



Review

Reviewing social-ecological resilience for agroforestry systems under climate change conditions



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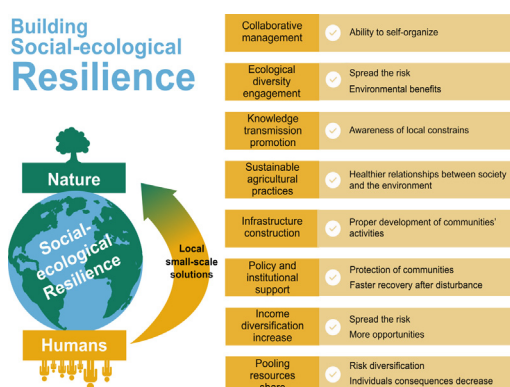
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HIGHLIGHTS

- Agroforestry systems require adaptation measures to deal with climate change.
- Understanding social-ecological resilience is key to adapt to global change issues.
- Changes in historical nature-human interactions are transforming landscapes.
- Local communities create small-scale solutions with significant global impact.
- Description of practical strategies aimed at enhancing social-ecological resilience.

GRAPHICAL ABSTRACT



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ABSTRACT

Global change is shaping social-ecological systems, threatening both natural and socio-economic ecosystems as a whole. Landscapes with combined nature-human interactions are particularly vulnerable to changing climatic conditions. Therefore, there is a need to find viable and practical solutions for the preservation and recovery of the affected systems. A relevant way to cope with disturbances is to promote social-ecological resilience through the use of strategies targeting the social-ecological system as a whole, in order to ensure an efficient self-reorganization of a landscape. This study presents a research innovation by clarifying the concept of social-ecological resilience while being focused on providing a useful tool for landscape managers. For doing so, the research first defines social-ecological resilience and aims to give a clear idea of its characteristics and application features. Second, it explains the importance of social-ecological resilience for landscapes, focusing on the relationship of humans with nature and traditional ecological knowledge (TEK) for biodiversity conservation. Third, it proposes guidelines and measures for the promotion and enhancement of social-ecological resilience. The outcomes of the study show a broad perspective on the concept of social-ecological resilience to understand the necessary adaptation to global change. As findings, this research highlights the significance of nature-human interactions for agroforestry systems, citing also the potential contribution that digital innovation can play for the conservation of those interactions in a sustainable way. Moreover, it uncovers the key role of local communities in building social-ecological resilience through the application of a variety of described

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strategies that can have a relevant impact and be useful for landscape management practices to face upcoming challenges linked to climate change.

Contents

1.	Introduction	2
2.	Materials and methods	3
3.	Results	3
3.1.	Social-ecological resilience concept	3
3.2.	Resilience to what, of what, for what	4
3.3.	Relevant measurement indicators	5
4.	Discussion	5
4.1.	Nature human interactions	6
4.2.	Traditional ecological knowledge (TEK) as a way forward	6
4.3.	Guidance on operational strategies for building social-ecological resilience.	7
5.	Conclusions	8
	CRedit authorship contribution statement	8
	Data availability	9
	Declaration of competing interest	9
	Acknowledgements	9
	References	9

1. Introduction

Increasing global environmental pressures could lead to the crossing of critical ecological thresholds. When these thresholds are surpassed, major changes are triggered, affecting the structure and function of ecosystems and the broader social-ecological systems in which they are embedded (Shackleton et al., 2018). Humanity is a major driver in global change and shapes ecosystem dynamics from the small scale of local environments to the whole biosphere of the planet (Folke, 2006). Moreover, humans contribute to more than 95 % of the rapid temperature rise by emitting greenhouse gases, especially due to burning of fossil fuels, deforestation and land-use changes that emit greenhouse gases (Hosen et al., 2020).

Actions like these are triggering climate change scenarios that suggest a largely deterioration of renewable natural resources, such as agricultural soils or water resources; posing a threat to sustainable management (Jacobs et al., 2016) and to human livelihood (Hellin et al., 2018). In fact, if the increased frequency or severity of climatic events does not allow time for ecosystem function to recover before the next hazard occurs, ecosystems may decline, failing to provide essential services, for example, by ceasing to provide fresh water supply, as a result of several droughts. Ultimately, this will cause the ecosystem to transform into an undesirable state (Jacobs et al., 2016).

These phenomena cause climate change to become a significant concern for land and resource management, creating an urgent need to build social-ecological capacity to address uncertain environmental changes (Mori et al., 2013). Nevertheless, although social and ecological systems are affected by the changing climate, the conservation behaviors of local and global societies play a fundamental role in determining the future climate (Mori et al., 2013) such as through the implementation of adaptation measures or strategies aimed at mitigating climate change. However, some approaches to nature conservation, like those defined by strong prohibitions on land and resource use, were founded on the conception of “nature” and human society as separate entities. The role that local communities have played in shaping many globally important ecosystems has, in fact, been ignored through processes of co-evolution (van Oudenhoven et al., 2011). Now, however, it is known that synergies between traditional ecological knowledge (TEK) and scientific knowledge can also contribute to biodiversity conservation (Shokirov and Backhaus, 2020). In fact, social-ecological systems are being increasingly recognized as a tool for the

conceptualization of human-environmental systems and the development of resilience-enhancing governance methods (Hosen et al., 2020).

Social-ecological systems are complex systems with feedback and cross-scale dynamic interactions (Folke, 2006) that include ecological, social and economic elements as well as the interactions between them (Cumming et al., 2015). Feedback interactions occur when a part (or all) of the system's output is used as input for subsequent actions, making them relevant to the dynamics and outcome of the system. Therefore, it is necessary to first understand that social-ecological systems can have multiple states that have the inherent features of change and uncertainty (Olsson et al., 2004), shaping the basins of attraction they may have. Basins of attraction are defined as states in which the systems tend to remain and where they can find their equilibrium (Walker et al., 2004).

Due to this complexity of the social-ecological systems, a major challenge is to better understand these systems with the aim of building their resilience to face climate change conditions. But, for the enhancing of resilience, it is first needed to understand its meaning. Resilience is a concept with multiple definitions, partly due to the widespread use of the term in different disciplines and systems (Nikinmaa et al., 2020).

Walker et al. (2004) defines **resilience** as the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedback. When looking at the resilience of social-ecological systems, the human-natural system is considered as a whole. Hence, understanding their social and economic component is as fundamental as understanding their ecology if we are to analyze and manage their resilience (Cumming et al., 2015).

Consequently, whether the social-ecological system at a given site is resilient to different disturbances will fundamentally depend on both the starting-point ecological conditions and the social conditions at that location (Aslan et al., 2021). Since the social factor is relevant in social-ecological systems, humans have the added capacity to anticipate and plan for the future by acting on the landscape. Such interventions can, however, modify the structure and functions of ecosystems. This is why a broader **interdisciplinary perspective** on resilience is needed for these systems.

Social-ecological resilience is defined as the ability of a social-ecological system to accommodate disturbances without shifting into an alternative state with different functions and processes (Folke, 2006; Walker et al., 2004), understanding people and nature as interdependent systems (Folke et al., 2010). In fact, social-ecological resilience refers to the

“humans in the environment perspective” (Reyhani et al., 2017) and places a strong focus on the adaptive and transformative capacity of the social part of the system (Nikinmaa et al., 2020).

A historical connection between natural and human factors can be found in agroforestry systems. Indeed, strong links between agricultural landscapes and socioecological heritage have been observed (Cusens et al., 2022). However, as a consequence of climate change conditions, these interactions between nature and humans are affected, which can transform landscapes. It needs to be considered that it is the quality of these relationships that dictates the strength of ecological and social resilience, a fundamental fact for adaptation in the wake of global climate change (Wang et al., 2018). Accordingly, addressing socioecological resilience is challenging as the impacts of extreme climate events can be devastating and disruptive to social and economic activity, as well as to natural ecosystems (Jacobs et al., 2016).

Because landscapes are characterized by integrating both the social and the ecological system, conducting the combined assessment of social-ecological resilience is challenging but necessary to adequately predict recovery (Aslan et al., 2021). Part of the difficulty lies in the fact that social-ecological resilience continues to be a hazy concept for decision makers. These challenges prevent a correct and widespread implementation, raising the necessity of introducing guidelines towards the goal of an operational use (Chapin et al., 2021).

For sustainable landscape management, it is essential to understand the role of the different stakeholders (Mansourian et al., 2020) in order to have a clear picture of the analyzed system. For this, it is necessary to identify which ecological or socio-economic disturbances challenge the system and to define which attributes need to be resilient for facing them. In addition, it is necessary to integrate science with people's perceptions to develop better management policies and interventions (Chettri et al., 2021), which may help in its successful implementation and is important to understand the goal of the resilience actions. Therefore, management actions should first take into account and answer the following questions: resilience to what, resilience of what (Carpenter et al., 2001) and resilience for what (Charnley et al., 2017). For example, when facing resilience to wildfires of forest ecosystems, managing resilience is important for sustaining social values (like safely maintaining homes and infrastructure) or ecological values (like conservation of biodiversity) (Charnley et al., 2017).

In summary, this study aims at clarifying the concept of social-ecological resilience and at facilitating its application in agroforestry landscapes. To do so, a literature review methodology was applied to select different case studies that promote the building of social-ecological resilience in their respective ecosystems. As a result, the following objectives are intended to be achieved:

1. To understand the concept of social-ecological resilience, focusing on what factors can landscapes be vulnerable to.
2. To analyze how important the social-ecological resilience concept can be in a climate change context, where changing conditions are affecting human-nature interactions.
3. To develop guidance to promote or build social-ecological resilience for landscape management.

2. Materials and methods

A literature review was carried out to understand how the concept of social-ecological resilience is currently assessed in the scientific literature. A search was performed in the Scopus database using the following sequence; (TITLE-ABS-KEY (“soci* ecological resilience” OR “soci*-ecological resilience” OR “soci*ecological resilience”) AND TITLE-ABS-KEY (manag* OR plan* OR conser* OR policy) AND TITLE-ABS-KEY (forest* OR landscape* OR agro* OR biodivers* OR “climate change”) AND NOT TITLE-ABS-KEY (urban)).

Applying the search string in the Scopus database guaranteed that results were published in scientific journals. The specific keywords were used to find papers aligned with the research objectives. Therefore, the

first condition of the sequence refers to all the orthographic possibilities of the term social-ecological resilience. In the second condition, keywords are intended to find studies that describe ways of managing or applying the term in practice. In the third condition, it was searched for the desired systems or conditions for the study. Finally, the sequence left out to urban areas, as this was not the scope of this study. The objective in this part was to find as many articles as possible that were suitable for this study, and then to screen them for making a final selection.

The search initially yielded a total of **230 journal articles** published until February 2022, which was the date defined by the authors as the final deadline for published articles to be included in this study.

As the objective of the search is to find articles with case studies that promote social-ecological resilience in agroforestry landscapes, all initially identified abstracts were screened, and two criteria were applied in order to make the final selection. First, the concept of “social-ecological resilience” in the abstract or in the title had to be related to an active verb (e.g., manage, build, improve). That way, it was ensured that reviewed papers propose action towards a more practical understanding of the social-ecological resilience concept. Second, the abstract had to focus on natural terrestrial systems (e.g., forests ecosystems, agricultural landscapes, mountain areas). The aim here was to discard analyses not centered in land natural environments (e.g., marine analyses). Papers that followed both criteria were the ones finally considered (Fig. 1).

In the case studies, a combination of geographies of more and less technological regions has been found. However, 34 of the total refer to case studies developed in less modernized regions, which has a strong influence on the results. Communities in these regions have been less exposed to the effects of modernization and a more sustainable and tradition-sensitive transition may still be possible. In the more modernized regions, it was considered that communities experienced a highly transformative effect during the last centuries and traditional habitats may have almost completely disappeared.

As this research has analyzed case studies from less and more modernized regions, it provides a general point of view and a broader perspective on social-ecological resilience can be obtained. In fact, it is because of this combination of case studies, that results obtained on how to foster social-ecological resilience can be useful for the practical application of management actions for the overall range of landscapes threatened by climate change.

Additionally, some other papers related to the objectives were also selected and reviewed, as they have provided a more theoretical view of the resilience concept. These studies were identified from references found in the initial search papers. They sum up to the previous list, making up a **total of 57 papers** referenced for this literature review.

3. Results

3.1. Social-ecological resilience concept

The first objective of the paper is to understand the concept of social-ecological resilience, giving a clear picture of its characteristics for practical use. In fact, studies have demonstrated a lack of operational facilities for managers (Chapin et al., 2021).

Social-ecological resilience assumes the existence of multiple basins of attraction (Folke et al., 2010) and the focus is on shaping those states in which the systems tend to remain via changing the social part of the system (Nikinmaa et al., 2020) in order to keep them in their desired state. Humans have the capacity of influencing in both negative and positive ways the complex system, so they can co-work towards a positive impact.

It should be noted then that social-ecological resilience includes the characteristics of resistance, recovery, adaptive capacity and the ability to transform (Folke et al., 2010). This complexity is basically what differentiates the social-ecological resilience concept to other scientific used concepts (like ecological or engineering resilience) (Nikinmaa et al., 2020). Social-ecological resilience is characterized by these three fundamental features (Carpenter et al., 2001):

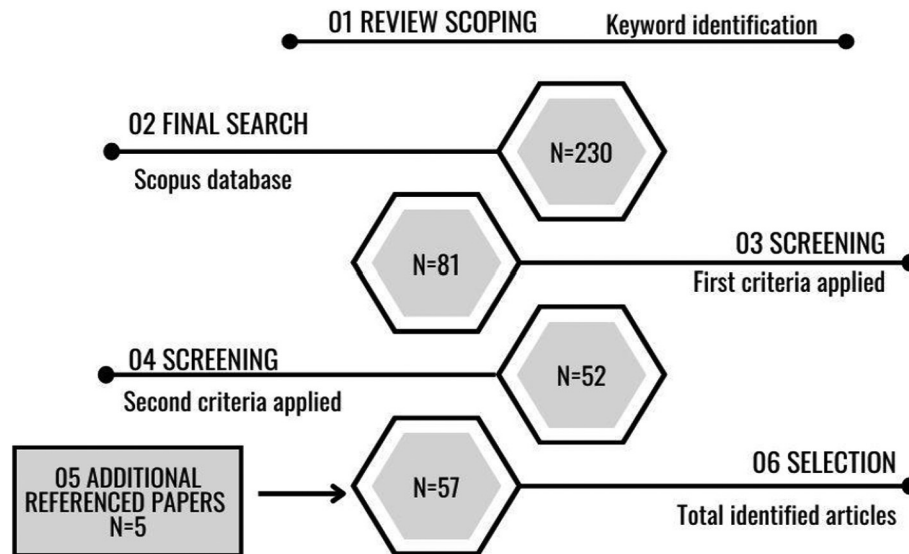


Fig. 1. Diagram of article selection for the review.

1. The amount of change a system can undergo while remaining within a desired basin of attraction.
2. The degree to which the social-ecological system is capable of self-organization.
3. The building capacity of a social-ecological system to learn and adapt. In this adaptive capacity, feedback loops can play a great role if resilient social-ecological systems are able to learn from previous input actions after an impact or change and adapt the feedback output produced.

It is important to note that resilience does not imply that systems should bounce back to desired states after perturbations, but rather that they will persist with change in desirable states (de Vos et al., 2016). Hence, social-ecological resilience emphasizes on transformation and self-evolution of the system.

3.2. Resilience to what, of what, for what

Management actions aiming at the fostering of social-ecological resilience need to consider the questions of resilience to what, of what and for what. In this study, case studies of the application of social-ecological resilience from the identified literature have been analyzed and assembled in Table 1. This table aims to group the main factors used for the study of social-ecological resilience to understand how landscapes are vulnerable. To this end, it was analyzed which disturbances threaten them, which attributes are important to maintain to face them and what are the objectives of promoting this resilience. Factors were separated between two different categories (ecological and socio-economic). This was done both to have a better visual understanding and to observe in which category most of the factors were identified.

Resilience to what can be defined as the ecological or socio-economical disturbances that challenge the social-ecological system. In

Table 1

Percentages of the factors in relation to the total attributes identified for each question. They have been extracted from the reviewed case studies.

Factors	Resilience to what	Resilience of what	Resilience for what
Ecological	<ul style="list-style-type: none"> • Climate change conditions (rising temperatures. Decrease in precipitation) 27.1 % • Extreme events (20.8 %) o Wildfires 8.3 % o Drought 8.3 % o Floods 4.2 % • Disturbance agents (pathogens, invasive species) 8.3 % • Land and forest degradation 8.3 % • Melting glaciers 2.1 % 	<ul style="list-style-type: none"> • Forest ecosystem practices 11.4 % • Biodiversity 9 % • Community dependent forests 6.8 % • Ecosystem services 4.5 % • Forest fragments connectivity 4.5 % • Soil and freshwater quality 4.5 % • Habitat provision 2.3 % • Protected areas 2.3 % • Natural reforestation 2.3 % 	<ul style="list-style-type: none"> • Biodiversity conservation 13.2 % • Safe species migration pathways 3.8 % • Transforming agricultural systems to biocultural refugia 3.8 % • Species safe wellbeing 3.8 % • Ecological integrity and health 3.8 %
Socio-economic	<ul style="list-style-type: none"> • Globalization & modernization 12.5 % • Changes in land use 8.3 % • Socioeconomic pressures 4.2 % • Marketization of resources 4.2 % • Human conflicts 2.1 % • Petro-chemical agricultural systems 2.1 % 	<ul style="list-style-type: none"> • Traditional Practices (20,3 %) o Traditional Ecological Knowledge (TEK) 9 % o Pastoral social-ecological system 4.5 % o Plant-based food production 4.5 % o Traditional Healthcare System 2.3 % • Water security of communities 9 % • Organic farming & agriculture 6.8 % • Adaptive capacity management 6.8 % • Cultural connections with nature 4.5 % • Ecosystem & landscape management 4.5 % 	<ul style="list-style-type: none"> • Community welfare and preservation of values 15.1 % • Human wellbeing 15.1 % • Maintenance of farming and agricultural systems 11.3 % • Better resource availability 9.4 % • Food security & survival 5.7 % • Sustainable economic development and poverty alleviation 5.7 % • Increase in landholder income and diversification of opportunities 5.7 % • Social & gender equity 3.8 %

this column, a higher percentage of factors were identified within the ecological category, meaning that disturbances affecting the studied systems mostly have an ecological origin. Specifically, climate change and extreme climatic events were the most studied disturbances (27.1 % and 20.8 % of the studies for resilience to what, respectively). Within the extreme events, wildfires and droughts were studied at the same percentage rate (8.3 %). Nevertheless, socio-economic factors that affect the studied social-ecological systems were also identified and the highest percentages were found for the disturbances of globalization and modernization (12.5 % of the studies), followed by changes in land use (8.3 %).

As to which key functions and structures the stakeholders within a system might wish to maintain over time in the face of potential disturbances (**resilience of what**); factors were identified almost in equal quantity of percentage within the ecological and socio-economic categories. By this it can be observed that stakeholders value in similar rates the preservation of factors from both categories in the context of social-ecological resilience. Traditional practices and water security of communities were the most studied attributes to face disturbances (20.3 % and 9.0 % of the studies, respectively) for socio-economic factors. As of the ecological ones, forest ecosystem practices (11.4 %), biodiversity (9.0 %) and community dependent forest (6.8 %) were the most studied ones.

Finally, for the column of **resilience for what**, the table clearly shows a higher percentage of factors within the socio-economic category, which means that most of the objectives for managers on building socio-ecological resilience are aimed at targeting the conservation and enhancement of socio-economic systems. In particular, community welfare and preservation of values, human wellbeing and maintenance of farming and agricultural systems (15.1 %, 15.1 % and 11.3 % respectively) were the most studied goals of social-ecological resilience implementation. As for the ecological factors, biological conservation was also identified in a high percentage of the cases reviewed (13.2 % of all the studies) and was the most studied goal in the ecological category itself.

3.3. Relevant measurement indicators

The challenge is when resilience measurement takes place. The space and time scale become crucial too for determining the resilience of a landscape because these aspects change (Folke, 2006) and a system can be resilient just on the moment of the measurement, but maybe not later. As a matter of fact, social-ecological resilience concepts lack established indicator frameworks that could easily be adopted by managers (Nikinmaa et al., 2020).

Conventional indicators of ecosystem health (such as species richness or soil nutrients) fail to capture the social dimension (van Oudenhoven et al., 2011) because in social-ecological systems the relevant factors come from **social-ecological interactions**, where human communities adapt to their environment and change that environment in the process.

Nevertheless, some general **enabling factors** can also be considered important for understanding and measuring social-ecological resilience of a system. These factors are presented below and are drawn primarily from Baumber et al. (2020) complemented by information found in other case studies reviewed:

- **Buffers and redundancies:** Extra capacity that a system holds in reserve. It is a way of storage (del Mar Delgado-Serrano et al., 2015) and some examples of it could be a reserve of capital, water or organic matter. It can help to minimize the severity of a disturbance or to enable a faster recovery.
- **Monitoring and sharing information:** A regular, systematic collection of data that has the capacity to gather information in a transparent and shared way. Together with the transmission of traditional knowledge, they are important indicators of the resilience of a system (Hosen et al., 2020).
- **Management in the right scale:** This refers to whether a system maintains the right balance between: (i) connectedness (connections to neighboring systems and higher system levels so there can be exchange

and support between them) and (ii) modularity (autonomous units in which self-organization is enhanced at the local level and threats can be isolated to stop them spreading). A right equilibrium between the two dimensions can mean a high level of resilience.

- **Heterogeneity:** Includes economic diversity, cultural diversity, biological diversity and response diversity. This way the system has a bigger range of available pathways and can spread the risk.
- **Social capital:** It refers to the level of social cohesion within the social system and includes effective leadership, trusted relationships between key stakeholders, collaboration and reciprocity.
- **Feedbacks:** Observing and analyzing if the system can produce feedbacks that pushes back against disturbance is key to determining resilience. In fact, closed feedback loops can produce surprising and unexpected dynamics (Cumming et al., 2015) in the systems. This is because when a part (or all) of the system's output is used as input for subsequent actions, the resulting effect can either reinforce (positive) or dampen (negative) change, influencing the dynamics of the ecosystem (Tagliari et al., 2021).

These factors work as enabling indicators of how resilient a social-ecological system is and they are presented as measurement considerations in a general way, aiming at better understanding the whole concept of social-ecological resilience.

4. Discussion

The presented results aim at achieving the first objective of the study as they provide a broad theoretical understanding of **social-ecological resilience**. As a summary, the results part helped to (i) have a general definition of the concept, (ii) understand what factors create disturbances in the environment, (iii) define what key system functions are important to address the challenges, (iv) know what objectives managers aim to achieve, and (v) give some considerations and measurement indicators. The second objective aims to understand the key role that social-ecological resilience plays in the current context of global change.

As a matter of fact, the world continues to struggle in order to find viable solutions to mitigate and adapt to a number of critical issues facing the Earth, such as degradation of ecosystem services, drying up of water sources or declining food productivity (Wang et al., 2018). The future scenario of climate change is not certain; and the question is not so much what exact changes occur, but the fact that there is always the possibility that they will occur. Consequently, and given that there is a high probability of problems occurring, it is urgent to rethink strategies to cope with unequivocal and continuous climate change (Mori et al., 2013) to which we must adapt to.

In fact, adaptation to climate change presents unprecedented methodological challenges given the uncertainty and complexity of the hazard (Kopprio et al., 2014). Historical approaches applied to deal with climate-sensitive hazards or resource management (such as water resource management) may no longer be valid to cope with this complex global change. As a consequence, the intensification and normalization of extreme events (Jacobs et al., 2016; Devisscher et al., 2021) is making some communities particularly vulnerable to environmental, economic and social shocks (Shumsky et al., 2014).

Some of the case studies reviewed reflect the reality of several developing countries facing the same challenge of developing while maintaining profit-generating natural resources. The application of a new logic in nature conservation projects integrated into economic development presupposes new ways of acting and thinking (Aza et al., 2021).

So, there is an urgent need to research and develop innovative adaptation mechanisms (Providoli et al., 2010) in order to increase social-ecological resilience. Yet, the strong and urgent call to implement climate adaptation strategies should not be an excuse to define adaptation goals and assess its success following a single dimension focused on livelihoods (Rodríguez-Solorzano, 2014).

However, local communities are often best placed to guide research on the ecological and social processes affecting their livelihoods (Hosen et al., 2020). Thus, this measurement to understand social-ecological resilience can be conducted using qualitative assessment methods to understand the social mechanisms of adapting to and shaping change (Olsson et al., 2004). In addition, the enabling factors presented previously can help to better understand the landscape and be useful in defining strategies that approach the system as a whole. At the same time, in order to plan these adaptation strategies, it is important to understand **nature-human interactions**. Of special relevance is comprehending how these connections are important for the social-ecological resilience of landscapes.

Learning about nature-human interactions, along with understanding traditional ecological knowledge, supports the second objective of the paper and helps to see how important it is to build social-ecological resilience for climate change adaptation.

4.1. Nature human interactions

Social-ecological systems have inherent interactions between the social and ecological systems. Knowledge to monitor, interpret and respond to these connections is crucial to strengthen the capacity to cope with uncertainty and change (Olsson et al., 2004). Landscapes that have coevolved with anthropogenic activities over time require their continuity in order to preserve the existence of certain species and ecosystem services (van Oudenhoven et al., 2011). This conceptual view is important for addressing climate change, especially at the local scale, because the impacts of climate change on society and human well-being are deeply connected to the impacts on the ecological systems on which humans depend (Mori et al., 2013; Cusens et al., 2022).

The findings of this research indicate that humans are highly dependent on nature and the long-term persistence and effective management of both cannot be achieved in isolation. Ecological diversity and biodiversity conservation are fundamental to securing ecosystem services, which are key to the survival of humans and biodiversity. To ensure that this relationship is resilient in the face of climate change threats, ecological, cultural and livelihood diversity must be preserved and promoted (Wang et al., 2018), engaging with the quality and strengths of social-ecological resilience.

Building resilience provides many benefits to ecosystems that, through feedback loops, ultimately benefit the entire complex system, including local populations in the area (Honrado et al., 2017). In this sense, the **multi-functional landscapes** proposed by Ens et al. (2016) are a great way to obtain ecocultural outcomes that provide a positive impact on social-ecological resilience. Multi-functional landscapes contain diverse uses, states or management practices. This diversity of practices is part of the traditional heritage of communities and their relationship with the natural system (Cadena et al., 2014) that has social, economic and ecological benefits (Ens et al., 2016).

But nature and human interactions have changed drastically in recent centuries and not all communities have retained their traditional practices (Shokirov and Backhaus, 2020). For example, alpine pastures and manual mowing of meadows where machinery cannot be used in mountain valleys (Milestad and Hadatsch, 2003) are getting lost. However, not only have these traditional practices been lost, but also the entire communities that held the knowledge have been changed and transformed by modernization. This has implications for ecological resilience and, given that a high human dependence on ecosystems in the communities was found (Wang et al., 2018), the system could shift to an undesirable state if the social system fails to renew itself (Milestad and Hadatsch, 2003; Teague and Barnes, 2017). Nevertheless, modernization should not be considered a threat in itself. It is important to learn what the social system is capable of doing with the means currently available to avoid degradation of the ecological system. In this sense, the use of technological practices combined with the TEK of each community can be a useful way to cope with future climate change scenarios and to re-enhance the sometimes lost connections between human activities and the natural environment.

4.2. Traditional ecological knowledge (TEK) as a way forward

TEK can be considered as the memory of the human environment in landscapes. The deeper this memory, the more traditional ecological knowledge can be expected to reflect the complexities of these dynamics and facilitate communities' adaptation to change (van Oudenhoven et al., 2011). Resilience theory perceives traditional knowledge as the basis of observation and long-standing responses to climate shocks and stresses; therefore, it enhances the capacity to manage impacts (Hosen et al., 2020). Indeed, enhancing communities' cultural knowledge and social-ecological heritage in innovative ways would improve the resilience of social-ecological systems in the future, as well as their contribution to climate change mitigation and biodiversity conservation (Marull et al., 2019), which demonstrates the relevance of transferring and maintaining traditional ecological knowledge to deal with shocks (Calvet-Mir et al., 2016).

Knowledge is conceived as the product of local ecological understanding accumulated over time and learned from past mistakes and crises. It is an evolutionary process and the result of adaptive and transformative responses to environmental, social and cultural pressures and changes (Zank et al., 2019). Many studies have shown that economic factors are among the most important factors affecting degradation and resilience at the community level (Cotroneo et al., 2021), creating communities that are more vulnerable and less able to innovate and seek solutions, especially if they are not supported by institutions (Bhalerao et al., 2021).

This tends to be true especially in **small-scale cases**. The idea that climate change is a global phenomenon tends to automatically produce arguments that responses must also be large-scale and responses at the local level are rarely thought of. As an example, it has been found that small rivers (Lebel et al., 2010) or small patch fields in the Amazon (Vogt et al., 2015) receive much less attention than other large rivers or large land areas, respectively in management discussions and for policy action. But small scale is also relevant (Ota et al., 2020) and traditional knowledge is mostly preserved in small communities. Thus, both collective and individual capacities, on the one hand, and system properties, on the other, are very important for enhancing resilience at the local level through agency and self-organization (Zank et al., 2019).

In fact, some papers like Zank et al. (2019), Ota et al. (2020) and Tagliari et al. (2021) suggest that local community peoples are ideal environmental administrators. Through the use of traditional knowledge, most communities have managed to maintain sustainable traditional agricultural practices, traditional forest management and conservation practices and traditional livelihoods in their territories (Hosen et al., 2020). Indeed, despite modernization and mechanization, traditional knowledge continues to play an important role in conservation (Shokirov and Backhaus, 2020). Learning from communities, cultures or peoples that have been able to maintain their traditional ecological knowledge and practices is key to building social-ecological resilience.

This research, therefore, argues that social-ecological resilience can play an important role in adaptation to climate change conditions, using TEK as an important tool for resilience building. The relevance of social-ecological resilience for landscapes has also been explained through nature-human interactions, agreeing with the second objective of the study. The change in social-ecological management regimes affects the whole social-ecological system, but the way to manage it presents difficulties that are not easy to solve. TEK is presented as the set of traditional memories that communities have accumulated over centuries about their relationship with nature and the practices that ensured the sustainable conservation of the environment in which they lived. In this way, communities were aiming for their survival and the preservation of their people, their social-ecological heritage and the ecological values they possessed. These objectives of preservation can be common to nowadays societies facing the problem of climate change.

Nevertheless, one perceived **drawback** from TEK is that historical states may no longer be sustainable today due to observed climatic conditions. Climate change produces conditions never seen before and adaptation strategies that were useful for local communities in the past may not be suitable for the future. However, it has been observed that TEK is not a static, nor a

straightforward practice to follow. In contrast, the knowledge systems consist of a dynamic approach (Hosen et al., 2020) and are useful for finding innovative ways to solve challenges. In this sense, the great value of communities' cultural and ecological knowledge together with nowadays digital innovations can produce a combined solution to enhance social-ecological resilience in today's conditions.

4.3. Guidance on operational strategies for building social-ecological resilience

The last goal of this paper is to show some guiding strategies used in the reviewed case studies to build social-ecological resilience and that these can inspire landscape management practices.

Social-ecological systems have change and complexity as fundamental characteristics (van Oudenhoven et al., 2011). Given this complexity, efforts to maintain social-ecological systems in static or historical states may no longer be sustainable given the observed and predicted changes in the climate system (McWethy et al., 2019). To address this, resilience shifts the focus from mere optimization (e.g., of performance levels) and efficiency to adaptability, resilience, development and flexibility (Falkenmark and Rockström, 2008). Therefore, an important aspect of future management is adaptive management, which minimizes uncertainty and is the best approach for dealing with external shocks, giving the complex non-linear dynamics of social-ecological systems (Hosen et al., 2020).

The basic strategies found in the case studies reviewed are presented in below and are complemented by Table 2. Reviewed examples of each of the strategies are presented in this table so that it is easy to analyze how they are helping the local communities in which they are being applied. But first, a general key point that helps to cope with climate change scenarios is **learning to live with change and uncertainty** (Reyhani et al., 2017; Porcuna-Ferrer et al., 2020). Given that knowledge about the complexity and interconnectedness of ecosystems is incomplete, accepting change

and living with uncertainty can be crucial for a resilient system. This engages the **transformative capacity** of resilience, which can re-define the system and make a positive change in the relationship between humans and nature (Olsson et al., 2004; McWethy et al., 2019). That said, the first strategy found in the case studies reviewed is **collaborative management**. Enhancing cooperation and collective action in landscape management provides the ability to self-organize (Reyhani et al., 2017), which is an important element in building social-ecological resilience (Hellin et al., 2018). Specifically, a key point to promote this collective action is to strengthen social networks and foster greater interaction between different stakeholders (Charnley et al., 2017). The examples found in Table 2 show how important collaborative management has been for strengthening social-ecological resilience.

Another strategy is **ecological diversity**, which is an important strategy for maintaining resilience and could bring additional benefits to the environment even in a short period of time (Dymond et al., 2014). Indeed, it has been argued that natural diversification of cultivated products increases resilience to climatic shocks because it spreads the risk of harvest failure and also provides farmers with a greater margin of opportunity to switch crops in response to changing circumstances (del Mar Delgado-Serrano et al., 2015; Nordhagen et al., 2017). However, a limitation here is that diversity does not always convey resilience if that heterogeneity includes vegetation conditions that are not resilient to the disturbances they face (Charnley et al., 2017), so proper analysis is needed to first determine which species are suitable for a particular ecosystem.

The third strategy is to **promote knowledge transmission**, which is related to the previously explained importance of traditional ecological knowledge for social-ecological resilience. In this sense, traditional knowledge fills unstudied gaps in science and can provide insights into local impacts and adaptations (Reyhani et al., 2017). In fact, cultural values, which are maintained through oral traditions and traditional festivals,

Table 2
Reviewed examples from each of the strategies that aim at building social-ecological resilience.

Strategies	Reviewed examples
Collaborative management	<ul style="list-style-type: none"> The study on araucaria forests (Tagliari et al., 2021) shows that bottom-up co-management offers a possible solution to conservation dilemmas, as it effectively incorporates the principles of resilient thinking: management of feedbacks, maintenance of ecological diversity, and broad participation of different stakeholders. Similarly, a social-ecological system on the Tibetan plateau (Gongbuzeren et al., 2018) has shown considerable improvement in resilience by maintaining community governance. Another example is a collaborative forest management program in Ghana (Akamani and Hall, 2019) where the impact of the program at the community level was moderately positive.
Engaging ecological diversity	<ul style="list-style-type: none"> Wild plant diversity (Thorn et al., 2020) has shown some collateral benefits such as helping to prevent erosion from torrential rains or increasing immunity among food insecure communities where malnutrition is high. Mixed-species reforestation and the use of non-commercial timber for alternative products can improve forest health (Ota et al., 2020; Devisscher et al., 2021). Also, reforestation can increase human capital, improving the knowledge and skills of smallholders and generating direct or indirect employment opportunities.
Promoting transmission of knowledge	<ul style="list-style-type: none"> A study of home gardens in the Catalan Pyrenees (Calvet-Mir et al., 2016) highlights the importance of transmitting and maintaining local knowledge and how this helps transform home gardens from an agricultural system to biocultural havens. Another case study of communities in Brazil (Zank et al., 2019) focuses on collective learning for health systems. This promotes the sharing of experiences, ideas, and social context to maintain ongoing knowledge.
Shared pooling resources	<ul style="list-style-type: none"> Multiple-paddock grazing provides tangible and substantial advantages if well planned and adaptively managed (Teague and Barnes, 2017). Community shared seed banks were observed as potential ways to improve local community self-organization capacity in western Guatemala (Porcuna-Ferrer et al., 2020). However, the limitations found here show that shared strategies for risk reduction are most effective when only a few participate.
Building infrastructure	<ul style="list-style-type: none"> Reversing the abandonment of rural infrastructures (drinking water, health, education, transport, communication) seems crucial for the preservation of landscapes and communities (Cotroneo et al., 2021).
Policies and institutional support	<ul style="list-style-type: none"> Reviewed example of a plan for small-scale agriculture in Guatemala (Hellin et al., 2018) to engage municipal authorities in developing policy measures for local farmer organizations along with financial assistance that has been successful.
Sustainable agricultural practices	<ul style="list-style-type: none"> Carbon farming has increased income generation opportunities for rangeland owners in Australia (Baumber et al., 2020). However, it has its limitations because carbon farming also has the potential to erode the social-ecological resilience of rangelands, which requires careful management and policy responses. Agroforestry practices (Geburu et al., 2019) help alleviate farmers' livelihood problems through improved access to fuelwood and employment and income opportunities, thus improving their resilience. Renewable energy sources and sustainable agroecological practices have helped some family farms in Cuba adapt to climate change shocks, maximizing socioecological resilience (Rodríguez and González, 2018).
Increase income diversification	<ul style="list-style-type: none"> The example of community-based tourism activities (Gu et al., 2012; Hellin et al., 2018) aims to create social capital with the idea of instilling a sense of ownership and improving the capacity of local communities to provide goods and services. Another example is increasing farmers' income through the production and marketing of local agricultural products to help preserve traditional resource management practices and prevent land use conversion or abandonment (Gu et al., 2012).

have shaped how communities govern their resources and how they promote and maintain social cohesion among them. This is why the traditional way of life of communities must be recognized and sustained to support resilient social-ecological systems (Hosen et al., 2020). Some characteristics enhanced with knowledge transmission include social memory, heterogeneity, social learning, and adaptive capacity (Calvet-Mir et al., 2016), features that help maintain active knowledge, allowing local communities to promote their social-ecological resilience (Zank et al., 2019).

Another strategy is the **pooling of resources**. Pooling allows farmers to share risks with a group of people working together on a given activity (Rodríguez-Solorzano, 2014). This increases the availability of natural resources in case of disturbances, diversifying risk and decreasing the consequences on individuals. In one example reviewed, it is found that sharing grazing land showed numerous benefits for farmers (Teague and Barnes, 2017). In another from Guatemala (Porcuna-Ferrer et al., 2020), potential benefits were also observed, however, some limitations were identified here. Indeed, to achieve a capacity for self-organization and build socioecological resilience, the community first has to overcome structural gender inequalities, social fragmentation and mistrust.

Another strategy for building socio-ecological resilience is the **construction of infrastructures** since this is necessary for communities to be able to develop their activities. In fact, the availability of infrastructure is an important factor of physical capital because it enables the action of extension agents, the diffusion of technology from farmer to farmer or the added value of products (Ota et al., 2020). It is also useful as storage infrastructure to create additional capacity in a system in the form of reserve (Baumber et al., 2020).

One relevant strategy that has been found is to have **policy and institutional support**. In social-ecological systems, sometimes rapid socioeconomic changes could disrupt the functional links between culture and biodiversity (Gu et al., 2012), so it is important to develop policy measures to strengthen social-ecological resilience. Indeed, policies aimed at maintaining key agricultural landscapes provide socioecological resilience in the face of drivers of change that affect linked cultural heritage and agricultural values (Cusens et al., 2022). In addition, financial assistance programs would help to more quickly recover affected systems after a disturbance occurs (Charnley et al., 2017) by avoiding consequences that could be devastating. In fact, in one example reviewed (Hellin et al., 2018), financial resources are used for both common property resource management and microcredit schemes for individual households, thereby reducing the likelihood of conflicts over access and use of these resources and ultimately contributing to greater social-ecological resilience.

Sustainable agricultural practices, where healthier relationships between society and the environment are established, are another strategy that contributes to building socio-ecological resilience. These practices do not necessarily require the use of high-tech adaptation methods, but effective measures such as changes in planting and harvesting times, crop rotation or agroforestry can work just fine (Bhalerao et al., 2021). The examples in Table 2 show numerous benefits for farms, such as increased biomass reserves that can allow landowners to better recover from drought (Baumber et al., 2020); reduced incidence of natural hazards and floods, and reduced migration of rural people to urban areas to earn a living (Gebru et al., 2019) or the establishment of a closer and stronger connection with the natural environment, making efficient use of available local resources, as well as respecting and working with the cycles of nature (Rodríguez and González, 2018).

Finally, the last strategy presented consists of **increasing income diversification**. Indeed, diversification of income sources and skills are used to spread the risks related to disturbances at the household level (del Mar Delgado-Serrano et al., 2015). An example, found in Table 2, is community-based tourism activities in which local community members participate in tourism planning and implementation processes (Gu et al., 2012; Hellin et al., 2018). By doing so, local communities can increase income diversification and have more opportunities in times of disturbances.

Response strategies and adaptation options are variable and context-specific, making governance complex because in many cases it encounters

challenging problems (Shackleton et al., 2018; Urquiza and Billi, 2020). Moreover, the adaptation strategies used should be accompanied by government interventions that favor the local communities to improve resilience (Bhalerao et al., 2021). In fact, these communities must find adaptation solutions and be engaged with the strategies that are useful for them. This way conditions can be enabled to establish ownership and responsibility for adequate project implementation (Shokirov and Backhaus, 2020). In other words, those who bear the risk also have to get the benefit. Without this type of incentive, investment to increase resilience to climate change and future shocks will remain unattractive (Devisscher et al., 2021). In addition to this, it is worth highlighting the importance that digital innovation can bring to assist and facilitate adaptation measures. Modernization can engage in the transformative capacity of humans, allowing for a faster re-definition of a system and technology is a great tool when combined with the knowledge that promotes the social-ecological resilience of a landscape. For example, in humid tropics, innovation gives smallholders the choice of reforestation and to use more advantageous land-use practices (Ota et al., 2020). Also, new technologies are a relevant mode of knowledge transmission for home gardeners (Calvet-Mir et al., 2016).

Overall, this review contributes to clarifying the concept of social-ecological resilience, trying to cover from the definition to its features found in the scientific literature. In the context of climate change, social-ecological resilience plays an important role because nature-human interactions are changing and affecting the systems in which they interact. The presented specific strategic practices that can be applied by local communities aim at being helpful for operational management of landscapes.

5. Conclusions

The overall objective of this research was to uncover the relevance of social-ecological resilience for agroforestry landscapes in a context of global change, where it has proven to be an effective approach to address the challenges ahead. The main findings highlight the importance of re-thinking the interactions between nature and humans, emphasizing the high value of common responsibility in landscapes, in terms of ecosystem service provision and biodiversity conservation. Digital innovation and technology must play a key role for the maintenance of these interactions, providing replicable and transferable sustainable practices. It is emphasized that TEK and community-based management are essential for building social-ecological resilience and, in fact, become an optimal framework for involving local people in landscape management and conservation practices. In this sense, the application of the different described strategies can become valuable for the management of agroforestry systems and may contribute to face the upcoming challenges of climate change.

In conclusion, there is complexity around how to manage social-ecological systems. From our understanding, there are still some gaps in the scientific literature: i) A broader interdisciplinary perspective on the management of social-ecological systems incorporating and involving all stakeholders; and ii) In-depth research into the role that digital innovation and technology can provide for local communities in building their social-ecological resilience. Such additional studies would help to better understand resilient social-ecological landscapes, which is necessary to advance the definition of these more sustainable systems to address the challenges of global change.

CCRediT authorship contribution statement

Esteve Viñals: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Visualization, Project administration. **Roser Maneja:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision. **Martí Rufi:** Writing – review & editing. **Miquel Martí:** Writing – review & editing. **Neus Puy:** Conceptualization, Methodology, Validation, Writing – review & editing, Supervision, Funding acquisition.

Data availability

No data was used for the research described in the article.

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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