# Coral Reef Arks: Molecular mechanisms underlying the demise and recovery of coral reef ecosystems

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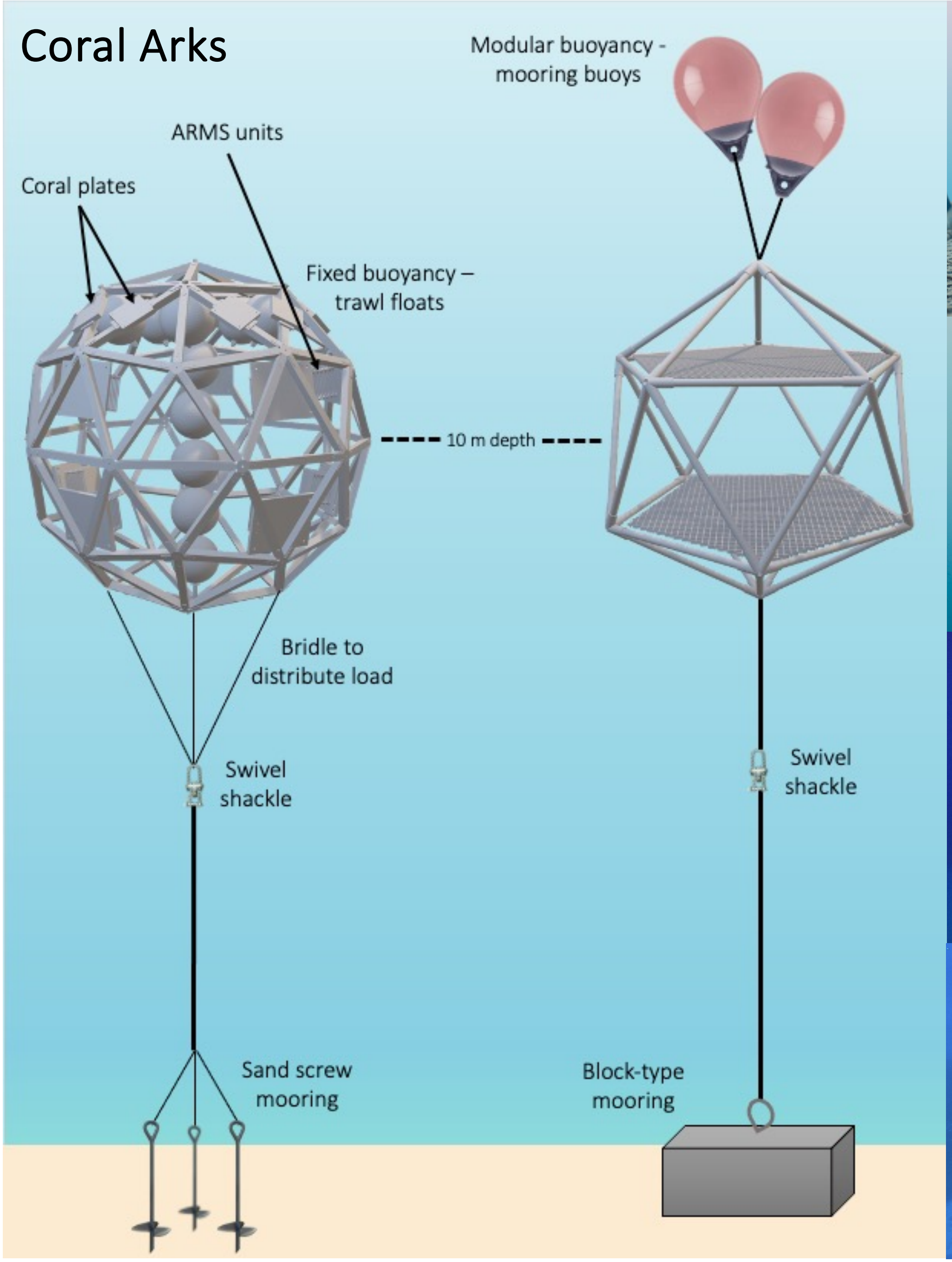
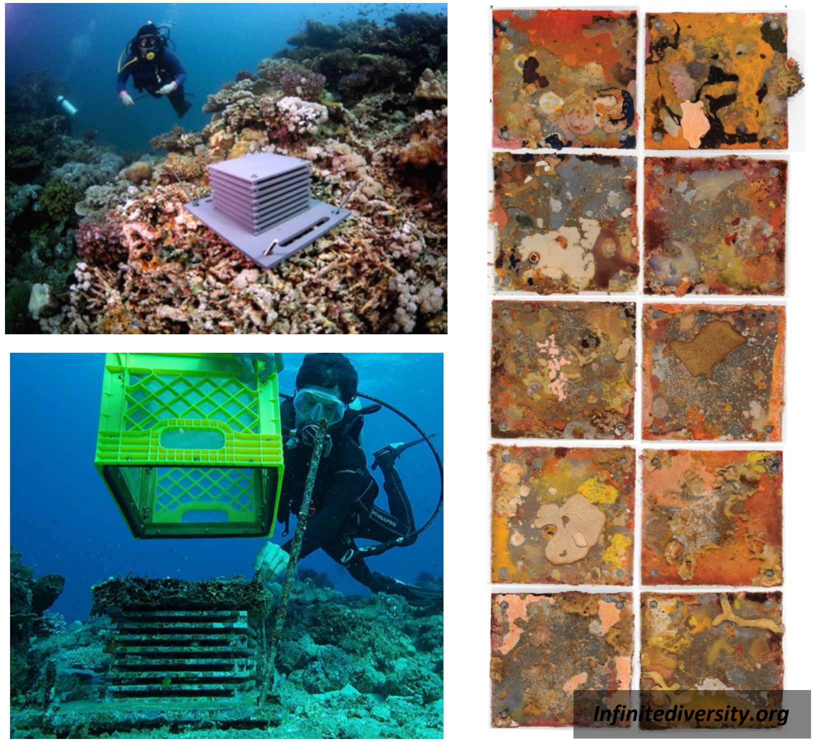
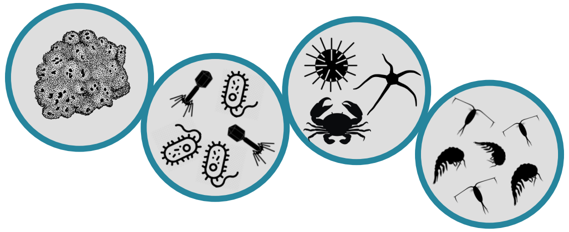
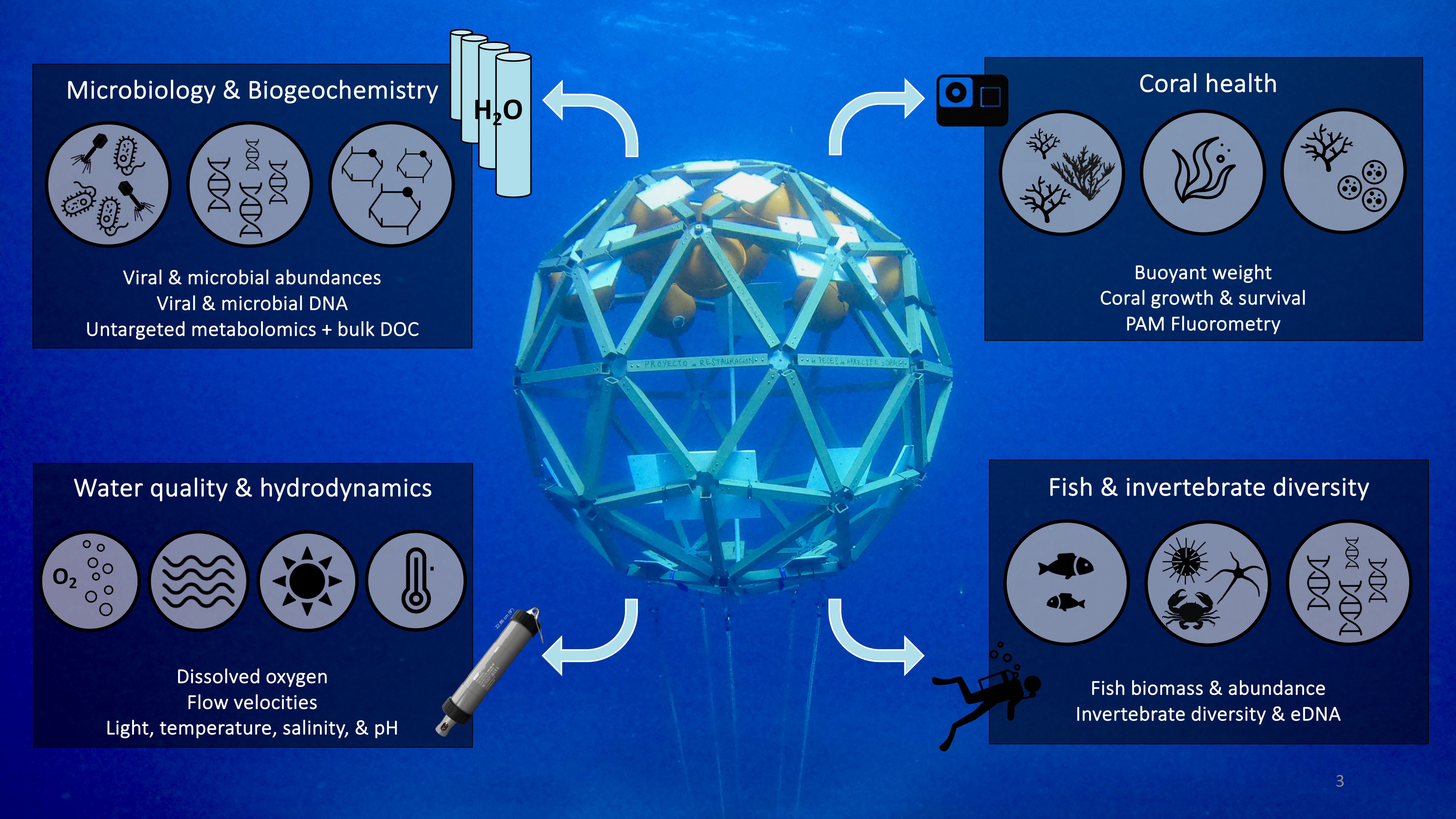


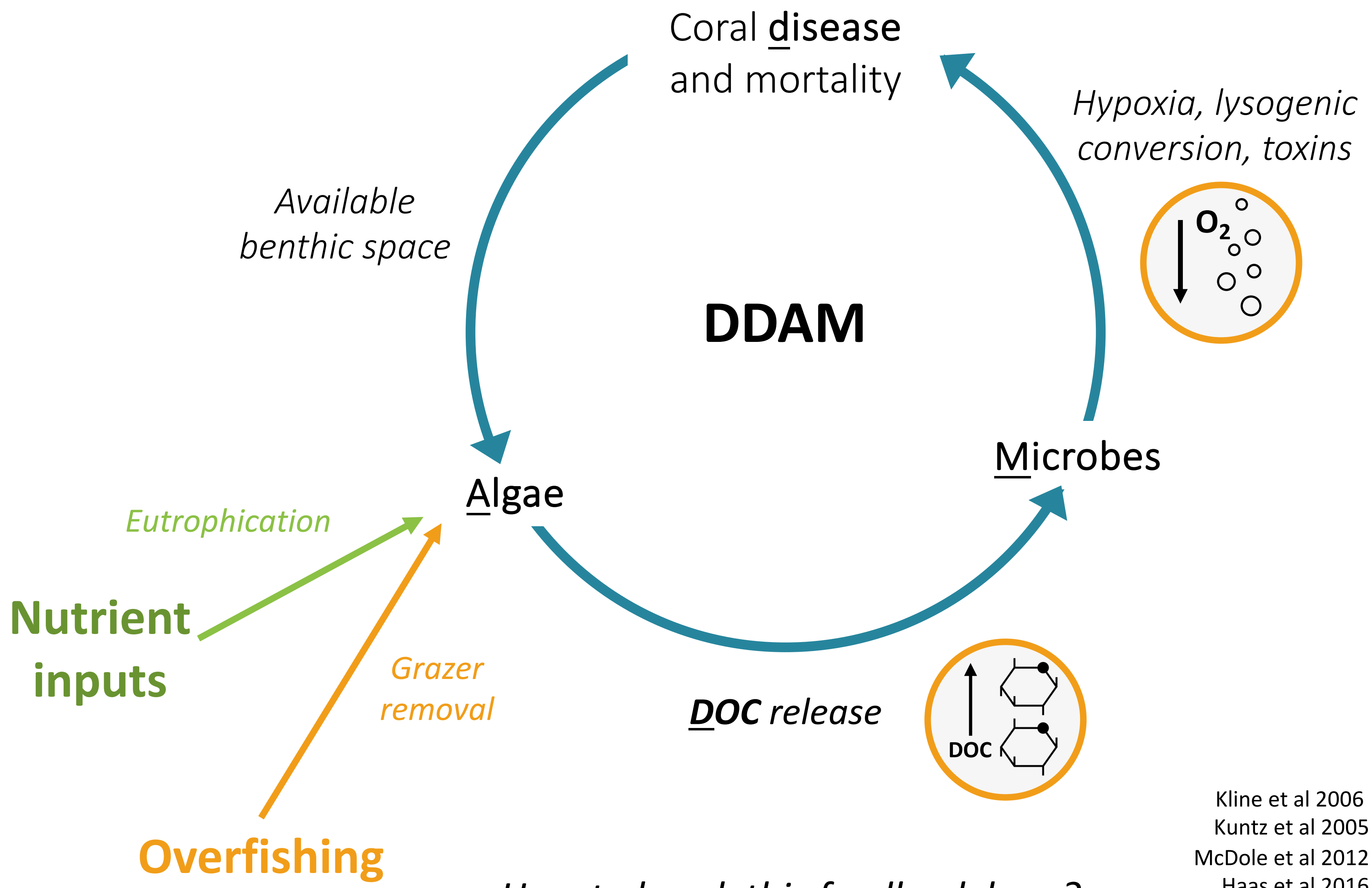

**Autonomous Reef Monitoring Structures (ARMS):** collect and move coral reef biodiversity.

- Nutrient recycling/remineralization
- Shelter for demersal zooplankton
- Detritivory/export of OM




Microbiology & Biogeochemistry
$H_2O$
Viral & microbial abundances
Viral & microbial DNA
Untargeted metabolomics + bulk DOC
Coral health
Buoyant weight
Coral growth & survival
PAM Fluorometry
Water quality & hydrodynamics
$O_2$
Dissolved oxygen
Flow velocities
Light, temperature, salinity, & pH
Fish & invertebrate diversity
Fish biomass & abundance
Invertebrate diversity & eDNA
PROYECTO RESTAURACION

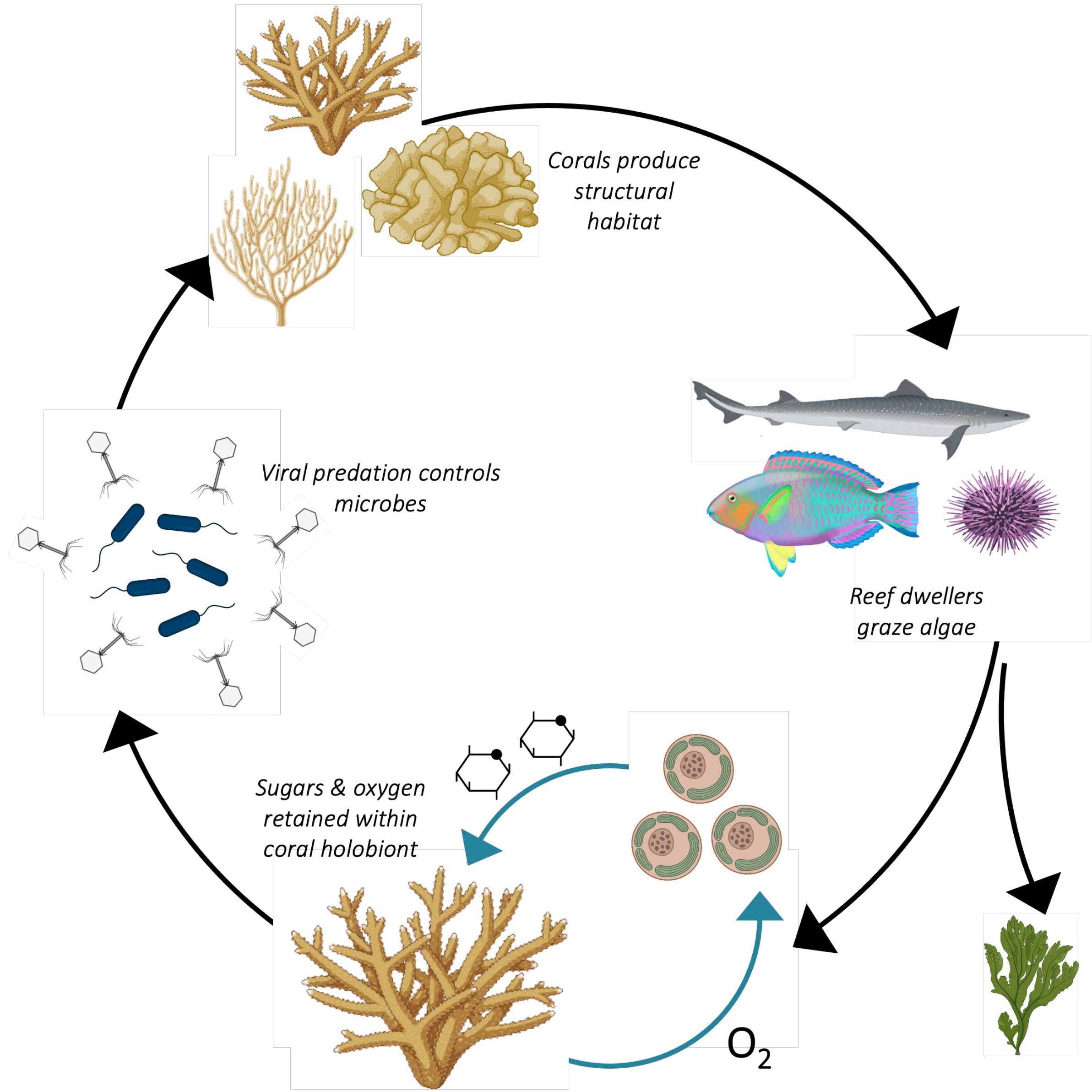
# Microbialization poses a major challenge to reef-building initiatives

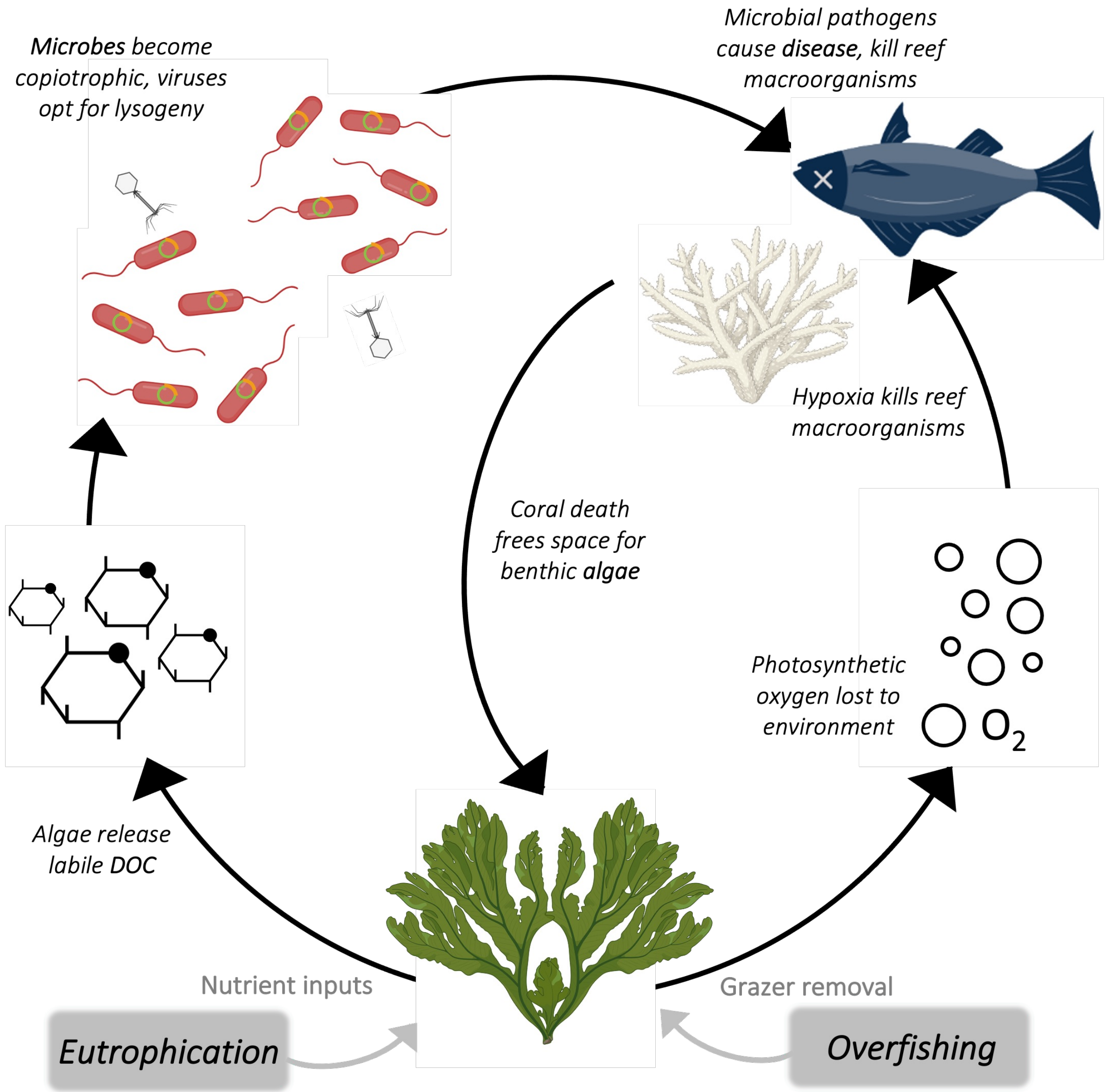

*How to break this feedback loop?*

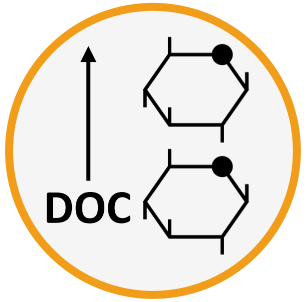
Kline et al 2006
Kuntz et al 2005
McDole et al 2012
Haas et al 2016

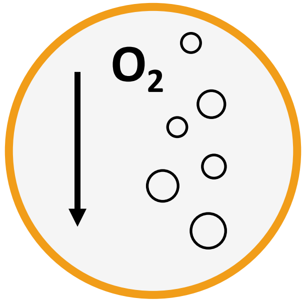
## Healthy coral reef




## *DDAM* – Impacted coral reef





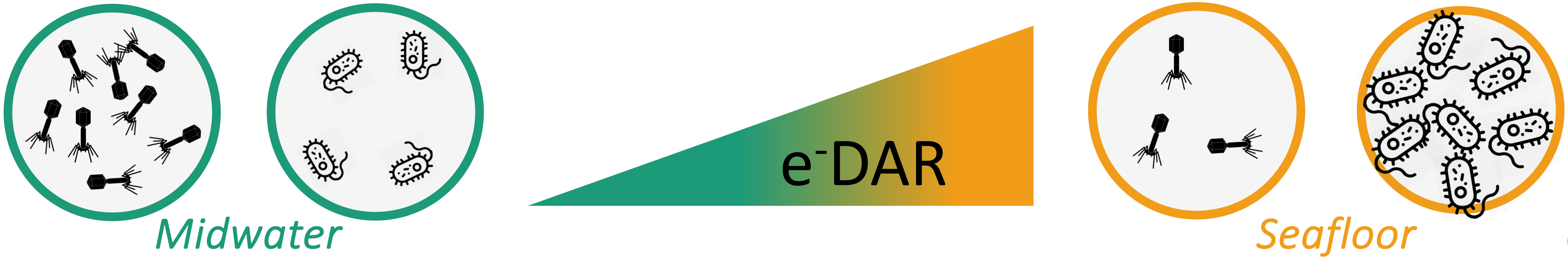




## *Working Hypotheses:*

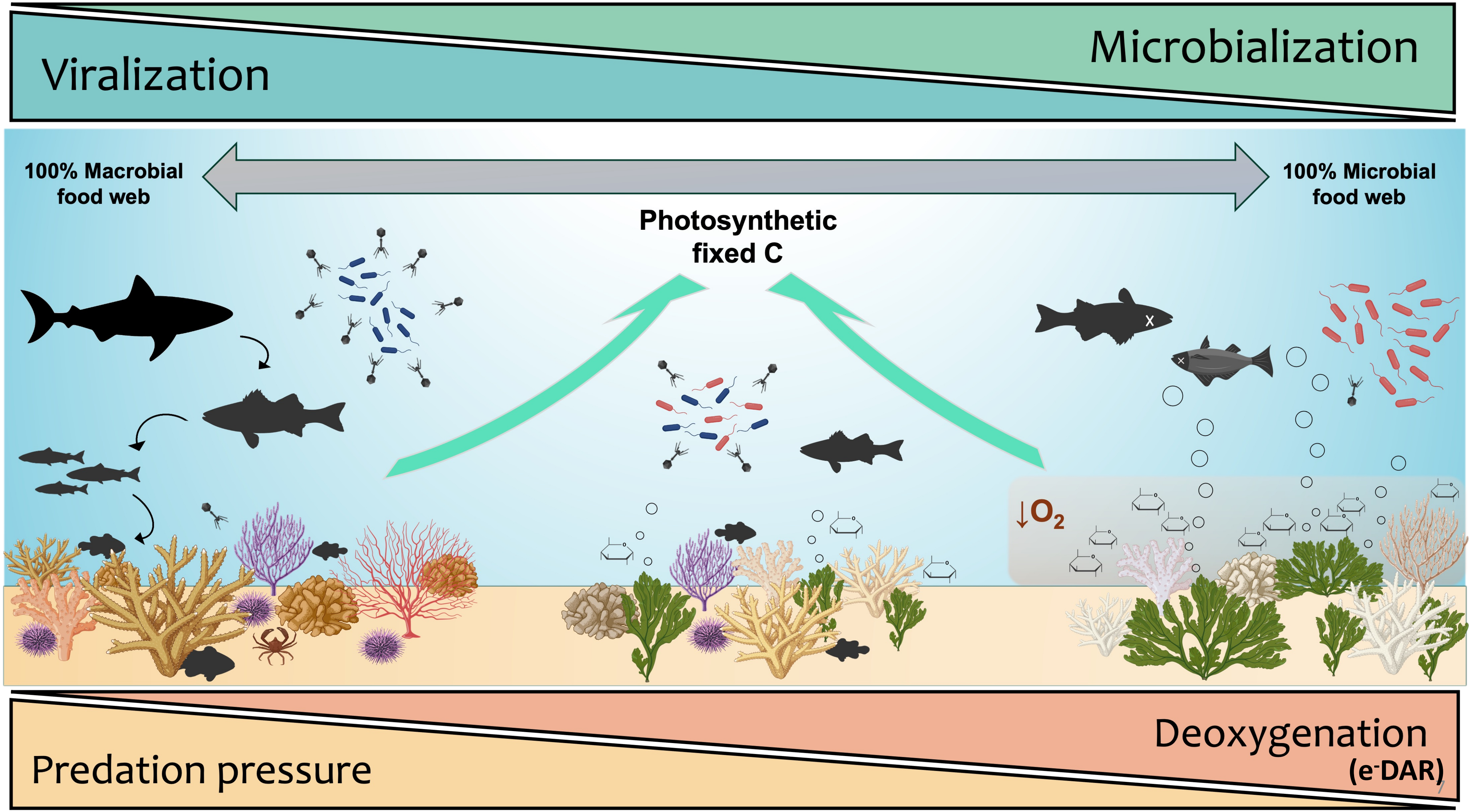
*$H_1$: The ratio of electron donors (DOC) to electron acceptors ($O_2$) in the ecosystem - $e^-$DAR - determines reef community structure.*

*$H_2$: When **$e^-$DAR** is high, microbes dominate. Low **$e^-$DAR** favors reef communities dominated by macrobes (coral + fish).*

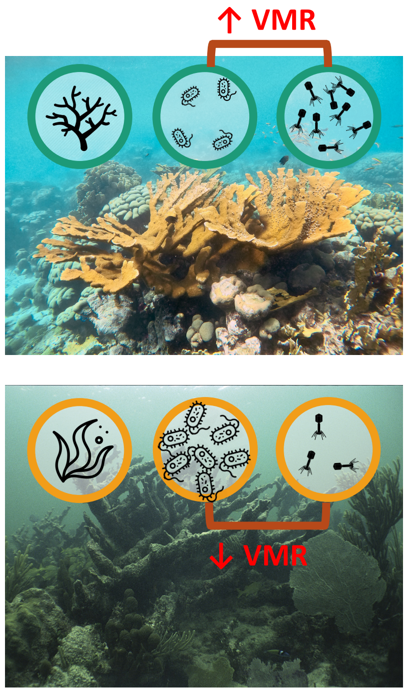
***$H_3$: Moving a reef up into the midwater will reduce $e^-$DAR, and therefore microbialization.***



Microbialization vs viralization – competing processes

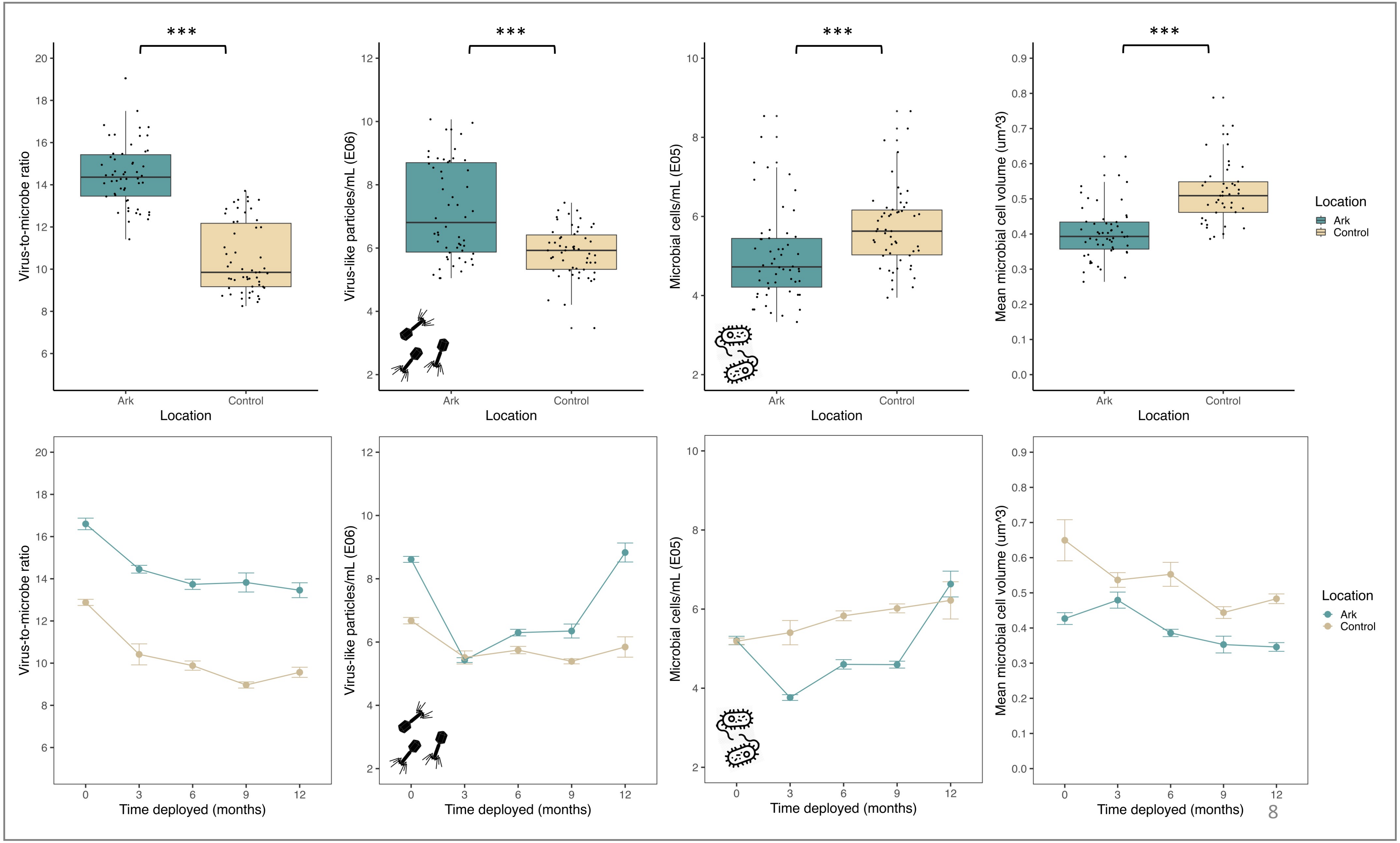


# Arks look more *viralized* than control sites and are stable through time

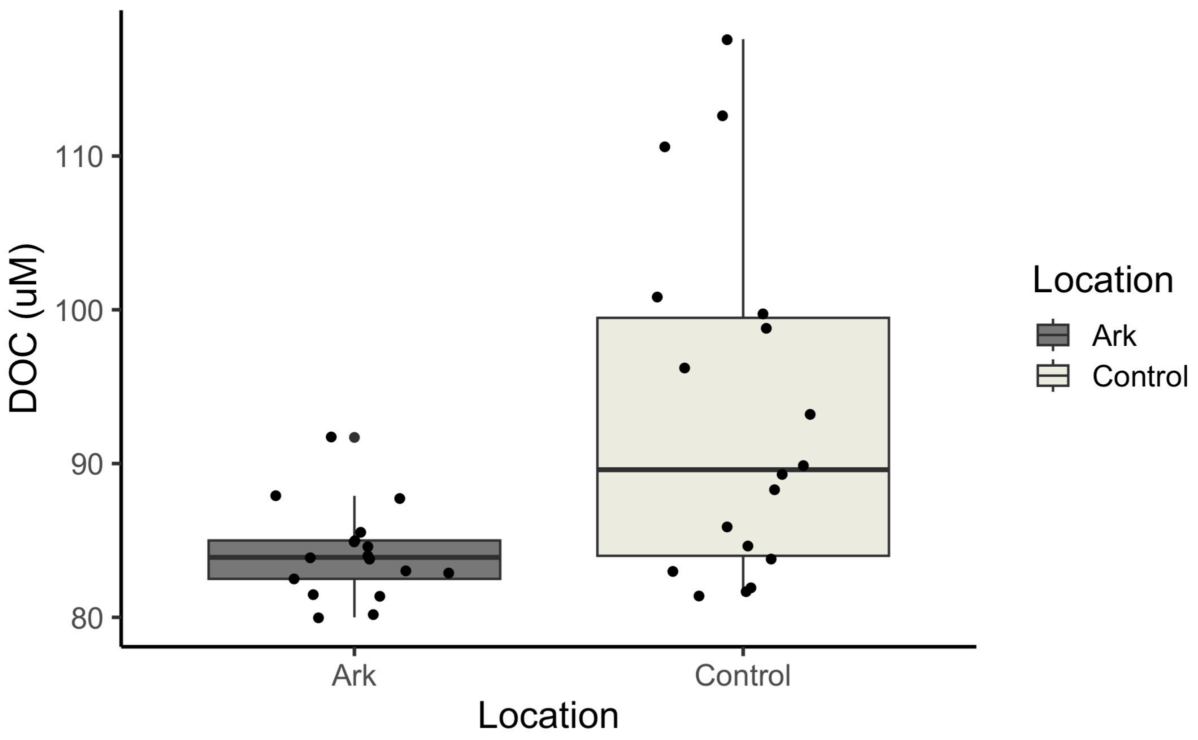



- High VMR = viral predatory control on microbes

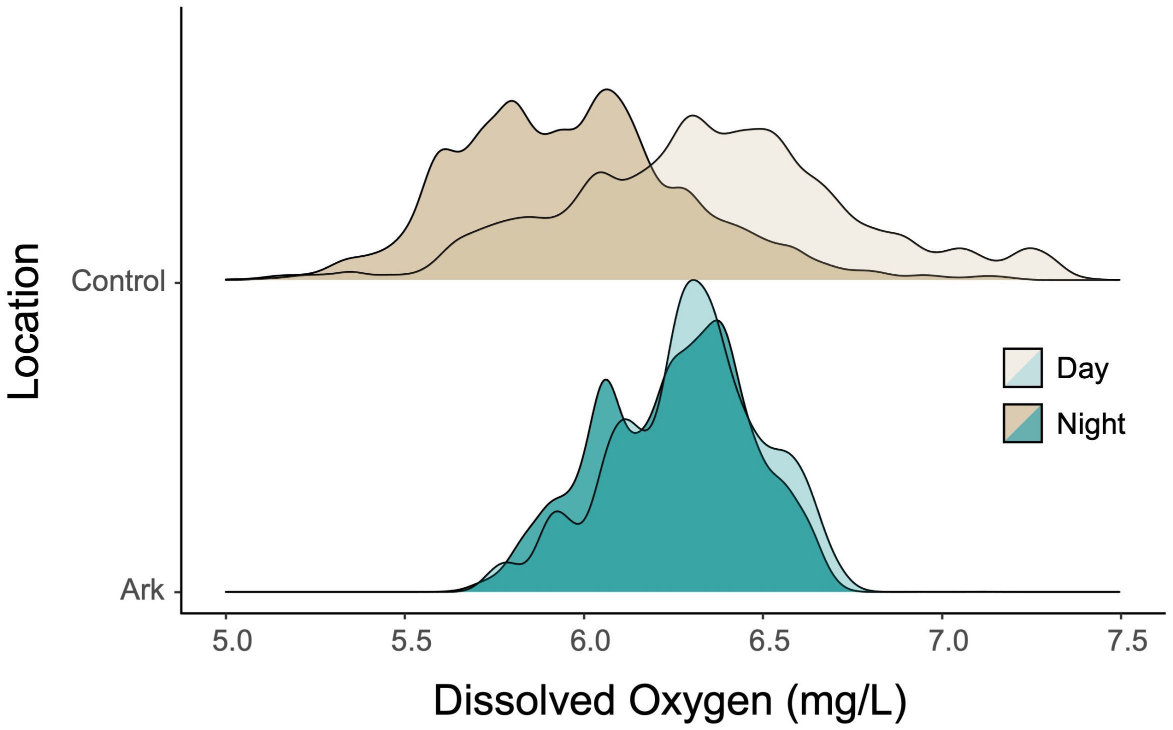
- Smaller cells = less energy shunted into microbes, more available for macrobes.



# $e^-$DAR is reduced at the Arks relative to the control sites

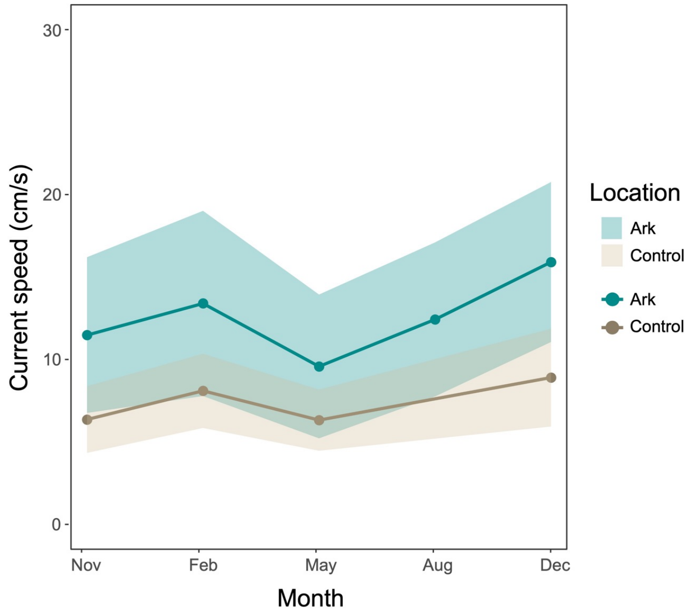



Arks sites have <u>**lower**</u> DOC concentrations

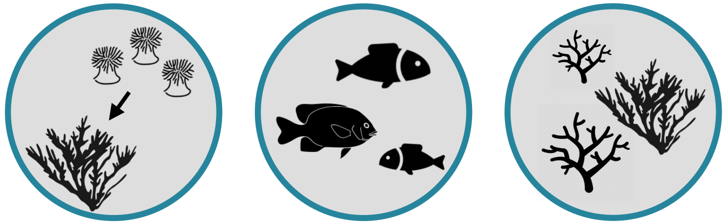


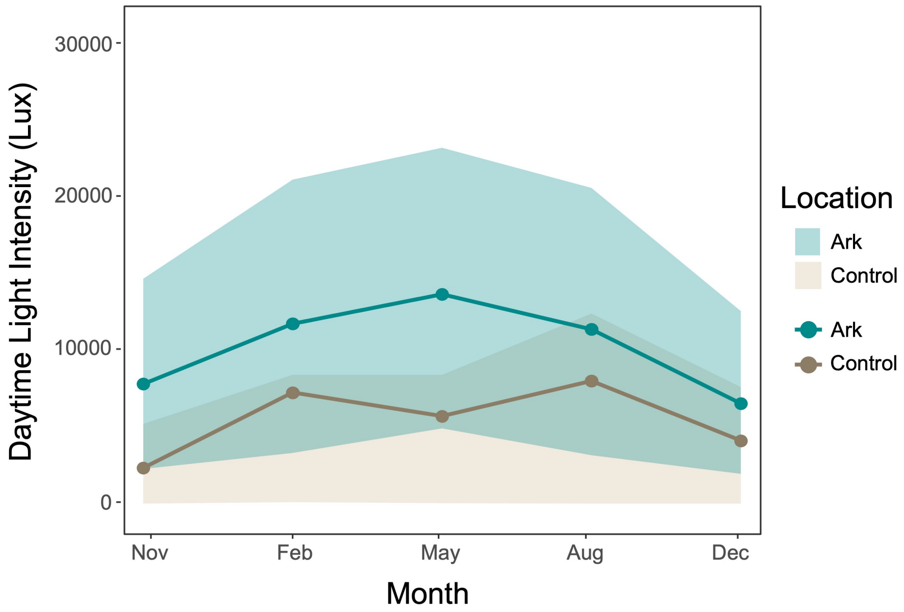

Arks sites have <u>**higher**</u> average dissolved oxygen concentrations, especially at night

# Midwater Arks display consistently better water quality conditions relative to seafloor sites

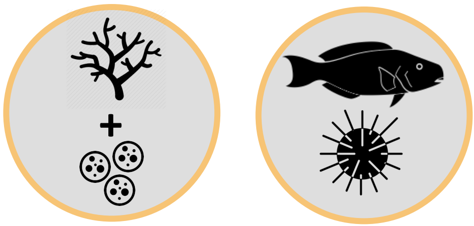


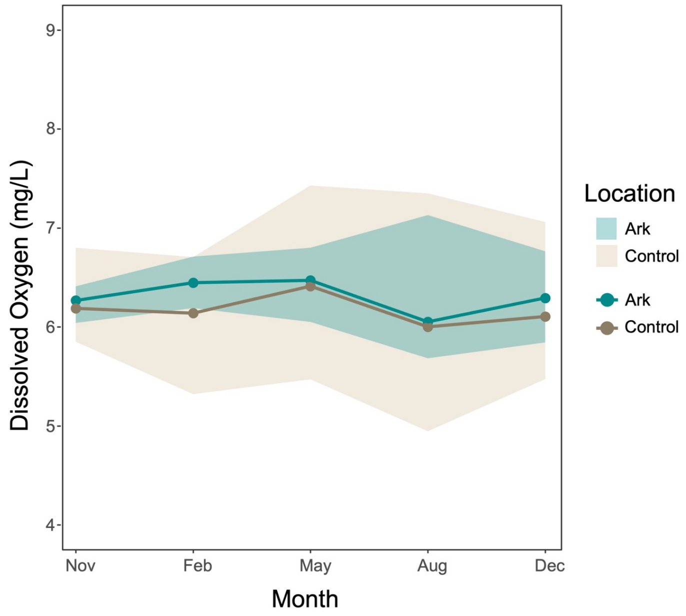

Arks sites have **higher** average flow speeds



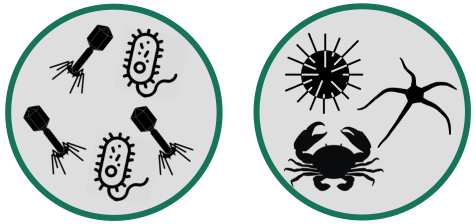



Arks sites have **higher** average light availability

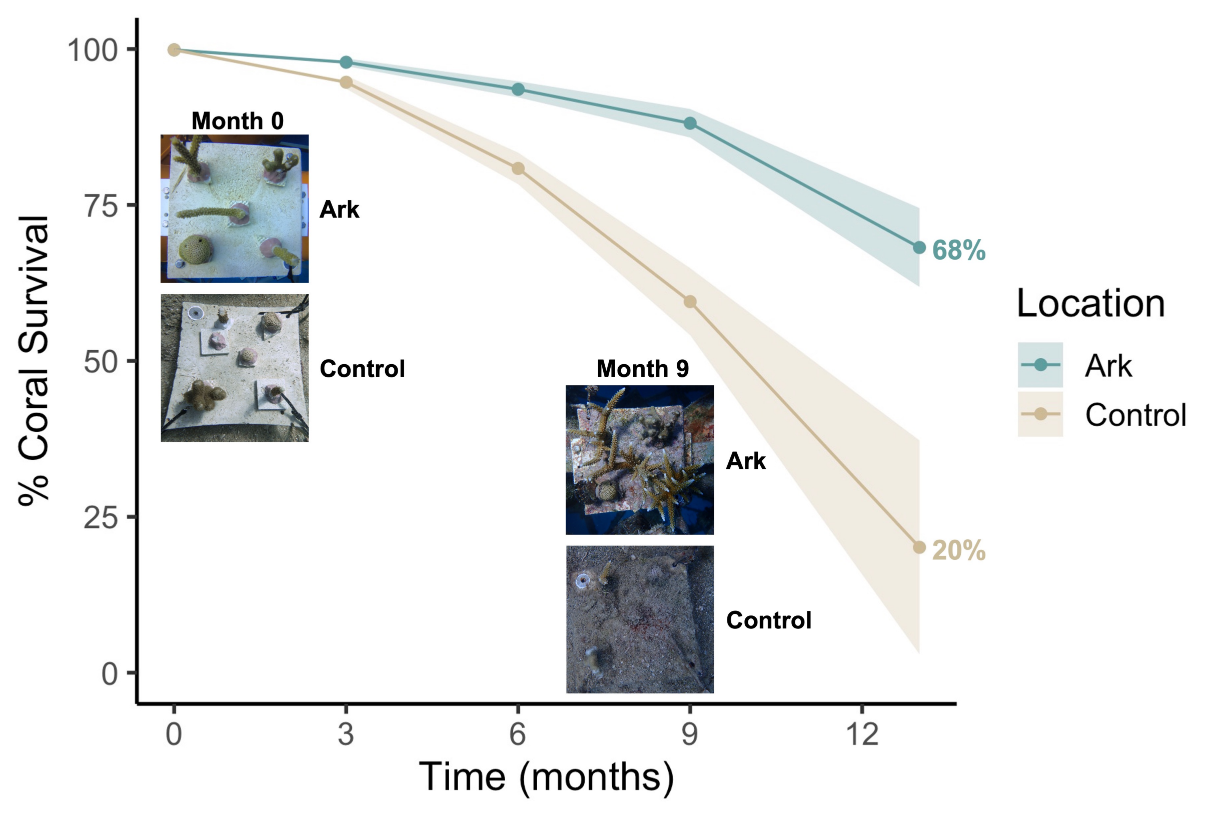




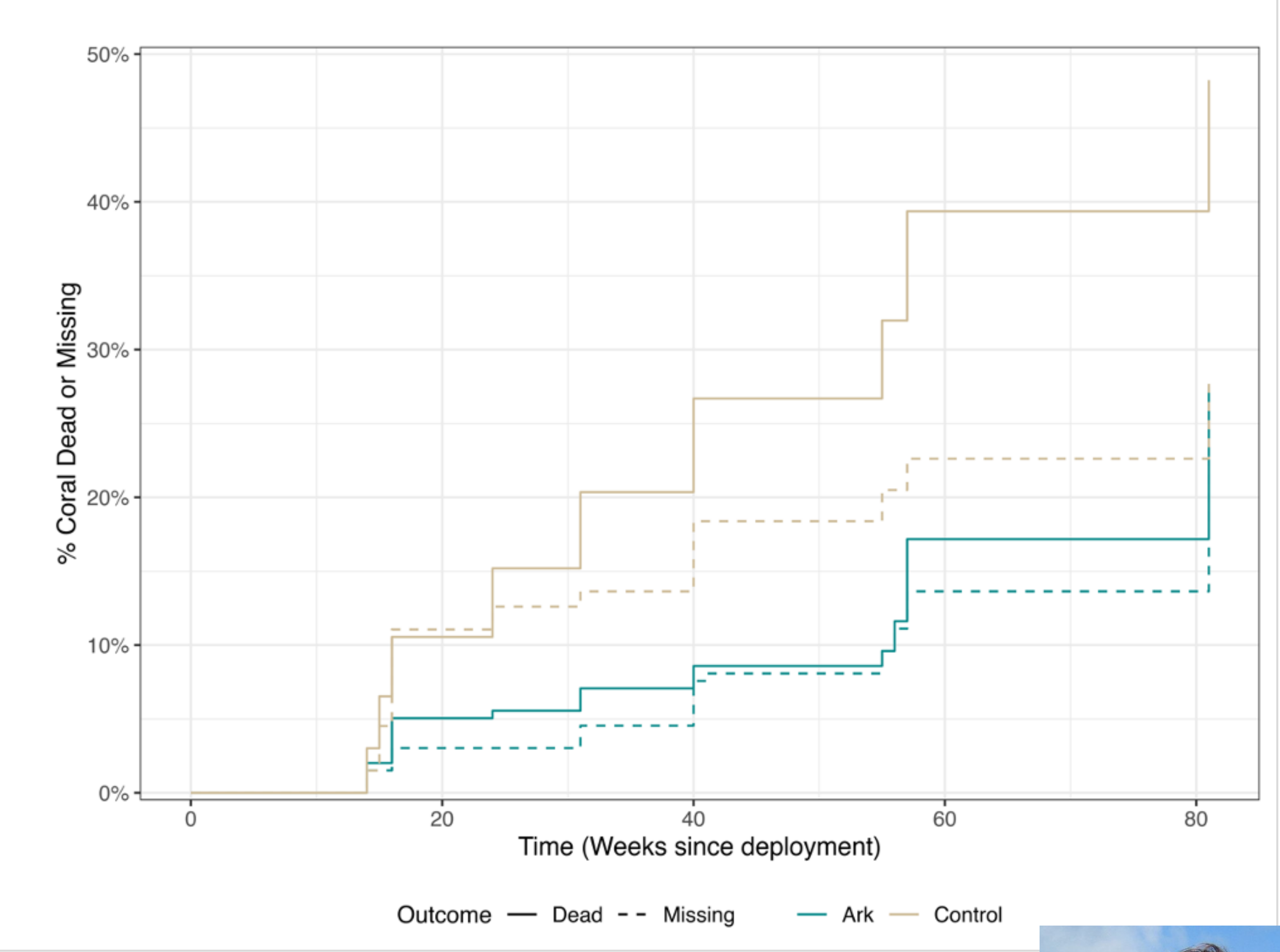

Arks sites have **higher** average dissolved oxygen

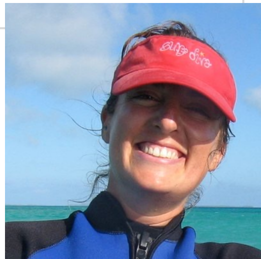


All species of corals (8 spp) transferred to Arks and Control sites survived better on Arks after one year

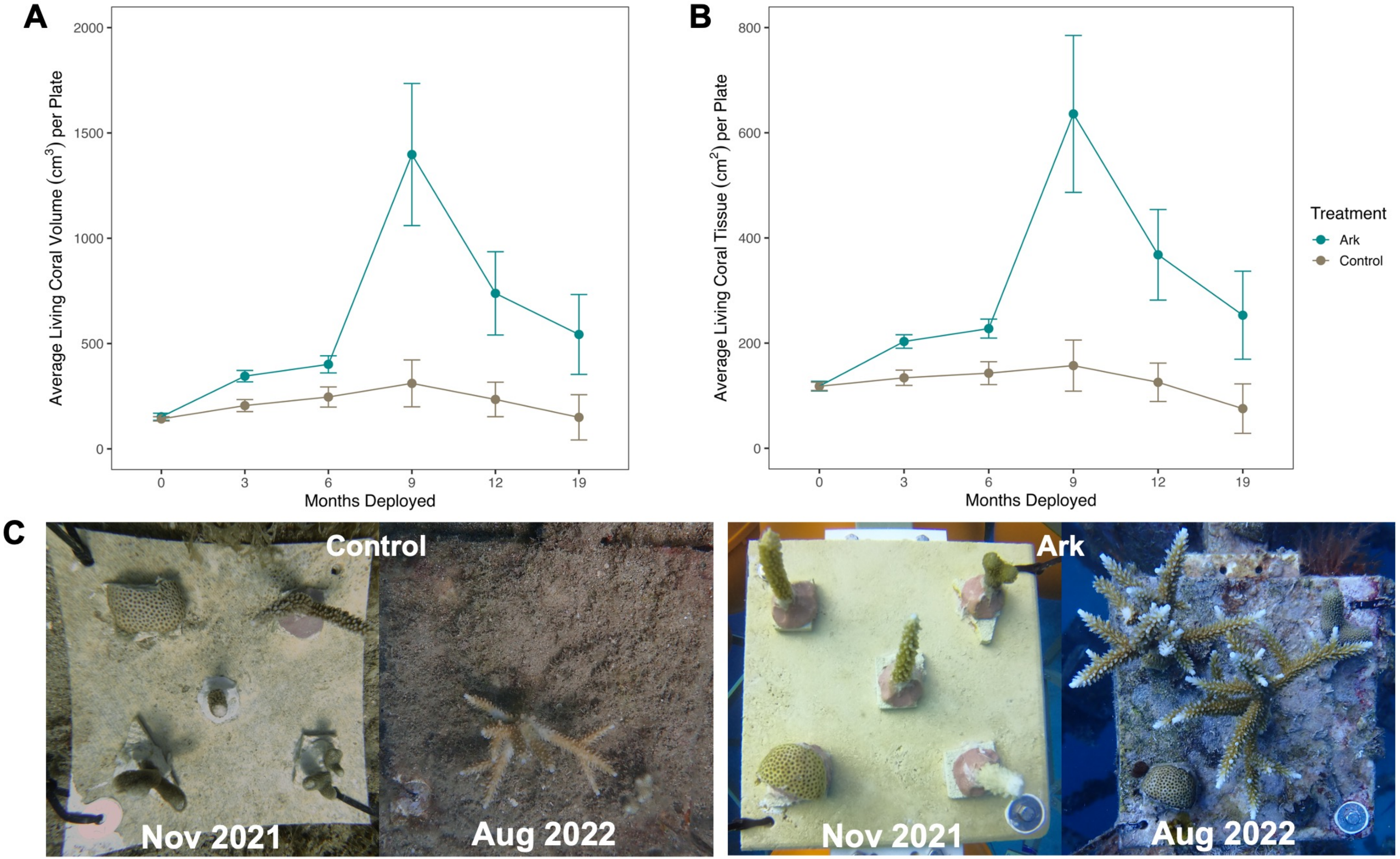



Competing risks analysis shows corals are less likely to die or go missing on Arks than at Control sites →

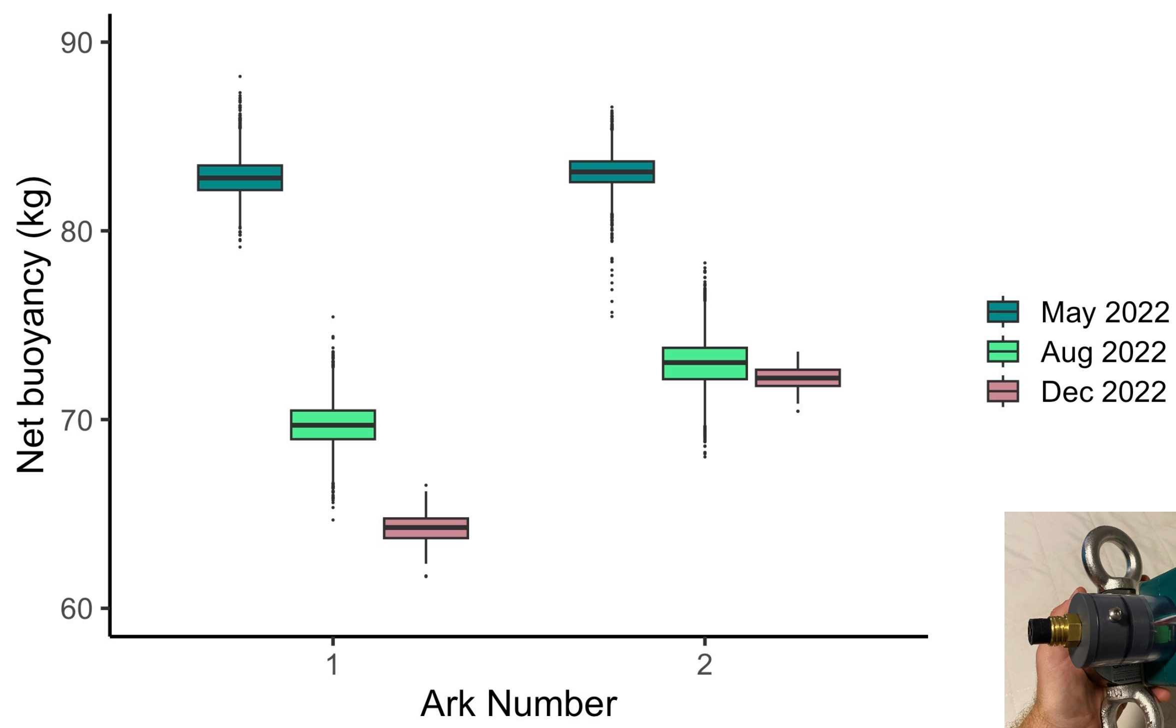


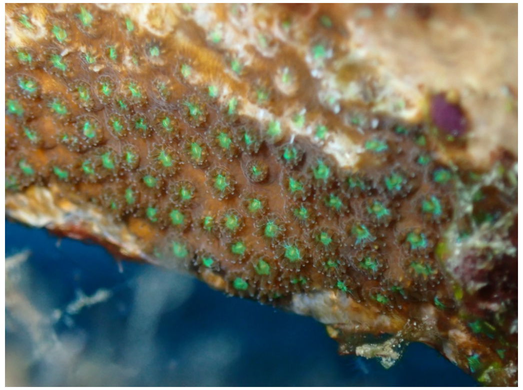
# Corals grew better on the Arks relative to control sites



# Community level calcification on Arks makes them get heavier

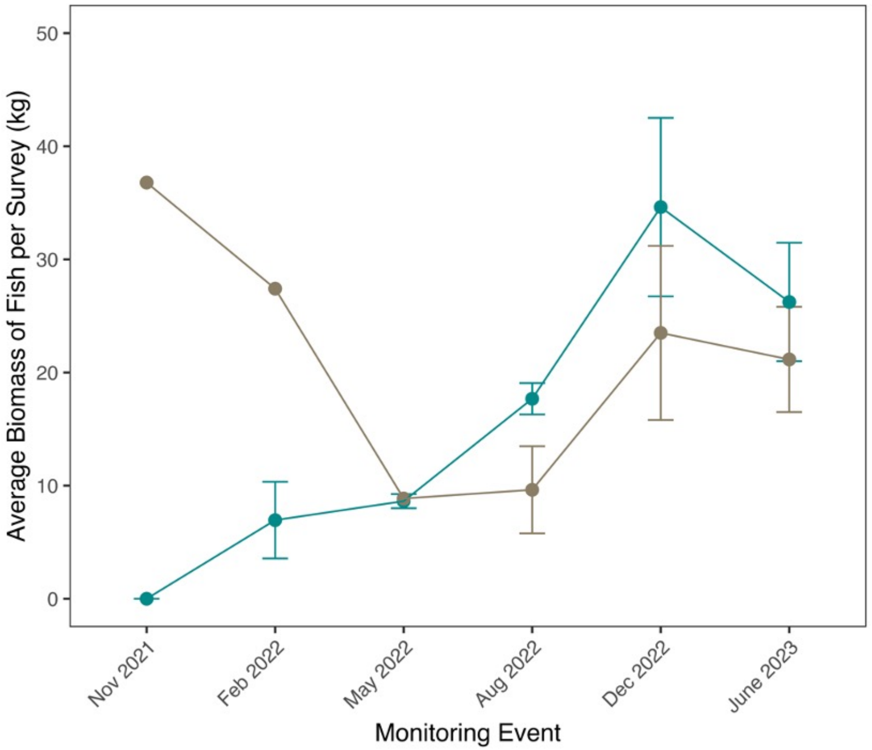


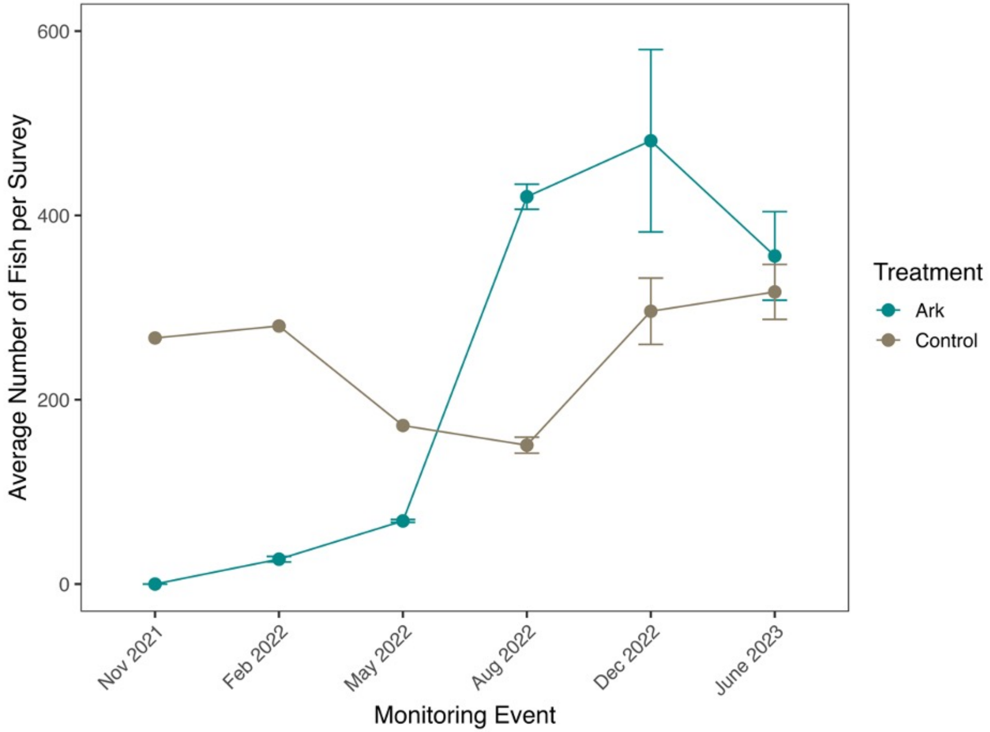

Estimated accretion rate of the community is 690 g/m$^2$/year, which is comparable to rates in the literature (CAUs).



*Active recruitment of larvae to Arks*

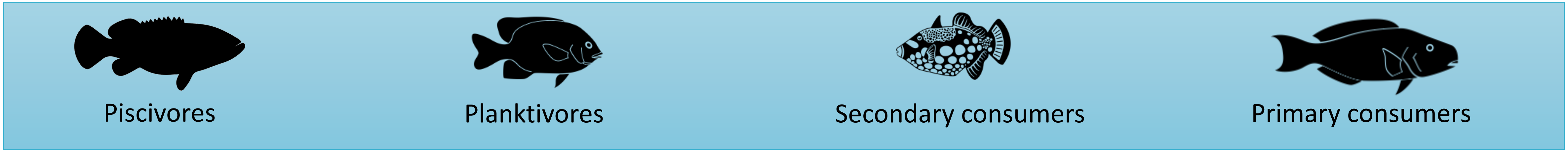

Arks recruit LOTS of fish, possibly by establishing zooplankton communities

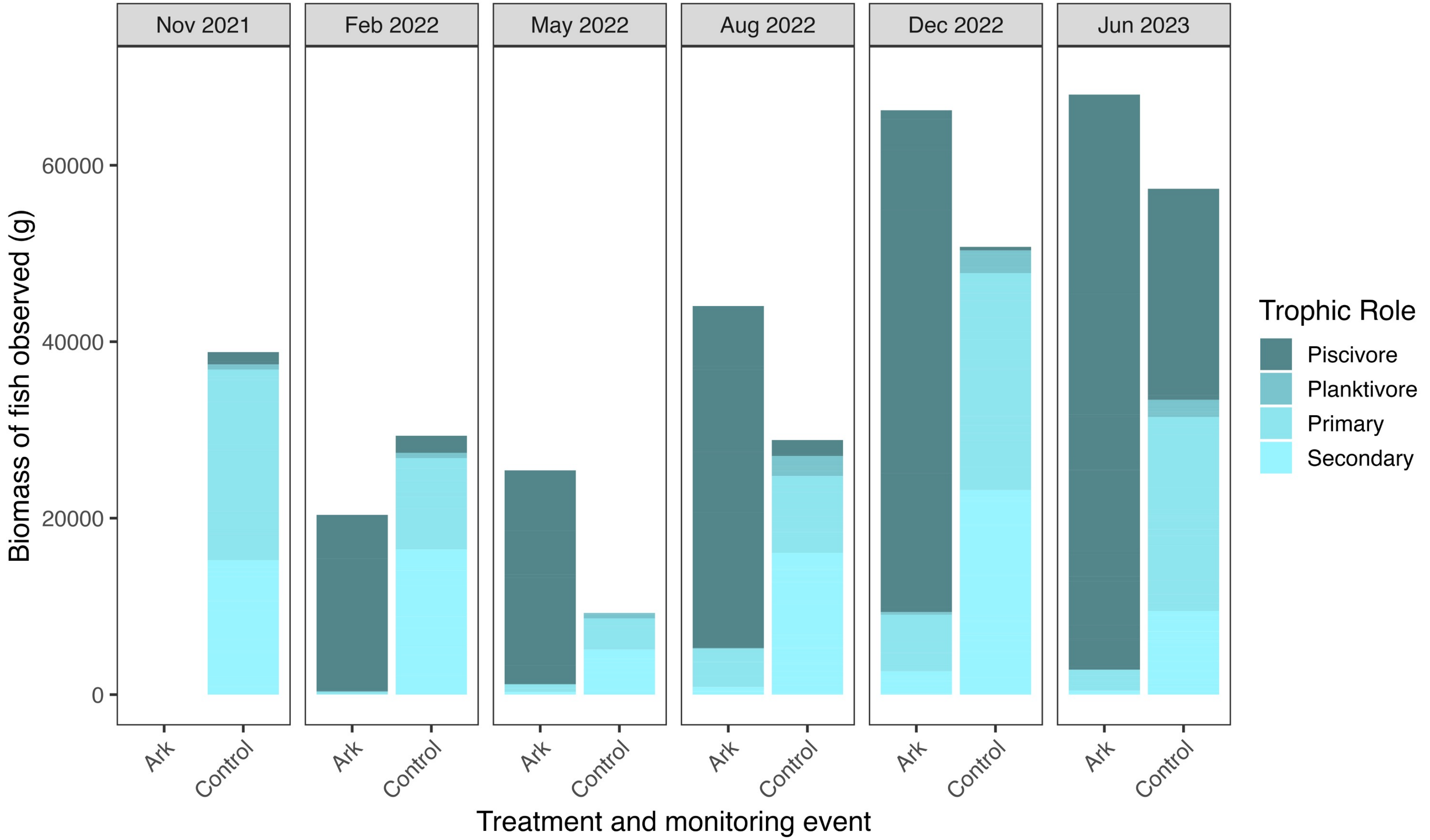


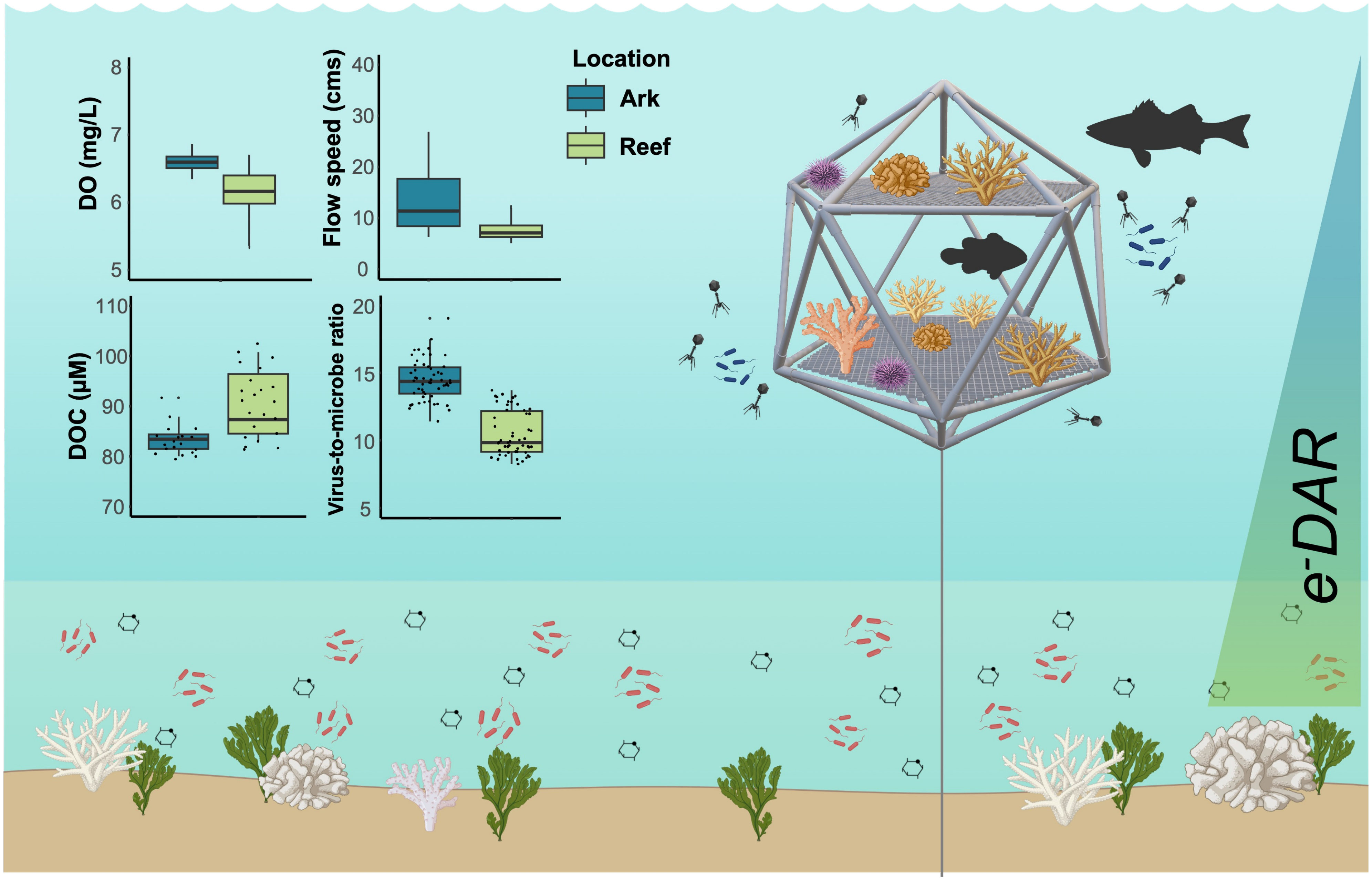

Fish biomass really starts to take off after the 6-month mark, when the ARMS were added.

# Arks have "top down" fish communities dominated by piscivores → viralization



# Ok, so reducing e⁻DAR fixes microbialization, but creates a new problem?

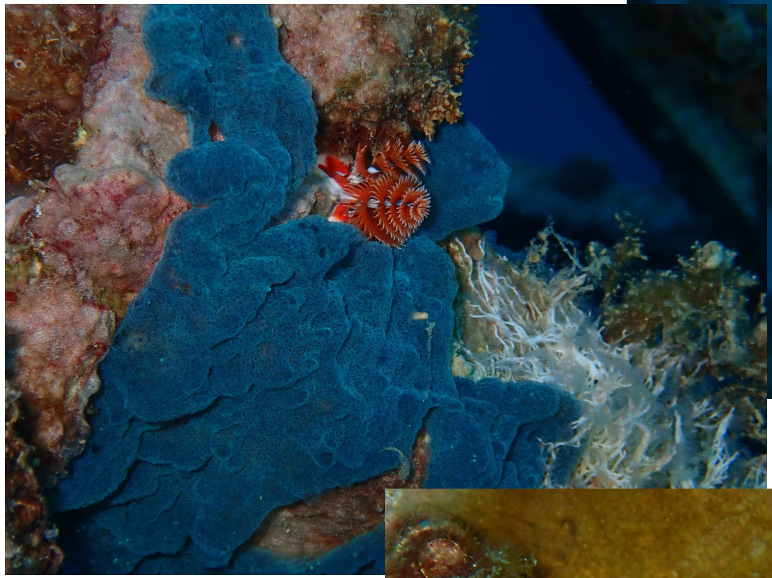



Corals benefitted from improved conditions, but all the other suspension feeders benefitted too, beginning the…

**benthic war**

DUH DUH DUHHHHHH

What are we missing here? How can we help corals win the **benthic war**?



# Process-based metrics to measure on coral reefs

| Reef processes (flux-based measures) | | Method |
|---|---|---|
| Sedimentation/ bioerosion | Shape of sand grains (derived from herbivory or erosion) | Microscopy |
| | Sedimentation rates | Sediment traps |
| Calcification/ accretion | $CaCO_3$ accretion | Calcification accretion units (CAUs) |
| | Community accretion via buoyant weight | Strain gauge or analytical balance |
| Herbivory | Acoustics/sound for fish and invertebrate grazing | Hydrophone |
| | Grazing rates/ grazing assays | Imaging, quantify bite marks |
| | | Standardized biting assay - squid pops |
| Primary production | NCC:NCP | BEAMS/SeaPhOx |
| | Algae isotopes | Delta15N/C:N in algae |
| | Oxygen production/loss | Ebullition rate, $O_2$ production (light) and $O_2$ consumption (dark) for ps vs rspn |
| Nutrient uptake/release | Urea as proxy for $NH_4$ --> $NO_3$ | Spectrophotometry |
| | Remineralization incubation experiments | Closed Benthic Incubation Tents (cBITs), ARMS |
| Energy dynamics | Microbial heat | Microcalorimetry |
| | Electron donor to acceptor ratio (eDAR) | ?? |
| | In situ bacterial growth rates | ?? |
| | Biological oxygen demand | BOD chambers |

| Physical properties | | Method |
|---|---|---|
| Hydrodynamics | Current speed/ direction | ADCP/ADV, tilt current meters |
| | Turbulent kinetic energy | ADV |
| | Fluorescein | Fluorescein sensor/video analysis |
| Structural complexity | Mass rugosity | Chain and tape method, structure from motion 3D models |
| | 3D Photogrammetry | Imaging + reconstruction |
| | Fractal dimension | Structure from motion 3D models |
| | Total surfaces available per unit volume | ??, 3D photogrammetry |
| Water quality | Depth vs distance from reef (ratio) | Depth gauge/CTD |
| | PAR/Light | PAR meter |
| | Temperature | Temp sensor/ multiprobe/CTD |
| | Dissolved $O_2$ | DO optode/ multiprobe |
| | pH | pH sensor/ multiprobe |
| | Salinity | Salinity sensor/ multiprobe/CTD |
| | Bulk DOC/TOC | High temp catalytic oxidation |
| | Labile fraction of DOC | ?? |
| | Nutrients (DIN:DIP ratio) | Flow injection analysis |

| Biological properties | | Method |
|---|---|---|
| Biomass | Calcifier biomass | Image analysis, sampling + weighing of standardized units, buoyant weight |
| | Total biomass of herbivores (fish and inverts) | Length-weight relationships |
| | Fish abundance/biomass | Stereo video analysis or stationary point counts |
| | Abundance/biomass of demersal plankton | Plankton traps, plankton camera, acoustic backscatter from ADCP |
| Fluorescence | Chl-a, GFP, OFP intensity | PAMERA - multispectral in situ camera |
| | GFP fluorescence as proxy for $O_2$ | |
| | Benthic community composition via pigment spectra | Hyperspectral camera |
| | Fv/Fm of corals/algae | PAM Fluorometry |
| Microbial ecology | Virus to Microbe ratio (viral and microbial abundances) | Epifluorescence microscopy |
| | Microbial biomass and mean cell volume | Epifluorescence microscopy/ flow cytometry |
| | Protist abundance | Epifluorescence microscopy |
| | Heterotrophic:Autotrophic bacteria ratio | Flow cytometry |
| | Lytic to temperate viral dynamics | Electron microscopy, induction analysis, metagenomics |
| Biodiversity | Species richness + species evenness | eDNA + metabarcoding |
| | % benthic cover | image analysis |
| | invertebrate diversity | direct counting, eDNA + metabarcoding |

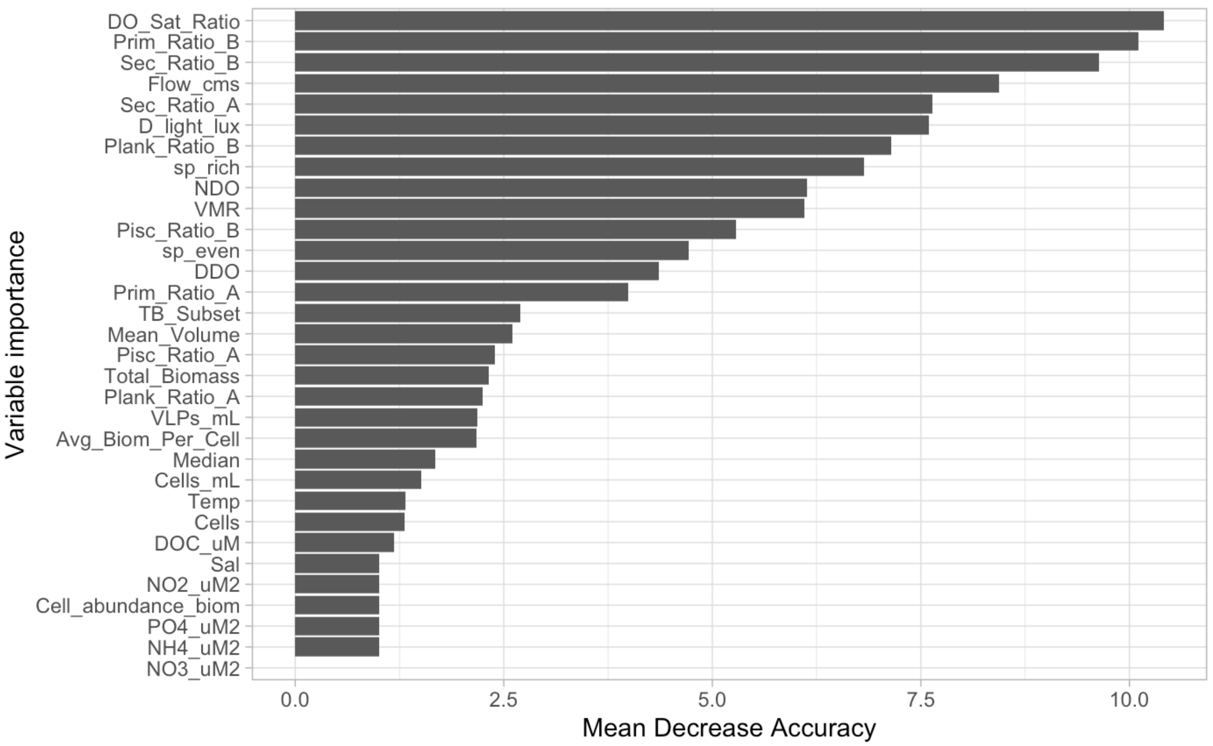
| -omics | |
|---|---|
| Metagenomics + Viromics | Virulence factors, immune and defense genes |
| | Carbon metabolism pathways (metabolic efficiency) |
| | Dominant microbial taxa (opportunistic pathogens, N fixers) |
| | Integrase/ excisionases (lysogeny) |
| | Phosphorus/nitrogen metabolism (remineralization) |
| | Dominant viral families (i.e., vibriophages, cyanophages), |
| Metabolomics | DGTS passive sampling for bleaching risk |
| | Lability of dissolved organic carbon compounds |
| | N and P content of exudates (macronutrient recycling processes) |
| | Energetic content of photosynthetic exudates |

| Confounding factors |
|---|
| Sampling time of day |
| Hysteresis |
| Sampling duration (short to long term) |
| Sampling frequency |

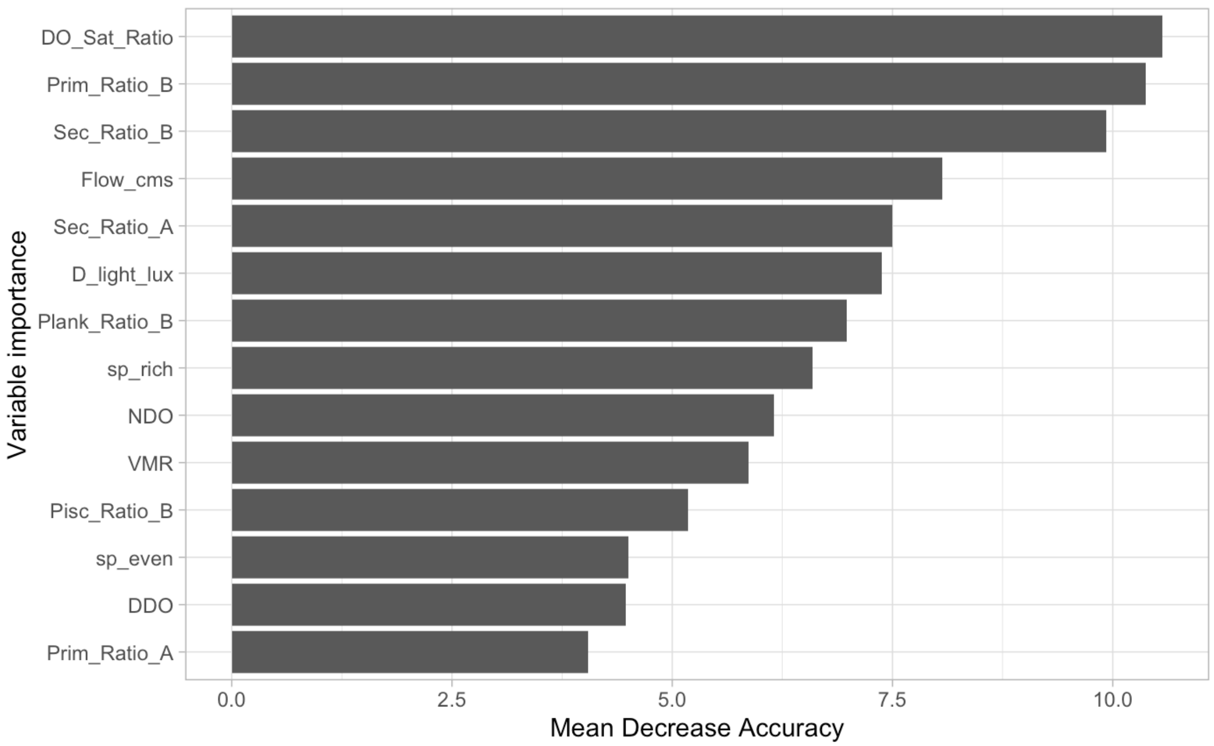
**Mentioned multiple times**

On a supervised random forest, the **best** predictors of whether a sample was collected from an Ark or seafloor control site were:

1. Dissolved oxygen (nighttime and daytime)
2. Fish biomass – all trophic guilds
3. Flow speeds
4. Light intensity
5. VMR

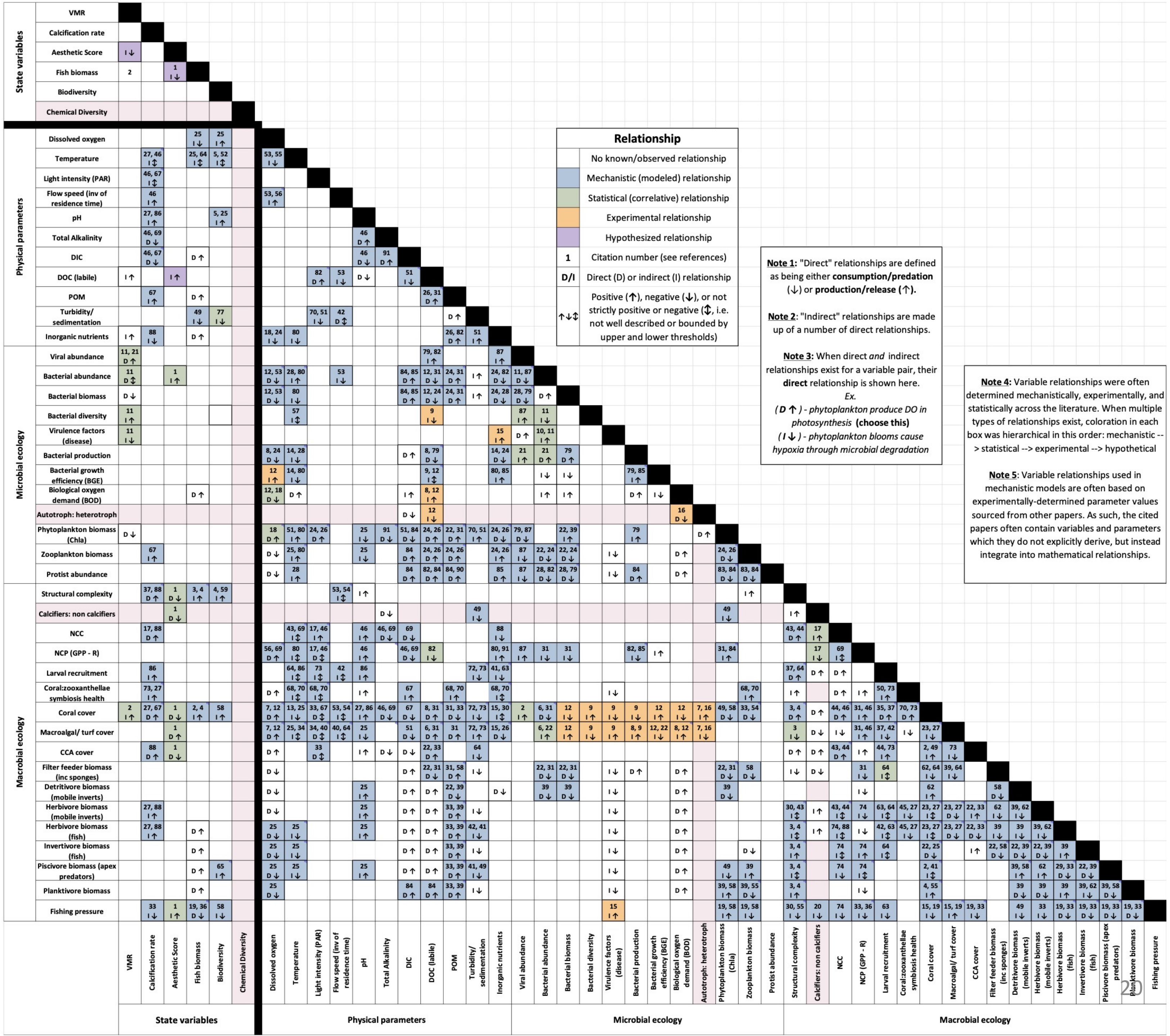



All variables




Most significant variables

# Integrating coral reef models to understand variable relationships



# Acknowledgments

SERDP
DOD · EPA · DOE

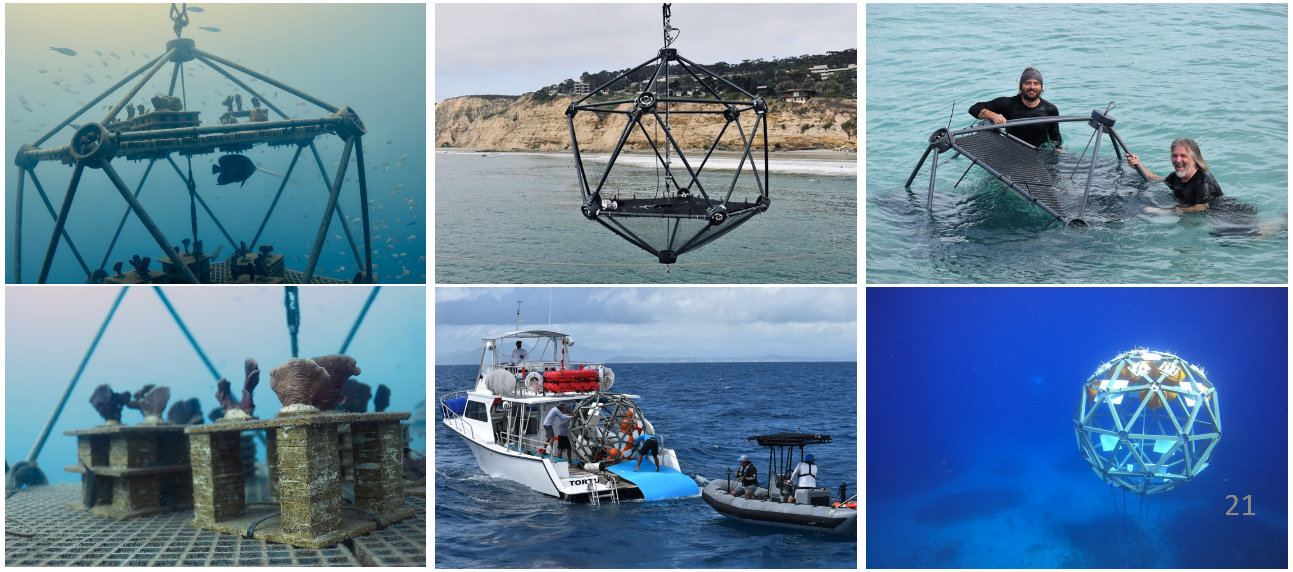
ESTCP

GORDON AND BETTY
MOORE
FOUNDATION

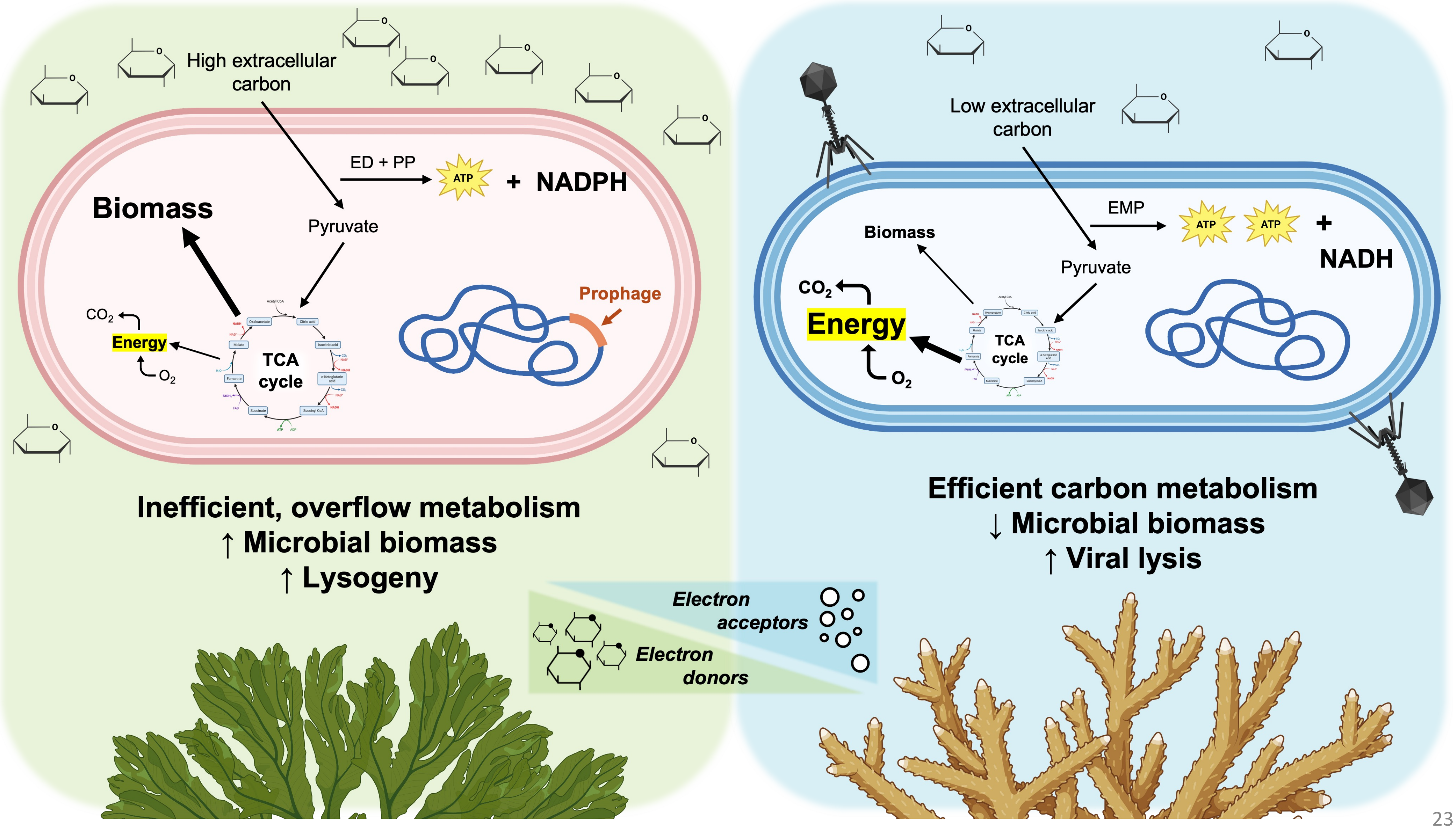
NAVFAC
Naval Facilities Engineering Systems Command
NAVFAC Atlantic

Jacobs

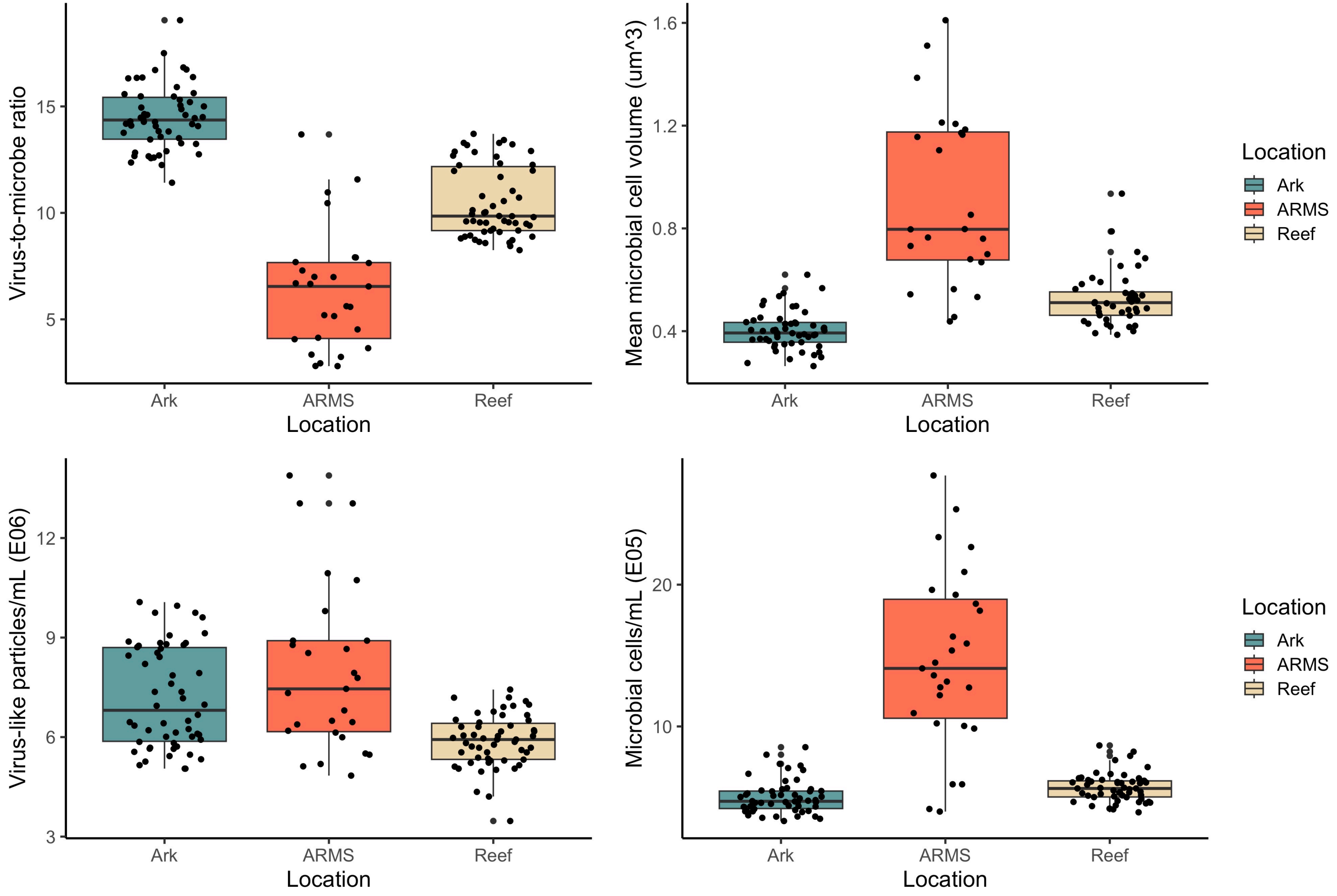
CARMABI

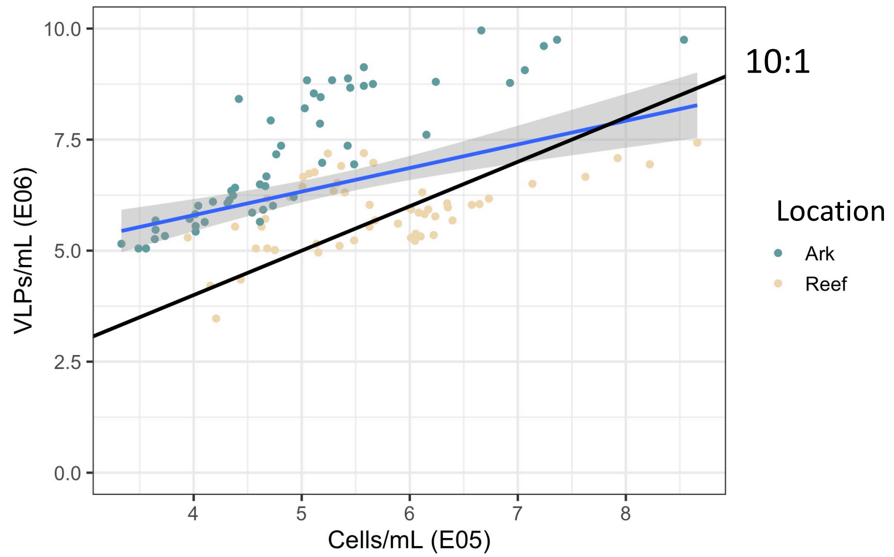


# Molecular mechanisms driving microbialization



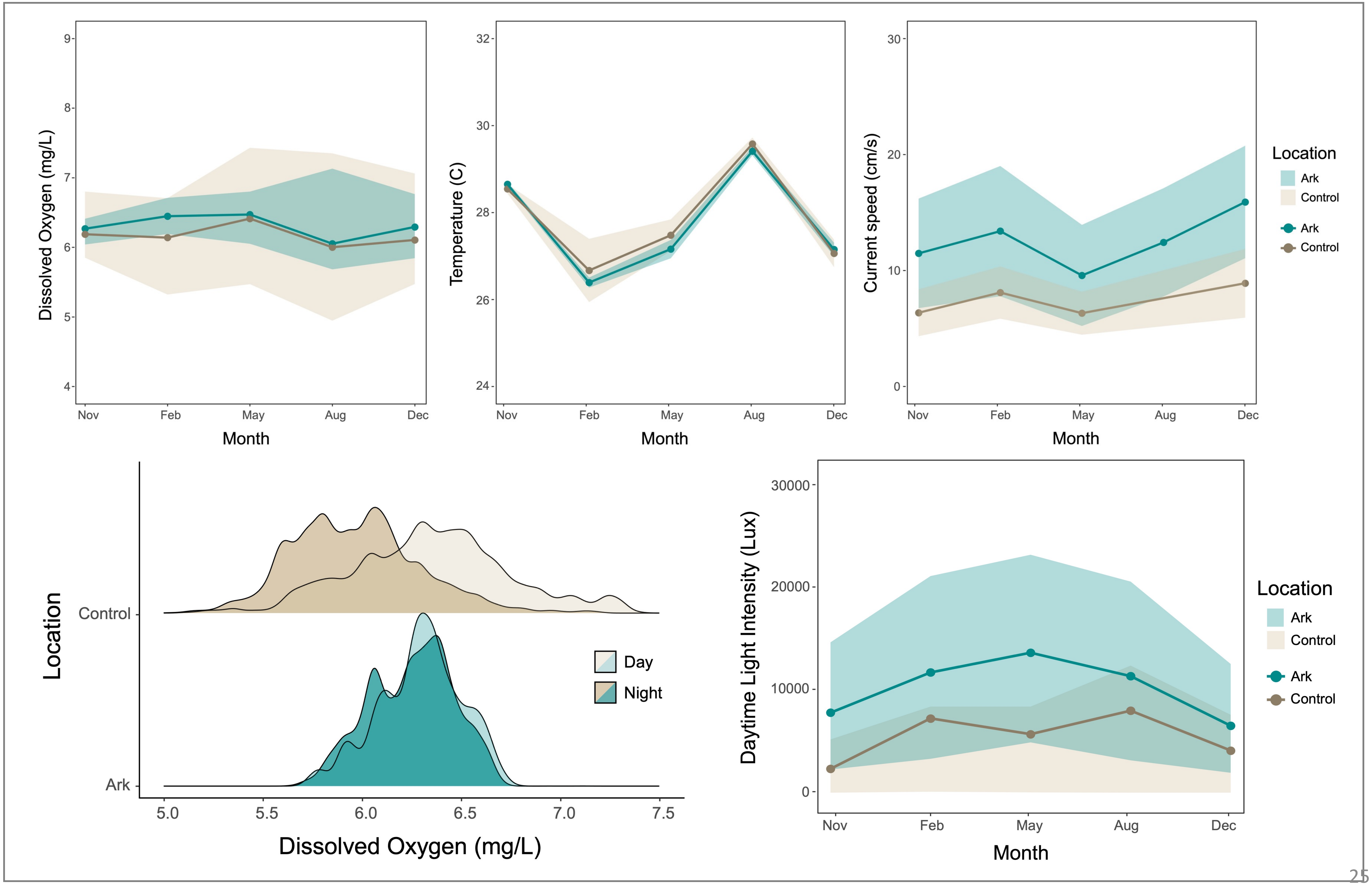
# ARMS units look like little paradises for microbes ☺

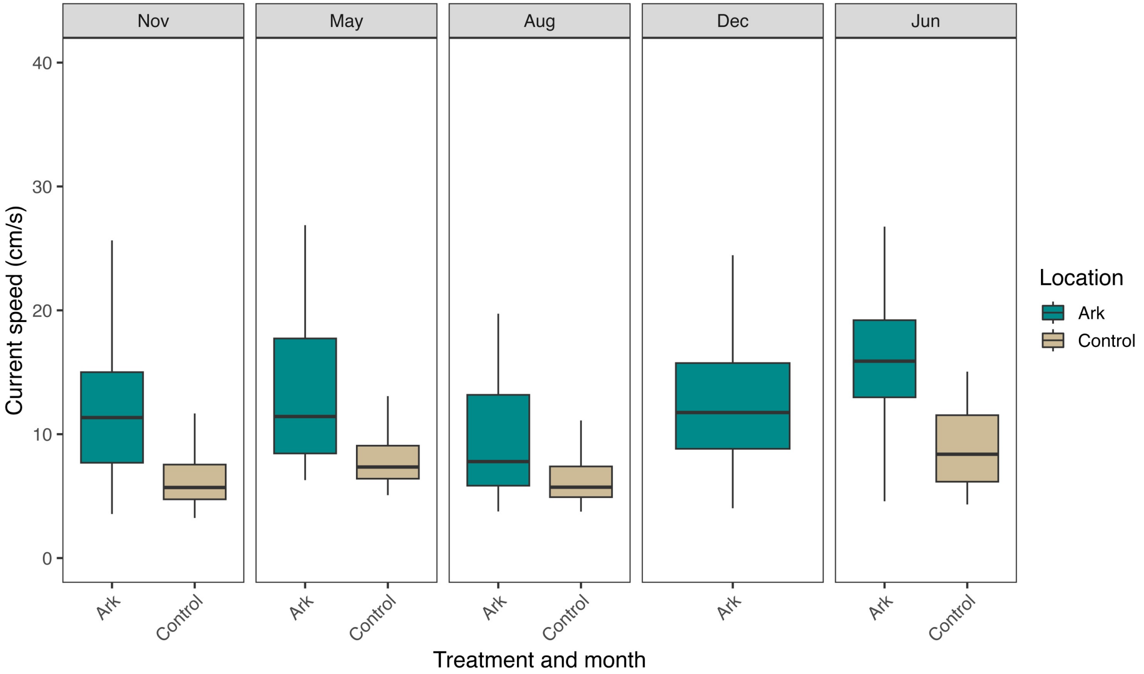


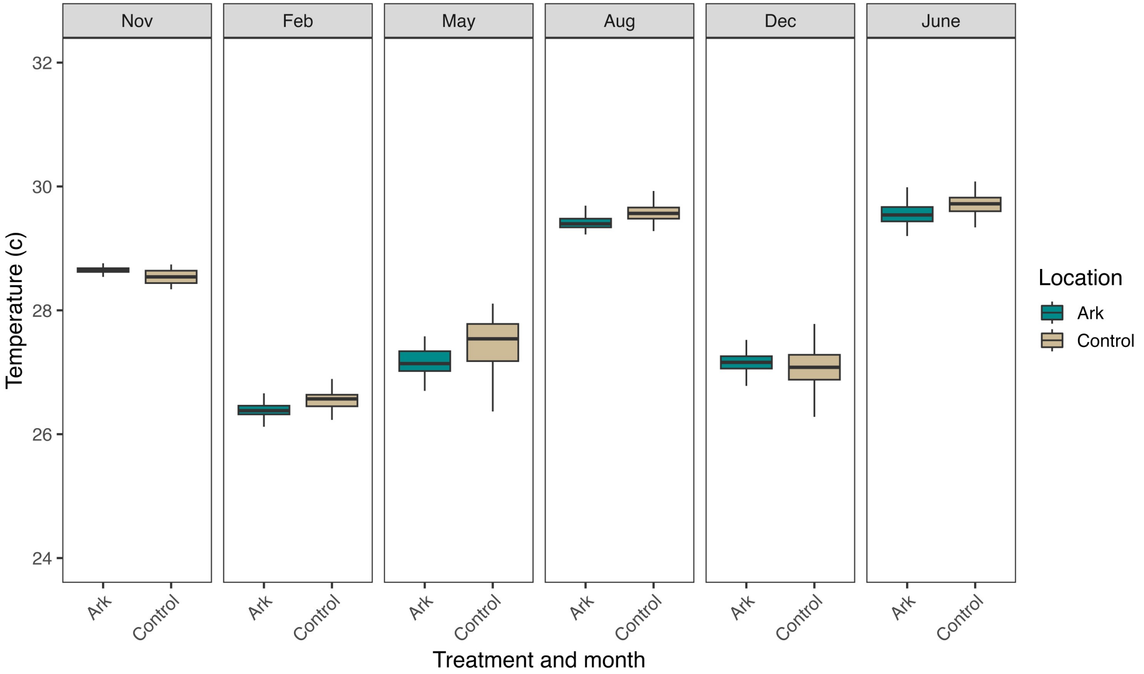



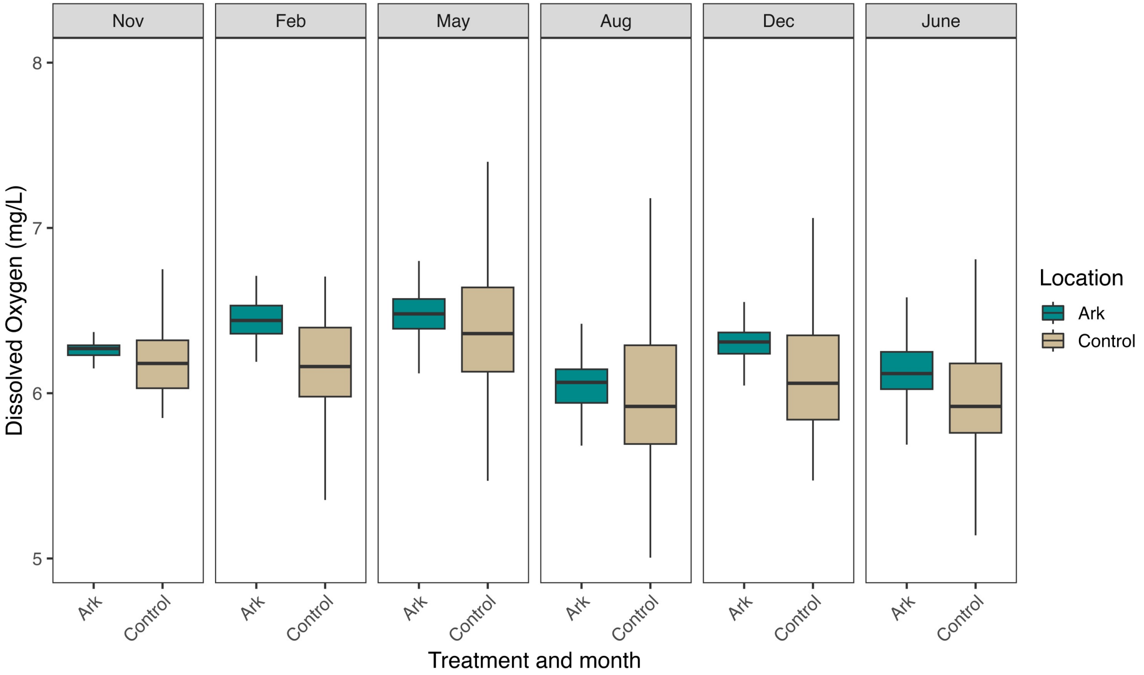

- As microbes increase in abundance, viral predators opt for lysogeny in favor of lysis

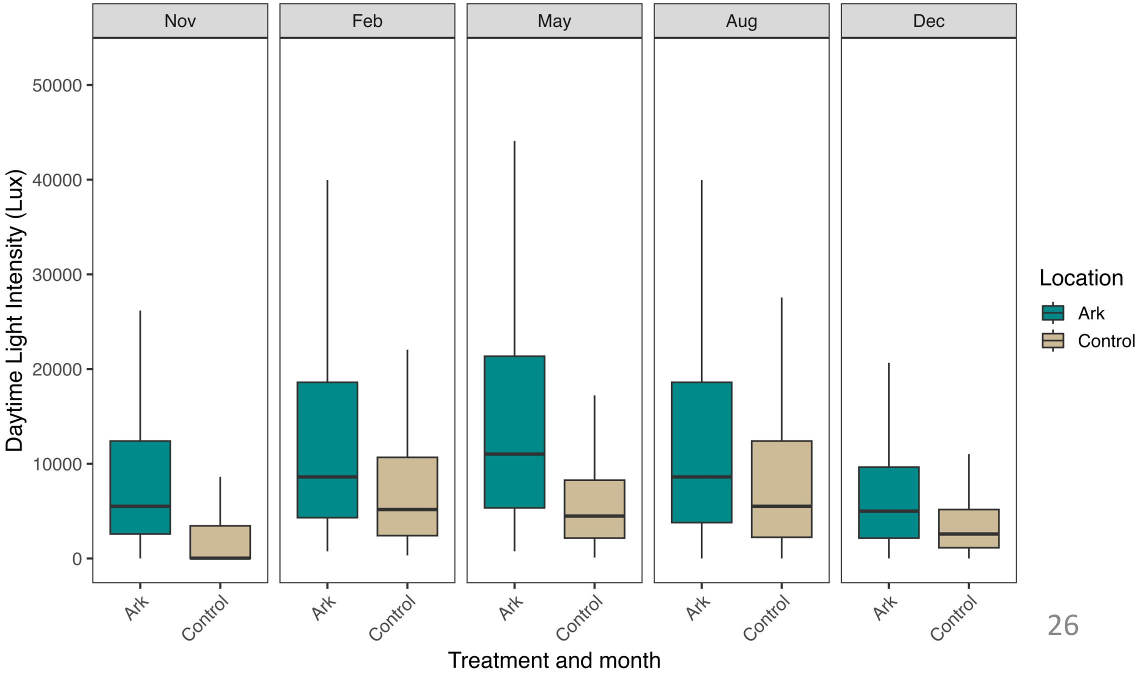
- Viral communities display piggyback-the-winner (PtW) dynamics (Knowles et al 2016)

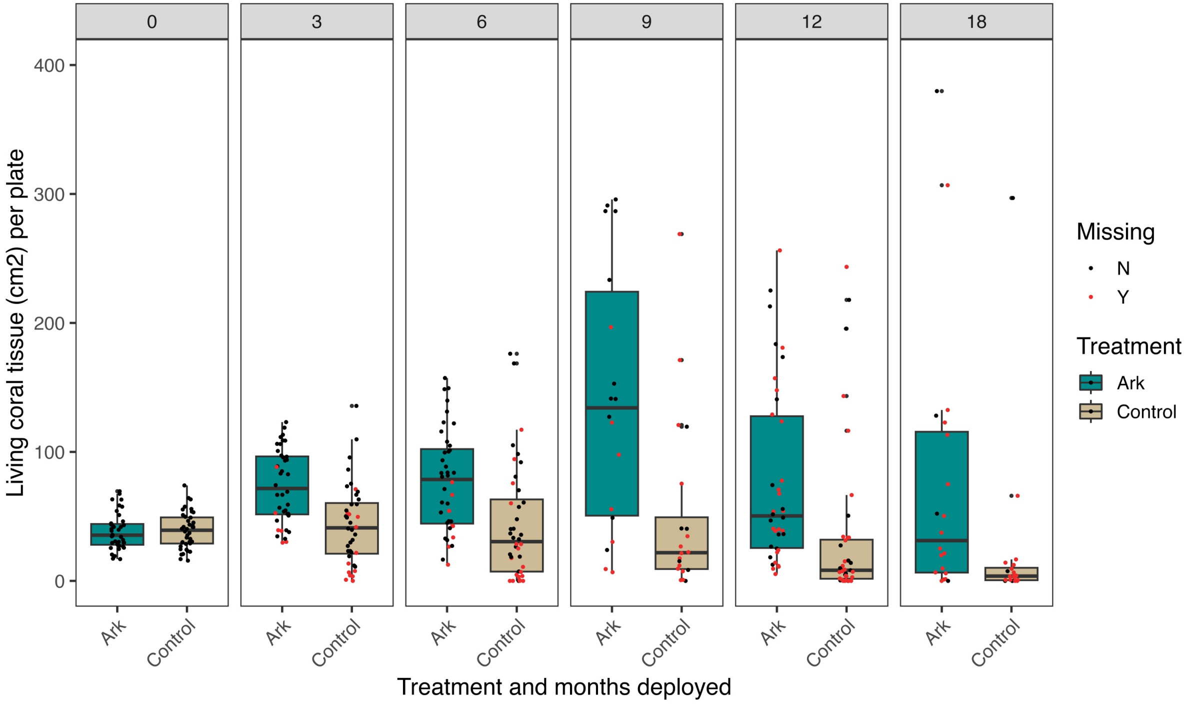

Dissolved Oxygen (mg/L)
Temperature (C)
Current speed (cm/s)
Month
Nov
Feb
May
Aug
Dec
Location
Ark
Control
Day
Night
Dissolved Oxygen (mg/L)
Daytime Light Intensity (Lux)

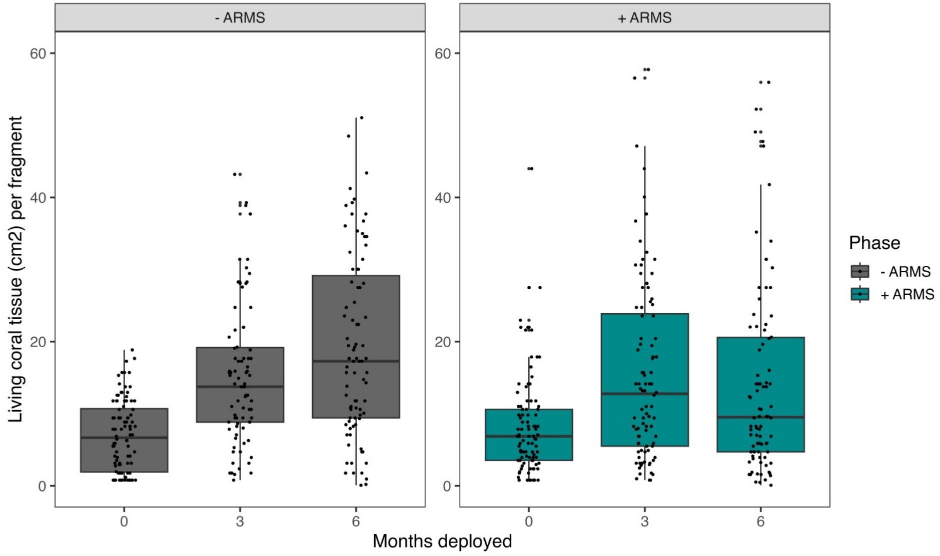

Nov
May
Aug
Dec
Jun
Current speed (cm/s)
0
10
20
30
40
Ark
Control
Treatment and month
Location
Ark
Control

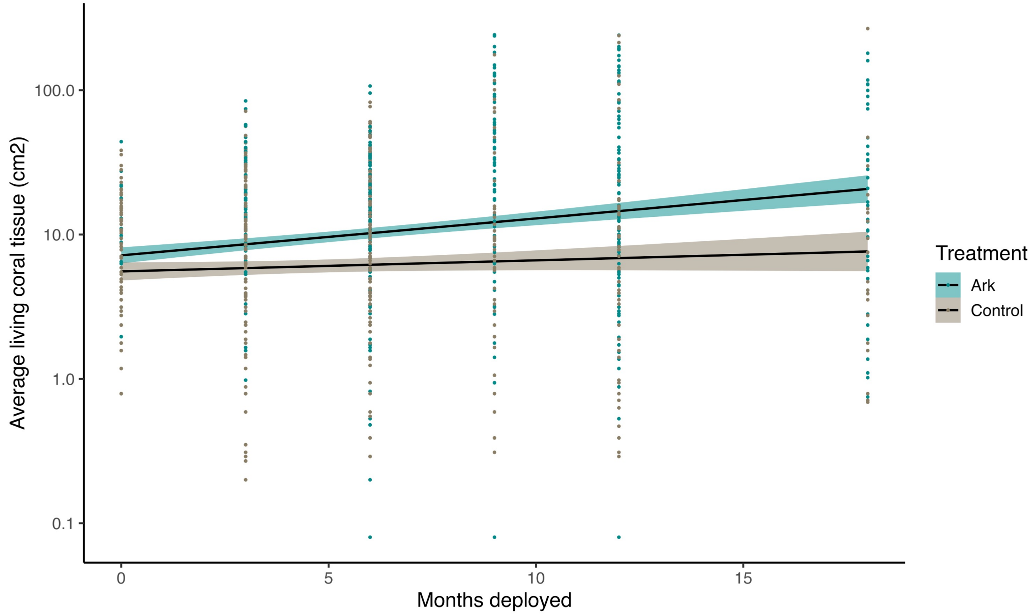

Nov
Feb
May
Aug
Dec
June
Temperature (c)
24
26
28
30
32
Ark
Control
Treatment and month
Location
Ark
Control

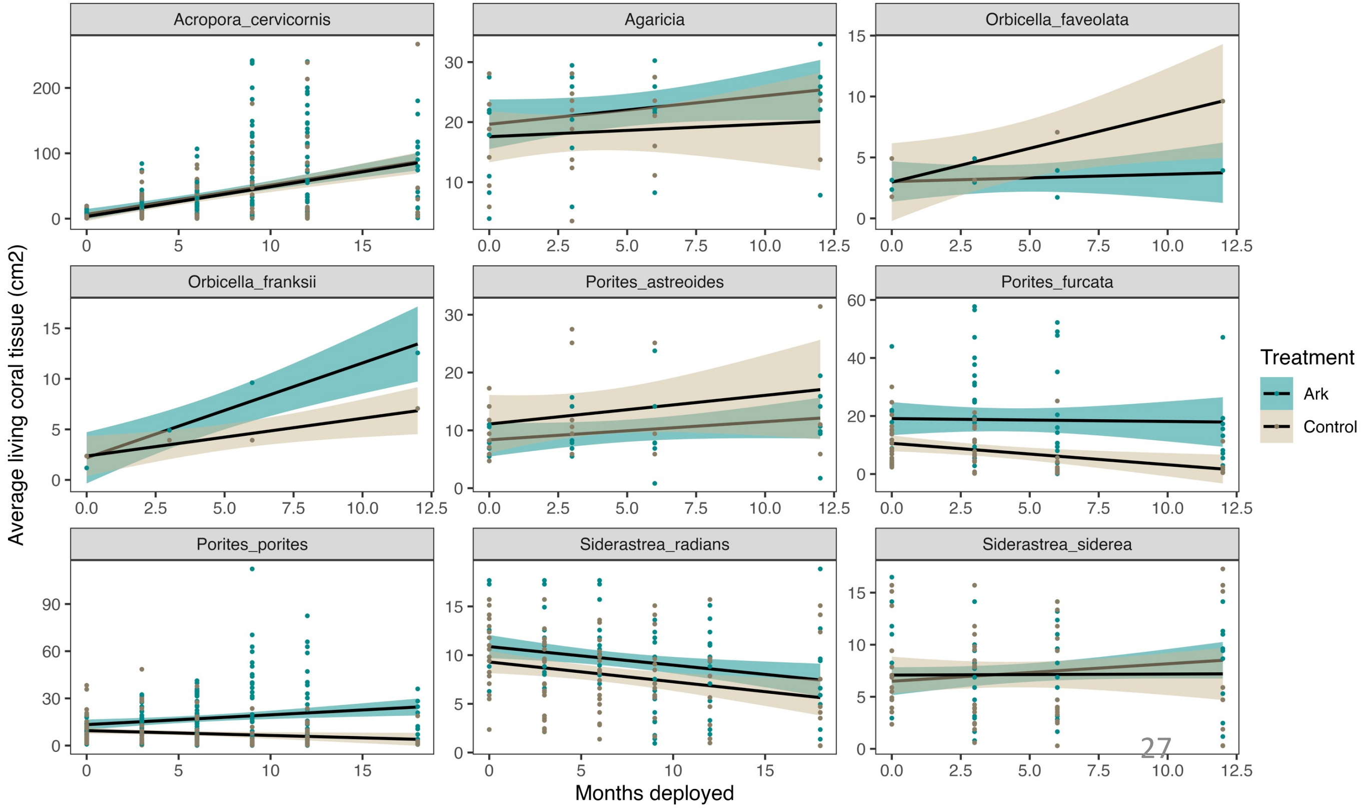

Nov
Feb
May
Aug
Dec
June
Dissolved Oxygen (mg/L)
5
6
7
8
Ark
Control
Treatment and month
Location
Ark
Control


Nov
Feb
May
Aug
Dec
Daytime Light Intensity (Lux)
0
10000
20000
30000
40000
50000
Ark
Control
Treatment and month
Location
Ark
Control


0
3
6
9
12
18
Living coral tissue (cm2) per plate
Treatment and months deployed
Ark
Control
Missing
N
Y
Treatment
Ark
Control


- ARMS
+ ARMS
Living coral tissue (cm2) per fragment
Months deployed
Phase
- ARMS
+ ARMS


Average living coral tissue (cm2)
Months deployed
Treatment
Ark
Control


Acropora_cervicornis
Agaricia
Orbicella_faveolata
Orbicella_franksii
Porites_astreoides
Porites_furcata
Porites_porites
Siderastrea_radians
Siderastrea_siderea
Average living coral tissue (cm2)
Months deployed
Treatment
Ark
Control