



Identifying social–ecological gaps to promote biocrust conservation actions

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Abstract. Globally, most bare-looking areas in dryland regions are covered by biocrusts which play a crucial role in modifying several soil surface properties and driving key ecosystem processes. These keystone communities face important threats (e.g. climate change) that place their conservation at risk and in turn the sustainability of the ecosystems they inhabit. Therefore, there is an urgent need to develop ecosystem management strategies to ensure their protection. However, to provide a solid path towards biocrust conservation, the understanding by stakeholders and governance structures of the ecological functions of these communities, their role as benefit providers, and the pressures threatening their important effects are indispensable. Whereas the ecological scope of biocrust has been widely studied in the last decades, the social dimension of their role remained unexplored. By reviewing literature in biocrusts from a social–ecological approach, here we identified knowledge gaps and new research areas that need to be addressed in order to produce scientific knowledge that better guides dryland conservation policies and actions. This research agenda is a prerequisite to advance biocrust conservation.

1 Introduction

Most open areas in dryland regions around the world are covered by biological soil crusts or “biocrusts” (Rodríguez-Caballero et al., 2018a), which are poikilohydric communities composed of associations between soil particles and eukaryotic algae, cyanobacteria, lichen, mosses, and liverworts growing together with heterotrophic micro-decomposers in a faunal food web (Bowker et al., 2018). By covering the soil surface, biocrusts play a key role in maintaining arid ecosystems at the global scale, as they promote biodiversity (Bowker et al., 2010a), direct numerous key ecosystem processes (reviewed in Weber et al., 2016), and provide multiple regulating services (Concostrina-Zubiri et al., 2017; Rodríguez-Caballero et al., 2018b). For example, it has been demonstrated that although biocrusts only represent a very thin layer at the soil surface, they regulate soil biogeochemical and water fluxes (Chamizo et al., 2016; Maier et al., 2018)

and form a cohesive network that stabilizes soil (Belnap et al., 2014).

Biocrust-forming organisms are well adapted to aridity and survive some of the most extreme environments on Earth (i.e. polar regions or hyperarid deserts). However, they are highly vulnerable to subtle changes in climate conditions and to disturbance derived from human activities (Maestre et al., 2013; Reed et al., 2019). Consequently, global biocrust coverage is expected to decrease dramatically by the end of this century (Rodríguez-Caballero et al., 2018a). In addition, manipulation experiments on different regions revealed that disturbance and climate change will cause the loss of some biocrust constituents such as lichens and mosses, leading to a community shift towards early cyanobacteria dominance. Both biocrust coverage loss and community composition changes are expected to have strong negative impacts on soil biodiversity and on the functioning and resilience of

dryland landscapes (Maestre et al., 2013; Ladrón de Guevara et al., 2014; Reed et al., 2019).

Given the importance of biocrusts for the sustainability of global drylands and the increasing pressure these communities undergo and that threatens their conservation, there is an urgent need to develop legal frameworks that underpin the protection and conservation of these keystone communities. Scientific evidence obtained from more than 2 decades of intensive research around the world (reviewed in Belnap and Lange, 2003, and Weber et al., 2016) represents a great resource to support the importance of biocrust conservation and the achievement of sustainable biocrust management in dryland ecosystems. However, it is widely recognized that there are barriers between science and governance decision-making that hinder translation of the scientific evidence to conservation actions (Ellison, 2016). In an attempt to address this conservation challenge, there are certain voices within the international research community that encourage adopting new research framings focused on producing knowledge able to properly inform policy actions and management practices (Mastrángelo et al., 2019). Within the multiple conservation framings in use today (Mace, 2014), literature increasingly recognizes the social–ecological approach as an adequate scientific means to achieve it (Ban et al., 2013; Díaz et al., 2015; Mastrángelo et al., 2019). The social–ecological approach is based on the paradigm of “people and nature” and emphasizes the importance of institutions and social structures for transitioning towards sustainable interactions between human societies and the natural environment (Mace, 2014). Adopting the so-far underused social–ecological perspective would be a novel approach for biocrust researchers to build new scientific knowledge to address the demanding challenge in drylands which is the conservation of biocrust communities.

The BIOCOST project (<http://www2.ual.es/cecoul/costras-biologicas/>, last access: 19 September 2020) aims to deal with the current biocrust conservation challenge by means of facilitating the use of scientific evidence for policy actions and management practices. In order to instigate the project, we selected Spain as a pilot area. Given the extent (about 75 % of the national territory; Martínez-Valderrama et al., 2020) and the whole range of favourable environmental conditions for biocrusts, Spanish drylands are characterized by a great diversity of biocrust-forming organisms that play a crucial role in many ecosystem processes and represent an excellent field laboratory to work with biocrusts (Maestre et al., 2011). Indeed, Spain has become one of the world’s biggest spots for biocrust studies (Rodríguez-Caballero et al., 2018a), as reflected in the increasing trend of research groups doing biocrust research over the past decades (Maestre et al., 2011). As a first step to achieve this goal, we conducted a literature review on biocrusts through the lens of a social–ecological approach with the aim of (1) analysing how biocrust research has evolved in Spain, (2) identifying to which extent biocrust research has contributed to different

knowledge areas required for supporting biocrust conservation, and (3) elucidating knowledge gaps and new research opportunities for conservation actions.

2 Conceptual framework

To develop the study, we used the conceptual framework adopted by the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) (Díaz et al., 2015) (Appendix A, Fig. A1). The IPBES framework is built upon a social–ecological approach and aims at providing a shared language that catalyses the generation of new scientific knowledge for supporting policy formulation and implementation on conservation biodiversity. According to Díaz et al. (2015), the IPBES framework is formed by 16 elements (six categorized components and 10 linkages among them) that represent a social–ecological system that operates at various scales in time and space (Appendix A, Fig. A1). These six components and concepts are (1) nature, “the natural world with an emphasis on biodiversity, ecosystems, ecosystem structure and functioning, the evolutionary process, the biosphere, living natural resources”; (2) nature’s contributions to people, “all the benefits that humanity obtains from nature, including ecosystem goods and services”; (3) anthropogenic assets, “highlight that a good life is achieved by a co-production of benefits between nature and various assets built by people, and it refers to built infrastructure, health facilities, knowledge, technology, and financial assets, among others”; (4) institutions and governance systems and other indirect drivers of change, “the ways in which people and societies organize themselves and their interactions with nature at different scales”; (5) direct drivers of change, “natural direct drivers are those that are not the result of human activities and whose occurrence is beyond human control, whereas anthropogenic direct drivers are those that are the result of human decisions and actions”; and (6) good quality of life, “the achievement of a fulfilled human life”. The complex interactions among these six components are represented through 10 listed linkages (Appendix A, Fig. A1). This conceptual framing was specifically adapted to the study case of biocrusts to generate a new biocrust-based conceptual framework that accounted for natural, social, and institutional aspects involving biocrust research.

3 Methodological approach

To examine biocrust research background generated in Spain, we first conducted a literature review. We used *Scopus* to identify all papers containing the terms “biocrust”, “biological soil crust”, and “microphytic crust” in the title, abstract, or keywords. The literature search was conducted on 28 June 2019. We restricted the literature review to articles in English and Spanish. We did not include review papers to avoid duplicate evidence. For each retrieved article, we

identified authors, year of publication, keywords, and study site. Then, we selected those articles conducted in Spanish regions. We reviewed the full text of the articles and established associations between the generated knowledge in each article and the different elements of the IPBES framework (Appendix A, Fig. A1). Associations were established across the six categorized IPBES components (nature, nature's contributions to people, anthropogenic assets, institutions and governance systems and other indirect drivers of change, direct drivers of change, and good quality of life) if generated knowledge provided further information about them (e.g. a study analysing direct effects of biocrusts in soil stability or biodiversity implied one association with the nature component). Associations with the interactions among the six IPBES components (linkages from 1 to 10) were assigned to those studies analysing the influence of any constituents of an IPBES component in any other component. For instance, a study focused on the implications of climate change (direct driver of change component) in biocrust composition (nature component) implied one association with "linkage number 3". In doing so, we used a binary scale (0, not associated; 1, associated) according to Mastrángelo et al. (2019). We established as criteria that the scientific knowledge contained in a single article should imply more than one association with the IPBES elements. In addition, we identified whether publications highlight implications for conservation practice. A simple binary option of ones and zeros was used to indicate the existence (or not) of recommendations for guiding management strategies and actions for biocrust conservation.

4 Results and discussion

Biocrusts were described in Spain almost 50 years ago (Crespo, 1973; Llimona, 1974; Crespo and Barreno, 1975). However, their ecological functions remained quite uninvestigated until the 1990s (Maestre et al., 2011). It was during the XXI century when biocrust science in Spain experienced an important upsurge, following the global trend described by Bowker et al. (2018) and probably motivated by the first publication of the biocrust book *Biological Soil Crusts: Structure, Function and Management* (Belnap and Lange, 2003). In this regard, it should be noted that the literature review did not capture the mentioned original studies because the term biological soil crusts was not employed in such studies (i.e. Alexander and Calvo, 1990; Calvo-Cases et al., 1991; Guerra et al., 1995; Canton et al., 2001). From 2000 to 2019, more than 90 peer-reviewed articles analysing biocrust communities within the Spanish regions have been published (Fig. 1). This research represents about 10 % of the total number of biocrust articles published on a global scale during the same period. These numbers position Spain as one of the hot spots of biocrust science, and their relevance would probably increase if we considered that during the last decade many Spanish researchers have been in-

involved in international projects and networks that focused their research effort in other regions that were not considered in this review. During the analysis of the identified articles, we established 239 associations between the scientific knowledge generated in each study and the IPBES elements (Appendix B, Table B1). These associations encompassed four of the six main components (nature $n = 150$; nature's contributions to people $n = 10$; anthropogenic assets $n = 18$; good quality of life $n = 2$) and 2 of the 10 linkages (linkage between direct drivers of change and nature (linkage number 3), $n = 49$; linkage between nature and nature's contributions to people (linkage number 4), $n = 10$) (Fig. 1).

As observed in Fig. 1, the biocrust research community has a strong focus on fundamental natural sciences with most effort aimed at the nature component (150 associations). In particular, biocrusts' structure, composition, and functioning (57 % of the total associations within the nature component), their effects on water availability, biogeochemical fluxes and other non-living natural resources (19 %), and their contribution to ecosystem biodiversity (18 %) have fuelled most research interests (Fig. 2). Regardless of taxonomic composition, all these studies identified biocrusts as a biodiverse (Concostrina-Zubiri et al., 2014a; Blanco-Sacristan et al., 2019) and multifunctional component of Spanish drylands (Maestre et al., 2011) that controls biogeochemical cycles (i.e. Castillo-Monroy et al., 2010; Maestre et al., 2013; Delgado-Baquerizo et al., 2010; Escolar et al., 2015; Miralles et al., 2018), regulates water availability (i.e. Chamizo et al., 2013a, 2016; Cantón et al., 2020), and protects soil from water erosion (Lazaro et al., 2008; Chamizo et al., 2012c). Some other studies have also evaluated the linkages and interactions between all these positive effects of biocrusts and the performance of other living natural resources (5 %) such as vascular plants (i.e. Luzuriaga et al., 2012; Rodríguez-Caballero et al., 2018b) or vertebrates (Eldridge et al., 2010; Fig. 2).

The second IPBES element that most called the attention of biocrust researchers in Spain has been the response of biocrusts to natural and anthropogenic direct drivers of change, which is represented by the linkage between drivers of change and nature or linkage number 3 (49 associations; Fig. 1). Here, the effect of both natural and anthropogenic drivers on biocrusts has been analysed in a similar proportion (Fig. 2). Most of these studies concluded that, in a similar way as observed in other regions of the world (Reed et al., 2019), Spanish biocrusts are also endangered by ongoing climate change and land-use intensification. Predicted temperature increase and changes in precipitation pattern over the Mediterranean basin (IPCC, 2013) will affect the coverage and spatial distribution of biocrust communities and may lead to a community shift from well-developed lichen- and moss-dominated biocrusts to early cyanobacteria (Maestre et al., 2013). This, as well as physical alteration of biocrusts by human activities (i.e. trampling), will reduce their coverage,

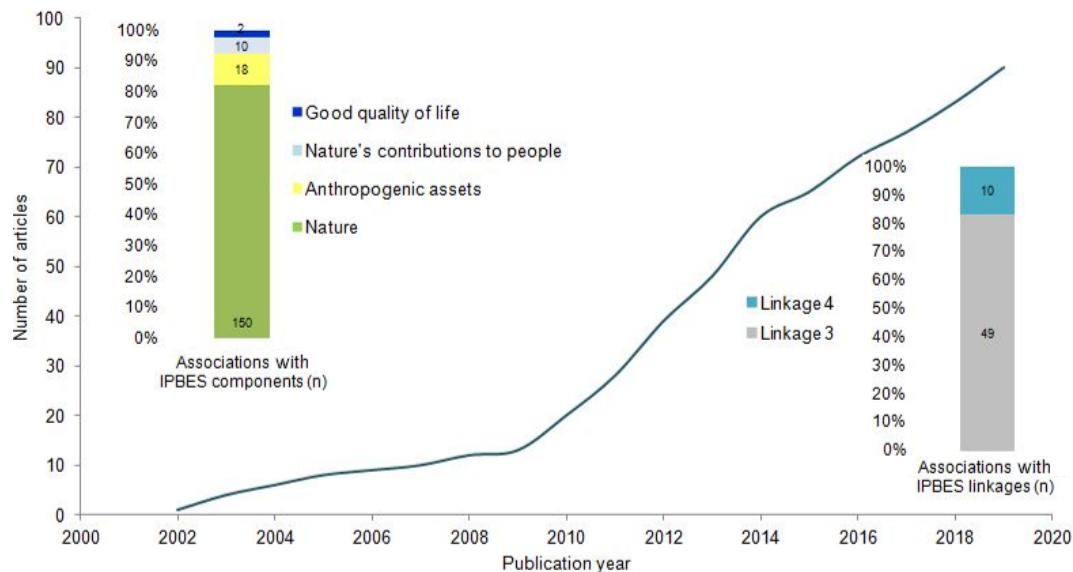


Figure 1. Evolution of the number of articles published regarding biocrust topics in Spain. Bar charts represent the contribution of these publications to the different IPBES components and linkages. Linkage numbers 3 and 4 refer, respectively, to linkage between direct drivers of change and nature and linkage between nature and nature's contributions to people.

biodiversity, and capacity to provide services and benefits to society (Rodríguez-Caballero et al., 2018c).

The notion of ecosystem services has not been very popular within the biocrust community, even though such a notion is hypothesized to represent a powerful communication tool for raising awareness about benefits that society derives from nature (Abson et al., 2014; Kadykalo et al., 2019). Only 10 studies have somehow adopted an ecosystem service perspective, represented by the linkage between nature and nature's contributions to people or linkage number 4 (10 associations; Fig. 1). All of them elucidate the potential benefits of biocrust maintenance for regulating services through processes such as atmospheric CO₂ fixation (i.e. Maestre et al., 2013; Miralles et al., 2018) and other biogeochemical fluxes that affect soil fertility (García-Palacios et al., 2011; Chamizo et al., 2013a), erosion control (Rodríguez-Caballero et al., 2018c; Chamizo et al., 2012b), or water regulation (i.e. Eldridge et al., 2010; Chamizo et al., 2016; Rodríguez-Caballero et al., 2018c). The rest of the ecosystem service categories (i.e. provisioning and cultural) is still outside the research focus. Ecosystem service studies are hypothesized to be helpful in facilitating understanding of scientific discourse on the benefits of nature to the people (Abson et al., 2014). Thus, the underrepresentation of studies dealing with this topic, in comparison with the number of studies focused on the natural component, may hinder the possibility for biocrusts and their benefits to be known and understood by the policy community and general public. This fact has been indeed confirmed by one recent study that, by incorporating the social perspective in biocrust research, demonstrated the lack of awareness of so-

ciety concerning the benefits/ecosystem services provided by biocrusts (Rodríguez-Caballero et al., 2018c). Some reasons that explain such a lack of consciousness concerning the role of biocrusts as providers of ecosystem services to society could be (1) the false perception of drylands as barren lands due to low plant cover and existence of large open areas between plants which are commonly believed to be “devoid of life” and (2) the predominant composition in many biocrust communities of microscopic organisms, not visually evident, which represents an additional obstacle to draw the attention of the general public towards their high representativeness and relevance in drylands. This reinforces the idea that new studies are needed in the ecosystem service field to make evident the benefits provided by biocrusts to people. There is also a demand for quantifying the importance of these keystone communities for the maintenance of human well-being (good quality of life component) in dryland regions, which is an important component of the IPBES framework that has also been largely unaddressed by the researchers (two associations; Fig. 1).

Our literature review also sheds light on an increasing interest of the biocrust community in generating applied knowledge, rather than focusing on empirical natural sciences, as demonstrated by the 18 associations within the anthropogenic assets component (Fig. 1). Applied research efforts have been mainly focused on the development of new biotechnological tools to restore degraded drylands by recovering biocrusts and the services they provide (Ballesteros et al., 2017; Román et al., 2018). Practical methodologies for biocrust mapping, monitoring, and modelling (i.e. Rodríguez-Caballero et al., 2017; Blanco-Sacristan et al.,

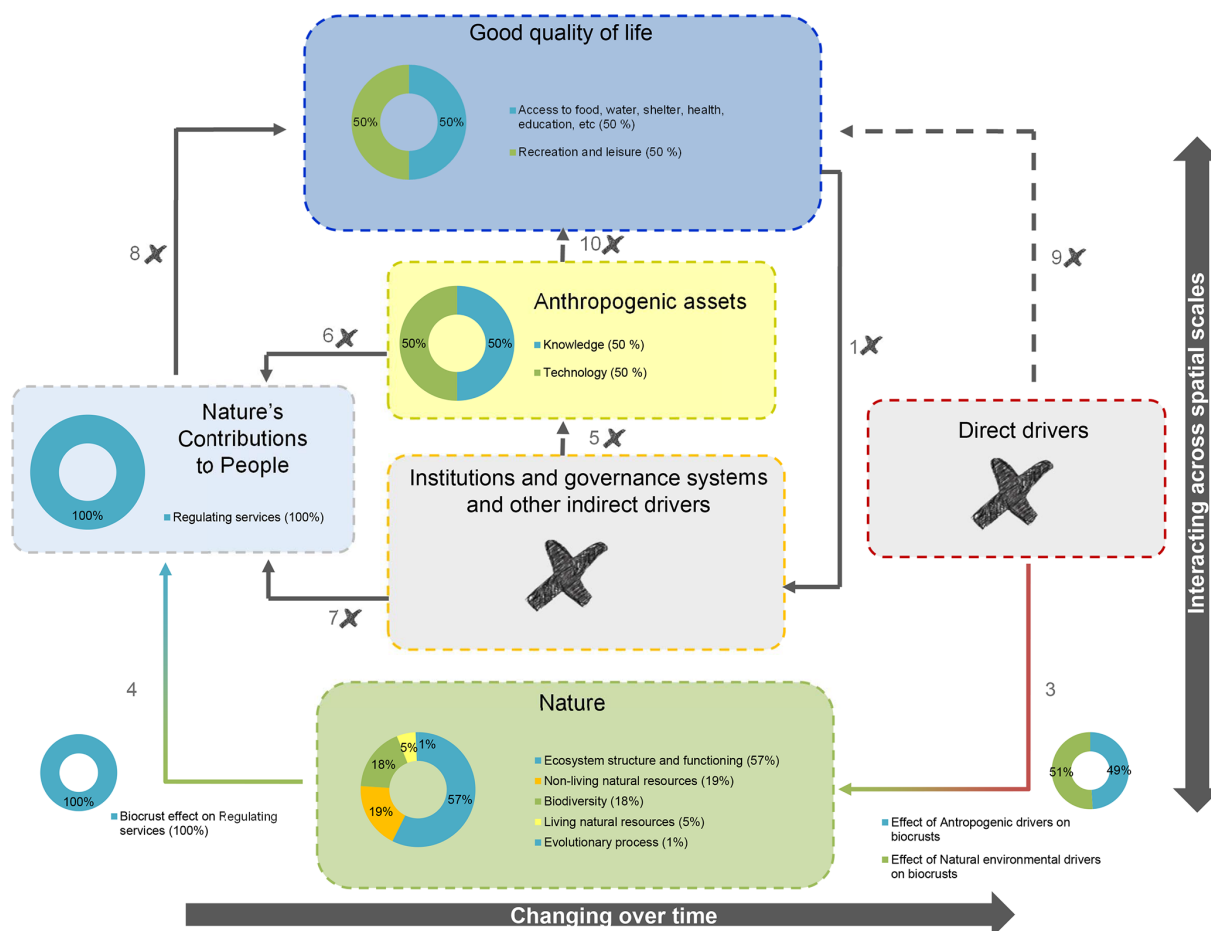


Figure 2. Distribution of biocrust research efforts across the IPBES conceptual framework. Percentage of associations between the knowledge generated in each article and the different elements (six categorized components and 10 linkages among them). The main components are represented by boxes whereas lines represent the linkages among them. The percentage of associations is represented by categories within each element and indicated by the area of the pie chart. Crosses indicate knowledge gaps. Figure adapted from Díaz et al. (2015).

2019; Román et al., 2019) as well as basic knowledge on biocrust ecosystem management that may help land managers to incorporate biocrusts into land-use policies aimed at ensuring drylands sustainability (i.e. Ochoa-Hueso et al., 2011; Rodríguez-Caballero et al., 2015b; Blanco-Sacristan et al., 2019) have also been developed. In addition, we have identified an increasing number of scientists who have begun to be concerned with making recommendations for guiding management strategies and actions for biocrust conservation (11 % of total analysed studies) (Appendix B, Table B1). For example, several researchers recommended considering biocrust presence before disturbance activities, in order to promote best action plans for further recuperation of the native community (García-Palacios et al., 2011; Williams et al., 2017). Others suggested considering biocrust effects on water redistribution processes (Maestre and Cortina, 2002; Rodríguez-Caballero et al., 2018b, 2019) or carbon fluxes (Escolar et al., 2015; Rey et al., 2017).

While there is an increasing concern between scientists for aligning their research with the policy domain, progress in using the scientific knowledge generated for supporting policies and strategies to manage, conserve, and regenerate biocrusts still remains insufficient. There are reasonable grounds to assume the above since legal and institutional frameworks that claim the protection and conservation of biocrusts are absent in Spain, an issue that was already pointed out by Maestre et al. (2011), who brought out the absence of a Spanish red list of endangered biocrusts as evidence of their non-protection. In fact, our review revealed that there are no studies associated with the institutions and governance systems and other indirect drivers component (Fig. 2). This means that we did not find studies specifically focused on facilitating changes in institutional practices and encouraging individual behaviours aimed at protecting biocrusts. Unfortunately, the lack of legal frameworks that protect the conservation of biocrusts appears to go further than Spain and applies also to other countries around

the world. In an attempt to address this policy-relevant gap, we found that recent initiatives have been launched by the biocrust community in different regions. For example, we can mention the Soil Crust International Project (SCIN, <http://www.biodiversa.org/120>, last access: 19 September 2020), whose objective was “to achieve both better appreciation of the functioning and importance of biocrusts in Europe and to add value by contributing to the development of better and simpler soil protection practices and policies”. However, we still must push harder in this direction in order to catalyse institutional and social changes for promoting effective biocrust conservation in the short-term.

are needed across countries and regions to build a ranking scheme based on both failures and achievements related to the incorporation of biocrust evidence into conservation policies.

5 Conclusions

This study reveals that scientific knowledge generated on biocrust from an ecological perspective during more than 2 decades of intensive research in Spain has significantly contributed to a fundamental understanding of biocrust structure and functions and the ecological relevance of the ecosystems where they live. In this period, we also found that there was an increasing concern among scientists for aligning their research with conservation strategies to manage and restore biocrusts as well as for emphasizing the benefits that society obtains from them. However, studies focusing on strengthening the connection of biocrust research with policy domain and institutional practices still remain insufficient. This underpins the need to tackle the social dimension of the biocrust role. Therefore, it is timely to reflect on the biocrust research background and on the development of future directions of this burgeoning field of science to promote policy actions and management strategies with a special focus on biocrust conservation. On this basis, we call for a transition from an “ecological research perspective” to a “social–ecological research perspective” into the biocrust area, if advancing towards the implementation of biocrusts’ conservation strategies is the goal. The adoption of the “social–ecological research perspective” is needed to (1) produce research that better informs policy and society about the role of these keystone communities and (2) promote the best available evidence on the biocrusts role which can be used to support conservation actions. To deal with this novel research approach, it is necessary for biocrust science to adopt inter- and transdisciplinary work schemes that facilitate collaborative work between scientists from a range of disciplines (e.g. ecology, sociology, and economic sciences) and non-scientist actors related to representative biocrust areas (e.g. practitioners, environmental advocates). These work schemes will allow us to create communities of practice representing science, policy, and society which will work together to promote evidence-based conservation practices on biocrusts and build new road maps that contribute to the preservation of these dryland representative communities from regional to global scales around the world. To move forward in this subject, further studies

Appendix A: IPBES framework

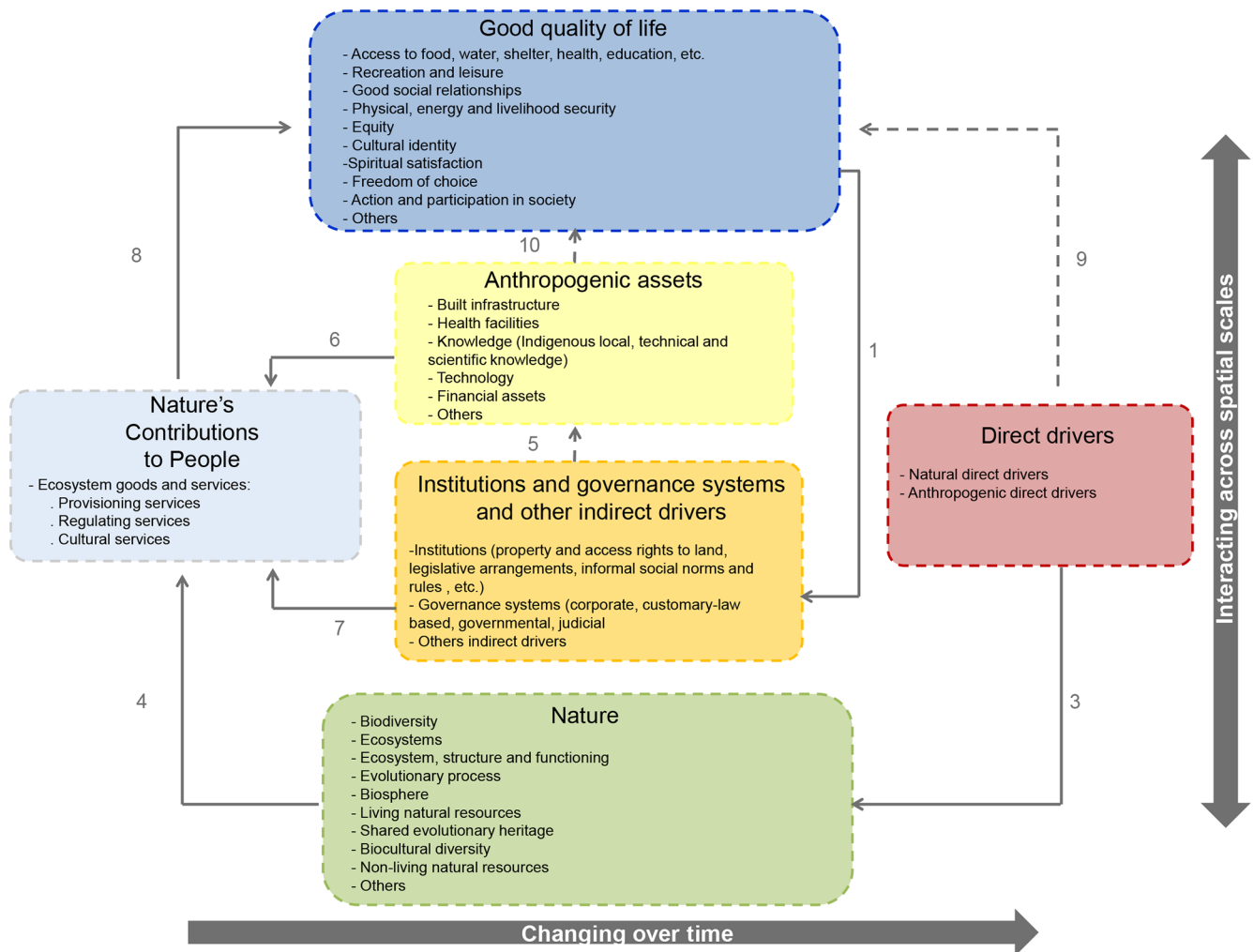


Figure A1. The IPBES framework guiding this research (reproduced from Díaz et al., 2015). Boxes denote six components (nature, nature's contributions to people, anthropogenic assets, institutions and governance systems and other indirect drivers of change, direct drivers of change and good quality of life) and categories within each one. Arrows from 1 to 10 represent the linkages among the six components across different temporal and spatial scales.

Appendix B: Associations of biocrust knowledge across the IPBES framework and identified implications for conservation practice

Table B1. List of references on biocrust research analysed in the study and identified associations in four of the six IPBES components (nature, nature's contributions to people, anthropogenic assets, and good quality of life) and 2 of the 10 linkages ("linkage number 3" (linkage between direct drivers of change and nature) and "linkage number 4" (linkage between nature and nature's contributions to people)). Those IPBES elements for which no associations were identified are not included in the table. Identified implications for conservation practice in references are also shown. Full references can be found at the end of the paper.

ID	References on biocrust research analysed in the study	Identified associations with IPBES components (n)				Identified associations IPBES linkages (n)		Identified implications for conservation practice
		Nature	Nature's contributions to people	Anthropogenic assets	Good quality of life	Linkage 3	Linkage 4	
1	Maestre and Cortina (2002)	1	0	0	0	0	0	1
2	Maestre and Cortina (2003)	1	0	0	0	1	0	0
3	Maestre (2003a)	1	0	0	0	0	0	0
4	Maestre (2003b)	1	0	0	0	0	0	0
5	Cantón et al. (2004)	1	0	0	0	1	0	0
6	Souza-Egipsy et al. (2004)	1	0	0	0	0	0	0
7	Maestre et al. (2005)	2	0	0	0	0	0	0
8	Pintado et al. (2005)	1	0	0	0	1	0	0
9	Martínez et al. (2006)	2	0	0	0	1	0	0
10	Escudero et al. (2007)	2	0	1	0	0	0	0
11	Lázaro et al. (2008)	2	0	0	0	1	0	0
12	Maestre et al. (2008)	2	0	0	0	0	0	0
14	Maestre et al. (2009)	2	0	0	0	1	0	0
15	Bowker et al. (2010b)	2	0	0	0	1	0	0
16	Castillo-Monroy et al. (2010)	2	0	0	0	1	0	0
17	Chamizo et al. (2010)	2	0	0	0	0	0	0
18	Cortina et al. (2010)	1	0	0	0	1	0	0
13	Delgado-Baquerizo et al. (2010)	2	0	0	0	0	0	0
19	Eldridge et al. (2010)	2	1	0	0	0	1	0
20	Maestre et al. (2010)	2	0	0	0	1	0	0
21	Bowker et al. (2011)	3	0	0	0	0	0	0
22	Castillo-Monroy et al. (2011a)	2	0	0	0	0	0	0
23	Castillo-Monroy et al. (2011b)	1	1	0	0	0	1	0
24	García-Palacios et al. (2011)	2	1	0	0	1	1	1
25	Gotelli et al. (2011)	2	0	1	0	0	0	0
26	Miralles-Mellado et al. (2011)	2	0	0	0	0	0	0
27	Ochoa-Hueso and Manrique (2011)	1	0	1	0	1	0	0
28	Ochoa-Hueso et al. (2011)	1	0	1	0	1	0	0
29	Bowker and Maestre (2012)	1	0	0	0	1	0	0
30	Chamizo et al. (2012a)	2	0	0	0	1	0	0
31	Chamizo et al. (2012b)	1	0	1	0	0	0	0
32	Chamizo et al. (2012c)	2	0	0	0	1	0	0
33	Chamizo et al. (2012d)	2	1	0	0	0	1	0
34	Escolar et al. (2012)	2	0	0	0	1	0	0
35	Luzuriaga et al. (2012)	3	0	0	0	1	0	0

Table B1. Continued.

ID	References on biocrust research analysed in the study	Identified associations with IPBES components (<i>n</i>)				Identified associations IPBES linkages (<i>n</i>)		Identified implications for conservation practice
		Nature	Nature's contributions to people	Anthropogenic assets	Good quality of life	Linkage 3	Linkage 4	
36	Miralles et al. (2012a)	2	0	0	0	0	0	0
37	Miralles et al. (2012b)	1	0	0	0	0	0	0
38	Miralles et al. (2012c)	1	0	0	0	0	0	0
39	Rodríguez-Caballero et al. (2012)	2	0	0	0	1	0	0
40	Bowker et al. (2013)	2	0	0	0	1	0	0
41	Chamizo et al. (2013a)	2	0	0	0	1	0	0
42	Chamizo et al. (2013b)	2	1	0	0	1	1	0
43	Delgado-Baquerizo et al. (2013a)	2	0	0	0	0	0	0
44	Delgado-Baquerizo et al. (2013b)	2	0	0	0	1	0	0
45	Delgado-Baquerizo et al. (2013c)	2	0	0	0	0	0	0
46	Maestre et al. (2013)	2	1	0	0	1	1	0
47	Miralles et al. (2013)	2	0	0	0	0	0	0
48	Rodríguez-Caballero et al. (2013)	2	1	1	0	1	1	0
49	Bastida et al. (2014)	3	0	0	0	0	0	0
50	Berdugo et al. (2014)	2	0	0	0	0	0	0
51	Büdel et al. (2014)	3	0	0	0	1	0	1
52	Concostrina-Zubiri et al. (2014a)	2	0	0	0	1	0	0
53	Concostrina-Zubiri et al. (2014b)	1	0	0	0	1	0	0
55	Ladrón de Guevara et al. (2014)	1	0	0	0	1	0	0
56	Maier et al. (2014)	2	0	0	0	0	0	0
57	Mendoza-Aguilar et al. (2014)	1	0	0	0	0	0	0
58	Miralles et al. (2014)	1	0	0	0	1	0	0
59	Raggio et al. (2014)	1	0	0	0	1	0	0
60	Rodríguez-Caballero et al. (2014a)	2	0	0	0	0	0	0
61	Rodríguez-Caballero et al. (2014b)	1	0	0	0	0	0	1
54	Escolar et al. (2015)	1	0	0	0	1	0	0
63	Ladrón de Guevara et al. (2015)	1	0	1	0	0	0	0

Table B1. Continued.

ID	References on biocrust research analysed in the study	Identified associations with IPBES components (<i>n</i>)				Identified associations IPBES linkages (<i>n</i>)		Identified implications for conservation practice
		Nature	Nature's contributions to people	Anthropogenic assets	Good quality of life	Linkage 3	Linkage 4	
64	Rodriguez-Caballero et al. (2015a)	1	0	0	0	0	0	0
65	Rodriguez-Caballero et al. (2015b)	2	0	1	0	0	0	1
66	Chamizo et al. (2016)	2	0	0	0	0	0	0
62	Delgado-Baquerizo et al. (2016)	2	0	0	0	1	0	0
68	Ochoa-Hueso et al. (2016)	3	0	0	0	1	0	0
70	Uclés et al. (2016)	2	0	0	0	0	0	0
71	Williams et al. (2016)	2	0	0	0	1	0	0
72	Ballesteros et al. (2017)	1	0	2	0	1	0	1
67	Chamizo et al. (2017)	2	1	0	0	1	1	0
74	Ochoa-Hueso et al. (2017)	1	0	0	0	1	0	0
75	Raggio et al. (2017)	1	0	0	0	1	0	1
69	Rey et al. (2017)	2	1	0	0	1	1	0
76	Rodriguez-Caballero et al. (2017)	1	0	1	0	0	0	0
77	Williams et al. (2017)	2	0	0	0	1	0	0
78	Cano-Díaz et al. (2018)	2	0	0	0	0	0	0
79	Concostrina-Zubiri et al. (2018)	2	0	0	0	1	0	0
73	Lafuente et al. (2018)	2	0	0	0	1	0	0
80	Miralles et al. (2018)	1	0	0	0	1	0	0
81	Rodriguez-Caballero et al. (2018b)	2	0	0	0	0	0	0
82	Rodriguez-Caballero et al. (2018c)	1	1	0	2	0	1	1
83	Williams et al. (2018)	2	0	1	0	1	0	1
84	Blanco-Sacristán et al. (2019)	1	0	2	0	0	0	0
85	Concostrina-Zubiri et al. (2019)	2	0	0	0	1	0	0
86	Lorite et al. (2019)	2	0	0	0	1	0	1
87	Rodriguez-Caballero et al. (2019)	1	0	0	0	1	0	0
88	Roman et al. (2019)	0	0	2	0	0	0	0
89	Roncero-Ramos et al. (2019a)	0	0	2	0	1	0	0
90	Roncero-Ramos et al. (2019b)	3	0	0	0	0	0	0
Total		150	10	18	2	49	10	10

Data availability. No data sets were used in this article.

Author contributions. MDLR and ERC conceived and conceptualized the study. ERC conducted the bibliographic search. MDLR and ERC jointly analysed data, designed the manuscript, and wrote the original draft of the manuscript. SC and YC wrote and edited the manuscript. All authors revised and approved the final version of the manuscript.

Competing interests. The authors declare that they have no conflict of interest.

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