Climate change and bioinvasion impacts on reef and canopy-forming macroalgae and shelf fisheries catch in the southeast Mediterranean Sea

Storylines 34 & 35

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Introduction to FutureMARES

The EU Horizon project FutureMARES (2020-2024) was designed to develop science-based advice on viable actions and strategies to safeguard biodiversity and ecosystem functions to maximise natural capital and its delivery of services from marine and transitional ecosystems in a future climate. The program investigates effective habitat restoration, conservation strategies and sustainable harvesting at locations across a broad range of European and other marine and transitional systems. The restoration of habitat-forming species (plants or animals) and habitat conservation (e.g. marine protected areas, MPAs) represent two nature-based solutions (NBS) defined by the EU as "resource efficient actions inspired or supported by nature to simultaneously provide environmental, social and economic benefits that help to build resilience to change". A third action that will interact with these two NBS and have positive effects on marine biodiversity is nature-inclusive harvesting (NIH) such as the sustainable farming of plants and animals at the base of marine food webs and ecosystem-based management practices for traditional (artisanal) and commercial fisheries.

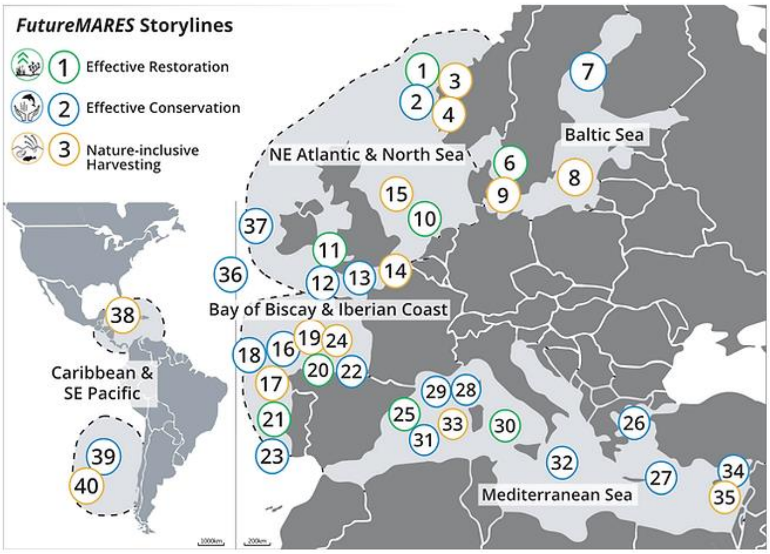


Figure 1: *Overview of FutureMARES Storylines*

FutureMARES was designed to:

- advance the state-of-the-art forecasting capability for species of high conservation value,
- explore new and less carbon intensive aquaculture production methods,
- perform modelling analyses geared towards informing the development of climate-smart marine spatial planning approaches, and
- provide an assessment of ecosystem services based on scenarios of climate change and the implementation of NBS and NIH.

This document provides a summary of activities conducted in FutureMARES in a specific area on specific NBS and/or NIH. The activities are multi-disciplinary and include marine ecology (analyses of historical time series and experiments performed in the field and laboratory), climate change projection modelling (future physical, biogeochemical and ecological changes), economic analyses and social-ecological risk assessments. Many of these components and analyses were co-developed with local and regional stakeholders through regular engagement activities. The work presented in this Storyline document represent activities conducted by a large number of FutureMARES project partners. Broader comparisons and syntheses (across regions and/or topics) are provided in the FutureMARES deliverable reports submitted to the European Commission (www.futuremares.eu).

Regional Storyline Context

The Levantine basin is the easternmost ecoregion in the Mediterranean. Within the Levantine basin, the south-eastern Mediterranean (SEM) corner, represents the trailing-edge of distribution of native Atlanto-Mediterranean and endemic Mediterranean species where they are exposed to the most extreme temperature and salinity conditions in this marginal sea. Many of the species that occur in the western Mediterranean or even in the northeast (e.g., the Aegean Sea) do not occur in the SEM. This means that the native biodiversity is generally lower in the SEM. There are also very few species that are known to be endemic only to the SEM (Coll et al. 2010), among them is the canopy-forming brown algae *Gongolaria rayssiae* (formerly *Cystoseira rayssiae*) (Mulas et al. 2020). The coastal areas (coastline and shallow shelf) are mainly sandy in the south and rocky in the north.

Figure 2: *A vermetid reef in north Israel; a unique and endangered ecosystem. Credit: Gil Rilov*

The SEM is a hotspot for ocean warming and bioinvasions of non-native species, mostly of tropical origin (Coll et al. 2010, Edelist et al. 2013, Rilov et al. 2018, Rilov et al. 2019). Coastal waters are warming ca. four times faster in this region than the global average with an assessed increase by 1.5-3 degrees over the last three decades, and hundreds of mostly tropical non-native species have invaded in the past century and a half (many of which are invasive non-natives - INS, senso lato the revised very broad definition of Soto et al. 2024 for invasive species) while dozens of native species populations have collapsed or completely disappeared (Rilov 2016). Marine heatwave index analysis shows that currently the entire summer period in the SEM region can be considered as one continuous and strong heatwave that has been intensifying over the past decade (Fig. 3). Invasion rates have also been accelerating in the past few decades, assumingly at least partly because of warming. There is also an increase in the synoptic systems that create extreme desiccation events in the rocky intertidal ecosystem (Zamir et al. 2018).

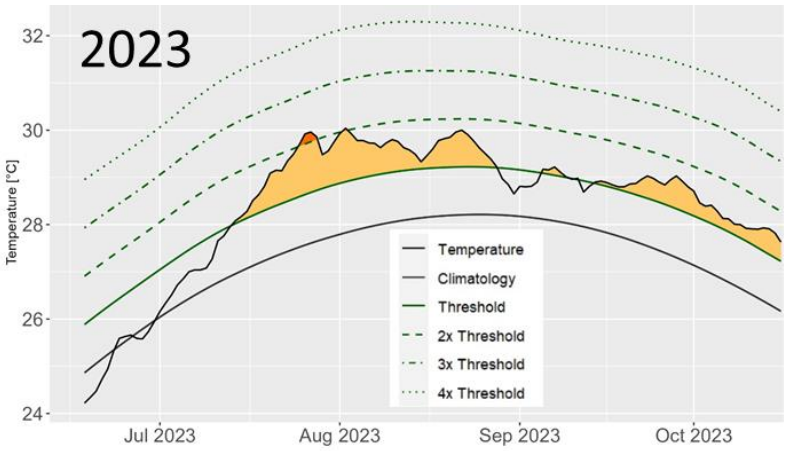


Figure 3: *Marine heatwave "events" in the coastal area near Haifa, Israel, detected from satellite SST data during the summer of 2023 by using the Hobday definition (Hobday et al. 2018) and the Marine Heatwave R program (Schlegel and Smit 2018).*

Furthermore, sea level rise is severe threat to the regional intertidal ecosystems because of the small tidal range and the topographic structure of the rocky intertidal zone in the region. Most of this zone is composed of flat vermetid reefs found in the low shore level, and they will permanently drown with only a small increase in sea level (Rilov et al. 2021). The community on this zone is highly seasonal, dynamic and is experiencing strong ecological shifts, some may be partly related to climate change (Rilov et al. 2020b). On top of these global stressors, there is also a strong influence of overfishing by different sectors (Rilov et al. 2018). Other human impacts may include increase in the number and volume of desalination plants, a gradual increase in marine aquaculture (fish in cages, and macroalgae on land) and oil pollution threats, as was demonstrated in an extensive tar pollution event from a passing offshore tanker in February 2021.

Figure 4: *Documenting an algal beaching after a strong desiccation event on the Israeli shore. ©: Gil Rilov*

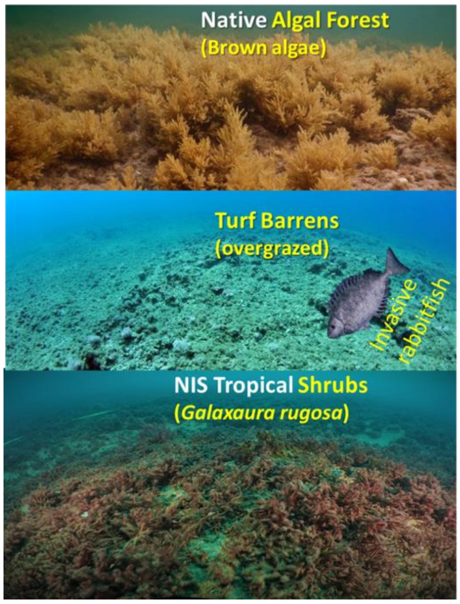


Figure 5: *Current status of Levant reefs. Small and patchy native brown algal forests, domination of turf barrens and rapid takeover of INS tropical macroalgae. © Gil Rilov*

There is growing evidence that populations of dozens of non-harvested native species have already collapsed in the past several decades on the Israeli coast (Rilov 2016). For one (sea urchin, *Paracentrotus lividus*) we have experimental evidence that warming may have been the main driver (Yeruham et al. 2015), while competition with invasive rabbitfish for food has probably also contributed to its extirpation (Yeruham et al. 2020). The large tropical, invasive, urchin, *Diadema setosum,* gained a foothold in the Levantine region in 2006 in Turkey and was spreading on northern Levantine coast ever since. Only very recently, during the FutureMARES project, it has started to spread also on the Israeli coast (Zirler et al. 2023), and it is rapidly increasing in numbers with potential strong impacts on reef communities. The combination of warming and bioinvasions results in major reshaping of coastal benthic communities as well as fisheries stocks, and undoubtedly changes ecosystem functions and possibly services.

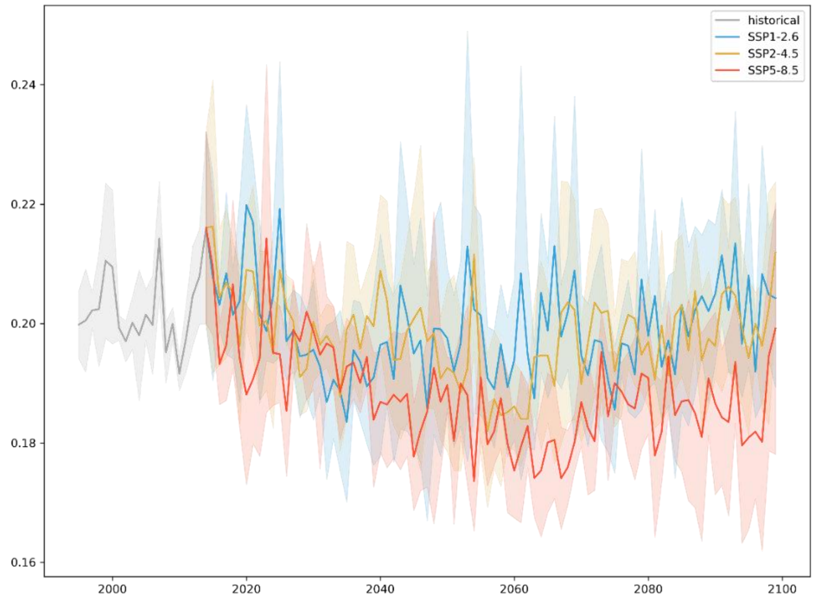
A decade of surveys indicated that intertidal (Rilov et al. 2020b) and shallow reefs communities (Rilov et al. 2018), as well as trawl catch composition (Edelist et al. 2013, Arndt et al. 2018), have been heavily transformed from their original ecological state and will probably continue to do so. Overfishing has dwindled populations of predators and native assemblages of herbivores and fish are, in many places, dominated by alien species such as the mollusc assemblage (Rilov 2016). Macrophyte communities are dominated by turf “barrens” (probably caused by rabbitfish overgrazing) and, in many areas, there is an increasing cover of alien macroalgae, while native habitat-forming brown macroalgae, which are known to be a major reef component in the Mediterranean Sea with multiple functional roles, have very low cover, are very patchy (Rilov et al. 2018) and are also highly seasonal (collapse in early summer) (Mulas et al. 2022).

In the region, functional MPAs (NBS2-conservation) do maintain greater fish communities and predator biomass but alien species are a major component inside these reserves (Rilov et al. 2018, Frid et al. 2021). Preliminary data indicates that, inside a well-functioning MPA, the macrophyte community is more diverse (although dominated by alien species) and possibly with higher biomass than in areas outside the reserve thus benthic ecosystem functions may be more intact in the MPA. The question then rises, what is the role of tropical invaders in an area where local biodiversity is rapidly shifting by warming and bioinvasions and should we protect them or remove them from MPAs (NBS2). Fishery catch is also becoming more and more dominated by invaders (a tropicalization process facilitated by warming), some are commercially important and some become a hazard (Edelist et al. 2013). This shift appears to be driven mostly be warming water and less by competition with invasive non-native species (INS) or overfishing (Givan et al. 2018). The question then rises how should INS be treated in the context of sustainable harvesting (NIH).

The information in this document should help inform key stakeholders such as the Israeli Ministry of Environmental Protection; Israeli Ministry of Interior; Israeli Ministry of Energy; the Israel Nature and Parks Authority (INPA); and the Fisheries Department under the Ministry of Agriculture and rural development in how to consider climate change and bioinvasions in conservation and marine spatial planning strategies.

Projected impacts of climate change

There are currently no regional projections for ocean warming, acidification, extreme events or sea level rise, and climate change research (e.g., in experimental planning) relies on global projections. Therefore, models and experimental design still rely on global projections. However, FutureMARES has made projections of physical and biogeochemical impacts of climate change in the region including three IPCC scenarios (SSP126, SSP 245 and SSP 585 (for background see Deliverable Report 2.2).



Chlorophyll (in mg m-3) at 5m depth

Potential Temperature (in degrees C) at 5m depth

Figure 6: *Climate projections for the Israeli waters in the Mediterranean Sea. The figures were produced using trend preserving statistical downscaling (Lange, 2019) of a multi-model ensemble Earth System Model historical simulations and future projections from the CMIP6 archive trained on reanalysis datasets from the Copernicus Marine Environment Monitoring Service.*

Geographical Maps were extracted from the full dataset by averaging over the following periods, consistent with the periods considered in the IPCC AR6 WG1 report:

- present day: 1995-2014
- near future: 2021-2040
- mid future: 2041-2060
- far future: 2080-2099

Time-series plots were produced averaging over the area of interest for each storyline and show the ensemble mean in the full lines and the range of model responses in the shaded areas as represented by the 2.5 and 97.5 percentiles of the ensemble. Credit: Momme Butenschön, Euro-Mediterranean Center on Climate Change.

With regard to ecological impacts, initial single species and assemblages' experiments on benthic species indicate that most native species will become increasingly vulnerable and with higher risk of regional extirpation as temperature will continue to rise while most tropical aliens will be more resilient (e.g., Rilov et al. 2022).

Scenarios describing future society and economy

FutureMARES developed three policy-relevant scenarios for NBS and NIH based on commonly used IPCC frameworks (for more details see hyperlink). These scenarios were regionalised based on stakeholder perspectives to guide activities such as model simulations and risk assessments.

(GS) Global Sustainability (SSP126) - Low challenges to mitigation and adaptation

The world shifts gradually but pervasively to a more sustainable path, emphasising inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, investments in educational and health accelerate lower birth and death rates, and the emphasis on economic growth shifts to an emphasis on human well-being.

(NE) National Enterprise (SSP385) - High challenges to mitigation and adaptation

A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to focus on domestic or regional issues. Policies shift over time to be oriented more on national and regional security. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development.

(WM) World Markets (SSP585) - High challenges to mitigation, low challenges to adaptation

The world increasingly believes in competitive markets, innovation and participatory societies to produce rapid technological progress and train and educate people for sustainable development. The push for economic and social development is coupled with exploiting abundant fossil fuel resources and adopting resource and energy intensive lifestyles around the world.

Figure 7: *The three, broad scenarios that were regionalised to guide activities in FutureMARES. © FutureMARES project*

At the present time, key policies are the MSP maritime Policy for Israel's Mediterranean Waters, Israel SEA (guidelines for offshore petroleum & natural gas exploration), Israel planning & declaring MPAs (coastal and marine), and Israel Species protection (threatened, ecologically important). In terms of fishing regulations, there are the Breeding season moratorium, new restrictions and regulations on trawl fishing, and new regulations on recreational fishing (quotas, ban on spearfishing for SCUBA divers). Nature reserves exist in areas where benthic features serve as habitat for territorial predatory fish (such as Groupers). Israel committed to international treaties to protect 10% of its territorial waters by 2020. INPA strives to achieve 20% protection of Israeli Mediterranean territorial waters. The general plan to achieve that is with a coastal MPA network covering most shelf habitats. So far, less than 1% is protected with seven, mostly very small, declared MPAs. Most of them protect shallow reef habitats. In the past few years there is a large push to increase the number and size of MPAs to approach 20%. Three more MPAs are approved (two larger) and four more are suggested (most large). MPA research has also dramatically increase in the past half-decade with regular BioBlitz style MPA monitoring every two years. A new initiative for the design of MPAs in the Israeli EEZ is currently being promoted by INPA and the Israeli Society of Nature Protection.

Sport fishing is a key activity, especially in the vicinity of coastal rocky reefs and abrasion platforms. It is likely that a ban on sport fishing in MPAs will be a conflict with sport fishing activities. Professional (very small sector), artisanal and sport (a growing and large sector) fishing depend on healthy reef habitats but placing MPAs is already creating huge tension and conflict with these stakeholders/users because of distrust and misconceptions and relatively poor communication with these sectors. Snorkelling and diving also depend on the health of these ecosystems but here there is less conflict and perhaps a support by these stakeholders. Especially the implementation of marine conservation can create conflict with the above-mentioned activities (in case all recreational fishing activities will be prohibited in the nature reserves/MPAs).

In the future, under the GS scenario, the policy situation for marine protection improves. The pending MPAs are approved, enforced, and monitored, and will also adapt to the changing climate. In case many Rocky Reefs are included in large nature reserves and sport fishing will be banned, it is obvious that sport fishing will no longer exist within them (it will affect the fishermen but be an improvement for nature). The small but destructive trawl fishery is totally banned. Fishermen must adapt and for a while they suffer, but eventually they see the benefits of a healthy network of large MPAs that reduce the edge effect and also exports fish outside their boundaries (Ohayon et al. 2021). In the long run, fish populations are restored inside MPAs and spill over occurs. Other sea-users certainly benefit. In the NE scenario, environmental policy stays as is or changes in negative way. No more MPAs are approved and existing MPAs are not monitored or even enforced. Fishermen are happy at first but when the sea eventually empties due to increased overfishing they suffer, but probably blame this on other “stressors”. All other sea users suffer too. The WM scenario, too, brings about negative change in terms of the marine environment. Some new MPAs are approved and declared, but not those that are perceived to conflict with the oil and gas industry, or open sea aquaculture. Sophisticated technology is used for monitoring and enforcement.

Fishermen of all sectors are satisfied that no more pieces of the ocean are being "taken" from them. Other sea users do not see the full benefits of extensive ocean protection. Trawl fishing is free and without any restrictions, benthic and mid-water fish species and invertebrates (along with non-target species) suffer great losses. Bottom integrity is damaged and fish populations and invertebrate populations decline. This has a long-term negative impact on traditional activities (like fishing).

FutureMARES research needs

Regional physical and biogeochemical projections of climate change impacts are needed at spatial scales relevant for assessing biological impacts in offshore and rocky intertidal habitats.

The fast warming and highly invaded region of the Israeli coast in the southeastern Levantine basin, quite probably represents the future of many areas in the Mediterranean Sea to the north (e.g., the Aegean Sea) and west (the entire Western Mediterranean); therefore, information on the risk to climate change impacts of dominant or important habitat forming native and invasive macrophytes and their consumers, as well as species key for fisheries is needed. Determining the rate of fisheries tropicalization is also important, as the shift in community composition due to INS invasion and reduction in thermally sensitive native species may also affect fisheries sustainability.

Knowledge is needed to compare the functions and the relative contribution of different shallow reef macrophyte communities (native, invasive, turf) to habitat provisioning (benthic biodiversity) and carbon uptake to understand if alien macroalgae can replace some of the functions and services lost with the reduction of native macroalgae by warming and invasive consumers (i.e. rabbitfish). As these community shifts also occur in MPAs where alien species can also be highly abundant (e.g., the rabbitfish) (Rilov et al. 2018), such information is also highly relevant for MPA monitoring and management. For example, potential mechanisms of control of the veteran INS, rabbitfish, and the new invasion of the lionfish (Phillips and Kotrschal 2021) (e.g. selective fishing) to remove the pressure of native habitat-forming macrophytes and prey fish, and thus increase the algae prevalence need to be explored. Furthermore, an assessment is needed for potential shift in fish biological traits due to the invasion of INS, as shift in traits can be translated to shifts in ecosystem functions and in fisheries catches value.

FutureMARES research (T = Task – see program structure at futuremares.eu)

- **T1.1**: Retrieve available environmental data, species composition data along with long-term (1990-2019) fisheries data for the Israeli coast;
- **T1.2** Compilation of published data about abundance and traits (including information on the thermal limits) of selected endemic and invasive fish and invertebrate species characteristic and their distribution in relation to depth, impacts of fishing pressure to assess shifts in community temperature index and biological traits due to bioinvasions and ocean warming;
- **T2.1** Testing in-situ vs. SST data and marine heatwave (MHW) trends for the southeast Levant;
- **T2.3** Test future distribution of key native and invasive macrophytes under future thermal conditions bases on regionalised IPCC projections;
- **T3.1** Examine ocean warming risk to native & invasive macrophytes (seasonal metabolic variation, thermal performance curves) and their consumers to understand resilience to MHW of native (e.g, *Gongolaria* and *Sargassum*) vs. invasive (e.g, Galaxaura Lobophora) macrophytes, and explore the seasonal dynamics of the macrophyte community and metabolism and the potential contribution of these habitats to Blue Carbon; Explore the thermal sensitivity of several native and invasive (veterans and new) macrophyte consumers.
- **T3.2** Conduct mesocosm experiments to explore adaptation potential to MHWs (macrophyte and key invertebrates);
- **T.3.3** Assess the population connectivity within the Mediterranean Sea of key intertidal grazer snails that are abundant on the Israeli coast to evaluate their rescue potential by other populations in the case of mass mortality driven by marine heatwaves
- **T5.1** Climate Risk Assessment for several elasmobranch species abundant in catches;
- **T7.1 & 7.2** Engagement with policy makers at national, regional or EU level, and international level (IPCC, IPBES, through FishMIP collaboration);
- **T8.1** Engage stakeholders to regionalise scenarios and provide other input on project activities in NBS2 (MPAs) and NIH (future sustainable fishing). Presenting final results in a special FutureMARES-sponsored event of scientists and stakeholders discussing the challenges of marine conservation at the age of climate change.

2. Research conducted

2.1 Ecological Knowledge

To assess climate vulnerability and future climate risk to species, accurate knowledge of temperature exposure is required. We found that basing experiments and species distribution models for our study region only on satellite data includes a considerable underestimation of actual temperature extremes, as revealed by comparing remote sensing SST data and data from in-situ loggers deployed in the shallow subtidal rocky shore on the Israeli coast (Fig. 8). In situ logger showed up to 2.5ºC hotter and 5ºC colder temperatures compared to remote sensed values.

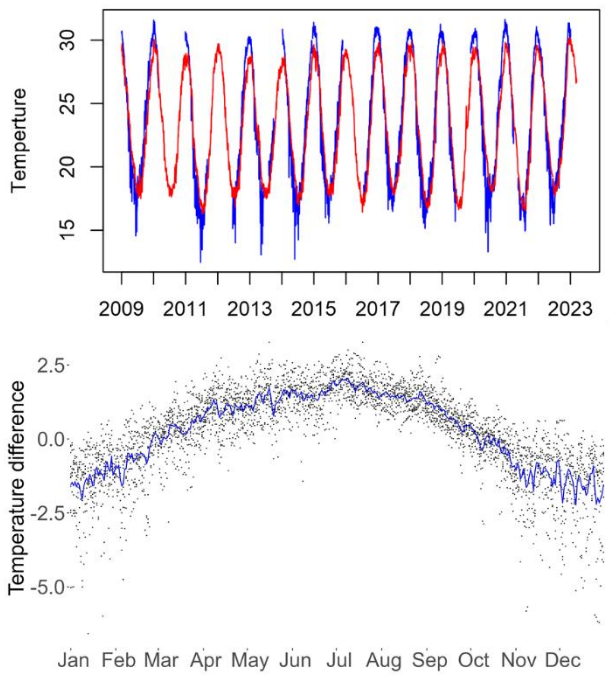


Figure 8: *The difference between in-situ measured temperatures at 0.5m on the shoreline hear Haifa, Israel (blue line), and satellite driven SST values (red line) for the same pixel on the shore along the years (top panel) and the within months along the year for the entire period (bottom panel - blue line indicates running mean).*

Based solely on the SST data, the native sea urchin *Paracentrotus lividus,* for example, should still be alive on the Israeli coast as the maximum values in the SST data do not exceed 30ºC and the urchin's thermal threshold for survival was shown to be 30.5ºC. However, the in-situ logger showed that every summer temperatures rise above 31ºC which are deadly for the urchin and that is probably the main reason why it has disappeared from the Israeli shore (Yeruham et al. 2015). This might be true for other regions and thus deploying in-situ loggers, especially in shallow coastal waters, is highly recommended for experiments and projections.

When applying the Hobday et al (2018) MHW index on long term satellite SST data for the Israeli coastal waters, we find a sharp increase in MHW events and durations, especially in the last decade

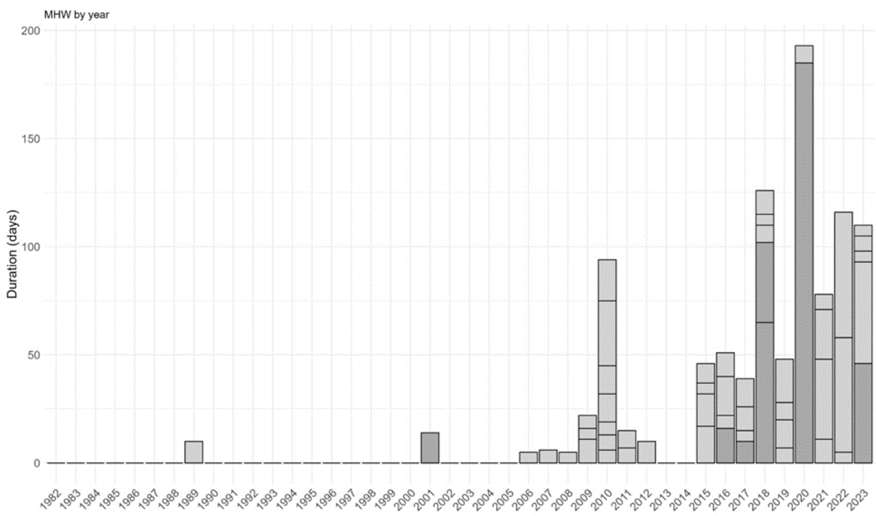


Figure 9: *Marine heatwave events and duration between 1982-2023 for the Israeli coast based on SST data.*

where in some years the accumulated MHW days reached close to 200 days (Fig. 9).

Long-term fishery independent trawl catch surveys done intermittently for 40 years for the Israel Fisheries Department allowed us to calculate the community temperature index (CTI) of the fish community over the Israeli Mediterranean shelf. The analysis revealed a fast increase (annual change of 0.047°C, Fig. 10a) in CTI while the annual increase of SST was slightly higher (0.047°C) resulting in strong correlation between the two (Fig. 10b). This CTI shift was due to strong tropicalization (the increase of warm affinity species, mostly tropical INS, 37%) and deborealization (the reduction of cold affinity species, mostly natives, 34%) of the fish assemblage (Fig. 10c).

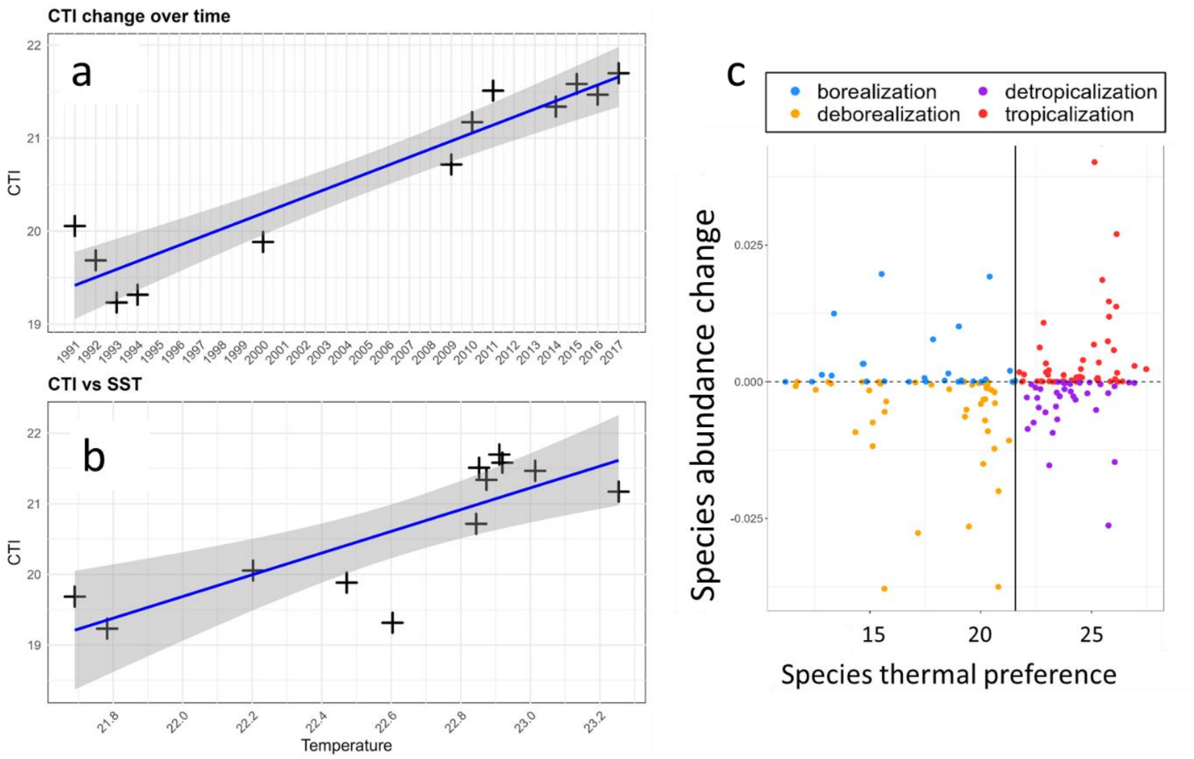


Figure 10: *CTI analysis for the Israeli trawl fisheries catch from the early 1990s to 2020). Change in CTI over the years (a), the correlation between CTI and SST (b) and change in species abundances indicating the levels of borealization, deborealization, detropicalization, and tropicalization of the catch (c).*

Among the species with the highest increase in abundance (most are INS), the one with the greatest change is the tropical invader, *Nemipterus randalli,* which has a high commercial value, and the second is the poisonous invasive catfish, *Plotosus lineatus*, which has no commercial value and in fact creates many problems for fishers when handling the catch (Fig. 11). Among the species that had the strongest decrease (mostly natives with commercial value), the species with the highest abundance loss is a native *Mullus sumuletus* that has high commercial value.

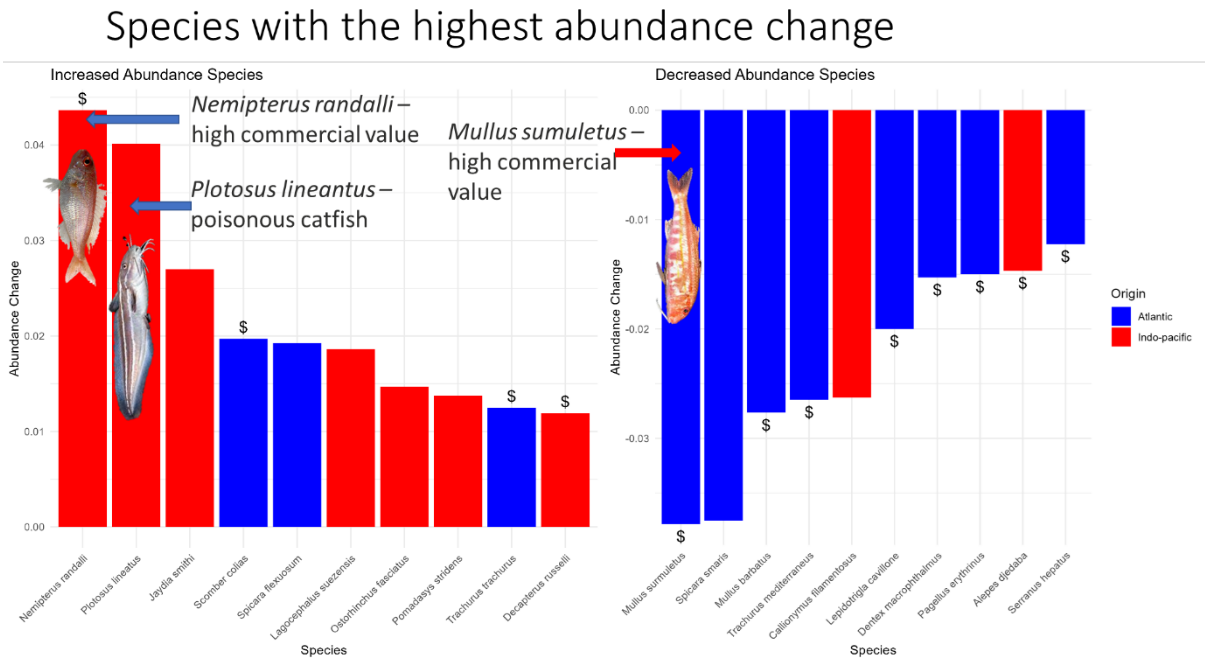


Figure 11*: Rates of abundance change (slope of the regression line to the log-transformed abundances) of shelf fish between the 1990s and 2020. The ten highest increase and ten highest decrease species are shown. A dollar sign indicates a commercial species.*

With regard to shallow reef macrophyte communities, lab temperature performance experiments revealed that the two native forest-forming brown algae *Gongolaria rayssiae* and *Sargassum vulgare* have a much lower thermal optimum for photosynthesis than the two tropical INS, the Pacific *Galaxaura rugosa* and the Atlantic *Lobophora schneideri,* both with an optimum over 31°C (Fig. 12). This means that the growth season of the natives may have already shrunk with the current warming, and they are at high risk of reduction in population viability or even regional extinctions with continuous ocean warming, especially under the RCP 8.5 scenario that predicts warming close to 4 degrees by the end of the century.

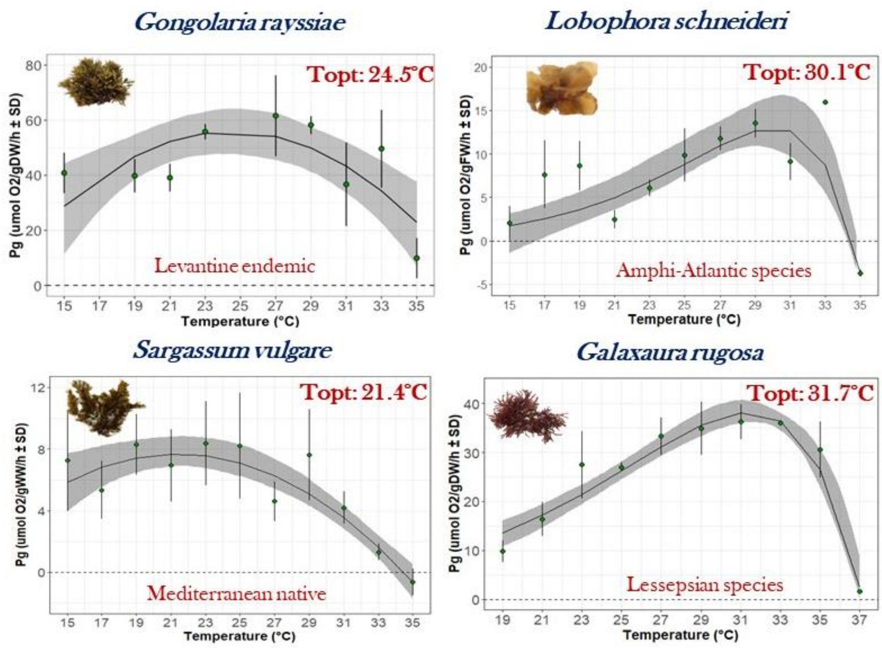


Figure 12: *The thermal performance curve of gross photosynthesis (per gram wet or dry weight, depending on the species) for the four study macroalgae.*

Furthermore, while the INS species have high cover on the reef year-round, the native species (only the Gongolaria is shown) is abundant only in the spring season (Fig. 13), when in summer it shads its branches which regrow only in late winter. It should be noted that these species occupy different areas on the reef and rarely share the same location. This difference in seasonally is also expressed in their metabolic rates (oxygen production, carbon uptake and calcification rates) as measured in lab incubation measurements (Fig. 14). Based on these results, an annual carbon budget calculation indicates a much higher potential blue carbon of the INS than the native seaweed (Fig. 15).

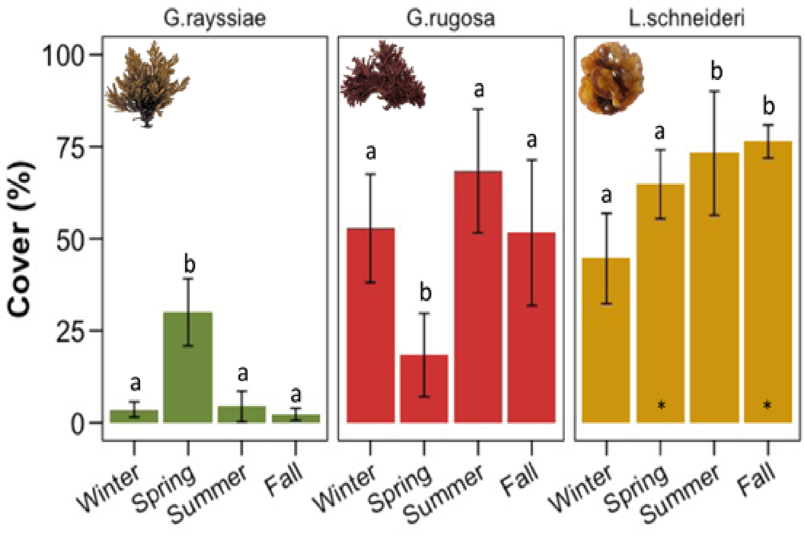


Figure 13: *Seasonal means in cover of the main study species.*

These results suggest that alien seaweed invaders surpass the annual carbon uptake of the natives and that in principle INS seaweeds can offset (or restore) the loss of Blue Carbon due to loss of native seaweeds because of warming or overgrazing by the invasive rabbitfish.

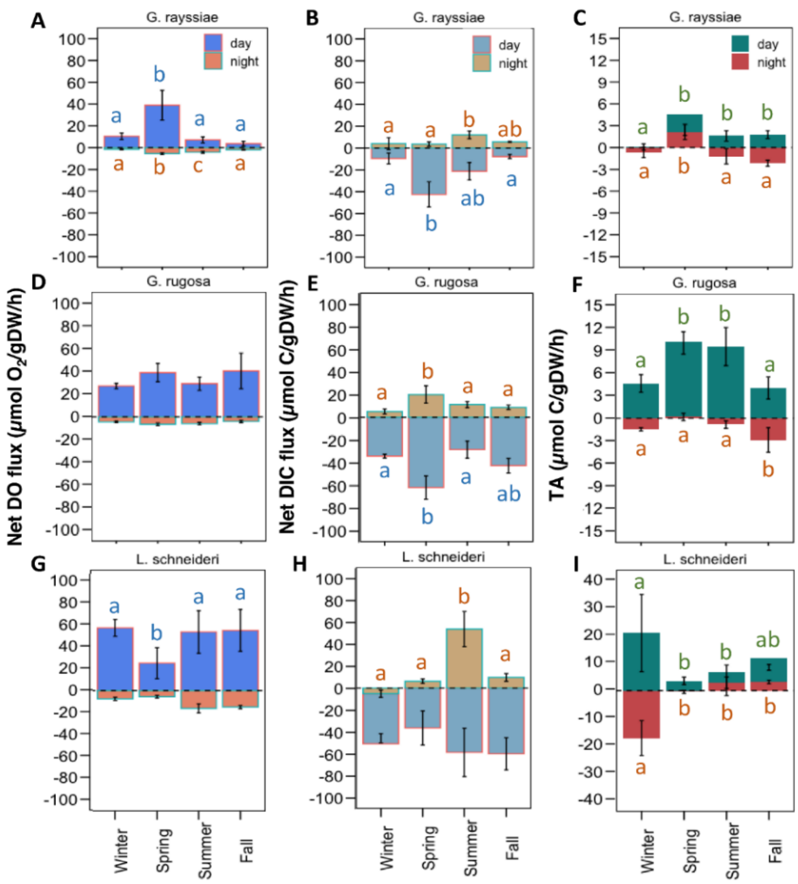


Figure 14: *Ex-Situ single species incubations average metabolic rates measured in G. rayssiae, G. rugosa and L. schneideri seaweeds under day and nighttime conditions: Net Production (NP) and respiration (R) are measured as changes in (A) dissolved oxygen (DO) and (B) dissolved inorganic carbon (DIC). (C) Rates of total alkalinity (TA) production (positive) and uptake (negative) assumed to be caused by CaCO3 dissolution and calcification, respectively. Different letters show seasonal differences within the same habitat.*

Field sampling of the entire seaweed communities, as well as the turf (overgrazed) community, with their associated species, reveals that while all seaweed communities have much higher taxa richness than the turf community (Fig. 16a), the composition of the associated assemblages (other algae and invertebrates) are quite different and they also vary seasonally (Fig. 16b) This means that while carbon uptake may be preserved by the INS (or even surpass that of the native) due to comparable metabolic functioning, habitat provisioning functions are quite different between the seaweed communities, probably due to their different structural traits; therefore they can maintain high diversity, but a relatively different one compared to the native forest.

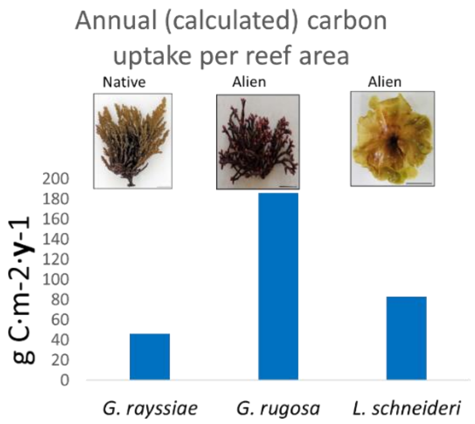


Figure 15*: Calculated annual carbon uptake by the three study seaweeds indicating that even today there is much higher Blue Carbon potential for the NIS species.*

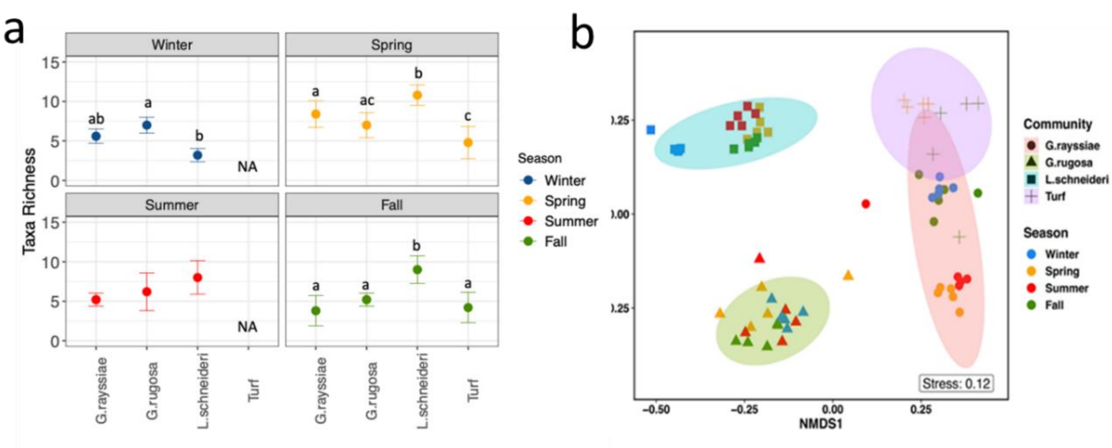


Figure 16: *Taxa Richness (a) and community similarity (b) of the four communities collected from the quadrats at different seasons. The seasonality is strongest in the native forest forming Gongolaria rayssiae as can be seen in the nMDS ordination.*

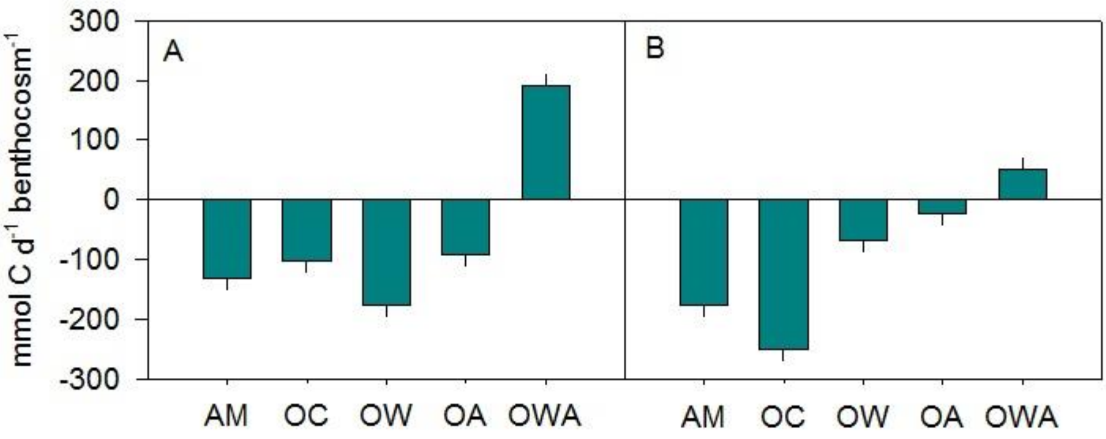


Figure 17: *Total sequestered dissolved inorganic carbon, as a result of photosynthesis, respiration, calcification, and dissolution in the benthocosms, in winter (A) and summer (B). Negative values indicate carbon sink, positive values indicate carbon source. AM = ambient conditions, OC = ocean cooling by 2 degrees, OW = ocean warming by 3 degrees, OA = ocean acidification by -0.4 pH units, OWA = a combination of OW and OA.*

When we exposed, in an outdoor flowthrough open mesocosm system, the endemic native forest-forming species, *Gongolaria rayssiae,* together with several main consumers within its community to past colder temperatures and future warmer and more acidified waters, thus simulating future conditions under climate change in both winter and summer experiments, we found a shift to a community with more INS (that recruited as larvae from the nearby open sea), higher epiphytic biomass, and overall shift in functioning from a net autotrophic (carbon sink) to net heterotrophic (carbon source) community in both winter and summer (Fig. 17).
This means that climate change will fundamentally shift both the habitat and metabolic functioning of this endemic community to a more degraded state that may eventually change from a sink of carbon to a source due to the domination of biomass of alien consumers.

With regard to native and INS seaweed consumers, we found that the native herbivores crab that live on seaweeds, *Acanthonyx lunulatus*, has a thermal optimum lower than current summer maxima; that the fast spreading alien urchin *Diadema setosum* is fully functional until 34°C, and the veteran alien rabbitfish, *Siganus rivulatus*, increases its metabolic and consumption rates until 28°C and then it slightly reduces at higher temperatures, but the fish is still fully functional also at 34°C. This finding again suggest that native herbivorous consumers might be very sensitive to warming, as was convincingly indicated in the collapse on the native urchin, *Paracentrotus lividus* discussed above (Yeruham et al. 2015). Recent findings also indicate low abundances of *Paracentrotus* in the southern parts of the Aegean Sea, perhaps indicating early signs of a population reduction also in this region (Nikolaou et al. 2023) as was suggested in the earlier work.

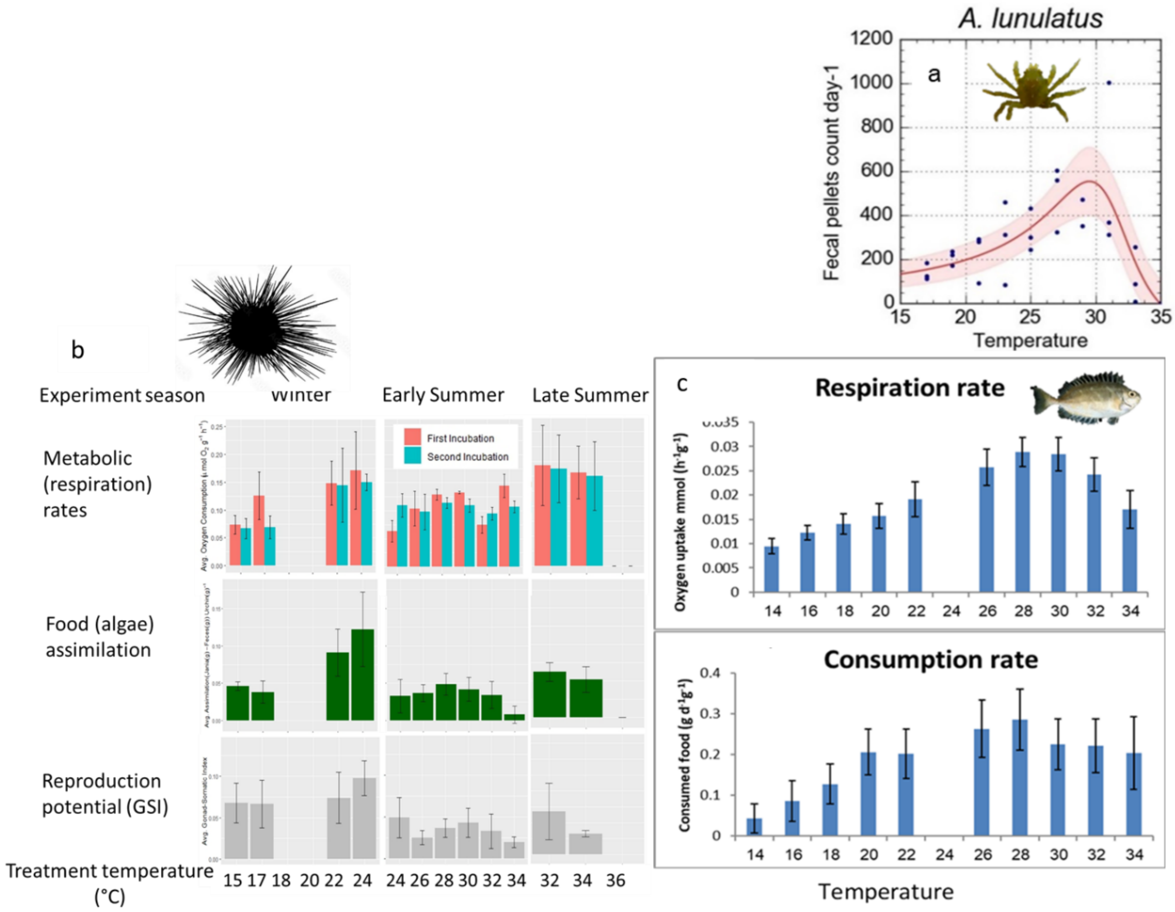


Figure 18: *The thermal performance curve of native and alien macroalgae consumers. The native crab, Acanthonyx lunulatus (a) where performance was measured by the production of faecal pellets, the alien urchin Diadema setosum (b) where performance was measured by metabolic rates, production of faecal pellets and reproduction potential (as measured as gonado-somatic index), and the alien rabbitfish, Siganus rivulatus, based on respiration and food consumption (c).*

2.2 Projections of future biological effects

Together with partners from NIVA, we have projected the habitat suitability of the two native and two INS seaweeds based on the TPC data shown above using environmental suitability index (ESI) under the three SSP scenarios. We find a clear reduction in suitability for the two native species under the worst scenario and for *Sargassum* under the much more moderate scenarios (Fig. 19). By contrast, the two INS increase their suitability in the region under future warming scenarios that level off under the more moderate scenarios by mid-century.

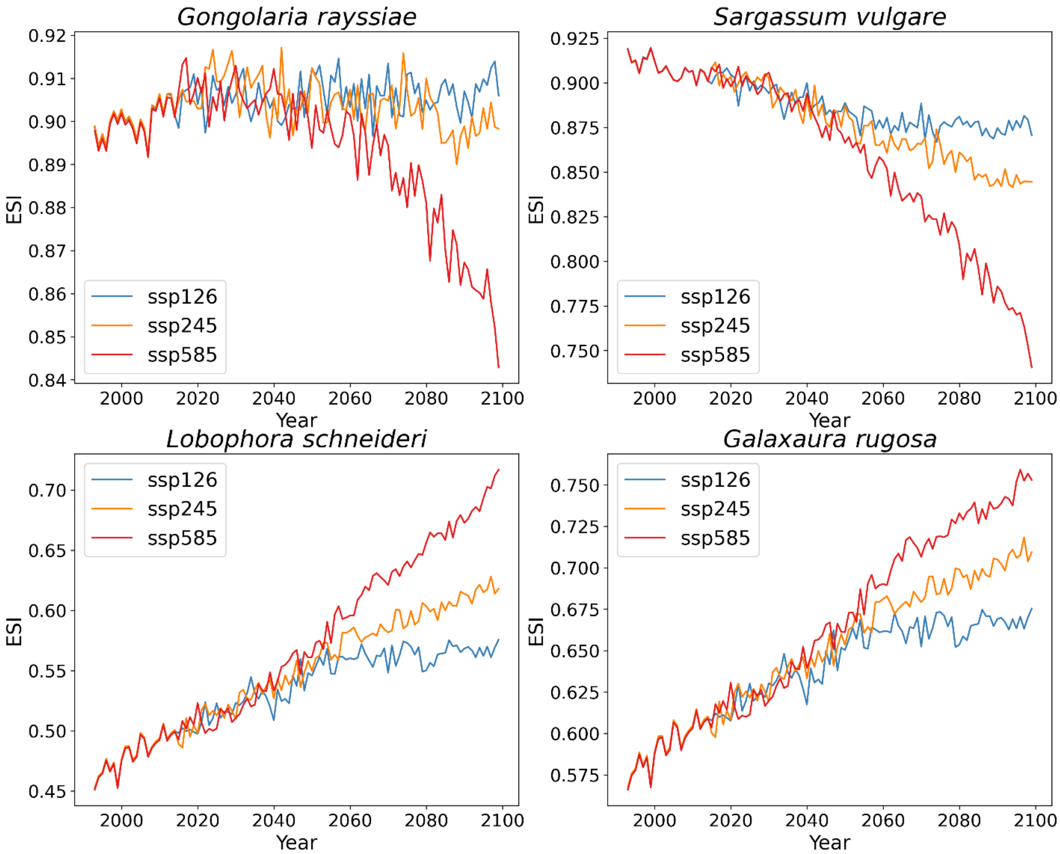


Figure 19: *The environmental suitability index for the four seaweeds for the Israeli coast*

Spatial seasonal modeling of ESI indicates that, as we indeed observe in the field, the two native species should not exist in the summer months even today, but towards the end of the century under the worst-case scenario they will not exist even in the spring, meaning that the populations will disappear from the reefs in the study region (Fig. 20). For the endemic, *G. rayssiae*, under all scenarios, habitat suitability during the winter will also drop to zero in mid-century when winter temperatures no longer go below 20°C (Fig. 21); this threshold is based on observations indicating that this alga needs a cold-snap signal below 20°C to start growing its branches that also carry its reproductive organs later in the season. We can see that even for the tropical invader from the Atlantic, *L. schneideri,* summer will become too warm under the worst-case scenario by the end of the century (Fig. 20). These projections confirm the experimental results that the endemic macroalgae, one of the only two members of the *Cystoseira* sensu-lato genera in the region, may be at the brink of both local and global extinction.

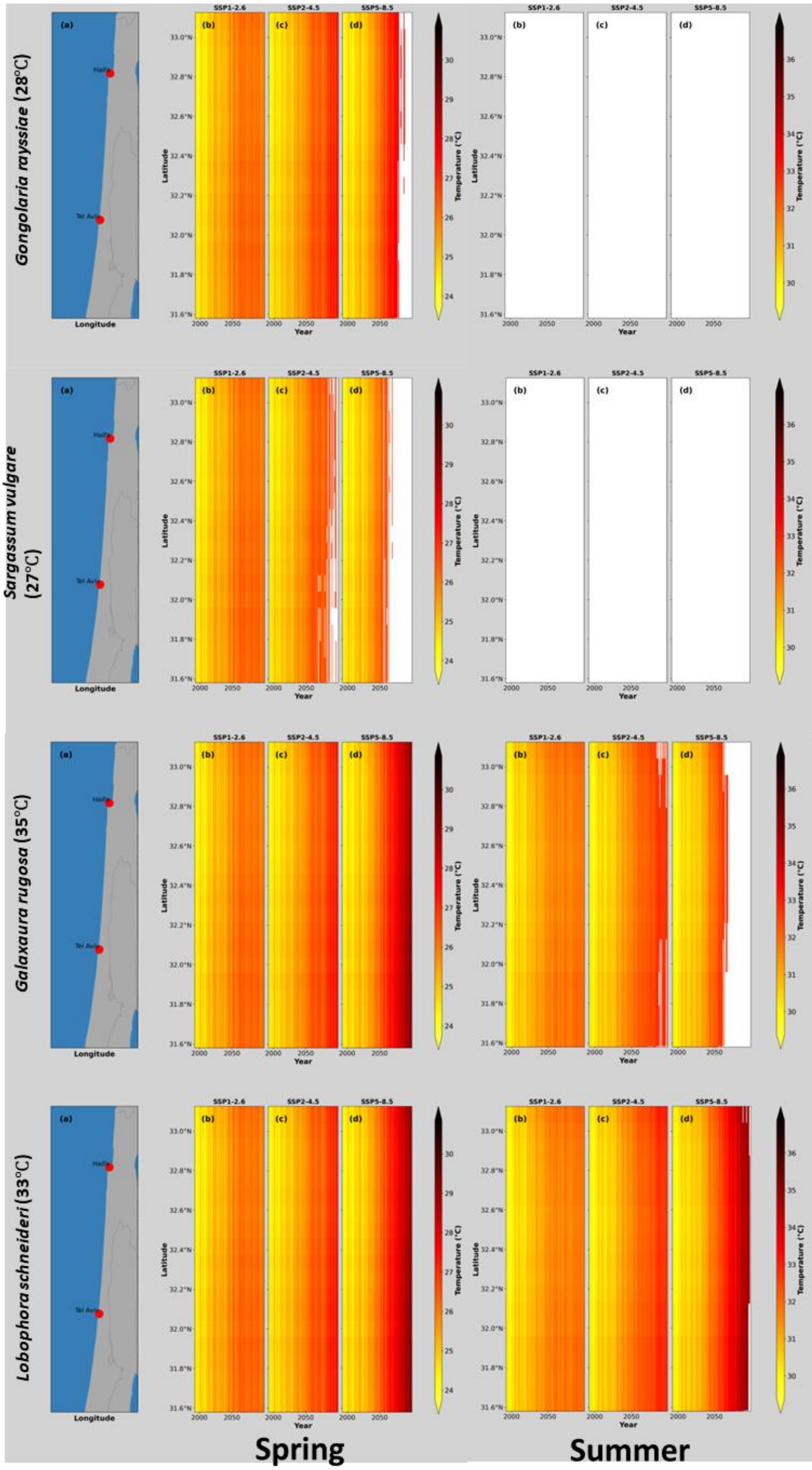


Figure 20: *Habitat suitability assessment for the four study macrophytes. Projected SST for the coastal pixels along the Israeli coast under the three scenarios for two seasons: spring and summer. When the maximum of annual temperature crosses the set temperature threshold for each species, it means that the site is not suitable for that species existence during the specific season, and the area is marked as blank (white)*

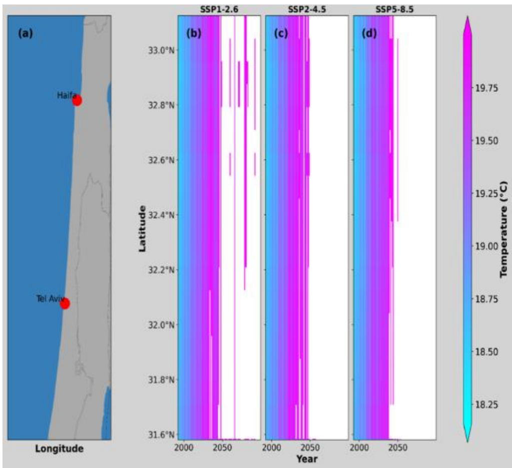


Figure 21: *Projected SST for the Israeli coast under the three scenarios for Gongolaria in winter. When the maximum of annual temperature crosses the set temperature threshold of 20°C, it means that the site is not suitable for Gongolaria regrowth, (white).*

Finally, we predict that as low winter temperatures - which may still represent a barrier for many potential tropical species that have not yet arrived to or established yet in the Mediterranean - will continue to disappear, as the winters get considerably warmer over the years (see the reduction in “cold snaps”, the opposite of MHWs, on the Israeli coast in the past four decades, Fig. 22), this barrier will dissolve and more and more tropical non-native species will establish in the Levantine basin and then spread to the north and west, among them perhaps even tropical corals.

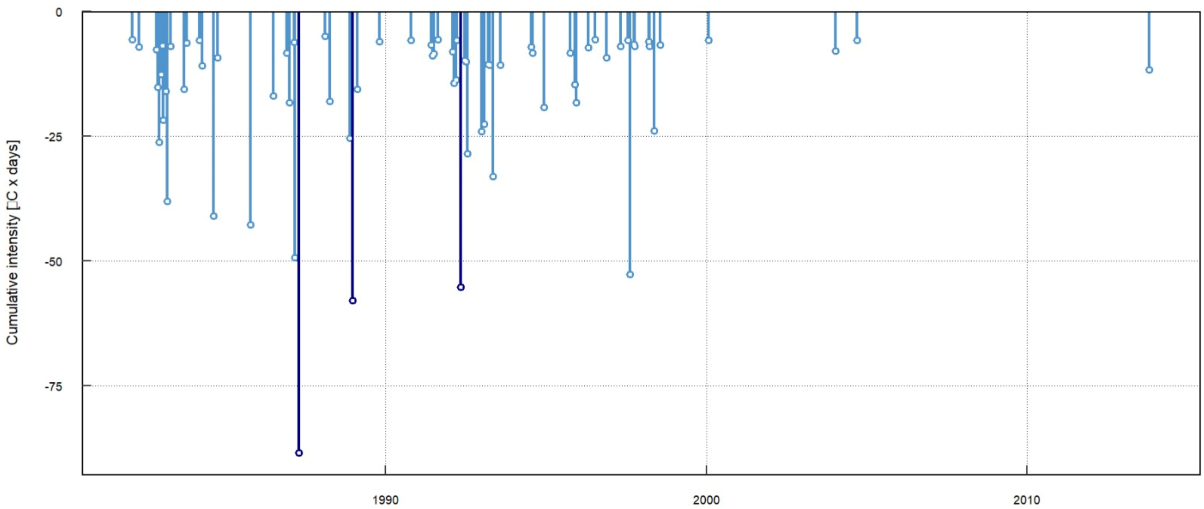
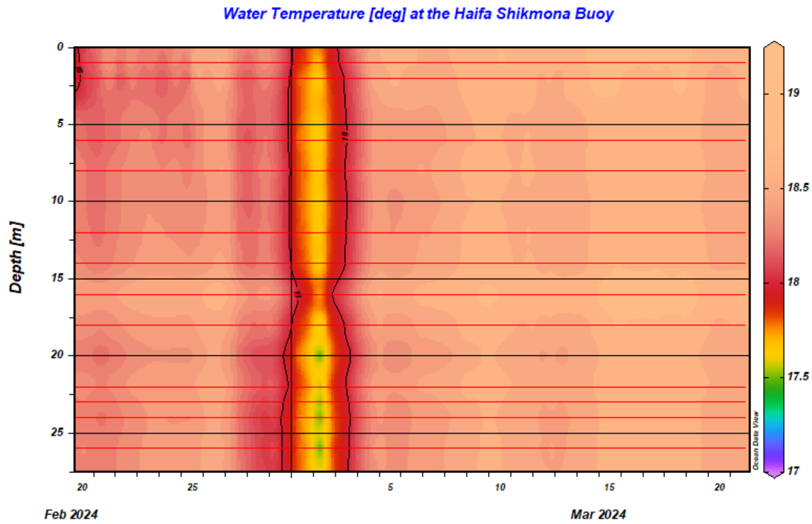


Figure 22: *Degree days of cold snap events (below the 90th lower climatic percentile) over the past four decades on the Israeli coast, based on SST data.*

Indeed, a new record of the soft coral *Dendronephthya* sp. was recently discovered at 45 m depth on the Israeli coast (Nativ et al. 2023); reef-building corals that are considered to have a low temperature threshold of around 18°C, could be next to establish. In the winter of 2023-2024 during the coldest months of the year, February-March temperatures down to 27 meters dropped below that threshold only in a single day, as indicated from IOLR's new thermistor chain located on the reef 2 kms offshore Haifa at 27 m depth (Fig. 23). The years 2023-2024 are characterized by a very strong El Niño event (Lian et al. 2023, Cheng et al. 2024, Jiang et al. 2024), and thus this exceptionally warm winter may be an outlier, but it does fit the general warming trend (Fig. 22).

Figure 23: *In-situ temperatures measured at 12 depths with a thermistor chain on a buoy 2kms off the coast of Haifa and IOLR Data showing late February and most of March 2024, the coldest months of the year. Red lines indicate the depth of the loggers. This data is displayed online at:* [*https://isramar.ocean.org.il/isramar2009/station/shikmonaTC.aspx*](https://isramar.ocean.org.il/isramar2009/station/shikmonaTC.aspx) .



3.1 Social-ecological considerations and stakeholder engagement

The Israeli Mediterranean coast is rapidly going through a phase or even regime shift from a warm temperate ecoregion with natives of Atlantic evolutionary origin into a more sub-tropical or tropical ecoregion with more and more mostly Indo-pacific representatives, driven by the local extinction of native species and the rapid establishment of tropical invaders (Fig. 24 top). The novel ecosystems that are created form new species interactions (Fig. 24 bottom), and possibly introduce many biological traits that are novel in the region, which together are expected to be ultimately result in shifts in ecosystem functions and services. Such major shifts driven by climate change represent increasing challenges to marine conservation efforts and will require highly adaptive strategies and even new definitions for what is considered conservation success as biodiversity considerably shifts so rapidly (Rilov et al. 2020a).

Climate change, and bioinvasions, must be considered in MSFD programs of measure and adaptive marine spatial planning, but so far, very few European countries have done that (Rilov et al. 2020a). There are many questions to consider with regard to sensible conservation strategies in hotspots of climate change and bioinvasions such as the Israeli coast. Among the most important ones is how to treat the invaders in the system. As global efforts have demonstrated, most successful invaders cannot be effectively eradicated, and as in MPAs they are inherently protected as well, we must investigate and understand how these species function in the system to know how to possibly deal with and manage them.

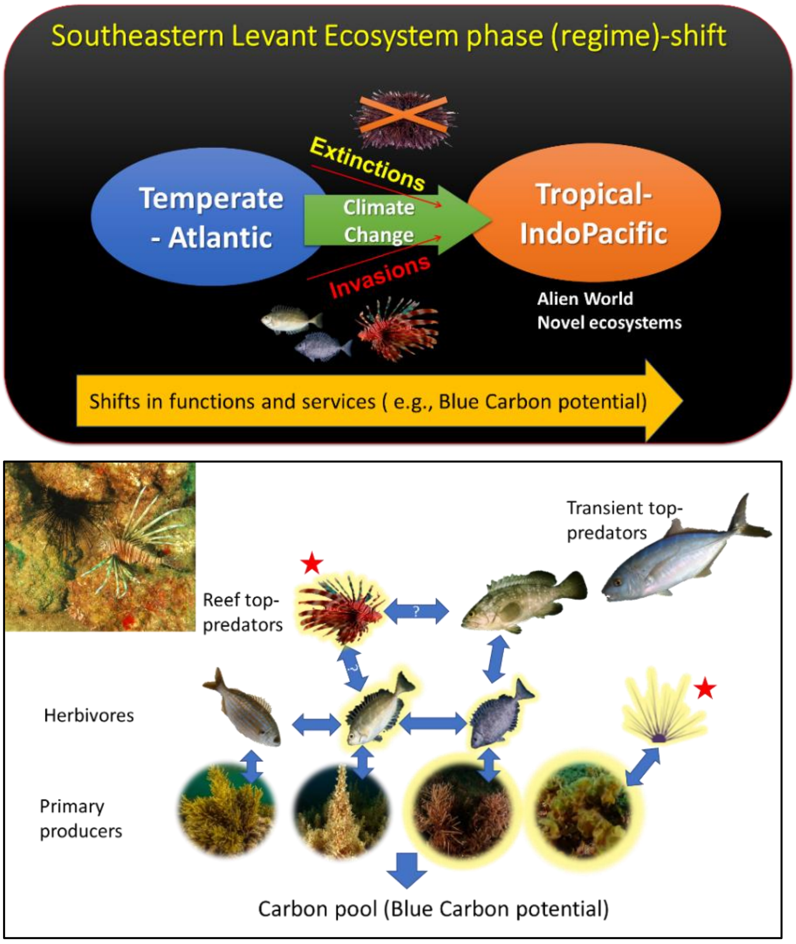


Figure 24: *Illustrations of shifts in ecoregion characterises in the Levantine basin resulting in probably shifts in services (top), and new interactions that form in shallow reef communities due to the arrival of tropical alien species at different trophic levels (bottom). NIS are indicated with yellow hallow and, red stars represent new arrivals that became abundant on the Israeli coast during the course of the FutureMARES project – indicating haw dynamic this ecosystem is). In the inset the alien urchin and alien lionfish can be seen side by side, just like in the Red Sea.*

As the Levantine basin will continue to lose many thermally sensitive species due to warming (with most evidence so far coming from mollusca and urchins in the region), perhaps invaders with similar traits can replace them functionally and thus should be considered as beneficial to the system – sort of an NBS. The populations of others that are known to be very problematic, like the rabbitfish and lionfish and several pufferfish, should be controlled, at least in MPAs to remove their impact on macroalgae and fish prey. Targeted fishing on them for consumption can be considered too. This is already done at the small scale in the neighboring cautery, Cyprus, were one can find rabbitfish and lionfish on restaurant menus today. We have demonstrated here that tropical invasive seaweeds can be partial substitutes for the expected loss of thermally sensitive seaweeds under future warming, at least in terms of some metabolic functioning and the restoration of biodiversity in overgrazed turf areas where these invaders now form large meadows. Restorations of populations of native species impacted by warming and/or competing or consuming invaders should be viewed unfortunately as mostly inconceivable, and thus efforts should be placed in conserving food-webs and ecosystem functions instead (Rilov et al. 2020a).

Importantly, we should view the Israeli Mediterranean coastal region – "the" global hotspot of marine bioinvasions and one of the global hotspots of ocean warming - as the ***canary-in-the-coal-mine*** for the rest of the Mediterranean in the coming decades, with the expected intensification of warming and bioinvasions, and thus lessons learned from this region can prepare stakeholders and decisionmakers for the years to come in other regions.

The take-home messages resulting from the work within these storylines are quite novel. The need for creative and adaptive thinking with regard to the challenges of marine conservation in climate change and bioinvasion hotspots where the native community is rapidly replaced by tropical species is clear. In order to communicate these messages and discuss them with stakeholders, we organized two events in the COP27 Climate Summit in Sharm el-Sheikh in November 2022, one in the Israeli Pavilion and one in the Mediterranean Pavilion (Fig. 25). Further, in documents related to MPA planning in Israel, developed by the Israel Society for Nature Conservation and the INPA, Prof. Rilov contributed text that the importance of the incorporation of climate change considerations in their planning and justifications.

Figure 25: *Prof. Gil Rilov moderating a discussion on the challenges of marine conservation at the age of climate change in the Mediterranean Pavilion during the COP27 summit.*

Finally, we organized a coupled FutureMARES-ACTNOW sponsored event on July 4th, 2024, where we brought together marine scientists studying climate change and its impacts in the region and stakeholders and policymakers to discuss the challenges of marine conservation at the age of climate change and with high exposure to invasive species. The stakeholders and decision makers included the chief scientist, Prof. Noga Kornfeld-Shor and the executive responsible for climate resilience, Mr. Rani Amir, of the Ministry of the Environment as well as the Red Sea and the Mediterranean Sea marine ecologists of the Nature and Park Authority, Alon Rothschild, who manages biodiversity policy at the Society for the Protection of Nature in Israel. Ilan Nisim, the executive responsible for nature protection in the Ministry of Energy also attended the event. At the end of the meeting, there was a panel discussion of the stakeholders led by Prof. Rilov. This event was picked up by the media https://www.timesofisrael.com/at-first-marine-climate-confab-scientists-paint-worrying-picture-with-few-solutions/ .

Figure 26: The climate change and conservation challenges event at IOLR. *Prof. Gil Rilov moderating a a panel discussion on the challenges of marine conservation at the age of climate change. The Ministry of Environmental protection gives an opening talk (bottom, middle)*

Figure 27: FutureMARES student explains about her FutureMARES experiments in IOLR's mesocosm facility on the impact of temperature on the invasive sea urchin, Diadema setosum and the impacts of the invader on the reef ecosystem.

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