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Unveiling emerging interdisciplinary research challenges in the highly threatened sclerophyllous forests of central Chile

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Abstract

Background The potential ecosystem collapse of forests in Mediterranean-type ecosystems (MTEs) by unprecedented droughts is worrisome due to the impacts on its exceptional biodiversity and human well-being. However, research integrating the impacts of global change drivers, forest resilience and the challenges facing human-nature relationships is still scarce.

Methods and results Using the central Chile megadrought and recently massive forest browning event as a model scenario, we identified, through a scientific literature review and an interdisciplinary scientific workshop, the research priorities and questions to address for MTEs in a context of global change. Our results highlighted knowledge gaps that need to be covered, particularly in social and environmental sciences, with an emphasis on soil science. Research priorities must focus on (1) the understanding of interactive effects of global and local anthropogenic drivers on MTEs and (2) the evaluation of the potential impacts of MTEs collapse on human well-being and ecosystem functioning.

Conclusions We highlight the need for a collaborative approach involving scientists, landowners, managers/administrators, and policymakers to apply adaptive forest management against the current socio-environmental challenges under a global change context.

Keywords Adaptation, Climate change, Droughts, Mediterranean forest, Socio-ecosystems

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Introduction

The collapse of ecosystems due to global change, with its consequences on human well-being, requires an urgent commitment from scientists and policymakers to look for new interdisciplinary approaches to face the impacts of such events. Mediterranean-type ecosystems (MTEs) are at the forefront among the most threatened ecosystems in the world. Despite that, seasonal drought events occur naturally in these ecosystems; their frequency, intensity, and duration are expected to increase over the next 30 years, regardless of emissions scenarios [1]. As in most socio-ecosystems, MTEs biodiversity co-evolved with the human population for thousands of years to generate resilient societies and ecosystems [2]. However, human activities in the last centuries have highly impacted MTEs, resulting in these ecosystems being included within the 36 global biodiversity hotspots of exceptional value for global conservation [2, 3]. Moreover, climate anomalies inducing extreme drought events in these ecosystems have resulted in an abrupt decline in forest productivity and massive tree die-off events [4–6]. Nevertheless, MTEs still sustain a remarkable species richness and endemism. They provide a wide range of services, such as carbon sequestration, medicinal plants, and scenic beauty, to highly populated areas (~500 million people), even with their reduced 2% of the world's terrestrial surface. Within this scenario, the potential consequences of observed changes in MTEs, including the possibility of massive ecosystem collapse - a transition beyond the thresholds of natural variability, in which resilience capacity is exceeded, involving the loss of key ecosystem features - and the loss of societal benefits, have created pressing uncertainties that need to be urgently addressed [7].

MTEs of central Chile can offer relevant learnings and key insights to similar socio-ecosystems worldwide. This type of forest ecosystem overlaps with 65% of the country's total population and concentrates many natural resource-demanding economic activities, such as intensive agriculture, forestry, urbanization, and mining. At the local scale, rural communities have developed management practices with negative consequences for the forests, such as logging, grazing, deforestation, and fires. In contrast, some other particular practices have returned positive outcomes, such as fire reduction, maintenance of habitat mosaics, and seed dispersal [8]. At a regional scale, MTE forests have suffered a large extent of surface loss due to land-use change [9, 10], which continues today through an explosive urban expansion and the conversion to vineyards, exotic fruit orchards, and timber tree plantations [10–12]. This constant surface reduction and poor conservation efforts, including a very low (~ 1% of the total surface) representativeness in the National System of Protected Areas, has led to this unique ecosystem in a highly threatened state [13].

The threatened condition of Chile's MTE forests is exacerbated by climate anomalies, suggesting that climate change effects here may occur sooner than expected. These include the period between 2010 and 2022, representing the driest and warmest decade since at least the 14th century [14, 15]. Given the intensity and duration of this "megadrought", extensive forest areas, mainly dominated by evergreen species, turned abruptly brown and suffered a significant reduction of their vegetation cover by massive tree die-off, with negative consequences in their productivity [16, 17]. This case of forest browning was extraordinary due to the extension it covered (latitudinal range of ~ 500 km), the synchronicity in which it happened (less than 100 days), and the difference in species compositions and management legacies affected [16]. Although forest browning events caused by severe drought have been reported in California [18], South Africa [4], the Mediterranean basin [19], and Australia [20], a recent global analysis that includes all MTEs showed that both the magnitude of the browning and of the megadrought in central Chile, are unprecedented phenomena [21].

Considering the present and future climate scenarios, which predict increases in aridity in central Chile, the possibility of a massive ecosystem collapse of Chile's MTE forests is extremely worrisome, especially given the potential consequences for its exceptional biodiversity and human well-being. Therefore, there is an urgent need to (1) understand and identify what are the social and environmental drivers behind massive forest browning, (2) anticipate the impact of this phenomenon in communities well-being and ecosystem functioning, and (3) design adaptive strategies under future climate scenarios, to offer critical insights to other MTEs and related socio-ecosystems. To achieve these goals, we must consolidate and synthesize the state of knowledge about the central Chile MTE forests and identify the main gaps, which we conducted by two different approaches. First, we performed a scientific literature review and categorized information in five themes: (1) topic of study, (2) biological level of organization, (3) source of information, (4) spatial scale and (5) global change drivers. In addition, we conducted an interdisciplinary scientific workshop to identify research and knowledge gaps related to the drivers underlying forest browning in MTE of central Chile; the impacts of this phenomenon in socio-ecosystems; and, adaptation alternatives under future climate change scenarios. With these two sources of information, we identified collaborative research priorities and research questions to address in a context of global change for central Chile with a broader scope.

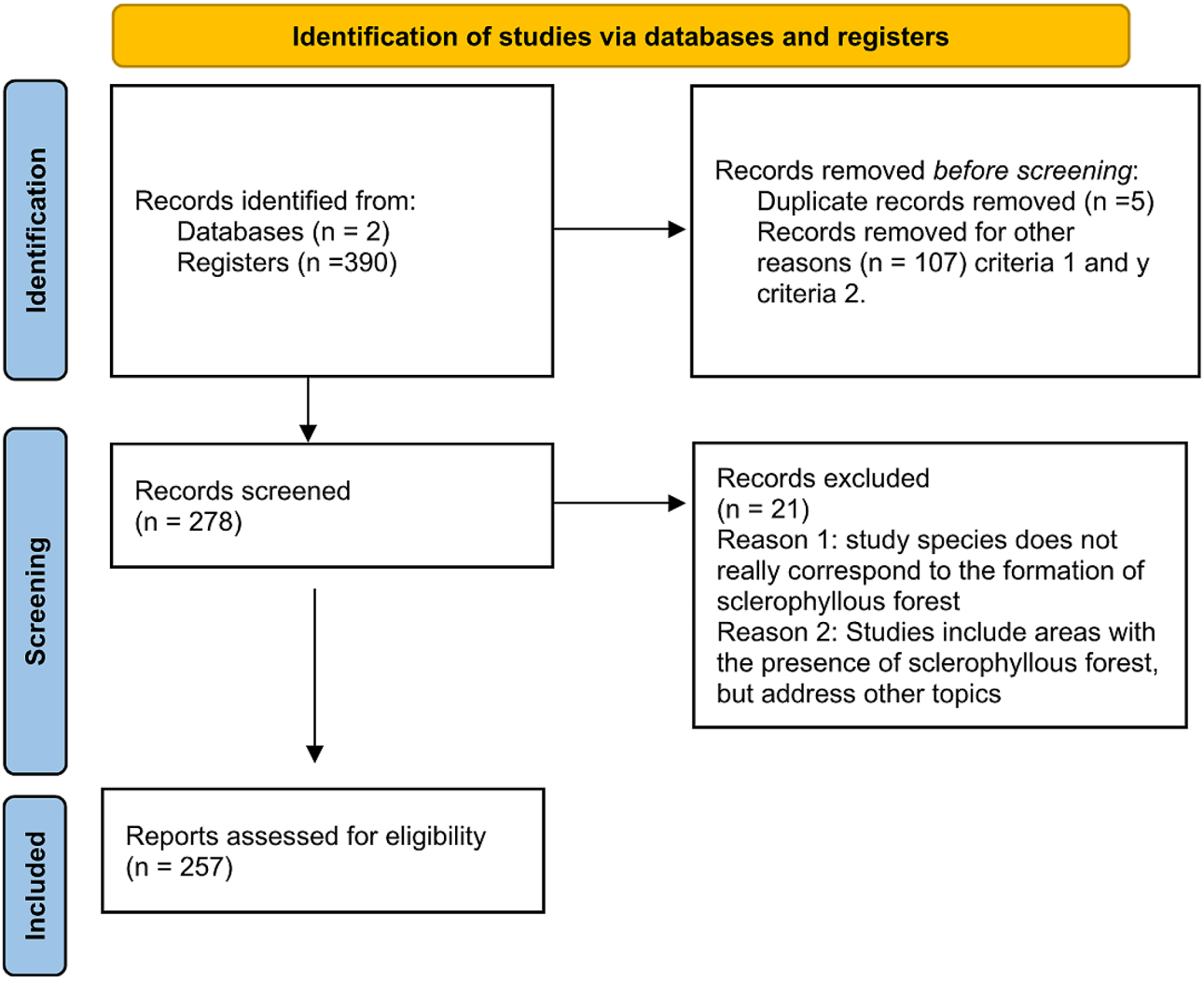

Fig. 1 Flow diagram with the different phases of our systematic review. (adapted from PRISMA). See Table 1 for the Criteria information selection

Table 1 Decision tree for the selection of articles that were included in the literature review (based on Martínez-Harms et al. 2021)

Criteria	Answer	Action
1: Research topic.	Yes	Go to Q2
Does the study address or investigate central	No	Exclude
Chile MTE forest or its ecosystem?	Unclear	Go to Q2
2: Research topic.	Yes	Include
Is the study located within the presence of the	No	Exclude
central Chile MTE forest?	Unclear	Include

Methods

Literature review

We searched peer-reviewed scientific articles using the Clarivate Analytics Web of Science (WoS) and the Scientific Electronic Library Online (Scielo) databases (Fig. 1). The search was conducted including titles, abstract and keywords using the following keywords: (sclerophyllous* OR matorral OR "mediterranean forest" OR "mediterranean ecosystems" OR "mediterranean shrubland" OR "Mediterranean-type" OR "mediterranean environment") AND (Chile OR "Central Chile"). This search allowed us to identify the scientific papers from natural and social sciences. The search was not restricted to a specific period of time (Fig. 1).

Once we obtained the paper collection, we used a decision tree protocol as the first exclusion criterion [22] (Table 1). When available, we extracted the following information from the selected articles: (1) Topic of study (i.e., plants, animals, microorganisms, socioecology or soil); (2) Biological level of organization (i.e., species, population, community, ecosystem, landscape or biome); (3) Sources of information (i.e., field observational data, field experimental data, laboratory data, remote sensing data, modeling data or collection data); (4) Spatial scale of the study (i.e., local or regional), and (5) Global change drivers (i.e., biotic invasion, climate change, drought, fire, land use change). We acknowledge that other types of publications, such as technical reports and

an undergraduate and postgraduate thesis, had valuable information; however, these were not included in this study given their heterogeneity of sources and, therefore, systematization.

Interdisciplinary workshop

In May 2021, we organized the workshop "Opportunities for Transdisciplinary Research in the Sclerophyllous Forest in the Face of Global Change." The workshop aimed to establish, from a socio-ecological perspective, the primary research directions that focus on three key themes: (1) Drivers, (2) Impacts, and (3) Adaptation of the central Chile MTE forest to global change. Its overarching goal was to promote collaboration among three main research centers in Chile, specializing in terrestrial biodiversity, ecology, and climate change. To achieve this objective, the researchers from each center were carefully evaluated based on their respective research topics, and those whose areas of expertise aligned with the workshop objectives were invited to participate. However, it was detected that the field of socioecology was not adequately represented across the centers. Consequently, external experts were invited to bridge this gap.

Thirty-three scientists from ecology, climatology, socioecology, and agricultural sciences participated. Participants were randomly distributed among groups, ensuring gender and subdisciplines representativeness. Participants of each group proposed ideas or concepts in response to the main questions and justified their answers. The discussion was recorded and analyzed with descriptive qualitative analysis using principles of Grounded Theory and open coding procedure. To avoid redundancy, we grouped repeated or similar ideas. We organized the information in a mind map that connected our main categories, Drivers, Impacts, and Adaptation with the concepts that arose throughout the workshop. For example, though "heat waves" are classified as Drivers, the concept is included under "extreme events" including other climatic events. The knowledge gaps identified by participants were grouped, and the resulting categories were used to define research questions. Finally, with the collected data from the literature review and interdisciplinary scientific workshop, we identified the research fields in the past and the current knowledge gaps.

Results

Literature review

The literature review found 257 articles (Fig. 1) that studied the sclerophyllous forest ecosystem of central Chile between 1976 and 2022 (46 years). A marked imbalance between research topics was evidenced, with plant and native animal species being the topics that concentrate 91.4% of articles (Fig. 2a). Studies on plants and animals have maintained a sustained growth over time since 1976 (Fig. 3a). The relevance and sustained growth of these study topics over time could be associated with the importance of central Chile as a global biodiversity hotspot. In contrast, socio-ecological topics, soil-related studies focusing on physico-chemical properties and soil biological aspects, had a lower representation in the scientific literature, with almost no growth between 1976 and 2012. However, socio-ecological themes are becoming increasingly relevant in this ecosystem (Fig. 3a). Studies at the plant species and community levels concentrate more than 80% of the publications carried out in the central Chile MTE forest, while biome studies are represented by only 3.1% of the scientific literature (Figs. 2b and 3b). This could be because conducting biome-wide studies requires complex comparative analysis between one or more MTE's across the globe, which requires greater international collaboration efforts and funding.

Regarding the "sources of information" category, 61.4% of the data was obtained from field observational studies, while modeling and remote sensing data represents approximately 10% (Fig. 2c). However, such methodological approaches have shown a rapid and sustained increase in recent years due to emerging studies focusing on understanding landscape dynamics (e.g., changes in ecological niche distributions as a result of climate and land use changes), and because of the increased supply of satellite imaging data. Furthermore, the number of local-scale studies doubles that of those conducted at regional scales (Fig. 2d). The latter is consistent with biome-wide studies being the least represented in the scientific literature. Finally, when we analyze by type of global change driver (e.g., land use change, fire, drought), the results showed that about 70% of articles do not explicitly identify the presence of these anthropogenic disturbances in the study area (Fig. 2e). Finally when we analyze by type of global change driver (e.g., land use change, fire, drought), the results showed that about 70% of articles do not explicitly identify the presence of these anthropogenic disturbances in the study area (Fig. 2e). The disproportion found between studies covering global change drivers and those that do not could be explained by how contemporary certain drivers are. For example, studies that directly incorporate climate or land use change have only started in 2009. Another explanation could be the type of analysis typically used to work with these drivers, such as data modeling and remote sensing, which have accelerated in recent years.

Interdisciplinary workshop

Two main types of drivers were recognized by workshop participants, according to the origin and spatial scale in which they occur: local and global drivers. First, local drivers were associated with the historical and current

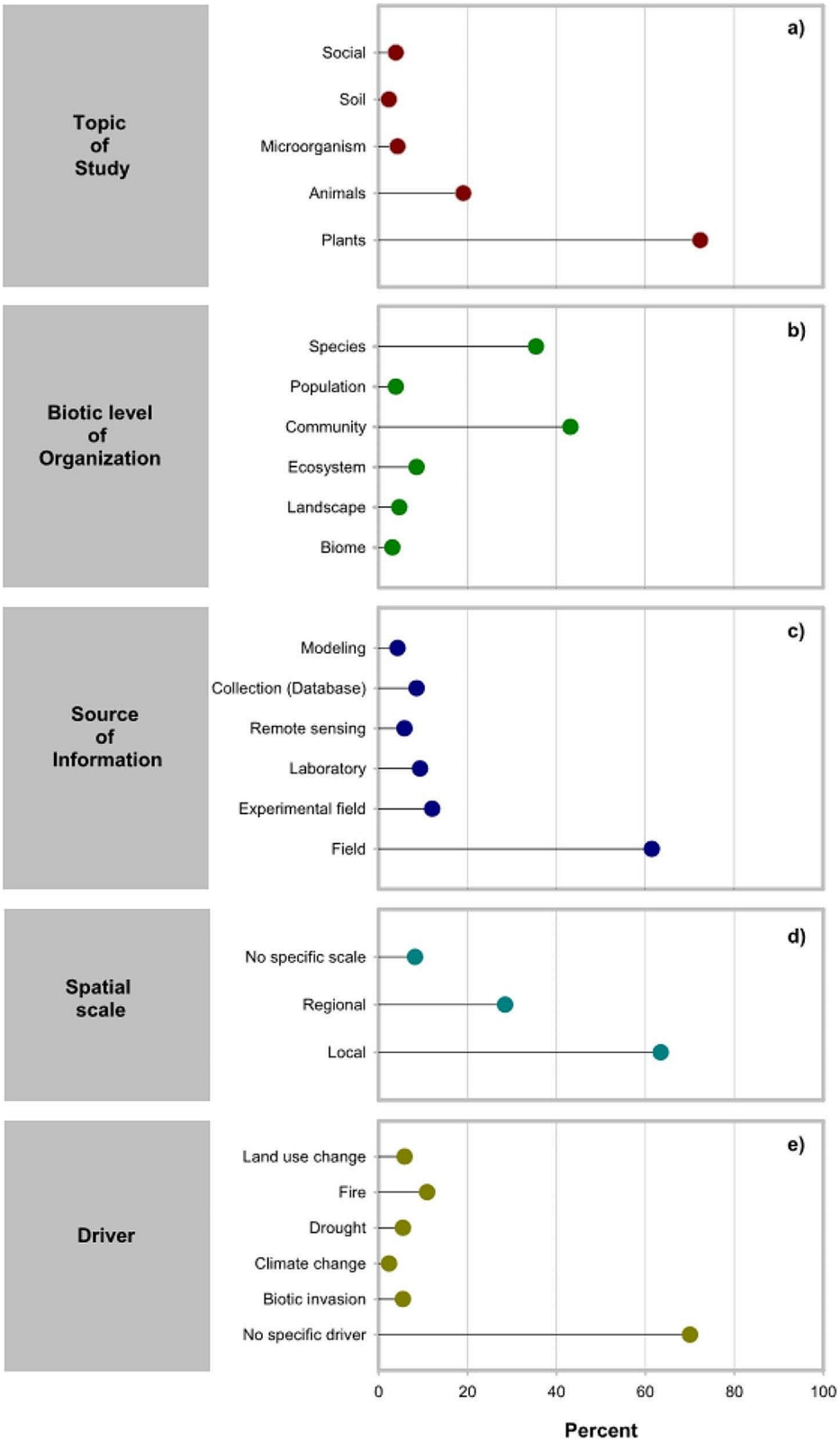

Fig. 2 Topic of studies, level of organization, source type of information, spatial scale, and global change driver considered appearing in reviewed articles ($n = 257$) about central Chile MTE forest

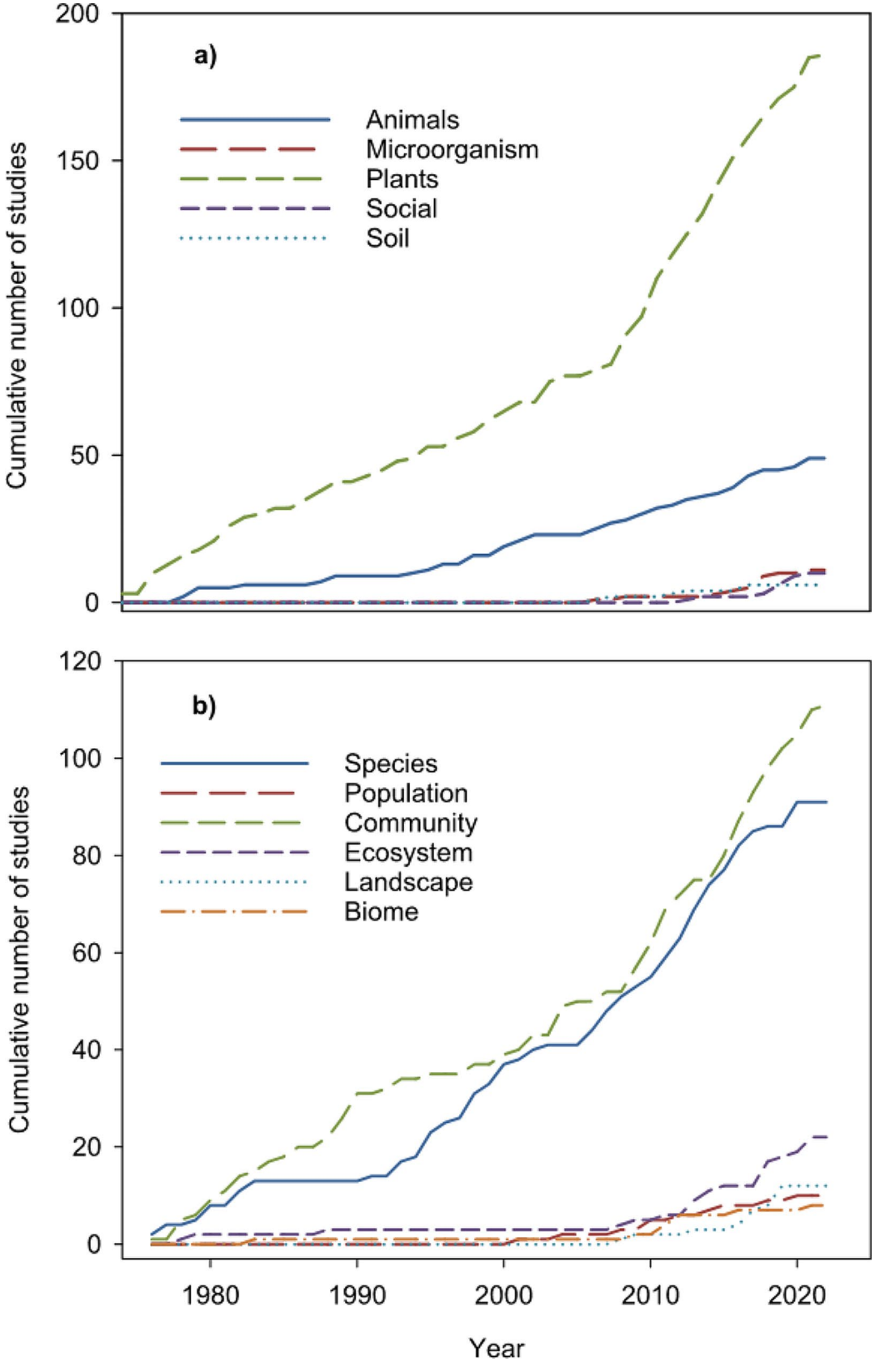

Fig. 3 Historical trend of central Chile MTE forest ecological publications (cumulative number of studies) as a function of (**a**) the topic of study and (**b**) the level of biological organization

management that had contributed to the loss and degradation of the central Chile MTE forest. The participants pointed out that public policies have contributed to (1) forest loss by land use change to agricultural and urban use, (2) poor management of water resources in the territory, and (3) maintaining a weak institutional framework associated with the management and conservation of nature. Global drivers are related to climate change, which is suggested to be responsible for triggering forest decline. The main global driver identified is the sustained decrease in rainfall during the last decades, which at the local scale is confirmed by the megadrought that began in 2010 and continues today. In addition, the rise in temperatures and more frequent occurrence of heat waves are also proposed as global drivers of ecosystem collapse. Thus, one priority line of research should investigate the interaction between heat waves and the decrease in precipitation and its effects on forest survival. In addition, there is an urgent need to determine the role of interacting local and global drivers in forest response, as well as possible positive and negative feedback with potential cascade effects that could accelerate the process of forest loss.

The possible impacts of an MTE ecosystem collapse were categorized according to their effects and consequences on forest composition and structure, ecosystem functions, and society. For forest composition and structure, it was recognized that the impacts can occur at different biological levels of organization. For example, at the species level, the need was pointed out to evaluate the effects of forest decline on the mortality and survival rates of trees, shrubs, and herbs. Given the current lack of information, we need to pay special attention to evaluating the direct and indirect impacts of forest alterations on animal species, from herbivores and frugivores to top predators and to the possible species loss or displacement. At the community level, there is a high uncertainty regarding how species interaction networks, such as pollination and seed dispersal processes, would respond to a possible ecosystem collapse. Also, we need to investigate if ecosystem collapse may lead to new communities due to species replacement, changes in the relative abundance of different species, and/or local extinctions. Impacts on forest structure and composition could influence ecosystem features and functions. For example, special concern exists over the hydrological and biogeochemical cycles, particularly water and carbon dynamics occurring in soil environments. Another impact pointed out by participants was the possible alteration of the soil-vegetation-atmosphere interaction, and of the capacity of the ecosystem to regulate moisture and atmospheric surface temperature.

Potential impacts of ecosystem collapse on society included cultural aspects, nature's contributions to people (NCPs) and landscape planning. Regarding culture, there is a concern for the loss of traditional knowledge and local traditions, and a need to evaluate impacts on the perception and sense of belonging that society has with the forest. From the NCPs approach, the importance to evaluate the impacts on soil production, regulation of the water cycle, and recreation, among others, was recognized. Finally, for land planning, further studies on the rural-urban migration regime and the effect of an increased likelihood of natural disasters, such as wildfires and floods, on human communities' vulnerability were highlighted as necessary.

For adaptation alternatives under future climate change scenarios, workshop participants pointed out the need to sharpen our research focus on understanding the mechanisms that allow species to survive under extreme drought conditions. Participants also suggested exploring the influence of socioeconomic factors on the forest's capacity for resilience and the adaptive capacity of local human communities within a matrix of declining forests. It was highlighted that it is necessary to expand collaboration networks to non-academic actors to face the challenges involved in a potential ecosystem collapse. This is to increase the exchange of knowledge, co-construct research/action proposals, and solutions, and have greater knowledge dissemination to society. Finally, participants emphasized that in creating and sustaining such a diverse collaboration network or knowledge co-production strategies, it is necessary that people involved, including academia and policymakers, should have three key traits: humility, patience, and generosity.

To synthesize, we present an outline of the identified priority research topics and emerging issues, grouped into the drivers behind the massive forest browning, the potential impacts on communities well-being and ecosystem functioning, and the adaptative strategies under future climate scenarios (Fig. 4). We also introduce, for each of these areas (drivers, impacts and adaptation), a series of research questions proposed as examples of what still sorely needs to be investigated (Table 2). Of particular interest are questions related to (1) the effect of natural resource management (water, land, forest) on forest browning, (2) ecological and ecophysiological aspects associated with the tolerance ranges of forest species and communities to drought conditions, and (3) the consequences of forest browning on biotic interactions, ecosystem processes, and human well-being. Many of these questions may require long-term studies and monitoring, encompass various areas of knowledge, and necessitate interdisciplinary work to be answered.

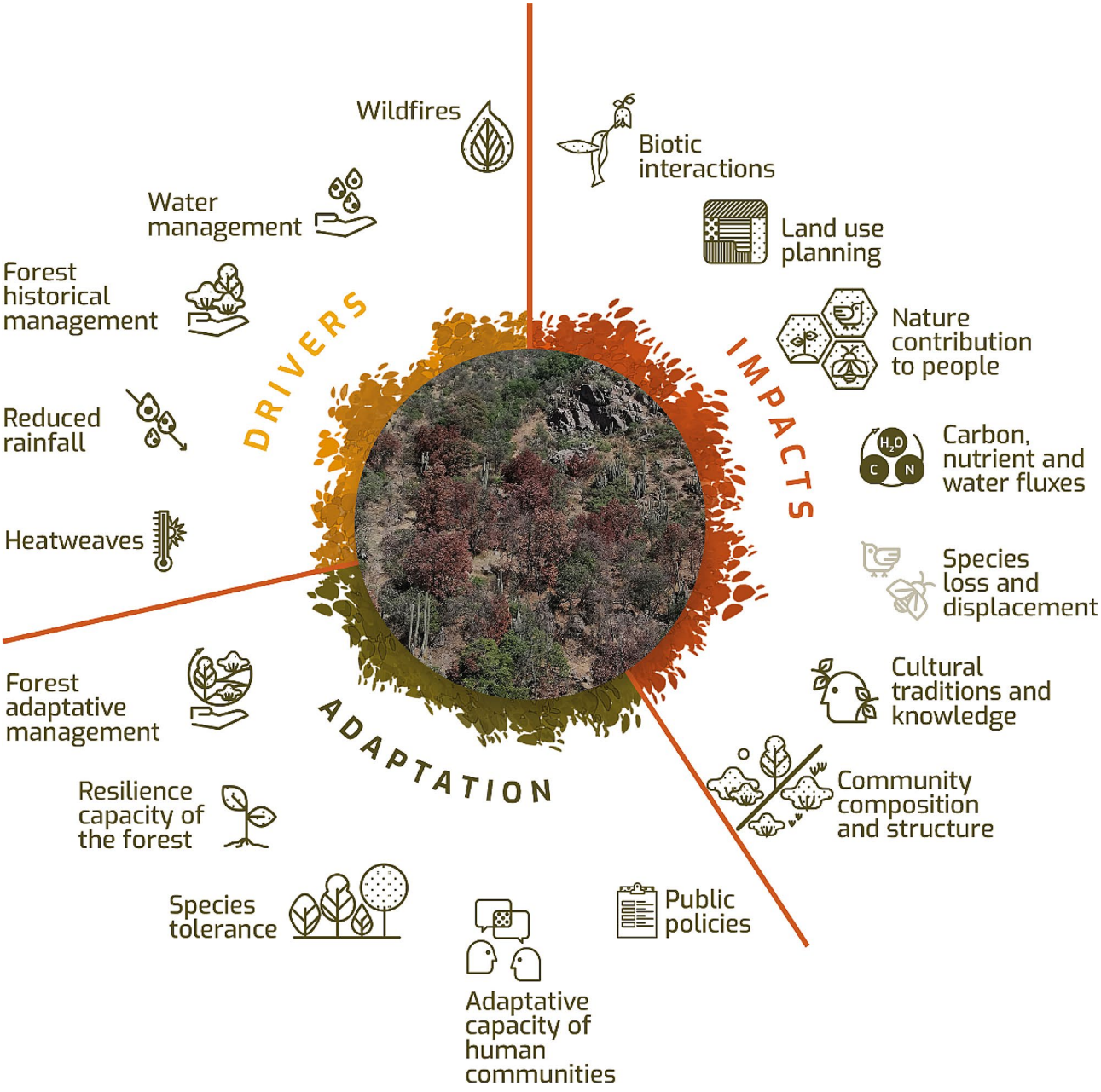

Fig. 4 The identified priority research topics and emerging issues for central Chile MTE forest, grouped into the drivers behind the massive forest browning, the potential impacts on communities well-being and ecosystem functioning, and the adaptative strategies under future climate scenarios

Discussion

Scientific research and conservation efforts in MTEs have historically prioritized the study of ecological and evolutionary processes of plant species. This emphasis arises from the notable level of species richness and associated endemism that share these biomes and because all five MTEs are considered biodiversity hotspots [3]. Considering the distinctive characteristics of MTEs, where the exceptional biodiversity coexists with a high human population density and where an increase in drought frequency in the next 30 years is expected regardless of emission scenarios [1], we propose developing a research agenda to investigate the potential ecosystem collapse of central Chile MTEs forests under a socio-ecosystem perspective. To achieve this objective, the literature review has identified knowledge gaps in specific research topics. Concurrently, the interdisciplinary workshop has established research priorities and addressed emerging issues within these areas. The information derived from both sources (literature review and workshop) reveals common points and contradictory aspects, particularly regarding the forces driving the decline of the

Table 2 Research questions and research proposed formulated by the workshop participants to improve our understanding of the decline of the central Chile MTE forest. The research questions are organized by drivers, impacts, and adaptation without any order of priority

Categories	Research question
Drivers	
Water Resources Management	• Did the overuse of groundwater in central Chile watersheds, condition the forest water status in the face of the megadrought?
Forest Management	• Did the current management and the type of forest management amplify the magnitude of the forest decline in 2019 (hyper-drought)?
Soil-vegetation-atmosphere feedback	• Do the decrease in soil moisture and native vegetation cover alter atmospheric conditions at a local and/or regional scale? • Could these alterations amplify the effects of the drought?
Forest fires	• Did past fires influence the forest response to the megadrought?
Impacts	
Ecological (composition, structure and functioning of the forest)	• What are the tolerance thresholds of the species that make up the sclerophyllous forest to water stress and high temperatures? • What consequences will the megadrought have on pollination and seed dispersal processes? • Will new communities be formed due to changes in relative abundance of species and/or by new processes of colonization and extinction of species? A reduction in tree cover and tree size, • Would it affect the water and nutrient retention capacity in the soil? • How would carbon fluxes be altered? • How would it affect the ability to regulate humidity and atmospheric surface temperature?
Social and cultural	• What impact does the loss of greenery in the forest have on the perception of conserving this ecosystem? • What knowledge and traditional knowledge could be lost with the loss of the forest? • Will visits to private and state natural parks decrease as a result of the decline of the forest in the central zone? • Do inhabitants of urban-rural interface areas have a higher perception of the risk of floods or forest fires as a result of the decline of the forest?
Adaptation	
Management approach of the sclerophyllous forest	• Identify localities that were not severely affected by the drought to define protection areas against future extreme drought events and where propagation material of native species (seeds, cuttings, bulbs, etc.) can be provided.
Biological and ecosystem approach	• Evaluate the physiological strategies and functional traits of the species that survived the hyper drought event of summer 2019. • Determine the relationship between the functional diversity of plant species and the resistance to that which leads to processes of forest decline. • Compare the adaptive capacity against the drought of plantations of exotic species (avocados, citrus, pines) vs. native species in natural forests.
Socio-ecological approach	• Relate the recovery capacity of the forest with the socioeconomic characteristics of the territory. • Study the adaptive capacity of local communities (humans) that live around forests that have suffered processes of decline and degradation. • Learn about and support forest protection initiatives carried out by local communities and by those who make productive use of forest resources (e.g. non-timber forest products).

sclerophyllous forest. On the one hand, the workshop concluded that there is a consensus among experts that the primary drivers are land use change, forest management practices, water and temperature changes, and increased forest fires. However, the reviewed articles on this topic do not directly attribute these factors to the decline of the sclerophyllous forest. This indicates that the available data are not sufficiently convincing to establish causality, suggesting the need for longer-term studies. When contrasting the information from both sources, convergent points appear about emerging questions concerning the rapid changes occurring in forest ecosystem functioning. These questions are crucial for exploring new research lines, such as adaptive silvicultural management, assisted migration, local extinction of endangered species, conservation of seed sources, and species replacement.

From a socioecological approach, both sources of information emphasized the necessity of incorporating an interdisciplinary perspective, with social sciences playing a central role, to determine and evaluate the underlying factors and impacts of forest decline on various dimensions of the human-forest relationship, including human well-being. MTEs should be understood as socio-ecological systems, recognizing the crucial role of all stakeholders in managing and conserving forests. Despite the overall degraded conditions, the MTE forests of central Chile still hold significant socio-ecological value, serving as a key component in the well-being of rural communities [23].

Both sources of information highlighted the need to incorporate an interdisciplinary perspective, with social sciences as a central component, to determine and evaluate the underlying factors and the impacts of forest decline on different dimensions of the relationship between humans and forests, including human well-being. MTEs should be understood as socio-ecological ecosystems, recognizing the key role of all stakeholders in managing and conserving the forests. Despite the overall degraded conditions, central Chile MTE forests still have an essential socio-ecological value, a key component in the well-being of rural communities [23]. In these areas, the forest provides several contributions, such as the provision of material (e.g., food, energy, water, and medicinal resources), regulation of processes (e.g., regulation of freshwater, quality of air, pollination, nutrient cycles), and creation or maintenance of the conditions for learning, inspiration, supporting identities, and physical and psychological health [24, 25]. Even these contributions can have a high economic value for rural households [26]. Small and medium landholders from rural communities are particularly relevant for sustainable forest management since they own more than 62% of the native forest under formal tenure in central Chile [27]. Further, forests contribute considerably to human well-being in urban areas, providing space for recreational and cultural activities and preventing natural disasters such as flooding [28–30]. Therefore, a fundamental role of social sciences would also be to assess the adaptive capacity of rural and urban communities to future forest scenarios, including the potential collapse of the ecosystem.

The need to include soil science was also highlighted in both source information, primarily for a better understanding of the whole forest ecosystem's resilience to climate change. Soil science is particularly relevant because forest resilience to climate change relates to soil abiotic and biotic conditions responding to environmental stressors [31]. In Chile, scientific research on the effect of climate change on soil biodiversity and related ecosystem processes is incipient, particularly within MTEs [32, 33]; thus, to better anticipate and design sustainable management practices, soil status, particularly biological conditions, and functions also responding to climate change need to be considered as crucial elements.

In light of global change, similar research priorities have been proposed for other MTEs, such as assessing the effect of the interaction between global and local anthropogenic (e.g., historical land use) drivers on forest decline and how it will affect the provision of ecosystem services on human well-being [34–36]. Nevertheless, we also observed differences in research priorities, mainly in social topics related to the impacts and adaptation capacity of society to forest decline, such as detecting the potential loss of cultural knowledge and traditions in local communities and changes in the vulnerability of human communities by an increase in the probability of natural disasters by the forest decline. Adaptation strategies highlight the need to implement correct adaptive management strategies with a transdisciplinary approach involving scientists, land managers, land users, administrators, and policymakers. To achieve this goal, improving the interaction knowledge between scientists and the different actors of society is necessary. First, we propose to strengthen the interaction between scientists to improve the understanding of the relationship of biophysical factors and their impact on the functioning and structure of the ecosystem, which would reinforce the capacity for early prediction of future climate variability that impacts the forest. Second, the interaction between forest users and land managers with the scientific world should be improved to accelerate the implementation of adaptive management practices that guarantee the provision of environmental services. The creation of knowledge co-production strategies could also be evaluated [37]. Finally, the interaction with governing institutions should be improved to generate public policies that guarantee forest biodiversity conservation and the provision of goods and environmental services to local communities. Improving forest governance based on scientific evidence is an urgent call, mainly considering that Chilean forest institutions have received low social support and are perceived as unfair by small and medium forest owners [38, 39]. More scientific evidence is needed to understand the underlying factors and mechanisms that affect forest management by owners, as well as other factors involved in building positive relationships between people and environmental institutions [40]. Although much of the research on adaptation is related to aspects such as drought or other climatological aspects, there is still little information available specifically for MTE forests [41].

Conclusions

This study identifies crucial gaps and priorities in research concerning the Mediterranean-type ecosystems (MTEs) of central Chile, especially in the face of global change. The interdisciplinary approach, combining a systematic literature review and a scientific workshop, helped identify that social and soil science is the main research gap needed to understand better these ecosystems' drivers, impacts, and adaptive strategies. There is a critical need to enhance research on the socio-ecological relationships between forests and rural communities. This includes understanding the impacts of forest decline on human well-being, the distribution of nature contributions, the loss of cultural knowledge and traditions, and the development of adaptive strategies to mitigate natural disasters caused by the forest decline. The resilience of MTE forests to climate change is intricately linked to

soil conditions. Our findings highlight the importance of studying soil biodiversity and related ecosystem processes to anticipate and design sustainable management practices. Our study also underscores the need for evidence-based public policies that guarantee forest biodiversity conservation and the provision of environmental services. Strengthening forest governance through scientific evidence and improving the interaction between scientists, land users, and governing institutions is crucial. Examining the potential ecosystem collapse of MTEs from a socio-ecological perspective can enhance our understanding of the environmental and human driving forces that promote ecosystem changes. Its application, however, requires rapid progress in incorporating social and soil sciences to effectively integrate the whole human dimension and foster a more ecosystemic approach to forests. The information provided in this study serves as a foundation for future transdisciplinary research by building a research agenda to fill the knowledge gaps urgently needed to solve forest socio-ecosystems at the verge of collapse.

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Author contributions
C.A.D., S.V., J.F.O., A.M. and N.P. contributed to conceptualization and study design. Material preparation, data collection, and analysis were performed by C.A.D., S.V., J.F.O., and C.C. The first draft of the manuscript was written by C.A.D., S.V., J.F.O., F.Z.R., and C.R., and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability
The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors have no competing interests to declare that are relevant to the content of this article.

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