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Mobilizing the transformative power of research for achieving the Sustainable Development Goals☆

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ABSTRACT

This paper addresses the important question of how research 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 towards a focus on how SDGs are enabling transformative change. A conceptual approach is presented based on the notion that research should build bridges across three types of SDGs: ones that reflect socio-technical system change, directionality, and framework conditions. This proposition is explored empirically through a case study of Mexican scientific knowledge production using methods from bibliometric and social network analysis. Our results can help to provide a diagnostic of how knowledge production is contributing to the SDGs and can be used in science, technology and innovation policy, in particular transformative innovation policy.

1. Introduction

The 17 Sustainable Development Goals (SDGs) set out in the United Nations 2030 Agenda create a space to stimulate thinking and action about transformative changes in our economy and society. Therefore, the SDGs should not be seen as a set of individual goals, they potentially represent a new interlinked transformative way to think about how to address societal challenges. As the 2015 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. For us this overarching goal is represented by the notion of transformation, which is in fact flagged in the strapline of Agenda 2030: 17 SDGs for *Transforming our World*[1] (United Nations, 2015).

The SDGs invite a deep reflection about the choices and directions for public investments in scientific knowledge production. The main question we address in this paper is: how might it be possible to unlock the transformative potential of scientific knowledge production for addressing the SDGs? We seek to answer this "how" question through a specific methodology, which involves 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 scientific knowledge production system, between which areas and what type of research is more likely to be a catalyst for transformations?

Our question echoes wider calls for a new framing for science, technology and innovation (STI) policy focused on transformative change by a number of authors (see for example: Bloomfield and Steward, 2020; Diercks et al., 2019; Schot and Steinmueller, 2018; Weber and Rohracher, 2012). This framing interprets transformative change as a fundamental change in socio-technical systems that address social and ecological challenges. This new framing of STI policy moves beyond two earlier framings that focus on stimulating economic growth through investment in R&D and the production of new knowledge without taking into account whether this knowledge addresses social and ecological issues (frame 1) and investment in learning among actors

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

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operating in national, regional or sectoral innovation systems (frame 2). This is about building links across actors, often with a focus on firms, and enhancing absorptive capacity (of knowledge) among actors. As Lundin and Schwaag (2018) have noted, a framing of STI policy that focuses on transformative change has a strong fit with the principles of the SDGs. We build on the notion that to be consistent with the SDGs, frame 3 STI policy should consider how to produce scientific knowledge that can assist transformation.

The paper is structured as follows. In Section 2 we engage with the literature on measuring progress towards the SDGs. We emphasize that whilst discussions about measurement have rightly been on systems, synergies and trade-offs, a focus on transformative processes require the opening up of scientific knowledge production for specific types of SDGs interactions needed for transformative change to happen. In Section 3 we present a methodology using bibliographic coupling (network analysis) measuring cognitive proximities to help identify interactions across SDGs and knowledge communities. We analyze and compare journal publications from the Web of Science (WoS) and SciELO databases (English and Spanish/Portuguese languages respectively). In Section 4 we present an empirical study of the Mexican research system using this methodology. Mexico was chosen for the empirical analysis because of the working relationship and familiarity of the authors 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, 2016, 2017) in the region, and with a significant number of actors working in the science and technology system. We consider Mexico a revealing (or critical) and representative case study for exploring our research question and testing our methodology that can be used for showing the power of our argument about the need to focus on transformative potential. We thus argue that if we can answer our research question for the Mexican case, it is likely we can do this also for other cases using our methodology (Flyvbjerg, 2006). In Section 5, we discuss the main outcomes of our study and in Section 6 we present policy implications.

2. From single SDGs to interactions and transformations

Empirical studies of progress on SDGs stress that a key area of research is to understand the interlinkages between SDG goals (Allen et al., 2018; McCollum et al., 2018; Nilsson et al., 2018; Weitz 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 mechanisms because of their inability to provide adequate insights on possible synergies and trade-offs (McCollum et al., 2018; Nilsson et al., 2018; Weitz et al., 2018). For example, discussions around the meeting points in Clean Water (SDG 6), Clean Energy (SDG 7) and Zero hunger with its emphasis in sustainable food (SDG 2) emphasize the necessary integration of goals across systems (Timko et al., 2018).

Measuring progress on meeting SDG targets also requires making extra efforts to improve the quality of data, explore new sets of metrics and the use of these to provide indicators of progress that may help to construct impact assessment of different policies (Rafols et al., 2021). 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 et al., 2017; Sachs et al., 2019; 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) https://www.oecd.org/dac/development-co-operation-report-2016.htm (OECD, 2016), the United Nations Development Group (2016) https://sustainabledevelopment.un.org/content/documents/127761701030E_2016_VNR_Synthesis_Report_ver3.pdf (United Nations, 2017), and the United Nations Division for Sustainable Development (2017) https://unstats.un.org/sdgs/report/2019/The-Sustainable-Development-Goals-Report-2019.pdf (United Nations, 2019). At the same time, the general trend for models inspired by systems thinking (Le Blanc, 2015; Weitz et al., 2018) is to involve the identification of clusters of interconnected targets and integrated models (Le Blanc, 2015; McCollum et al., 2011) that are based on machine learning techniques and are being used to label and analyze SDGs (Duran-Silva et al., 2019). Another important and positive development is that various SDG measurement projects using bibliometrics methods have developed controlled vocabularies (thesaurus) for labeling publications using policy documents related to the SDGs[2] (Duran-Silva et al., 2019; Rafols et al., 2021).

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 set of challenge exists of developing a methodology to enable a grasp of where scientific knowledge interaction or even integration is taking place (or could take place) that can support the transformational change inherent in the SDG ambition (Abson et al., 2017). This demands the development of an analytical framework that specifies which type of dynamic interconnectivity between different types of goals and feedbacks can be associated with transformational change.

To develop this framework we draw on the sustainable transitions literature (Grin et al., 2010a, 2010b; Köhler et al., 2019; Markard et al., 2012; Geels, 2007, 2018; Konrad et al., 2008; Papachristos et al., 2013; Raven and Verbong, 2007; Rosenbloom, 2020) which suggests that transformations are generated through changing socio-technical systems. Recent work on multiple system change suggests that single system change is often not possible if other related systems are not changed too. For example, changing the mobility system by electrification demands a change of the energy system. The Deep Transition framework, goes a step further and argues that system change as well as linked system change needs to move in a similar direction (Schot and Kanger, 2018; Sutherland et al., 2015). However, for this to happen cognitive bridges are needed across socio-technical systems. Actors need to agree on which directions to use for changing the systems (Imaz and Sheinbaum, 2017; Kanger and Schot, 2019; Stirling, 2009).

The above suggests that an understanding of different phases of transitions processes and what these involve are important. For instance, Hölscher et al. (2019) point out that the use of transition and transformation concepts has been used to describe a continuum from changes at societal sub subsystems (for example energy, mobility, cities) to larger-scale changes in whole societies. Other studies point out that niche activities are often initiated in isolation during the early stages of transitions (Papachristos et al., 2013; Raven and Verbong, 2007; Schot and Kanger, 2018; Sutherland et al., 2015) sometimes within specific scientific fields, whilst at more advanced stages involve coupling socio-technical systems via rule settings (meta-rules) and material ties (e.g., infrastructure complementarities). We build on these by suggesting that the evolution of transition process through SDGs can show interlinkages taking place across multiple socio technical systems and can highlight research links between socio technical systems and the values that drive the use of science and technology, such as reducing poverty, limiting $C0_2$ emissions and respecting human rights. This can help to counter, for example, "carbon tunnel" visions which strive for "net" zero emissions while ignoring other sustainable goals.

Hence, the argument is made for a gradual shift to sustainable systems in all these areas. The new systems should be based on new

[2] Examples include How Science, Technology and Research and Innovation are contributing to the Sustainable Development Goals (sirisacademic.com) and STRINGS – Science technology research and innovations for the global goals

normative commitments related to the notion of sustainable development. These normative commitments relate to ecological (environmental) and social goals and can be called new directions or directionalities (Imaz and Sheinbaum, 2017; Kanger and Schot, 2019; Stirling, 2009). There may be a range of possible directions, representing different values and interest. Thus, conceptual linkages across the SDGs can help to trigger common directionalities in the processes of transformative change.

Sustainability transitions research does not prescribe which direction is better, it only asserts that the direction embedded in the current systems is not sustainable and integrated responses are required that combat the combined challenges of poverty, inequality (in terms of inclusion), climate crisis and severe biodiversity losses. For this, we need new relationships across these systems that can be optimized and address these directions. For example, we require Clean Energy systems with links to End of Hunger (Sustainable food) that address No Poverty, Reduced Inequality and addressing Climate Action. In this context it is important to note that transforming socio-technical systems is therefore about establishing new cognitive linkages across systems and working across system dimensions, from science and technology to user preferences, cultural perceptions, industry strategies and policy measures. Hence, system change is multidimensional and involves many actors who are related to these dimensions. Therefore, to be successful and to enhance the democratic quality of the transformation process, voice and power need to be given to a wider group of actors, including universities and research centres, governments, firms and civil society in a participatory and inclusive process.

Sustainability transitions research thus argues that for meeting the SDGs we need new relationships across socio-technical systems that are optimized and address sustainability related directions. For example, we require Clean Energy systems with links to End of Hunger (Sustainable food) that address No Poverty, Reduced Inequality and addressing Climate Action. The literature however goes one step further. System change is multidimensional and involves many actors. Therefore, to be successful and to enhance the democratic quality of the transformation process, voice and power need to be given to a wider group of actors, including universities and research centres, governments, firms and civil society in a participatory and inclusive process (Grin et al., 2010a, 2010b). These aspects are also included in the SDG 16 and 17, and represent a specific category or type of SDG addressing transition governance.

Using the sustainability transitions literature, we are thus able to suggest a framework for assessing whether a research system is producing relevant knowledge for moving societies in a transformational direction. The starting point is that the 17 SDGs can be broken down into three types: A first type is SDGs which we refer to as "socio-technical systems" that describe areas of provision of basic needs such as Zero Hunger (SDG 2) (which is related to sustainable food); Health and Wellbeing (SDG 3); Inclusive and Equitable Quality Education (SDG 4); Clean Water (SDG 6); Clean Energy (SDG 7); Industry, Innovation and Infrastructure (SDG 9); Sustainable Cities and Communities (SDG 11), and Life below Water (SDG 14). The second type is SDGs that express new social and ecological directionalities that need to be incorporated in the process of socio-technical system change. These directionalities are captured in the following SDGs: No Poverty (SDG 1); Gender Equality (SDG 5); Decent Work and Economic Growth (SDG 8); Reduced Inequalities (SDG10); Responsible Production and Consumption (SDG 12); Climate Action (SDG 13) and Life on Land (SDG 15). In Fig. 1 we use the notion of traversal directions because these directionalities need to intersect with socio-technical systems. The third type of SDG refers to the requirement for wider participation and networking across actors which assumes specific governance and political conditions in which societies can discuss, negotiate and navigate different transformational trajectories of development. These are exemplified in Peace, Justice and Strong Institutions (SDG 16) and Inclusive Partnerships (SDG 17). In summary, the three categories of SDGs outlined above can therefore be

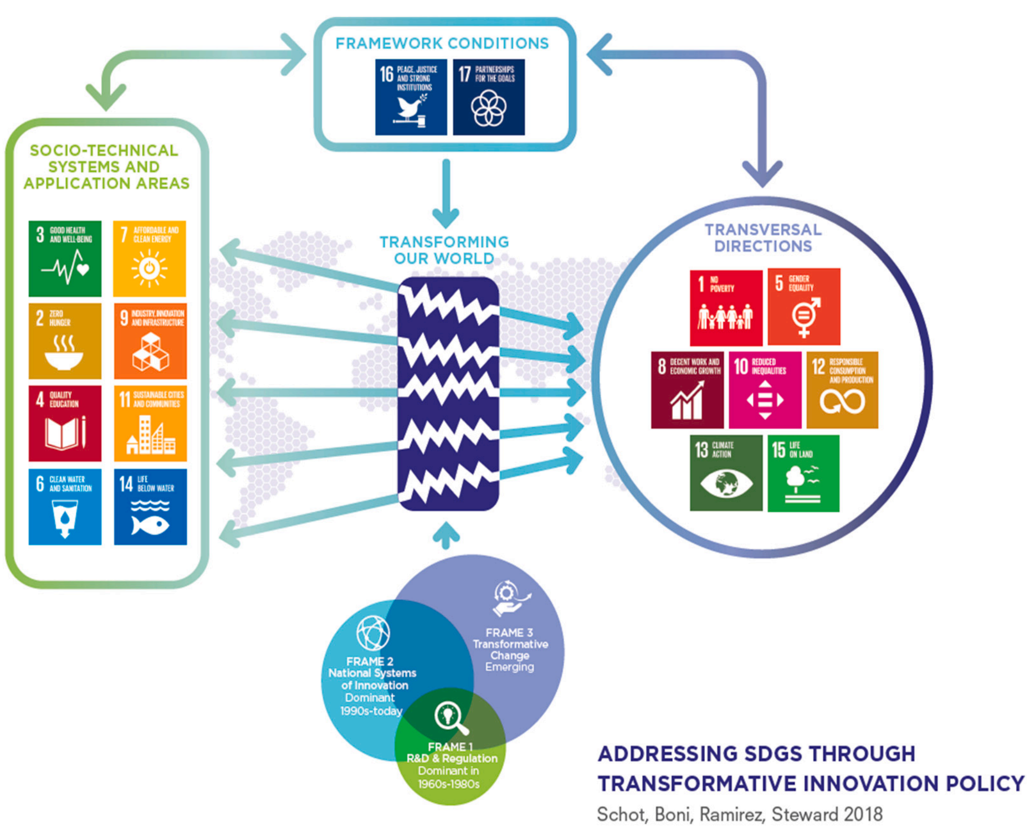


Fig. 1. SDGs are grouped into three categories: Socio-technial systems, transversal directionalities and framework conditons, Adapted from Schot et al. (2018).

distinguished in the following way (see Fig. 1):

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

Aggregating SDGs 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, a careful inspection of each goal and the targets attached to it shows that a dominant approach exists when addressing each goal (to access this classification see "Availability of data and materials"). For example, in the case of Zero Hunger (SDG 2), this is composed of eight targets. 2.1 and 2.2 are related to social and environmental goals and are therefore akin to directionality, while the other remaining targets are related to the food production, which corresponds to a socio-technical system (double the agricultural productivity, ensure sustainable food production systems, maintain the genetic diversity of seeds, rural infrastructure, world agricultural markets and functioning of food commodity market). Therefore, there is a tendency to focus on transforming the food production system in this SDG and we therefore label it as a socio-technical system type of SDG. Likewise, Life Below Water (SDG 14) is labelled as a socio technical system because it refers predominantly to the fishing system, whilst Life on Land (SDG 15) is placed as directionality SDG because it refers primarily to biodiversity loss.

The proposed framework is aligned with conclusions of others studies such as Cornell et al. (2013), who argue that the scientific knowledge system should integrate multiple stakeholders, disciplines and build bridges across multiple sustainability goals. The integration of diverse knowledge has also been emphasized by (Rafols and Meyer, 2010) who explain the growth of the bio nanoscience, a new industry that emerged by integrating different sources of knowledge using bibliometric similarity methods. They in turn built on broader discussions on the importance of diversity of knowledge sources (Boschma et al., 2014; Heimeriks and Balland, 2016; Heimeriks and Leydesdorff, 2012; Stirling, 2007, 2009) to break narrow disciplinary trajectories of knowledge that will struggle to address complex social and economic problems. Moreover, common visions around multiple SDGs can reduce possible trade-offs and foster synergies between them (McCollum et al., 2018; Nilsson et al., 2018; Rafols et al., 2021), and as Marshall et al. (2018) have argued building bridges between different academic areas is a means of producing knowledge that can achieve transformations.

3. Methodology and data analysis

This section explains how the framework presented in Fig. 1 is operationalized. The proposed method is based on identifying cognitive similarities within scientific knowledge publications associated with the SDGs. Specifically, we look at the frequency of scientific knowledge publications that integrate new social and environmental normative commitments or directionalities with multiple socio-technical systems in a context of peace, justice, and partnership. This is analysed using network analysis and bibliography coupling (cognitive similarities) of scientific publications related to the SDGs. Bibliographic coupling provides a structural analysis of conceptual interactions between scientific publications by measuring their cognitive similarity as expressed in their common bibliography (co-bibliography network, see section 1 in supplementary material). The co-bibliography network is composed of publications (nodes) connected by their common references (weighted link) that reflects their conceptual and cognitive similarity.

We use the core-document approach (Glänzel and Czerwon, 1996; Jarneving, 2007; Subir and Shymal, 1983) to identify academic publications associated with the SDGs topics (see sections 1 and 2 in supplementary material for further discussion). This allows us to identify consolidated cognitive knowledge trajectories expressed in clusters of scientific publications that have the highest cognitive interrelatedness while excluding publications that can be misidentified as SDG related. These publications act as a proxy of knowledge communities since formal collaboration, knowledge diffusion, and cognitive communication take place within them. Our use of bibliographic coupling as an indicator of knowledge integration builds on a broad tradition of similar work (Bornmann, 2013; Garfield, 2006; Rafols et al., 2010; Rafols and Meyer, 2010) both in the natural and social sciences and can be seen as a proxy to identify research that can potentially supports new transformative approaches to societal challenges raised by the SDGs. The potential for this is uncovered by mapping the SDG interactions taking place.

The diversity of interconnections between SDGs within the co-bibliography network are studied and this can identify how SDGs are interacting in the cognitive dimension of knowledge production through publications. This is based on showing diversity of interactions in which the generation, consolidation and growth of knowledge emerges through the construction of "building blocks of knowledge" (Boschma et al., 2014; Castaldi et al., 2015; Frenken et al., 2007; Heimeriks and Balland, 2016; Heimeriks and Leydesdorff, 2012; Leydesdorff and Heimeriks, 2001). Therefore, cognitive relatedness between SDG scientific publications is the main analytical strategy by which we understand scientific knowledge integration.

The importance of cognitive integration lies in that it can influence the directionality of evolution of research systems. In other words, cognitive integration can act as the device of action and change. We therefore argue that cognitive integration is a key mechanism and a good indication of transformative directions. Notice that our framework does not focus on mapping synergies and trade-offs. By contrast, we aim to identify to what extent scientific publications are integrating research on socio-technical systems and new social and environmental directionalities. Thus, studying cognitive integration of scientific publications can help tell us something about directionality. This process of reflection (ex-post) can contribute to shaping and enhancing synergies across the SDGs.

To evaluate the interactions between SDGs we use Triad Analysis as a proxy of SDG cognitive integration. This allows us to detect the interconnectivity between groups of three articles connected in the co-bibliography network based on their SDGs associated to those publications. As argued, this cognitive interconnectivity represents building blocks across SDGs and provides an understanding of their cognitive similarity. Triad analysis involves "detailing groups" of three connected nodes (triads) in network analysis jargon. The method involves finding the most common cognitive triads in the co-bibliography network (Burgin, 2018), which we can then use to determine the most common cognitive relationships between our three SDG categories through Triad Census Distributions (TCDs) (Aarstad, 2013). Triads generate circuits, which is a key feature of communities and is therefore a useful approach in networks for looking at connections because they are considered more resilient in a network structure, since a break in one connection does not isolate other nodes as would be the case in dyads (Aarstad, 2013; Burgin, 2018; Newman, 2001).

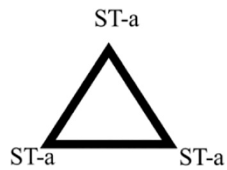
Referring back to Fig. 1, we can use triad analysis to detect connections between different forms of SDGs. This leads to 21 possible configurations of cognitive relationships of triads (see below), which we propose can be split into three categories of triads. Table 1 illustrates the cognitive interactions that can emerge from the combinations of these se between different SDGs.

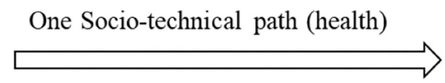
We see that firstly there are triads that are made up of just one SDG (e.g., health which we classify as Sociotechnical systems SDG). Research coming only from, for instance, health backgrounds may produce new knowledge but is more likely to remain within narrower and normative/traditional cognitive boundaries (Heimeriks and Balland, 2016; Leydesdorff and Heimeriks, 2001). Group 2 includes triads where cognitive bridges are built between two SDGs. They can be made up by SDGs from

Table 1
Possible triad combinations from Fig. 1.

<table>
<tr><th>Triad Types</th><th>Illustrative example</th></tr>
<tr><td>1. Triads composed of just one SDG which can come from sociotechnical systems, Transversal directionalities or framework conditions.

One category:

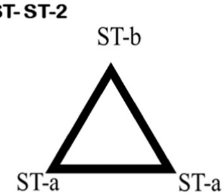
ST-ST-ST-1
TD-TD-TD-1
FC-FC-FC-1</td><td>one category


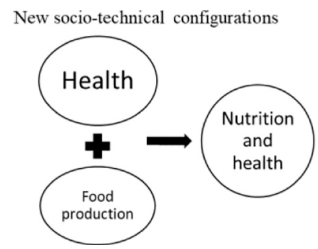

</td></tr>
<tr><td>2. These triads are composed of two SDGs which can be come from one or two SDGs categories:

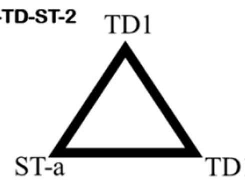
One category:

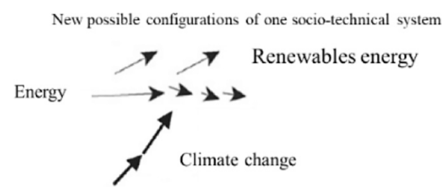
ST-ST- ST-2
TD-TD-TD-2
FC-FC-FC-2

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




Two categories
TD-TD-ST-2



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

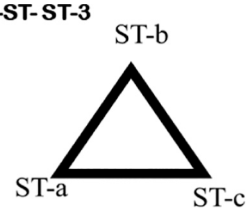
one category:

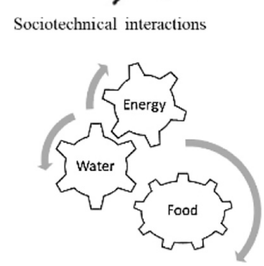
ST-ST-ST-3
TD-TD-TD-3

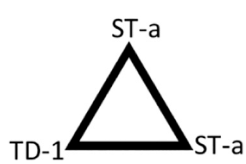
Two categories:

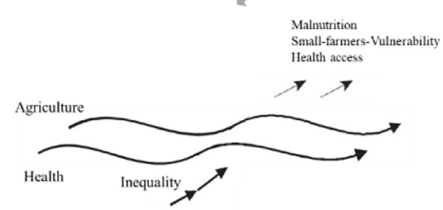
ST-ST-TD-3
TD-TD-SD-3
ST-ST-FC-3
TD-TD-FC-3
FC-FC-SD-3
FCFC-TD-3

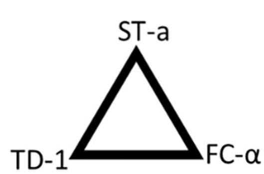
Three categories:

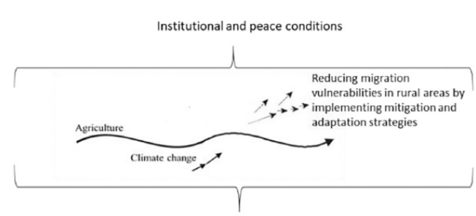
ST-TD-FC-3</td><td>one category
ST-ST- ST-3




Two categories
ST-ST-TD-3




Three categories
ST-TD- FC-3



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

Notes: The interaction with the triads represents cognitive links between SDGs. In each triad nodes are the SDGs, meanwhile the edges are cognitive interactions in our case common references. ST: Socio-technical System; TD: Transversal Directionalities and FC: Framework Conditions. The numbers in each type of triads represent how many different SDGs are interacting (for example ST-ST-ST-3 could be equivalent to SDG3- SDG4- SDG6). The letters within the triads represent where there are different types (following categories shown in Fig. 1) of SDGs are interacting. For example, three categories could be SD16, SDG3, SDG10. SDG16 would be an SDG in FC (Framework condition), that we have labelled α. SDG3 would be an SDG in ST (socio technical) we have labelled 1 and SDG10 would be an SDG in TD (transversal directionality) which we have labelled a.

one (e.g., ST1-ST2) or two SDG categories. This category may support more complex interactions between SDGs, for instance knowledge that combines two socio-technical systems such as End of Hunger (sustainable food; SDG2) and Health and Wellbeing (SDG 3) that might support socio-technical interactions such as nutrition and health (Table 1, row 2-column 3).

Triads might also combine SDGs from two different categories. For instance, Feng et al. (2010) and Beuchelt and Badstue (2013) undertake a study of conservation agriculture by integrating knowledge about Sustainable Food (SDG 2) with Reduced Inequalities (SDG10). This is an example of a study combining sociotechnical systems SDGs and Transversal directionalities SDGs in their research (Table 1, row 5-column 3). This research framework could support new ways of thinking about production and consumption of food that help to address inequality. The final group includes triads that combine three different SDGs and can come from all three SDG categories. For instance, the nexus project https://www.water-energy-food.org/resources/projects/) between Clean Energy (SDG 7), Clean water (SDG 6) and Zero Hunger (SDG 2) (sociotechnical systems) in developmental contexts addresses configurations relevant to produce alignments between sociotechnical systems that address disruptive technologies. Another example of this is the research by Arbour (2018) that manages to combines human migration with Climate Action (SDG 13) incorporating Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4), and Sustainable Cities and Communities (SDG 11) links to Gender Equality (SDG 5), Reduced Inequalities (SDG 5) and Climate Action (SDG 13) as well as Peace, Justice and Strong Institutions (Table 1, row 6-column 3).

In summary, we can identify triads of publications that integrate knowledge domains 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 towards social, governance and environmental goals, thus addressing complex societal challenges in more holistic ways. This approach and the interactions they show can suggest where synergies are taking place in practice in the research system.

3.1. Data selection

Our methodological approach for selecting only the publications most strongly associated to the SDGs is based on firstly developing a thesaurus to identify scientific publications related to SDGs. Second, bibliometric data was gathered from two data sets related to Mexico, the Web of Science (276,501 sources), a comprehensive English language database of research publication and SciELO Citation Index (50,823 sources)[3] a Spanish and Portuguese language database of scholar publications[4] (see Fig. 2).

Our thesaurus of 2101 search items was constructed by means of the following steps. We extracted key terms from the UN official list of Goals, Targets and Indicators (885 search items). The method for constructing the thesaurus began with a preliminary set with 884 search items in Web of Science and SciELO to identify a first set of papers related to SDGs. We also enriched our data set by selecting some of the key words suggested by Duran-Silva et al. (2019) and the Colombian Green Book (Colciencias, 2018). Not all the key words were used partly because of the large range of key words for each goal (for example Duran-Silva et al. (2019)) vocabulary contains around 622 key keywords in Health and Wellbeing (SDG 3) compared to 101 for No Poverty (SDG 1). This may create a high correlation between the number of keywords and the number of scientific publications labelled. Therefore, a more careful analysis of the words chosen for inclusion was undertaken, particularly around Decent Work and Economic Growth (SDG 8), Industry, Innovation and Infrastructure (SDG 9) and Inclusive Partnerships (SDG 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.[5] For instance, in Decent Work and Economic Growth (SDG 8), we only included bibliometric sources related to economic issues that also contain sustainability and/or directionality topics.

The number of search items in every SDG was limited to between 101 and 140.[6] This permitted the different goals to have a better balance in terms of how they were represented. Search items were categorized into two groups. A first group of 780 search items that are always together, such as “climate change” or “clean energy”. A second group consisted of 1323 topics that mix two or more terms that are not always together such as “economic” and “sustainability” (to access the thesaurus see “Availability of data and materials”).

We acknowledge that the use of a thesaurus can generate a possible biased picture of the interactions between the SDGs because existing conceptual links across the SDG targets can influence the conceptual linkages identified in the co-bibliography network. For instance, Poverty (SDG 1), Zero Hunger with its focus on Nutrition (SDG 2) and health and well-being (SDG 3) are closely related. In contrast, there are less closely conceptual linkages between No Poverty (SDG 1), Climate Action (SDG 13) and Responsible Production and consumption (SDG 12). This is a limitation of our method and indeed any other approach that uses thesaurus or meta-languages to identify SDGs publications.

However, our results suggest that this bias may not be present in triad analysis. Our argument is as follows: Previous studies of most common SDG interaction, such as Le Blanc (2015), found that frequent expected cognitive interactions, for example between SDGs are (zero poverty) SDG 1 and (Decent work and economic growth) SDG 8. However, our results don’t mimic these and in fact show a more complex set of interactions which reflect the place-dependent specific nature of cognitive relationships. Therefore, the nature of interactions are likely to vary across different contexts and our study provides an example of this trend.

3.2. Data filtering and construction of co-bibliography networks

In terms of the bibliometric analysis, two co-bibliography networks were generated from Web of Science and SciELO Citation Index information. Co-bibliography networks are composed of nodes (bibliometric data sources), ties (frequency of common references) and attributes (17 SDGs). A first trawl using our thesaurus allowed us to identify 100,246 and 23,912 sources in WoS and SciELO respectively. Once those publications or sources that have at least one tag from the thesaurus were identified (Fig. 2), we proceeded to evaluate which proportion of them correspond to misidentifications. Some tags that could be produced by synonymic or other factors associated to language were identified. To

[3] The query was CU = Mexico* in WoS, and AD = Mexico* in SciELO, and we took information from 2002 to 2019.

[4] 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 et al., 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.

[5] For a more detail discussion about different interpretation of the SDGs in the context of Thesaurus development see Rafols et al., 2021.

[6] A first approach considering different length of the key words in every SDGs performed a correlation of 0.7236 between the number of keywords and the number of SDGs labelled. Therefore, we enriched those SDGs which did not have a extend number of key words, having as a result a decrease to −0.005 on this correlation.

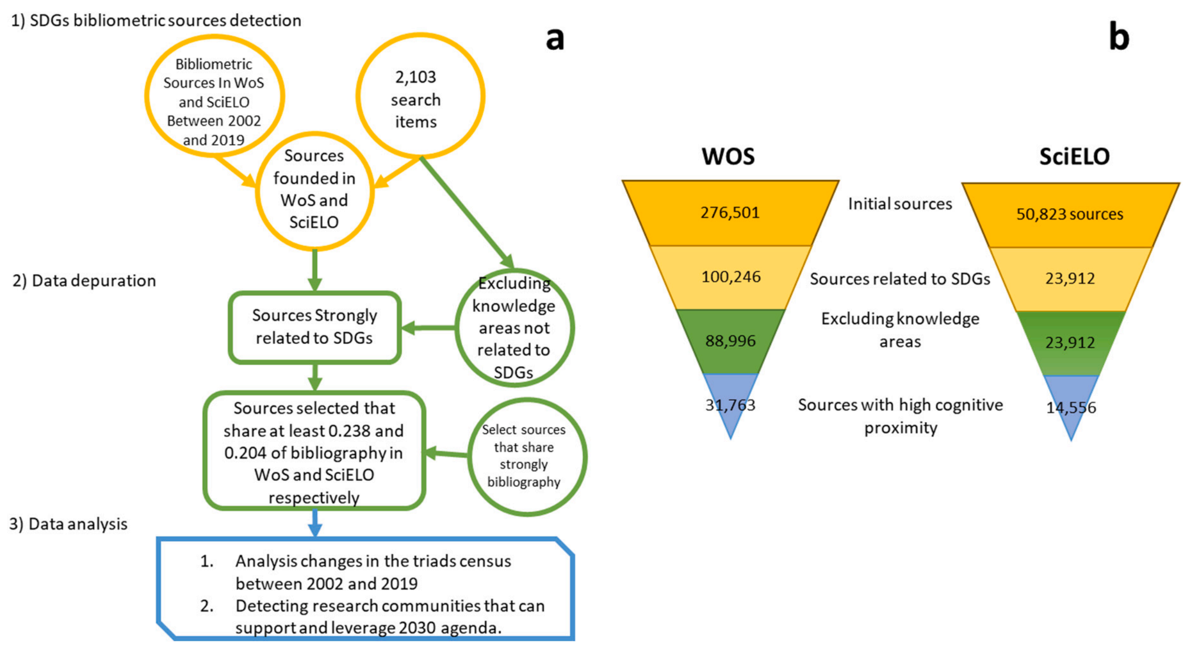


Fig. 2. Analysis of steps with bibliometric database. a) Process of data cleaning, depuration and analysis. b) Number or bibliometric sources remaining after each step of processing.

evaluate the proportion of misidentifications (false trues) we chose a random sample of 2000 sources in SciELO and 4000 in WoS. Subsequently, for each source of this sample, we manually determined whether they were actually related to SDG agenda. The proportion of misidentifications (or error type I) was of 1.2 % (CI: 1.189–1.202)[7] in SciELO and 13.30 % (13.291–13.320) in WoS.

To sift out the publications outside of the scope of the SDGs in WoS, we identified publications located in 16 "areas of knowledge" (e.g. Acoustics, Astrophysics, Crystallography, Optics, history, literature) that accounted for the highest proportion of non-SDG papers (all of them with a proportion of 70 % outside the scope of the SDG key words in our thesaurus). Consequently, we reduce the sources error type-I to 6.60 % (6.593–6.614) in WoS.

Subsequently we used bibliography coupling networks (BCN) to integrate publications related to the SDGs as recommended by (Rafols et al., 2021) and included the semantic and cognitive communities (Estañol et al., 2017; Grauwin and Jensen, 2011) structure of sources. BCN establishes the similarity between sources as the normalized number of references that each pair of sources has in common (this varies between 0 –no coupling- and 1 –complete coupling). As such, the network is composed of a collection of nodes that represent sources and a pool of interactions or strong links between them that are defined through bibliographic similarity. The metric proposed by Kessler (1963) and implemented by Grauwin and Jensen (2011) is used which measures the bibliographic coupling similarity ω_{ij} between sources i and j as the intersection of the references (R), over the lists of references (Eq. (1)).

$$\omega_{ij} = \frac{|\mathscr{R}_i \cap \mathscr{R}_j|}{\sqrt{|\mathscr{R}_i||\mathscr{R}_j|}} \quad (1)$$

[7] In order to define possible levels of confidence of the error estimation we ran a bootstrap analysis. This consists in generating artificial samples from the original sample. Our bootstrap analysis is composed by 10,000 subsamples; for each we estimated the percentage of remaining misidentified sources as well as the percentage of well-identified sources that get lost after filtering (error type-II, or false negatives). We express the estimated errors as confidence intervals with confidence of 95 %.

Notice that, as Grauwin and Jensen (2011) argue, ω_{ij} constitutes weighted links that reinforce denser (or highly similar) areas in the network, controls for the differences in size of different pairs of sources, and therefore facilitate the identification of meaningful cohesive groups of sources. In order to identify the lower limit of meaningfulness of ω_{ij}, we iteratively remove the links (*weak*) weighted less or equal than a critical threshold that consistently indicate meaningful cognitive association.

We noticed that the network is almost fully connected because a similarity measure is established between nodes, nevertheless not all similarities are equally meaningful (Jarneving, 2007). We use the "core document" approach to establish a threshold to reduce non-meaningful information (Boschma et al., 2014; Glänzel and Czerwon, 1996; Heimeriks and Leydesdorff, 2012; Jarneving, 2007; Subir and Shymal, 1983). This approach aims to identify 'hot topics' to study consolidated areas of knowledge (Boschma et al., 2014; Heimeriks and Leydesdorff, 2012; Jarneving, 2007). Our study intends to find scientific publications deeply associated with the SDGs. For example, a publication can mention climate change (or any other SDG topic) in the title, abstract, or keywords, without developing this topic in the main document (see Rafols et al., 2021). Such "fake" SDG publications are likely to have few references in common with core documents discussing the SDGs. Therefore, setting a threshold permits us to significantly reduce the selection of non-SDGs related papers.

We acknowledge that the possible limitation of using the core document approach is to neglect younger fields and emerging topics (Glänzel and Czerwon, 1996; Jarneving, 2007). This approach has usually established thresholds between 0.30 and 0.50 (Jarneving, 2007)), eliminating a substantial number of publications and references. Jarneving (2007) proposed that a threshold around 0.10 might sufficiently reduce random edges while keeping several nodes and links in the network. However, unrelated topics could take part of the sample. Alternatively, thresholds beyond 0.30 might generate fragmentation and the loss of structural properties of the network (see supplementary materials section 2).

To overcome this methodological challenge, our iteration involved removing links of less than a given value and also included the calculation of the modularity, using Louvain algorithm (De Meo et al., 2011). This methodological strategy helps us to identify the highest cognitive relatedness between publication without losing key structural properties of the network (see supplementary materials section 2). This approach also allows us to reduce the number of non-informative interaction and publications. We traced a threshold of link meaningfulness using as criterion the network modularity that detects well-established communities with strong cognitive affinity or knowledge communities (for more detail see supplementary material section 4). The threshold was set as 0.204 in SciELO and 0.203 in WoS, which were the points where we can reach the maximum modularity.

In addition, we only consider in our analysis the nodes connected to the largest component and within communities larger than 10 nodes. This was done to consider only that core knowledge that is most consolidated in the research system. Modularity maximization and considering only the great component allows us to identify those publications in knowledge structures (research communities), rather than only labelling scientific publication with SDGs topics (Rafols et al., 2021). As result, the BCN for SciELO was composed by 14,556 nodes and 65,711 edges with a misidentification error type-I of 0.6 % (0.595–0.605) and, 31,763 nodes and 60,861 edges an error of 5.9 % (5.89–5.91) in WoS. The Modularity values were 0.754 and 0.962 respectively (Table 2).

To establish the possible bias of the threshold approach, we estimate how our main results might vary when using different thresholds (see supplementary material section 3). Notice that the thresholds selected in our analysis are around 0.20, while other authors as explained previously proposed values around 0.25. We learnt from this analysis that the same network being cut-off from 0.10 and 0.25 did not show different results for the triads analysis nor the main configuration of the communities. Therefore, we conclude that our results are not significantly affected by where the threshold is traced.

Finally, we compare the modularity optimization with a null model to identify how the selection of this threshold may bias the analysis of the network (see supplementary material figure a-b). The result of the null model indicates that non-random links are lost during the optimization process. However, the structure of the network on key metrics (i.e., transitivity, number of triangles, and number of communities) of this model do not experience a major change. This suggests that although possible meaningful links are lost during the optimization process, the proprieties of the networks are not deeply changed and therefore our results bring an accurate picture of the network structure.

3.3. Establishing the attribute of the papers

In terms of determining the relevant SDGs for each of those publications that remained connected in the BCN, there are several options. For example, this 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 (Delgado-Ramos, 2018; Reynolds and Borlaug, 2006).

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. First, one SDG 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 criterion 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 that node as many times as number of attributes (SDGs) to undertake Triad Census Distribution analysis.

Table 2
Network metrics. Description of the most relevant metrics of the co-bibliography networks.

	WoS		SciELO	
Threshold	0	0.20	0	0.20
Nodes	82,054	31,763	20,049	14,556
Edges	5,938,030	60,861	692,459	65,711
Density	1.8E-3	1.0E-4	3.4E-3	6.0E-4
Transitivity	0.39	0.40	0.47	0.50
Modularity	0.69	0.96	0.65	0.75
Communities	27	194	37	66
Triangles	4E+8	192,852	2.30E+7	2,714,550
Degree Centralization	2.79E-2	3.80E-3	5.11E-2	2.25E-2
Betweenness centralization	4.9E-3	7.66E-2	9.0E-3	3.48E-2
Mean degree	144.68	3.83	69.06	9.03
SD degree	230.81	4.38	101.47	26.15
Mean link weight	0.05	0.29	0.10	0.32
SD Link weight	0.05	0.11	0.07	0.13

Note: Metrics are shown for Web of Science (WoS) and SciELO citation index (SciELO). We present the metrics of the networks without stabilising a threshold (0) and the networks' metrics after stabilising a meaningful threshold (0.20) following modularity maximization.

3.4. Data analysis

Following Fig. 1, two complementary analyses are used: triads census distribution (Fig. 5a and b) generated between triplets of connected nodes as described in Table 1, and identifying knowledge communities, the results of which are illustrated in Fig. 7a and b. The analysis is conducted in *R 4.0* (R Core Team, 2019). We include a simplified representation in which nodes represent SDGs and the links between them are the number of links in the bibliography coupling networks (BCNs) that connect sources tagged with the corresponding SDGs (Fig. 6a and b). Finally, the BCNs were plotted using Gephi 0.9.2 (Figs. 7a and 6b) (Bastian et al., 2009).

Triad Census distribution allowed us to identify strong and weak cognitive ties between SDG publications. We firstly identify triads between papers within the co-bibliography network (Fig. 7a & b)– three papers interconnected by common bibliography. Secondly, we use the attribute of these papers (type of SDG) to distinguish the "identity" of the triad previously identified. For example, three papers interconnected by End of Hunger (SDG 2), Clean Energy (SDG 7) and Climate action (SDG 13). In this case we count this triad (SDG2-SDG7-SDG-13) once. When doing this calculation, we found that all possible triads combination (916) between the 17 SDGs existed within the co-bibliography network, and therefore there are no structural holes or inexistent combinations of SDGs.

Triad analysis identified overarching trends of how SDGs are linked in publications. The community analysis 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 publications that share significant proportions of their bibliographies. This analysis allows us to observe the topics that 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 18 years (2002–2019).

Each community of knowledge detected assesses particular topics related to SDGs. Describing in detail each community is beyond the scope of this paper, nevertheless we cluster them into a small set of groups that conserve the relational structure of SDGs. For each community we define the composition of SDGs associated in the corresponding sources. With respect to the relation SDG – community, we build a matrix that relates each SDGs community with each SDG according to the number of papers labelled in each of these goals. This matrix was used to conduct a correspondence analysis (CA).[8] Using the information provided by the CA, we then conduct a Johnson hierarchical clustering analysis that identifies groups of communities that are similar in their composition of SDGs. Those groups or clusters were used to make a simplified cartography of the knowledge related with SDGs. We do this procedure for SciELO and WoS (Fig. 6a and b). Finally, knowledge community's analysis and the triads census distribution are integrated in a heatmap to identify which communities are catalysing multiple SDGs as proposed in Fig. 1 (see supplementary material section 4).

3.5. Study case: evaluating SDGs in Mexico

The methodological framework is implemented in the Mexican scientific publications system. This case is relevant as Mexico has committed to implementing the SDGs and represents an important country facing major SDG-related challenges. A cursory description of existing studies of Mexico and SDGs shows a mixed picture. Data using indices proposed by Schmidt-Traub et al. (2017) show progress 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, Sustainable Cities and Communities (air quality; SDG 11), Inclusive and Equitable Quality Education (primary education enrolment and adult literacy; SDG 4), Clean Energy (access to electricity and energy intensity; SDG 7) and Peace, Justice and Strong Institutions (freedom of assembly and freedom of movement; SDG 16) 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 Equality (gender violence; SDG 5) Reduced Inequalities (SDG 10), No Poverty (SDG 1), Sustainable Cities and Communities (air pollution in big cities; SDG 11), Clean Energy (reduction of carbon emissions) and Decent Work and Economic Growth (labour conditions in rural areas; SDG 8) (Federal Government Mexico, 2018). The contrasting results suggest possible gaps between some indicators and policy maker perspective about SDG capacities, priorities and implementation.

In terms of investment in the overall system, according to CONACYT (2017), the National Expenditure on Science, Technology and Innovation (GERD) increased by 10.09 % between 2010 and 2015, subsequently falling by 10.37 % between 2015 and 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 and 2017 (CONACYT, 2016, 2017). From 2002 to 2019 the number of scientific publications increased significantly from 7225 to 29,282 bibliometric sources per year (Fig. 3). In terms of our measure of publications related to SDGs, these increased from 598 to 2927 bibliometric sources per year between 2002 and 2019, an increase from 21.61 % to 40.59 % (Fig. 3). These broad descriptive figures suggest an important increase in SDG-related activity and new researchers in the Mexican science and technology system. The next section lays out and discusses the results highlighted in the methodological above proposition.

4. Analysis of SDG interconnectivity trends

In this section we evaluate key aspects of knowledge production in the form of publications related to specific SDGs (Fig. 4). Here we see that WoS publications related to Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4), Industry, Innovation and Infrastructure (SDG 9), Peace, Justice and Strong Institutions (SDG 16), and Clean Water (SDG 6) have the highest frequency of bibliometric sources, while Inclusive Partnerships (SDG 17), Sustainable Cities and Communities (SDG 11), Reduced Inequalities (SDG10) and No Poverty (SDG 1) have the lowest. Similarly, education, health and innovation are the highest frequent SDGs in SciELO, whilst less attention has been paid to Clean Energy (SDG 7), Inclusive Partnerships (SDG 17), Sustainable Cities and Communities (SDG 11) and Life below Water (SDG 14). It is important to notice that the difference between the highest and lowest areas of research is significant, suggesting important imbalances and different knowledge dynamics in the SDG-related research in Mexico.

However, as outlined earlier, the focus of our methodology lies in cognitive proximities 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 and will allow us to observe thematic trends through the frequency of interactions of SDGs. Fig. 5 (a) based on Web of Science shows that the category socio-technical systems based on heterogeneous SDGs (STSTST-3, STSTST-2) are the most dominant category of triad and the most common triads are Inclusive and Equitable Quality Education (SDG 4), Health and Wellbeing (SDG 3) and Industry, Innovation and Infrastructure (SDG 9) (see numbers 2–4 in Fig. 5a). Other common triads are represented by two Peace, Justice and Strong Institutions (SDG 16), Inclusive and Equitable Quality Education (SDG 4) and Health and Wellbeing (SDG 3) (see numbers 5–7 in Fig. 5a). It is significant that the "directionalities" category only becomes frequent when interacting with others, especially Responsible Production and Consumption (SDG 12) with Health and Wellbeing (SDG 3) and Inclusive and Equitable Quality Education (SDG 4) (see number 1 in Fig. 5a). Lastly, we notice that Health and Wellbeing (SDG 3) and Inclusive and Equitable Quality Education (SDG 4) dominate triads in the latter periods (see supplementary material section 2).

Publications in the Spanish and Portuguese SciELO (5ii) shows a similar pattern with combinations of Inclusive and Equitable Quality Education (SDG 4), Industry, Innovation and Infrastructure (SDG 9) and Peace, Justice and Strong Institutions (SDG 16). One significant result is that a triad composed of only SDG 10 (inequality) appears, but in isolation (see number 1 in Fig. 5b). Furthermore, sociotechnical systems triads are less diverse in SciELO, they usually are connected in isolation or only two sociotechnical systems are connected (see numbers 2–6 in Fig. 5b). Peace, Justice and Strong Institutions (SDG 16) is also an important SDG, building bridges with Health and Wellbeing (SDG 3) and Inclusive and Equitable Quality Education (SDG 4) (see numbers 7–9 in Fig. 5b).

With respect to how SDG research has evolved, three periods can be extrapolated from supplementary material graph c. First, a period from 2002 to 2006 characterized by directionalities SDGs. During this period, Zero Hunger (SDG 2), Gender Equality (SDG 5), end No Poverty (SDG 1), Reduced Inequalities (SDG 10) and Climate Action (SDG 13) were highly frequent. Then a period characterized by sociotechnical systems Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4) and Industry, Innovation and Infrastructure (SDG 9) are highly frequent. Lastly, a period between 2012 and 2019 in which Peace, Justice and Strong Institutions (SDG 16) builds bridges with many sociotechnical systems and directionalities (see complementary material figure d). In both SciELO and WoS, the important topics of No Poverty (SDG 1), Climate Action (SDG13), Life on Land (SDG 15) and Gender Equality (SDG 5) do not appear in any of the dominant triads.

The results are significant. Socio technical approaches are dominant in SDGs-related research. Secondly, the annual composition of publications in terms of SDGs shows significant change in the dominant of triads especially in SciELO suggesting possible transitions in research priorities during the period evaluated.

[8] This is a multivariate technique that reduce the complex space of variables (SDG) into a set of synthetic dimensions (typically 5) that account for the common variance of variables. These new dimensions configure a new space of relation between the categories (communities) assessed.

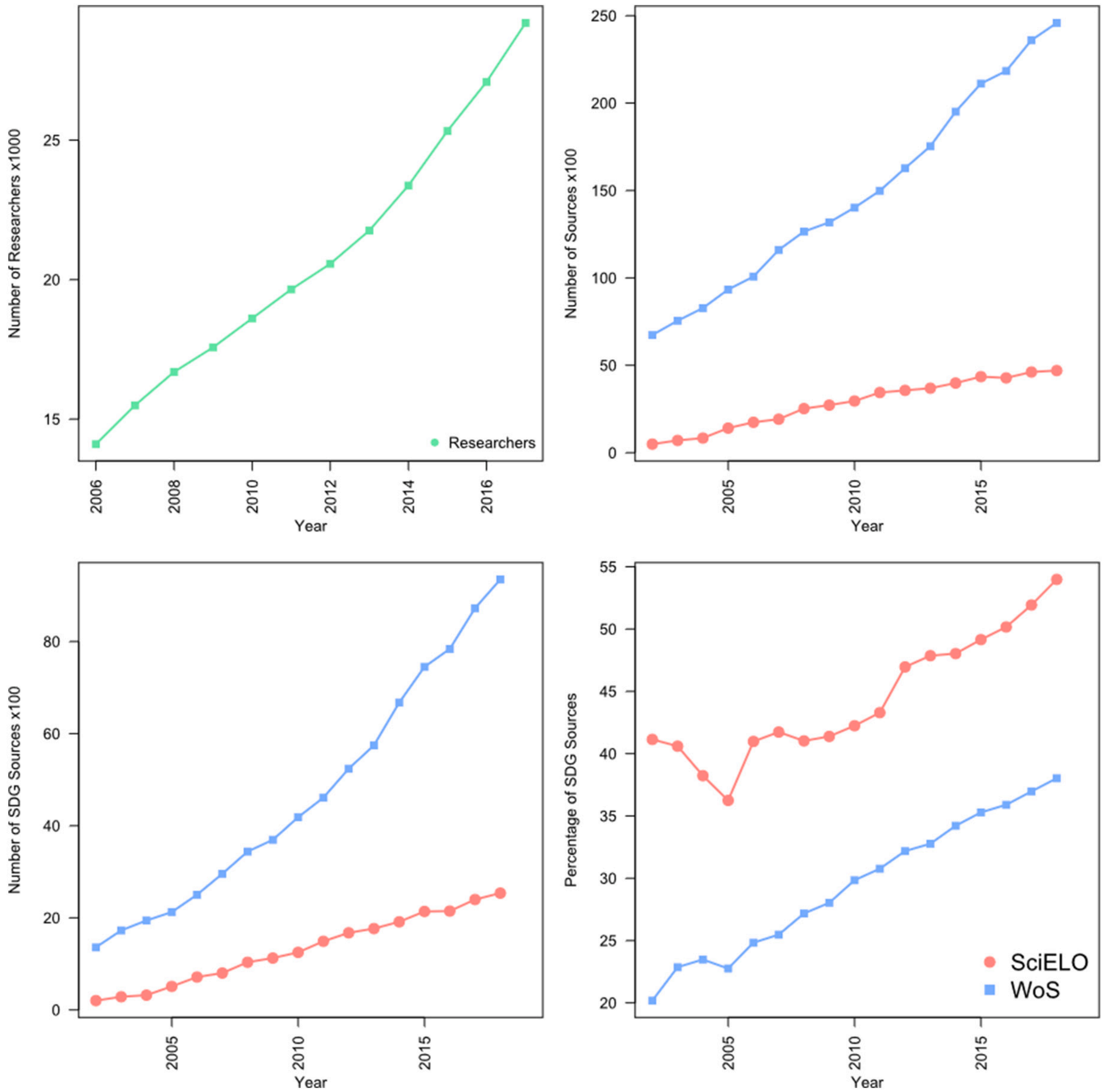


Fig. 3. The graph shows the increase in the number of recognized researchers in the national innovation system (a), the number of sources downloaded (b), the number of sources related to SDGs (c), the number of Mexican publication and the percentage of sources related to SDGs between 2002 and 2019 (d). The information related to the number of NIS researchers 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 (blue) and SciELO (red) citation Index (information downloaded in April 2020). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 6 (a) and (b) provides an alternative representation of the interaction between SDGs, but here we graphically emphasize connectivity patterns between socio technical systems, directionalities and framework conditions. Counting the number of interactions between SDGs identified in the co-bibliography network (weighted degree, represented by the size of circle), we see that in the WoS knowledge network, Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4), Health and Wellbeing (SDG 3) and Industry, Innovation and Infrastructure (SDG 9) were the most frequent "socio technical" SDGs, while Responsible Production and Consumption (SDG 12) was by far the most dominant "transversal direction" SDG over the time period. In addition, Peace, Justice and Strong Institutions (SDG 16) has a significant number of interactions with sociotechnical systems SDGs. Interaction of transversal directionality SDGs occurs primarily with socio technical systems, not with other transversal directionalities.

The significance of Fig. 6 is that it reveals how less common SDGs appear through connections built with other SDGs. For example, studies on gender are strongly associated with health and education. Also figure c in the supplementary material details how, between 2013 and 2017, inequality (SDG 10) builds relationships with education (SDG 4) and peace (SDG 16) and between 2016 and 2019 with infrastructure (SDG 9) and climate change.

The SciELO knowledge network in Fig. 6 (b) shows a similar pattern of triads as WoS. Although health (SDG 3), education (SDG 4) and innovation and infrastructure (SDG9) and responsible consumption and production (SDG 12) are also dominant, other SDGs appear in building transitivity triads. Supplementary materials figure d shows that inequality builds bridges with Health and Wellbeing (SDG 3), Peace, Justice and Strong Institutions (SDG 16) and Life on Land (SDG 15) between 2002 and 2005. We also see important connections between framework conditions related to peace and justice (SDG 16) in SciELO building triads with Health and Wellbeing (SDG 3) and Inclusive and Equitable Quality Education (SDG 4) that became a highly dominant triad from 2015 to 2019. No Poverty (SDG 1) appears only between

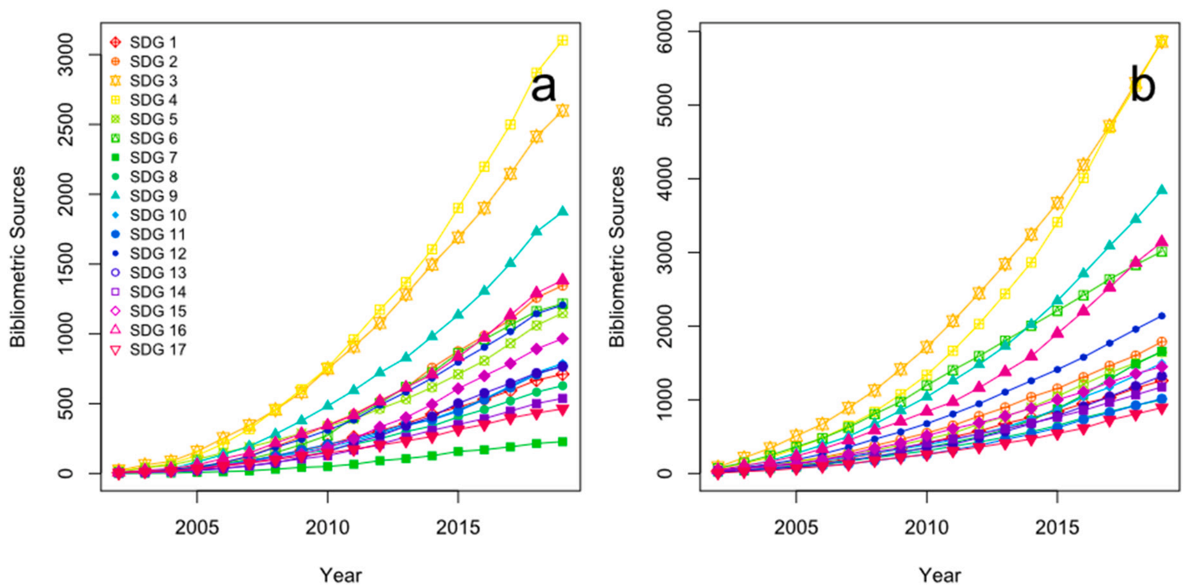


Fig. 4. The line graph shows the frequency of bibliometric sources from 2002 to 2019. This frequency is calculated from SciELO Citation Index (a) and Web of Science (b) information.

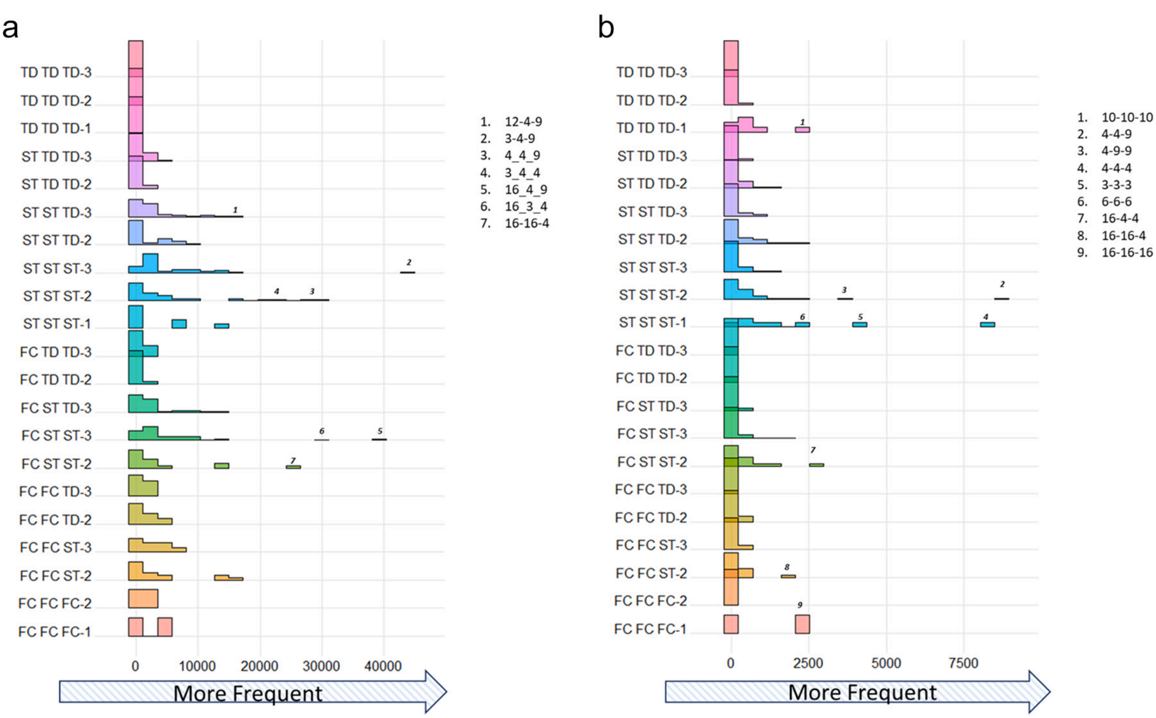


Fig. 5. (a): Triad analysis in WoS.
(b) Triad analysis in SciELO.
Analysis of triads through socio technical systems and transversal directions. The figure shows the consolidation of the network from 2006 to 2017.
Note: The y axis represents the 10 triads shown in Table 1, the x-axis presents the number of triads identified in the co-bibliography network: ST: Socio-technical System; TD: Transversal Directionalities: Framework Conditions.

2002 and 2004 and 2014–2016. Climate Action (SDG 13) is completely absent. Summarising, we find that the most dominant triad patterns in WoS and SciELO are concentrated in the socio-technical systems section of Fig. 1 and within this concentrated on Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4) and Industry, Innovation and Infrastructure (SDG 9). The SciELO database shows a significant role of Peace, Justice and Strong Institutions (SDG 16) in the last three-time windows (2015–2017).

4.1. *Analysing key knowledge communities*

Triad analysis identified overarching trends of how SDGs are linked in publications. This section evaluates knowledge communities in more detail and observes the topics that groups of researchers are working on. We then take a more detailed look at the actual communities and their topics, which is illustrated in Fig. 7(a) and (b). Every colour in the maps represents a cluster of research communities that is summarised by its

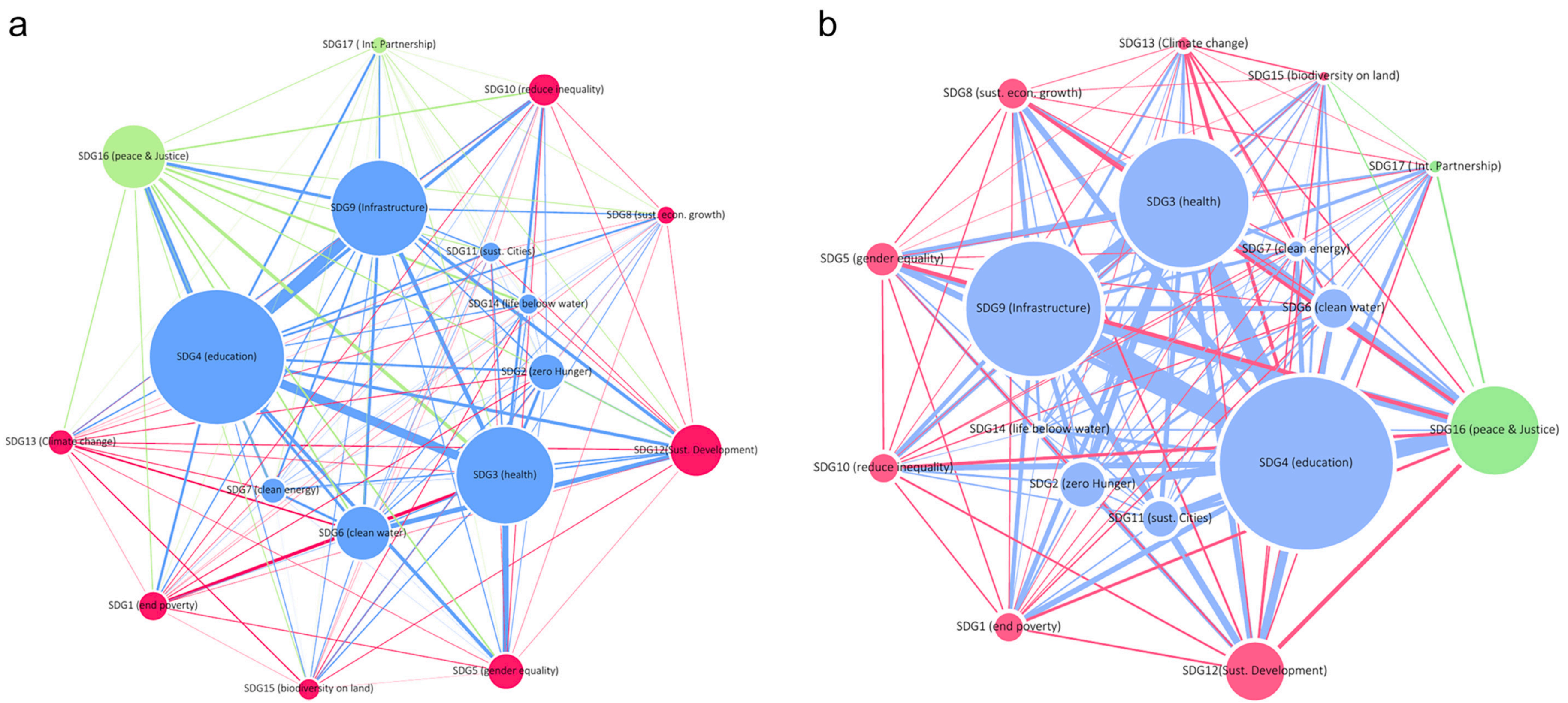


Fig. 6. (a): WoS relationships between socio technical systems and transversal directions.
(b): SciELO relationship between socio technical systems and transversal directions

Note: Fig. 6 (a) and 6(b) The size of the nodes indicates the number of papers identified in each SDG. The edges are the common bibliography between these scientific publications. In other words, the cognitive interactions between SDGs. Node colours represent the SDG category proposed in Fig. 1. Blue: sociotechnical systems; Red: transversal directionalities; green: framework conditions.

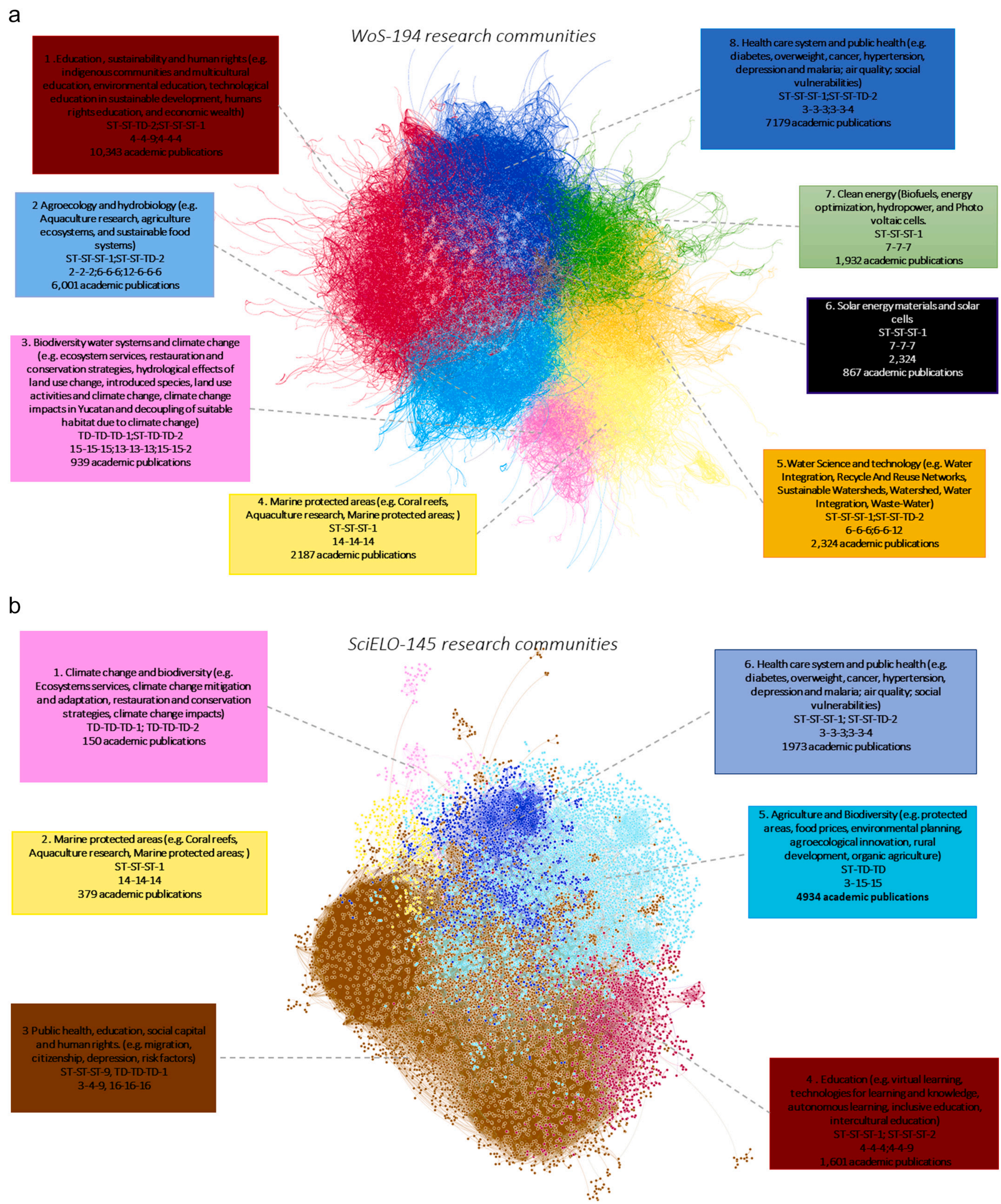


Fig. 7. (a) Web of Science knowledge network. The parameters of plotting were Force atlas 2 (tolerance 1.0, approximation 1.2 and gravity 0.001. Nodes: scientific publications. Edges: common bibliography Every Square shows the main topics of the cluster, the most common type of triads, the number of research communities and the number of bibliometric sources. It was graphed using Gephi 0.92.
(b) SciELO knowledge network. The parameters of plotting were Force atlas 2 (tolerance 1.0, approximation 1.2 and gravity 0.01. Nodes: scientific publications. Edges: common bibliography. 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.

label. We found eight clusters in WoS and six in SciELO (classification undertaken according to a correspondence analysis and *Johnson cluster* similarity where communities were organized according to the frequency of SDGs bibliometric sources; see methods and analysis section).

Knowledge communities are clustered in 8 groups: 1) education, sustainability and human rights, 8) health care system (non-communicable and communicable diseases) and public health strategies that are related to reducing vulnerabilities such as water, air pollution or malnutrition. There are two clusters working on water: 2) development of sustainable technologies to reduce the contamination of water from agriculture (production and consumption) and 5) research that focuses on developing technologies for water treatment. In addition, there are two clusters working on clean energy: cluster 6) focuses on solar energy and cluster 7 on biofuels and energy optimization. Finally, two clusters are connected to planetary boundaries: Cluster 3) working on water, climate change and biodiversity on land where conservation and regeneration of ecosystems are the main strategies to address ecosystem degradation, and cluster 4) working on strategies to conserve biodiversity in marine areas.

It is significant that some clusters are much more diverse in terms of SDGs than others and therefore conduct research in a different manner. Cluster 4 (life below water), 5 (water technology), 6 (solar energy) and cluster 7 (bioenergy) work primarily on just one socio technical SDG and can therefore be regarded as more single system focus. By contrast, cluster 8, combines health quality, and social problems (vulnerability and malnutrition). Cluster 2 also has an important nexus between water, agriculture and energy, while cluster 3 has nexus between biodiversity and land use. Finally, cluster 1 has an emphasis on education based on environmental and human rights topics.

For SciELO (Fig. 7b), the network can be grouped into six clusters working on 1) climate change and biodiversity, (2) marine protected areas, 3) public health, and education strategies to address human rights in vulnerable communities, 4) education related to technology and autonomous learning 5) production and consumption strategies to manage water and agriculture systems and 6) public health. 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 Clean Water (hydrology; SDG 6) and Zero Hunger (agroecology; SDG 2) are most important, but Inclusive and Equitable Quality Education (SDG 4) and Peace, Justice and Strong Institutions (SDG 16) work with Reduced Inequalities (SDG10) and No Poverty (SDG 1). 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 clusters working on water quality. In Fig. 7(a) cluster 5 is narrowly technological and incorporates papers only in Clean Water (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 (Durán-de-Bazúa et al., 2008; Zurita et al., 2014) from wastewater in industry and households. There is no mention of other SDGs, for example cities (SDG 11), Zero Hunger (SDG 2) or Responsible Production and Consumption (SDG 12) 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 cluster 2 that focuses on Clean Water (SDG 6), but also incorporates Zero Hunger (agriculture; SDG 2). Therefore, the latter looks at the effect of one socio technical systems on another (Cortés-Jiménez et al., 2007; Delgado-Ramos, 2018). Cluster 3 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 opens a discussion about unsustainable practices, climate change impact in water supply, and conservation and restoration strategies to avoid flooding (Corral-Verdugo and Pinheiro, 2006; Saldaña-Fabela et al., 2011). This connects Clean Water (SDG 6), Responsible Production and Consumption (SDG 12), Climate Action (SDG 13) and Life on Land (SDG 15) thus embracing greater complexity that builds bridges between different types of SDGs and can help to open up ways of thinking about common problems that are more sensitive to societal needs.

Finally, we calculate triads within the knowledge communities to identify where SDG categories proposed in Fig. 1 are being integrated (supplementary material section 4). We see few examples of SDG research communities that combine SDGs from sociotechnical systems, transversal directionalities and framework conditions. This result concurs with our previous discussion and findings, that integrating the three SDG categories proposed in Fig. 1 would appear to be challenging. Nevertheless, where they exist (supplementary material section 4), these can be further studied to understand how they might catalyse and trigger synergies around multiple types of SDGs.

5. Discussion

Our main research question has been how to unlock the transformative potential of scientific knowledge production for addressing the SDGs? We have sought to answer this question by developing a specific framework to assess what type of knowledge production contributes to transformative change necessary to address the SDGs, and by developing a new methodology to use the framework. In this paper we have applied the framework and methodology to the Mexican research system.

Three important and interrelated findings can be highlighted and discussed. Firstly, our analysis shows (based on descriptive evidence from both WoS and SciELO databases) that over an 18-year period there has been a considerable increase in research and publications in SDG related areas in Mexico. This should be seen as a positive development, yet it is far from sufficient to address the transformative ambition of the SDGs. And even without this focus on transformation it is significant to see that some areas of chronic and prolonged problems in Mexico have grown very slowly over the last 20 years, No Poverty (SDG 1) and Reduced Inequalities (SDG 10) being the salient examples. Secondly, triad analysis also shows that much of the production of knowledge, particularly from the WoS database, revolves around four socio-technical systems SDGs: Health and Wellbeing (SDG 3), Inclusive and Equitable Quality Education (SDG 4), Industry, Innovation and Infrastructure (SDG 9) and Peace, Justice and Strong Institutions (SDG 16). Moreover, and thirdly, where links with directionality SDGs take place, it is predominantly with just one SDG, Responsible Production and Consumption (SDG 12). Therefore, the research system (either through the system of funding or perhaps the preference of researchers to approach problems through narrow formats) appear to pivot knowledge production related to SDGs primarily around what we have framed as socio-technical system SDGs. Thus, although there is a growing number of SDG related publications, the transformative potential of these publications is still rather low, since cognitive integration across the three types of SDGs identified in our framework is low.

Our proposition is that the transformative potential of scientific knowledge production can be enhanced if these links emerge and thus a greater integration of knowledge across SDGs that emphasises socio-technical system change, directionality and framework conditions could be accomplished. This means focussing less on single goals than on how key SDG topics are combined. Here triad and community analysis has allowed us to make visible some important examples to build on. In particular, triad analysis shows that some SDGs that explicitly emphasize directionality and/or framework conditions are connected to SDGs from socio technical system categories. For example, the supplementary material document (Section 4) shows that research on Health and Wellbeing (SDG 3) connects with Gender Equality (SDG 5), whilst Industry, Innovation and Infrastructure (SDG 9) appears as an enabler of Decent Work and Economic Growth (SDG 8). Also, research on Inclusive and Equitable Quality Education (SDG 4) and Peace, Justice and Strong Institutions (SDG 16) are able to integrate No Poverty (SDG 1) and Reduced Inequalities (SDG 10) agendas. In addition, figure (c and d) shows links between Zero Hunger (SDG 2) and Life on Land (biodiversity, SDG 15). In addition, the community analysis using a different way of measuring how knowledge is integrated, identifies eight knowledge clusters in WOS and five in SciELO, some of which show evidence of cross-cutting research in areas such as Health and Wellbeing (SDG 3), access to Clean Water (SDG6), Life on Land (SDG 15, in particular biodiversity, agroecology) and Inclusive and Equitable Quality Education (SDG 4). We argue that these scientific knowledge clusters do harness the transformative potential of research systems since they are building bridges between SDGs.

A final point concerns the implications of limiting the study and analysis on formal scientific publications from two publications databases in English, Spanish and Portuguese languages. This limitation is not a principled decision but a pragmatic one due to the facility that the use of publications as a unit of analysis provides for bibliometric analysis. However, this limitation defines the boundary and scope of our results and creates a tension regarding how to consider and combine knowledge not included through publications. The importance of non-codified and experiential knowledge is recognized in some science, technology and innovation literature where there is an appreciation and understanding of how knowledge that goes beyond codified scientific and technical can complement each other and create synergies. For example, Jensen et al.'s (2007) discussion of "Doing, Using and Interacting" (DUI- mode) highlights the importance of organizational capacity for learning (through employee skills and experiential learning) to complement the more traditional Science and Technology and Innovation (STI) mode of learning. Other approaches from fields such as citizen science go further by suggesting that non-scientific formalised knowledge is critical for broadening the agenda, direction and priorities of science and technology studies (Hess, 2016), whilst from the global south there has been important work on the informal economy Kraemer-Mbula and Wunsch-Vincent (2016) that incorporate generation of knowledge in non-scientific ways.

For the purposes of our proposed methodology there are three possible ways to address this point. Firstly, the results of the formal study can be used in a reflection process with other types of actors. They can indicate where biases may come up and this can be integrated into the presentation of the results. A second option would be to look in formal publications for references to this type of informal knowledge and for collaboration with other actors. For instance, bibliometrics methods can help identify where non-academic actors are present within research communities (Arroyave et al., 2021; Romero et al., 2018; Shiffrin and Börner, 2004). In the same direction, bibliometric methods can contribute to the evaluation of alignment between scientific publications and social needs and demands (Ciarli and Ràfols, 2019).

A third option could be to locate papers that specifically undertake research that incorporates collaborations between non-scientific and formal knowledge research. A useful example of this is the study of the social movement in defence of the urban wetlands undertaken by Ramirez et al. (2020) in Bogota. Here a grassroots activist movement produced knowledge of poor water quality and pollution exposure through participative monitoring. This was supported by actors in the formal science system who provided environmental diagnoses and testified in court cases brought against construction companies. Synergies between the technical knowledge of the scientists was fused with the grassroots and lay knowledge to produce a set of new protocols for the Bogota aqueduct company to manage urban wetlands based on principles of resilience of natural ecosystems. This describes a successful case of how strong synergies was able to transform urban planning. This is particularly important in marginalised localities that are often hamstrung through lack of support from the science and engineering institutions.

As discussed, whilst our methodological approach alone does not resolve the question of how different forms of knowledge can be treated equitably, it can help to build a bridge between policymakers, researchers and other actors working on SDG topics by reflecting on the directions of scientific knowledge production and to identify non-academic actors within the research communities. This identification may help to localize where relevant ground experimentation is taking place. Similarly, the reflection about knowledge directions in more science-oriented communities can help societal actors to identify alternatives that can help build bridges with the research system.

6. Conclusion

Randers et al. (2018) argue that limiting oneself to economic approaches or addressing the 17 goals simultaneously is unlikely to be enough to achieve the 2030 agenda. We agree with this argument. They make four main recommendations for clustering and focusing on specific combinations. A focus on the acceleration of Clean Energy (SDG 7) transitions to Zero Hunger (sustainable agriculture; SDG 2); active Reduced Inequalities (SDG 10); and encouraging investment in Inclusive and Equitable Quality Education (SDG 4). Our approach is different. It delivers a more bottom-up and contextual analysis mapping what is happening in the research system and building on that. For example, in the Mexican context, actors from the scientific knowledge system are already establishing links between Inclusive and Equitable Quality Education (SDG 4) and Peace, Justice and Strong Institutions (SDG 16), and based on our analysis we suggest links could be established with Reduced Inequalities (SDG 10) and No Poverty (SDG 1). However, beyond such examples, we argue that if the research investment and research output continue to pivot to such a degree within a small number of SDGs and moreover focus first and foremost on socio- technical systems SDG, the transformative potential of scientific knowledge production will be limited. To articulate the point in a different way, Mexican STI policy can seek to stimulate research in under-researched areas such as poverty and inequality not only by investment on single SDGs, but also by developing a knowledge base that integrates a diverse set of knowledge, combining specific socio-technical systems with knowledge that emphasises what we have called directionalities and framework conditions. In this paper we have emphasized that particular types of SDGs need to become more connected. We have not suggested a specific scale for assessing transformative potential for drawing a sharp distinction between including or not including transformative potential is too crude. Rather, we see this as a continuum, where transformative knowledge production can be enhanced in several ways and in many steps and that mapping the specific knowledge context as is done in the proposed methodology is a useful step.

The analysis also sheds light on a second important arena of discussion raised by this paper that concerns 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 researcher consultation through dyad analysis. However, ex-ante understanding of all the possible interactions across different contexts is likely to be a difficult task. We present a different empirical approach that could significantly add value to existing approaches because it maps emerging research clusters and knowledge communities that can unlock the transformative potential of scientific knowledge production for a specific context.

The sustainable development goals motivate important discussions around public policy and research agendas, including questions about whether, to what extent and how scientific knowledge production is helping to build a knowledge base that can help open up new sustainable pathways of development. We suggest that analysis of knowledge communities and triads can help policy makers to map and locate specific areas for strengthening of transformational type of research. We are, however, not advocating a top-down approach to steer research. Rather, that the type of mapping we have done can assist a bottom-up approach in which policy-makers, research funders and researchers reflect on the knowledge produced and encourage mutual learning on how to build an enabling environmental for integration of knowledge across the SDGs. We would like to stress that it may be important to involve societal actors in this discussion and try to locate data sets that represents their knowledge development (Bunders et al., 2010; Lang et al., 2012). In fact, we emphasize the importance of knowledge production that combines practical on the ground experimentation with scientific knowledge to learn how transformational synergies and trade-offs work would work in specific contexts.

These recommendations imply that the proposed method can be integrated in all three frames for STI policy and beyond that also would assist in orientating them towards each other (Schot and Steinmueller, 2018). Frame 1 is about stimulating R&D, and knowledge production. Our suggestion is to do this in such a way that this knowledge production helps to address the SDGs. We have focused on scientific knowledge production, but we acknowledge the need to include other forms of knowledge production into the analysis, including innovation processes by using, for example, databases of projects or innovation surveys. Frame 2 is about developing links and learning across a network of actors, again our approach will make visible links and learnings of knowledge communities that are oriented towards addressing the SDGs, but we may need to extent the analysis to include other types of actors. These insights can then be used to interview actors about barriers and opportunities for further development of their communities, for example through interviews or a survey. Finally Frame 3 is about experimenting with transformative change, and the development of niches that may lead to socio-technical change towards the SDGs. Our method may assist in locating these niches and connecting their development to network development and scientific knowledge production. This would imply that frame 1, 2 and 3 policies become more coordinated.

A final concluding point is the implications of our study (and other similar studies such as Rafols et al., 2021) and methodological approaches for policy and the attainment of the SDGs. These are significant. We propose an "ex-post" approach that involves mapping existing knowledge communities, analysing and contrasting how these are addressing SDG related challenges and subsequently reflecting with policymakers, researchers and other relevant societal actors interested in SDGs topics. This can help encourage transformative synergies by incorporating a more diverse set of actors such as firms and citizen science groups. We acknowledge that our study cannot identify if and how these actors and organizations are collaborating within non-scientific research communities and we propose that further development of our methodology should consider the analysis of the frequency and diversity of these societal actors - for instance, by mapping the number of NGOs or societal actors involved in each community. Nevertheless, there are also fundamental questions to address around limited agency of non-science communities to allow this to happen. Science systems can at least begin to address these issues. This can include universities adopting strategies of inclusive innovation and encouraging researchers to work on techniques for recalibrating socially robust knowledge for the common benefit of society.

CRediT authorship contribution statement

Oscar Yandy Romero Goyeneche: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing – original draft. **Matias Ramirez:** Conceptualization, Methodology, Writing – original draft, Supervision, Project administration, Funding acquisition. **Johan Schot:** Conceptualization, Writing – original draft, Funding acquisition. **Felber Arroyave:** Methodology, Software, Formal analysis, Investigation, Data curation.

Declaration of competing interest

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

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Availability of data and materials

Data and code are available at https://doi.org/10.6071/M3138F. Data and code will be also available from the corresponding author. Reasonable questions about the coding can be directed to Oscar Romero oscaryandyromerogoyeneche@gmail.com or Felber Arroyabe fjarroyaveb@gmail.com

Appendix A. Supplementary Materials

Supplementary data to this article can be found online at https://doi.org/10.1016/j.respol.2022.104589.

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