Unit 4
Marine Productivity

In this unit, you will

- ***Discover patterns in global primary productivity.***
- ***Compare terrestrial and marine productivity.***
- ***Explore the key resources required for productivity.***
- ***Correlate variations in marine productivity with limiting resources.***
- ***Investigate sources of marine nutrients.***
- ***Synthesize observations to evaluate the causes of dead zones.***

NOAA

The ocean provides up to 20 percent of the world's food supply.

Warm-up 4.1

Bounty from the sea

Seafood makes up 20 percent of the world's food supply, with over one billion people depending on its resources for survival. As seafood harvests have increased over the past two centuries, populations of some species of marine life have decreased and have even become extinct. Given the ocean's vast area, it is difficult to locate, monitor, and track changes in stocks of commercially important fish and shellfish. Thus, scientists frequently use satellites to indirectly assess the health of fisheries and the ocean ecosystem.

A key indicator of the ocean's health is *primary productivity,* or the rate at which new organic material is produced through *photosynthesis* (Figure 1 at left). Photosynthesis is the process by which plant cells containing the green pigment *chlorophyll* use sunlight to convert water and carbon dioxide into the food (sugars and starches) and oxygen needed by most other organisms. Satellites can measure the amount of chlorophyll contained in single-celled plants in the ocean's surface layer, from which we can estimate primary productivity.

Food chains (Figure 2) and more complex food webs (Figure 3) illustrate feeding relationships among organisms in biological communities. At the base of food chains and webs are *autotrophs*, which produce their own food for growth and reproduction through photosynthesis. In the ocean, the primary autotrophs are phytoplankton, microscopic single-celled

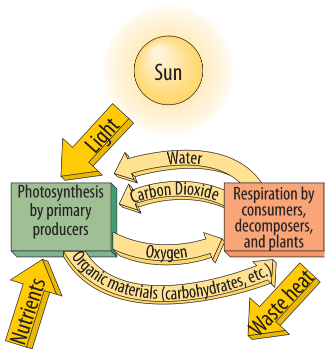


Figure 1. Photosynthesis and respiration.

Autotroph — ("self-feeder") organism that makes its own food rather than consuming other organisms.

Heterotroph — ("other-feeder") organism that consumes other organisms.

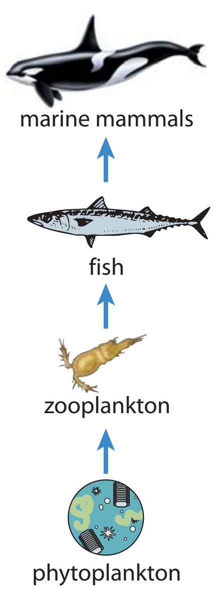


Figure 2. Simple marine food chain. Arrows represent the transfer of energy from one organism to another through consumption.

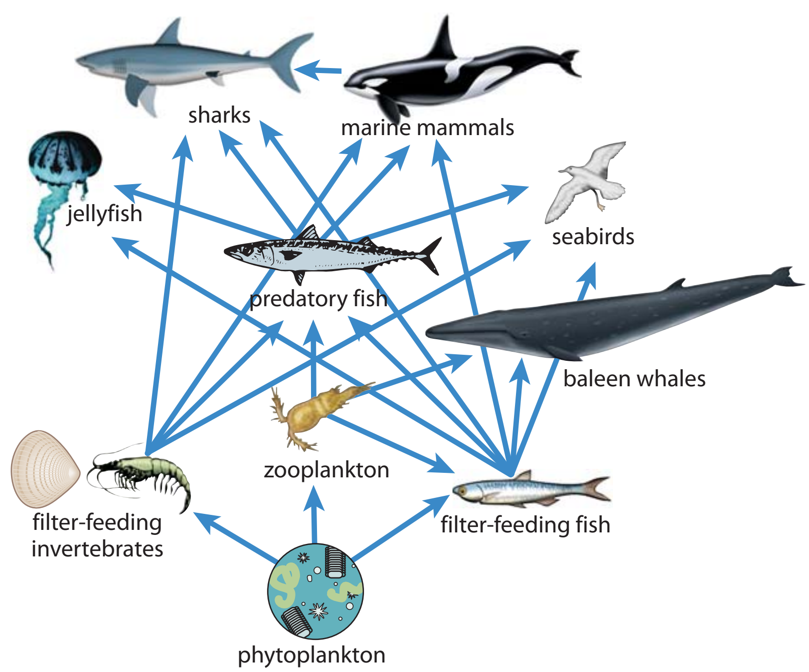


Figure 3. A marine food web.

plants that drift near the ocean surface. The remaining organisms in food webs are *heterotrophs*, which obtain food by feeding on other organisms.

Biotic community — group of interdependent organisms inhabiting the same region and interacting with one another.

Anchovies — a type of small fish, similar to sardines, that eat zooplankton.

Tuna — a type of large predatory fish that eat other fish.

The preservation of each link in a food web is critical for maintaining diverse and healthy *biotic communities*. However, certain organisms are more critical than others.

1. Examine the complex marine food web in Figure 3 on the previous page. Add anchovies (**A**), tuna (**T**), and humans (**H**) where you think they fit best. Draw arrows as needed to show consumption of and by other organisms.

2. What do you think would happen if all of the autotrophs were removed from the marine food web?

3. What do you think would happen if one of the heterotrophs, such as the predatory fish, were removed?

4. How do humans influence food webs?

Respiration — process by which organisms oxidize or "burn" food, producing water and carbon dioxide.

Nutrients — chemical compounds that are used by bacteria and plants as the building blocks for organic material. Common nutrients include:

- phosphates (PO_4^-)
- nitrates (NO_3^-)
- silica (SiO_4^-)
- iron (Fe^{3+})

Photosynthesis requires four key ingredients: water, sunlight, nutrients, and carbon dioxide. For marine autotrophs like phytoplankton, there is plenty of water available in the oceans. Carbon dioxide is also abundant in ocean waters. It is released as a by-product of *respiration*, and it is readily absorbed into the ocean from the atmosphere. Thus, water and carbon dioxide are not limiting resources for photosynthesis or primary productivity in the ocean. However, marine productivity is controlled or limited by the availability of the other two necessary resources — sunlight and nutrients.

5. How do you think the availability of limiting resources might vary in the ocean? (Where or when would they be high or low?)

6. Considering the availability of limiting resources, where would you expect phytoplankton to be most productive or least productive? (Near the equator or near the poles? Near the coast or in the open ocean?)

7. How is the productivity of autotrophs important to society? Describe three different ways in which a severe decrease in primary productivity would affect society.

   a.

   b.

   c.

Investigation 4.2

The life-giving ocean

Photosynthesis

The general chemical equation for photosynthesis is:

$$6\,CO_2 + 6\,H_2O \xrightarrow{\text{sunlight}} C_6H_{12}O_6 + 6\,O_2$$

carbon dioxide — water — glucose (carbohydrate) — oxygen

NASA

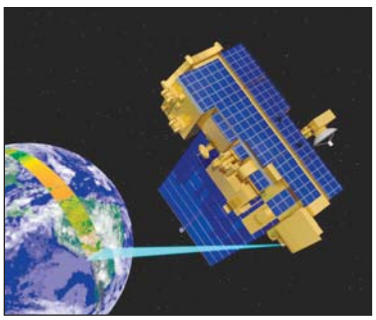


Figure 1. The MODIS (MODerate-resolution Imaging Spectrometer) instrument on the Terra satellite is the latest tool for measuring primary productivity from space.

Phytoplankton are tiny — several of them could fit side-by-side across the width of a human hair — but collectively, they pack a wallop. Phytoplankton are *primary producers*, serving as the first link in almost every food chain in the ocean. They transform water and carbon dioxide into carbohydrates, which they use for producing energy for growth and reproduction. Phytoplankton, in turn, are food for other organisms, passing carbohydrates and other nutrients up the food chain. Because phytoplankton release oxygen during photosynthesis, they also play a significant role in maintaining the proper balance of Earth's atmospheric gases. Phytoplankton produce about half of the world's oxygen and, in doing so, remove large amounts of carbon dioxide from the atmosphere.

Given the central role of phytoplankton in stabilizing the mixture of gases in Earth's atmosphere and in providing food for other organisms, it is important to monitor their location and rate of productivity. Although it is impossible to directly measure the productivity of phytoplankton on a global scale, there are several ways of making indirect calculations. One method relies on the distinctive way that chlorophyll, the green pigment in phytoplankton and other plants, reflects sunlight. By using satellites to measure the chlorophyll concentration of the ocean surface layer, scientists can estimate the rate at which phytoplankton produce carbohydrates (Figure 1). Because carbon is the key element in the process, productivity is measured in terms of kilograms of carbon converted per square meter of ocean surface (kgC/m^2) per year.

Global primary productivity

Primary productivity — the rate at which new organic material is formed by photosynthesis.

In this exercise you will examine global *primary productivity* and its relation to the factors that support phytoplankton growth.

- Launch ArcMap, and locate and open the **ddoe_unit_4.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **Primary Productivity** data frame and choose Activate.
- Expand the **Primary Productivity** data frame.

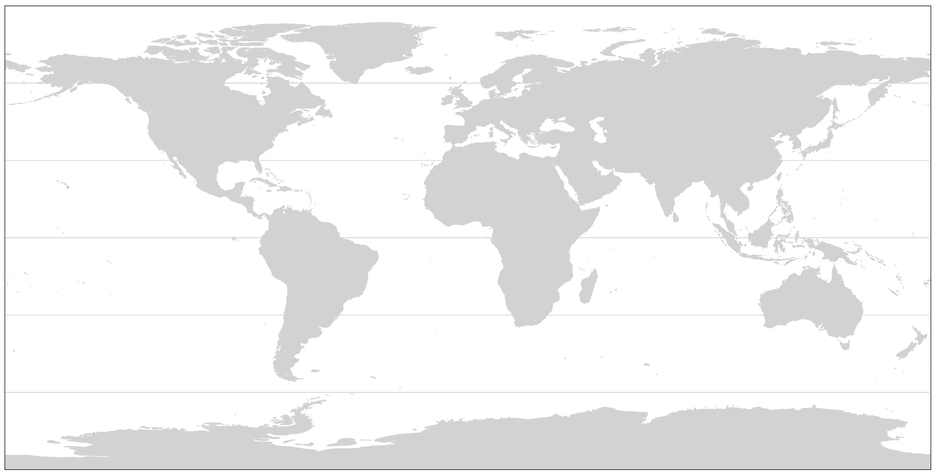
This data frame shows the average annual primary productivity for terrestrial and marine environments. During their respective winters, regions near the north and south poles receive little or no sunlight, making satellite measurements impossible. Nonetheless it is reasonable to assume that, with no sunlight during winter, there is relatively little primary productivity in these regions .

1. What colors represent areas of highest and lowest productivity?
   a. Highest.

   b. Lowest.

2. On Map 1, circle the land areas with the highest productivity using solid lines, and the land areas with the lowest productivity using dashed lines.

Map 1 — Areas of highest and lowest productivity



- Turn off the **Terrestrial Productivity** layer.
- Using the Zoom In tool, examine, in detail, the areas with the highest marine productivity.
- When you are finished, click the Full Extent button to zoom back out to view the entire map.

3. Mark the ocean areas with highest productivity on Map 1 using the label **H** (high), and the ocean areas of lowest productivity using the label **L** (low).

4. Where is marine productivity generally
   a. highest?

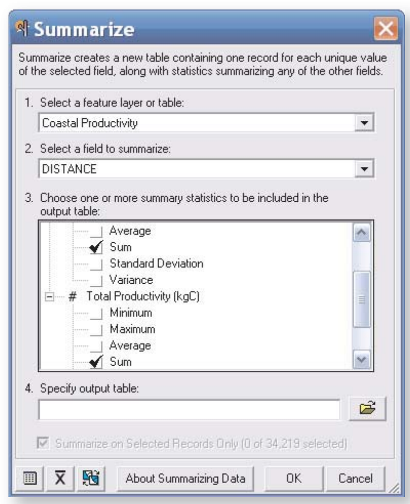
   b. lowest?

5. Compare the locations of regions of high terrestrial and marine productivity on Map 1. Describe any geographic patterns or similarities in their distribution.

Productivity and distance from coast

Next, you will examine productivity near the coastline in greater detail.

- Turn off the **Marine Productivity** layer.
- Turn on and expand the **Coastal Productivity** layer.
- Click the Summarize button Σ.
- In the Summarize window, select **Coastal Productivity** as the **feature layer**.
- Select **Distance** as the **field to summarize** in the drop-down menu.
- Double-click **Area (sq km)** to display the statistics options, check **Sum.**



- Next, double-click **Total Productivity (kgC)** to display the statistics options, check **Sum,** and click **OK**. (Be patient — summary tables may take a while to process.)

In the resulting summary table, the **Sum TOTAL_Prod** field gives the total productivity, and the **Sum_PROJECTED** field gives the total area, for each coastal zone. These values are very large, in the trillions. One trillion is the word for the number value 1,000,000,000,000.

Converting to trillions

Move the decimal point 12 places to the left, then round to the appropriate decimal place.

Example:

27656585301787.3

= 27.7 trillion

Calculating average productivity

To calculate average productivity, divide the Total Productivity by the Total Area. Be sure to write both measurements in trillions, so the trillions will cancel each other.

Example:

$$\frac{\text{Total Productivity}}{\text{Total Area}} = \frac{27.7 \text{ ~~trillion~~ kgC}}{211.0 \text{ ~~trillion~~ m}^2}$$

$= 0.13 \text{ kgC/m}^2$

Nutrients — chemical compounds that are used by bacteria and plants as the building blocks for organic material. Common nutrients include:

- phosphates (PO_4^-)
- nitrates (NO_3^-)
- silica (SiO_4^-)
- iron (Fe^{3+})

6. Record the total productivity and total area for each coastal zone in Table 1. Round productivity and area to the nearest 0.1 trillion. (See sidebar for help with converting values to trillions.)

Table 1 — Marine productivity with distance from coastline

Coastal zone	Total productivity *trillion kgC*	Total area *trillion m²*	Average productivity *kgC/ m²*
Open Ocean (> 960 km)	27.7	211.0	0.13
Far (640 – 960 km)			
Mid (320 – 640 km)			
Near (0 – 320 km)			

7. Calculate the average marine productivity for each zone and record your results in Table 1. Round to the nearest 0.01 kgC/m^2. (See sidebar for help calculating average productivity.)

8. What happens to the level of marine productivity as the distance seaward from the coastline increases?

9. Of the resources necessary for photosynthesis (water, sunlight, carbon dioxide, and nutrients), which do you think is most likely to change with distance from the coast to produce the pattern you observe in Table 1? Explain your answer.

Close the summary table.

Understanding the patterns

In this section, you will determine when and where sunlight and nutrients control marine productivity. You will examine nitrates and phosphates, but other nutrients like silica and iron affect productivity in similar ways.

Turn off and collapse the **Coastal Productivity** layer.

Turn on the **Marine Nutrients** layer group.

Turn on and expand the **Nitrates** layer.

Micromoles

Micromolarity is a measure of concentration used to describe very weak solutions. The metric prefix *micro* represents one millionth. A *mole* is 6.02×10^{23} molecules (or atoms), so a micromole is one millionth of a mole, or 6.02×10^{17} molecules. That seems like a lot, but when dissolved in a liter of water (55.5 moles, or about 3.34×10^{25} water molecules) it's only one molecule of nutrient for every 200 million water molecules. That's a weak solution.

Latitude bands

Low latitudes

0° – 30° N and S
near equator

Middle latitudes

30° – 60° N and S
between equator and poles

High latitudes

60° – 90° N and S
near poles

Nitrates and phosphates are important nutrients that are used by autotrophs for building complex molecules needed for growth and development. The **Nitrates** layer displays the average annual level of nitrates in the world's oceans in terms of *micromolarity*, or millionths of a mole of nitrate per liter of seawater (see sidebar).

10. Which latitude bands have the highest and lowest concentrations of nitrates? (See *Latitude bands* sidebar for help.)
    a. Highest.
    b. Lowest.

Turn off and collapse the **Nitrates** layer.

Turn on and expand the **Phosphates** layer.

The **Phosphates** layer shows the average annual concentration of phosphates in the world's oceans in terms of micromolarity.

11. Which latitude bands have the highest and lowest concentration of phosphates?
    a. Highest.
    b. Lowest.

12. Are the patterns for both nutrients similar? If not, how do they differ?

Turn off and collapse the **Phosphates** layer.

Turn on the **Solar Radiation Flux** layer.

This layer shows the average annual solar radiation that strikes Earth's surface, in watts per square meter (W/sq m).

Click the Media Viewer button and open the **Solar Flux Movie**.

This animation shows changes in solar radiation throughout the year. The time of year and the legend appear at the bottom of the image.

View the movie several times.

Use the **Solar Radiation Flux** layer and the **Solar Flux Movie** to answer the following questions.

13. Near what latitude is the average solar radiation throughout the entire year

    a. highest?

    b. lowest?

14. How does the pattern of nutrient concentration you noted in questions 10 and 11 compare to the pattern of solar radiation? Explain your answer.

- Close the Media Viewer window.
- Click the Media Viewer button, and open the **Productivity Movie**.

This animation shows marine productivity throughout the year. The time of year is indicated at the top of the image, and the legend appears at the bottom. Black areas at high latitudes are where there was no sunlight during the winter; you may assume these areas have relatively little productivity.

- Study the movie to examine how productivity changes throughout the year. Focus on only the extreme high and low levels of productivity. You will need to play the movie several times to fill in Table 2.

15. In Table 2, enter the months and season when productivity is highest and lowest in each hemisphere. (See sidebar for help with the seasons.)

Table 2 — Productivity extremes by hemisphere

Hemisphere	Months of high productivity	Season	Months of low productivity	Season
Northern				
Southern				

- Close the Media Viewer window.

Earth's Seasons are

- Caused by the tilt of Earth's axis.
- Opposite in the Northern and Southern Hemispheres.

Dates (typical)	Hemisphere	
	N	S
Dec 21 – Mar 20	Winter	Summer
Mar 20 – Jun 21	Spring	Fall
Jun 21 – Sep 22	Summer	Winter
Sep 22 – Dec 21	Fall	Spring

There is very little seasonal variability in nutrients in the high-latitude oceans because the *thermocline,* or temperature gradient between shallow and deep water, is small, due to low solar-radiation input. This allows free circulation between deep nutrient-rich water and shallow nutrient-poor water. The year-round strong solar radiation in equatorial regions creates a strong thermocline (warm shallow water and cold deep water), which inhibits shallow- and deep-water circulation. Equatorial upwelling does bring nutrients to the surface in some areas, but nutrient levels are generally low at low latitudes, particularly during the summer when the air is very stable and winds are weak.

16. Discuss the influence that each of the following factors has on productivity at *high* latitudes, and how productivity in high-latitude regions may change with the seasons.

    a. Sunlight.

    b. Nutrients.

17. Discuss how sunlight and nutrient levels contribute to the productivity pattern at *low* latitudes, and how productivity in that region may change with the seasons.

    a. Sunlight

    b. Nutrients

In the next activity, you will learn more about marine productivity, the sources of marine nutrients, and the processes that bring nutrients to the surface near the coastlines and in the open ocean.

Quit ArcMap and do not save changes.

Reading 4.3

Resources for productivity

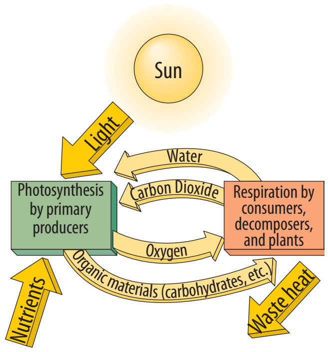


Figure 1. Photosynthesis and respiration.

NOAA

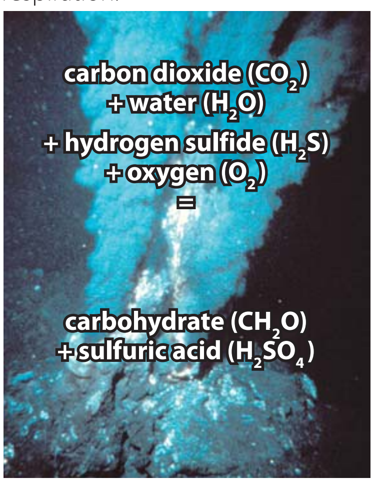


Figure 2. Process of chemosynthesis.

NOAA

Figure 3. Tube worms at hydrothermal vents consume chemosynthetic bacteria.

Mean, green food-making machines

With few exceptions, life on Earth depends on **photosynthesis**, the biological process that converts solar energy and inorganic compounds into food. Only autotrophs or "producers," including green plants and phytoplankton, are capable of photosynthesis. They contain the pigment **chlorophyll**, which uses solar energy to convert carbon dioxide and water into carbohydrates (Figure 1). The amount of carbon converted to food by autotrophs is referred to as **primary productivity**. Autotrophs use some of this food immediately, and store the remainder for later use, to be converted back to energy through the process of **respiration**. Phytoplankton are consumed by other organisms which are, in turn, consumed by other organisms up the food chain. Collectively, these consumer organisms are called **heterotrophs**.

Exceptions to the rule

Green plants and phytoplankton are not the only organisms capable of synthesizing their own food. In the last 40 years, scientists have discovered biological communities that are not based on the sun's energy. The autotrophs in these communities are microbes that convert carbon dioxide and water into food using chemicals rather than sunlight. This process is called **chemosynthesis** (Figure 2). Chemosynthetic bacteria thrive in the high temperatures and pressures of environments like deep-sea volcanic vents. They synthesize food using the chemical energy of sulfur compounds emerging from the vents. Chemosynthesis supports a diverse community of organisms (Figure 3).

Food for thought—bottoms up!

Food webs illustrate the feeding relationships among organisms in a biotic community. The arrows represent the transfer of energy from one organism to another through consumption (Figure 4). Autotrophs produce most of Earth's atmospheric oxygen as a by-product of photosynthesis, and are

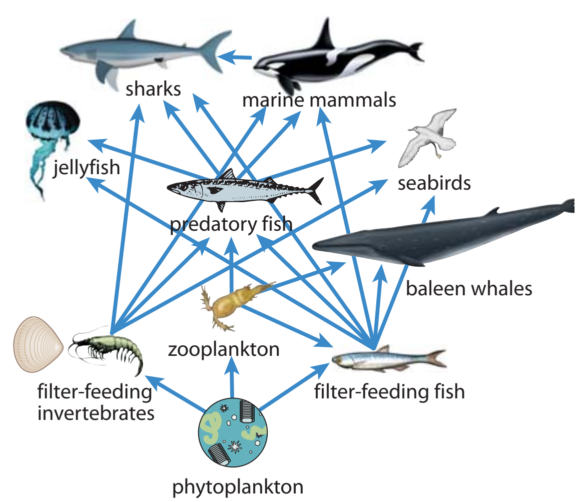


Figure 4. Marine food web.

the foundation of nearly all terrestrial and aquatic food chains. Thus, primary productivity in terrestrial and marine environments is a key indicator of the overall health of the environment. Our ability to monitor primary productivity has profound economic and environmental importance.

1. Compare and contrast the two processes that autotrophs use to synthesize food.

2. What does the number of arrows leading *from* one organism to others suggest about that organism's importance in the food web?

3. What does the number of arrows leading *to* an organism suggest about that organism's likelihood of becoming endangered or extinct?

Resources for photosynthesis

Primary productivity levels vary with season and geographic location. You have identified and examined regions of extremely high and low productivity on land and in the ocean. These patterns of productivity are dictated by the availability of the resources necessary for photosynthesis. Autotrophs require carbon dioxide, water, sunlight, and nutrients to photosynthesize (Figure 1 on the previous page). When these resources are not present in adequate amounts for photosynthesis, they are referred to as limiting factors. Below, you will examine the likelihood of each resource being a limiting factor in productivity.

Carbon dioxide

Carbon dioxide is not likely to be a limiting factor in terrestrial or marine photosynthesis because it is plentiful in the atmosphere, as a result of respiration and human activities. As organisms convert food into energy, they release carbon dioxide (Figure 1). When humans burn fossil fuels like petroleum, coal, and natural gas, huge quantities of carbon dioxide are released into the atmosphere. Carbon dioxide is readily absorbed into the ocean from the atmosphere, so it is in good supply there as well.

Water

Water is often a limiting factor for productivity in terrestrial environments. Productivity in deserts is very low because deserts lack the water needed to sustain many plants. In the ocean, water is never a limiting factor.

Sunlight

In the context of productivity, the sun's most important role is providing the light energy that drives photosynthesis. The availability of light to autotrophs varies, depending on latitude, season, and time of day. Therefore, there are places and times where sunlight is a limiting factor.

Nutrients

Autotrophs use inorganic compounds containing nitrogen, phosphorus, potassium, calcium, silicon, and iron to build organic molecules. The concentrations of these **nutrients** vary throughout the environment. Nitrogen and phosphorus are particularly important because they are required in large quantities and play a critical role in growth and reproduction. Inorganic forms of nitrogen are the building blocks for amino acids, proteins, and genetic material (DNA, RNA). Similarly, phosphorus is an essential component of energy transport molecules (ATP), genetic material, and structural materials (bone, teeth, shell).

Despite the abundance of nitrogen gas in the atmosphere, it is often a limiting resource because it can be utilized by autotrophs only in certain forms. In the **nitrogen cycle**, nitrogen gas is converted to its most useful form, nitrate, through a series of reactions carried out by bacteria and fungi in the soil (Figure 5). Nitrates may be utilized by land plants, or may be carried to the ocean in groundwater or runoff and used by phytoplankton.

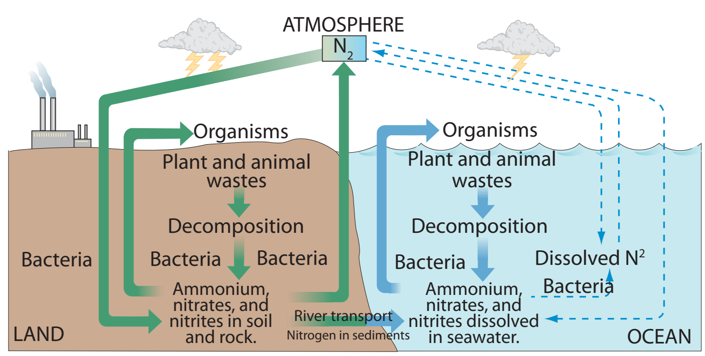


Figure 5. The nitrogen cycle.

Unlike nitrogen, phosphorus never exists as a gas. Phosphorus originates in rocks in Earth's crust in the form of phosphate salts, which are liberated from rocks by weathering (Figure 6 on the following page). Phosphates are also an ingredient in some detergents and fertilizers. Precipitation carries phosphates into the soil, and runoff and ground water transport them to the ocean.

Organic or inorganic?

The terms **organic** and **inorganic** originally came from the idea that chemical compounds could be divided into two categories: those coming from or composed of plants or animals (organic), and those extracted from minerals and ores (inorganic).

Chemists now think of organic compounds as those that contain carbon. This definition works well for many compounds, but there are exceptions. For example, carbon dioxide is a carbon-based compound, but it is not considered organic.

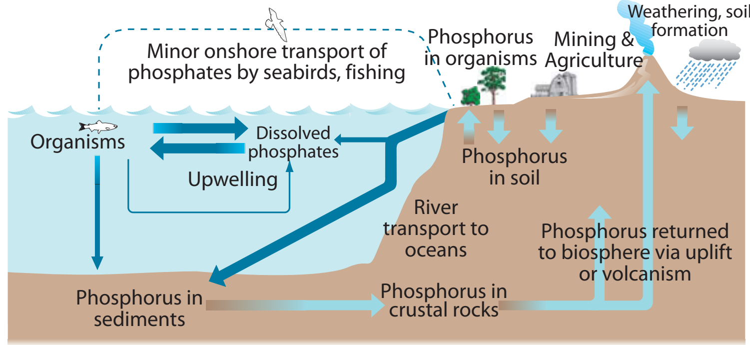


Figure 6. The phosphorus cycle.

4. Various human activities contribute additional nutrients to the ocean ecosystem. How might these additions influence marine productivity?

Sources of nutrients

Most of the nutrients utilized by phytoplankton in surface waters originate on land. Nitrates and phosphates in the soil dissolve easily in water. These nutrients are easily leached or removed from the soil by precipitation and runoff, and are carried by groundwater, streams, and rivers to the ocean. Near the coasts, phytoplankton thrive on the nutrients entering the ocean from land, resulting in high productivity. However, large portions of the nutrients entering the ocean are not utilized and eventually sink to the ocean floor, accumulating in the sediment.

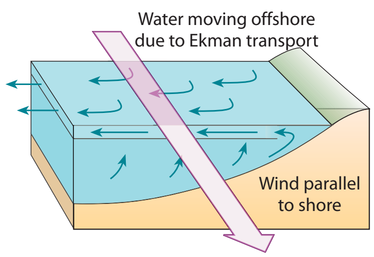


Figure 7. Coastal upwelling.

Not all nutrients enter the ocean from land. When marine plants and animals die they sink to the bottom, where decomposition liberates the nutrients, making them available for use again. However, except in shallow waters over the continental shelf, the nutrients on the ocean bottom can be utilized only when they are brought from the depths to the surface via **upwelling**, the upward movement of deep, cold bottom water to the surface. Coastal upwelling occurs in nearshore environments where strong winds blow parallel to the shore (Figure 7). **Ekman transport** causes the surface currents to deflect away from the shore, which pulls deep, cold, nutrient-rich water toward the surface. As you learned in Investigation 2.2 and Reading 2.3, Ekman transport is an offset between a current direction and its associated wind. In the Northern Hemisphere Ekman transport is deflected to the right, and in the Southern Hemisphere Ekman transport is deflected to the left. This phenomenon is caused by the Coriolis effect and by the slowing and deflection of water due to friction among successively deeper layers of water.

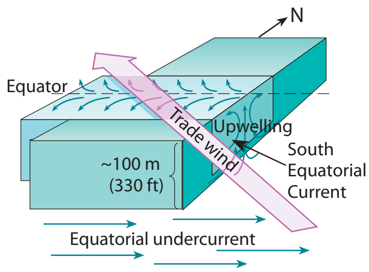


Figure 8. Equatorial upwelling.

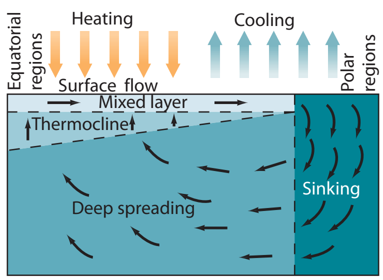


Figure 9. Schematic cross section of the ocean from equatorial to polar regions, showing change of depth to thermocline with changing latitude.

Upwelling also occurs in the open ocean, near the equator. Equatorial upwelling is controlled by ocean currents — water moving westward on either side of the equator is deflected toward the poles and is replaced by cold, nutrient-rich water from below (Figure 8).

In the previous examples, upwelling is characterized by either winds or currents that move surface water and allow deeper water to "well up" in its place. The action of the wind or current is especially important in regions where there is a strong **thermocline**, a region where the water temperature changes rapidly with depth (Figure 9). Waters near the equator typically have a strong thermocline that traps nutrients in the cold, deep waters below, where they eventually sink to the ocean floor. At low latitudes, the mechanical action of strong winds or currents is necessary for nutrient-rich waters to penetrate the thermocline and rise to the surface.

In contrast, in high-latitude regions, upwelling can occur without the help of strong winds. These regions receive little or no sunlight, resulting in a weak or nonexistent thermocline. As dense water sinks, it is replaced by an equal volume of nutrient-rich water rising from the adjacent depths.

5. What process makes nutrients in deep-ocean sediments accessible to marine phytoplankton drifting near the ocean surface?

6. Explain how the strength of the thermocline affects the availability of nutrients to primary producers.

7. Human activities can increase levels of nutrients in the ocean. Describe how human activities could influence the levels of *other resources* important in photosynthesis.

Too much of a good thing?

Previously, you observed that a shortage of one or more resources can decrease productivity. It may surprise you to learn that there can also be too much of a good thing when it comes to photosynthesis. For example, if the amount of solar energy received by the ocean were to intensify dramatically, tropical oceans could become too warm for photosynthesis to proceed properly.

Similarly, nutrients can be present in quantities so high that they become harmful. High levels of nutrients in coastal waters may cause a sharp increase in phytoplankton, which reduces light penetration, clogs the gills of marine organisms, and pollutes the water with waste products, some of which are toxic to other marine life. This may lead to **hypoxia**, a dramatic decrease in dissolved oxygen, or even **anoxia**, a total absence of dissolved oxygen, which can drive away mobile organisms and kill **sedentary organisms**.

Two conditions contribute to hypoxia in subsurface waters.

- **Stratification,** or layering of the water column. Nutrient-laden runoff flowing into the ocean is less dense than salt water and floats on the surface. In summer, warm weather and calm seas inhibit mixing of the shallow, warm water with deeper, colder water. As a result, the oxygen from photosynthesis remains at the surface.

- **Increased decomposition** at depth, due to higher surface productivity. Phytoplankton die or are eaten by other organisms, creating large amounts of organic waste that sinks to the ocean floor. As the waste decomposes, nutrients are recycled but oxygen is also consumed, creating hypoxic conditions.

Sedentary organisms — organisms that are attached to a surface and cannot move freely.

The Gulf of Mexico is an important U.S. commercial fishery. In 2002, the Gulf accounted for 16.9 percent by weight (771,000 metric tons [850,000 U.S. tons]) and 24.7 percent by dollar value ($693 million) of the entire U.S. fish and shellfish catch. Each summer, a large hypoxic region known as the **Mississippi River dead zone** forms off the coast of Louisiana (Figure 10). The lack of dissolved oxygen in this region causes both the quantity and the diversity of economically important marine life to decrease dramatically, with potentially dire economic consequences.

Figure 10. Location and extent of the 1993 Mississippi River dead zone.

8. Describe how an increase in nutrient levels can actually *lower* marine productivity in the marine ecosystem.

9. Name two human activities that could result in an overabundance of nutrients being delivered to coastal waters. Explain your answer.

Is the Mississippi River dead zone unique?

In the U.S. alone, more than half of the estuaries experience hypoxia during the summer; up to a third experience anoxia.

10. How might reduced light penetration affect primary producers as well as other animals higher up the food chain?

In the next investigation, you will examine changes in the Mississippi River dead zone from 1986 to 1993, and investigate patterns in the distribution of dead zones around the world.

Investigation 4.4

Dead zones

There are parts of the ocean where no fish swim, and where the bottom may be littered with the remains of bottom-dwelling crabs, clams, and worms. These areas, known as *dead zones*, pose a growing environmental concern. The causes of dead zones are complex and involve pollution in the form of excess nutrients from agriculture, industry, urbanization, and other sources.

Creating a dead zone

One of the largest dead zones in the world occurs in the northern Gulf of Mexico, where the Mississippi River flows into the open ocean off the coast of Louisiana. Starting in the 1950s, the waters of the Mississippi River began to show signs of elevated nutrient levels, particularly nitrogen compounds from agricultural runoff in the Mississippi River basin. At the same time, a dead zone began to form adjacent to the Mississippi delta in the Gulf of Mexico.

In this investigation, you will look at the size of the Mississippi River dead zone over time, and compare it to dead zones on the east coast of the U.S. and around the world. This will help you to better understand how and where dead zones form, and to predict where they may develop in the future.

- Launch ArcMap, and locate and open the **ddoe_unit_4.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **Mississippi River Dead Zone** data frame and choose Activate.
- Expand the **Mississippi River Dead Zone** data frame.

The Mississippi River dead zone

Watershed — the total area of land drained by a river and its tributaries.

This data frame shows the Mississippi River and the Mississippi River *watershed*. The 31 states that are either partially or completely within the Mississippi River watershed boundary are shown in gray.

The Mississippi River watershed covers are large part of the 48 contiguous states, and many activities affect the quality of the water before it empties into the Gulf of Mexico. Next, you will examine how water is used, to identify possible sources of the excess nutrients in the Mississippi River dead zone.

- Turn on the **Water Consumption** layer.

Water-use sectors

- *Commercial* — facilities and institutions including hotels, restaurants, hospitals, and schools.
- *Domestic* — household use.
- *Industrial* — producing steel, chemicals, paper, plastics, minerals, petroleum, and other products.
- *Power* — steam-driven electric generators. (Does not include hydroelectric power.)
- *Mining* — extracting minerals, oil, and natural gas.
- *Agriculture* — raising animals and irrigating crops.

This layer consists of pie charts for the 48 contiguous states, each showing the percentage of water consumed by six major water-use sectors (see sidebar). The overall size of each pie represents the total amount of water consumed by that state, and the slices represent the percentage of water used by each water-use sector.

1. Which activities are the primary consumers of water in states within the Mississippi River watershed?
   a. Eastern portion of the watershed.

   b. Western portion of the watershed.

2. How might these activities contribute to nutrient enrichment of the Mississippi River?

Turn off and collapse the **Water Consumption** layer.

Turn on the **Precipitation** layer.

This layer shows average precipitation, in centimeters per year. Areas with low precipitation are shown in yellow and brown, and areas with high precipitation in blue.

3. Where is precipitation in the Mississippi River watershed
   a. highest?

   b. lowest?

Runoff from the land is one mechanism for transporting nutrients from farms and fields to the river.

4. Study the precipitation patterns, then predict where you would expect runoff to be highest in the Mississippi River watershed.

- Turn off the **Precipitation** layer.
- Turn on the **Runoff** layer.

This layer shows average runoff within the Mississippi River watershed, in centimeters per year. Dark blue represents high runoff and light blue represents low runoff.

5. Which part of the Mississippi River watershed has the highest annual runoff?

6. Describe any relationships you observe between the precipitation and the runoff patterns.

7. How might levels of precipitation and runoff influence the size of the Mississippi River dead zone?

- Turn off the **Runoff** and **Mississippi River System** layers.

Development of the Mississippi River dead zone

In this section, you will look at the extent of the dead zone during four different time periods, and compare the size of the dead zone to the climate data for the Mississippi River watershed during those four periods.

- Click the QuickLoad button.
- Select **Spatial Bookmarks**, choose **Gulf of Mexico**, and click **OK**.

In 1985, scientists began sampling water off the Louisiana coast to monitor the extent and characteristics of the Mississippi River dead zone.

- Turn on the **Mississippi River Dead Zone** layer group.
- Turn on the **1986 Dead Zone** layer.
- Click the Identify tool .

- In the Identify Results window, select the **1986 Dead Zone** layer from the list of layers.
- Click inside the dead-zone to display the area of the dead zone for that year.

8. Record the area of the dead zone in Table 1. Round to the nearest 1 km^2.

Table 1 — Mississippi River dead-zone data

Year	Area km^2	Area rank	Drought appearance
1986			
1988			
1990			
1993			

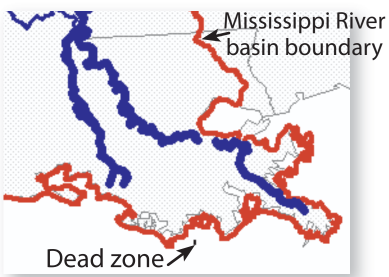


Figure 1. Location of 1988 Mississippi River dead zone.

- Turn off the **1986 Dead Zone** layer.
- Repeat these steps using the **1988 Dead Zone**, **1990 Dead Zone,** and **1993 Dead Zone** layers. Remember to turn on each layer and select it in the Identify Results window. Record the area of each dead zone in Table 1. See Figure 1 for the location of the 1988 dead zone.
- Close the Identify Results window.

9. In Table 1, rank the areas of the dead zones from 1 (largest) to 4 (smallest).

- Close the Identify Results window.
- Turn off all **Dead Zone** layers.
- Click the QuickLoad button.
- Select **Spatial Bookmarks**, choose **U.S. 48** , and click **OK**.
- Turn on the **Mississippi River Basin PDSI** layer group.
- Turn on the **1986 Drought Index** layer.

In the **Mississippi River Basin PDSI** layer group, green (index > 0) represents areas that are wetter than normal, and brown (index < 0) represents areas that are drier than normal.

10. In Table 1, describe the overall climate of the Mississippi River watershed for each of the four years, using one of the following descriptions: *very wet*, *wet*, *dry*, or *very dry*. Turn the four **Drought Index** layers on and off as needed to complete the table.

11. Using the data in Table 1, describe how the areas of the dead zones appear to respond to the climate conditions in the Mississippi River watershed.

12. Explain the changes in the area of the dead zone in terms of runoff and nutrients in the Gulf of Mexico.

The Mississippi River dead zone is not the only one in the U.S. or the world. Next, you will examine potential factors that may contribute to the formation of other dead zones.

Global dead zones

- Click the QuickLoad button.
- Select **Data Frames**, choose **Global Dead Zones**, and click **OK**.

The **Global Dead Zones** data frame shows the locations of dead zones throughout the world.

13. Describe the locations of the two primary clusters of dead zones.

Dead zones and population

Some scientists have noted that dead zones are related to the density of human populations of the adjacent continents. Many believe that dead zones may become the most significant human impact on oceans and ocean ecosystems in the 21st century. In this section, you will investigate this idea and the ways in which increasing populations influence the size and number of dead zones.

14. If dead zones are related to areas with high population density, where on the map would you expect to find areas with high population density?

You can test your prediction by looking at the global population distribution, and see how it relates to the current distribution of dead zones.

- Turn on the **Global Population** layer.

The **Global Population** layer shows the population for 1°× 1° *cells* (approximately rectangular regions within a grid) over Earth's surface.

How large an area is a 1° x 1° cell?

The spacing between latitude lines is fairly constant, but the spacing between longitude lines decreases with distance from the equator. Thus, the areas of 1° x 1° cells get smaller with increasing distance from the equator.

At the equator, a 1° x 1° cell has an area of about 12,500 km^2. At 60° latitude, the area of a 1° x 1° cell is only half that size, about 6200 km^2.

15. Some scientists argue that high population density cause dead zones. Examine the global patterns of population density and dead zones. Describe any observations that

    a. *support* (provide evidence in favor of) the idea that high population density causes dead zones.

    b. *refute* (provide evidence against) the idea that high population density causes dead zones.

There appears to be a connection between high population density and the formation of dead zones, but it is not a clear or consistent relationship. One possibility is that there is some important difference (other than size) between the populations adjacent to the regions where dead zones form and those near regions where dead zones do not form. Next, you will explore the possibility that *economic differences* among populations are a factor in the formation of dead zones.

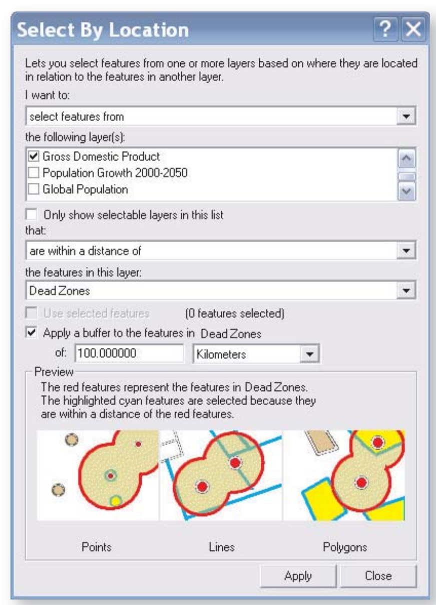
- Turn off the **Global Population** layer.
- Turn on the **Gross Domestic Product** layer.

Gross Domestic Product (GDP) is the total value of goods and services produced by a nation within that nation's boundaries. Indirectly, it is a measure of the resources (energy, raw materials, people) available to and utilized by that nation.

Now you will determine the average GDP of countries adjacent to dead zones and compare it to the average GDP of countries without dead zones.

- Click the Select By Location button.
- In the Select By Location window, construct the query statement:

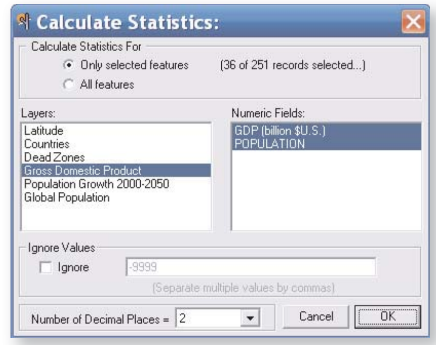
  I want to **select features from** the **Gross Domestic Product** layer that **are within a distance of** the features in the **Dead Zones** layer.
- Check the box to **Apply a buffer to the features in Dead Zones** and enter 100 kilometers.
- Click **Apply**.



- Close the Select By Location window.

The countries that are near dead zones will be outlined. Next you will calculate statistics on the selected data.

- Click the Statistics button.
- In the Statistics window, calculate statistics for **only selected features** of the **Gross Domestic Product** layer, using the **GDP (billion $U.S.)** and **Population** fields. (Hold down the shift key to select multiple fields.)
- Click **OK**.



In the Statistics window, the number of countries adjacent to dead zones is given as the **Number of Records** and the GDP and population of those countries are given as the **Total**.

16. Record the number of countries (**Number of Records**), the GDP (**Total**), and the Population (**Total**) in Table 2. Record the values in the units shown in the table, to the nearest whole number for Total GDP and to the nearest 0.01 billion for Total Population.

Per capita [Latin] — for each person.

Why use GDP per capita?

A large country may have a higher GDP than a smaller country simply because it has more people, even though the people in the smaller country may individually produce more goods and services. To correct for this, we use GDP per capita (i.e., per person) — the amount of goods and services produced by a country, divided by the number of people in that country.

Table 2 — Relationship of GDP per capita and presence of dead zones

	Number of countries	Total GDP *billion $U.S.*	Total population billion	GDP per capita
Near dead zones				
Not near dead zones				

- Close the Statistics window.
- Select the **Gross Domestic Product** layer.
- Click the Switch Selection button.

The countries that are *not* near dead zones will be outlined. Next you will calculate statistics on the selected data.

- Click the Statistics button.
- In the Statistics window, calculate statistics for **only selected features** of the **Gross Domestic Product** layer, using the **GDP (billion $U.S.)** and **Population** fields. (Hold down the shift key to select multiple fields.)
- Click **OK**.

In the Statistics window, the number of countries not adjacent to dead zones is given as the **Number of Records** and the GDP and population of those countries are given as the **Total**.

17. Record the number of countries, GDP, and population values for countries not adjacent to dead zones in Table 2 on the previous page.

- Close the Statistics window.

18. Calculate the GDP per capita both for the countries near dead zones and for the countries not near dead zones, and record them in Table 2. (Divide the Total GDP by the Total Population.)

19. How do the GDP per capita values differ for the two groups of countries?

20. How might GDP be a better indicator than population for the future development of dead zones?

In 2005, the world's population was about 6.1 billion people. By 2050, it is expected to increase to 8.9 billion, with the largest growth in countries having low GDP per capita.

21. If the total global GDP — the sum of all the goods and services produced by all nations — increases at a similar rate, what effect do you think it will have on the size and location of dead zones?

- Close the Statistics window.
- Quit ArcMap and do not save changes.

Wrap-up 4.5

Searching for solutions

The Gulf of Mexico is suffering from the effects of industrial and agricultural pollution, population growth, and urban development. The Gulf receives 1.1 trillion m^3 (300 trillion gallons) of runoff each year that contains a vast collection of pollutants originating from factories, hog-waste ponds, heavily fertilized farms, golf courses, and residential lawns, as well as oily grime from urban runoff.

Although these chemicals pose serious health hazards, the added nutrients pose the biggest problem, triggering a series of events leading to the formation of the Mississippi River dead zone. Excess nutrients have also been implicated in the deaths of coral reefs, decline of sea-grass beds, occurrence of red tides, and declining health of *estuaries* around the Gulf of Mexico.

Estuary — body of water where a river meets the ocean, mixing fresh river water with ocean water.

What are red tides?

Red tides are caused by seasonal reproductive surges, or blooms, of certain species of marine algae. During a bloom, colored pigments in these tiny one-celled plants discolor the ocean surface, giving it a reddish-brown appearance.

Most of these algae species are harmless, but a few produce potent chemical neurotoxins (poisons that affect the nervous system). These toxins cause widespread fish kills, contaminate shellfish, and can be deadly to humans and other animals that eat contaminated seafood.

1. Describe the cascade of events that leads to the formation of a dead zone, beginning with the addition of excess nutrients. Be sure to discuss how the presence of excess nutrients affects primary producers and other consumers in the food web.

Although the Mississippi River dead zone is the largest in the U.S., it is not the only one. Next you will determine the effect your community has on dead zones off the U.S. coasts.

- Launch ArcMap, and locate and open the **ddoe_unit_4.mxd** file.

Refer to the tear-out Quick Reference Sheet located in the Introduction to this module for GIS definitions and instructions on how to perform tasks.

- In the Table of Contents, right-click the **U.S. Dead Zones** data frame and choose Activate.
- Expand the **U.S. Dead Zones** data frame.

This data frame shows the major rivers and watersheds in the contiguous U.S. Find the approximate location of your city or town on the map.

- Using the Zoom In tool, locate and zoom in on the region you live in.
- Click the Identify tool.
- In the Identify Results window, select the **Major Rivers** layer from the drop-down menu.
- Next, click on the major river nearest to your town.

2. What major river carries runoff from your region to the ocean?

- In the Identify Results window, select the **Major Watersheds** layer from the drop-down menu.
- Click on the watershed in which your town is located.

3. What is the name of the major watershed in which your town is located?

- Close the Identify Results window.

Science can tell us a lot about how dead zones are created and their impact on the environment. However, cleaning up dead zones requires significant changes in our behavior as a society.

Search the Internet to learn more about the sources of pollution, the economic impact of dead zones, and the technological solutions to the problem; then answer the questions on the following page. Some example Web sites are provided on page 164 to help you begin.

4. Discuss how your city or town contributes to the formation of a dead zone. Think about local residential, commercial, agricultural, and industrial practices.

Mitigate — to make less severe.

5. Discuss how you might mitigate the negative impact of some of these activities.

Media Viewer shortcuts

To open these Web pages from within ArcMap, click the Media Viewer button and choose the appropriate entry from the list of Web sites.

Exploring Solutions

Dead Zone Research

Hypoxia

Red Tides

Gulf in Peril

Web sites on the Gulf of Mexico dead zone

Potential Solutions for Gulf of Mexico's "Dead Zone" Explored

Discusses the impact of the dead zone as well as ecological and technological approaches to reducing the nutrient flow into the ocean.

http://researchnews.osu.edu/archive/hypoxia.htm

Environmental Literacy Council

Provides an overview of the problem and links to major government and research groups investigating the problem and solutions.

http://www.enviroliteracy.org/article.php/1128.html

National Center for Appropriate Technology (NCAT)

Discusses causes of hypoxia and the human activities that contribute to it. Also discusses approaches to reducing nutrient flow to the ocean.

http://www.ncat.org/nutrients/map.html

The Gulf of Mexico Dead Zone and Red Tides

Discusses the effect of the dead zone on the quality and quantity of fish and seafood stocks in the Gulf of Mexico.

http://www.tulane.edu/~bfleury/envirobio/enviroweb/DeadZone.htm

Deep Trouble — The Gulf in Peril

Series of articles in the Naples (Florida) *Daily News* outlining all the issues facing the Gulf of Mexico and potential solutions.

http://web.naplesnews.com/deeptrouble/index.html

Quit ArcMap and do not save changes.