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Nested biogeochemical interactions in seagrass ecosystems

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Abstract

Seagrass meadows are globally distributed coastal ecosystems that engineer complex habitats for a plethora of lifeforms colonizing the plant surfaces and the sediment. These lifeforms are not limited to multicellular life: microbial communities are found associated to both the plant and the faunal community at several degrees of metabolic integration, creating with their hosts more complex forms of individuality called holobionts or metaorganisms. The currency of these "trades" is often the exchange of nutrients or an enhanced access to basal resources that otherwise would limit ecosystem diversity and functioning. Thus, seagrass meadows are not only habitat-forming (autogenic) ecosystem engineers, but also allogenic ecosystem engineers that modify the biophysical environment. Of primary importance among seagrass-associated animals are macroinvertebrates, which link benthic primary production to higher-level consumers. However, little research to date has been conducted to study plant-invertebrate-microbe associations in seagrass meadows and their role in biogeochemical cycling of key nutrients, such as carbon (C) and nitrogen (N).

Therefore, in chapter 1 of my thesis I summarize the state of the art on invertebrate-microbe associations as biogeochemical engineers in seagrass sediments. Further, to explore our current collective knowledge on potentially relevant but neglected plant-invertebrate-microbe associations, I build a bipartite network of associations consisting in marine invertebrate genera from seagrass ecosystems and microbe taxa from the NCBI database. This analysis provides a snapshot of the diversity of invertebrate-microbe associations from Mediterranean seagrass ecosystems, showing how microbial taxa can be key links connecting diverse invertebrate bioturbation habits and clear clustering depending on the benthic position of epifauna vs infauna.

Deciphering microbial communities associated with seagrasses is paramount not only for the study of their biodiversity, but also for any prospective management and conservation plan facing climate change. As I uncover in chapter 2, the phyllosphere microbial community structure of *P. oceanica* naturally growing within CO_2 vents of Ischia (Italy) is largely unaffected by the reduced pH mimicking future ocean acidification (OA). Conversely, key nitrogen transformation rates accelerated, with particularly high rates of N_2 fixation but also increases in potential nitrification, denitrification and anammox, highlighting that plasticity of the *P. oceanica* microbiome may be key to the resilience of these ecosystems to OA.

I build upon these multipartite interactions under environmental stress in chapter 3. Using mesocosms, we tested the facultative mutualism between the chemosymbiotic lucinid clam *Loripes*

orbiculatus and the seagrass *Cymodocea nodosa* on sediments from a highly polluted area, and found that the interaction between clams and plants benefitted both organisms and promoted plant growth irrespective of the sediment typ. In particular, *C. nodosa* had higher leaf growth, leaf surface, and leaf biomass when associated with the clams, consolidating the notion that nested plant-invertebrate-microbe associations promote ecosystem functioning.

Chapter 4 delves into a different and less explored plant-invertebrate-microbe association, that between the cyanosponge *Chondrilla nucula* and the seagrass *P. oceanica*. Commonly growing on hard substrates, *C. nucula* in the area of Bacoli (Italy) is found as epibiont of *P. oceanica* surrounding the upper portion of the rhizome. I argue that this association can be described as a facultative mutualism by i) quantifying the benthic distribution of the sponge within the seagrass meadow, verifying mutual (spatial) dependence, and ii) by quantifying net fluxes of organic and inorganic nutrients in incubations with the sponge and the plant (alone or in association), which indicate that the plant and the sponge holobionts may benefit from each other's metabolism.

This thesis provides novel insights into the field of symbiosis research using a holistic approach spanning from ecology to biogeochemistry and microbiology, yielding results of potential interest for innovative seagrass conservation and restoration protocols.

Keywords: *Posidonia oceanica*, *Cymodocea nodosa*, *Loripes orbiculatus*, *Chondrilla nucula*, microbial community, facilitative interactions, biogeochemical cycling, environmental stress.