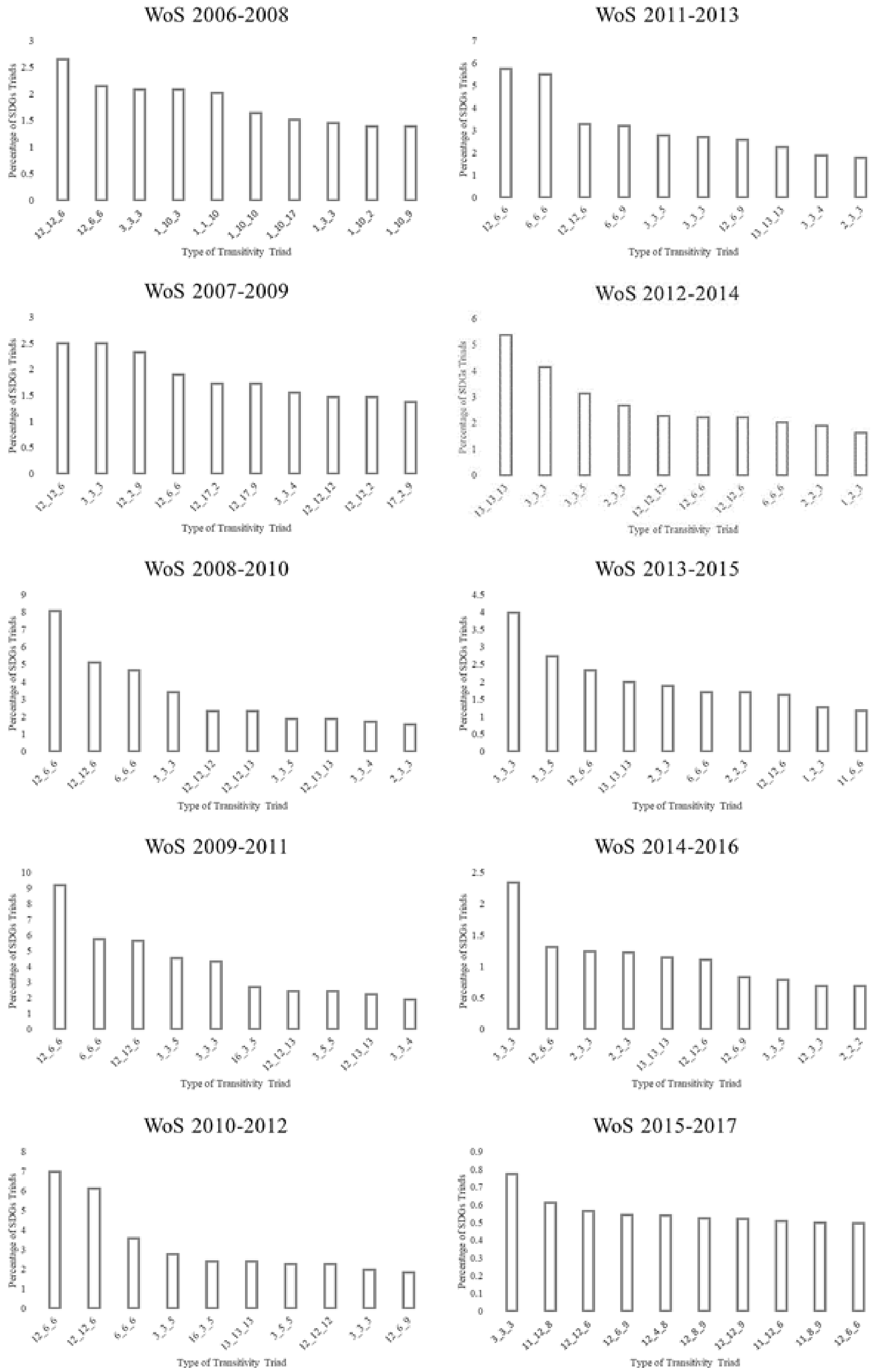
WoS 2006-2008
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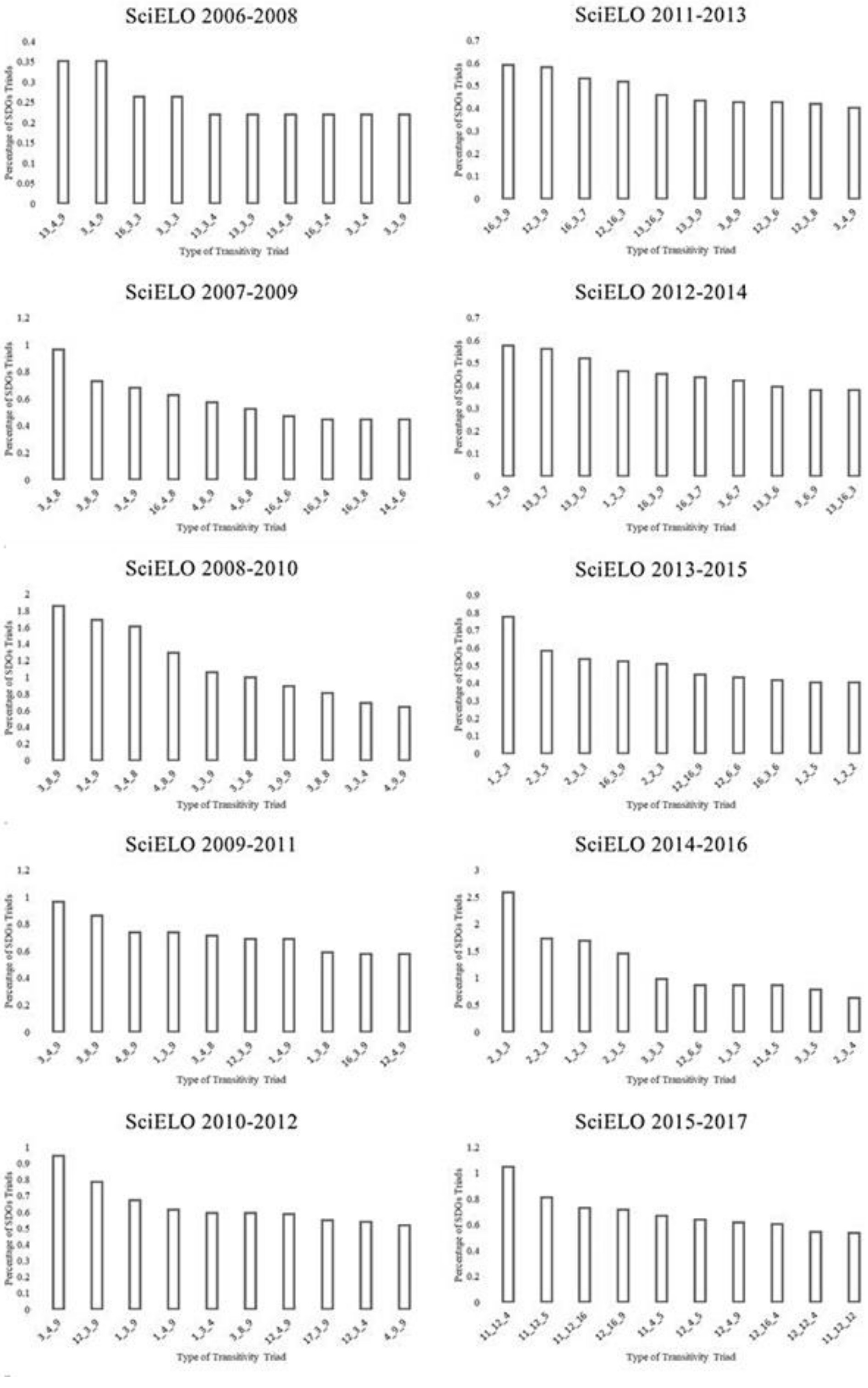
Percentage of SDGs Triads
Type of Transitivity Triad



Appendix 1: Transitivity triads Distribution according to SDGs researcher sources. The bar graphs show the percentage of triad found in WoS and SciELO Citation Index in 10-time frames. It represents the dominance of triads in different periods of times. The x axis shows the type of triad, where it illustrates the number of SDG that conform every triad. The percentage of the SDGs triads changes trough the time so as to show the most frequent triad in every period.

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