

REEF SURVIVOR

Designed by Dr. Rowan Martindale

Game Objective: Build a healthy, **diverse** reef **ecosystem** that can survive natural disasters!

Learning Objective: This game teaches players about the following topics:

- A. **Reef building and dwelling organisms** (e.g., corals, bivalves, algae, sponges), both modern and ancient examples.
 - i. Where they live on a reef (e.g., what is delicate vs. what is strong, where do certain types of builders do well/poorly).
 - ii. How starting **geography** and **bathymetry** affect reef growth.
 - iii. How **sessile, benthic organisms** may **colonize** new areas (**planktic juveniles**).
 - iv. The **niches** and **ecological competition** (e.g., for space) in reef communities
 - B. The process of evolution over long timescales.
 - i. The only way to add **genetic variation** to a **population** is to:
 - have a **mutation** (**mutations** are natural and random, they can be positive, negative, or neutral in different scenarios); or
 - have juveniles **migrate** before they settle (**migration** is limited geographically; **sessile organisms** can only **migrate** when they are **planktic juveniles**).
 - ii. **Natural selection** takes place when certain **organisms** survive or go **extinct** in the face of different perturbation events.
 - ***Teacher Note:** Evolution happens in a Darwinian way (e.g., everyone evolves, useful traits do better than non-useful traits, new variation is only introduced with mutation or migration).*
 - C. Different **environmental events**, natural disasters, and **stressors** that impact reef communities.
 - i. Communities can be affected by short-term events (e.g., storms, hurricanes, high nutrient levels), long-term events (e.g., anoxia, heatwave), or multiple stressors.
 - D. Geological time
 - i. The game is played over millions of years
 - ii. Many disasters occur over centuries, millennia, and mega-annums (i.e., hundreds, thousands, millions of years) and include climate change, sea level change, glaciation, ocean acidification, and ocean anoxia.
 - E. Mechanisms by which reef communities can be **resilient** (either naturally or through human intervention) in the face of changing conditions.
 - i. High **diversity** allows reefs to survive and **adapt** to **environmental** changes.
 - ii. **Migration** of tolerant **organisms** can help keep a community alive.
 - iii. Decreased nutrient runoff or overfishing can help promote healthy reefs.
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TEACHER NOTES (IN PURPLE)

Gameplay Protocol

There are several details that need to be **reviewed a few weeks before playing the game with your class.** Be sure the students have at least a week to read over the game instructions and complete the pre-lab assignment. You will also need to print the game and find D12 dice.

Lab/class time:

This game is designed to fit in a **2-hour lab period** with a pre-lab assignment, a post-lab assignment, and a quick online survey.

- If you only have 1.5 hours, you could probably play 3 rounds.
- If you only have a 1-hour timeslot, you could play over 2 classes IF you have space to store the game boards (e.g., if they can set them to the side and come back to them, you should be fine). If not, you could play a "Practice round" the first day so they learn how to play the game and then play 3 rounds in the second class.
- If you have a longer lab period, the students could play 5 rounds, do a more thorough follow up, or work on the post-lab with their team (there are some questions that ask them to look at other boards, so this is easier if they are still there... alternatively, they can swap photos of their boards).

Instructions

Here's what you need to know before playing the game (i.e., please read this ~ 1 week before playing the game with your class). Note: there is some preparation needed, namely, printing the game (or popping out tokens), cutting score sheets, cards, and organisms, folding game booklets, etc.

- Have the students read the gameplay instruction booklet, watch the video (preferably both) as homework before they play the game. A bit of background will make things run much smoother (and will help the students learn) and help them plan a winning strategy).
- Get the game boards ready (or have TAs prep the boards) before the class/lab (i.e., set out the organisms in bags or cups and get the coral triangle ready). The game should take anywhere ~1.5 to 2 hours depending on how engaged the students are.
- Please check out the Teacher notes we have provided (we have run this game several times and know what makes things easier). We have also included ways to challenge advanced students, integrate fossil collections, or make the game easier/faster if you have less time.
- In addition to the student follow-up worksheet, the Teacher notes have possible "follow up discussion topics" and questions you can ask your class following or during gameplay.
- If in doubt, the written instructions take precedence over the cards (not all the details fit on the game cards), so if there is a question of the order of operations or what cards can be played on what organisms, have the students consult the manual (i.e., the booklet)

What's In the Game?

Reef Builder Tokens (Squares)

- Boulder Coral (80)
- Branching Coral (71)
- Finger Coral (80)
- Platy Coral (70)
- Soft Sponge (35)
- Carbonate Sponge (35)
- Encrusting Sponge (35)
- Carbonate Alga (70)
- Bivalve (70)
- Bryozoan (35)
- Microbialite (35)

Reef Dwellers (circles)

- Fish (20)
- Snail (20)
- Urchin (20)

Reef Coverers (hexagons)

- Fleshy Alga (72)

Game boards

- Coral Triangle Board (1)
- Nursery Boards (4)
- Reef Environments (5)

Mutations

- Stronger Skeleton (52)
- Weaker Skeleton (70)
- Acid resistance (50)
- More Offspring (70)
- Fewer Offspring (60)
- Tolerant of Cold Climates (52)
- Tolerant of Hot Climates (72)
- Tolerant of High Nutrients (52)
- Tolerant of High Sediment Load (50)
- Tolerant of Low Oxygen (60)

D12 Dice (4)

Disaster Card Deck (18 Purple, 4 Grey)

Cheat Sheets (4)

Score Cards (one per player)

Game Booklet (at least 2 per table)

"Who's Winning" Scoresheet (1 per table)

Printing Instructions

Almost all Print and Play elements can be printed on 8.5" x 11" paper or cardstock (you will also need D12 dice, the same number as the number of players). We suggest 100lb card stock, 65lb or plain paper would work but it will be harder to work with and will not last as long. In the instructions below, a table is 4 "players" (each player group can be 1 to 3 students, so for 24 students there could be between 2 and 6 tables).

Gameplay booklet: Print off two (or more) Gameplay booklets on paper (double sided, short edge binding).

The Game Boards: Print off at least one of each kind of reef board per table on cardstock (it's good to print several extras, that way multiple players can have the same board).

The Coral Triangle: On cardstock, print off one Coral Triangle Board per table.

Nurseries: On cardstock, print off one nursery board per player; each PDF makes 2 nursery boards; cut in half.

Disaster Cards: Print off the card set on cardstock (double sided, short edge binding); cut the cards out.

Organism tokens: On cardstock, print off the Print and Play organisms (P&P Builders, Dwellers, and coverers); instructions for the number of copies per table are in the file names/on the image.

Mutation tokens: On cardstock, print off the mutation tokens (three copies per table).

Cheat Sheets: On cardstock, print off copies of the "cheat sheet", 2 for each table should be sufficient.

Order of Operations Cheat Sheets: Print off copies of the "cheat sheet" for each player on paper. Each PDF makes 2 cheat sheets, they can be cut in half if printed double sided (short edge binding) or folded if printed single sided.

Notebooks: Print off one "notebook" on paper for each student (it's good to have a few extras on hand in case there are any user errors).

Scoreboard: Print off one scoreboard for each table (on cardstock).

***Note:** If you want to play with more than 4 players, you will need to print more reef gameboards, nurseries, cheat sheets, notebooks, organism tokens, and mutation tokens.*

INTRODUCTION

Welcome to “Reef Survivor!”. *This game is designed to be fun, collaborative, and competitive while also helping players learn about reef **ecology**, **evolution**, **extinction**, and **resilience** in the face of **environmental** change.*

Each player (or team of players) is in charge of a reef **ecosystem**; throughout the game, you are the conservation expert in charge of keeping your reef healthy. A healthy reef **ecosystem** is a **diverse** reef (**diversity** = lots of different kinds of species) with lots of reef builders (e.g., corals, sponges, and bivalves) and reef dwellers (e.g., fish, snails, and sea urchins). Over time, **environmental** conditions can change; for example, global temperatures rise or fall, and more or less nutrients are washed off the land and onto the reef. Over many years and generations, species may change as well through **genetic mutation**, the influx of new **organisms** (**migration**), and **environmental** pressures that affect **organisms** in different ways (**natural selection**). For example, one coral may be more tolerant of warm waters than another, so they are more likely to survive (and thus produce **offspring**) in a heatwave; the resulting community of corals is thus more likely to have a tolerance to warm waters.

How to read the Game Rulebook (leaflet): Useful tips or common questions can be found in boxes (like this one). Terms you may not be familiar with (i.e., new vocabulary) will be **colored blue and in bold**; these terms are defined in the back of the rulebook. You will find detailed descriptions of the **bathymetric profiles** of the different game boards on page 3, the characteristics and **environmental** preferences of the reef **organisms** on pages 5, 8, 18-19 (you can think of this as their “stats”), the possible **mutations** on page 10 and 20-21, as well as the disaster cards on pages 22-24. An index of terms used can be found on pages 25-27.

GAME SET UP

Note that this game is currently written for four players or teams; however, it can be played with as few as one or two people and as many as you have game boards and tokens for!

- **Teacher Note:** *The game set-up should be done as homework before class, so students are familiar with the game components before play (this helps them strategize). You can include formative assessments/quizzes in this activity (see example assignments).*
- **Teacher Note:** *The set-up is currently for 4 players per table (multiple tables in a classroom); however, you can have more or fewer players per table to make the numbers work (provided you have enough tokens); one could even play solo against the environment). Each “player” can also be a team of two students, which encourages collaboration and discussion of strategy (more than two starts to get a little distracting).*
- **Teacher Note:** *If you want to emphasize strategy and collaborative learning, you could have different tables play against each other; this would encourage the four players to work together (i.e., decreasing competition but increasing collaboration).*

Pick Your Game Board

Before you start gameplay, choose the setting where your reef will grow (any one of five different **carbonate environments** shown on the next page); each player will select a game board with 30 spaces for reef builders.

Note that **different environments have unique bathymetries** (depths) of the water (**light blue is shallow water, medium blue is moderate depth water, and dark blue is deep water**). See the diagram on the next page which covers what these environments look like from Google Earth (map view) as well as what they would look like if you took a “slice” through the ecosystem and looked at it from the side (cross-sectional view).

The setting you choose is important. First, some **organisms** can only live in shallow or deep water and some events will only impact reef **organisms** in the shallow or deep water. Secondly, more organisms can grow vertically in deeper water than in shallow water.

***Pro Tip:** It’s important to have a strategy when choosing your board and organisms. Be sure to think about what combination of organisms and game board would be best given the disasters you may encounter!*

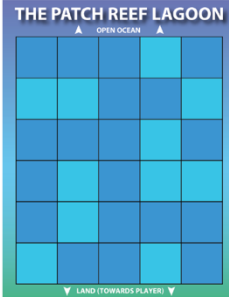

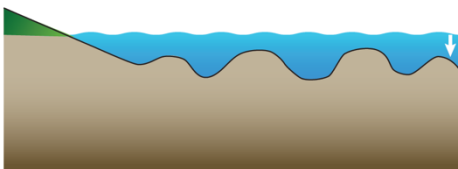
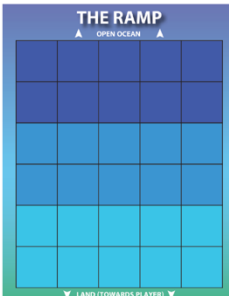
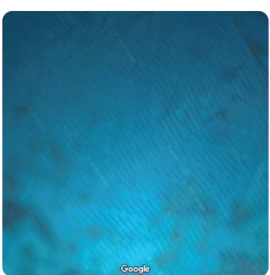
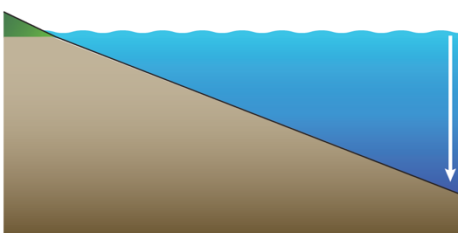
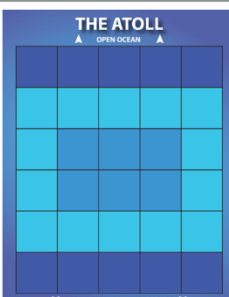
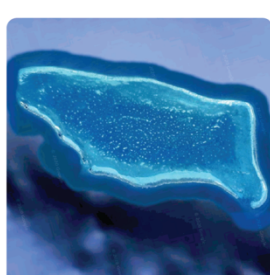
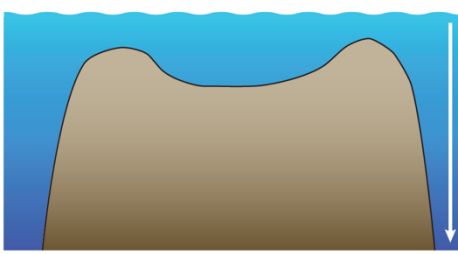
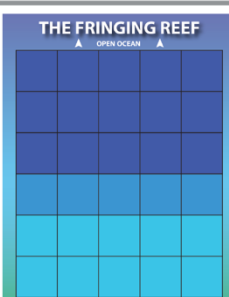
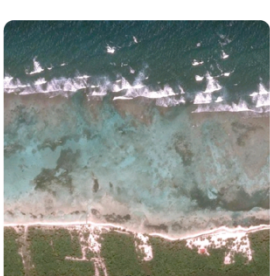
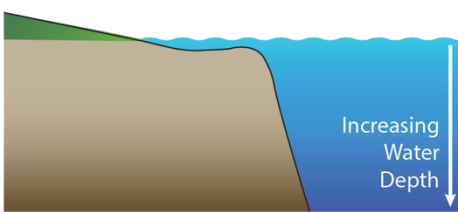
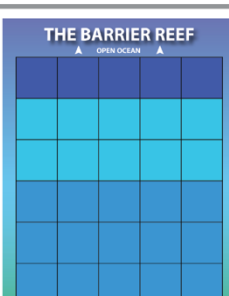

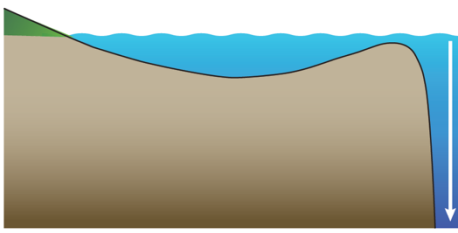
A note about the spaces on the board: The board has 30 spaces but in the natural world there are lots of spaces on a reef for **organisms** to grow. Each reef builder token takes up one space, but your reef may grow larger than these 30 spaces. Reef Dwellers do not take up space on your board.

In the natural world, reefs are not two-dimensional, and **organisms** grow on top of other **organisms**. If you run out of space on the board, you can start to grow upwards! **One builder can grow on top of another reef builder** (they cannot grow on the fleshy algae or reef dwellers). Do not move the builders that are established, the new juvenile must stack ON TOP of the previous reef builder (i.e., do not reorder stacks of builders).

There are stacking **limits based on water depth**. In the deep water, organisms can stack 3 builders deep; in moderate water depths, organisms can stack 2 builders deep; in shallow water depths, organisms cannot stack (i.e., the reef can only be one reef builder deep).

All the reef builders stacked will count towards your score at the end of the round; however, at the start of the round, only the top reef builders will remain on your board (all the reef builders that are “built on” will count for the total number of organisms/diversity but are then removed from the board).

If you have more organisms than spaces on your reef, the unplaced juveniles die off (keep in mind that they could migrate to another reef that does have space for them).

Game Board (Map View)	Natural Example (from Google Maps)	Cross Section View
<p>THE PATCH REEF LAGOON</p> 		
<p>THE RAMP</p> 		
<p>THE ATOLL</p> 		
<p>THE FRINGING REEF</p> 		
<p>THE BARRIER REEF</p> 		

Start Growing your Reef

Every player starts with five **reef building** organisms of their choosing (square tokens). Reef builders and dwellers are all worth the same amount; select your community based on the **organism** characteristics or “stats” (see *organism details on pages 18-19 of the rule book*), your board **bathymetry**, and whichever you think is going to help you build the best reef!

A note about the species tokens: Although the reef species tokens depict one reef builder, dweller, or coverer; in reality, many corals are colonies of hundreds of individuals. Moreover, since this game represents millions of years of Earth history and thus generations of these species through time, the tokens symbolize multiple generations of communities and colonies, not single individuals. **The game designers have simplified a few things for gameplay!**

Choose any five reef builders from the list below (see *details about these reef organisms in the chart on the next page and pages 19-20; you can pick more than one of the same builder type*):

- Boulder Coral (e.g., *Diploria labyrinthiformis*)
- Branching Coral (e.g., *Acropora palmata*)
- Finger Coral (e.g., *Porites porites*)
- Platy Coral (e.g., *Agaricia fragilis*)
- Soft Sponge (e.g., *Aplysina fistularis*)
- Carbonate Sponge (e.g., *Sycon ciliatum*)
- Encrusting Sponge (*Crambe crambe*)
- Carbonate Algae (e.g., Crustose Coralline Algae, *Lithothamnion calcareum*)
- Bivalves (e.g., *Tridacna squamosa*)
- Bryozoans (e.g., *Lodictium phonecium*)
- Microbialites (e.g., stromatolites)


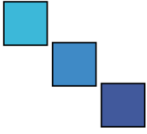


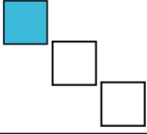
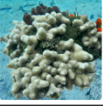


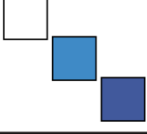

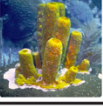
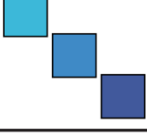


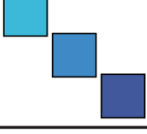


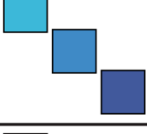






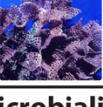








Pro Tip: Have a strategy; think about what combination of organisms and game board would be best given the disasters you may encounter! Remember that you get double points for a diverse reef and fleshy algae will become an issue if your reef builders do not recruit dwellers.

- **Teacher Note:** You can modify the reef builders, their characteristics, or who recruits to match the fossil reef builders in your area or the geological period your class is studying.

A note about the different organisms: Reef builders are all **sessile organisms** as adults, which means once they have established on a space they cannot move.

When the **reef builders reproduce** their **juvenile offspring** (babies) are **planktic** (float in the water column) and so can drift to new areas (i.e., spaces on the board). Since the reef dwellers (snails, urchins, and fish) are **mobile**, they can crawl on top of or swim above the reef; they are not fixed to the board as adults like the reef builders.

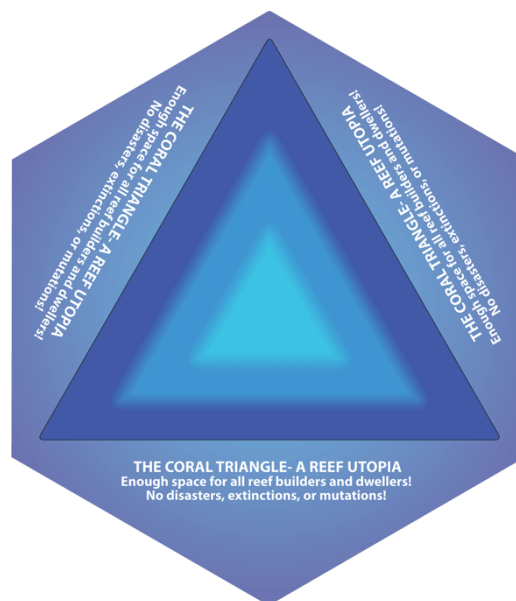
Once you have selected your reef building community, place them in your **ecosystem** (i.e., place the tokens anywhere on your board). Note that some reef builders do better in some areas and not others (e.g., a strong coral will do better in shallow water than a delicate coral) and **some builders cannot live in certain environments at all.**

Reef Builder	Depth Range	Characteristics/Traits (+ = Recruits Dwellers)	
Boulder Coral 		+  Carbonate Skeleton	Colony of hundreds of individuals Zooxanthellae live inside coral tissue & photosynthesize.
Branching Coral 		+ Carbonate Skeleton	Colony of hundreds of individuals Zooxanthellae live inside coral tissue & photosynthesize.
Finger Coral 		+ Carbonate Skeleton	Colony of hundreds of individuals Zooxanthellae live inside coral tissue & photosynthesize.
Platy Coral 		+  Carbonate Skeleton	Colony of hundreds of individuals Zooxanthellae live inside coral tissue & photosynthesize.
Soft Sponge 		Network of tiny glass spicules or fibers/tissues like chitin	
Carbonate Sponge 		 Carbonate Skeleton or Spicules	
Encrusting Sponge 		 Carbonate Skeleton	Encruster
Carbonate Alga 		+  Carbonate Skeleton	Encruster
Bivalve 		+ Carbonate Skeleton	Zooxanthellae live inside soft tissue & photosynthesize.
Bryozoan 		 Carbonate Skeleton	Colony of hundreds of individuals 
Microbialite 		Colonies of microscopic organisms form sticky mats that trap carbonate sediment	  

Set up the Coral Triangle

In the middle of your region (i.e., the table) is a reef utopia: the Coral Triangle (which is [a real place!](#)). The Coral Triangle is an **environment** that contains all the different reef builders and dwellers, but no fleshy algae; it never gets hit with disasters and has a steady state population (one token of each reef builder and dweller always remain in the Coral Triangle). Add one of each reef builder and dweller to the Coral Triangle.

- **Teacher Note:** To create more time for gameplay, set up the Coral Triangle ahead of the class. For the first time playing the game, it is not advisable to have mutated builders in the Coral Triangle, i.e., just have un-mutated reef builders in the Coral Triangle).



Game Play Variation: If you wish to add more variety to the game, you can mutate the Reef Builders in the Coral Triangle. To do this, as reef builders are added to the Coral Triangle, roll the D12 and have them gain a **mutation** (as in Phase 1C of playing the round); each player can take a turn, or if someone is done their reef set up early, they can get the Coral Triangle set up. Declare what **organism** is **mutating** then roll a D12 die to determine the **mutation** and add the appropriate token(s) (see details about the genetic mutations on the cheat sheet or pages 20-21). Another variation is that the reef builders could mutate as they are collected. As always, as these **organisms** propagate, their **offspring** carry their **mutations** with them.

Now you have established your reef community and it's time to see if it will thrive. Take a step back and jump ahead a million years into your reef's future!

PLAYING A ROUND (1 million years each)




Phase 1: New Friends and Mutations

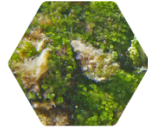
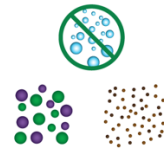
Since you last checked in on your reef community a significant amount of geological time has passed... 1 million years (or 1 Ma)! After a million years and multiple generations, your reef community has grown and undergone **evolution** as it thrives in its **ecosystem**! You note some changes to the community:

- A. Your healthy reef has acquired some reef dwellers (circular tokens). In this happy setting, you find fish, sea urchins, and snails living happily, eating away at any fleshy algae that have overgrown your reef. For every two corals, bivalves, and carbonate algae on your board, you can collect and support one fish, urchin, or snail (note: since it takes two builders to support a dweller, always round down, e.g., if you have 5 recruiters, only 2 dwellers can be supported). At this point in the round (after you have recruited your dwellers), EACH reef dweller eats ONE fleshy algae token from your board (i.e., remove those pieces from the board). **One fish, snail, or urchin can only eat one token of fleshy algae per round**, so be sure you keep track of those fleshy overgrowths!
- **Note: Phase 1A is the only time when reef dwellers can eat fleshy algae** (i.e., there is no other time in the round when you lose fleshy algae from your board).
 - **Reef dwellers MUST ALWAYS BE SUSTAINED by two reef builders** (i.e., don't collect more at the start of the round if you can't sustain more dwellers, and remove dwellers if your builders die off). You can only recruit new dwellers at the start of the round, but you can lose them later in the round; if you don't have enough reef builders to sustain your dweller community, you will lose your dwellers.
 - **Reef Dwellers do not take up space on your board.** Reef dwellers are mobile (they swim or crawl around) and so are NOT sessile like the reef builders, which means they might leave if the reef becomes less healthy. Reef dweller tokens can stack on the reef builders, sit on the side of the reef game board, or hang out in empty spaces.
 - **Reef dwellers do not mutate or reproduce in gameplay** (again, a simplification). If you run out of one kind of dweller, just choose others.
 - **Remember: Covered reef builders DO NOT recruit or support reef dwellers.**
 - Too many urchins can also be a problem. If you have more than 5 urchins on the board, they will start to eat your **juvenile** reef builders. In other words, any urchins in excess of 5 eats the juveniles of that number of corals reef builders; so, if you have 7 urchins, two of your corals will have all their juveniles eaten (no offspring).
 - ***Teacher Note:** Feel free to vary the duration of gameplay to achieve your learning goals (e.g., maybe each round is a decade, or a thousand years).*
- B. Some green algae have grown in your **ecosystem**. Add 5 fleshy algae (hexagonal tokens) to your reef (you choose where to put them); fleshy algae are each worth NEGATIVE one point.
- If there are no empty spaces for your fleshy algae tokens in your **ecosystem**, the fleshy algae will grow over your reef builders (taking them mostly out of play). If fleshy algae are added to your board, they are ALWAYS placed somewhere (if you are instructed to

place fleshy algae in a spot that already has fleshy algae, place the fleshy algae one space over). **Reef builders cannot build over fleshy algae.**

- **Covered reef builders cannot reproduce, evolve, or recruit reef dwellers. Reef builders covered by fleshy algae are not worth any points, but if the algae are eaten off, they can recover in the next round.**
























Reef Dweller	Characteristics/Traits
Sea Urchin 	Closely related to starfish, these urchins hang out on reefs munching away on the reef carbonate and fleshy algae. Too many urchins (>5) can be a problem, they will start to eat your juvenile reef builders!
Fish 	The fish swim around the reef cleaning off the fleshy algae as they graze.
Snail 	These spiraling reef dwellers have a long history of success in geological time but have a strong carbonate skeleton meaning they might get hit by some disasters.
<p><i>For every 2 corals , bivalves, & calcareous algae on your board, collect one fish, urchin, or snail (dwellers MUST EACH BE SUSTAINED at all times)</i> <i>Each reef dweller can eat one token of fleshy algae per round!</i> <i>Reef dwellers can move between and stack on the reef builders, they do not mutate or reproduce in gameplay.</i></p>	

Reef Coverer	Characteristics/Traits
Fleshy Alga 	<p>These soft green algae grow quickly. If there are no empty spaces, the fleshy algae will grow over your reef builders meaning they cannot reproduce, evolve, or recruit and are not worth any points.</p> 
<p><i>Fleshy algae take over any unoccupied space in your ecosystem.</i> <i>They are worth NEGATIVE one point and do not mutate or reproduce in gameplay.</i></p>	

- C. Through the generations of **reproduction**, your reef builders have **mutated**! **Genetic mutations** are normal and natural in any **population**; in fact, all your reef builders could be mutating at any time, but many of these mutations are invisible! These **mutations** add **genetic variation** to your community and so could be helpful, harmful, or neither (i.e., neutral). As these **organisms** propagate their **offspring** will carry the **mutation** with them.
- Each player had TWO notable mutations in their **population**. Since order doesn't matter, everyone can **mutate** their organism at the same time, but it's a good idea to have players verbally declare what builder they are **mutating** and place their finger on the token as they roll the dice (to decrease the opportunities for cheating). Alternatively, you can go around the board one-by-one.
 - Choose a reef builder on your board and declare it as the builder you will be **mutating**. Roll the D12 die to determine which **mutation** occurred and what new traits your reef builder acquired. Then add the **mutation** token(s) to your organism for the traits they acquire (*see details about the genetic mutations in the chart on the next page and on pages 20-21*). Repeat this process for a second reef builder; players can choose the same builder or a different reef builder for the second mutation. After each roll of the D12, use the following list to determine the resulting **mutation**:
 1. Stronger Skeleton
 2. Acid resistance BUT Weaker Skeleton
 3. More Offspring
 4. Fewer Offspring
 5. Tolerant of Cold Climates
 6. Tolerant of Hot Climates
 7. Tolerant of Low Oxygen
 8. Tolerant of hot water BUT Weaker Skeleton
 9. Tolerant of High Nutrients
 10. Tolerant of High Sediment Load
 11. Tolerant of Low Oxygen BUT Fewer Offspring
 12. Invisible Mutation

Pro tip: keep an eye on who has the good juveniles to trade!

A note about mutations: Some mutations **cancel out other mutations or inherent organism characteristics** (e.g., if an organism with a weak skeleton mutates a stronger skeleton, it now has a "normal" skeleton; if an organism with a weak skeleton mutates a weaker skeleton, nothing happens). Others do not (e.g., organisms can be tolerant of both hot and cold climates).

Roll Result	Description of Genetic Mutation	
	A mutation occurred and now your reef builder builds a stronger skeleton able to withstand strong waves and stormy weather. This token cancels out a weak skeleton or mutation.	
	Your reef builder is now resistant to lower pH (acidic) waters BUT it builds a weaker skeleton and can no longer withstand strong waves. This token cancels out a strong skeleton or mutation.	
	A mutation occurred and now your reef builder produces MORE offspring (2 offspring instead of 1) . This token cancels out a mutation for fewer offspring.	
	A mutation occurred and now your reef builder produces FEWER offspring (0 offspring or "steady state" population) . This token cancels out a mutation for more offspring.	
	A mutation occurred and now your reef builder can tolerate cooler climate , so colder waters or seasons don't damage this organism!	
	A mutation occurred and now your reef builder can tolerate warmer climate , so hotter waters or seasons don't damage this organism!	
	A mutation occurred and now your reef builder can tolerate lower oxygen levels in the water (i.e., dysoxia, hypoxia, or anoxia).	
	Your reef builder can now tolerate warmer climate (i.e., hotter waters) BUT it builds a weaker skeleton . This token cancels out a strong skeleton or mutation.	
	A mutation occurred and now your reef builder can tolerate high nutrient levels in the water (i.e., nutrification).	
	A mutation occurred and now your reef builder can tolerate high sediment loads in the water.	
	Your reef builder can now tolerate lower oxygen levels in the water BUT produces FEWER offspring (0 offspring, "steady state" population) . This token cancels out mutations for more offspring.	
	A mutation occurred but it doesn't change any characteristic expressed by the organism (no change in the organism's traits).	<i>NONE</i>

Phase 2: Spawning and Migration

Once you have added to your community and carried out your **mutations**, reef builders **reproduce**.

- A. **Spawn** - Each reef builder on your board spawns one identical juvenile (the same builder with all the same **mutations** as their parent) unless you have a reproductive mutation. **Genetic mutations** are inherited by **offspring** from their parents. **All juveniles eventually must go on a game board but place them in your “nursery” while you work out where to place them or how to trade them.**

A note about the spaces on the board: Although adult reef builders are **sessile** (i.e., once established on a space they cannot move) their **juvenile offspring** (babies) are **planktic** (float in the water) and so can drift to new areas (i.e., spaces on the board). If you have more organisms than spaces on your reef, unplaced juveniles die (keep in mind they could migrate to another reef that has space for them). Reef Dwellers do not take up space on your board.



- B. **(Skip in Round 1)** Shifting currents bring new recruits from the Coral Triangle! The player with the lowest overall score AND the player with the lowest score in the last round each recruit reef builders (note: this could be two different players or one player twice; if there is a tie, both players recruit). The player(s) select any reef builder in the Coral Triangle and acquire two of their juvenile offspring (i.e., the player gets two identical juveniles, but the parent stays in the Coral Triangle). **Coral Triangle juveniles are swept into the player’s nursery where they can settle on their reef or migrate to another reef (be traded).**
- C. **Migrate (Trade)** - Since **juvenile offspring** are **planktic**, they float to new areas on your reef or the reef of the player next to you (they can only **migrate** one player to the left or right). This is how **sessile organisms migrate** to new areas. Keep the **juveniles** in the “nursery” until you work out where to place them on your board or how to trade them. Talk to your neighbors to work out juvenile trades; **there are no rules to the trades, as long as both players agree!** After a trade has been made, **place the new juveniles on your reef** (i.e., it cannot be traded again).

Pro Tip: *This phase is where you can work together (collaborate), or against (compete) other players, so be strategic!*

A note about trades (Migrations): There are no rules to the **migration** trades as long as both **players agree to it!** You can do a one-for-one swap if each of you has a good reef dweller, or if you have an excellent reef dweller, you could also ask for two, three, or more reef dwellers in return. If you want to collaborate and you have different **bathymetries**, try to match the reef builder with the **environment** in which they will do the best! If you want to be nice, you can gift a specimen to a player whose reef was just decimated. Or you can keep all your juveniles on your own reef!

Once everyone is done trading, **place all the juveniles on your reef as sessile adults (there should not be any left in the nursery)**. If you have more organisms than spaces on your reef, the unplaced juveniles die off (keep in mind that they could migrate to another reef that does have space for them).

A note about running out of spaces on your board: The board has 30 spaces, but your reef may grow larger than your board. In the natural world, reefs are not two-dimensional, and **organisms** grow on top of other **organisms**.

If you run out of space on the board, you can start to grow upward! **One builder can grow on top of another reef builder** (they cannot grow on the fleshy algae or reef dwellers). Do not move the builders that are established, the new juvenile must stack ON TOP of the previous reef builder (i.e., do not reorder stacks of builders).

There are stacking **limits based on water depth**. In the deep water, organisms can stack 3 builders deep; in moderate water depths, organisms can stack 2 builders deep; in shallow water depths, organisms cannot stack (i.e., the reef can only be one reef builder deep).

All the reef builders stacked will count towards your score at the end of the round; however, at the start of the round, only the top reef builders will remain on your board (all the reef builders that are “built on” will count for the total number of organisms/diversity but they will then be removed from the board).

Reef Dwellers do not take up space on your board.

Gameplay Variation: *If you wish to add more variety to the game, you can play a modification where the stacked organisms stay on the board in successive rounds and modify the water depth (e.g., if you have 2 builders in the deep water, that space now counts as shallow water, so a builder that cannot build in deep water could now occupy that space). This modification makes the game a bit more realistic but can be harder to keep track of for new players.*

Competition: As your reef grows (especially during/after round 3) you will notice that is harder to find space on the board for your reef builders. This is true in the real world as well; many corals fight each other to get more space on the reef!

Phase 3: Catastrophe!

After all the new juveniles have settled into their reef, **DISASTER STRIKES! All the reefs on the table (except the Coral Triangle) get hit with a catastrophe.** Separate short-term and long-term Disaster Cards and shuffle each deck. ***See pages 22-24 for the disasters you may encounter!***

- Unless otherwise noted, disasters only impact the topmost reef builder (i.e., builders that have been grown over by another builder may stand a chance).
- Unless otherwise noted, disasters do not impact fleshy algae.
- If you have an odd number, always round down (e.g., half of 7 builders die = 3).
- If the instructions do not say which builders or dwellers to remove, you get to choose (so choose wisely!)

Note: In a **standard game** there are four catastrophe intervals (4 rounds); if you don't have enough time for all 4 million years, you can just play for 3 (but fewer disasters detract from gameplay). If you are enjoying yourself and want to keep going, you can play extra rounds.

- Round 1: You only encounter **ONE short-term event**.
- Round 2: You encounter **TWO short-term events**.
- Round 3: You encounter **ONE long-term event**.
- Round 4: You encounter **TWO short-term events**.
- Round 5 (and additional rounds): You encounter **ONE short- AND ONE long-term event**.

From the appropriate deck, pull out one or two cards (see instructions above); disaster cards apply to every reef on the table (except for the Coral Triangle) in the order they are drawn! Follow the instructions on the card for what happens to your reef community. Make a discard pile for used disaster cards (if you want to be more realistic, you can shuffle the cards back into the deck, disasters can strike more than once in real life!).

Assess whether you have lost any reef dwellers; remember, **each dweller must always be sustained by two builders**. If you lose builders, you may lose some of your dwellers as well.

- ***Teacher Note:*** Feel free to choose a subset of disaster cards to tailor the game to a specific topic you are teaching, e.g., climate change, anthropogenic stresses, etc.

In Phases 1-3 the reef evolves: It is important to note that although every reef faces the same disaster, the ramifications of these disasters are not uniformly bad for all **organisms** on the table. Since there are different **organisms** with unique characteristics and **mutations** or **migrations** have added **variation** to the **population** of each type of reef builder, survival rates will be uneven on your board and across the table. Some events will be catastrophic for the entire board, whereas others will only impact certain groups. Together, this aspect of gameplay is an important representation of the core tenants of **natural selection** and **evolution**:

- a) there is a **population** of **organisms** that are variable (have variable traits)
- b) in every generation, there are more offspring produced than survive and reproduce
- c) **environmental stresses** can cause some **organisms** to die off or reproduce less
- d) the pattern of who survives and reproduces is nonrandom
- e) the survivors pass their **genetic code** onto their **offspring** (traits are **heritable**)

Some **organisms** with beneficial **adaptations** will survive, whereas others will not. Survival may also be impacted by random chance. As well-adapted **organisms** (survivors) proliferate, the community composition shifts through geological time depending on the luck of the draw (e.g., mutation) and survival through disasters (e.g., **natural selection**).

If all of one type of **organism** is killed off, they have gone **extinct**! If they have just been lost from your board (or part of the boards on the table) we call this “**extirpation**” which means the species is gone from the local area but not from the entire world’s oceans. **Extinction** is forever, but if there are pockets where certain **organisms** have survived, they may be able to repopulate the reef. Some **organisms** will have an easier time of weathering disasters than others. In the **fossil** record, preferential **extinction** or survival can help us understand what disasters or long-term environmental changes impacted a community.

A note about catastrophes: Although this game has specific short-term and long-term disasters happening on a specific schedule, natural disasters can happen anytime and may coincide with other catastrophes. The catastrophe timeline is predetermined to make the gameplay better!

Phase 4: Survey your reef

Following the disaster, it is time to see who survived and tally your score for the round (use your notebook to calculate the score and then post your score on the “Who’s Winning?” scoreboard). You will award points after each disaster using the following rules:

- You get **one point for each reef builder and reef dweller** on the board (unless covered by fleshy algae). This is the reef’s population size.
- **Lose a point for every square with fleshy algae.**
- **Diversity** counts double! Two points for every different type of **organism** on the board (e.g., if you have a boulder coral, three finger corals, a fish, and two fleshy algae, you would get an additional 8 points, 2 x 4 types of organism). **Mutations** of the same type of **organism** do not count for **diversity** (i.e., two boulder corals, one with a weaker skeleton still count as one species, there is just variation within that species).
- **All the stacked reef builders count towards your score** (both total number and diversity) at the end of the round; however, only the top-most reef builders will remain on your board into the next round. Not only do you get a bonus for having more than 30 organisms but if the disaster takes out one of your top builders, the one underneath might have survived!
- **Bonus Points! Get a bonus for each of the following achievements** (note: some game boards may not allow you to get a particular bonus):
 - **Resilience (5 points)** – You have quite a bit of variation within a species of reef builder! Get this bonus if you have four (or more) of the same type of reef builder each with UNIQUE POSITIVE mutations (i.e., any mutation except for weaker skeleton or fewer offspring).
 - **3-D Reef (5 points)** – Your reef builders are becoming skyscrapers! You have at least 3 sets of reef builders that are 3 stacks tall!
 - **Coastal Protection (5 points)** – Your reef is now strong enough to protect the land nearby! You have TWO rows that are filled with reef builders (2 x a row of 5 builders) between the open ocean and land.
 - **Catch an Error** – Someone wasn’t paying attention and made a mistake sometime this round (e.g., put a builder in the wrong place or forgot to add fleshy algae). If you catch their error you get to steal their reef dwellers before everyone tallies their score (i.e., you get their reef dwellers, and they lose their dwellers for the reef survey). You can only keep them in the next round if your reef can sustain that many dwellers; the person who lost them can re-recruit dwellers in Phase 1.
- **Remove any stacked organisms after tallying the scores (only the topmost builder remains)!** All the reef builders that are “built over” by other builders should be removed before the next round. Just like in real life, there is a cost to having something grow over a reef builder (it also keeps the reef stacks from getting too unwieldy).
- **Keep the reef builders that are overgrown by fleshy algae** as they can recover!

***Pro Tip:** Take a moment to make some notes about your strategy after each disaster. Why did the disaster hit your organisms? Could you have placed them in a better part of the reef? What*

impending disasters might hurt your reef in the next round? Do you have enough diversity or recruiting builders?

- **Teacher Note:** *Students often skip this part, so it's a good idea to go around and spark a discussion about strategy with the students as they are adding up their points. You can also use this to encourage consideration of impending disasters or organism traits etc.*

Players should also tally the total score for their region (i.e., the population size and diversity of the entire table) and add this score to the “Who’s Winning?” scoreboard.

- **Teacher Note:** *Part of the assessment for the game can be having your students track the diversity of their reef community through time. Depending on the goals of your class/lab and the level of the course, have them plot up range charts or diversity plots (or both), ask them to assess the diversity of their board (alpha diversity) and their table (gamma diversity) at the end of each round. Have them mark in the disasters that hit and any extinctions. You can have them count/calculate the diversity at the end of each round or just compare diversity between tables at the end of play.*

Use this notebook to keep track of your reef community through time.

Use this notebook to keep track of your reef community through time.

[illegible]

Bonus Points!

- Resilience (5 pts) - 4+ of the same type of reef builder each with UNIQUE POSITIVE mutations.
- 3-D Reef (5 pts) - 3+ sets of builders 3 stacks tall!

Bonus Points!

- Coastal Protection (5 pts) – TWO rows filled with reef builders between the open ocean and land.
- Catch an Error – If you catch someone's error, steal their reef dwellers for this round (i.e., their dweller points).

Who's Winning?

Use this scoreboard to track your table's diversity through time (and everyone's progress in the game).

Round of Play	Player 1	Player 2	Player 3	Player 4	Cumulative Points	Total Diversity of the Table (Number of Organism Types)
Round 1						
Round 2						
Round 3						
Round 4						
Round 5						
Round 6						
Round 7						
Cumulative Points						

The game is played for 4 million years. Repeat the instructions for a round of play (Phases 1 through 4, or the text between the *** in the rulebook) for a total of four rounds or four catastrophe intervals.

- **Teacher Note:** You can play the game for as many rounds as you have time for. It's best if you get at least 3 rounds in, but you can do 4, 5, 6, or 7 depending on how long you have in the class and how engaged the students are.

WINNING THE GAME

The most **resilient**, **populous**, and **diverse** reef through geological time wins. The sum of all your points over all four rounds is your final score. The person with the highest total score at the end of the game is the winner.

- **Teacher Note:** You can always change the point structure to suit your needs (e.g., want to foster collaboration? Give a team bonus points if every player wins at least one hand! Covering multiplication? Have them multiply the points of their rounds instead of adding them. Discussing alpha versus beta, versus gamma diversity, ask them to use the classes reported diversity/range charts as simulated data and synthesize an assessment of the "global" classroom.

Reef Organisms

Reef Builders:

- **Boulder Coral** (e.g., *Diploria labyrinthiformis*) – This coral has a **strong carbonate skeleton** and **can live in any water depth**. Although this coral looks like one big rock (or a brain!), it's a colony of hundreds of individuals that have a **friendly alliance with algae** (called **zooxanthellae**) that live inside the coral tissue and **photosynthesize** (the **zooxanthellae** get a place to live, and the corals get the energy made during **photosynthesis**).
- **Branching Coral** (e.g., *Acropora palmata*) – This coral has a **carbonate skeleton** and **can only live in the shallowest water depth**. Although this coral looks like a rack of antlers, it's a colony of hundreds of individuals that have a **friendly alliance with algae** (called **zooxanthellae**) that live inside the coral tissue and **photosynthesize** (the **zooxanthellae** get a place to live, and the corals get the energy made during **photosynthesis**).
- **Finger Coral** (e.g., *Porites porites*) – This coral has a **carbonate skeleton** and **can live in any water depth**. Although this coral looks like a bunch of little fingers, it's a colony of hundreds of individuals that have a **friendly alliance with algae** (called **zooxanthellae**) that live inside the coral tissue and **photosynthesize** (the **zooxanthellae** get a place to live, and the corals get the energy made during **photosynthesis**).
- **Platy Coral** (e.g., *Agaricia fragilis*) – This coral has a **delicate carbonate skeleton** and **can only live in medium to deep water depth**. Although this coral looks like a bunch of stacked plates and bowls, it's a colony of hundreds of individuals that have a **friendly alliance with algae** (called **zooxanthellae**) that live inside the coral tissue and **photosynthesize** (the **zooxanthellae** get a place to live, and the corals get the energy made during **photosynthesis**).
- **Soft Sponge** (e.g., *Aplysina fistularis*) – This sponge is anything but square and **can live in any water depth**! These sponges can be made up of network of **tiny little glass spicules or other fibers or tissues like chitin**; it is quite the survivor, it can even live in cold waters!
- **Carbonate Sponge** – This sponge can kind of look like a coral (or some scoops of ice cream), but it has a **strong carbonate skeleton (or is made of carbonate spicules)** and **can live in any water depth**.
- **Encrusting sponge** (*Crambe crambe*) – This sponge is rock hard, has a **strong carbonate skeleton**, and **can live in any water depth**. As an encruster, it coats rocks and dead coral like icing on a cake!
- **Carbonate Algae** (e.g., Crustose Coralline Algae, *Lithothamnion calcareum*) – This kind of algae is the good kind for reef building! Although often small or encrusting (and bubblegum pink!), these algae have a **strong carbonate skeleton** and **can live in any water depth**.
- **Bivalves** (e.g., *Tridacna squamosa*) – This bivalve (related to clams) has a **carbonate skeleton** and **can live in medium to deep water depth**. Like the corals, these bivalves have a **friendly alliance with algae** (called **zooxanthellae**) that live inside their soft tissue and

photosynthesize (the **zooxanthellae** get a place to live, and the bivalves get the energy made during **photosynthesis**).

- **Bryozoan** (e.g., *Iodictium phonecium*) – Bryozoans have a **delicate carbonate skeleton** and **only live in medium to deep water depth**. This Bryozoan is a colony of hundreds of tiny individuals and can live in cold waters!
- **Microbialites** (e.g., stromatolites) – These colonies of microscopic organisms form sticky mats that trap carbonate sediments and make large domes of solid rock. They only **live in medium to shallow water depth** but can survive in low oxygen, high nutrient, or high sediment settings.

Reef Dwellers:

*For every two corals, bivalves, and calcareous algae on your board, you can collect one fish, urchin, or snail. Each reef dweller can eat one token of fleshy algae per round! Since these **organisms** can crawl or swim above the reef (i.e., their tokens can stack on the reef builders); they are not fixed to the board (and can live anywhere on the reef). These reef dwellers do not **mutate** or **reproduce** in gameplay.*

- **Sea Urchin** (e.g., *Diadema antillarum*) – Although they look like little ocean hedgehogs, sea urchins are more closely related to starfish. These urchins hang out on reefs munching away on the reef carbonate and fleshy algae. Too many urchins can also be a problem. If you have more than 5 urchins on the board, they will start to eat your **juvenile** reef builders (any urchins in excess of 5 eats the juveniles of that number of corals reef builders; so, if you have 7 urchins, two of your corals will functionally not **reproduce**).
- **Fish** (e.g., *Scarus vetula*) – A healthy reef brings in beautiful reef fish! The fish swim around the reef cleaning off the fleshy algae as they graze.
- **Snail** (e.g., *Turbo fluctuosa*) – These spiraling reef dwellers have a long history of success in geological time but have a **strong carbonate skeleton** meaning they might get hit by some disasters.

Reef Coverers:

- **Fleshy Algae** – These soft green algae can grow quickly, outgrowing and smothering the reef builders. They slurp up nutrients, handle low oxygen and high sediment, and can take over a reef if you're not careful! Fleshy algae take over any unoccupied space in your **ecosystem**, **do not reproduce**, and are worth NEGATIVE one point. If there are no empty spaces for your token, the flesh algae will grow over your reef builders (taking them mostly out of play). **Covered reef builders cannot reproduce, evolve, or recruit reef dwellers. Reef builders covered by algae are not worth any points, but if the algae get eaten off, they can recover in the next round. Unless otherwise directed, disasters do not affect fleshy algae.**

Genetic Mutations

Select one of your reef builders (declare which you are mutating, e.g., place your finger on the token as you roll) then roll a D12 dice for a genetic mutation (no limit to the number of mutations per organism). Some mutations cancel out other mutations or inherent organism characteristics, whereas others do not. For example, if an organism with a weak skeleton mutates a stronger skeleton, it now has a “normal” skeleton (if an organism with a weak skeleton mutates a weaker skeleton, nothing happens), BUT organisms can be tolerant of both hot and cold climates. Roll the D12 die to determine which **mutation** occurred and what new traits your reef builder acquired based on the list below. Each player had TWO notable mutations in their **population** (i.e., roll twice).

1. **Stronger Skeleton** – A mutation occurred and now your reef builder builds a stronger skeleton able to withstand strong waves and stormy weather. ***This token cancels out a weak skeleton or mutation.***
2. **Acid resistance BUT Weaker Skeleton** – A mutation occurred which changes two traits. Your reef builder is now resistant to lower pH (acidic) waters BUT it builds a weaker skeleton and can no longer withstand strong waves and stormy weather. ***This token cancels out a strong skeleton or mutation.***
3. **More Offspring** – A mutation occurred and now your reef builder produces MORE offspring (2 offspring instead of 1). ***This token cancels out a mutation for fewer offspring.***
4. **Fewer Offspring** – A mutation occurred and now your reef builder produces FEWER offspring (0 offspring or “steady state” population). ***This token cancels out a mutation for more offspring.***
5. **Tolerant of Cold Climates** – A mutation occurred and now your reef builder can tolerate cooler climate, so colder waters or seasons don’t damage this organism!
6. **Tolerant of Hot Climates** – A mutation occurred and now your reef builder can tolerate warmer climate, so hotter waters or seasons don’t damage this organism!
7. **Tolerant of Low Oxygen** – A mutation occurred and now your reef builder can tolerate lower oxygen levels in the water (i.e., dysoxia, hypoxia, or anoxia).
8. **Tolerant of Hot Climates BUT Weaker Skeleton** – A mutation occurred which changes two traits. Your reef builder can now tolerate warmer climate (i.e., hotter waters) waters BUT it builds a weaker skeleton and can no longer withstand strong waves and stormy weather. ***This token cancels out a strong skeleton or mutation.***
9. **Tolerant of High Nutrients** – A mutation occurred and now your reef builder can tolerate high nutrient levels in the water (i.e., nutrification).
10. **Tolerant of High Sediment Load** – A mutation occurred and now your reef builder can tolerate high sediment loads in the water.
11. **Tolerant of Low Oxygen BUT Fewer Offspring** – A mutation occurred which changes two traits. Your reef builder can now tolerate lower oxygen levels in the water BUT produces FEWER offspring (0 offspring or “steady state” population). ***This token cancels out a mutation for more offspring.***

12. Invisible Mutation – A mutation occurred but it doesn't change any characteristic expressed by the organism (no change in the organism's traits).

Disaster Cards

In a **standard game** there are four catastrophe intervals (4 rounds); if you don't have enough time for all 4 million years, you can just play 3 (but fewer disasters detract from gameplay). If you are enjoying yourself and want to keep going, you can play extra rounds. **Separate short-term and long-term Disaster Cards and shuffle each deck.**

- Round 1: You only encounter **ONE short-term event**.
- Round 2: You encounter **TWO short-term events**.
- Round 3: You encounter **ONE long-term event**.
- Round 4: You encounter **TWO short-term events**.
- Round 5 (and additional rounds): You encounter **ONE short- AND ONE long-term event**.

From the appropriate deck, pull out one or two cards (see instructions above); disaster cards apply to every reef on the table (except for the Coral Triangle) in the order they are drawn! **Follow the instructions on the card for what happens to your reef community.** Make a discard pile for the used disaster cards (or if you want to be more realistic, you can shuffle it back into the disaster deck, disaster can strike more than once in real life!).

- Unless otherwise noted, disasters only impact the top-most reef builder (i.e., builders that have been grown over by another builder may stand a chance).
- Unless otherwise noted, disasters do not impact fleshy algae.
- If you have an odd number, always round down (e.g., half of 7 builders die = 3).
- If the instructions do not say which builders or dwellers to remove, you get to choose (so choose wisely!)
- **Remember, reef dwellers must always be sustained by two builders each.**
- ***Teacher Note:** Many of these disasters have modern or geological examples. Extension activities could include readings or projects about some of these events (e.g., Hurricane Harvey's impact on the Flower Garden Banks, the 1983-84 Diadema (urchin) Die Off, heatwaves on the Great Barrier Reefs).*

Short-term Disasters (purple edges)

- **Predator on the loose** – Swim away! Some very hungry predator has come along and eaten up all the fish on your reef; without these fish, fleshy algae start to overgrow your reef. Remove all the fish from all reefs for this round of play and add three fleshy algae to each reef.
 - ***Teacher Note:** Depending on the local time interval, this predator could be humans (overfishing), a shark, an Ichthyosaur etc.*
- **Nutrification** – After a large rainstorm, nutrients from nearby landmasses flood into the ecosystem, polluting the reef! All spaces on the board closest to the land are overgrown by fleshy algae unless the organism is tolerant of high nutrients (i.e., cover builders with fleshy algae). Note: if there is no land mass, you're ok!

- ***Teacher Note:** This is a good card for discussing Earth Systems connections, i.e., how nutrients from land impact marine systems.*
- **Pollution** – The crystal-clear waters of your reef are getting dirty! Sediments and nutrients from the land nearby got dumped onto your reef ecosystem! All organisms with **zooxanthellae** within two squares of land die unless they have a mutation that makes them tolerant of EITHER high nutrients or a high sediment load). Note: if there is no land mass, you're ok!
 - ***Teacher Note:** This is a good card for discussing Earth Systems connections, i.e., how nutrients and sediments from land impact marine systems.*
- **Deep freeze** – It's the coldest winter on record... Even here in the tropics the waters are getting chilly. Half of all reef builders in the deep water die unless they are tolerant of cooler water (e.g., they have a cold-tolerant mutation or organism characteristics).
- **Heatwave** – This summer is a scorcher, with record setting temperatures around the region! Half of all reef builders in the shallow water die unless they are tolerant of warmer water (e.g., they have a heat-tolerant mutation or organism characteristics).
- **Hurricane (near miss)** – A bad tropical storm blows through, missing the reef but making landfall nearby. Lots of rainwater runs over the land and floods the rivers, delivering freshwater and too many nutrients to the reef! The freshwater kills off all your sea urchins and the nutrients cause fleshy algae to take over all spaces on the board closest to the land unless that organism has a high nutrient tolerant mutation. Note: if there is no land mass, the rain (freshwater) still kills off all your sea urchins!
- **Hurricane (hit)** – Batten down the hatches, it's hurricane season! A bad tropical storm blows through and hits the reef! All reef builders in the shallow waters get battered by the waves and break unless they are encrusters or have strong skeletons (mutation or general characteristic). Delicate organisms in the middle depth (or those with a weakened skeleton) also break and die.
- **Gale Force Winds** – A bad storm blows through and hits the reef with big waves! All reef builders in the shallow waters get battered by the waves and break unless they are encrusters or have strong skeletons (mutation or general characteristic). Note: if there is no land mass nearby, the storm is extra rough and so all reef builders in the shallow waters die, no matter how strong they are.
- **Urchin Disease** – A nasty disease rips through the waters killing off all the sea urchins on your reef this round. Without the urchins, fleshy algae start to creep in; add two fleshy algae to each reef.
- **Coral Disease** – A nasty disease rips through the reef killing off all of the most abundant corals on your reef (i.e., the coral with the most 'individuals' is the one impacted by the disease, if it's a tie, choose which one you will sacrifice).
- **Spring Hypoxia** – Spring rains bring nutrients and freshwater into the ocean. As microbes gobble up the nutrients, they deplete the water of oxygen causing a short-term hypoxic event. All organisms (including stacked organisms) on the spaces of the board closest to the land die off unless they have a mutation for low oxygen tolerance. Microbialites and fleshy algae survive.

- **Tsunami Warning** – The Earth quakes and there’s a massive tsunami! Encrusters and reef builders with strong skeletons survive. Half of the remaining reef builders in shallow and medium water depths break and die.
- **Recruitment Problem** – Your reef is fine this round, but no new reef dwellers can be recruited in the following round.
- **Invasive Species** – A fast-growing coral takes over! Roll the dice to see which row of your reef is affected and remove everything from that row (reef dwellers are not affected); then place five Finger Corals on that row of your game board! A 1 means the corals take over the first row (the one closest to you), a 2 means the corals take over the second row, 3 = third row, and so on (for 7 through 12, subtract 6 from the roll, i.e., $7 - 6 = 1$, $12 - 6 = 6$, etc).
- **Invasive Fleshy Algae** – A bad algal bloom takes over your reef! Roll the dice to see which row of your reef is affected, then place five Fleshy Algae on that row of your game board (covering any reef builders in the way)! A 1 means the Fleshy Algae take over the first row (the one closest to you), a 2 means the Fleshy Algae take over the second row, 3 = third row, and so on (for 7 through 12, subtract 6 from the roll, i.e., $7 - 6 = 1$, $12 - 6 = 6$, etc).
- **Reproductive Stress** – Conditions are stressful for your reef builders and reproduction slows down. Remove all “More Offspring” mutations from all reef builders on the table.
 - *Teacher Note: This is a good card for discussing epigenetics and how environments can impact gene expression.*
- **Bad Luck** – It’s not your day, the reef gets hit with two catastrophes! Draw two additional cards, both events apply to all reefs (except the Coral Triangle).
- **Calm Seas** – Continue playing, no disasters today!

Long-term Disasters (grey edges)

- **Carbon Dioxide Pulse** – Too much carbon dioxide in the atmosphere! This change brings about warmer temperatures and more acidic conditions for thousands of years. Deep water environments experience lower pH and shallow waters experience lower pH AND higher temperatures. All reefs lose all carbonate organisms in the deep water unless they have an acid tolerant mutation AND lose all carbonate organisms in the shallow water unless they are BOTH acid and heat tolerant.
- **Oceanic Anoxic Event** – Long-term warming and changes in global conditions have resulted in an oceanic anoxic event. All organisms (including stacked organisms) in the deep water depths die off unless they have a mutation for low oxygen tolerance.
- **Corrosive waters from below** – Ocean currents change bringing up the coldest, most acidic water from the deep ocean. Lose any reef builder (including stacked organisms) made of carbonate in the deep waters unless they have a cold or acid tolerant mutation.
- **Glaciation** – Over tens of thousands of years glaciers build up at the North and South Poles. These glaciers freeze and store water from the ocean making the sea level drop, exposing the shallow reef. Reefs lose ALL organisms (including stacked organisms) in the shallow water for one round, then the glaciers retreat, and normal sea levels return.

Terminology Used (alphabetical)

Adapt – Over many generations, through the process of natural selection, an organism may evolve physical and behavioral traits (adaptations) to make survival/reproduction more likely in an environmental setting (higher evolutionary fitness for the particular environmental setting).

Adaptation – An adjustment (trait) of organisms to their environment to improve their chances of survival in that particular environmental setting (fitness).

Bathymetry – The depth of the ocean relative to sea level, essentially “underwater topography” or underwater terrain.

Benthic organism – An organism that lives on, in, or near the ocean bottom, also known as the benthic zone.

Carbonate – Formed from or predominantly made of calcite, aragonite, or other similar minerals.

Carbonate organism – An animal, plant, or single-celled life form that makes a structure (e.g., shell or skeleton) out of a carbonate mineral (e.g., calcite or aragonite).

Colonize – The process by which a species spreads to live in new areas. It often refers to the successful immigration of a population to a new area.

Diversity – The number of different types of organisms in a given community (also referred to as biodiversity or richness); usually measured as number of species.

Diverse – A community or population containing a high number of different types of organisms.

Ecological Competition – The struggle between organisms for resources they need to survive and reproduce within an environment. Some examples of these resources include food, water, shelter, light, territory, and space.

Ecosystem – A biological community of interacting organisms and their physical environment.

Encruster – an organism that attaches to the surface of something forming a hard crust.

Environment – The surroundings or conditions of an area in the natural world.

Environmental event – A (relatively) rapid change in the conditions of the environment, either regionally or globally.

Evolution – The changes in the characteristics or traits of biological types or species in a population over long intervals of time (multiple generations). The change in gene frequency within a population from one generation to the next.

Extinction – When the last existing member of a species dies; when there are no more living members of a species (that can reproduce) on the planet.

Extinct – A species that has no living members left.

Extirpation – A species that ceases to exist in a geographic area of study, but still exists elsewhere. Local extinctions are contrasted with global extinctions.

Fossil – The remains or impression of a prehistoric organism preserved in petrified form or as a mold or cast in rock.

Gene – The basic physical and functional unit of heredity (how traits are passed from one generation to another).

Genetic/Genetically – Relating to genes and heredity (e.g., genetic code, or genetic mutation).

Genetic Variation – Differences between individuals or populations as a result of gene frequencies.

Geography – The nature and relative arrangement of places and physical features.

Heredity – The passing on of physical or mental characteristics genetically from one generation to another such traits are heritable).

Juvenile – An individual organism that has not yet reached its adult form, sexual maturity, or size.

Marine – An organism that grows or lives in the ocean.

Microbe – A microscopic organism. In the game, the microbe breaks down the tissues of the organisms you are trying to fossilize during decay.

Microbial – Relating to or characteristic of a microscopic organism.

Migrate – To move from one region or habitat to another (noun = **migration**).

Mobile – An organism that has the ability to move around or change locations.

Mutate – To undergo a change in a gene or genes resulting in a variant form that can be transmitted to subsequent generations (noun = **mutation**).

Natural Selection – The differential survival and reproduction of individuals due to differences in their expressed traits or characteristics. It is a key mechanism of evolution.

Niche – The role of an organism within its community; niches may be occupied by different organisms in different localities or at different times.

Offspring – The young born of an adult organism (e.g., children are the offspring of their parents).

Organism – An individual animal, plant, or single-celled life form.

Photosynthesize – Generate sugars or other substances by means of Photosynthesis.

Photosynthesis – a process used by algae, plants, and other organisms to convert light energy from the sun into chemical energy to fuel the organisms' activities.

Planktic Organism – An organism that floats or drifts within the ocean water column between the ocean surface and the seabed.

Population – The number of organisms of the same species that live in a particular geographic area at the same time.

Reef – A hard structure on the ocean floor that is built by a community of organisms.

Reef Building Organism – An organism that creates the framework or structure of the reef with its body or skeleton.

Reef Dwelling Organism – An organism that lives on or benefits from interacting with the reef community.

Reproduction – The biological process by which new individual organisms (i.e., "offspring") are produced from their "parents" (verb = **Reproduce**).

Resilience – The ability of an organism, population, or community to withstand or recover quickly from difficult conditions or sudden change (adjective = **Resilient**).

Sediments – sediments (e.g., sand, mud, and gravel)

Sessile Organism – An organism that is anchored to a substrate and cannot move about freely.

Species – A group of living organisms consisting of similar individuals capable of exchanging genes or interbreeding.

Stressors – Something that causes a state of stress for a community or organism.

Stress – The physical, chemical, and biological conditions that diminish the productivity or success of organisms or the development of ecosystems.

Tsunami – a long high sea wave caused by an earthquake, submarine landslide, or other disturbance.

Zooxanthellae – single-celled algae that photosynthesize and live cooperatively inside many marine animals, such as corals. Zooxanthellae not only help the animals survive by photosynthesizing food, but they also result in beautiful colors! In turn, the animal provides the algae with a protected environment and nutrients.