WP 4 Deliverable 4.3

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Assessment of ecosystem change, recovery success and ecosystem service change following restoration

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Contents

Summary of Deliverable

This report aims to assess ecosystem change, recovery success, and ecosystem service change following the restoration of *Cystoseira sensu lato*. It synthesises data collected from AFRIMED sites to date as well as evidence from a systematic literature review on the ecosystem services delivered by *Cystoseira* macroalgal forests. The database listing the studies included in the review is available on request.

1 Context, aims and structure of the report

The AFRIMED (Algal Forest Restoration in the Mediterranean Sea) project aims to develop, test, and promote a protocol for the effective restoration of macroalgal forests formed by brown macroalgae defined as *Cystoseira sensu lato (Cystoseira s.l.*) in the Mediterranean Sea. This group of brown algae includes species formerly belonging to the genus *Cystoseira* C. Agardh and now classified in the three genera *Cystoseira*, *Ericaria* Stackhouse and *Gongolaria* Boehmer. Forests formed by these brown macroalgae play a key role in maintaining the stability and productivity of marine and coastal ecosystems and in delivering several ecosystem services with important societal and economic benefits. Despite this, they are typically overlooked and their contributions to people and planetary health are not well understood. By strengthening our knowledge and enabling the restoration of these important macroalgal habitats, AFRIMED is working to strengthen the resilience of coastal ecosystems and support the sustainable development of the blue economy in the region.

Over the last four years, AFRIMED has developed and tested restoration techniques for *Cystoseira s.l.* at a number of sites in six countries around the Mediterranean. Assessing the preliminary outcomes of these restoration activities in terms of *Cystoseira s.l.* recovery success, ecosystem and ecosystem service change is a critical part of the project. A full assessment of restoration success and impacts will likely require monitoring of recovery and change over a longer timeframe. However, a preliminary assessment can provide valuable insights to inform future and ongoing restoration activities.

This deliverable aims to bring together the information available to date from the AFRIMED sites on ecosystem change, recovery success and ecosystem service change following restoration activities. This is supplemented with a literature-based assessment of the ecosystem functions and services of *Cystoseira s.l.* to summarise the value they provide to people and understand the potential benefits of restoring lost or degraded macroalgal forests in the Mediterranean Sea.

The deliverable will address two key questions:

1. How can ecosystem change and recovery success following the restoration of *Cystoseira s.l.* in AFRIMED sites be measured?
2. What ecosystem service changes can be expected following the restoration of *Cystoseira s.l.?*

By addressing these questions, this deliverable will contribute towards understanding the state of knowledge on the nature of the relationship between habitat restoration and ecosystem service generation.

The **second section** of the report gives background on the important role *Cystoseira s.l.* play within marine ecosystems, the current state, and pressures of *Cystoseira s.l.* forests in the Mediterranean, and the need to understand the relationship between restoration success and ecosystem service generation in order to maximise the delivery of ecological and socioeconomic restoration outcomes. The **third section** presents and assesses currently available information from AFRIMED sites on restoration activity and ecosystem service change. The **fourth section** outlines the process and findings of a literature assessment of the ecosystem services of *Cystoseira s.l*. The **fifth section** brings together evidence from the project and literature to discuss the two key questions the report aims to address. The **final section** presents concluding remarks and open questions for further research.

2 Background: Macroalgal forest restoration and ecosystem services

Marine and coastal ecosystems and biodiversity are vital for sustaining human life on Earth. Humans derive much of their needs including oxygen, drinking water, climate regulation, food and materials from oceans and coasts (UN n.d.). As with terrestrial ecosystems, the health of ocean and coastal ecosystems are currently facing a range of human-driven threats including pollution, ocean warming, acidification and the spread of invasive alien species. These threats are expected to have significant impacts on oceanic and coastal ecosystems, including loss of diversity and ecosystem functions which underpin a range of important marine ecosystem services. This will have considerable impacts on a range of marine habitats and the species and people who depend on them for food, shelter, materials, and other services they provide.

Forests of canopy-forming brown macroalgae are recognised as important biodiversity hotspots in intertidal and subtidal zones of most temperate regions. The macroalgae forming these forests are keystone species which create structurally complex habitats providing food and shelter to a diversity of understory species. Like terrestrial forests, macroalgal forests carry out important ecosystem functions including primary production and nutrient cycling. In the Mediterranean Sea, macroalgal forests are typically comprised of fucalean brown algae that belong to the *Cystoseira sensu lato* (s.l.) complex. This group includes the genera *Cystoseira, Ericaria and Gongolaria*.

These genera belong to the Sargassaceae family of seaweeds and encompass 46 species (*Cystoseira* 24*, Ericaria* 10, and *Gongolaria* 12; (Guiry and Guiry 2020)) distributed across the Mediterranean and the temperate north-eastern Atlantic. Their highest diversity, however, is found in the Mediterranean Sea (de Sousa et al., 2017). They are important foundation species crucial to biodiversity and ecosystem functioning (Bermejo *et al.* 2018). Some Mediterranean populations have been declining at an alarming rate due to various human-driven stressors. These pressures, including eutrophication, overgrazing, and the impacts of urbanisation, are expected to be aggravated under climate change with increasing ocean temperatures (Bermejo *et al.* 2018). As a result, biodiverse and structurally complex macroalgal forests are being replaced by simpler habitats, such as turfs or sea urchin barrens, with detrimental effects to the biodiversity of intertidal habitats (Verdura *et al.* 2018).

The distribution of *Cystoseira s.l.* forests in the Mediterranean, the drivers of their loss, and methodologies for restoring habitats have been well documented in the literature (Blanfuné *et al.* 2019; Fabbrizzi *et al.* 2020). However, the ecosystem functions and services they provide are less well documented and are often inferred from studies on analogous ecosystems such as kelp forests.

The central role of macroalgal forests in marine ecosystems and their decline in various locations across the Mediterranean, makes them important candidates for restoration. Active restoration has been identified as a promising tool for recovering *Cystoseira s.l.* forests. In the EU, several projects have focused on developing these approaches (e.g., MERCES EU, AFRIMED and ROCPOP-life).

A key challenge for the effective upscaling of marine ecosystem restoration is a lack of a general agreement about clear criteria for success. It is important to define clear and measurable benchmarks to monitor restoration and assess when goals are achieved (Abelson *et al.* 2020). It is increasingly recognised that restoration must integrate social and ecological priorities. The consideration of ecosystem services within restoration projects can help achieve this. Ecosystem services are the benefits that ecosystems deliver to humans (Barbier 2017). These include provisioning services (goods and material benefits such as food and water), maintenance and regulation services (such as erosion control and pollution control), and cultural services (such as recreation opportunities and spiritual value). Mainstreaming ecosystem services into restoration decision-making can help maximise the delivery of ecological and socioeconomic restoration outcomes. Projects are more likely to be successful when they include ecosystem service generation in their objectives as this helps increasing awareness of the benefits restoration can deliver for people thereby increasing stakeholder engagement and support (Abelson *et al.* 2020). To achieve this, we must first understand the relationship between restoration success and ecosystem service generation and how restoration success can be measured in terms of ecosystem service delivery.

3 Evidence from AFRIMED sites

3.1 Collection of information from AFRIMED sites on recovery success, ecosystem, and ecosystem service change

Measuring the effect and success of macroalgal forest restoration in terms of ecosystem service change requires methods for identifying, quantifying, and monitoring ecosystem change, recovery success and ecosystem service delivery following restoration. Here, we provide an overview of available information on ecosystem change, recovery, and ecosystem services collected from AFRIMED sites to date.

Information and data for the assessment of recovery success, ecosystem and ecosystem service change, and the potential benefits of *Cystoseira s.l.* restoration were sought from the AFRIMED sites through various channels. This included an exercise at one of the AFRIMED general assemblies, a questionnaire and direct email exchanges with the sites.

3.1.1 Recovery success and ecosystem change information from AFRIMED sites

AFRIMED partners carrying out fieldwork at project sites were asked which ecological indicators they use to measure *Cystoseira s.l.* condition (**Table 1**). Where available, the partners were asked to share relevant condition data for the assessment of recovery success and ecosystem change at their sites.

Table 1 *Indicators of Cystoseira condition used by the AFRIMED sites.*

Indicator	Number of sites	Which sites?
Cover (canopy cover/extent)	6	Spanish National Research Council (CSIC) – Spain INALE (HAO-DIMITRA) – Greece Stazione Zoologica Anton Dohrn (SZN) – Italy Università Politecnica Marche (UNIVPM)/ECOREACH – Italy University Chouaib Doukkali (UCD) – Morocco Université Côte d'Azur (UCA) – France
Maturity	3	Faculty of Science of Bizerte (FSB) – Tunisia INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy
Fertility	3	FSB – Tunisia INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy
Presence/absence	3	CSIC – Spain UCA – France
Growth rate	2	INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy
Salinity	1	FSB - Tunisia
Dissolved Oxygen	2	FSB – Tunisia INALE (HAO-DIMITRA) – Greece

Indicator	Number of sites	Which sites?
Hydrodynamics of water	2	FSB – Tunisia INALE (HAO-DIMITRA) – Greece
Nutrients	1	FSB - Tunisia
Thalli height	1	INALE (HAO-DIMITRA) – Greece
Benthic associated biodiversity	1	UNIVPM/ECOREACH – Italy
Density and population structure (proxy of age: main axis length)	1	UCA – France

AFRIMED partners were also asked to specify indicators for what would be considered successful restoration of *Cystoseira s.l.* (**Table 2**). The most common metrics were increase in substratum coverage and macroalgal growth, reproduction, and persistence. Other indicators were related to the ecosystem service benefits of restoring *Cystoseira s.l.*, such as improvements in water quality, biodiversity enhancement, and recovery of ecosystem services.

Table 2 *Indicators of Cystoseira restoration success, including in terms of ecosystem service generation, identified by the AFRIMED sites.*

Indicator	Number of sites	Which sites?
Increase in extent (cover)	6	FSB – Tunisia CSIC – Spain INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy UCD – Morocco UCA – France
Persistence	4	FSB – Tunisia INALE (HAO-DIMITRA) – Greece SZN – Italy UNIVPM/ECOREACH - Italy
Growth	4	FSB – Tunisia INALE (HAO-DIMITRA) – Greece SZN – Italy UNIVPM/ECOREACH – Italy
Reproduction	4	FSB – Tunisia INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy UCA – France
Biodiversity enhancement	4	FSB – Tunisia CSIC – Spain UNIVPM/ECOREACH – Italy UCA – France
Resistance to storms	2	INALE (HAO-DIMITRA) – Greece UNIVPM – Italy
Recovery of ecosystem services	2	CSIC – Spain UCA – France
Water quality improvement	1	FSB - Tunisia
Length of seaweed	1	SZN – Italy
Density and population structure (proxy of age: main axis length)	1	UCA – France

3.1.2 Ecosystem service change information from AFRIMED sites

To identify the ecosystem service recovery potential from restoring *Cystoseira*, AFRIMED partners were asked which benefits they expect to see for local communities from the restoration activities (Table 3). The partners were also asked what data related to ecosystem services they were collecting (

Table **4**). Where available, the partners were asked to share relevant data for the assessment of ecosystem service change.

Table 3 *Perceived benefits of Cystoseira s.l. restoration for local communities expected by AFRIMED sites.*

Benefit	Number of sites	Which sites?
Ecosystem productivity	3	INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy UCA – France
Nursery for commercial species	2	INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy
Refugia for commercial species	2	INALE (HAO-DIMITRA) – Greece UNIVPM/ECOREACH – Italy
Habitat structuring	1	FSB – Tunisia
Nutrient and carbon cycling/fixation	1	FSB – Tunisia
Production of biomass	1	FSB – Tunisia
Oxygen production	2	INALE (HAO-DIMITRA) – Greece FSB – Tunisia
Improved fisheries opportunities	1	SZN – Italy
Increased eco-tourism	1	SZN – Italy
Job opportunities	1	SZN – Italy
Diversity	1	UCA – France
Water clarity	1	UCA – France
Wave dampening/attenuation	2	INALE (HAO-DIMITRA) – Greece UCA – France
Cultural ecosystem services (following increased awareness)	1	UCA – France

Table 4 *Parameters related to ecosystem services being measured by AFRIMED partners.*

Ecosystem service related data parameters	Number of sites	Which sites?
Associated biodiversity	3	CSIC – Spain UCA – France UCD – Morocco
Oxygen production	2	CSIC – Spain INALE (HAO-DIMITRA) – Greece
Nutrient uptake	1	CSIC – Spain
pH	1	CSIC – Spain
Wave attenuation	1	INALE (HAO-DIMITRA) – Greece
Productivity	1	UCA – France

3.2 Ecosystem change and recovery success in terms of ecosystem service change measured at AFRIMED sites to date

Several AFRIMED partners are measuring and monitoring ecosystem services. However, currently available data are limited meaning there is insufficient information to adequately assess ecosystem change, recovery success and ecosystem service generation changes to date. This is due to delays in the collection of data caused by the COVID pandemic as well as the fact that these changes occur over long time periods and are therefore likely not yet detectable. At this stage, sites are focused on developing pioneering restoration protocols and evaluating their success. Here, therefore, we use a case-study approach highlighting some of the preliminary information shared by AFRIMED partners to illustrate some initial findings.

3.2.1 Eastern Macedonia, Greece (INALE (HAODIMITRA)): Regulating services

Work at this site has focused on two regulating services, disturbance prevention and moderation (wave attenuation) and oxygen production.

Wave attenuation:

The effect of *Ericaria barbatula* on attenuating wave energy was assessed by measuring the dissolution rate of gypsum cones as a relative measure of mass transfer within forests of different densities. Macroalgal forest cover (%) was found to be the best indicator of disturbance prevention and moderation.

Oxygen production:

Experiments to model photosynthesis and seasonal productivity changes of *Gongolaria barbata* from Greece, Italy, and Spain were conducted using oxygen production measurements per biomass and chlorophyll-a fluorescence transients. The final data of the experiments are in preparation.

3.2.2 Cala Teulera, Menorca, Spain (University of Girona): Biodiversity indicators

Two restoration techniques were tested at the Cala Teulera site in Spain. In-situ recruitment of individuals using wild collected zygotes and recruits was successful while ex-situ recruitment, using recruits cultured in laboratories, was deemed unsuccessful. In-situ recruitment was successfully carried out using both natural (boulders) and artificial (clay) substrates.

Data on growth, maturity, and fertility of *Gongolaria barbata*, and changes in associated benthic meio and macrofaunal biodiversity were collected after restoration. The indicators used included species richness, Shannon diversity Index, Pielou evenness index, and biomass. After only one year of monitoring, no strong effects in terms of enhancement of biodiversity could be detected compared with sites without *Gongolaria barbata.*

For this site no specific data on ecosystem service indicators were collected. Although biomass data can contribute to estimating the carbon sequestration potential of *Cystoseira s.l.*, most of the carbon captured in biomass is stored for short periods of time until it is consumed. To contribute to carbon sequestration, carbon must be stored in long-term sinks. As such, an understanding of how much carbon is exported to more permanent deep ocean carbon stores is needed to measure *Cystoseira s.l.* carbon sequestration benefits.

3.2.3 French sites

Different restoration techniques were used in the French sites (in situ, ex situ) in places where natural forests are present and in sites where they were present in the past. Unfortunately, in places were forests disappeared in the past, the herbivorous pressure did not allow the development of a new forest and it was therefore not possible to assess eventual ecosystem service recovery.

3.3 How long does it take to restore *Cystoseira*?

AFRIMED partners were asked about the timeline for *Cystoseira s.l.* recovery, and when macroalgal forests are functionally restored. Several partners answered that they were unsure of the timeline, one partner estimated that it could take approximately five years, with another saying 5-10 years. This is supported by experimental evidence which suggests that densities and size structure distributions of *Cystoseira s.l.* forests were comparable to those of natural reference populations after six years (Verdura *et al.* 2018).

4 Literature-based assessment of *Cystoseira* ecosystem services

To supplement the available preliminary information from the AFRIMED sites, a systematic literature review on the ecosystem services provided by *Cystoseira s.l.* was conducted. The aim of the literature assessment was to find evidence for *Cystoseira s.l.* ecosystem services to determine the potential benefits of restoring macroalgal forests in the Mediterranean Sea and to what extent these benefits can be measured.

4.1 Literature review approach

4.1.1 Literature review search strategy

A list of potential *Cystoseira s.l.* ecosystem services was compiled to guide the literature search shown in **Table 5**. The list was created building on inputs from experts at an AFRIMED meeting in Morocco, in March 2020 followed by a high-level literature search for *Cystoseira s.l.* and comparable, functionally similar species.

***Table 5** List of potential Cystoseira s.l. ecosystem services.*

• Nursery ground	• pH regulation
• Fishing and aquaculture	• CO_2 sequestration and climate change mitigation
• Habitat formation	• Protection of coast
• Traditional use	• Climate adaptation
• Increased genetic diversity	• Biofilter and bioremediation (absorption of pollutants)
• Feeding site for fish and invertebrates	• Use as bioindicator
• Nutrient cycling (organic matter, nitrates, phosphates)	• Diving, snorkelling, and tourism
• Primary production	
• Oxygen production	

The literature review was conducted between January and April 2022. Only peer-reviewed papers in English language published between January 2015 and August 2022 were included. The Web of Science search engine and publication database was searched using pre-determined combinations of keywords. *Cystoseira* keyword combinations included: '*Cystoseira*' + 'Type of Ecosystem Service'; '*Cystoseira*' + 'Mediterranean' + 'Type of Ecosystem Service'; '*Cystoseira*' + 'Type of Ecosystem Service' + 'Restoration'. All inclusion and exclusion criteria and keywords are listed in **Table 6**.

__Table 6__ Inclusion and exclusion criteria for literature review.

INCLUSION CRITERIA/Keywords	EXCLUSION CRITERIA
Cystoseira	Papers published before 2015
Macroalgae	Locations outside of the Mediterranean Sea
Mediterranean Sea	Seagrasses
Mediterranean	Associated Ecosystems
Ecosystem Restoration	Non-English language
Ecosystem Services	Non-academic Literature
Type of ecosystem service: • Tourism • Nursery • Fishing • Carbon Sequestration • Coastal Protection • Aquaculture • Bioremediation • Biodiversity • Climate Change Adaptation • Oxygenation • Nutrient Cycling • Climate Change	Non-*Cystoseira* species

4.1.2 Literature review process

The papers found through our search strategy were screened and 81 papers which met the inclusion criteria were identified. This list was expanded using a snowballing approach, screening relevant papers cited within the original papers, or through more targeted searches for specific services. In this way, 33 additional papers were identified bringing the total number of eligible papers up to 109. After reading their abstracts, 67 papers were included in the final literature assessment. These papers were entered in a database using a Microsoft Excel Spreadsheet. The full literature review process is outlined in **Figure 1**.

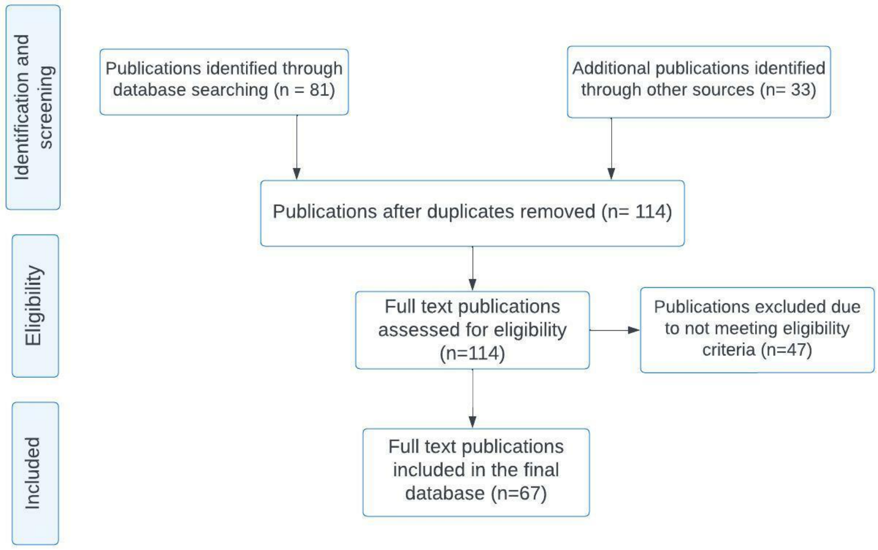

***Figure 1** Literature review process.*

Figure 2 highlights the type of studies included in the literature review. Most (42) of the studies were fieldwork based. Studies classified as 'Other' were typically literature reviews or laboratory-based studies.

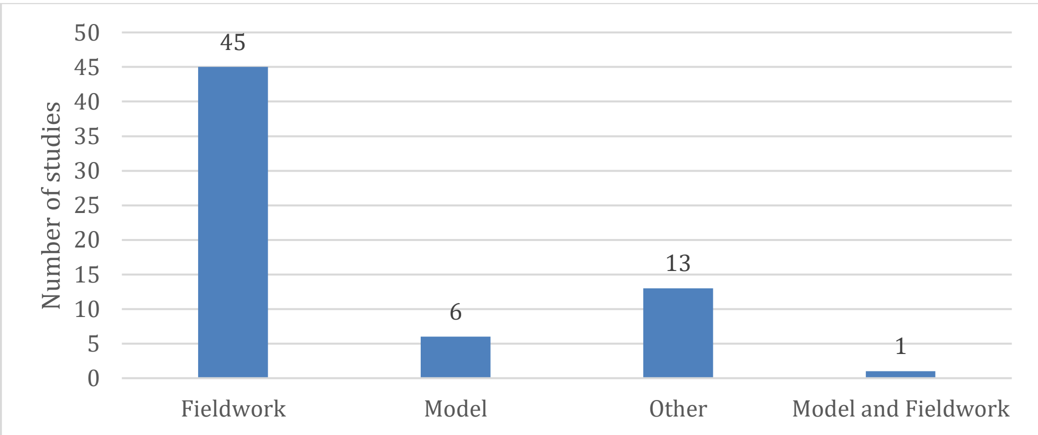

***Figure 2** The number of studies categorised by study type.*

4.1.3 Data collection and categorisation

Data were extracted from the 67 papers included in the literature database. This data was recorded against 27 categories as shown in **Table 7**. Ecosystem services were classified according to the [Common International Classification of Ecosystem Services (CICES) v5.1]. The International Union for Conservation of Nature (IUCN) typography for habitat restoration was utilised to classify ecosystem restoration specifics.

Table 7 Data categories recorded in the literature review database.

Data category	Variable
Paper characteristics	ID
	Paper title
	Author
	Publication year
	Link
	Literature type
Ecosystem function or service or biodiversity/resilience	Function or service or enhanced or biodiversity/resilience
Type of evidence	Evidenced/potential
Search details	Search
	Alternative search terms
Study details	Location
	Site info
	Cystoseira species
	Associated ecosystems and species
	Key findings
Ecosystem functions	Ecosystem function
Biodiversity and resilience	Supporting species richness and diversity
	Enhanced ecosystem resilience
Ecosystem services according to CICES	Section
	Division
	Group
	Class
	Ecosystem benefits
Ecosystem restoration specifics	IUCN Restoration technique
	Model or fieldwork
	Status of project
	Restoration benefits
	Restoration costs/trade-offs
	Biodiversity status

The category **'Type of evidence'** refers to whether papers contained direct evidence for a given ecosystem service, or whether ecosystem services were described but not directly researched. The latter were considered studies showing 'evidence for potential'. These suggest some expert agreement on the likely delivery of the ecosystem service by *Cystoseira s.l.* but did not provide direct evidence supporting or quantifying the service.

For papers that were not focused on one specific **'Location'**, such as literature reviews, location data were entered as N/A. These papers were included in the final database if Mediterranean-based studies were covered in the review and the findings were applicable to the Mediterranean region.

Papers were also categorised according to whether they addressed **'Ecosystem functions, ecosystem services or biodiversity/enhanced resilience'**. Under CICES, ecosystem services are those which directly deliver concrete benefits for people (Liquete *et al.* 2016a). Some of the 'ecosystem services' of *Cystoseira s.l.* identified by the experts and in the literature could not be classified under CICES. While processes like primary production and nutrient cycling would be considered 'supporting services' under the ecosystem service classifications of the Millennium Ecosystem Assessment (Millenium Ecosystem Assessment 2005) or The Economics of Ecosystems and Biodiversity (De Groot *et al.* 2010), CICES excludes supporting services as they are not directly benefitting people (Haines-Young and Potschin 2012). Instead, these processes are considered as ecosystem functions that underpin the delivery and maintenance of other services. Ecosystem functions are commonly defined as "the capacity of natural processes and components to provide good and services that meet human needs, directly or indirectly" (De Groot *et al.* 2002). For this assessment, the ecosystem functions identified by the experts and in the literature were classified into seven key categories:

1. Primary productivity,
2. Food provisioning,
3. Habitat forming and structuring,
4. Refuge and protection from physical and biological agents.
5. Nutrient cycle maintenance,
6. Oxygen production.

When considering food provisioning and the role of *Cystoseira s.l.* within food webs, some of the identified studies focussed on the loss of *Cystoseira s.l.* forests driven by high densities of herbivorous fish (*Sarpa Salpa*), sea urchins and molluscs. Where the focus of the study was on the negative consequences of overgrazing by these species, the papers were excluded. Studies were only included if they identified the contribution of *Cystoseira s.l.* to maintaining food webs as an ecosystem function.

Increased genetic diversity ('Biodiversity' in the literature search) was also listed as an 'ecosystem service' by AFRIMED experts. In our review, we classified increased biodiversity and enhanced resilience as separate to ecosystem functions and services. Biological taxonomic, functional, and genetic diversity are closely linked to ecosystem functions and the services they support. Living creatures and their diversity form an integral part of ecosystems and their resulting functions and processes. In addition, biodiversity can increase ecological integrity and resilience to external shocks thereby stabilising the delivery of ecosystem services (Liquete *et al.* 2016b) (**Figure** 3). Biodiversity and enhanced resilience therefore contribute to the long-term delivery of ecosystem services.

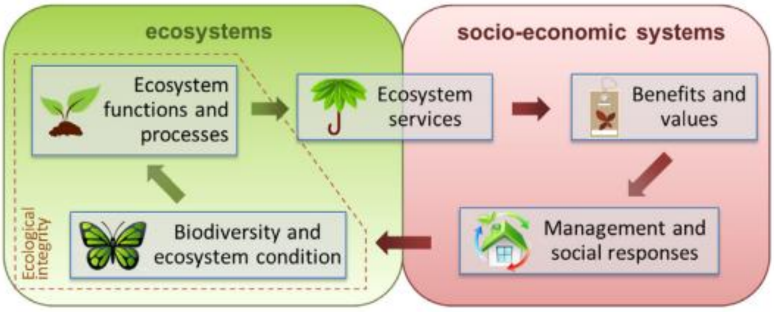

***Figure** 3 The relationship between Biodiversity and ecosystem resilience, ecosystem functions and ecosystem services. Source:* Liquete *et al.*(2016).

4.1.4 Levels of supporting evidence and supplementary studies

For several of the ecosystem services and benefits identified by AFRIMED experts, no direct evidence was found in the *Cystoseira s.l.* literature to confirm the experts' assumptions. In these cases, the search was broadened to include supplementary studies considering *Cystoseira s.l.* species beyond the Mediterranean Sea and studies on other functionally and ecologically comparable brown macroalgal species. These studies were not included in the literature-based assessment of *Cystoseira* ecosystem functions and services. However, these supplementary studies were used as indirect evidence to support the discussion of potential services provided by *Cystoseira s.l.* species that would require further investigation (see Chapter 5).

The literature assessment revealed different levels of supporting evidence for the delivery of different ecosystem service or functions by *Cystoseira s.l.*. To understand the available evidence, the following categories were applied: (1) direct evidence and (2) evidence for potential as defined in the data collection as well as (3) indirect evidence from supplementary studies looking at other species and locations, and (3) only expert judgement. For each of these types of evidence, levels of support were defined according to the number of studies providing evidence for the service or function (**Table** 8).

***Table** 8 Levels of supporting evidence for ecosystem services of Cystoseira s.l. species in the Mediterranean Sea.*

Type of evidence	Level of support	Description
Directly evidenced	Well-supported	Direct evidence from > 10 studies
	Supported	Direct evidence from 5-10 studies
	Weakly supported	Direct evidence from < 5 studies
Potential	Well-recognised	Recognised but not supported by direct evidence (or mentioned as potential) in > 10 studies

Type of evidence	Level of support	Description
	Recognised	Mentioned in 5-10 studies
	Weakly recognised	Mentioned in < 5 studies
Indirectly evidenced and potential	Supported outside the Mediterranean	Indirect or potential evidence from studies outside the Mediterranean
	Supported in comparable species	Indirect or potential evidence from studies on functionally/ecologically similar species
Expert judgment	Supported by expert knowledge	Identified by AFRIMED experts but not supported by direct, potential, or indirect evidence

4.1.5 Methodological limitations and solutions

Several key limitations must be considered when interpreting the results of this literature review.

English is not the first language of countries within the Mediterranean basin. Therefore, key papers may have been missed as only English papers were included. However, since most peer-reviewed literature is published in English we expect that the key literature will be captured.

Grey literature was also excluded. This may result in some evidence on ecosystem services (particularly those benefiting local communities) to be missed. However, this study focused on peer-reviewed evidence, as grey literature may contain biases or inaccuracies.

The bulk of the literature review was undertaken during early 2022. Articles published since then may therefore have been missed. However, some will have been captured as the review spanned over a period of months up to August 2022. In addition, only papers from 2015 on were considered in the review. So relevant literature published before then will have been excluded. A quick preliminary search suggested that 2015 was the year when the most relevant publications on the topic of macroalgal ecosystem services started to be released.

Papers were used as evidence for ecosystem functions and services provided by *Cystoseira s.l.* in general. However, functions and services will vary by species. To consider this, the specific *Cystoseira s.l.* species addressed in a study was recorded in our database where available. Similarly, the generation of ecosystem services is dependent on a range of context dependent factors including ecological, geographical, and socioeconomic factors as well as past and current management and restoration measures.

4.2 Results literature-based assessment

4.2.1 *Cystoseira* ecosystem services, functions, and biodiversity benefits

A final list of 21 ecosystem services, functions, and biodiversity benefits were identified. This was based on ecosystem services highlighted as relevant by experts as well as those identified through the literature review. Table 9 shows the final list and whether evidence for each given service and function was found through the literature review. The corresponding CICES classification for those classified as ecosystem services are shown in Table 9.

Table 9 *Final list of ecosystem services and functions explored in the literature review. The table shows how they relate to the services identified by AFRIMED experts, whether they are classified as ecosystem functions, ecosystem services, or biodiversity/resilience benefits, and whether evidence for them was found in the literature.*

Cystoseira ecosystem function or service	As identified by AFRMIED experts	Evidence
Ecosystem functions		
Primary production	Primary producer	Yes
Food provisioning	Feeding site for fish and invertebrates	Yes
Habitat forming and structuring	Habitat former	Yes
Refuge and protection		Yes
Nutrient cycling	Nutrient cycling (organic matter, nitrates, phosphates)	Yes
Oxygen production	Oxygen production	Yes
Biodiversity and Resilience		
Supporting species richness and diversity	Increased genetic diversity of *Cystoseira s.l.* and associated species	Yes
Enhancing ecosystem resilience		Yes
Ecosystem services		
Material and extract use (wild or cultivated)		Yes
Nutraceutical use (wild or cultivated)		Yes
Source of energy (wild or cultivated)		No
Nursery habitat	Nursery ground	Yes
Carbon sequestration and storage	CO2 sequestration	No
pH regulation	pH regulation	No
Coastal protection	Protection of coast	Yes
Pollution control	Biofilter (absorption of pollutants)	Yes
Invasive species control		Yes
Bioindicator	Use as bioindicator	Yes
Enabling recreation	Diving, snorkelling	No
Traditional use	Traditional use	No
Enabling tourism	Tourism	No

Of the 67 papers included in the literature assessment, 32 papers provided direct evidence or evidence for potential delivery ecosystem services by *Cystoseira s.l.* and 22 for ecosystem functions (11 of which also looked at biodiversity/ resilience benefits), 8 included information on both services and function (2 of which also looked at biodiversity/ resilience benefits), and 3 papers for biodiversity/ resilience (**Figure 4**).

Most of the papers (39) presented direct evidence for the delivery of these

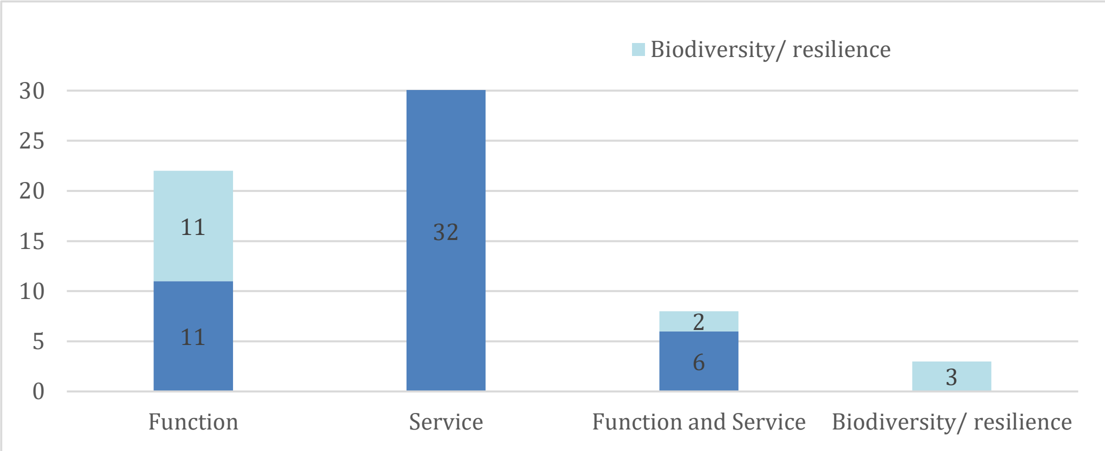

Figure 4 *Number of studies looking at ecosystem functions vs services and those looking at Biodiversity/resilience as well as functions and services or separately.*

ecosystem services or functions while 26 merely presented evidence for the potential delivery of a service (**Figure 5**). The remaining three papers covered both potential and direct evidence.

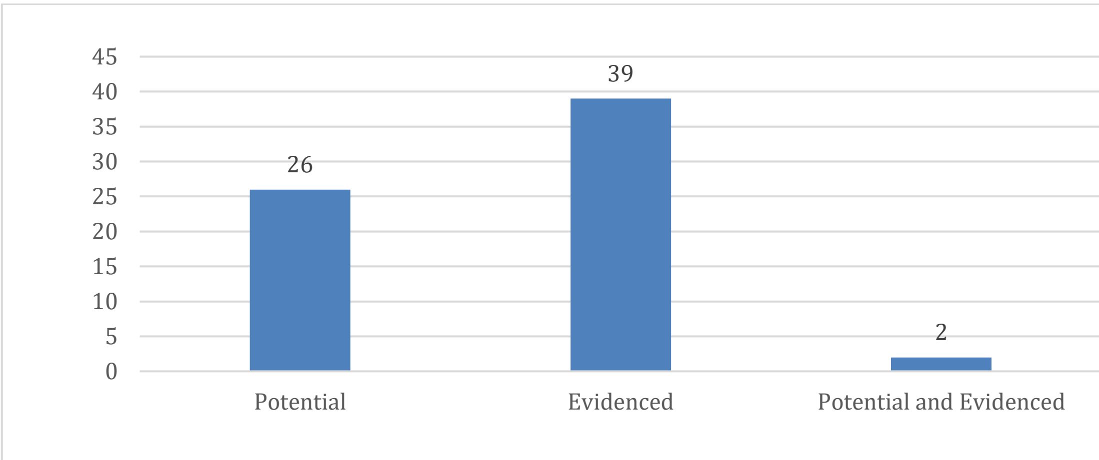

Figure 5 *Number of studies presenting direct evidence for ecosystem functions/services vs potential evidence.*

Table 10 *Ecosystem services included in the assessment and how they relate to the CICES classification v5.1 Section, Division, Group, and Class. Provisioning services are shown in green, Regulation and maintenance services in blue, and Cultural services in purple.*

Ecosystem Service	Section	Division	Group	Class
Direct use or processing of materials (wild or cultivated)	Provisioning (biotic)	Biomass	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Fibres and other materials from wild plants for direct use or processing (excluding genetic materials)
	Provisioning (biotic)	Biomass	Cultivated aquatic plants for nutrition, materials or energy	Fibres and other materials from in-situ aquaculture for direct use or processing (excluding genetic materials)
Nutrition use (wild or cultivated)	Provisioning (biotic)	Biomass	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Wild plants (terrestrial and aquatic, including fungi, algae) used for nutrition
	Provisioning (biotic)	Biomass	Cultivated aquatic plants for nutrition, materials or energy	Plants cultivated by in- situ aquaculture grown for nutritional purposes
Source of energy (wild or cultivated)	Provisioning (biotic)	Biomass	Wild plants (terrestrial and aquatic) for nutrition, materials or energy	Wild plants (terrestrial and aquatic, including fungi, algae) used as a source of energy
	Provisioning (biotic)	Biomass	Cultivated aquatic plants for nutrition, materials or energy	Plants cultivated by in- situ aquaculture grown as an energy source
Nursery population and habitat	Regulation and Maintenance (biotic)	Regulation of Physical, Chemical, Biological Conditions	Lifecycle maintenance, habitat, and gene pool protection	Maintaining nursery populations and habitats (Including gene pool protection)
Carbon sequestration and storage	Regulation and Maintenance (biotic)	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans
pH regulation	Regulation and Maintenance (biotic)	Regulation of physical, chemical, biological conditions	Atmospheric composition and conditions	Regulation of chemical composition of atmosphere and oceans
Coastal protection	Regulation and Maintenance (biotic)	Regulation of physical, chemical, biological conditions	Regulation of baseline flows and extreme events	Hydrological cycle and water flow regulation (Including flood control, and coastal protection)
Pollution control	Regulation and Maintenance (biotic)	Transformation of biochemical or physical inputs to ecosystems	Mediation of wastes or toxic substances of anthropogenic origin by living processes	Bio-remediation by micro-organisms, algae, plants, and animals
Invasive species control	Regulation and Maintenance (biotic)	Regulation of physical, chemical, biological conditions	Pest and disease control	Pest control (including invasive species)
Bioindicator	Cultural (biotic)	Direct, in-situ and outdoor interactions with living systems that depend on	Intellectual and representative interactions with natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge

Ecosystem Service	Section	Division	Group	Class
		presence in the environmental setting		
Recreation	Cultural (biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Physical and experiential interactions with natural environment	Characteristics of living systems that that enable activities promoting health, recuperation or enjoyment through active or immersive interactions
Traditional use	Cultural (biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge
Tourism	Cultural (biotic)	Direct, in-situ and outdoor interactions with living systems that depend on presence in the environmental setting	Intellectual and representative interactions with natural environment	Characteristics of living systems that are resonant in terms of culture or heritage

4.2.2 Study locations

The location of each study was mapped at the country level using GIS to visually show the geographical distribution of studies across the Mediterranean. As shown in **Figure** 6, most of the studies originated from Italy, Spain, France, Croatia, and Greece. Only five studies were from either Tunisia or Algeria. Several studies had no exact location due to being literature reviews or laboratory-based studies. Six studies referred to the Mediterranean Sea broadly without naming specific countries. These were included in the review but were not mapped.

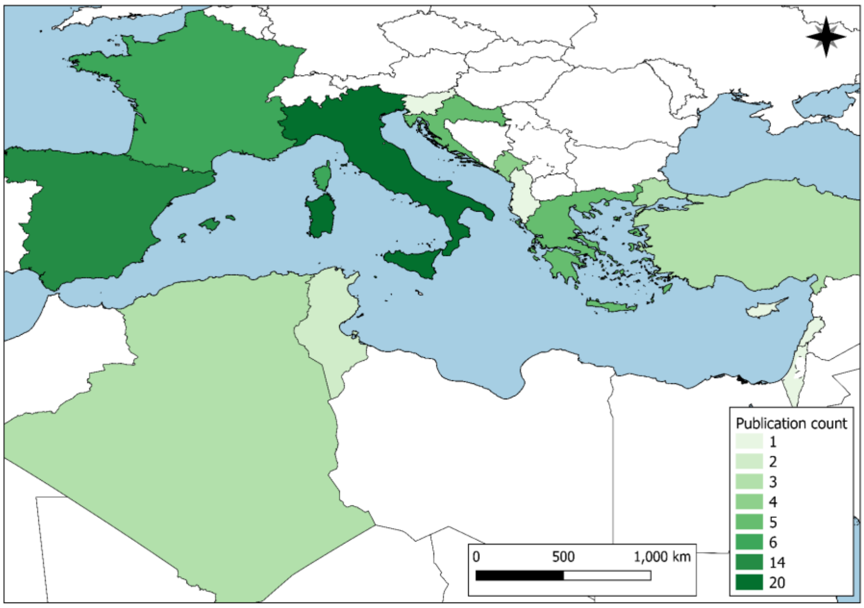

***Figure** 6 Geographic distribution of the studies included in the literature review. Number of studies originating from each country around the Mediterranean.*

4.2.3 Species studied

Most of the reviewed papers (24) did not refer to a specific *Cystoseira s.l.* species when giving direct or potential evidence for its functions and services and instead referred to the *Cystoseira s.l.* complex or genus in general. Most of the papers were published before the taxonomic revisions of Orellana *et al.* (2019) and Molinari Novoa and Guiry (2020). Therefore, species currently belonging to the genera *Ericaria* and *Gongolaria* were usually reported with the old names, as species of *Cystoseira*. Of the papers focusing on a particular species, the most frequently studied was *Cystoseira compressa* (mentioned 13 times). Other species such as *Ericaria amentacea* (as *Cystoseira amentacea*), *Ericaria brachycarpa* (as *Cystoseira brachycarpa*), *Cystoseira foeniculacea, Ericaria crinita* (as *Cystoseira crinita*), *Gongolaria montagnei* (as *Cystoseira spinosa* and *Cystoseira montagenei*), *Gongolaria barbata* (as *Cystoseira barbata*), *Ericaria selaginoides* (as *Cystoseira tamariscifolia*) and *Cystoseira humilis* were mentioned in 3 papers or more. As shown in **Table 11**, other species were only mentioned one or two times.

Table 11 Cystoseira species mentioned in the reviewed studies.

Species	Count	Species	Count
General: *Cystoseira* spp.	24	*Gongolaria rayssiae*	2
Cystoseira compressa	13	*Ericaria barbatula*	2
Ericaria amentacea (also previously known as *Cystoseira stricta*)	9	*Gongolaria sauvageauana*	1
Ericaria brachycarpa	8	*Gongolaria algeriensis*	1
Cystoseira foeniculacea	5	*Cystoseira schiffneri*	1
Ericaria crinita	5	*Ericaria mediterranea*	1
*Gongolaria montagnei (*previously known as *Cystoseira spinosa* and *Cystoseira montagenei)*	4	*Cystoseira humillis var. myriophylloides*	1
Gongolaria barbata	4	*Gongolaria baccata*	1
*Ericaria selaginoides (*previously known as *Cystoseira tamariscifolia)*	3	*Gongolaria elegans*	1
Cystoseira humilis	3	*Cystoseira corniculata*	1
Ericaria zosteroides	2	*Cystoseira montagnei*	1

4.2.4 Links to restoration techniques

As the focus of the literature review was on the relationship between *Cystoseira s.l.* restoration and ecosystem services, information on restoration measures applied within studies was recorded where available. However, the majority (49) of the reviewed papers, did not mention a restoration technique. Restoration techniques which were most used were in situ and ex situ enhancement of recruitment. Protection as part of Marine Protected Areas was also utilised.

4.2.5 Ecosystem functions and biodiversity benefits of *Cystoseira*

Most studies identifying ecosystem functions of *Cystoseira* species presented potential or direct evidence for their habitat structuring/ forming functions and their role in supporting species richness and diversity (Figure 7). Other studies showed evidence for refuge and protection, food provisioning, primary production, oxygen production, nutrient cycling, and enhanced ecosystem resilience.

Although it is helpful to categorise the ecosystem functions into distinct groups, they are not discrete categories. Ecosystem functions do not occur in isolation and the processes underlining them are often interdependent or linked. Therefore, the delivery of these functions is highly interconnected.

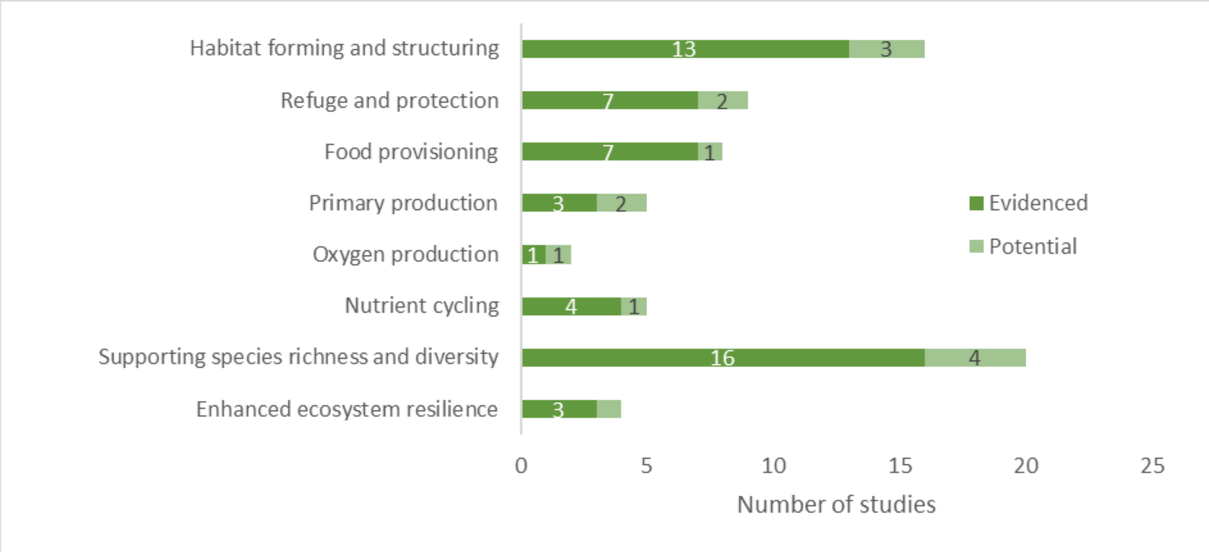

***Figure** 7 Number of studies showing potential and direct evidence for the ecosystem functions and biodiversity and ecosystem resilience benefits provided by Cystoseira.*

4.2.5.1 Habitat forming and structuring

There is wide consensus that *Cystoseira s.l.* species play an important habitat forming function in the temperate shallow rocky bottoms of the Mediterranean. Like other canopy-forming algae, their physical and ecological characteristics provide structurally complex habitats which meet the needs of a variety of different taxa. Piazzi et al. (2018) found *Cystoseira s.l.* forests are home to 597 taxa in temperate rocky reefs. These include mobile and sessile organisms such as fish, invertebrates such as molluscs and nematodes, epiphytic algae, and bacteria (Chiarore *et al.* 2019; Hinz *et al.* 2019; Bianchelli and Danovaro 2020a). Thus, *Cystoseira s.l.* are crucial habitat forming species that support diverse marine species communities.

The degradation and loss of canopy-forming macroalgae reduces their habitat forming function (Capdevila *et al.* 2016). Species abundance in *Cystoseira s.l.* forests has been linked to habitat size and algal complexity (Ape *et al.* 2018). The degradation of *Cystoseira s.l.* leads to declines in both habitat size and complexity. This compromises their ability to provide habitat to the species living within them. *Cystoseira s.l.* degradation therefore has long-term impacts on the species that depend on them for habitat (Thiriet *et al.* 2016; Catra *et al.* 2019; Pinna *et al.* 2020a).

4.2.5.2 Refuge and protection

Cystoseira s.l. forests provide refuge and protection to several species. Their high structural complexity creates shelter from both biological agents, such as predators, and physical agents, such as waves (Thiriet *et al.* 2016; Bekkby *et al.* 2020). This is one of the attributes which make *Cystoseira s.l.* forests suitable habitats for some species and is therefore linked to their habitat providing functions. Similarly, degradation and loss of *Cystoseira s.l.* limits their protective function (Pinna *et al.* 2020b).

4.2.5.3 Food provisioning

Cystoseira s.l. species play an important role in food webs. They provide a direct food source for herbivores and omnivores and they host invertebrate prey species for consumers (Kruschel and Schultz 2020). The amount of food resources and the diversity of trophic strategies they support depends on the *Cystoseira s.l.* habitat extent and condition. *Cystoseira s.l.* loss has been linked to decreased quantity and quality of food resources as well as reduced trophic complexity (Bianchelli and Danovaro 2020b; Mancuso *et al.* 2021).

4.2.5.4 Primary production

Cystoseira s.l. forests are highly productive habitats. *Cystoseira s.l.* are important primary producers and are therefore central to carbon cycling and making energy and nutrients available within ecosystems (Medrano *et al.* 2020). The biomass produced can be exported to adjacent benthic and pelagic ecosystems through food webs. The degradation of *Cystoseira s.l.* habitats can reduce this function as, for example, *Cystoseira s.l.* produce higher primary producer biomass than invasive seaweeds (Mancuso *et al.* 2022).

4.2.5.5 Oxygen production

Although only one study was found directly measuring the oxygen production of *Cystoseira s.l.* species and one other study only mentioned in passing as a service by one study (De La Fuente *et al.* 2019; Sant and Ballesteros 2021) . Despite this lack of direct evidence, oxygenation is certainly a key function of *Cystoseira s.l.* Macroalgae play a central role in oxygen production. This is linked to their primary productivity function in terms of biomass. As autotrophs, they photosynthesise, thereby sequestering carbon, building biomass, and releasing oxygen. This is linked to primary productivity which considers the outcomes of photosynthesis in terms of biomass.

4.2.5.6 Nutrient cycling

Nutrient cycling is mentioned in the literature as one of the key ecosystem processes to which *Cystoseira s.l.* contributes (Cebrian *et al.* 2021; Mancuso *et al.* 2021). Macroalgal species, including *Cystoseira s.l.* genus species, absorb and assimilate nutrients dissolved in water and are therefore part of inorganic and organic nutrient cycling. They have high nutrient turnover ranging from days to weeks. In the literature, these functions are mostly looked at in relation to their role in bioremediation and biomonitoring. *Cystoseira s.l.'s* ability to absorb nutrients with high turnover makes the algae good bioindicators able to detect rapid changes in environmental conditions (Signa *et al.* 2020). Two studies highlight that the introduction of invasive macroalgal species into structured native macroalgae habitats, such as *Cystoseira s.l.* forests, can alter the nutrient cycling functions of these ecosystems (Mancuso *et al.* 2021; Mancuso *et al.* 2022).

4.2.5.7 Supporting species richness and diversity and enhancing ecosystem resilience

The ecosystem functions outlined above all support healthy populations of a variety of species, thereby promoting higher biodiversity and, in turn, biodiversity supports the sustained delivery of these functions. The high structural complexity of healthy *Cystoseira s.l.* forests create diverse niches which provide habitat, shelter, and food for a range of species with different life cycles and ecological needs. Well-functioning *Cystoseira s.l.* forests can thereby indirectly maintain and enhance the multitude of ecosystem functions and services delivered by the diverse species they support.

Healthy *Cystoseira s.l.* forests also promote ecosystem resilience and enhance the long-term viability of the populations living within them. Higher taxonomic, genetic, and functional diversity can increase ecosystem's ability to withstand external physical and biological disturbances (Sarà *et al.* 2021). In addition, *Cystoseira s.l.* provide habitat to juveniles which is important for the replenishment and long-term sustainability of populations (Thiriet *et al.* 2016).

The loss and degradation of macroalgal forests reduce their functions, thereby reducing the diversity and abundance of species they can support. *Cystoseira s.l.* forest loss, degradation, and replacement with alternate ecosystems dominated by opportunistic and invasive species, have been linked to reduced species abundance, richness, diversity, and functional diversity for fish, molluscs, nematodes, and other invertebrates (Thiriet *et al.* 2016; Bianchelli and Danovaro 2020b; Pinna *et al.* 2020b; Mancuso *et al.* 2021; Mancuso *et al.* 2022).

4.2.6 Ecosystem services

As shown in Figure 8, most studies on *Cystoseira s.l.* ecosystem services presented potential or direct evidence for regulation and maintenance of ecosystem services. Within this, nursery populations and habitats had the most evidence (11 studies), followed by pollution control. Carbon sequestration and storage, invasive species control, and coastal protection were supported by a single paper each. Studies were also found giving evidence for the potential use of *Cystoseira s.l.* provisioning services for direct use or processing of materials (9), and nutrition (6). Finally, only one cultural ecosystem service type was captured by the literature review with nine studies showing evidence for the use of *Cystoseira s.l.* as a bioindicator.

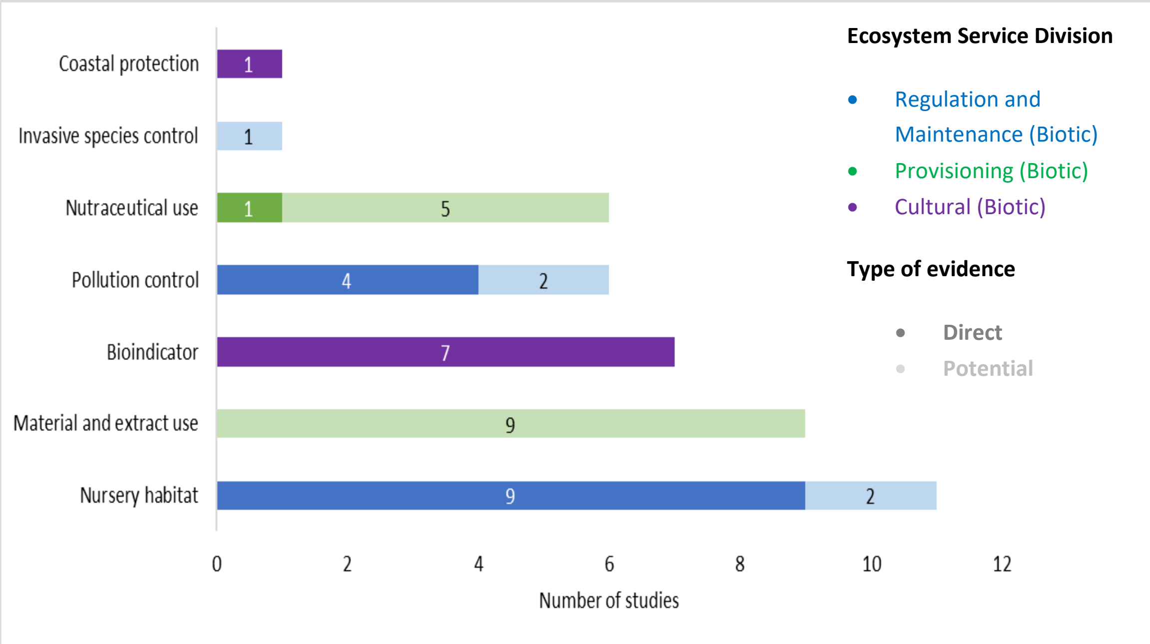

***Figure** 8 Number of studies showing potential and direct evidence for the ecosystem service benefits of Cystoseira s.l..*

4.2.6.1 Nursery populations and habitat maintenance services of *Cystoseira*

The role of *Cystoseira s.l.* in maintaining nursery populations and habitats is the most frequently mentioned and recognised ecosystem service in the reviewed literature (e.g. Hinz *et al.* 2019). The macroalgae are an important source of food, shelter, and habitat for juvenile fish in the Mediterranean Sea, thereby supporting the condition, growth, and long-term survival of fish species. It is important to highlight that ecosystem services, unlike functions, deliver concrete benefits for people (Liquete *et al.* 2016b). Nursery ecosystem services support populations or habitats of useful or iconic species that can benefit people. Most studies focus on juveniles of common and abundant fish and molluscs in the Mediterranean Sea including socio-economically important species such as *Scorpaena spp*. and *Serranus spp.* (Thiriet *et al.* 2016).

The ability of *Cystoseira s.l.* to deliver nursery services declines with ecosystem degradation or loss. Healthy *Cystoseira s.l.* forests are patchy by nature providing a range of structural complexity that supports juvenile species with diverse habitat requirements (Cuadros *et al.* 2019). *Cystoseira s.l.* forests therefore support a higher diversity and abundance of socio-economically relevant species than structurally less complex assemblages such as sea urchin barrens or turf (Thiriet *et al.* 2016).

Despite clear evidence that healthy *Cystoseira s.l.* forests can deliver key nursery services, studies conclude that not enough evidence is currently available to measure the importance or magnitude of this service (Hinz *et al.* 2019). The relationship between juvenile fish populations and their algal habitats is not straight forward. The importance of a given algae to given fish is likely context-dependent, varies spatially and seasonally. Moreover, it is impacted by natural stochastic processes leading to high variability (Hinz *et al.* 2019). As a result, it is challenging to quantify nursery value and there is no consensus on how to assess it (Liquete *et al.* 2016b).

4.2.6.2 Direct use or processing of materials and extracts from Cystoseira

Although *Cystoseira s.l.* are currently not harvested or cultivated for direct use, they are a potential source of valuable compounds and are future candidates to be cultivated in the Mediterranean (Trikka *et al.* 2021). The exploration of commercial uses and industry applications for macroalgal extracts is an area of active research. A review looking at the therapeutic potential of 200 different compounds extracted from *Cystoseira s.l.* species found a wide range of potential applications (Bruno de Sousa *et al.* 2017a). These compounds showed antifungal, antibacterial, antifouling, anti-inflammatory, antileishmanial, anticancer, antiviral, anti-atherosclerosis, anti-osteo-arthritic, anti-diabetic, anti-obesity, and anti-cholesterol reducing properties (Bruno de Sousa *et al.* 2017b). Other studies included in our review supported these findings showing evidence for compounds with antioxidant and anti-inflammatory properties and the potential to provide active ingredients for drugs (Bruno de Sousa *et al.* 2017; Messina *et al.* 2019; Julião *et al.* 2021; Kord *et al.* 2021). For example, *Cystoseira s.l.* are a potential source of fucoidans which are US Food and Drug Administration approved compounds with a range of benefits including antiangiogenic, antibacterial, anticancer, antioxidant benefits (Benslima *et al.* 2021). Another study found that *Cystoseira s.l.* extracts could be used in cancer treatments as they have anti-proliferative activity on cancer cell lines (Montalvão *et al.* 2016). Studies looking at the temporal patterns in the biochemistry of *Cystoseira s.l.* to determine the optimal harvest timing and conditions to extract these useful compounds including photoreceptors and antioxidants (Celis-Plá *et al.* 2016).

4.2.6.3 *Cystoseira* for nutraceutical use

Despite no evidence found of *Cystoseira s.l.* being harvested or cultivated for nutritional uses, *Cystoseira s.l.* extracts have potential uses within the food sector. Several *Cystoseira s.l.* compounds have been identified as potential sources of nutraceuticals, food supplements, functional foods, preservatives, and food additives such as emulsifiers (Benslima *et al.* 2021; Trikka *et al.* 2021). Functional foods provide benefits to targeted body functions and/or reduce disease risk (Donato-Capel *et al.* 2014). Evidence exists for important health benefits of edible *Cystoseira* species thanks to their high level of bioactive compounds (Trica *et al.* 2019). *Cystoseira s.l.* and their extracts could help reduce risk of non-communicable diseases such as cardiovascular diseases, cancers, type 2 diabetes/metabolic syndrome, auto-immune diseases as well as improving cognitive function (Montalvão *et al.* 2016; Trica *et al.* 2019; Bianchelli and Danovaro 2020). In addition, *Cystoseira s.l.* compounds could be used as food additives to improve the storage of food, such as fatty fish, or to enhance its nutritional value (Oucif *et al.* 2018). For example, *Cystoseira compressa* which could be used for nutritious additives to produce fish-based products (Hentati *et al.* 2019). Some evidence also exists for the potential of using *Cystoseira s.l.* to improve current agricultural and aquacultural production. For example, antimicrobial properties of some *Cystoseira s.l.* extracts could potentially help control fish and shellfish pathogens in aquaculture, and could be used in poultry diets (Mlambo *et al.* 2022; Stabili *et al.* n.d.). In addition, *Cystoseira s.l.* could contribute to the cultivation of existing crops by being used as fertiliser or to enhance resilience to salt stress in barley (Atzori *et al*. 2020; Bensidhoum and Nabti 2021; Cioroiu Tirpan *et al.* 2021).

4.2.6.4 Pollution control services of *Cystoseira*

Macroalgal species naturally absorb and accumulate inorganic pollutants in their surroundings making them a good candidate for bioremediation and the biological treatment of water (Deniz and Karabulut 2017). Several studies were found presenting direct evidence for the bio absorption of heavy metals by *Cystoseira*. Deniz & Karabulut (2017) and Deniz and Tezel (2017) showed that a seaweed mix including *Cystoseira s.l.* species can be used to remove zinc and copper ions in water. Stabili *et al.* (2019) mentioned that *Cystoseira s.l.* could be used for the bioremediation of nutrient pollution as it can reduce nitrogen and phosphorus loads pollution from fish farming. In addition, Meroni *et al.* (2018) found that *Ericaria amentacea* (previously known as *Cystoseira amentacea*) canopies were linked to lower toxic algae densities. They highlight that restoring canopy-forming macroalgae such as *Cystoseira s.l.* can have human welfare benefits through reducing the magnitude and exposure to toxic algal blooms.

4.2.6.5 Invasive species control services of *Cystoseira*

Cystoseira s.l. might play a role in increasing resilience to invasive alien species, though evidence in the literature is currently inconclusive. One study in our review showed some support for the potential of some *Cystoseira s.l.* species to resist the spread of the invasive alien algal species *Caulerpa cylindracea* (Piazzi *et al.* 2018). However, the study did not detect a strong significant impact of *Cystoseira s.l.* on invasive alien species spread. The ability of *Cystoseira s.l.* to control invasive alien species spread is likely highly context dependent, influenced by disturbance effects, and will vary between *Cystoseira s.l.* and alien species to species as different species have different ecologies. Bulleri *et al.* (2016) found that some *Cystoseira s.l.* species either had no effect on *Cystoseira cylindrical* invasion or had a positive effect on invasion.

4.2.6.6 Coastal protection services of *Cystoseira*

Evidence from one conference paper showed that *Ericaria barbatula* forests play a role in attenuating waves thereby potentially reducing coastal erosion. Species abundance was the best indicator for this service. However, more studies are needed to evaluate the ecological and environmental factors that determine the generation of coastal protection services across different locations, seasons, and *Cystoseira s.l.* species.

4.2.6.7 Bioindicator services of *Cystoseira*

Several studies demonstrated the use of *Cystoseira* species as indicators for water quality and pollution (e.g., Blanfuné *et al.* 2016). This was classified as a cultural service due to the contribution this macroalgal property makes to scientific investigation. *Cystoseira s.l.* have been most frequently used as indicators for ecological quality and biomarker for anthropogenic pollutants in coastal waters (Benfares *et al.* 2015; Blanfuné *et al.* 2016b). A body of studies has shown macroalgal communities are effective bio-indicators for the assessment of water quality using a range of biotic indices (e.g., the EEI-c index and the CARLIT index) (Orfanidis *et al.* 2011; Badreddine *et al.* 2018). This is due to the well documented sensitivity of these species to human disturbance. In Europe, *Cystoseira s.l.* are one of the Biological Quality Elements (BQE) used to assess the ecological quality of coastal water bodies under the European Water Framework Directive (2000/60/EC) (Bianchelli and Danovaro 2020b). Macroalgae have also been extensively used as indicators of specific pollutants including heavy metals and nutrients. The macroalgae accumulate metals from their surrounding water environment allowing them to be detected even at low concentrations. For example, studies have used *Cystoseira* to assess trace concentrations of chromium, lead and cadmium (Benfares *et al.* 2015). *Cystoseira s.l.* transplantation has also been used for the biomonitoring of anthropogenic nutrient pollutants. The macroalgae absorb nutrients from the environment making them reliable and sensitive indicators of nutrient enrichment (Signa *et al.* 2020). Therefore, *Cystoseira s.l.* provide useful services to assess, monitor, and manage human impacts on coastal waters.

The bioindicator services of *Cystoseira s.l.* can be classified under CICES as "characteristics of living systems that enable scientific investigation or the creation of traditional ecological knowledge". In addition- to supporting scientific investigation through their ability to monitor water quality, *Cystoseira s.l.* and its derivates could support other areas of research. Although few other research applications for *Cystoseira s.l.* have been explored, our review identified other potential uses such as in regeneration mediums (Esserti *et al.* 2017).

5 Discussion

5.1 Ecosystem change and recovery success following *Cystoseira* restoration

Restoration success can be assessed using a range of methods and indicators to identify, measure, and monitor the anticipated outcomes of restoration. Restoration success encompasses a range of elements including biodiversity and ecosystem resilience benefits, ecosystem change, and enhanced ecosystem function and service delivery. AFRIMED partners are currently collecting data on the following variables which can be used to determine restoration success (**Table 12**).

Table 12 *Measures of recovery success in terms of ecosystem change, biodiversity and ecosystem resilience, and ecosystem services being considered by AFRIMED partners.*

Recovery success elements	Variable being measured
Ecosystem change	Increase in extent (coverage)
	Persistence
	Growth
	Reproduction
	Density
	Length of thallus
Biodiversity and ecosystem resilience change	Biodiversity enhancement
	Associated biodiversity
	Resistance to storms
Ecosystem service change	Recovery of ecosystem services
	Water quality improvement
	Oxygen production
	Nutrient uptake
	pH
	Wave attenuation
	Productivity

Insufficient information is currently available from AFRIMED sites to evaluate the effects of restoration on these variables. Once available, this data will generate valuable insights into how best to measure *Cystoseira s.l.* recovery success and what factors influence it. This will help identify and assess how contextual factors and restoration techniques determine restoration success. In addition, data on ecosystem service change will contribute to our understanding on the nature of the relationship between habitat restoration and ecosystem service generation and to identify thresholds of restoration success. Filling these knowledge gaps can address challenges in mapping changes to ecosystem service provision resulting from restoration success (Drakou *et al.* (2017). The topic of mapping ecosystem service change is addressed in more detail in AFRIMED Deliverable 4.2 'Current state and recommendations for mapping marine ecosystem services'. Finally, several AFRIMED partners will be collecting data on services which are currently underrepresented in the literature, such as oxygen production, pH regulation, and wave attenuation, which could help address key knowledge gaps.

5.2 Ecosystem service changes following *Cystoseira* restoration

Understanding and measuring the relationship between habitat restoration and ecosystem services can (1) support decision-making to maximise the delivery of socioeconomic benefits from restoration and (2) demonstrate the benefits restoration can bring to people. In addition, a better understanding of the impact of restoration on ecosystem services can contribute to assessing recovery success as success can be measured in terms of benefit generation. To do this the additional ecosystem services generated thanks to restoration must first be recognised, then quantified, and finally valued in terms of their human welfare gains (Hynes *et al.* 2021a).

Cystoseira s.l. species have a unique role in supporting healthy Mediterranean coastal ecosystems and the many benefits they provide to people. Studies to date show a clear recognition for the role of *Cystoseira s.l.* in providing a range of ecosystem services and functions. The ongoing loss and degradation of *Cystoseira s.l.* macroalgae in the Mediterranean will likely threaten the continued delivery of these benefits. However, currently available information is insufficient to reliably quantify the impacts of *Cystoseira s.l.* loss or to assess the potential of *Cystoseira s.l.* restoration action to enhance ecosystem service delivery.

AFRIMED sites are currently using ecosystem service indicators to monitor ecosystem service changes after restoration. However, this data is not available yet and a longer monitoring timeframe is likely needed to detect changes. Our literature review on the ecosystem services of *Cystoseira s.l.* species provides some indications of the service changes which might be expected from *Cystoseira s.l.* restoration.

5.2.1 Evidence for the ecosystem functions of *Cystoseira* species

5.2.1.1 Direct evidence and potential for *Cystoseira* functions

***Cystoseira s.l.* delivers important ecosystem functions and biodiversity benefits**

Cystoseira s.l. species are well recognised as 'ecosystem engineers' due to their central contribution to maintaining the health and stability of temperate marine rocky bottom habitats. Their physical and ecological properties are part of the ecosystem processes which underpin the delivery of key ecosystem functions. *Cystoseira* form a patchwork of dense forests which provides habitat, shelter, and food to a diverse range of marine species at different stages of their life cycles. Being one of most productive habitats in the Mediterranean Sea, *Cystoseira s.l.*

forests are central to food webs (Bianchelli *et al.* 2016). These functions all support the delivery of ecosystem services which have direct benefits for people.

5.2.1.2 Indirect evidence for *Cystoseira* functions from other species and regions beyond the Mediterranean

Potential oxygenation function of *Cystoseira s.l.*

Although only one study was found directly measuring the oxygen production of *Cystoseira s.l.*, these species photosynthesise, so their oxygen production function is undeniable. The measurements recorded in the literature and those from AFRIMED partners show similar values of oxygen production from Cystoseira s.l. (around 170 µmol O_2 Ash Free Dry Weight^{-1} hour^{-1})(Sant and Ballesteros 2021). Some studies on similar organisms support their likely oxygen production function. Attard *et al.* (2019) explored oxygen fluxes of macroalgae canopies and found considerable oxygen production by *Fucus vesiculosus* canopies year-round. Macroalgal canopies seem to have among the highest daily net ecosystem metabolism compared to seagrasses, bare sediments, and coralline algal beds. The scarcity of studies investigating macroalgal canopy productivity and its associated functions, including oxygen production, show these functions remain understudied.

5.2.2 Evidence for the ecosystem services of *Cystoseira* species

5.2.2.1 Direct evidence for *Cystoseira* ecosystem services

Nursery habitat and biomonitoring are the most evidenced *Cystoseira s.l.* ecosystem services

The reviewed studies present direct evidence for the nursery habitat and population maintaining services of *Cystoseira s.l.* and for their use as bioindicators. The role of *Cystoseira* habitats in supporting juvenile populations of Mediterranean species is well supported. Crucially, they contribute to the health and long-term survival of socio-economically important Mediterranean species with commercial, cultural, and recreational value (e.g. *Scorpaena* and *Serranus* fish species) (Thiriet *et al.* 2016). Several studies also support the delivery of cultural services by *Cystoseira s.l.* through their applications as bioindicators enabling research and management of coastal ecosystems.

5.2.2.2 Evidence for potential *Cystoseira* ecosystem services

***Cystoseira s.l.* potentially support a much larger range of ecosystem services**

Despite a relative lack of studies showing direct evidence for the delivery of other ecosystem services, a range of potential services were highlighted through the literature review. These services include applications which are still in early stages of development, such as the direct use and processing of *Cystoseira* materials, nutrition uses, and pollution control.

Although *Cystoseira s.l.* are not currently cultivated or harvested at a large scale, a growing number of studies are exploring novel uses for *Cystoseira s.l.* and its extracts. These provisioning services include *Cystoseira s.l.* compounds with medicinal properties and health benefits, and which can be used as food additives, or to improve farming of existing crops. This shows that the potential provisioning services of *Cystoseira s.l.* could be used as renewable sources of materials with diverse industrial applications. However, scaling up the currently underdeveloped sustainable seaweed sector in the Mediterranean will likely face various challenges including an uncertain regulatory framework, low consumer interest and public awareness on the benefits of seaweed, and a lack of investment (Ktari *et al.* 2022a).

Although only a few studies showed direct evidence for the role of *Cystoseira s.l.* in bioremediation, their ability to accumulate heavy metals and organic pollutants make them a promising source of pollution mitigation services.

Weak evidence was found supporting the potential of *Cystoseira s.l.* to control invasive species spread. Although some studies showed some *Cystoseira s.l.* species might slow down the spread of an invasive macroalgal species, more studies are needed to confirm this potential benefit.

5.2.2.3 Indirect evidence for potential *Cystoseira* ecosystem services from other species and regions beyond the Mediterranean

No direct evidence was found for several of the ecosystem services explored in the literature review including (1) protection against physical agents such as wave action and coastal erosion, (3) carbon sequestration and storage, (4) energy use, and (5) recreation and tourism. For these potential services, the search was expanded to include evidence from other brown macroalgae with analogous properties to *Cystoseira s.l.* as similar ecosystem functions may likely underpin the delivery of similar ecosystem services. Some studies suggest *Cystoseira s.l.* ecosystem functions are comparable to those of other forest-forming brown macroalgae, such as kelp, as these species also play key roles in habitat provision, primary production, and nutrient cycling (Ferrario *et al.* 2016).

Potential coastal protection services of *Cystoseira s.l.*

We found little direct evidence for wave attenuation or coastal protection services of *Cystoseira s.l.* (Thibaut *et al.* 2016; De La Fuente *et al.* 2019). However, this does not suggest that these services are not being delivered by the macroalgae, rather that they have not been well researched.

Some evidence exists for the coastal protection functions of other brown macroalgae. Protection from coastal erosion and flooding has been increasingly recognised as an ecosystem service provided by vegetated marine ecosystems. A comparative study in Australia found that kelp beds significantly attenuated waves (Morris *et al.* 2020). However, there are still significant gaps in understanding which species are best suited to provide these services and under what conditions. Another study looking at the brown algal genus *Sargassum* found that species of this genus could help mitigate coastal erosion (Innocenti *et al.* 2018). The seaweeds reduced wave attenuation by up to 12%, scouring velocity by 46% and dune erosion by 103%. These studies in functionally similar species suggest that *Cystoseira s.l.* could indeed play a role in coastal protection. However, dedicated studies are needed to confirm the delivery of these services and their magnitude. AFRIMED will contribute to this by measuring wave attenuation benefits in two sites.

Potential climate change mitigation role of *Cystoseira s.l.*

Carbon sequestration and storage was identified as a potential benefit of *Cystoseira* by AFRIMED. However, we found little direct evidence for this in the literature review. The role of blue carbon, the carbon sequestered and stored by marine and costal ecosystems, is recognised as crucial to climate mitigation. Vegetated coastal habitats, such as macroalgae, are particularly important carbon sinks. Blue carbon studies to date have focused on seagrass meadows, mangroves, and salt marshes and have mostly excluded macroalgal habitats despite growing evidence for their potential to store carbon (Krause-Jensen and Duarte 2016a; Raven 2018a). Although no studies were found looking at the climate mitigation benefits of *Cystoseira* specifically, macroalgal forests are increasingly identified as an important source of blue carbon. However, the potential contribution of macroalgae to carbon sequestration has been controversial due to uncertainties surrounding exported macroalgae and the permanence of carbon sequestered (Ortega *et al.* 2019).

Most macroalgae grow on rocky shores where long-term carbon storage through deposition in sediment does not occur. Unlike rooted vegetation, they do not directly transfer carbon to sediments and most of the carbon they sequester is temporarily stored in their biomass until it is consumed by grazers and eventually mineralised by detritivores. However, recent evidence suggest that a significant fraction of carbon absorbed by macroalgae escapes consumption and is stored over longer time periods. This carbon is exported, sedimented, and stored in shelf and deep-ocean sediments (Krause-Jensen *et al.* 2018). Therefore, macroalgae significantly contribute to carbon sequestration beyond the habitats they occur in.

Calculating the precise scale of these benefits is challenging as there are still many unknowns and large scientific uncertainties. Despite this, some studies have calculated rough quantified estimates. A recent global study estimated that around 173 TgC yr^{-1} (with a range of 61–268 TgC yr^{-1}) could be sequestered by macroalgae (Krause-Jensen and Duarte 2016b). They estimated that most of this carbon is exported to the deep sea and a small fraction is buried in coastal sediments. This estimate is larger than those of seagrass coastal habitats showing the important contribution macroalgae could make to blue carbon. However, these estimates must be interpreted with caution, and they include a range of macroalgal species with different carbon sequestration abilities. Moreover, carbon sequestration potential varies spatially and temporally as cycling and storage is affected by a range of factors (Hendriks *et al.* 2020). For example. a site can be a net sink or net source of carbon depending on the season, sea-surface temperature, currents, and turbulence from storms.

The true potential of macroalgal restoration for climate change mitigation through the enhancement of carbon sinks is still unknown. A study looking at the carbon storage potential of Welsh marine ecosystems considered that macroalgal restoration is unlikely to be a significant climate mitigation strategy (Hendriks *et al.* 2020). This was due to uncertainties over the effectiveness and longevity of carbon sequestration. A recent study suggested that current global estimates might be largely overestimating the potential carbon sequestration from macroalgae(Gallagher *et al.* 2022). Currently, estimates are measured as the fraction of net primary production exported to the deep ocean. This overlooks carbon released from the consumption of external organic material which, when accounted for, could mean that macroalgae are net sources of carbon. This does not mean that macroalgal restoration will not contribute to climate change mitigation as the degraded ecosystems replacing healthy macroalgal habitats may be even larger sources of carbon. However, this demonstrates the difficulty of estimating the potential carbon sequestration of complex, open ecosystems.

Moreover, the ability of macroalgae, including *Cystoseira s.l.*, to contribute to climate change mitigation through carbon storage will be impacted by climate change. Marine habitats will experience a range of climate related changes leading to differences in distribution and biochemical processes which will affect carbon sequestration rates (Raven 2018b).

Potential use of *Cystoseira s.l.* as a source of energy

The use of *Cystoseira s.l.* as a source of energy was not supported by the literature review. However, a study in the Black Sea showed that *Polycladia indica* (previously known as *Cystoseira indica*) can be used to produce bioethanol (Cioroiu Tirpan *et al.* 2021). In addition, several studies show potential bioenergy uses for functionally similar species (Ghadiryanfar *et al.* 2016a; Ktari *et al.* 2022b). Brown macroalgae are potential sources of feedstock for biofuel and bioenergy production (Sudhakar *et al.* 2019). Similar applications could be possible in *Cystoseira s.l.* making them a potential alternative renewable energy sources from fossil fuels and thereby contributing to climate change mitigation. Moreover, studies highlight co-benefits of macroalgal cultivation including air pollution mitigation and employment (Kazemi Shariat Panahi *et al.* 2019). However, biofuel and bioenergy production from macroalgae will likely be costlier than the production of terrestrial biomass, and trade-offs must be carefully managed to ensure biodiversity conservation goals are prioritised (Ghadiryanfar *et al.* 2016b).

Potential pH regulation service of *Cystoseira s.l.*

Macroalgae have also been found to have the potential to support increased resilience to changing conditions in the ocean due to climate change. Through photosynthetic activity and biomass accumulation, macroalgae influence the chemical composition of the surrounding water body, increasing the overall mean pH and in particular increasing pH levels during the day. No evidence was found in the literature for pH regulating effects of *Cystoseira s.l.*. However, studies looking at other species suggest that macroalgae can buffer the effects of ocean acidification on the ecosystems they support and contribute to mitigating the effects of ocean acidification on associated calcifying species (Wahl *et al.* 2018; Doo *et al.* 2020; Gao and Beardall 2022).

Potential services of *Cystoseira s.l.* enabling recreation and tourism

The diversity of life supported by macroalgal forests can be reasonably assumed to make them attractive for recreational activities such as diving, snorkelling, and marine photography. Healthy *Cystoseira s.l.* forests are architecturally complex and structurally diverse meaning they can host a range of species with different habitat requirements and preferences. Amongst these are emblematic species such as the rainbow, ornate and peacock wrasse and nudibranchs (e.g., *Doto floridicola*) (Rodrigues *et al.* 2016; Cheminée *et al.* 2017; Chiarore *et al.* 2017; Cuadros *et al.* 2019). Few studies have attempted to quantify the cultural and recreational value of marine habitats when compared to other ecosystem services (Rodrigues Garcia *et al.* 2017). Despite this, biodiversity is considered an important factor in the choice of diving sites (Ruiz-Frau *et al.* 2013). Anecdotal evidence suggests that, in addition to supporting biodiversity and populations of species that are attractive to divers, *Cystoseira s.l.* can be of direct interest to divers thereby potentially directly enhancing the value of a diving site. For example, *Cystoseira* is mentioned in a Catalan diving site and a Greek diving site. There are several diving and snorkelling associations organising activities around other habitat-forming species such as *Posidonia oceanica* suggesting the same could be envisioned for *Cystoseira s.l.* Increased diving activity leads to recreational and cultural services for the divers while generating revenue and economic opportunities for local communities (Chimienti *et al.* 2017).

5.2.2.4 Summary of the evidence for the ecosystem services of *Cystoseira* species

Table 13 summarises the evidence supporting the delivery of ecosystem services and functions by *Cystoseira s.l.* species in the Mediterranean. This includes direct evidence and evidence for the potential generation of services and functions found through the literature review, as well as indirect evidence from comparable species and regions outlined in the sections above.

***Table** 13 Summary of the type of evidence and level of support found in the literature for the* Cystoseira *ecosystem services, functions and biodiversity benefits considered in the literature review.*

	Type of evidence	Level of support
Ecosystem function		
Habitat forming and structuring	Directly evidenced	Well-supported
Refuge and protection	Directly evidenced	Supported
Nutrient cycling	Directly evidenced and potential	Supported
Primary productivity	Directly evidenced and potential	Supported
Food provisioning	Directly evidenced	Supported
Oxygen production	Directly evidenced and expert judgement	Supported
Biodiversity benefit		
Supporting species richness and diversity	Directly evidenced	Well-supported
Enhanced ecosystem resilience	Directly evidenced	Weakly supported
Ecosystem service		
Material and extract use (wild or cultivated)	Potential	Well-recognised
Nursery habitat	Directly evidenced	Well-supported
Nutraceutical use (wild or cultivated)	Potential	Recognised
Pollution control	Potential	Recognised
Bioindicator	Directly evidenced	Supported
Source of energy (wild or cultivated)	Potential	Weakly recognised
Invasive species control	Potential	Weakly recognised
Carbon sequestration and storage	Indirect evidence for potential	Supported in comparable species
pH regulation	Indirect evidence for potential	Supported in comparable species
Coastal protection	Indirect evidence for potential	Supported in comparable species
Enabling recreation	Indirect evidence for potential	Supported in comparable species and by anecdotal evidence

	Type of evidence	Level of support
Enabling tourism	No evidence	No evidence
Traditional use	No evidence	No evidence

5.2.3 Quantifying *Cystoseira* ecosystem services

The ecosystem service benefits delivered by *Cystoseira s.l.* are difficult to quantify. Despite a strong support for assessed and potential ecosystem benefits delivered by *Cystoseira s.l.*, currently available evidence is insufficient to measure the value and magnitude of these benefits. Very few of the studies included in the review presented quantitative estimates of the ecosystem services considered (Cheminée *et al.* 2013). Moreover, the interpretation of ecosystem services and the measures and approaches used to assess them varied across studies making it challenging to compare values.

5.2.3.1 *Cystoseira* restoration and ecosystem service delivery: current evidence, knowledge gaps and challenges

Cystoseira s.l. ecosystem functions and services depend on ecosystem condition and extent. The studies reviewed suggested that *Cystoseira s.l.* habitat complexity and area are important to the delivery of functions and services. The degradation of *Cystoseira s.l.* forests leads to decreased habitat extent and patch-sizes and to ecosystem changes towards alternate states with lower structural complexity such as communities dominated by erect, non-canopy-forming invasive or opportunistic macroalgae, turf algae, or sea urchin barrens (Cheminée *et al.* 2013). The loss and degradation of *Cystoseira s.l.* will therefore likely reduce their ecosystem functions and associated services. As there is a lack of species which can fill the same functional role and ecological niche, this is expected to result in far reaching impacts on marine ecosystems in the Mediterranean (Buonomo *et al.* 2018). By increasing both habitat condition and extent, restoration is expected to enhance the delivery ecosystem functions and services.

Despite this evidence for a link between *Cystoseira s.l.* restoration and ecosystem service generation, several challenges currently prevent a reliable assessment of the nature of this relationship. For now, the ecosystem service benefits of restoring *Cystoseira s.l.* are fairly well-recognised, but barriers still exist for their measurement and valuation. These challenges must be considered when exploring the ecosystem service consequences of restoration action to identify thresholds and the importance of contextual factors and restoration techniques.

5.2.3.2 Challenges of measuring and valuing the ecosystem service benefits of *Cystoseira* restoration

The data collected through our literature review could not be used to measure and value the ecosystem service benefits of restoring *Cystoseira s.l.* This is due to the following key challenges which apply to *Cystoseira s.l.* as well as to measuring marine restoration benefits more broadly:

1) **Measuring and valuing marine and coastal ecosystem services requires tailored approaches**. Quantifying the value of the benefits provided by ecosystems to people faces many intrinsic challenges. There is no common framework to measure the many services provided by macroalgae. Measuring marine ecosystem services faces additional unique challenges due to the complex nature of marine ecosystems, and their relative inaccessibility and invisibility when compared to terrestrial systems (Lopes and Videira 2013). Marine processes are spatially and temporally dynamic as they occur in a three-dimensional space and the benefits from marine processes are often delivered beyond the habitat where they are generated (Townsend *et al.* 2018a). Moreover, there are significant knowledge gaps in our understanding of the production of marine ecosystem services (Barbier 2017). Studies looking at marine ecosystems represent a small proportion of the ecosystem service literature (Townsend *et al.* 2018b). One of the biggest challenges is a scarcity of spatial data. Some of the methods used to measure ecosystem service delivery on terrestrial systems, such as remote sensing, are less effective in marine habitats (Townsend *et al.* 2018b). In addition, different studies use different approaches and methods to measure and value ecosystem services making it hard to compare results between them. Some marine services have more consensus on how to assess them than others. Provisioning services for well-known commercial goods, such as fish harvest, can be more straightforward to measure and value, while valuing maintenance services and functions is often more challenging as these are typically not marketed (Barbier 2017). Valuing these services requires in depth knowledge of how marine structure and function influence and underline these services and how these directly and indirectly result in measurable benefits to people. For example, there is a variety of different perspectives on the definition of the maintenance of nursery populations and habitats as an ecosystem service. As a result, a wide array of indicators and proxies are used to measure nursery value ranging from species abundance to annual production of fish attributable to a habitat to the annual enhancement of commercial fish. Similarly, the value of more intangible benefits, such as cultural benefits, can be intrinsically

challenging to assess as they are shaped by subject's unique world views and perceptions (Small *et al.* 2017).

2) **There is no quantified baseline for the ecosystem service benefits of *Cystoseira s.l.*** Due to insufficient data and a lack of common approaches to quantify ecosystem services in coastal ecosystems, we cannot reliably estimate the current ecosystem service delivery of *Cystoseira s.l.*, even for the most well-researched ecosystem services. This baseline information is needed to determine whether restoration leads to changes in the delivery of ecosystem services.

3) **There is a lack of studies looking at ecosystem service delivery before and after restoration**. Studies looking at the impact of restoration in terms of ecosystem service delivery are limited compared to studies looking at the ecosystem service value of conservation (Hynes *et al.* 2021b). To understand the ecosystem service value of restoration, service generation should be measured before, during and after restoration action. Although comparing ecosystem service generation between pristine and degraded ecosystems can provide an indication of the potential ecosystem service value of restoring degraded ecosystems, these estimates do not reveal a full picture as restoration often cannot fully re-establish ecosystem service delivery. None of the studies included in the literature review quantified the impacts of restoration by measuring ecosystem service delivery before and after restoration. As a result, no reliable conclusions can be drawn on the changes in ecosystem service delivery after restoration.

4) **Timeframe and temporal fluctuations must be considered when measuring the benefits of restoration.** Restoration is a process that happens over long timescales. For Cystoseira, AFRIMED experts estimate restoration processes can take from 5-10 years. Thresholds needed for the enhanced delivery of ecosystem services may therefore require several years before they can be detected. In addition, temporal variation between seasons may impact ecosystem service generation meaning there is a need for measurements at different temporal scales and time points (Townsend *et al.* 2018b).

5) **Ecosystem service delivery is highly context specific**. The generation and value of ecosystem services depends on several context-specific variables including ecological and environmental characteristics, socioeconomic factors, status before restoration, current and past

management, and type of restoration action. For example, the value of an ecosystem in terms of coastal protection will depend on the coastal erosion risk at the site before restoration and on the proximity of vulnerable populations who would be exposed to that risk. Another complexity is that the interconnection of habitats may affect ecosystem service delivery, so connectivity between habitats should be considered when assessing benefits (Basconi *et al.* 2020a). Marine habitats do not exist in isolation and interact across seascapes and across the land-sea interface (Barbier 2017). The feasibility of including these considerations in marine ecosystems is limited due to a lack of knowledge in marine ecosystem boundaries, services, and connectivity (Basconi *et al.* 2020b). However, these are areas of active research and improvements in modelling and mapping approaches will likely provide better information in the future.

6) **Variation between *Cystoseira s.l.* species**. Although not a key objective of the review, the importance of *Cystoseira s.l.* species in delivering different ecosystem services, and the extent to which they are delivered, emerged. This is not surprising considering that these algae, previously included in a single genus, are now subdivided in three separate genera (*Cystoseira, Ericaria, Gongolaria*) and include species with widely different size and morphology. For example, Chiarore *et al.* (2019) found that different *Cystoseira s.l.* species played different roles in determining the natural capital values of the midlittoral habitats they supported. *Ericaria amentacea* had a high concentration of species in its understorey community compared to *Cystoseira compressa*. Due to the low number of studies on ecosystem services provided by *Cystoseira s.l.*, it is not possible to draw specific conclusions and comparisons of the roles different species play. However, further studies may wish to investigate these roles as it may be important to consider when assessing the potential benefits of *Cystoseira* habitat restoration.

7) **Interactions between different ecosystem services and functions**. The provision of ecosystem services depends on the ecosystem functions that underpin them. Moreover, often different ecosystem service types are not delivered in isolation; they interact in complex ways leading to synergies, trade-offs, and overlaps. It is therefore important to consider multiple ecosystem services and their interactions when assessing restoration success in terms of ecosystem service delivery.

6 Conclusions and open questions

Evaluating restoration success is central for understanding whether restoration goals are being achieved and to inform improvements in restoration practice. Assessing recovery success in terms of changes in ecosystems, biodiversity and resilience helps establish whether the ecological objectives of restoration are being achieved. Assessing changes in ecosystem service delivery provides information on the social and economic objectives of restoration. Measuring the socio-economic impacts of restoration interventions can increase awareness of the benefits that restoration can bring to people and help maximise positive socio-economic outcomes. Work being conducted under the AFRIMED project will contribute to the measurement of restoration success for *Cystoseira s*.l. macroalgal forests in the Mediterranean both in ecological and socio-economic terms. Although it is still too early to determine recovery success at AFRIMED sites, the information being collected will contribute to a better understanding of the thresholds and contextual factors determining restoration success in macroalgal forests.

The potential of healthy *Cystoseira s.l.* macroalgal forests to generate ecosystem services and support ecosystem functions is recognised in the literature. Despite a lack of studies evaluating to what extent these can be re-established through restoration, this supports the assumption that macroalgal forest restoration can enhance ecosystem service delivery. Moreover, there is a lack of studies measuring and valuing these services and functions and the related socio-economic benefits. As a result, it is currently not feasible to reliably quantify the expected changes in ecosystem service generation following the restoration of *Cystoseira s.l.* Several challenges and open questions need to be addressed to better integrate ecosystem services in the monitoring and assessment of macroalgal restoration success.

Several potential *Cystoseira s.l.* ecosystem services are currently not explored in the literature including carbon sequestration and storage, oxygen production, pH regulation, and coastal protection. More studies investigating the full range of ecosystem services delivered by *Cystoseira s.l.* are needed to explore the relationship between macroalgal forest restoration and ecosystem services provision. Crucially, studies covering different sites and timeframes are needed to understand how the ability of restoration to increase ecosystem service delivery is influenced by context-specific factors. Macroalgal restoration projects covering multiple sites, such as AFRIMED, provide valuable information to fill in the current knowledge gaps on the impacts of *Cystoseira s.l.* restoration on ecosystem services.

Other future areas of research include:

a) the development of frameworks and methods to measure and value *Cystoseira s.l.* ecosystem services,
b) the exploration of trade-offs and synergies between the delivery of different ecosystem services,
c) spatial and temporal variations in ecosystem service delivery,
d) differences in ecosystem service delivery between *Cystoseira s.l.* species,
e) thresholds in recovery success,
f) the influence of different specific restoration measures and contextual factors, including ecosystem condition before restoration, on ecosystem service delivery,
g) and how to value benefits in economic terms.

Answering these questions will help determine the potential of macroalgal restoration to improve ecosystem functioning, biodiversity, and ecosystem service generation. This will contribute to building a strong case for the restoration of these important habitats and to identify priority areas for the restoration of *Cystoseira s.l.*.

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