EDV 220F ENGINEERING ECOLOGY
Lecture Notes

Table of Contents

Lecture 1 What is Engineering?

Administrative Issues

These notes contain much of the basic material that you should know at the completion of this class. Additional material will be provided in class. The notes do not contain lecture slides and other visual aids (although many figures are included). They also do not contain the course schedule, the marking scheme, practice problems, etc. Because that information changes from year to year (and is often not finalized until the last minute), it will be handed out in class.

Course Objectives

1. Learn what engineering is,
2. Learn how to define and analyze a system, and
3. Learn enough ecology to recognize the extent of engineering impacts and environmental constraints.

What is Ecology?

The title of this lecture is "What is Engineering"? The answer to that question achieves the first objective of the course. Before we define engineering, however, we should define ecology.

> **Ecology**: The study of the structure and function of organisms and groups of organisms, and their interactions with each other and their physical/chemical environment.

As we continue through this course, keep this definition in mind. We will spend time on every aspect of this definition, but will do so primarily within the context of engineering activities.

What is Engineering?

A 1982 Webster's New Collegiate Dictionary provides the following definition for engineering:

> "The application of science and mathematics by which the properties of matter and the sources of energy in nature are made useful to humans in structures, machines, products, systems, and processes."

That is a pretty good definition, albeit slightly wordy. In Ontario there is also a legal definition for the practice of professional engineering:

> "Any act of designing, composing, evaluating, advising, reporting, directing or supervising wherein the safeguarding of life, health, property or the public welfare is concerned and that requires the application of engineering principles, but does not include practising as a natural scientist."

This definition comes from Professional Engineers of Ontario (PEO for short), the organization that is legally charged with regulating the practice of engineering in Ontario. It is even wordier than the dictionary definition.

Both definitions are similar. In essence, engineering is the practice of applying science and math to make things that are useful for humans. Neither definition mentions the practical constraints which must also be met when practicing engineering, constraints such as cost, environmental impact, and a variety of stakeholders in addition to your engineering clients that may have numerous, often conflicting objectives. The challenges arising from these additional constraints can be tremendous. Of course, these challenges are also what make engineering fun and lead to creativity.

Course objective 3 should make it clear that in this course, the constraint to be most carefully examined is the environment. Although not mentioned in the PEO definition, the environment is clearly identified in the PEO *Guideline: Professional Practice* as an important component of the professional engineer's duties. This course aims to provide you a start in achieving those tasks.

Definitions are important but dull. For the remainder of this lecture, we will examine engineering by looking at examples. Keep these examples in mind as we continue through the rest of the course.

Lecture 2 Potato Chips

Do you eat potato chips? I love potato chips. I think I like the salt and the fat the best. Did you know that if you eat an entire big bag of potato chips you will get a day's worth of certain vitamins? Of course, you may also get a week's worth of fat and calories, if you worry about that sort of thing. I also like corn chips, but today let's **focus on potato chips**.

Let's ask ourselves the following questions:

1. Do potato chips have an impact on the environment?
2. Does the manufacture of potato chips have an impact on the environment?
3. What processes are involved in manufacturing potato chips?

The Product

To answer these questions, first consider the product, i.e., the potato chip.

What is the product's use?

Human consumption.

Is there any environmental effect caused by the potato chip itself?

No, at least not directly.

To my knowledge, potato chips are neither greenhouse gases, nor ozone destroyers, nor cancer-causing, nor toxic waste (although health food experts might disagree there). So unlike some of the products of the industrial society, such as chlorofluorocarbons, potato chips themselves don't appear to cause an environmental effect.

Now let's back up a step.

Is there any peripheral material associated with the potato chip?

In other words, when you buy potato chips, do you simply go to the potato chip farm, pay the farmer and pluck potato chips off the potato chip tree? If you do, please e-mail me the address of the potato chip farm. Usually potato chips come packaged in a bag or a can. The **product** comes in **packaging**.

What is the **purpose** of the packaging?

1. Contain the product for easy transport and delivery to the consumer.
2. Protect the product to ensure product quality upon delivery.
3. Attract the consumer to purchase the product.

What **happens** to the packaging?

Well, I usually throw the bag in the trash. In other words, the **packaging** is **disposed**.

Does this have an environmental effect?

Yes, with the effect depending in part on how the package is disposed. If we include the package, the potato chip product does have an environmental impact.

Since we don't pick potato chips off of trees, there must be some other mechanism to move the potato chip bags to the consumer. Potato chips are **transported** from the manufacturing facility.

Is there an environmental effect from transportation?

Absolutely. As with packaging, the impact depends on how we transport the chips.

The Process

Figure 2-1 shows the potato chip as a product of a manufacturing facility. Let's look at this facility as an **engineering process**. We see that the potato chip process requires **raw materials** and **energy**. It produces a **product** (potato chips) and **residuals**. Note the use of the term **residuals** and not **wastes**. Wastes implies that there is no further use for the material. I would suggest that is a poor assumption to make. As we will see, in environmental systems, there is no such thing as waste — all mass must ultimately be recycled.

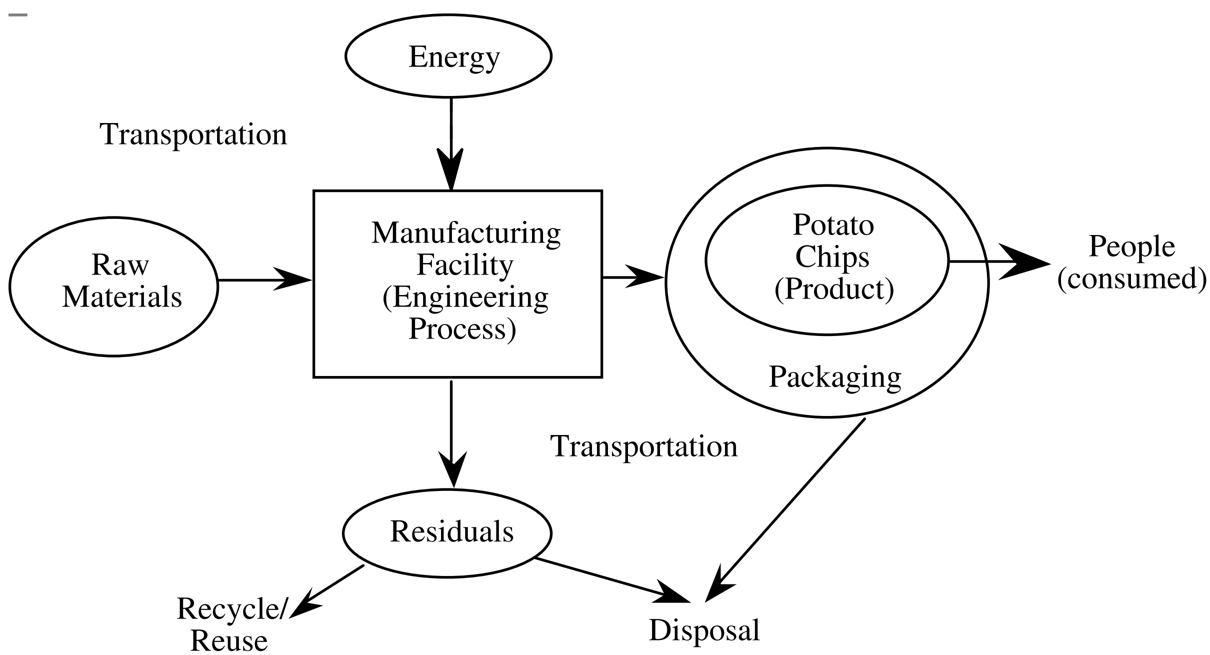


Figure 2-1 Simplified System Schematic for Potato Chips

What is the **goal** of the potato chip manufacturing process?

To meet product specifications.

What is the primary **constraint**?

Minimize cost per bag produced.

<u>How do we minimize cost</u>?

To answer this question, let's look at our engineering process to produce potato chips a little closer. The following sub-processes are likely required (Figure 2-2).

- Potato washing
- Potato peeling
- Potato slicing
- Potato cooking
- Potato chip packaging

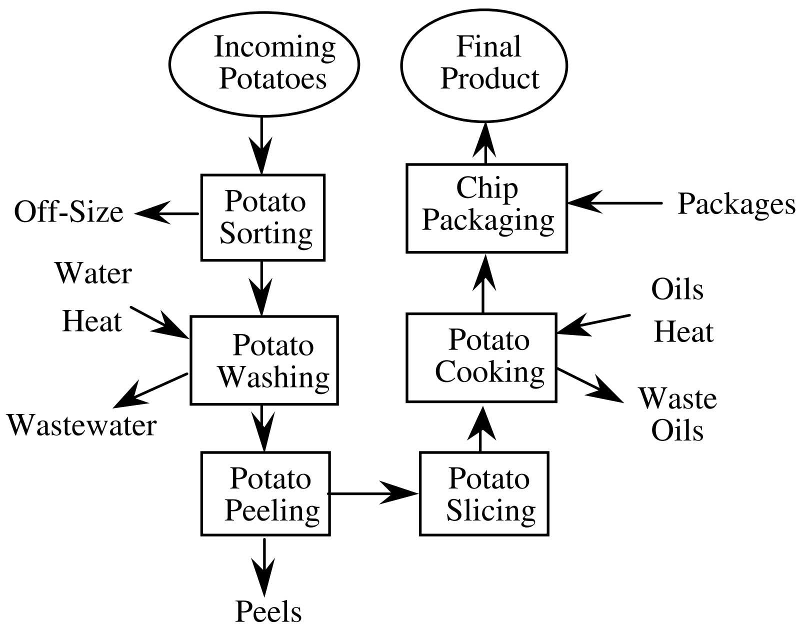


Figure 2-2 Possible Process Diagram for Manufacturing Potato Chips

As Figure 2-2 shows, each of these subprocesses produces a product, requires raw materials and energy and produces a residual. Immediately, two things come to mind to minimize cost:

1. <u>Reduce energy consumption</u>. Energy is used in every process, but particularly washing (steam) and cooking. Energy costs money, so reducing energy usage reduces cost.
2. <u>Reduce residuals</u>.
   a. Increase process efficiency. <u>Raw materials cost money</u>. Don't waste raw materials making residuals with inefficient processes.
   b. Recycle residual streams prior to disposal. <u>Disposal costs money</u>. Recycling will reduce the amount of residuals requiring disposal.
   c. Find customers for residuals. Customers pay money. This converts a residual into a product.

Steps 2 a.- c. are commonly called **pollution prevention**. These steps reduce the amount of pollution, which is represented by residuals, leaving the facility. This implies that improperly disposed residuals lead to pollution, which is in fact true.

Steps a. – c. were not developed for environmental reasons, however. We wrote them down as ways to reduce costs. They just happen to also be pollution prevention techniques. This observation is universal: **Pollution Prevention Pays**. Analyze any engineering process and you will see the same thing: the steps that you take to reduce residual generation will save you money while they also reduce the environmental impact of the process.

Raw Materials

Figure 2-1 shows that raw materials are required for the potato chip manufacturing process. The raw materials needed are primarily potatoes and other food materials, such as vegetable oils. Usually, the procurement of raw materials has a huge impact on the environment. For example, potatoes come from agricultural processes. Agricultural processes have a tremendous effect on the environment. Furthermore, potatoes and other raw materials must be **transported** to the manufacturing facility, so the process of transportation shows up again. Transportation also has an effect on the environment.

Residuals

We have already talked about residuals briefly. It is worth discussing them in more detail. Residuals end up in one of three phases:

1. Gaseous

    Includes waste gases, suspended particles, and suspended droplets

2. Liquid

    Includes non-aqueous liquids, materials dissolved in water and particles/emulsions suspended in water.

3. Solid

What options exist for residuals?

1. Recycle/reuse
2. Dispose

We already examined the idea of recycle/reuse and found that this would save money, as well as reduce environmental impact. We would consider recycle/reuse opportunities for each residual.

Let's consider disposal further. No matter how efficient the process is, at some point a residual will be generated. This fact arises from the law of conservation of mass and the second law of thermodynamics. Therefore, unless you find a way to sell all of the residuals, disposal will be required. And unless this facility is located in a place where the inhabitants have absolutely no regard for the environment, **disposal will cost money** because:

1. Landfill space costs (for solid wastes).
2. Air treatment technologies cost (can't discharge gaseous pollutants to air without treatment).
3. Water treatment technologies cost (can't discharge the water pollutants to receiving water bodies without treatment).

Energy

The last entity entering our potato chip plant is energy. The plant will probably need energy in the form of:

1. Electricity (pumps, lighting, etc.)
2. Steam (heating, processes)
3. Fuels (internal combustion processes)

This energy will probably arrive at the plant in the following forms:

1. Electricity from an outside utility - this is expensive!
2. Fuels for onsite generation - particularly of steam but also of electricity

Energy generation has **huge** environmental impacts (Figure 2-3). If combustion of fuels is used, there are significant productions of air pollutants. If nuclear material is used, there is the significant problem of disposal of waste material. Hydroelectric power doesn't have much of an impact <u>during</u> electricity generation, but <u>dam</u> construction and the resulting reservoir have signficant, and very visible, environmental impacts.

The impact on the environment from electricity generation goes beyond just the generating station and the impacts of that. If fuels are used, they must be **mined**. The mining process caused dramatic environmental change. And the fuels must be **transported** to the generating station. In short, the environmental impacts of energy generation are tremendous. And these impacts are incurred for any process requiring energy, not just potato chip manufacture. Therefore, to estimate the true environmental impact of a product or process, we must consider energy usage.

Transportation

I have noted several times that transportation is required to bring raw materials to the plant and take product from the plant to customers.

<u>What major modes of transportation may be used</u>?

1. Railroad
2. Trucks

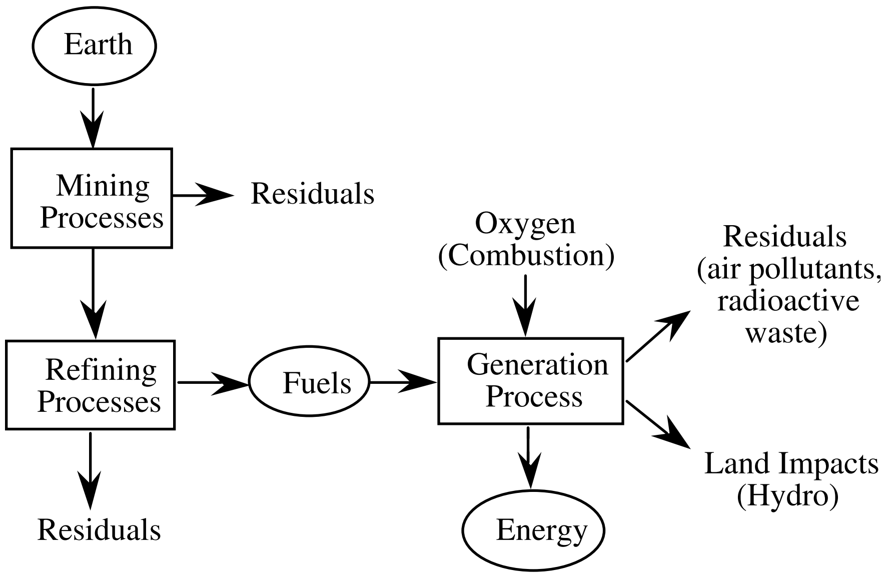


Figure 2-3 Schematic of Energy Generation Processes

3. Ship
4. Airplanes (not usually for raw materials, often for people)

Do these transportation modes impact the environment?

Absolutely. They all use combustion engines, burning fuels to produce the motive energy and also air pollutants. In fact, transportation is an engineering process, just like manufacturing potato chips. Therefore, we can do the same analysis on transportation and identify the product, raw materials, energy and residuals.

Additionally, all forms of transportation require some built **infrastructure**. The construction and presence of this infrastructure has an environmental impact. Infrastructure will be discussed in more detail later.

Construction

Another major engineering process that was required to manufacture potato chips was **construction**. Construction is directly related to infrastructure and will be discussed more later.

Wrap Up

We started with one simple product — potato chips — and ended up with a host of engineering activities. Each of these activities can have an impact on the environment. We will now switch gears and look at the environment and see if we can learn anything that might help us when we conduct engineering activities.

<u>Lecture 3</u> Fundamentals of Ecosystems – Mass

There are a number of places to start when looking at the environment. Ecology textbooks typically start with organisms and then work their way toward ecosystems. I'm going to start with ecosystems because this is where the physical laws governing ecology become most readily apparent (at least in my opinion).

Ecosystem: A self-sustaining biological system, an eco(logical) - system

Physically, an ecosystem consists of individual organisms, populations of organisms, communities of populations <u>and</u> the abiotic components needed for all those organisms, populations and communities to survive. Conceptually, an ecosystem is the information stored in all the interactions occurring between its physical components.

Ecosystems are complex. We will look at aspects of that complexity later. Now, though, we will look at ecosystems from the fundamental standpoint of basic physical laws. When we understand those laws and how they function in ecosystems, we will have the framework necessary to examine some of the specific components of ecosystems.

Basic Physical Laws Governing Ecosystems

1. Mass is conserved.

This law governs any examination of a system that contains mass of any form. Later, we will look at mass in different forms (e.g. configured into organisms). Keeping track of these specific forms is important for ecosystem analysis but over appropriate time scales, the types and number of organisms may change. Mass, however, remains conserved and can be tracked at an elemental basis through the ecosystem. Different elemental biogeochemical cycles can be examined that provide an indication of how mass is converted between different forms in ecosystems but nonetheless remains conserved overall.

2. Energy is conserved (1st Law of Thermodynamics).

This 1st Law of Thermodynamics means that, as with mass, energy cannot be destroyed or created. Also like mass, energy comes in different forms. Unlike mass, there is another law governing energy (the 2nd Law of Thermodynamics) that we will examine later.

Nuclear reactions can convert mass into energy or vice versa and so technically violate the two conservation laws noted above. For nuclear reactions, a combined law stating that mass and energy are simultaneously conserved must be used. While nuclear reactions are extremely important, they are outside the scope of this course and outside the scope of most ecosystem work. We will therefore use the two conservation laws and not the combined conservation law.

Mass in Ecosystems

A common belief about ecosystems is that mass is recycled within ecosystems. Certainly mass is conserved per the conservation law just stated. But must mass be recycled within ecosystems? To answer this question, let's start by conducting a mass balance around earth. Figure 3-1 shows the schematic needed.

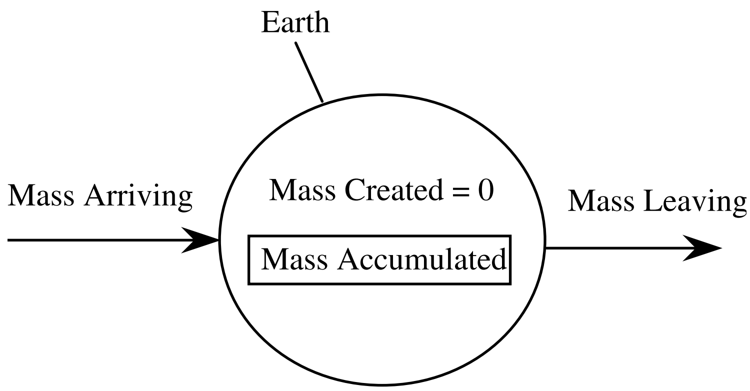


Figure 3-1 Mass Balance Around Earth

The equation of interest is:

Accumulation of mass on earth = Mass arriving – Mass leaving + Mass created

Mass is arriving on earth (Wood, 1999). Astronomers estimate that approximately 200 Mg of ice, dust and tiny meteorites fall to earth every day. Less frequently, about once every few days, 1-5 meter wide meteroids hit the earth's atmosphere. Fortunately, these items disintegrate upon descent, but nevertheless add their mass to the earth. Much less frequently, about once every 100 years or so, a 50-meter wide asteroid hits earth. The disintegration of objects of this size cause a significant explosion but not as large as the 200-meter wide asteroids that hit the earth about once every 5,000 years. The explosion from these asteroids could destroy a large city. Every 300,000 years or so, even larger asteroids (1-2 km wide) hit the earth. The impact of these objects can throw enough dust into the atmosphere to initiate a short global winter. Even less frequently than that, very large asteroids crash into the earth These asteroids are large enough to cause mass extinctions of species due to extensive climatic change.

Ignoring the bigger chunks, the minimum mass arriving on earth is 200 Mg/day = 73,000 Mg/year. This is a lot of mass. The mass of the earth, however, is approximately 5.98×10^{21} Mg. With our estimate, even a billion years of space dust will add far less than one-millioneth of the earth's mass. If adding the bigger asteroids increased the mass being delivered to the earth by

1,000-fold, the time required to add 10% to the earth's mass would be over 8,000 billion years. Certainly, from the time scale of interest to us (up to several hundred years), we can assume that the amount of mass arriving on earth is approximately zero.

Mass is leaving earth. Lighter molecules such as helium can escape earth's gravity. Additionally, we have launched probes into space to explore the solar system. Materials launched into orbit around the earth often crash back to earth as their orbits deteriorate and so may still be considered part of earth's mass on a longer term basis. From a practical standpoint, then, the mass leaving the earth can also be approximated as zero.

The mass created on earth is exactly zero. The creation of mass violates the law of conservation of mass and does not occur.

Plugging the numbers into our equation:

Accumulation of mass on earth $\cong 0$

In other words, the mass on earth is approximately constant and:

Total mass on earth is essentially limited.

This fact means that mass on earth must be recycled. Mass is not simply used and discarded. It may be transformed but it does not disappear.

While the earth is closed to mass and all mass must be recycled on earth (to ensure conservation of mass), must mass be recycled within an ecosystem? Consider Figure 3-1 again but this time replace the word "earth" with "ecosystem" and reexamine the mass balance equation.

Mass arriving = water + organisms + gases + any other mass that enters the ecosystem

Mass leaving = water + organisms + gases + any other mass that leaves the ecosystem

Mass arriving and leaving an ecosystem is neither equal to zero nor can be approximated as close to zero (as was the case with the earth). For example, all terrestrial ecosystems require water to sustain the organisms in the ecosystem. Precipitation is usually an important source of that water, yet it must enter the ecosystem from the atmosphere because it is not inherently part of the ecosystem. Similarly, much of the water entering as precipitation runs off, leaving the ecosystem (and entering another ecosystem such as a lake or ocean). This flow of mass into and out of ecosystems not only occurs, it is critical to the proper functioning of the ecosystem. So while the mass of the earth is indeed limited:

The mass within an ecosystem is not inherently limited.

In other words, ecosystems are open to mass. We will examine the movement of mass between ecosystems later when we examine the biogeochemical cycles for carbon, oxygen, nitrogen, phosphorus and sulfur.

Although not closed to mass, ecosystems do recycle much mass within them. A food chain is a good example. Primary consumers recycle the mass of primary producers, secondary consumers recycle the mass of primary consumers, etc. while detrivores recycle the mass of residuals. Although mass movement into and out of ecosystems is important ecologically, the common belief that mass is recycled within ecosystems is true enough for many approximations.

Lecture 4 Fundamentals of Ecosystems – Energy

Even the least diverse ecosystem has a stunning array of organisms attempting to survive. Additional complexity is uncovered virtually every day by biologists and ecologists. All of these organisms are made of matter, so clearly we must use the law of conservation of mass to examine these systems. The other fundamental law, that energy is conserved, is also required. We will begin to examine why energy is so important for understanding ecosystems in this lecture.

What is Energy?

Energy is the capacity to perform work, or at least that is the formal physical definition. Recall from physics:

Force = Mass x Acceleration

where: 1 Newton (N) of force = 1 $kg \cdot m \cdot s^{-2}$ and:

Energy = Force x Distance

where: 1 Joule (J) of energy = 1 $N \cdot m$ = 1 $kg \cdot m^2 \cdot s^{-2}$

= work required to move 1 kg of mass to the height of 10.19 cm (assuming the acceleration due to gravity is 9.81 $m \cdot s^{-2}$).

Energy is also presented in other units, in particular calories. 1 calorie is the energy required to raise the temperature of 1 g of water 1°C, from 15°C to 16°C. The unit Calorie (with a capital C) is equal to 1,000 calories and is the unit reported on foods (although usually using a small c instead of the proper notation). Perhaps more usefully:

1 calorie (not capital c) = 4.184 J.

Finally:

Power = Energy / Time

where: 1 Watt (W) = 1 $J \cdot s^{-1}$.

Power is not to be confused with energy although the electricity industry insists on selling energy with the somewhat confusing units of kWh. A kilowatt-hour is an energy unit, not a power unit, because the power term, kilowatt, has been multiplied by a time term, in this case hour.

$$1 \text{ kWh} = 1 \text{ kJ/s} \cdot 60 \text{ s/min} \cdot 60 \text{ min/h} \cdot 1 \text{ h} = 3{,}600 \text{ kJ}$$

Because energy is primarily of interest to us in ecology, not power, we will stick to the standard unit of J.

All Energy is Not Equal

The 1st Law of Thermodynamics clearly states that energy is conserved. Therefore, when conducting an energy balance around a system, energy is neither destroyed nor created. Like mass, energy can appear in different forms, however. Some forms of energy of importance to us from an ecosystem standpoint are:

a. Electromagnetic radiation. This comes in many wavelengths, such as ultraviolet which is damaging, visible which is used by photosynthetic organisms, and infrared, which is a means to transfer heat.

b. Chemical bond energy. This is the energy contained in the molecular structure. For example, the energy between C and H atoms in hydrocarbons that is released when hydrocarbons are oxidized to CO_2 and H_2O.

c. Chemical phase energy. This is the energy contained in molecules by virtue of the phase they are in. For example, water vapor contains much more energy than water and water contains more energy than ice. To form water vapor from water requires an energy input (your stove does this well but in the environment the energy is trapped from solar radiation) while condensing water vapor releases energy. The energy input to water to form water vapor is sufficient to move it from the oceans into the atmosphere against gravity so that it may later be condensed and fall as precipitation at much higher elevations.

d. Potential energy. Particularly as found in water. For example, water at the "top of the hill" can run down the hill, changing the potential energy to kinetic energy which can be converted to other forms. Additionally, water at higher temperatures and pressures has potential energy that can be recovered when the temperature is decreased or the pressure relieved.

e. Kinetic energy. The energy contained in moving matter. The deceleration of a moving object releases energy just as the acceleration of a stationary object requires energy.

f. Radioactive decay. Radioactive decay converts matter into energy following Einstein's famous equation $\Delta E = \Delta m \cdot c^2$ where ΔE is the energy produced from a mass destruction of Δm and c is the speed of light. Radioactive decay at the center of the earth provides the energy required for tectonic plate movement and volcanic activity and so is indirectly important from an ecosystem standpoint.

g. Thermal energy and Heat. Heat is technically energy in transit but is usually thought of (imprecisely) as the energy required to raise the temperature of matter. This latter is more precisely called thermal energy and is the energy stored in the kinetic motion of molecules that are not undergoing a phase change. "Waste heat" is energy that could not be captured for its primary use during the transfer from one form of energy to another, or during the use of a form of energy to produce work. As heat, waste heat is technically energy in transit and typically ends up as the kinetic motion of molecules, or low-grade thermal energy. The thermal energy arising from waste heat can have tremendous value in many engineered systems (for preheating raw material streams to operating temperature, for example) but cannot be directly used by organisms.

Not all forms of energy are equally useful for producing work. Because energy is defined as the capacity to perform work, energy that cannot be used, in some manner, to perform work is by definition not useful. For example, it is difficult to use low-grade thermal energy to perform work. While still energy, this form of energy is not useful. The problem is that energy is constantly being converted from useful forms to non-useful forms. This comes about from the 2nd Law of Thermodynamics:

2nd Law of Thermo: **The amount of useful energy in a system decreases with every transfer of energy.**

Another statement of the 2nd Law of Thermodynamics that we will examine later is: **For every spontaneous reaction that occurs, entropy increases.** This definition more precisely describes the molecular mechanisms involved because entropy is the measure of the randomness of a system.

Understanding the 2nd Law of Thermodynamics

The following ideas can assist in understanding the 2nd Law of Thermodynamics. First, the 2nd Law does not contradict the 1st Law. Energy is always conserved, but it may be in different forms. This concept of different forms causes us no trouble when dealing with mass – we know that mass comes in many different forms; that molecules can be rearranged with no loss of mass. Because energy is defined in terms of usefulness, however, the 2nd Law can cause confusion. The 1st Law does not say that only useful energy is conserved, it says that all energy is conserved.

Second, the 2nd Law does not state that energy cannot be made more useful. It only states that with every transfer of energy, a fraction of energy will become less useful. This idea is particularly important for understanding ecosystems. As we will see, ecosystems require photosynthetic organisms to capture electromagnetic radiation from the sun and convert it to chemical bond energy. Non-photosynthetic organisms such as humans cannot take sunlight and convert it into a form of energy that will fuel our cells and so solar radiation is relatively useless to us. We must have chemical bond energy. Photosynthetic organisms, then, can convert a "useless" form of energy, sunlight, into a "useful" form, chemical bond energy. This does not violate the 2nd Law because while photosynthetic organisms are converting sunlight into chemical bond energy, they are "throwing away" even more waste heat which ends up as low-grade thermal energy.

Third, following on from the second idea, real systems cannot operate at 100% efficiency from the standpoint of useful energy. Because usefulness is lost with every energy transfer, there is no way to convert energy that has been degraded back to usefulness. In other words, energy cannot be reused, making it very different from mass which can and must be reused.

Energy in Ecosystems

The ramifications of the 2nd Law of Thermodynamics for ecosystems are this:

Energy flows through ecosystems and it is the flow of energy that drives the cycling of mass in ecosystems.

Consider Figure 4-1 that shows a simple food chain. The non-usable energy is shown being lost as heat (which will end up as low-grade thermal energy). In light of the previous energy discussion we see that the primary producers capture the energy from the sun and use it to build cells (full of complex molecules with plenty of chemical bond energy) from inorganic starting materials (compounds that have less chemical bond energy). Imagine now, that after a good crop of primary producers has grown, the sunlight source ceases. What will happen?

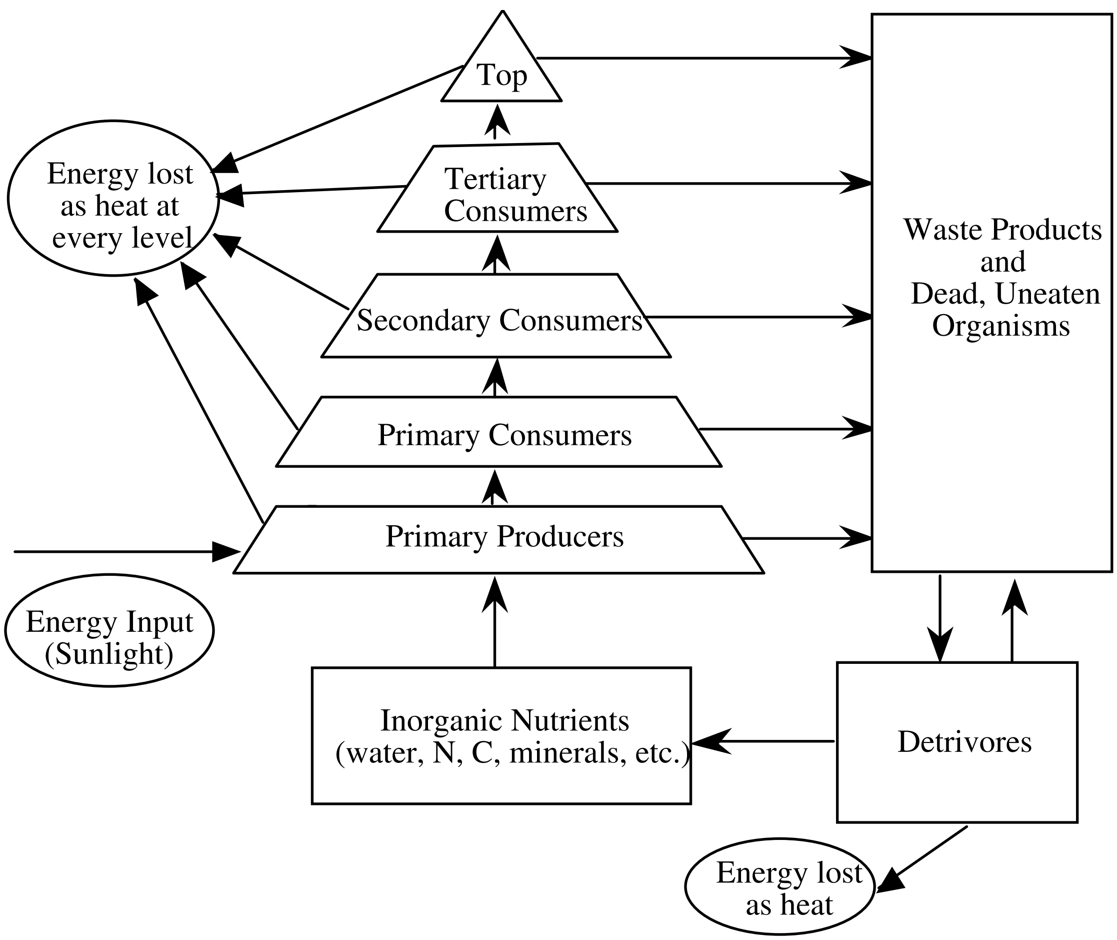


Figure 4-1 Schematic of a Food Chain showing Mass and Energy Movement

The loss of sunlight will not impact the upper levels of the food chain initially. Primary consumers will consume all the available primary producers and then stop. At that time, the mass of the primary producers will be either completely incorporated into primary consumers or remain as waste products. Secondary consumers will consume primary consumers, etc.

Eventually, the entire food chain will be exhausted and all of the mass will remain in the waste products and dead, uneaten organisms. Much of the chemical bond energy that was orginally produced by the primary producers will have been converted to non-usable forms as indicated by the energy arrows. Finally, the detrivores will consume the waste products and dead, uneaten organisms (including themselves), eventually releasing the originally captured energy to non-usable form. The mass will have been recycled and will be ready to be converted back into complex biochemicals. The energy has flowed from sunlight to non-usable thermal energy. The incoming energy can be accounted for because it was not destroyed but it cannot be used again by this food chain or ecosystem. To continue to cycle mass, however, now requires another input of usable energy – sunlight to the photosynthetic organisms. Otherwise, the mass remains at the bottom of the chain, unincorporated into biomass.

Fundamentals of Mass and Energy in Ecosystems

One final fundamental is needed before we can examine ecosystems further:

The earth continually receives energy input.

The earth is essentially closed to matter, but it is not closed to energy and continuously receives energy from the sun. The amount of energy that the earth receives is not limitless, but it is substantial. Because of photosynthetic organisms, the sun's energy is converted to chemical bond energy that sets up the cycle of mass described in food chains. Because the movement of energy in an ecosystem typically requires the movement of mass (because the energy is being moved in the form of chemical bond energy), a full understanding of mass and energy requires simultaneous mass and energy balances. Figure 4-2 shows a simultaneous balance around the earth. Clearly, from a global perspective, with mass remaining constant, the simultaneous balance simplifies to an energy balance. The energy received from the sun is absolutely crucial to the long-term sustainability of life on earth.

The simultaneous mass and energy balance for an ecosystem is more complicated as indicated in Figure 4-3. Mass enters an ecosystem either in a high or low energy state and can leave in either a high or low energy state. Additional energy arrives from the sun that can be used and non-usable energy (primarily as waste heat in the form of low-grade thermal energy) leaves the system. For any individual ecosystem, the sun's energy may not be required – enough mass containing useful chemical bond energy may enter to cause energy flow. This is the case with the novel ecosystems that have been found living near hydrothermal vents on the ocean floor. These ecosystems are far from the sun. All of the energy for organism growth comes from chemical bond energy in the chemicals issuing from the vents (the energy for organism growth DOES NOT come directly from the thermal energy contained in the superheated water – only from the chemicals, such as reduced sulfur compounds, that are in the water).

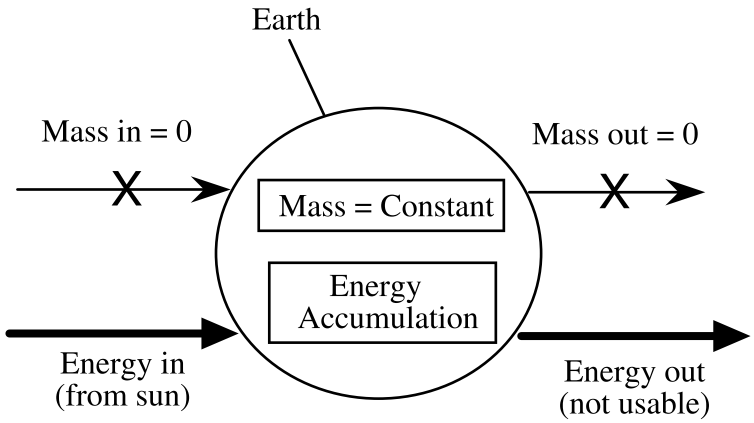


Figure 4-2 Mass and Energy Balances around Earth

Ecosystems that do not use solar radiation as the primary energy source are rare but they can exist. When all the ecosystems on the planet are summed, however, the balance becomes the one shown in Figure 4-2 where solar energy is required. So while individual ecosystems can survive without the sun, the reason is that energy is being provided from another ecosystem. This issue of ecosystems that produce net useful energy versus those that consume net useful energy will be discussed in the next lecture.

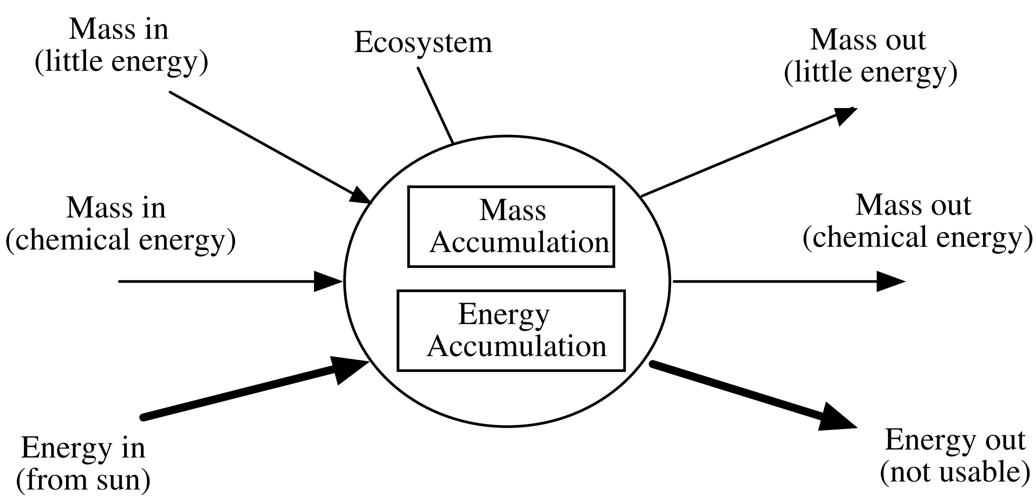


Figure 4-3 Mass and Energy Balances Around an Ecosystem

Lecture 5 Food Chains and Bioaccumulation

Food Chains

In the last lecture we looked at a generic food chain. Indeed, the food chain concept is so simple that in Ontario it is now taught in Grade 1. But as we saw in the last lecture, a food chain is not really about food, it is about the movement of energy. A simple definition of a food chain, then, is:

Food Chain: **Movement of energy from one trophic level to another**

A **trophic level** consists of all the organisms in an ecosystem that are the same number of steps removed from the **primary producers** that are responsible for converting electromagnetic radiation into chemical bond energy. For example, **primary consumers** are one level away from the primary producers, and eat primary producers. **Secondary consumers**, therefore, eat primary consumers, etc. Tracking down who eats whom can be complicated in real ecosystems. What happens, for example, when a **tertiary consumer** eats both secondary consumers and primary producers? In these complicated situations, it is more appropriate to discuss a **food web** than a **food chain**. Fortunately, we may leave that level of complexity to the ecologists.

Detrivores

A lot of chemical energy remains in the "waste" material. This material must be recycled in some manner or eventually all biologically available matter on earth would end up in a big rubbish pile. **Detrivores**, or **organisms that eat detritus** (waste materials), survive by consuming the waste material. The **detrivore chain** contains large scavengers like vultures, small scavengers like **worms, fungi, some insects** and ultimately **bacteria**. This chain is extremely important to ecosystems. When we examine biogeochemical cycles, we will see clearly how mass recycle in ecosystems and on earth depends on this part of the food chain. While the "classic" food chains that end in top predators may get a lot of attention, the detrivore chain may ultimately be most important. "Waste" is recycled by detrivores.

Engineering Impacts Arising from Food Chains

Food chains are one mechanism for spreading environmental impacts into the ecosystem. We will look at one example of that shortly, but to understand these impacts, some additional definitions and background are required.

What is toxicity?

Toxicity: The effect of toxic (poisonous, unhealthful) compounds. Toxicity is a broad, poorly defined term that incorporates many different mechanisms. Death is an extreme response to toxicity.

<u>What is acute toxicity</u>?

Acute Toxicity: Toxicity that is manifested rapidly, or <u>acutely</u>. Rapid death is an extreme acute response. However, death is not the only acute response.

Other acute responses include:

- Disease
- Loss of reproductive capability
- Severe mutations

Acute toxicity is due to:

- exposure to highly toxic compounds
- exposure to large doses of less toxic compounds in a short period of time

<u>What is chronic toxicity</u>?

Chronic Toxicity: Toxicity that is manifested slowly, or <u>chronically</u>.

In general, we think of chronic effects as those that take a long time to appear and are usually **due to long term exposure to small concentrations of toxicants**. Certain cancers in humans may be due to chronic effects — long term exposure to toxicants, in this case <u>carcinogens</u>. Another possibly important chronic effect is impact to the endocrine (hormonal) system. Many anthropogenic (human-made) chemicals mimic hormones and cause effects at very low concentrations.

<u>Why all the toxicity definitions</u>?

Often, toxicity is one of the first things that comes to mind when we think of the environmental effects due to human activities. Acute toxicity in the form of death is dramatic and easy to observe. Chronic toxicity scares most people: will we get cancer someday because of something in the environment? Many toxic effects, however, arise from the <u>designed use</u> of engineering products such as DDT (dichlorodiphenyltrichloroethane).

<u>Very Brief History</u>

1874:	First synthesized.
1939:	Paul Mueller, Swiss chemist, discovers insecticidal properties of DDT.
	DDT kills **lice** and **fleas** that spread **typhus** and **mosquitos** that spread **malaria**.
After 1939:	Massive applications of DDT to kill these disease-spreading insects.
1948:	Mueller awarded Nobel Prize for Physiology or Medicine.
1970s:	DDT use banned in North America

DDT goes from wonder compound, saving humans from disease, to banned substance in less than 40 years.

Why did DDT "fall from grace"?

1. DDT was a non-specific insecticide. It caused the death (acute toxicity) of many insects besides the target organisms.
2. DDT and chemical relatives caused severe acute effects to predators of insects killed by DDT. Later, we will examine predator / prey impacts due to dieldrin, a chemical cousin of DDT.
3. DDT caused a significant drop in the breeding success of carnivorous birds such as peregrines and eagles.

The third effect is the one that caught everyone's attention and led to the banning of DDT usage in North America in the 1970s.

We will look at the biochemical reason for the drop in breeding success of carnivorous birds due to DDT later. The ecological reason, however, is a combination of two factors: food chains and bioaccumulation.

Bioaccumulation

While food chains and webs are interesting in their own right, one practical reason to understand them is the problem of bioaccumulation.

Bioaccumulation: The concentrating of chemicals in species higher up the food chain.

What type of chemicals bioaccumulate?

1. Resistant to biodegradation
   a) Pesticides
   b) Heavy metals
   c) PCBs
2. Fat soluble (lipophilic)

Not all chemicals bioaccumulate. Most water soluble chemicals do not bioaccumulate to any significant amount. DDT, our example chemical, does bioaccumulate. It is resistant to biodegradation and it is fat soluble. Once DDT is in the fat of an organism, it will stay with the organism a long, long time, being removed only when the fat stores are metabolized.

To see the impact of the food chain on bioaccumulation, consider the following example.

Example 5.1

Consider the following food chain and assumptions.

Food Chain	Organism Mass	Organism Consumes	DDT Concentration
Zooplankton			0.04 mg DDT/kg organism
Minnow	5 g	62.5 g zooplankton	A
Needlefish	100 g	400 g minnows	B
Osprey	1,200 g	15,000 g needlefish	C

Estimate the DDT concentrations A, B, and C in minnows, needlefish and osprey, respectively.

Solution:

Assume that at each level, all of the DDT consumed remains in the consuming organism. The following calculation to determine A is:

A (mg DDT/kg minnow) =

$$62.5 \text{ g zooplankton} \times \frac{1 \text{ kg}}{1000 \text{ g}} \times \frac{0.04 \text{ mg DDT}}{\text{kg zooplankton}} \times \frac{1000 \text{ g}}{1 \text{ kg}} \times \frac{1}{5 \text{ g minnow}} = \frac{0.5 \text{ mg DDT}}{\text{kg minnow}}$$

Following the same procedure (do as a practice exercise):

B (mg DDT/kg needlefish) = 2.0 mg DDT / kg needlefish

C (mg DDT/kg osprey) = 25 mg DDT / kg osprey

The DDT concentration in the osprey was 625-times greater than the concentration in zooplankton but even so was not enough to kill the adult bird. It was high enough to cause a significant problem with egg structure, however. The details will be discussed later but in short the eggs were too weak to support the weight of the adult bird and cracked. As we will see when we examine populations, this impact on birth rates significantly decreased the populations of carnivorous birds high in the food chain.

In some cases, such as beluga whales in the St. Lawrence, the concentrations of bioaccumulated compounds can become toxic, in particular for nursing young. Mammal milk has a large component of fat and therefore accumulates toxic compounds. In severe cases, beluga whale milk has become so contaminated that it is toxic to the young. Interestingly, some of the whales were also so contaminated that when they died and washed ashore, they had to be disposed as hazardous waste.

As long as we produce and use compounds that are not water soluble and which do not readily biodegrade, bioaccumulation will remain a problem. Now, however, we should be able to predict which compounds (engineering products) are susceptible to bioaccumulate. With a knowledge of the relevant food chains, we could then predict which organisms will be affected.

Gobal Distillation

Surprisingly, DDT is still a concern. DDT use has not been banned worldwide and is still used as a pesticide in some countries, perhaps because no cheaper alternatives have been developed. The concern with DDT and other similar chemicals now is their transport to "pristine" environments, such as the Arctic and Antarctic as well as high mountains such as the Alps in Europe and the Rockies in North America, where they have never been used. In a process called **global distillation**, these compounds evaporate from Africa and India where they are used, travel via atmospheric circulation and then under sub-zero temperatures condense and precipitate. Colder regions become "sinks" for these compounds. This process explains why the fat of polar bears, for example, contain compounds that are not used nearby.

The concentrations of compounds like DDT that accumulate in arctic and high mountain regions are not acutely toxic (at least not so far). But these compounds do act as endocrine disruptors (chemicals that mimic hormones as indicated earlier). The impact of endocrine disruption on the receiving ecosystems is not known.

Another inadvertant result of global distillation is the contamination of "pristine" waters. We typically assume intuitively that high mountain waters are clean. While still perhaps cleaner than other waters, high mountain waters may now be contaminated with compounds that are transported atmospherically – like DDT.

And my point is…

Materials that enter the environment in one place don't stay there. Physical processes like global distillation and atmospheric movement transport contaminants around the world. Ecological processes such as food chains move and concentrate contaminants through organisms. We will see additional examples throughout the course of long-ranging, unexpected impacts.

Lecture 6 Energy Flow Through Ecosystems

Diagramming Ecosystems

While Figure 4-1 presents a qualitative view of energy flow through a food chain, it is not very useful for examining ecosystems quantitatively. Fortunately, ecologists have developed a set of symbols that can be used to prepare more quantitative figures, which can then be developed into formal mathematical models. The symbols are summarized in Figure 6-1.

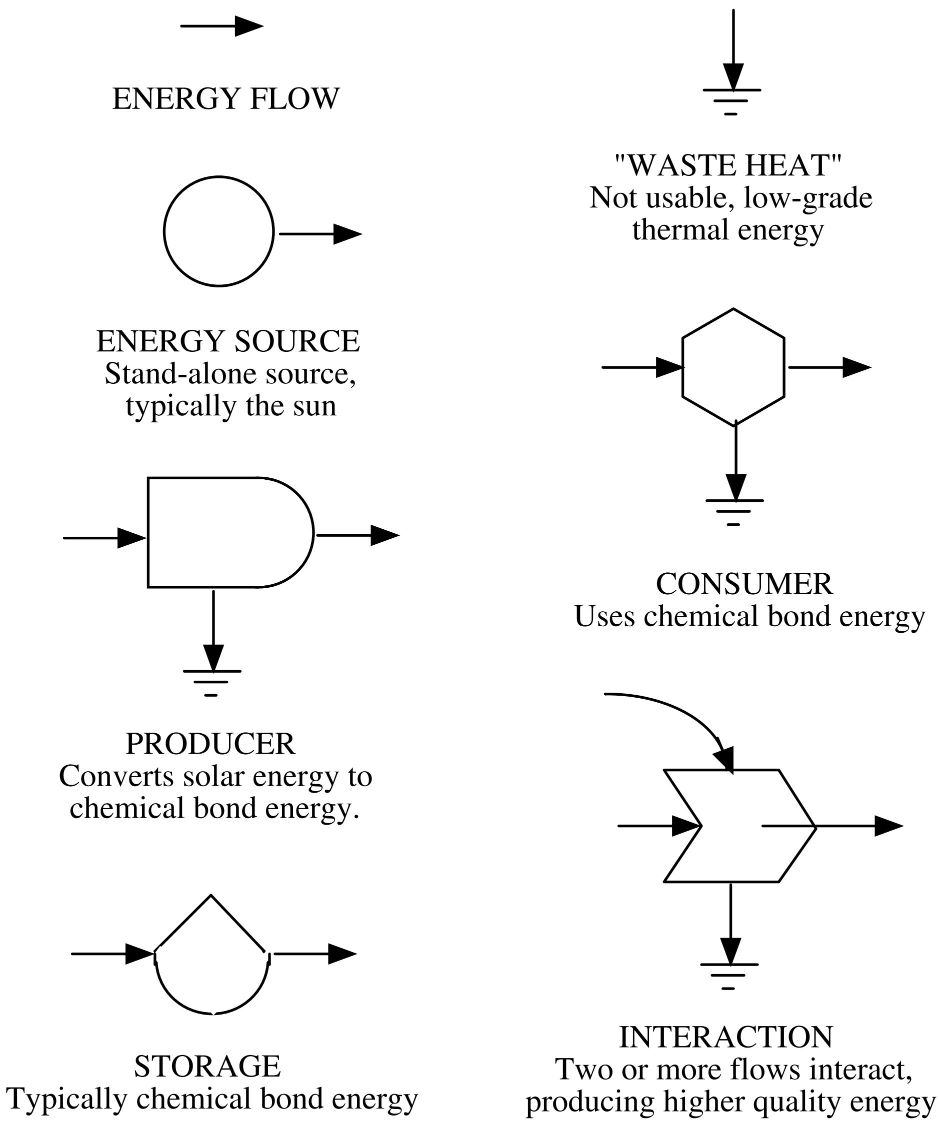


Figure 6-1 Symbols Used to Describe Energy Movement in Ecosystems

Notice that neither the energy source nor storage have energy losses but all other processes do.

The arrows around each symbol can be used for conducting energy balances. This can be seen more readily in Figure 6-2 where Figure 4-1 has been redrawn using the symbols in Figure 6-1. Consider the primary producers, for example. Energy is captured from the sun and converted to chemical bond energy. In the process, a fraction of the energy entering is made non-usable. The primary consumers obtain their energy by consuming primary producers, as indicated,

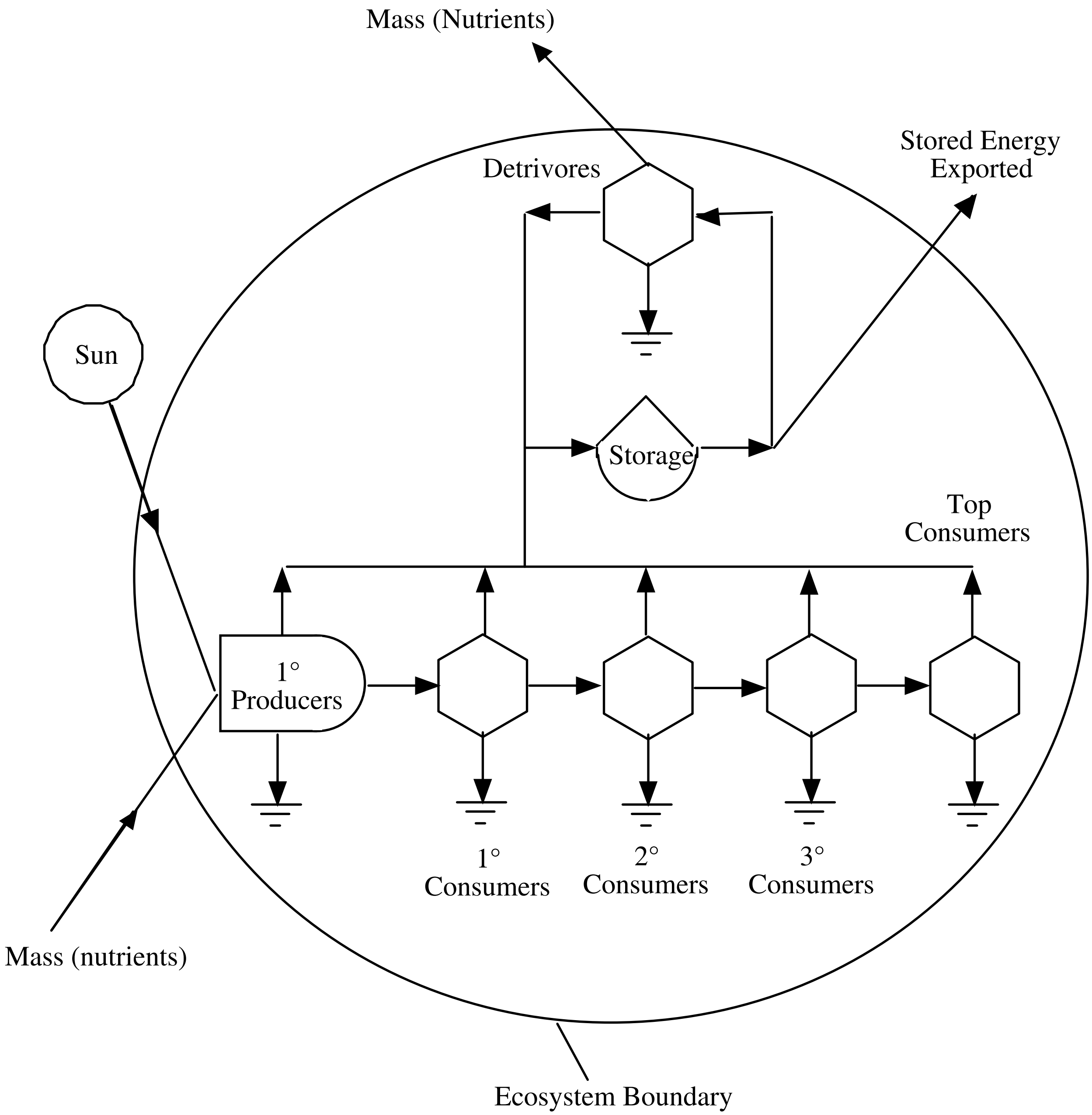


Figure 6-2 Food Chain from Figure 4-1 Drawn using Energy Symbols

while the chemical bond energy remaining in dead, uneaten primary producers is temporarily stored until detrivores consume it or it is transported out of the ecosystem, say by dissolution and run-off. The ecosystem is open to mass, as shown. For simplicity, energy is assumed to be provided only by the sun, but energy can and does cross the ecosystem boundary in the form of organisms too.

The organisms have been called producers and consumers based on where they are in the food chain. More technical names for these organisms are:

Photoautotroph: Organism that can convert light energy to chemical bond energy and convert carbon dioxide and other inorganic nutrients to organic molecules.

Heterotroph: Organism that can only obtain energy for life from chemical bond energy.

Energy storage is a key component of ecosystems. Autotrophs produce chemical bond energy which may be used immediately by heterotrophs or stored, either temporarily or for long times. Both Figures 4-2 and 4-3 showed energy accumulation terms. Storage is another term for accumulation. The storage symbol indicates how energy is stored in ecosystems in the form of chemical bond energy. Ecosystems that produce net useful energy do so by converting more of the sun's energy into chemical bond energy than is used by the organisms in the ecosystem. This stored energy can then be available for use by other ecosystems.

Energy Flow

Energy flow starts with an individual organism. Figure 6-3 shows a schematic of how energy is partitioned within an organism. Input may be sunlight or the consumption of another organism. Some fraction of the input will not be usable and will be lost immediately. The rest, including energy that had been stored (as fat, say) will be assimilated to be used by the organism. A large fraction of the assimilated energy may be required to provide maintenance or existence energy. For organisms such as humans, this would be the energy required to cause motion, for example. Included in this fraction is the energy lost as "waste heat" due to all other metabolic activities (including the "waste heat" here avoids having to add it to every single process).

What remains of the assimilated energy is used for production. Production includes the energy used for reproduction and growth, as well as energy that will be stored by the organism. Additionally, a fraction of the production energy is excreted. This is different from the non-usable, non-assimilated energy. In humans, for example, the urea in urine would contain production energy that is being excreted (to help the body maintain a nitrogen balance) while fiber in feces would be an example of non-assimilated energy – the fiber passes through unused.

The growth and reproduction fraction is available for the next organism in the food chain or is recycled via detrivores if the organism dies uneaten.

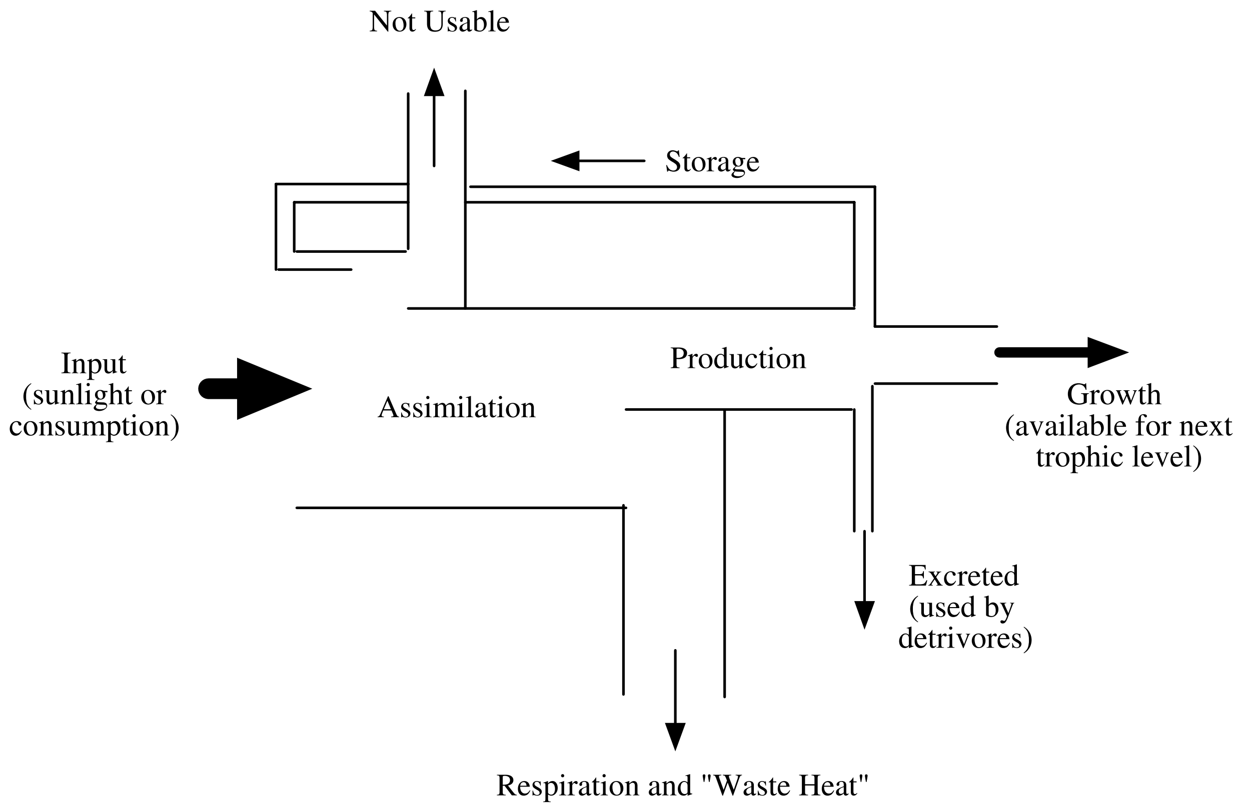


Figure 6-3 Partitioning of Energy in an Organism (adapted from Odum, 1997)

With an understanding of how each organism will process energy, we can now examine the overall movement of energy into and out of the ecosystem. Table 6-1 indicates that of all the energy striking the earth from the sun (approximately 21 million kJ per square meter per year, or 1.07×10^{22} kJ total per year, assuming the earth's radius is approximately 6.37×10^{6} m), only a tiny fraction is converted to chemical bond energy via photosynthesis. Because the amount of solar energy is so immense, however, even that tiny fraction amounts to 168,000 kJ per square meter per year or 8.6×10^{19} kJ overall per year.

Table 6-1 Solar Radiation Partitioning (adapted from Odum, 1997)

Energy Use	Percent
Reflected	30
Heating of the atmosphere and earth's surface	46
Evaporation of water	23

Wind, waves and currents	0.2
Photosynthesis	0.8

Although the fraction of energy captured by photosynthesis is small, the total energy available still seems large. How much is really available for higher trophic level organisms, such as humans? Ecologists typically assume that only 10% of the chemical energy in one trophic level can be stored in usable form in the next highest trophic level. In other words, the Growth term in Figure 6-3 will be, on average, only 10% of the Input term. The rest of the chemical energy is dissipated to non-usable form. If a human consumes about 8,300 kJ per day, and there are 6.2 billion humans, the food consumption of humans accounts for about 1.88×10^{16} kJ per year. The total energy captured by photosynthesis is only about 4,600 times more than this, which is not much of a margin once the 10% efficiency estimate is applied to each intervening trophic level. In fact, current human populations are only supportable because of the influx of stored energy to human systems that is currently being accessed.

The flow of energy can now be examined quantitatively. Consider Figure 6-2. For every 10,000 kJ available to the primary producers (the autotrophs), on average 1,000 kJ will be available for the primary consumers, 100 kJ for the secondary consumers, 10 kJ for the tertiary consumers and 1 kJ for the top consumers. The energy that is not passed up the food chain is dissipated as "waste heat" or stored in uneaten biomass (dead or alive). Nevertheless, although these efficiencies appear small, the sun continues to supply more energy every day. Storage is thus extremely important, because only a relatively short storage time is required to accumulate a tremendous amount of energy.

Energy Sustainability of Ecosystems

From an energy standpoint, there are two principle types of systems: **Basic solar-powered systems** and **Subsidized solar-powered systems**. Basic solar-powered systems can be sustained entirely with energy available directly from the sun (solar radiation used for photosynthesis) and indirect solar energy available from wind, water flow and precipitation. Many natural ecosystems are basic solar-powered systems. They are inherently sustainable because they require no more energy than can be provided by the sun. On occasion such ecosystems may nevertheless suffer, for example during a drought when precipitation falls below that normally needed by the organisms in the system. Over the longer-term, however, such periodicity will lead to the development of an ecosystem that is suitable for the conditions. This will be driven by the adaptation of individual organisms to the environment via natural selection. Many basic solar-powered ecosystems are also net producers of usable energy. In other words, these systems convert more solar energy into chemical energy than they need and thus export this extra energy, typically in the form of organisms, to nearby ecosystems.

A subsidized solar-powered system receives energy other than direct or indirect solar energy. For example, the chemical bond energy contained within an organism is not direct or indirect solar energy. If the organism moves from one system to another, it serves as an energy subsidy for the receiving system. The receiving system is obtaining energy that was captured initially in another system. A subsidized solar-powered systems may or may not be sustainable, depending on the rate of energy consumption in the system compared to the rate of usable energy production (due to photosynthesis) and energy input from other systems.

Many natural ecosystems are subsidized by energy entering the ecosystem from other ecosystems. For example, estuaries are highly productive, basic solar-powered systems. They do not require extensive chemical energy input, although the indirect energy from the tides is important to their productivity. A number of organisms spawn in estuaries and then move out of the estuary to complete their life cycle. The estuary, then, is a <u>net usable energy producer</u>. The ecosystems to which the migrating organisms move may be <u>net usable energy consumers</u>. These receiving ecosystems will nevertheless be sustainable if they do not consume more usable energy than is naturally supplied from the excess of other organisms.

All modern human systems are subsidized solar-powered systems. Earlier human societies subsidized direct and indirect solar energy with human and animal labor. These systems were not necessarily sustainable, however, depending on the ecosystem in which the humans were living. Modern human societies subsidize energy much more aggressively, using energy that was stored millions of years ago from basic solar-powered systems. The photosynthetic energy that had been captured was not dissipated into upper trophic levels as fast as it was stored in dead biomass. This stored energy was then converted to very high quality energy in the form of fossil fuels by the energy that causes geological acitivity (i.e. the radioactive decay occurring in the center of the earth). Current subsidized human systems are entirely non-sustainable in the long term because more usable energy is being consumed than is being renewably captured.

Lecture 7 Photosynthesis

Biochemical Energy Needs

Energy can enter ecosystems as electromagnetic radiation from the sun and as chemical bond energy in the mass entering the ecosystem (Figure 4-3). But in the energy balance around the earth (Figure 4-2), the sun was the only source of energy. The sun, therefore, is the fundamental energy source for organisms on earth. While we have spent some effort trying to understand energy flow and ecosystem impacts, we must now examine how the sun's energy is converted into chemical bond energy. In other words, we must examine photosynthesis.

Photosynthesis: The process of converting light energy into chemical bond energy.

Consider the following chemical reaction, the conversion of carbon dioxide (CO_2) and water (H_2O) into sugar (glucose, $C_6H_{12}O_6$) and oxygen gas (O_2):

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 \qquad \Delta G°(W) = +688 \text{ kJ/mol glucose}$$

Recall from chemistry that G stands for Gibbs free energy which is a measure of the chemical energy available from reactions. ΔG, then, stands for the change in free energy for the reaction shown. The formation of glucose from carbon dioxide and water <u>requires</u> energy. This is noted by the positive ΔG (by convention, positive free energies mean energy is required for the reaction to proceed). The ° notation means that this is the energy produced when the reaction is occurring at 1 atm pressure, at 25°C and with the activities (thermodynamic concentrations) of all the chemicals involved equal to 1. The (W) means the reaction is occurring at pH = 7.

If the glucose-forming reaction requires energy, the reverse of that reaction should release energy, which it does. The conversion of glucose to carbon dioxide and water is a common biochemical reaction in cells used to <u>produce</u> the energy needed by cells and organisms to survive. Non-photosynthetic (heterotrophic) organisms, in fact, must get the energy they need for survival solely from chemical reactions such as the glucose consumption reaction (the reverse of the reaction above). As discussed earlier, photosynthetic organisms (**photoautotrophs**) capture the sun's energy to produce glucose, and other compounds, from carbon dioxide and water. Photoautotrophs capture the useless energy (at least to heterotrophs) from electromagnetic radiation, the only energy entering the biosphere, and convert it to the useful chemical bond energy needed by all organisms.

To understand how photosynthetic organisms do this, we will break the glucose-forming reaction into two **half-reactions**. Half-reactions show clearly how electrons are being used. As we will see, electron movement is important to photosynthesis. The first reaction is a **reduction reaction**. A reduction reaction is one where atoms <u>receive</u> electrons. The reduction reaction of interest shows that CO_2, and in particular the carbon atom, is receiving electrons .

$6\,CO_2 + 24\,H^+ + 24\,e^- \rightarrow C_6H_{12}O_6 + 6\,H_2O$ Reduction reaction

The second half-reaction is an **oxidation reaction**. An oxidation reaction is one where atoms lose electrons. In the oxidation reaction shown, we see that H_2O, and in particular the oxygen atom, is losing electrons.

$12\,H_2O \rightarrow 6\,O_2 + 24\,H^+ + 24\,e^-$ Oxidation reaction

The overall chemical reaction to produce sugar from carbon dioxide and water is actually the process of taking electrons from the oxygen in water molecules, a process that forms O_2, and giving them to the carbon in carbon dioxide, a process that produces sugar.

Photosynthetic organisms carry out the above half reactions separately. The oxidation reaction is conducted during the **light phase** of photosynthesis and requires light. The reduction reaction (synthesis) is conducted during the **dark phase** (meaning light is not required). For many years, biologists believed that only plants and cyanobacteria (both phototrophs) were capable of synthesizing sugar from CO_2, hence the special terminology. Microbiologists have determined within the last 40 years or so that there are a number of groups of bacteria that can also synthesize organic compounds from carbon dioxide, including nitrifying organisms and methanogenic organisms. These organisms are not phototrophs but can nevertheless convert carbon dioxide to organic compounds using energy from inorganic molecules. Therefore, because the dark phase reactions are not unique to phototrophs, we won't discuss them further. That is okay because what truly distinguishes phototrophs are the light phase reactions.

Mechanism of Light Capture

Photosynthesis can occur because of special compounds (**pigments**) manufactured by phototrophs absorb light and use the absorbed energy to excite electrons to higher energy levels.

The primary pigment in most green algae and plants that absorbs light is **chlorophyll-a**. This pigment absorbs light at wavelengths of 420, 660, 670, 678, and 685 nm. Phototrophs have other pigments as well that can absorb light at different wavelengths.

Let's consider what happens when light strikes a pigment. Say that pigment A has an electron that can be excited by light of a certain wavelength, say 660 nm. When the electron is at a lower energy state we will denote that as A_e. When a quantum of light strikes A_e, the pigment absorbs enough energy to boost the electron to a higher energy level, A^e. But if all we had was this pigment, the electron would eventually drop back to its unexcited state, releasing light and heat (Figure 7-1).

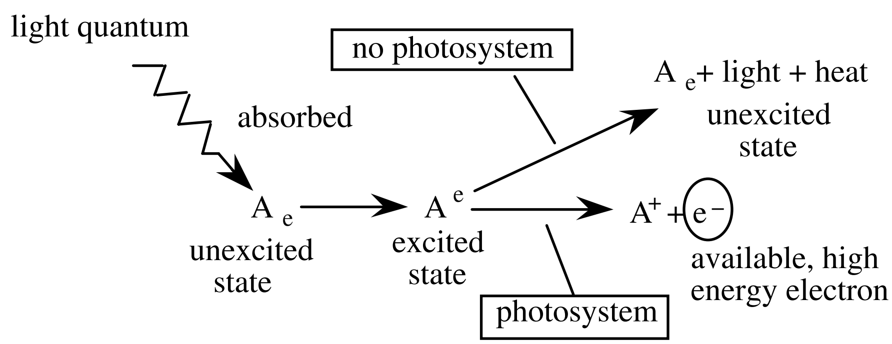


Figure 7-1 Schematic of Pigment Electron Excitement

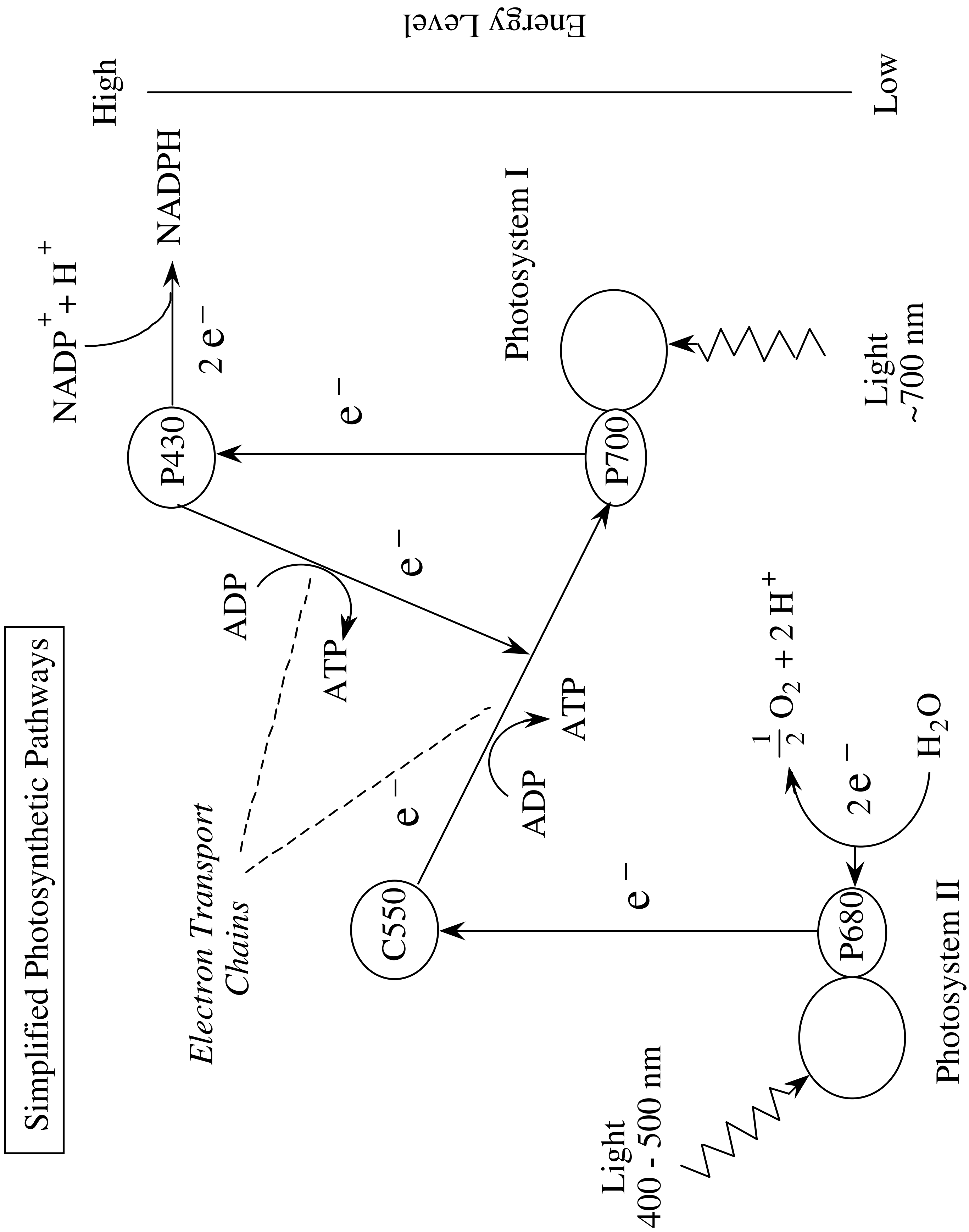
Fortunately, phototrophs build their pigments into a molecular system – a **photosystem** – to capture the energy for metabolic use. With a photosystem, the energy from light is captured on the pigment, exciting the electron to a higher energy state, as before. Now, however, the high energy electron can be removed from the pigment and made available to be used by the cell. The high energy electrons are used to reduce carbon dioxide to glucose, as indicated earlier. The high energy electron can also be used to produce other high energy chemical constituents that the phototroph can use to conduct other reactions in addition to constructing glucose from carbon dioxide and water.

Energy Conservation

Figure 7-1 presents a very simplified view. A better understanding of how energy is conserved from the high energy electron is shown in Figure 7-2. Notice at the far right of the figure a scale for energy level. The energy of the electrons on the oxygen in water is low (bottom center of figure) while the energy of the electrons in NADPH is high (top right corner of figure). NADPH is a complex organic molecule used by the cells of many organisms to carry high energy electrons to synthesis reactions. Cells don't have electric wiring to carry electrons and electrons cannot appear in free form (not attached to an atom) in cells. Where Figures 7-1 and 7-2 show electrons that appear to be "free", the electrons are actually affiliated with some other atom.

To see how the low energy electrons in water become boosted to the high energy electrons in NADPH, let's follow an electron through the pathways shown, starting in the lower left corner of the figure. Photosystem II absorbs light of wavelength 400-500 nm. The energy from this light is captured at the reaction center, P680. The absorbed energy activates an electron and sends it to C550, an intermediate electron acceptor. This leaves P680 short an electron. To conduct this reaction again, P680 must eventually recover the electrons that are boosted to C550.

This is done by taking electrons from the oxygen in water, causing the formation of molecular oxygen, as shown.


Simplified Photosynthetic Pathways
Energy Level
High
Low
NADP$^+$ + H$^+$
NADPH
2 e$^-$
P430
e$^-$
Photosystem I
P700
Light
~700 nm
ADP
ATP
Electron Transport
Chains
C550
P680
Photosystem II
$\frac{1}{2}$ O$_2$ + 2 H$^+$
H$_2$O
Light
400 - 500 nm

The electron at C550 now has enough energy for the cell to produce ATP from ADP. ATP (adenosine triphosphate) is a chemical in cells that temporarily stores energy. ADP (adenosine diphosphate) is the low energy counterpart. Once formed, ATP can be moved around the cell to the places that energy is needed. Just as NADPH moves electrons around the cell, ATP moves energy around the cell.

To form ATP from ADP, the electron must move down an electron transport chain (ETC). The ETC is a series of chemicals within an internal cell membrane that accept and release electrons readily, probably as close to electric wire as cells get. Using enzymes embedded in the membrane, the energy released as the electron moves "down" the chain can be captured as ATP. At the bottom of the chain, the lower energy electron is received by P700. Light collected by Photosystem I activates the electron again at P700, boosting it to P430 where it is at a very high energy level.

The electron at P430 can be used by the cell to generate energy or to form NADPH needed for synthesis. To generate energy, the electron drops down another ETC back to P700, in the process causing the formation of another ATP. The electron can be excited again and boosted back to P430 to repeat the process. When NADPH is required, the electron is taken from P430 and added to $NADP^+$ (the electron-short version of NADPH). Everything is fine after this cycle except that P680 is left short one electron. P680 gets its replacement electron off the oxygen in water, in the process oxidizing water to oxygen gas, in accordance with our oxidation reaction.

Importance of Photosynthesis

Photosynthesis is an extremely important process on earth for 2 reasons.

1. Photosynthesis facilitates the conversion of light energy and inorganic compounds to organic compounds needed by cells and organisms (as we have noted already).

2. Photosynthesis created molecular oxygen on earth and continues to do so today.

Item 2 is extraordinarily important to life on earth. The mechanics of biochemical energy generation (which we will not examine further) in conjunction with conservation of mass require that heterotrophic organisms have a compound onto which electrons can be placed after their energy has been captured for growth. Oxygen is the compound used by many organisms, including humans, to accept low-energy electrons. In the absence of oxygen, phototrophs could convert solar energy into chemical bond energy, but very few organisms could use that energy.

Oxygen is required to facilitate energy flow in all ecosystems that include multicellular organisms.

Appendix to Lecture 7: Light Quanta

A quantum of electromagnetic radiation provides a specific amount of energy, depending on the frequency of the light (Equation 7-1). The frequency of the electromagnetic radiation is related to the wavelength as per Equation 7-2.

$$\text{energy of one quantum (J)} = h\nu \qquad (7\text{-}1)$$

where: h = Planck's constant = 6.626×10^{-34} J s
ν = frequency of the radiation, s^{-1} (= hertz = Hz)

$$c = \lambda\nu \qquad (7\text{-}2)$$

where: c = speed of light, 3×10^{8} m/s
λ = wavelength of the radiation, m

With these equations we can readily calculate the energy in a quantum of electromagnetic radiation for any given wavelength. Because electrons are used by photoautotrophs, the wavelengths expected to be most useful would be those that provide just enough energy to boost an electron. These wavelengths happen to be those in the visible light range. Infrared wavelengths, which are longer and therefore less energetic, do not provide enough energy to boost electrons. Ultraviolet wavelengths, which are shorter and more energetic, provide too much energy. Indeed, ultraviolet wavelengths are energetic enough to damage DNA molecules. X-rays and gamma rays are even shorter and that much more energetic. These wavelengths can be dangerous to organisms.

Lecture 8 Oxygen and Carbon Cycles

When we looked at energy and mass flow in ecosystems, we assumed that over the earth, mass was approximately constant. Yet we know that mass is constantly changing form, i.e., molecules are constantly being formed and degraded. To track mass, then, we must look at elements, not molecules, because in non-nuclear reactions, elements are not changing.

A useful tool for tracking elements on earth is the **biogeochemical cycle**. As the name implies, we will track the element through biological, geological and chemical transformations. The cycle itself is simply an identification of the biological, geological and chemical processes of interest. Because we just finished discussing photosynthetic processes, we will look at the two biogeochemical cycles most affected by photosynthesis, the oxygen and carbon cycles.

Oxygen

A simplified biogeochemical cycle for oxygen is presented in Figure 8-1. Oxygen is primarily cycled between <u>water</u> and <u>molecular oxygen</u>. The water cycle (or hydrologic cycle) is itself crucial to ecological and engineered systems. It will be discussed briefly in later lectures and in more detail next term in EDV250, Hydraulics and Hydrology.

The main processes of interest in the oxygen cycle are:

a. <u>Photosynthesis</u>.
This process essentially removes the oxygen from water to form O_2 as we discussed last lecture. This is the only <u>natural</u> process that conducts this reaction in large enough quantities to matter ecologically. The importance of photosynthesis can best be emphasized by trying to imagine what would happen in the extreme event that all photosynthesis on earth stopped.

b. <u>Respiration</u>.
This is a general name for the biochemical oxidation of chemical compounds to produce energy needed for organism activity, growth and reproduction. This process converts O_2 back to water.

c. <u>Combustion</u>.
Since the first lightning strike started the first forest or grass fire, combustion has been a part of the oxygen cycle, albeit a minor part. The role of combustion has become more important since the start of the industrial era and the combustion of fossil fuels. Nevertheless, the impact of combustion directly on the oxygen cycle is relatively minor. It is shown in Figure 8-1 because of its role in other cycles.

Oxygen also appears in other molecules that are important for their <u>biological impact</u>, but are relatively minor on a mass basis. These are:

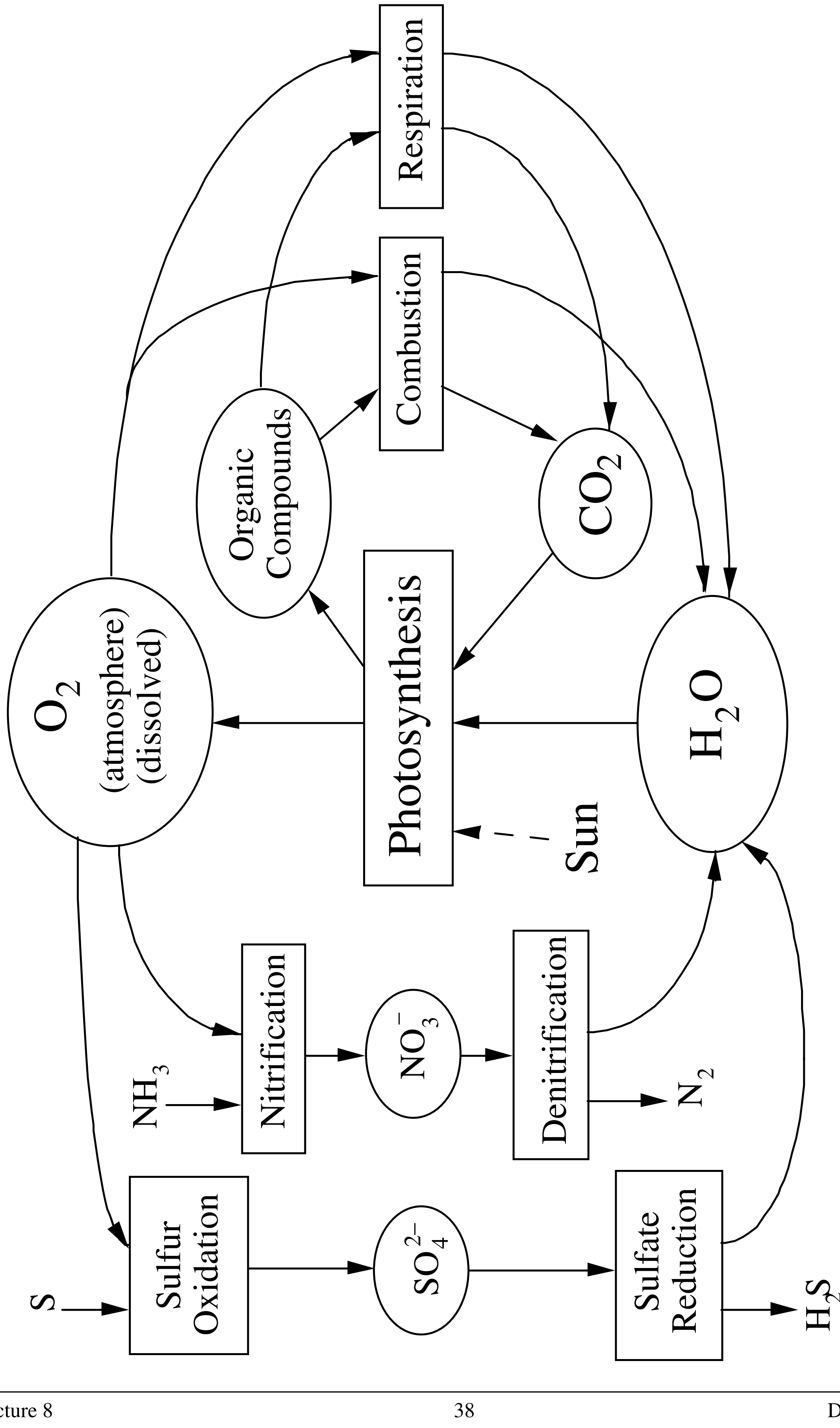


Figure 8-1 Simplified Oxygen Cycle

a. Carbon dioxide, CO_2.

Formed during respiration and combustion. Discussed in more detail in the carbon cycle.

b. Nitrate, NO_3^-.

Formed during nitrification, during fossil fuel combustion as nitric acid (HNO_3), and by lightning. Discussed in more detail in the nitrogen cycle.

c. Sulfate, SO_4^{2-}.

Formed as sulfuric acid by bacteriological oxidation processes (acid mine drainage, sewer corrosion) or fossil fuel (especially coal) combustion. Discussed more in the sulfur cycle.

Notice that nitrate and sulfate can undergo additional reactions to release the oxygen in the form of water, while releasing nitrogen or sulfur in another chemical form. The oxygen in carbon dioxide is cycled separately as part of the photosynthesis process.

From an energy standpoint, we see that energy is required to form oxygen gas from water. That stored energy is then released when chemical reactions with oxygen gas convert the oxygen back to water. The details of the energy release in the respiration processes in particular are mapped out in a food chain or food web, as we have discussed previously.

Carbon Cycle

Carbon is one of the most chemically diverse elements and is found in many forms of interest. The forms of most interest to environmental systems are:

a. CO_2

b. Organic compounds

Figure 8-2 provides a simplified biogeochemical cycle for carbon.

Forms of CO_2 are found in the atmosphere (as gaseous carbon dioxide), dissolved in water (as carbonate compounds), and in rock (limestones and other carbonate rocks). The CO_2 hasn't chemically changed, it is just configured slightly differently, so there is a constant physical/chemical interaction between these different pools of carbon. This is indicated in Figure 8-2 as double arrows between these three pools of carbon dioxide.

Figure 8-2 shows two processes for converting carbon dioxide into other compounds. One is photosynthesis. Photosynthesis is the production process for essentially all organic compounds on earth. It is also the production process for our food, and the food for almost every other non-photosynthetic organism on earth. The respiration process leading from the organic chemicals pool is the same one shown in Figure 8-1 for oxygen and simply summarizes the complex ecological energy flow chain set up in ecosystems.

Interestingly, photosynthesis is also the source of fossil fuels. Figure 8-2 simplistically shows this as a sedimentation process (of non-consumed organic material, typically dead organisms) followed by geological processes that convert the carbon compounds into fossil fuels.

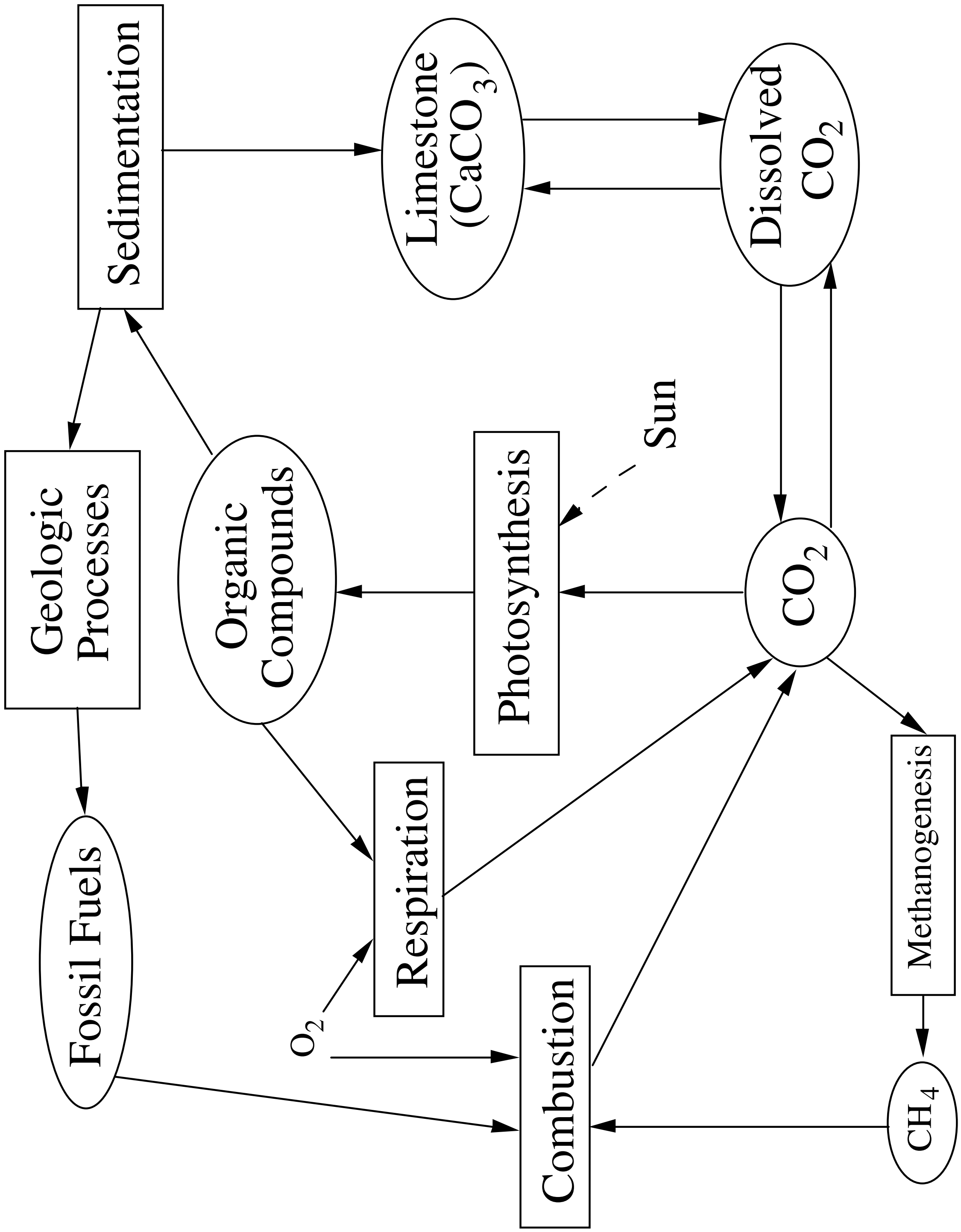


Figure 8-2 Simplified Carbon Cycle

So photosynthesis is ultimately the process that has provided most of the useful chemical energy available on earth, both for ecological systems and for human systems (including fossil fuels). Photosynthesis continues to convert energy from the sun's electromagnetic radiation into chemical energy, but not necessarily at rates fast enough for modern human civilization.

The other process for converting carbon dioxide is <u>methanogenesis</u>, the process of forming methane. Methane may be produced by the same geologic processes that produce fossil fuels, but that is already shown in the other loop. The methanogenic process of interest in this loop (lower left part of Figure 8-2) is facilitated by **methanogenic bacteria**. These organisms use very simple organic compounds or even hydrogen gas as their electron donor (food) to form methane.

Methanogenic bacteria are <u>extremely sensitive</u> to oxygen. The presence of oxygen completely inhibits their activity. The process of methanogenesis has a very important benefit for human systems: it can **convert waste into methane**. This process can happen naturally in swamps and landfills. If the landfill is designed properly, the methane produced can be mined. These organisms are also found in **anaerobic digesters** at wastewater treatment plants, a process that will be discussed in more detail later.

The quantitative impact of methanogenesis is relatively small in the carbon cycle, much smaller than Figure 8-2 would suggest. The quantitative benefit of methanogenesis to humans as a renewable energy source may be large, however. Currently, only a tiny, perhaps negligible, fraction of the energy available in waste materials is recovered for human use. Whether more complete recovery of this renewable energy source will provide enough energy to sustain our heavily subsidized solar-powered human systems will likely depend strongly on how efficiently we manage our energy resources.

Notice the human effect on the carbon cycle. We are rapidly oxidizing carbon that has been locked away as fossil fuels. The long-term impact on the carbon cycle is difficult to predict. In the short term we expect to see an increase in atmospheric CO_2 concentrations, which has been observed. The issues of global warming and possible climate change arise from this. Perhaps we will consume all of the available fossil fuels fast enough that global warming won't be an issue. In that case, human will face a tremendous energy shortage but at least we won't be pumping CO_2 into the atmosphere from reserves stored many millions of years ago.

<u>Lecture 9</u> Sulfur, Acid Rain and Global Warming

Most if not all human "eco"systems are energy sinks. High quality energy enters our systems and all we return is waste, both as waste heat and waste materials. Because mass is recycled, waste materials can ultimately be recovered. Energy is not recyclable, however. The important question, then, is whether human systems, while being energy sinks, are nonetheless sustainable from an energy basis. In other words, when an energy balance is conducted around human systems, is the energy entering less than or equal to the energy that would be provided by natural systems (= sustainable) or more than the naturally provided energy (= unsustainable)? Such a balance will show that current human systems are emphatically <u>unsustainable</u>. The reason is fossil fuels – **petroleum**, **natural gas** and **coal**.

The industrial age began at the time humans figured out how to harness the energy produced from fuel combustion for industrial purposes. Initially that energy was captured as steam but later it was captured as electricity and directly in internal combustion engines. Wood was first used as the fuel source but fortunately fossil fuels replaced wood. This discovery greatly slowed the destruction of the earth's forests, although such destruction is still occurring at tremendous rates.

Technologies that harness the energy of fossil fuel combustion are primarily responsible, directly and indirectly, for the human population explosion (more on that later). Improvements in agriculture have allowed us to feed more people than ever before. Phosphorus mining to produce fertilizer requires energy, the conversion of N_2 gas into NH_3 for use in fertilizer requires energy, pumping irrigation water from the water source to the fields requires energy, and operation of mechanized agricultural equipment requires energy. Without the energy from fossil fuel combustion, these activities could not be accomplished to the extent that they are today.

Fossil fuels are a limited resource. The organic matter from which they were formed was originally created by photosynthetic organisms millions of years ago. At that time, the earth's ecosystems were storing energy from the sun in the form of high quality chemical bond energy and there was a net accumulation of useful energy on the planet. While there is some indication that the processes that led to fossil fuel production may be still occurring today, the atmosphere and the ecosystems existing today are much different. Until further data indicate otherwise, we should assume that the amount of fossil fuels is indeed limited and the question remaining to argue about is when these fuels will be completely exhausted.

We could examine many issues related to fossil fuels. Mining the fuels, especially coal, has direct environmental impacts. Transporting and storing petroleum impacts the environment due to spills (especially from oil tankers) and leaks (from pipelines and storage tanks, especially the ones storing gasoline at your nearby gas station). Combusting the fuels produces residuals that also impact the environment. In this lecture we will focus on combustion residuals.

We have already examined two of the biogeochemical cycles that are directly affected by the combustion of fossil fuels – carbon and oxygen. We will now examine another biogeochemical cycle that is directly impacted by fossil fuel combustion – the sulfur cycle.

Sulfur Cycle

Sulfur (S) is a mineral and is predominately found in inorganic form (see the bottom right hand section of Figure 9-1). Sulfur may be found in conjunction with a metal, such as in iron sulfide (FeS) or calcium sulfate ($CaSO_4$), or in pure form. Simplistically, inorganic sulfur is oxidized by exposure to oxygen. In practice, this oxidation may be catalyzed by bacteria that can oxidize precipitated sulfides to sulfuric acid (H_2SO_4). If the sulfide is found in mine tailings that have been exposed to air, the result can be **acid mine drainage**. Acid mine drainage is a significant environment problem of its own due to inappropriate disposal of residuals from the mining process. If the sulfide is found in sewer gas, the resulting sulfuric acid can lead to **sewer crown corrosion**. This is particularly a problem in warmer climates and in sewers that have not been designed properly (i.e., keep sewage in them long enough for hydrogen sulfide to be formed in the sewer). Although not an environmental problem, sewer corrosion is a significant civil engineering problem.

Once sulfuric acid is formed, the sulfate may reprecipitate to form inorganic sulfur or be reduced by bacterial activity to hydrogen sulfide (the process occurring in sewers that then leads to sulfide reoxidation and sewer crown corrosion). The sulfate may also be used by organisms as a nutrient. Sulfur is a constituent of several biochemicals required by organisms, including a couple of amino acids.

Once incoporated into organisms millions of years ago, sulfur became incorporated into fossil fuels following the same geologic processes that created fossil fuels from carbon. Until the industrial age, most of these fossil fuels remained stored in the crust, and did not interact with the environment significantly. However, with fossil fuel combustion, the sulfur in the fuels became oxidized to SO_2, a gas which can be transported great distances in the atmosphere where it also dissolves into rain and reacts to become sulfuric acid, a major constituent of acid rain.

$$2\ SO_2 + O_2 + 2\ H_2O \rightarrow 2\ H_2SO_4$$

Acid Rain

The combustion of fossil fuels produces acid rain by oxidizing the sulfur in the fuels. Another source of acid rain is the nitrogen in air that is also combusted to form nitrogen oxides, NO_x (NO, N_2O, NO_2, etc.). These compounds are also gases that dissolve into rain and react to become nitric acid HNO_3.

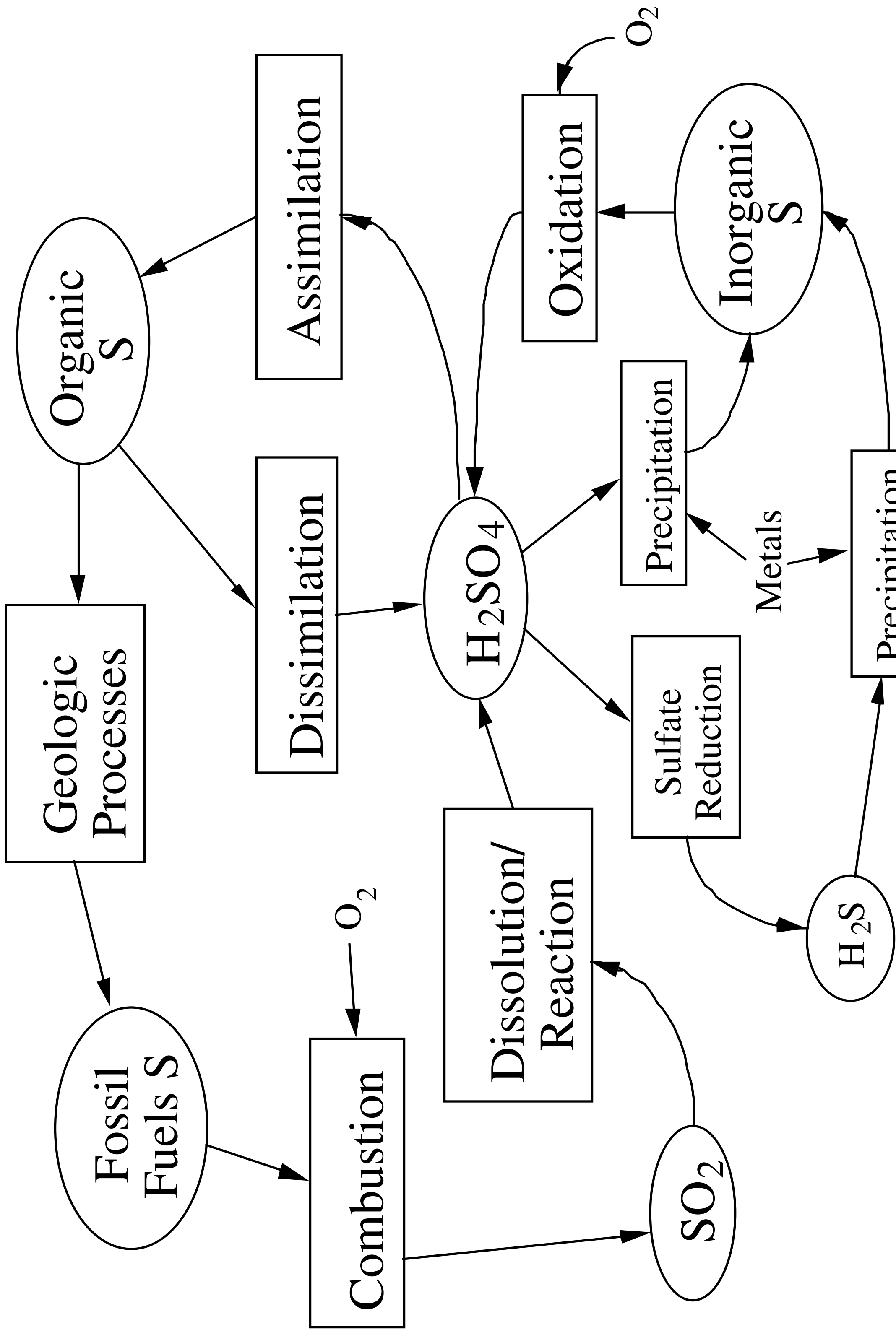


Figure 9-1 Simplified S Cycle

Acid rain may also be caused by other processes that emit acid-forming compounds but sulfuric and nitric acids are the predominant acids formed directly from the process of combusting fossil fuels. The impacts of acid rain on the environment are widely documented and include acidifying lakes, and thus killing everything in the lakes, to killing forests, directly and by acidifying the soil. Additionally, acid rain shortens the lifespan of constructed products such as bridges and buildings. The acid encourages more rapid corrosion of these materials.

There are several engineering challenges associated with minimizing acid rain production:

1. Producing clean (low sulfur) fuels.
2. Developing cost-effective scrubbers for exhaust stacks (scrubbers exist that work well, but they also are relatively expensive).
3. Developing low temperature combustion processes (NO_x formation is favored at higher combustion temperatures).

These challenges assume that fossil fuel combustion will remain the primary source of energy for human systems, at least until all the fossil fuels have been combusted.

Global Warming

There is no question that the concentration of CO_2 in the atmosphere has increased. Careful atmospheric measurements over the last 50 years or so have proven that. It appears very reasonable that the increase in CO_2 concentration may be at least partially due to fossil fuel combustion. The biogeochemical cycle for carbon (Figure 8-2) clearly showed that CO_2 is a major product of the combustion of carbon-based fossil fuels. There is also no question that CO_2 is a greenhouse gas, that is, it absorbs heat and by such absorption, assists in regulating the temperature of the atmosphere on earth. So, if these things are so clear, it should be clear that global warming is due to fossil fuel combustion, right?

Based on the meagre information that was provided in the previous paragraph, we cannot conclude that fossil fuel combustion is causing global warming. We could probably satisfy ourselves that such a link does in fact exist if we examined more carefully the scientific and engineering data that have been developed relating to this issue. While an interesting academic exercise, this is likely a waste of our time. Instead, we will simply assume that global warming is directly impacted by increased CO_2 concentrations that are directly due to fossil fuel combustion. Then we will use information that has been presented in this course to help us predict what may happen. An interesting thought exercise you should do is to identify whether this simplifying assumption has any true negatives. I would propose that there are no negatives to making this assumption and so there is no risk in making it.

Figure 8-2 presents most of the relationships of interest to this discussion. In addition to showing combustion producing CO_2, the cycle shows mechanisms for removing CO_2. Those mechanisms are photosynthesis, dissolution and precipitation. The increase in atmospheric carbon will result in increased movement to the other pools. For example, plants become more productive as the concentration of CO_2 in the atmosphere increases. Also, as the atmospheric CO_2 concentration increases, the maximum dissolved CO_2 concentration in the oceans also increases. The question that we can't answer is <u>how fast</u> do these mechanisms work? Are they fast enough to overcome our input of CO_2 into the atmosphere? Probably not, but more research is required to determine how fast these processes really are globally.

Perhaps the more important question is not whether global warming can be proven to be occurring due to fossil fuel combustion but rather what are the likely environmental effects? Predictions indicate that climates may change and local weather will become more severe. This will definitely impact environmental systems. Most organisms in a given ecosystem have evolved specifically for that ecosystem and cannot tolerate conditions that are much different. Climate and weather changes will definitely impact these organisms. Impacting one organism in an ecosystem will impact the entire ecosystem, most likely in ways that we can't even predict.

With all of this uncertainty, the unwillingness of government leaders in most countries to do anything useful with respect to potential global warming is perhaps understandable. Government leaders are generally not known for their vision and technical skills, but primarily for their abilities to fool enough people into electing them (at least in democratic societies). Our global economic systems are firmly founded upon the availablity of relatively inexpensive fossil fuels. The companies that extract and sell this fuel exert tremendous political pressure, both directly by lobbying politicians and indirectly in the marketplace, to not disrupt their extraordinary profits. The government leaders brave enough to tackle issues related to fossil fuel combustion and thus risk losing the next election, are extraordinarily rare. Sadly, the voting public in many jurisdictions remains too ill-informed to provide any useful leverage on their elected officials.

Engineers, on the other hand, must constantly deal with uncertainty. In the case of global warming, two key points are:

1. Many people are now beginning to feel that global warming is a potential problem. These people will begin to influence government leaders. More practically from the engineer's standpoint, these people and their organizations will begin to shut down engineering projects by convincing the people in local jurisdictions that potential projects are detrimental.
2. Fossil fuels will ultimately be consumed.

Both issues will greatly increase the cost of accomplishing engineering activities. So although uncertainty remains, the wise engineer will begin looking for solutions now.

The Problem – how to reduce the pool of atmospheric CO_2 (and the possibility for global warming)

The Constraints

– maintain or improve current standard of living

– maintain cost-effectiveness

Possible Solutions

1. Stop burning fossil fuels.

This will reduce CO_2 emissions but without a replacement energy source, there will be a **huge** decrease in world-wide standard of living. Fossil fuel consumption could be immediately reduced, however, by increasing the price of fossil fuels to more accurately reflect the environmental costs. If that is done, other energy generating processes may become cost-effective. This option also eliminates the problems of acid rain due to combustion.

2. Use solar energy indirectly (wind, hydroelectric).

Good idea, but hydroelectric, for example, has its own environmental impacts. The cost to convert wind to energy (electricity) has decreased substantially and in areas with high energy costs and the appropriate climate wind-generated energy is becoming a viable alternative.

3. Use nuclear energy.

This seemed like a good idea 50 years ago. It currently has limited political feasibility in North America due to the incompetence shown by North American utilities with respect to safety. Additionally, the issue of waste disposal remains. Furthermore, nuclear energy is extraordinarily expensive, more so than many alternatives. Anyone saying otherwise is selling nuclear energy. To prove this to yourself, just look at the costs of nuclear energy in Ontario over the last 10 years, in particular the costs to rehabilitate reactors that had been shut down. As the cost of fossil fuels continues to increase, however, expect more and more lobbying from certain political sectors to expand nuclear energy capability.

4. Stimulate photosynthesis and then use that material for fuel.

This option reduces the flow of carbon from the fossil fuel pool and will therefore lead to a reduction in atmospheric CO_2. Furthermore, this option is highly attractive to farmers who have seen their profits due to food production decline dramatically. Growing crops for conversion into energy compounds such as ethanol may be more profitable. While technically feasible, this strategy will ultimately not provide sufficient energy because the land needed to grow crops for fuels is also the same land needed to grow crops for food. Nevertheless, this strategy is presently receiving tremendous political support.

5. Use fuel cells.

Another hot topic these days, fuel cells convert hydrogen to water and generate electricity directly. The current idea is to convert natural gas into hydrogen and CO_2 to provide the hydrogen needed. While this improves the overall emissions equation and should be implemented, this approach is ultimately shortsighted. A renewable source of hydrogen is required, not one based on fossil fuels.

6. Recover energy from waste.

There are virtually no environmental reasons to not recover energy from waste but there are tremendous environmental benefits. The energy can be recovered as methane which can then be combusted or converted to hydrogen and CO_2 with the hydrogen used in fuel cells. The energy can also be recovered directly in liquid fuel form, as is the case with the production of diesel from waste vegetable oils and ethanol from waste agricultural products.

Only a few jurisdictions have truly embraced the concept of waste to energy. The reasons are political. Often, legal monopolies operate a region's electricity utility. These monopolies artificially keep electricity prices so low that electricity production options not owned by the monopoly are priced out of competition. Privatization of the electricity marketplace will likely not change the situation much in most jurisdictions because of entrenched political and economic interests. Ontario and Canada will likely continue to treat waste with energy-consuming processes while other jurisdictions around the world have recognized that waste is a truly renewable energy source and are leading the way with technology development.

While energy from waste makes sense technically, economically (when true costs are considered) and philosophically, it won't be enough. Other non-fossil fuel based energy production is also required.

7. Use solar energy directly.

The source of most energy on earth is the sun. Currently, our energy production schemes have used this energy indirectly (even fossil fuel energy originated from the sun). Ultimately, we must develop technologies that captures solar energy directly. The current challenge now is cost – because true accounting is not practiced, solar technologies remain expensive compared to fossil fuels.

The charge that solar energy is not applicable to all locations on earth is erroneous. Fossil fuels are not recovered at all locations on earth and yet we use them everywhere. The technical challenge is to distribute the solar energy collected in one location to another location. One possibility could be to use solar energy to split water into hydrogen and oxygen, transport the hydrogen to where it is needed, and then produce electricity with fuel cells. Undoubtedly other options will be developed.

8. Conserve energy.

The societies that humans have constructed were based on the assumption that energy was essentially free and unlimited. The result is that most of the processes we use are immensely inefficient from an energy standpoint. New processes and approaches must be developed that improve energy efficiency. Indeed, conservation is likely the most cost-effective method to "produce" energy. The problem is that big monopolies like petroleum companies and electricity generators do not make money when people conserve. They would rather sell people more fossil fuels and electricity. Conservation, then, must be promoted by energy consumers. This happens naturally when the price of energy increases. Allowing energy prices to rise, however, is a political nightmare and so politicians take the easy way and subsidize the cost to keep prices low. This is done either directly, as Ontario does it by paying the utilities the difference, or indirectly, as the United States does it, by waging war to secure control over energy supplies (wars are very expensive).

Summary

Fossil fuel combustion affects all of the biogeochemical cycles directly or indirectly (we will see later the impact on the nitrogen and phosphorus cycles) and causes, directly or indirectly, much environmental damage. Fossil fuel combustion has provided a large input of energy into the biosphere that supports human activities at levels that could not be previously supported. The diversity of the biosphere is being decreased due to these human activities (we will prove this later). Such diversity decreases could continue in the absence of fossil fuel combustion if another energy source was found. The direct impacts of fossil fuel combustion such as acid rain and global warming, however, would nevertheless be reduced.

<u>Lecture 10</u> Other Ecosystem Issues

Limiting Factors

Organisms grow to the extent allowed by the availability of nutrients and energy. For example, in sub-tropical deserts there is no shortage of energy from the sun. The lower latitudes ensure that the amount of sunlight available does not vary tremendously throughout the year. Nevertheless, sub-tropical deserts are known to have very little life. The limiting factor is, obviously, water.

Consider another example, the open ocean. Here the problem is definitely not the shortage of water. Lack of sunlight need not be a problem either – we can consider only the upper depths of the water in tropical regions. So why is the open ocean also relatively devoid of life (especially as compared to estuaries, for example)? Lack of nutrients, in this case nitrogen.

In both deserts and the open ocean, the lack of a crucial component for life limits the amount of life that can exist in that ecosystem. These limits are ultimately met in every ecosystem. In some ecosystems, however, the limiting factors may not be obvious. In rich ecosystems that appear to have no limits, there may be different limiting factors for different organisms. In agricultural systems that are fertilized and irrigated (to ensure that neither nitrogen, phosphorus, nor water are limiting factors), the lack of trace minerals may limit growth.

Limiting factors are not only due to the lack of something. Too much of something may also limit growth. Perhaps the best examples are mineral salts in soils. Plants have different tolerances to salt concentration and as the salt concentration in soil increases, fewer plant species thrive. At some point, the salt concentration of a soil may become high enough that no plants can survive. In this case, the excess of salt limits growth, just as the lack of water limits growth in deserts.

Ironically, salt concentrations in soil increase most rapidly where extensive irrigation for agriculture occurs. All natural waters contain some concentration of dissolved inorganic constituents. When irrigation occurs, a fraction of the water is used by the plant and evapotranspires to the atmosphere. The dissolved constituents, however, are not removed from the soil and remain behind. As more water must be added to grow more crops, more and more salt is left behind. Because salts are soluble, they can be removed from the soil – but only if a large excess of water is applied that will move the salts either into the groundwater or out to surface water bodies. In arid regions where irrigation is most commonly practiced, there is insufficient water to "flush" soils. The salinity increases and the productivity decreases.

Ecosystem Evolution

As we will see, individual species of organisms evolve in response to genetic changes. Ecosystems also evolve, but not for genetic reasons. To avoid confusion, ecosystem evolution is typically called succession.

Succession: The shifting from one ecosystem to another over time.

Primary succession refers to the development of an ecosystem in an environment that previously had no life. Primary succession is most readily observed today in lava fields. Lava from volcanoes is sterile (it is far too hot for life) and when it cools to form rock, nothing is living in or on it. Slowly, organisms colonize the rock and, given enough time, an ecosystem will develop. The initial ecosystem will be relatively primitive, consisting of plants that can survive with very limited soil. As this first ecosystem continues to thrive, actions of the organisms begin to modify the environment and can make it more favorable for other organisms. For example, as plants begin to obtain footholds in the cracks of rocks where thin layers of soil may accumulate, the growth of the plant roots begins to accelerate the conversion of rocks to soil. Furthermore, as the plants die, their organic matter can become incorporated into the soil, further improving it. Finally, the soil quantity and quality will be sufficiently improved that other plants may be able to thrive.

In the process of changing the environment to make it better for other organisms, the pioneer organisms may decrease their own competitiveness. When this happens, the pioneer organisms eventually are replaced, ironically by organisms that could not survive in the environment until the pioneer organisms changed it. Typically, as succession occurs, the ecosystems become more complex and diverse. At some point, a maximum diversity ecosystem may be achieved that does not succeed to another ecosystem. This stable ecosystem is called the **climax stage**.

Secondary succession refers to the same process, the shifting of ecosystems over time, but occurring from a different starting point. Secondary succession occurs at sites that had previously achieved a subsequent stage of succession but that were disturbed in some manner. Perhaps the clearest example is abandoned cropland in a temperate forest region like southern Ontario. The original ecosystem, a climax hardwood forest, was removed to allow agricultural activity. When the agricultural activity is abandoned for some reason (not a common occurrence), the ecosystems begin the process of succession, but now starting from the point of good soil and not bare rock.

Succession and Energy

Although the concept appears simple, succession is actually a complex ecological phenomenon. What is now clear is that individual organisms do not work together to facilitate succession, although the result may give that impression. Individual organisms are doing what all organisms do – trying to survive and reproduce themselves within the constraints of their environment and following the instructions of their genetic code. Ecosystem succession is not occurring in response to deliberate, organized organism actions. Ecosystems are not human societies.

Although all the factors affecting succession are not clearly identified, a common pattern has been observed on the basis of energy flow. Early in succession, ecosystems expend a larger fraction of the total energy entering the system on growth. Subsequent ecosystems expend a larger fraction of the total energy entering the system on maintenance (respiration). Note that these energy expenditures refer to the ecosystem as a whole, not to individual organisms. Conceptually, what this means is that ecosystems early in succession are accumulating chemical bond energy. If an energy balance is conducted on the system, we would find that energy is being retained in the form of increased growth. Ecosystems later in succession are reaching a steady-state with respect to energy. In other words, an energy balance would show that more of the energy entering the system is leaving as waste heat. The climax stage, then, occurs when no additional net accumulation of energy can occur for a location.

Different climax stages occur in different places because the limiting factors for each specific location are different. We would not expect the climax stage in Ontario, where cold winters cause a dramatic interruption in natural life cycles, to be the same as the climax stage in a tropical rain forest where conditions remain ideal for organisms throughout the year.

Allogenic Forces and Dynamic Issues

Succession rarely occurs in the neat, orderly fashion described in ecology textbooks. **Allogenic forces** (periodic, external inputs) disrupt succession. Fire and severe weather events, like hurricanes, are examples of natural allogenic forces. They can significantly disrupt the ecosystem, perhaps sufficiently to move the system from a climax stage to an earlier successional stage. If the allogenic forces occur frequently enough, a true climax system (defined as not accumulating net energy) may never occur. These areas will remain in the highly productive (energy-accumulating) stages. Estuaries are an example of these **pulse-stabilized subclimax ecosystems**. The periodic rising and falling of water levels and changing salinities of the water serve to thwart succession. As mentioned earlier, estuaries are net producers of energy. One reason is allogenic forces.

Agricultural systems provide an example of ecosystems that are repeatedly interrupted to keep them highly productive. Typically, a system is disturbed from its natural state by humans to convert it to agricultural land. Crops are planted and encouraged to grow. From an energy standpoint, the goal is to convert as much of the sun's electromagnetic energy into chemical bond energy as quickly as possible. If left untended, even a monocultured field may achieve some level of stability over time. However, at the point where the accumulation of energy is expected to be the highest, humans harvest the crop. Whatever remains of the ecosystem after harvesting is often then further modified to prepare the area for another round of crop growth. Agriculture, then, serves as perhaps the most extreme example of allogenic forces causing maximum productivity ecosystems.

Strategies for Survival

The mechanisms of individual organism survival are sometimes confused with ecosystem succession because of the parallels in energy flow that can be observed. As described above, ecosystem succession leads to systems that are more energetically balanced with respect to energy flow. In other words, succession leads to systems that accumulate less energy. As might be expected, the survival of species also depends on energy flow. In general, species have evolved one of two approaches to survival.

1. Grow fast, reproduce a lot, and ignore competitors and predators (r-adapted)
2. Grow slowly, reproduce more slowly, but improve reproduction odds by defending against competitors and predators (K-adapted)

Species that have evolved the first approach (r-adapted) accumulate energy in the form of many organisms. The species survives if it produces sufficient progeny so that at least one progeny (offspring) will reproduce before dying or being killed. Species that have evolved the second approach (K-adapted), however, expend less energy to produce progeny but then spend more energy to protect that progeny. At least one must be sufficiently protected to reproduce before dying or being killed. Protection may be passive (tree bark is thick to protect the tree from the elements) or active (mother bears aggressively pursue threats to their cubs).

These approaches are for species survival, however, not ecosystems. A climax ecosystem will contain species using both approaches. An early succession ecosystem may have fewer protective-approach species but that may be because with fewer species, those that are present have not needed to evolve protective approaches. Nevertheless, the ecosystem classification is independent of the species survival approach.

<u>Lecture 11</u> Ecosystem Types

An entire course could be dedicated just to learning about the different types of ecosystems. An entire university degree could be dedicated to studying just one of these ecosystems and a doctorate could be obtained by studying just one aspect of one of these ecosystems. Clearly, in one lecture, we cannot hope to examine that much material. Instead, we will identify the major groupings of ecosystems and examine, to widely varying degrees, the types of ecosystems within each. For more basic information about types of ecosystems, examine Smith (1996) noted in the reference list at the end of the notes.

Natural ecosystems can be divided into 4 major groups:

1. Non-forest
2. Forest
3. Freshwater
4. Saltwater.

The non-forest and forest groups are part of a continuum of terrestrial biomes and are sometimes lumped into a single larger group. Each of the major groups will be discussed and the specific ecosystems and their features identified.

Non-Forest Ecosystems

Table 11-1 shows 5 major ecosystems within the non-forest group. Each of these ecosystems represents the climax community given the limiting factors for the system. For example, a meadow containing grasses may be an early successional stage between a farm and a forest and thus while having some features of a grassland, is not technically a grassland ecosystem. The grassland ecosystem does not succeed to a forest but remains as a functioning ecosystem.

Table 11-1 Major Non-Forest Ecosystems and Characteristics

Ecosystem	**Precipitation**	**Limiting Factors**
Temperate Grasslands	25 – 75 cm/yr	Precipitation and periodic drought
Tropical Savanna	25 – 200 cm/yr	Extreme seasonal precipitation, low nutrients
Shrublands	Variable	Precipitation, allogenic forces
Deserts	7 – 40 cm/yr	Evaporation rate exceeds precipitation rate
Tundra	Variable	Temperature

The temperate grasslands occur in climates with high evaporation rates and periodic severe droughts. The precipitation levels are too low to support a forest (on average) yet too high to lead to a desert (on average). However, both biological and allogenic forces are also involved in maintaining a grassland. A distinctive biological trait of many grasslands is the presence of large grazing mammals (e.g. bison in North America). These organisms under natural conditions were present in large numbers and their grazing helped maintain the productivity of the grasslands. Fire also played a large role in maintaining grasslands by periodically burning shrubs that may take root and trees that may take root in the wetter grasslands. Without periodic fires, many grasslands could become either shrublands in the drier precipitation ranges or forests in the higher precipitation ranges. The periodic drought cycles also help maintain grasses as the principle vegetation.

Grasslands in the drier precipitation ranges are also subject to becoming deserts, especially when managed by humans. Overgrazing by cattle or sheep, for example, can destroy the capability of the grasses to withstand droughts. Farming alters the ecosystem completely, but if not done wisely, leaves the land susceptible to severe wind erosion during drought cycles, as well as leading to salt build up in the soil if irrigation is required (in the drier precipitation ranges). Because grasslands are water limited but otherwise biologically productive and are subject to a winter cycle, nutrients accumulate in the soil (in carbon and nitrogen compounds), which makes these ecosystems ideal for agriculture. Although grasslands once covered approximately 42% of the land surface of the earth (e.g. the prairies of North America, the steppes of Russia, the pampas of South America, the veldt of South Africa), much of that area today is cultivated. In North America, few of the original grassland ecosystems remain.

Tropical savannas look similar to grasslands but they have different limits. Because they are located at lower latitudes, tropical savannas are not subject to winter. Therefore, the major seasonal event is precipitation which is periodic with distinct wet and dry seasons. With no winter cycle, nutrients do not accumulate in the soil and nitrogen, in particular, is limiting. Savannas range in appearance from open grasslands to widely-spaced shrublands to thin forests with a grass understory, depending primarily on the nutrient availability.

Shrublands are considered as a ecosystem type, but often have characteristics of other ecosystem types, in particular deserts (where evaporation rates are high) or savannas which include shrubs. Shrublands are also an important successional stage for forests and so may not be a permanent ecosystem. Many shrublands have been maintained by human disturbances for hundreds of years, while others would have been stable without human influence. Shrublands are very susceptible to fire and many species have evolved to need fire to induce germination.

The distinguishing feature of deserts is not entirely their lack of precipitation (although that is important) but rather the balance between evaporation and precipitation. In a desert, the evaporation rate exceeeds the precipitation rate, typically by a factor of 7 to 50. Precipitation is sporadic with long periods of no precipitation in between, up to several years in some of the driest deserts. Organisms have evolved a variety of mechanisms to deal with the scarcity of water and even in the driest desert, organisms can survive. Deserts can be converted to agricultural land when irrigated. The principle concerns, though, are reliability of water source and salinization of soil. When groundwater is used as the water source, that water is typically "historic" in that it is not replenished but was trapped in the subsurface during a different climatic regime. Therefore, removing that water is equivalent to mining – it is gone from that location forever. Water mining to support human populations well above the normal carrying capacity has become common in many desert regions.

The limiting factor in tundras is temperature. Because they are so cold, tundras may have plenty of water that does not evaporate, even though the annual precipitation rate may be low. Tundra occurs in high latitudes and in high altitudes, although there are differences between the two. The high latitude tundra principally found in the Arctic regions of Canada, Scandanavia, Russia and Alaska contains a permanent frozen layer in the subsurface called **permafrost**. The surface of the ground thaws to varying depths in the summer, depending on the latitude and climatic conditions, but always remains frozen beneath. The permafrost is like rock with respect to its permeability to water and roots (neither can penetrate) but has much different structural characteristics (of importance to engineers trying to build structures on tundra). The high altitude, or **alpine**, tundra found high in mountains around the world may not have permafrost, in part due to the very shallow soil layer in the high mountains. Additionally, because of the topography, water runs off alpine tundra while it tends to accumulate in arctic tundra. Alpine tundras also tend to see more precipitation – although it is not any more useful to the organisms in most cases – as well as different light patterns. In the lower latitude alpine tundra, the light intensity is higher, while in the arctic tundra the light intensity is lower, but light is available for longer periods during the growing season (longer periods of daylight). Even with these distinct limits, tundra ecosystems have an astonishing diversity of organisms that have evolved mechanisms to withstand the cold.

Forest Ecosystems

The three major types of forest ecosystems are:

1. Coniferous forests
2. Temperate broadleaf forests
3. Tropical forests

The three major forest types are generally a function of latitude. The largest coniferous (**cone-bearing**) forests are the **boreal forests** (or taiga – the Russian name for coniferous forest) found in northern Canada, Russia and Europe. These forests are adapted to short summers and long, cold winters. Coniferous forests are also found in mountains (**montane coniferous forests**) and in along the western coast of North America (**temperate rain forests**). The temperate broadleaf forests are found in the intermediate latitudes between the coniferous forests and the tropical forests. There are a number of subsets of this major forest type including **temperate deciduous forests** (such as was originally the ecosystem for southern Ontario, as well as most of eastern North America, Europe and China), **temperate woodlands**, a more open ecosystem found in drier climates and actually a transition between coniferous forests and grasslands or shrublands, and **temperate evergreen forests**, occurring in subtropical regions of the world where there is a mix of evergreen broadleaf trees and coniferous trees. The tropical forests are found in the tropical latitudes.

Forests are stratified vertically and typically include a canopy, sub-canopy and the ground layer. This vegetative stratification leads to stratification of light, temperature and moisture. Forests are productive and efficient ecosystems. The nutrients and minerals are tightly retained in the forest biomass, principally in the trees that compose the bulk of the biomass. The allogenic effect of winter in non-tropical regions has the effect of maintaining the diversity of the coniferous and temperate forests below that of the tropical forests. Organisms must adapt to the periodic cessation of photosynthetic production in temperate and boreal regions and in essence start-up again every year while in tropical regions, production can occur year round.

Freshwater Ecosystems

Freshwater ecosystems occur everywhere on Earth that there is freshwater. These ecosystems are generally classified as:

1. Lentic (standing water)
2. Lotic (running water)
3. Wetlands

The freshwater ecosystems of Earth are under tremendous pressure because of the human requirement for water and space. The viability of freshwater ecosystems also depends in no small part on the state of the adjacent terrestial ecosystems. When we log a forest or farm a grassland or build a city on any ecosystem, we change the run-off to the streams and rivers, and thus impact the aquatic ecosystem. The state of freshwater ecosystems provides a very clear indication of the state of many other ecosystems.

Saltwater Ecosystems

The oceans and other salt water seas cover approximately 70% of the Earth's surface. As would be expected, these water bodies support a wide variety of ecosystems. Our understanding of these ecosystems has accelerated in the last 50 years as we have developed technology to study underwater environments. What remains very poorly understood is the link between terrestrial systems and ocean systems, and in particular the true impact of the oceans on moderating climate and the carbon cycle.

Just as climate and weather greatly influence terrestrial ecosystems, physical features also influence saltwater ecosystems. The key physical features that affect saltwater ecosystems are:

1. Temperature
2. Salinity
3. Pressure
4. Winds
5. Tides

The temperature differences, salinity differences and winds, in combination with the Coriolis force due to the Earth's rotation, set up major circulation patterns in the oceans. Although for the most part poorly understood, these circulation patterns lead to the phenomenon of **upwelling**. Upwelling occurs when deep, cool waters are brought against a continental barrier and forced to the surface. This occurs dramatically on the coast of Peru in South America, for example. The ecological importance of upwelling is not the temperature of the waters, but instead the nutrient content. Because the phototrophic zone in the ocean is very thin (light does not penetrate far into the water), the nutrients in this upper zone are depleted rapidly by phytoplankton (small floating photosynthetic organisms). When the phytoplankton die before being consumed, they sink out of the phototrophic zone and the nutrients contained in their biomass sinks as well. Once below the phototrophic zone, the dissolved nutrients will not be incorporated into biomass because, as with terrestrial systems, photoautotrophic organisms are primarily responsible for such incorporation (exceptions to this are the hydrothermal vent communities at the bottom of the oceans). The process of upwelling brings these nutrients continuously back into the phototrophic zone. At upwelling locations, tremendous diversity exists because photoautotrophic organisms are not nutrient limited and primary production is high.

The major saltwater ecosystems are:

1. The open ocean
2. Coral reefs
3. Estuaries
4. Upwelling regions

Hydrothermal vent regions constitute another very unusual ecosystem where the primary producers are not photosynthetic. Salt marshes, mangrove wetlands, rocky shores and sandy shores are additional saltwater ecosystems at the interface of the land and the water.

Coral reefs are a particularly aesthetic saltwater ecosystem. Coral reefs are found only in relatively shallow depths, preferably only 25 m but up to 70 m. The reef must have a solid foundation upon which to grow. The reef itself is constructed biologically by calcium carbonate secreting organisms. Coral organisms are typically considered the most important, but need not be so.

Coral reefs provide many examples of mutualistic behavior. The most prevalent, and perhaps important for the reef, is the symbiotic mutualistic relationship between the coral organism and **zooxanthellae**, the dinoflagellate algae that lives in the tissues of the coral polyp. The coral organism conducts photosynthesis during the day and thus obtains its carbon and much of its energy in that manner. At night, coral organisms are predators, feeding on zooplankton (small floating animals that feed primarily on phytoplankton and other zooplankton). This provides the nutrients needed by the coral organism (and it symbiotic aglae).

The reef produced by the coral organisms serves as a support structure for algae and a large variety of other organisms including bacteria and sponges. The environment in and around the reef leads to the proliferation of a large number of other organisms including mollusks, crustaceans, and fish – both herbivorous (feeding on the algae and coral) and predatory.

The health of coral reefs around the world is declining dramatically. Because of their productivity, coral reefs are ideal locations for fishermen. Fishing practices, however, typically damage the reef, either physically abrading the reef (anchors dropped onto the reef, boats scraping the reef, dynamite used to stun fish) or chemically damaging it (using cyanide to stun fish). Coral is also an ideal building material (calcium carbonate – same chemical as found in limestone). This has led to coral reefs being mined for the calcium carbonate. Another common problem facing coral reefs is bleaching. When bleaching occurs, the photosynthetic algae stop functioning and the coral loses its color. Bleaching can be temporary, but if it lasts too long, the coral organisms die. Two possible causes of bleaching are excessive nutrient additions from coastal run-off and increased water temperatures.

Summary

Only a very few ecosystems were examined in this lecture. What is important to recognize is that although self-sustaining, ecosystems interface with other ecosystems. This is particularly true for aquatic ecosystems which can be severely affected by changes to terrestrial ecosystems. Engineering activities undoubtedly affect at least one ecosystem directly. The indirect effects may be more difficult to determine.

Lecture 12 Cells and Metabolism

We have spent a bit of time thinking about the big picture of ecosystems. Now we will dig into the ecosystem and look at its biological parts: organisms, populations and communities. We will start by looking briefly into the biochemistry of organisms. Some of the next two lectures may be a repeat for those of you who remember biology from high school.

Let's start by defining an organism:

Organism: Self-contained biological unit that is capable of metabolism and reproduction.

Organisms are composed of cells. In other words, cells are the building blocks of organisms. Some organisms, such as bacteria and protozoa, are simply single cells.
What is a cell?

Cell: Self-contained biological package of molecules capable of metabolism.

Note the difference between the general definition of organisms and cells. Organisms must be capable of reproduction and metabolism while any individual cell need only be able to conduct metabolism. Clearly, some cells can also reproduce and can be considered both cells and organisms.

To better understand the definition of a cell, we must define metabolism.

Metabolism: Sum of all chemical reactions occurring in a living cell.

All cells are composed of at least three basic components (Figure 12-1):

1. **Cell membrane**
2. **Genetic material**
3. **Cytoplasm**

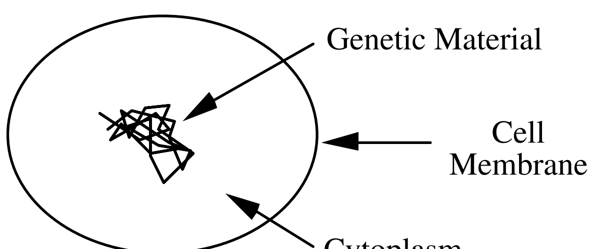


Figure 12-1. A Simple Schematic of a Bacterial Cell

Individual cells may have additional components such as **nuclei, cell walls** and **organelle**, but these are not necessary to meet the definition.

Cell membrane: Boundary between the cell and the rest of the universe.

A cell membrane is the cell's **system boundary**. Its structure and function are crucial. The cell membrane allows the cell to concentrate desired constituents within it. Without the cell membrane, every time the cell attempted to concentrate constituents, the constituents would diffuse away.

To provide an impermeable boundary, the cell membrane is constructed from a double layer of **phospholipids** (see Figure 12-2.)

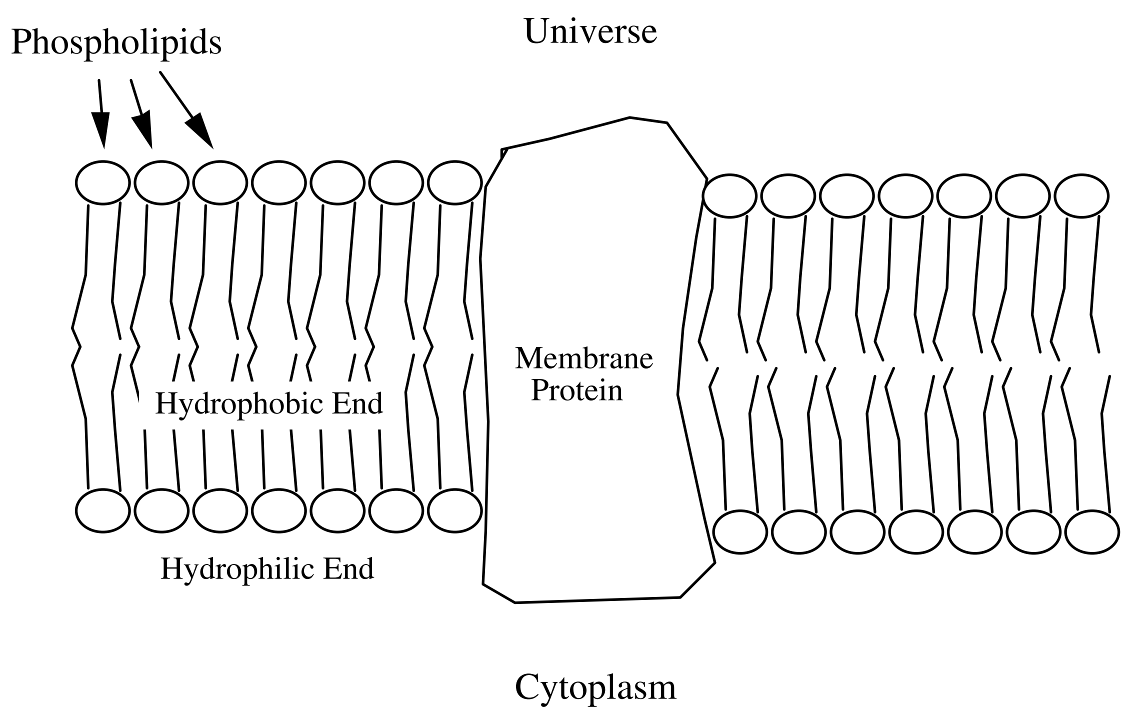


Figure 12-2. Schematic of a Cell Membrane

Phospholipids are large molecules that have **hydrophilic (water-loving)** ends and **hydrophobic (water-hating)** ends. The phospholipids line up so that the hydrophobic ends point toward each other, leaving the hydrophilic ends on the inside and outside of the cell. This provides an effective barrier to movement of constituents across the membrane. Hydrophilic compounds, such as water and salts, can't cross because they can't breach the hydrophobic center. Most hydrophobic compounds can't cross because of the hydrophilic barriers.

If the cell membrane contained only phospholipids, the cell would not function. Compounds must be able to cross the membrane, but in a controlled manner. To do that cell membranes contain **membrane proteins** that essentially act as "doors with security guards" to the cell and facilitate the movement of constituents across the membrane. Cell membranes also contain other structures/chemicals to accomplish specific tasks.

Genetic material: The chemical compounds that store information required by the cell.

Genetic material provides both the "blueprints" for the cell and the "operations manual". Without the blueprints, the cell can't build new cells and without the operations manual, metabolic processes won't work.

Genetic material is **DNA (deoxyribonucleic acid)**. DNA is a huge **polymer** consisting of long chains of connected **nucleotides**.

Polymer: Compound made from long chains of chemically bonded molecules.

Nucleotide: The basic molecules that are connected to form DNA.

All organisms on earth have DNA produced from <u>only 4 specific nucleotides</u>. DNA is extremely important ecologically and will be examined further in Lecture 13.

Cytoplasm: Everything else inside the cell that isn't genetic material or some other organelle.

When we use the word cytoplasm, we normally mean the water/salt solution in the cell that contains the other chemical compounds needed by the cell to conduct metabolism.

Proteins

Without the components we have already noted, a cell is not a cell. However, a cell is a pretty ineffective entity if it doesn't also contain some additional chemical components. Some of the most important of these are **proteins**. Proteins are also polymers. However, proteins are polymers of **amino acids**, not nucleotides. Most proteins on earth are formed from only 20 different amino acids.

Proteins perform a number of functions in cells.

1. <u>Structural</u>: Form the principal components of hair, horns and spider webs.
2. <u>Energy and material storage</u>: For example egg components.
3. <u>Transport</u>: For example hemoglobin (a protein) carries oxygen.
4. <u>Cell movement</u>: For example contractile proteins in muscle.

5. Chemical catalysts: **Enzymes**.

To refresh your memory:

Catalysts: Compounds that allow chemical reactions to occur faster under a given set of conditions, yet are not consumed by the reaction.

So enzymes are catalysts that facilitate biological reactions. For example, consider the oxidation of methane with oxygen:

$$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$$

Without a catalyst, this reaction requires a source of energy for initiation (for example a match). It then proceeds uncontrollably (at least as far as an organism is concerned) until either all methane or all oxygen is consumed. Combustion can be controlled but not to provide biological energy. Nevertheless, there are bacteria that conduct the above reaction at room temperature and capture the energy that is released chemically so that it can be used by the organism. This is accomplished by using enzymes to:

1. Lower the activation energy (i.e., so the reaction can start at room temperature)
2. Control the rate of reaction (so the energy can be captured and not wasted as heat)

One way to visualize enzymes is to consider them as this proteinaceous blob of a compound that has certain areas onto which compounds can temporarily bind and react. Consider the following simple schematic:

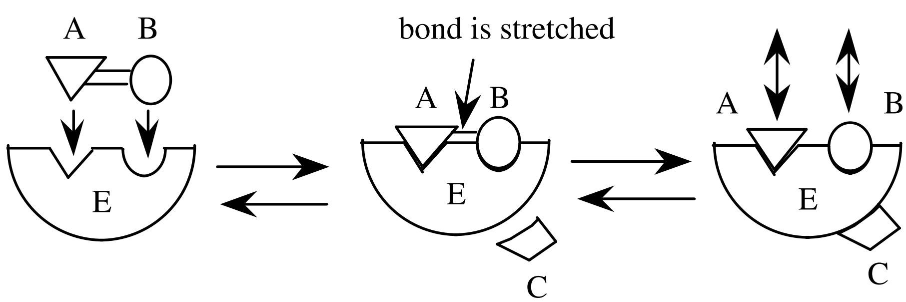


Figure 12-3. Schematic of Enzyme E Catalyzing the Breakdown of Molecule A-B

Molecule A-B has a certain shape. Enzyme E is constructed to have parts that fit the shape of molecule A-B. When A-B enters the enzyme, something has to change to assist the reaction. Figure 12-3 shows one possible way this can happen. Compound C attaches to a different part of Enzyme E, causing the enzyme to "stretch". The bond holding A and B together cannot withstand the "stretching" so A and B come apart and leave the molecule. Note that the reaction could also occur in the opposite direction, forming A-B from A and B. This is often true for enzymatic reactions.

Earlier, metabolism was defined as the sum of all chemical reactions occurring in a cell. Most of these reactions are catalyzed by enzymes. Metabolism can be divided into two primary subsets: **anabolism** and **catabolism**.

Anabolism: The chemical reactions conducted to build cell components (synthesis). For example, plants can take carbon dioxide and water and produce sugar, cellulose, and many other plant products. Anabolism is a lot like construction. It requires raw materials in the form of carbon, oxygen and other atoms or molecules, electrons, and energy.

Catabolism: The chemical reactions conducted to generate energy and electrons. Specifically, catabolic processes:

1. Provide energy to maintain cell activities such as movement and cell repair.
2. Provide energy to be used to synthesize new compounds and cells.
3. Provide electrons to be used for synthesis.

Where does the energy come from? It will come from catabolic reactions like this one:

$$C_6H_{12}O_6 \text{ (glucose)} + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \text{energy}$$

Using enzymes to facilitate the reactions, the cell is able to store the energy produced by catabolism to then be used for anabolism.

Example: DDT Inhibition of Eggshell Construction

The problem ospreys and other carnivorous birds had with DDT occurred at the enzymatic level. Recall that 25 mg/kg of DDT in an osprey was not enough to kill an adult bird. Nevertheless, osprey populations dropped dramatically. The problem was a decrease in birth rate due to decreased eggshell thickness. Birds with high DDT concentrations were laying eggs that were structurally unable to support the weight of the incubating parent. The eggs cracked and yielded no young.

What caused the eggshells to be too thin?

The construction of eggshells is a metabolic process. The bird's cells use enzymes to conduct the necessary chemical reactions. DDT and its metabolic derivatives (compounds like DDT can be transformed once they enter an organism, sometimes to less toxic compounds and sometimes to more toxic compounds) **inhibited the enzymes** in the eggshell gland. The inhibited enzymes in the eggshell gland were supposed to catalyze certain reactions to allow the construction of structurally sound eggshells. However, because these enzymes were inhibited, the required reactions did not occur fast enough. Meanwhile, eggshell construction continued.

To think about what was happening, imagine that a building was constructed with slow welders. The general contractor, however, desired the building to be constructed faster than the welders could weld and was unwilling to hire more welders. To keep up, the welders skipped joints. In this completely fictional example (welders would not skip joints in the real world), this practice continued until the building was completed. The structural deficiency of the building will depend on how many joints are not welded. When enough welds are missed, the building cannot support its design load and catastrophically fails. That is what happened to the osprey and other carnivorous bird eggs: the eggshell structure was too weak due to inhibited enzymes and the eggshell structurally failed.

Once DDT was banned in North America, bird reproduction increased. The inhibition of the enzyme was removed and egg shells could be constructed thick enough to support the parent's weight. Many of the carnivorous bird populations have recovered significantly, although other factors still threaten many of the populations.

Lecture 13 **DNA, Genetics and Ozone**

Recall from last lecture that DNA is a polymer of nucleotides that contains all the information needed by the cell. In short, the DNA of an organism defines the organism. To understand evolution, natural selection, and ecological diversity, we must know something about DNA.

All DNA is composed of only four types of monomers called **nucleotides**. The nucleotides are actually composite molecules with three distinct parts (Figure 13-1).

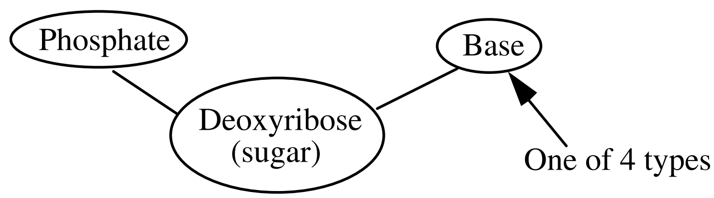


Figure 13-1 Schematic of a DNA Nucleotide

All DNA nucleotides contain a **phosphate group**, **deoxyribose** (which is a 5-carbon sugar molecule) and a **nitrogen-containing base**. The difference between the nucleotides is the base group. The bases are grouped as follows:

Pyrimidines: thymine **(T)** and cytosine **(C)**
Purines: adenine **(A)** and guanine **(G)**.

The DNA polymer is constructed by connecting the phosphate group of one nucleotide to the deoxyribose group of another monomer, as shown in Figure 13-2. This repeated connection of alternating sugars and phosphates is called the **sugar-phosphate** backbone. The bases are not connected in this chain but "hang out" from the backbone.

Each polymer is a **single strand** of DNA. To actually function in cells, DNA must contain two strands that wrap around each other in a **double helix** structure with one strand going in one direction and the other going in the opposite direction.

What holds these strands together?

Hydrogen bonds between pairs of bases, (**base pairs**).

Notice in Figure 13-2 that the base pairs are not random. Only the following bonds should occur:

adenine with **thymine**: A-T
guanine with **cytosine**: G-C

The **complementary base pair** structure is very, very important to how DNA works.

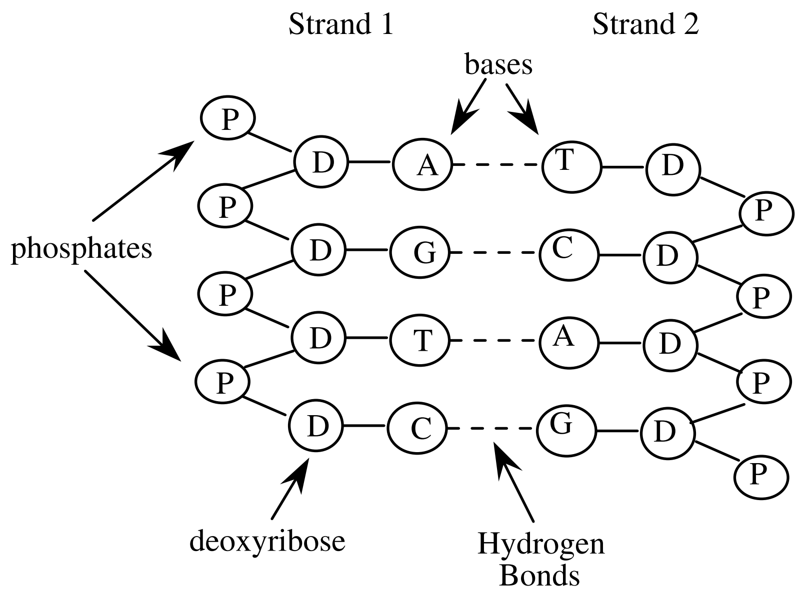


Figure 13-2 Schematic of the Hydrogen Bonding Between DNA Strands

DNA Replication and Gene Expression

Cells must use DNA for two crucial functions.

a. **Gene expression** – for making proteins in a cell,

b. **Replication** – to form a new cell.

Gene Expression.

Recall that DNA holds the "blueprints" or "building instructions" for the cell. Specifically, DNA contains the blueprints for the construction of the enzymes and other chemicals used by the cell to conduct metabolism. These blueprints are stored on genes.

Genes: Specific sequences of DNA that hold the code ("plans") for specific proteins.

We talked a little about proteins and their role in cells last lecture.

Gene Expression: The process of converting information stored on DNA into actual proteins.

Gene expression is a two step process which is summarized in Figure 13-3.

Transcription: Information copied off the DNA onto RNA

Translation: Information on RNA used by ribosomes to construct proteins from amino acids.

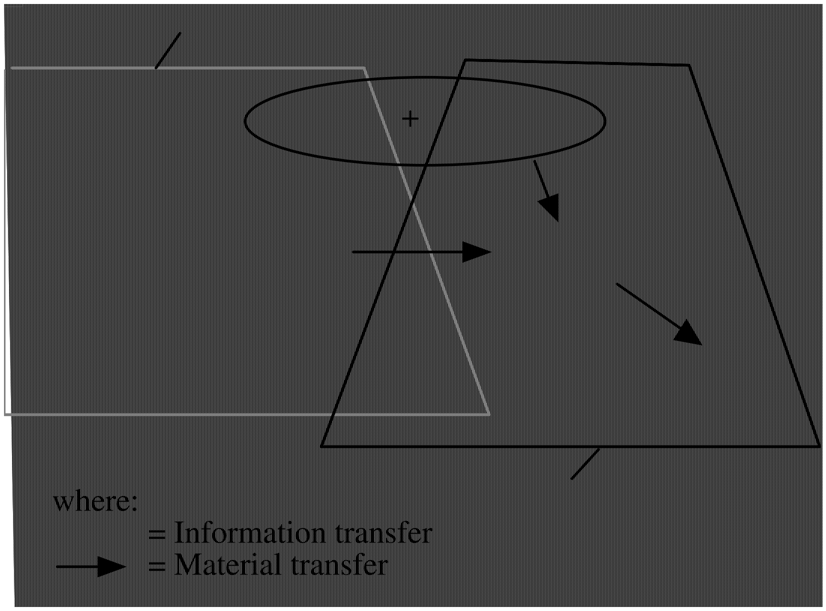


Figure 13-3 Transcription and Translation

where:

- Ribosomes: Protein "manufacturing" sites in the cell. Made from rRNA and proteins.
- RNA: Ribonucleic acid. Very similar to DNA. Made with ribose as the sugar instead of deoxyribose.

There are three types of RNA involved in these processes:

- rRNA Ribosomal RNA is a component of the ribosome.
- mRNA Messenger RNA actually carries the code for protein manufacture to be used in the ribosome
- tRNA Transfer RNA binds to specific amino acids and then matches with mRNA in the ribosome, ensuring that the amino acids are placed in the proper position.

Genes consist of codons.

Codons: A three base pair sequence that codes for a specific amino acid.

An example codon sequence is shown in Figure 13-4. During transcription, the series of codons for the entire protein is transcribed to the mRNA. The complementary codons are transcribed to the tRNA. Each tRNA will only bond with the amino acid that it is coded for. Then the tRNAs are lined up in the ribosome according to the mRNA matches and the amino acids attached to the tRNAs are bonded together to form a protein molecule. The details of gene expression are interesting but beyond the scope of this class.

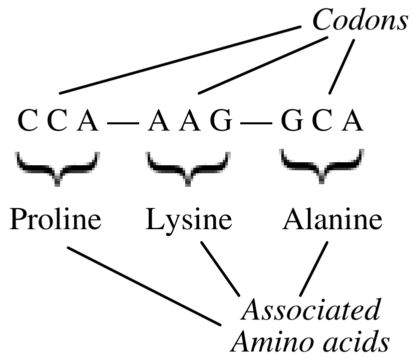


Figure 13-4 Example Codon Sequences

<u>What happens if the information provided by the DNA is wrong</u>?

1. The codon codes for the wrong amino acid.
2. The wrong amino acid is built into the protein.
3. The protein may or may not now work properly. This could have no effect or it could have a slow effect (chronic) or it may kill the cell/organism immediately.

<u>Where can the information from the DNA be misinterpreted</u>?

1. It can simply be wrong on the DNA (mutation – see below).
2. Something can corrupt the transcription process.
3. Something can corrupt the translation process.

It may be hard to imagine things happening at the molecular level with chemicals that you can't even spell. Consider the following example that illustrates exactly the same problem, simply at a different scale.

An engineer has developed plans ("blueprints") to construct a building. These blueprints specify exactly the type of steel beams to be used. The building is constructed.

<u>Where can incorrect information about the beams to use come from</u>?

1. The engineer didn't go to U.of T. and simply *specified the wrong beams* in the blueprints. This is like a mutation in the DNA.
2. The construction manager didn't go to U.of T., *read the blueprints incorrectly*, and ordered the wrong beams. This is like a problem in transcription.
3. The contractor didn't know which beams corresponded to what on the construction diagram and *used the wrong beams*. This is like a problem in translation. The information was correct throughout the process but the final construction process was wrong.

What happens if the wrong beams are used?

1. If the wrong beams are too strong, probably no problem at all. The building just costs more than expected. If a stronger building turns out to be necessary to handle a severe weather event (perhaps because building code was developed without considering the possible impacts of more severe weather due to global warming), then this building may "survive" (remain standing) when others do not.
2. If the wrong beams are too weak, and only a few of the wrong beams are used there may be no problem for a long time, unless the building is unexpectedly stressed.
3. If a large number of weak beams are used, the building will collapse.

So information and its transfer are critical to building construction just as they are to cell and organism operation. Gene expression is a vital role of DNA.

Replication

Gene expression is the nitty-gritty, "day-to-day" operation of the cell. Replication is more of a long term planning event. Because each cell must have DNA, every time a new cell is formed, there must be a mechanism to **copy** or **replicate** the DNA. The concept of the replication process is similar to the concept of the transcription process, although the actual processes are different. The information from the existing DNA is copied onto new DNA.

Wrong information in gene expression can come from the DNA or be caused during transcription or translation. Problems during replication cause errors directly in the new DNA. For example, a codon could be misinterpreted.

Mutations in DNA Lead to Variation

Imagine back in time to the very first cell/organism. At that time there was only one set of genetic information. There was no variation. When the cell reproduced, the daughter cells were supposed to be identical to the original, if the replication process occurred properly.

How did we proceed from then to now where there is an amazing amount of variety?

Mutations: Mistakes in the DNA code.

There are two primary types of mutations that could occur:

Point mutations: One nucleotide is replaced with another.

Frameshift mutations: A nucleotide is left out. Everything in the code is shifted by one. This messes up the codons.

What causes mutations?

1. Copying mistakes during replication.

2. Radiation such as UV light or cosmic rays (or other radiation from human activities) can damage an existing DNA strand.
3. Chemicals can damage an existing DNA strand. These chemicals are called **mutagens**. Natural chemicals can be mutagens as well as synthetic chemicals.

Evolution and Natural Selection

Mutations in DNA can lead to variation in organisms. Though simplistic, that's all we usually need to know. Mutations are random, however. That means that changes that occur may also be lost. There must be some environmental forces that allows certain changes to survive and others to die off.

Evolution: The process of accumulating genetic change to give rise to diversity.

Natural Selection: The presence of environment stress that makes some genetic changes more successful than others.

Natural selection is completely unbiased. It is just a simple fact that some mutations will give rise to organism changes that provide that organism an advantage for a given environment over organisms that don't have that change.

Consider, as an example, **peppered moths** in England (from Stirling, 1996).

Before Industrialization:	2% dark colored 98% light colored
After Industrialization (pre-1975):	90% dark colored 10% light colored
After air pollution controls (by 1989):	30% dark colored 70% light colored

The two colors of peppered moths arose from a mutation at some point. Before industrialization, dark moths stood out on light colored surfaces (such as the light-colored bark of certain trees), making them easy for birds to see and eat. So that mutation was less successful because it did not lead to an advantage in reproduction. After industrialization, however, soot began to cover many light surfaces. Now the white moths stood out and they were eaten by birds and the dark moths were more successful. After air pollution laws began to take effect, however, there was less soot covering light surfaces and once again dark colored moths stood out and made easier pickings for birds. So the colors shifted back again.

For further thinking: What happens to the information coded in the DNA of an organism when that species becomes extinct?

CFCs and Ozone

Who uses a refrigerator to cool her/his food? Who enjoyed the comfort of air-conditioned buildings and cars during hot summer days? These "luxuries" that we take for granted in Canada were made possible by the development and mass production of chlorofluorcarbons (CFCs). The refrigeration and air-conditioning processes work by absorbing ambient heat into a fluid that evaporates. The evaporated fluid is moved outside of the area being cooled and recondensed by compression. The condensed fluid is then reevaporated, absorbing more ambient heat and the cycle continues. Figure 13-5 shows a schematic of this process. While this process sounds simple, an important engineering problem was to find a fluid that evaporated at ambient temperatures, could be readily recondensed, and was safe enough to allow distribution in products being used by millions and perhaps billions of people.

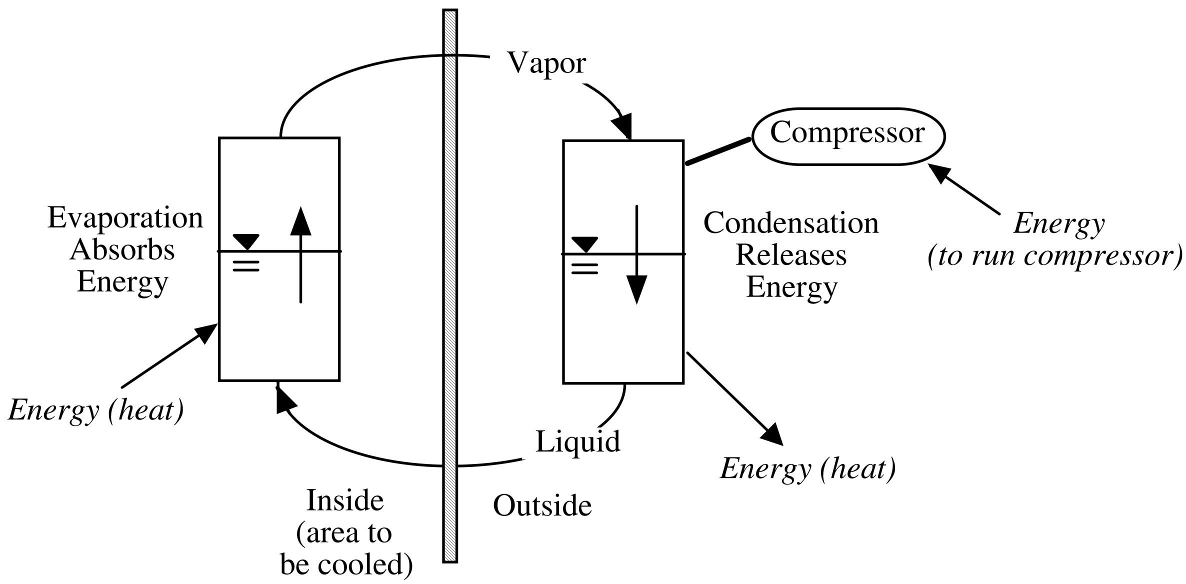


Figure 13-5 Schematic of a Refrigeration Cycle

CFCs meet the requirements noted above. They are non-flammable, relatively non-toxic and inert, at least on the surface of the earth. They also were easy to dispose: simply dump them and let them evaporate into the atmosphere. As with DDT, when CFCs were first mass produced they were considered wonderful compounds. Unfortunately, a full life cycle assessment was not done on them prior to widespread use.

As everyone now knows, the stratosphere contains ozone (O_3) that absorbs ultraviolet light. This is very useful for life because uv light is one of the causes of DNA damage and mutations. Unfortunately, as everyone should also now know, CFCs that have been "disposed" make their way to the stratosphere and act as catalysts to destroy ozone. Eventually the CFC molecules are also destroyed, but not before they have catalyzed the destruction of many ozone molecules. The resultant "thinning of the ozone layer" allows more uv light to penetrate to the earth's surface.

It is tempting to say "so what"? Humans can protect themselves from excessive uv light and therefore reduce their chances of skin cancer. The more important question is how the extra uv light is affecting the mutation rates of other organisms, in particular the small producers at the bottom of the food chain. Will changes arising from those mutations then affect the rest of the food chain, and ultimately entire ecosystems?

CFCs are another example, along with DDT, of a great engineering achievement which ultimately backfired because the engineers involved did not think broadly or ecologically enough. They did not have to be experts in ecology, they only had to appreciate the value of life cycle assessment and the possible sources of environmental impact that may occur at any point in the life cycle.

<u>Lecture 14</u> Defining Systems

We are now ready to move beyond organisms. Before we do that, let's consider a simple engineering product: a fence. Fences are so commonplace that we may not even think of them as an engineering product. The fence I have in mind, however, is a metal fence. The fence is actually constructed and repaired by non-engineers using unsophisticated tools but because it (the fence) is made of metal, we know that at least engineering processes were required to make the metal. In fact, the processes required to mine and process ore, refine iron, convert it to steel, etc. have significant impacts on the environment. But now, let's focus on the product itself, the fence.

The fence of interest is approximately 5,300 km long and stretches across Australia (see O'Neill 1997 for a complete description). It is called the Dog Fence and it was erected and is presently maintained for one reason: to separate dingoes (wild dogs) in the north from the sheep in the south. The problem is a predator-prey issue. Sheep were brought to Australia in 1788. Dingoes learned that sheep are slow, non-aggressive animals that are easy to kill, much easier than a wombat, for example. The perfect prey. Without the fence, the dingoes killed enough sheep to significantly affect the Australian sheep industry. Therefore, individual fences were constructed and around 1960 linked into one single fence.

The Dog Fence is a product that was specifically designed to separate **populations** of organisms.

<u>What is a population</u>?

Population: Group of organisms of the same species in a specific system

The populations of interest with respect to the Dog Fence are the dingo population south of the fence (which ranchers want to be zero), sheep populations, and kangaroo populations (we will see why later).

<u>What do we usually want to know about a population</u>?

1. How big is it?
2. How fast is it growing?
3. How fast is it shrinking?

We can answer these questions several ways.

1. Go out and measure population size over time.
2. Predict the population growth rate mathematically using some measured parameters.

Measuring population size is difficult and expensive. If we have some appropriate mathematical models first, we can keep measurements to a minimum. We will begin to develop mathematical models for population growth in this lecture and continue with this general topic through the next seven lectures.

General Population Model Derivation

Before any model can be developed, the system of interest must first be defined.

What is a system?

System: A specified group of processes with clearly defined boundaries

The key here is **boundary definition**. Boundaries are determined to meet two primary criteria:

1. Processes/areas of interest included. These are specified by you.
2. Convenience. Choose the boundaries that will simplify analysis as much as possible.

Other relevant factors may also be considered as needed.

Once the system is defined, we can examine what occurs within the system as well as what enters and leaves the system. For populations, the system can be any appropriate geographic area. Often we think of a system for organisms in terms of their **habitat**.

Habitat: **The physical, geographic place where organisms live.**

Habitat definitions are organism specific. For large organisms, habitat is sometimes defined in square kilometers of forest while small, specialized organisms may have habitat defined as square centimeters of tree bark or, for very small organisms, milliliters of water. Some organisms live in very strange habitats, like the guts of other organisms. In that case, the habitat definition may be square millimeters of intestine wall.

Once we have defined the system for the organism of interest, we must identify the processes occurring within this system.

What processes do you expect to occur with organisms in a habitat?

1. Reproduction (growth)
2. Death (non-consumptive - old age, disease)
3. Migration in
4. Migration out
5. Predation (the organism is consumed by a predator).

Figure 14-1 provides a simple representation of a possible system.

With the processes identified, we can conduct an **organism balance** on the system. This is done the same way as a mass balance, although it isn't technically a mass balance. However, since organisms are conserved, a legitimate balance may be performed.

The general organism balance for the system in Figure 14-1 is:

Accumulation of organisms in the system =

migration in – migration out + reproduction – death – predation

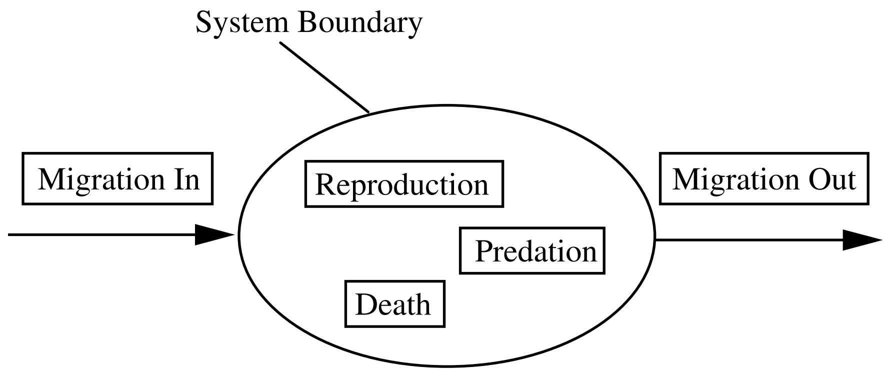


Figure 14-1 Simple System for Population Analysis

To be useful, the words must be converted into a mathematical expression. To do that, we need to define a number of terms.

N: number of organisms present in a specific system at time t.

Reality check:

Can there be a non-integer number of organisms in a system?

No! Although the equations being developed may provide non-integer answers, always round appropriately. However, if the units for N are organisms per unit system (instead of organisms total), for example birds per km^2, the normalization process can legitimately provide a non-integer.

Now define:

accumulation = dN/dt (accumulation terms always change with respect to time in a system)

Also define:

reproduction rate = bN, organisms produced per time

where:

b = Instantaneous specific reproduction rate, organisms produced per organism per time

In other words, b is the average, individual reproduction rate for all of the organisms in the system.

Define:

death rate = dN, organisms died per time

where:

d = Instantaneous specific death rate, organisms died per organism per time

Now let's exercise judgement and define the system of interest so that migration in and out can be ignored. This would be a reasonable assumption for sheep and kangaroos south of the Dog Fence but not for dingoes who do penetrate the fence. Also, for now assume there is no predation. For kangaroos south of the Dog Fence this would be a good approximation. The organism balance becomes:

$$dN/dt = (b - d)N$$

What other assumptions have been implicitly made?

1. Unlimited resources (discussed more later)
2. No toxic accumulation of wastes (ignore for the time being)
3. Ideal environmental characteristics; temperature, moisture, etc.
4. No competition (discussed more later, poor assumption for sheep and kangaroos).

In this case we can integrate the organism balance to solve directly for N. First separate the two variables, N and t:

$$dN/N = (b - d)dt$$

Now integrate between t = 0, N = N_o and t = t and N = N to get:

$$\ln(N/N_o) = \int(b - d)dt$$

If b and d are not functions of time, then integrating further gives:

$$\ln(N/N_o) = (b - d)t$$

Take the natural antilog (exponential) of each side to get:

$$N = N_o\exp[(b - d)t]$$

If b and d are constant, as we have assumed here, we may redefine them as:

r = b – d = net specific growth rate, units of organisms per organisms per time

This gives:

$$N = N_o\exp(rt)$$

This is the **exponential growth** equation. This equation predicts that the population at any time increases exponentially as a function of only time, the initial population, and r. Figure 14-2 illustrates this for four simulated populations.

We often want to know how fast a population is growing or dying. To do that, we solve for the growth rate which is the derivative with respect to time, dN/dt. Taking the derivative of our exponential growth equation:

$$dN/dt = rN_o\exp(rt)$$

Recognize that $\mathbf{N_o\exp(rt)}$ on the right-hand-side equals **N**. Substitute to get:

$$dN/dt = rN$$

which was the original equation before integration.

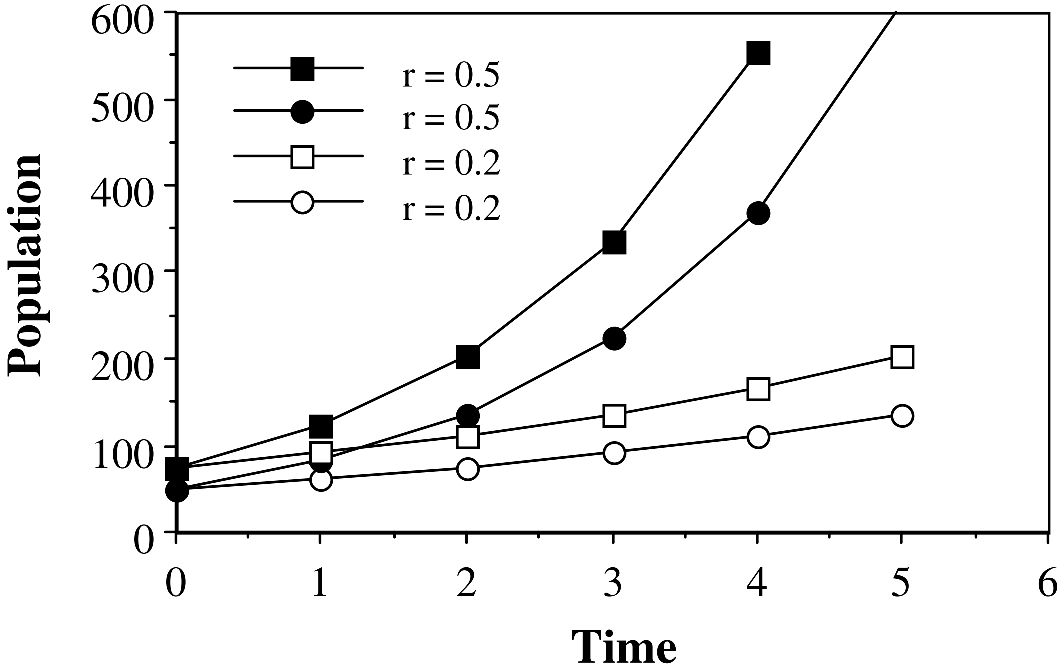


Figure 14-2. Exponential growth for 2 different initial populations and r values.

This equation shows that the rate of population growth is a linear function of the actual population. In other words, the rate at which the population changes increases as the population increases. This is an important point to recognize.

Example 14.1

The deer population of a 1,000 km^2 conservation area has been closely examined over the last 10 years. Five years ago, when the deer population was 25 deer (in the entire area), the birth rate was measured at 24 deer·yr^{-1} and the death rate at 22 deer·yr^{-1}. Migration into and out of the conservation area can be considered negligible. Assume b and d are constant.

a. What are the values of b, d and r for the deer population?

Birth rate = reproduction rate = bN

We know the birth rate and population 5 years ago so:

$24 \text{ deer·yr}^{-1} = b(25 \text{ deer})$

and: $b = 24 \text{ deer·yr}^{-1} / 25 \text{ deer}$

$\mathbf{b = 0.96\ yr^{-1}}$

Similarly:

death rate = dN

$22\ \text{deer}\cdot\text{yr}^{-1} = d(25\ \text{deer})$

$d = 22\ \text{deer}\cdot\text{yr}^{-1} / 25\ \text{deer}$

$\mathbf{d = 0.88\ yr^{-1}}$

Remember that $r = b - d$ so:

$\mathbf{r = 0.96 - 0.88 = 0.08\ yr^{-1}}$

b. What is the deer population today, assuming exponential growth?

The integrated form of the exponential growth equation is:

$N = N_o \exp(rt)$

(this can also be derived from an organism balance easily too, if you forget the equation)

$N_o = 25$ deer and $t = 5$ years so:

$N_5 = (25\ \text{deer})\exp(0.08\ \text{yr}^{-1}\cdot 5\ \text{years})$

$N_5 = 37.3$ deer

Wrong! The equation provide a non-integral value. Round appropriately to get:

$\mathbf{N_5 = 37\ deer}$

c. What was the growth rate of the deer population 2 years ago?

Exponential growth with constant b and d gives:

$dN/dt = rN =$ growth rate

To find the growth rate 2 years ago, first find N_3:

$N_3 = (25\ \text{deer})\exp(0.08\ \text{yr}^{-1}\cdot 3\ \text{years})$

$N_3 = 31.8$ deer

Now, if you were going to report this number, you must round to 32 deer. But you are going to use it in another equation, so don't round. Only round when necessary at the final answer.

The growth rate, then, is:

$dN/dt = 0.08\ \text{yr}^{-1}\cdot 31.8\ \text{deer}$

$\mathbf{dN/dt = 2.54\ deer\cdot yr^{-1}}$

Do we need to round here? No, the growth rate does not need to be an integer. Common sense, however, would suggest that we should round to one decimal, $2.5\ \text{deer}\cdot\text{yr}^{-1}$.

Lecture 15 Population Growth and Death

In the previous lecture we examined exponential growth. Such growth might describe kangaroo growth south of the Dog Fence immediately after the fence was constructed and dingoes stopped killing kangaroos. Certainly, the ranchers south of the fence would like exponential growth to describe their sheep flocks. Exponential growth can result in enormous growth rates. Exponential growth, however, ultimately requires unlimited resources.

What happens when resources become limited?

1. Death rate should increase as fewer resources are available to each organism.
2. Birth rate should decrease. Reproduction requires a lot of energy and the resources available to each organism have decreased.

If we assume limited, but replaceable resources (this is important, if the resources are limited and irreplaceable we obtain a different result) then at some point:

$b = d$ (birth rate = death rate)

so $r = 0$

and

$dN/dt = 0$

for our simple system with no migration in or out.

When $dN/dt = 0$

N = constant with respect to time

In other words, we have reached:

Steady-state: The condition when things do not change with time.

In this case, the population N is not changing with time and has reached steady-state. Note that we may or may not have reached:

Equilibrium: The condition when a system is at minimum free energy.

Systems in equilibrium are also at steady-state because things do not change with time. But systems at steady-state may not be at equilibrium. This distinction is important. At equilibrium a system has no incentive to change. At steady-state, such incentive exists, and so systems may change if perturbed. From a practical standpoint, equilibrium can rarely ever be achieved in natural systems. Instead we think of equilibrium as the point that a system is trying to achieve.

What does a constant N mean ecologically in the absence of predation?

1. Given a certain level of resources, the population can grow to only a certain size.

In other words, the laws of mass and energy conservation apply to ecological systems, just as they apply to every other system.

2. The population has reached its:

Carrying capacity: The maximum possible population for a given level of resources.

<u>How do we deal with carrying capacities mathematically</u>?

1. Develop b and d = f(resources).

This sounds simple but it isn't because we only have an incomplete idea how to measure the level of resources. We can measure the population, however. Simply count organisms!

2. Develop dN/dt = f(carrying capacity).

As strange as this may seem, it actually works pretty well mathematically. One equation that does this is the **logistic equation**:

$$\frac{dN}{dt} = r \cdot N\left(\frac{K - N}{K}\right)$$

where: **r = b – d** with b and d being the values for unlimited resources = constant.

K = carrying capacity = maximum population possible for the available resources

The integrated form of this equation with constant r and K is:

$$N = \frac{KN_o \exp(r \cdot t)}{K - N_o + N_o \exp(r \cdot t)}$$

where: N_o = initial population of organisms at t = 0.

A usual assumption of this expression is that K = constant.

<u>Does K have to be constant</u>?

No. K doesn't have to remain constant over time, although if it isn't, we need to conduct our integration differently. In fact, we will probably need to integrate the equation numerically.

The carrying capacity concept means that there are limits to the maximum population possible, even in the absence of predation. The ranchers south of the Dog Fence would like large sheep populations. However, the sheep population will only get as large as the carrying capacity for a given ranch. Unless ranchers somehow augment the carrying capacity (by trucking in food), the actual carrying capacity will be a function of rainfall (for grass growth) and other environmental limitations.

Example 15.1

Consider the conservation area in Example 14.1. Ecologists have estimated the carrying capacity to be 2,500 deer.

a. What is the deer population today, assuming logistic growth? How does that compare with the estimate using exponential growth?

Use the integrated equation for logistic growth. This equation would be provided in an exam situation. K = 2,500 deer, N_o = 25 deer, r = 0.08 yr^{-1} so:

$$N = \frac{2500 \cdot 25 \exp(0.08 \cdot 5)}{2500 - 25 + 25 \exp(0.08 \cdot 5)}$$

N = 37.1 deer

N = 37 deer

This result is essentially identical to that for exponential growth, indicating that because the carrying capacity of the conservation area is much larger than the population, the assumptions required for exponential growth are reasonable.

b. What is the deer population 45 years from now? 95 years from now? Calculate using both logistic and exponential growth.

The equations have been shown before so only the answers are provided here. The key is that t = 50 years and 100 years because the starting population of 25 deer occurred 5 years ago.

	45 years from now	95 years from now
N (logistic)	889 deer	2,420 deer
N (exponential)	1,365 deer	74,524 deer

Notice that although the carrying capacity of 2,500 deer is not reached 45 years from now using exponential growth, the logistic model still shows a much smaller population. The exponential model is clearly erroneous 95 years from now while the logistic model is still below the carrying capacity.

Stochastic Models

The models that I have presented so far are called **deterministic** models. Given any starting point, we feel that we can accurately determine the result. Deterministic models are used in many situations, both in ecology and in engineering. In fact, many of the physical models you will learn during your university career are deterministic. A key feature of deterministic models is:

One set of numbers goes in and one set of numbers comes out.

There is another classification of models in addition to deterministic models. These are **stochastic** models. Stochastic models attempt to deliberately account for variability. Simplistically, with stochastic models:

One set of numbers goes in and a distribution of numbers comes out.

Ecological processes are full of variability (or more honestly, events that we are unable to deterministically predict). Consider the following example:

Precipitation:

The average precipitation for two habitats is exactly the same – 500 mm per year. In one habitat the precipitation occurs relatively frequently in small events. In the other, precipitation occurs infrequently and unpredictably in large events.

Are the ecosystems that develop in these two areas the same, given everything else is the same (temperature, latitude, altitude, etc.)?

Not likely! However, that variability can be handled deterministically with averages. But what about the following questions?

Does the total precipitation in one place change from year to year?

Absolutely.

Do precipitation events in one place occur at the same time and with the same intensity every year?

Absolutely not.

For these situations (which are examined in more detail in hydrology courses), we can only predict the **probability** that these events might happen. So the key tool for stochastic processes is the probability that something will happen.

Weather isn't the only unpredictable factor affecting ecological processes and organisms. Organisms themselves are. For example, when we specify a specific reproduction rate, b, we are assuming that value is appropriate for all organisms. However, in fact b is an **average** value based on measurements of many organisms. Say b is 2 yr^{-1} for a specific organism. That means that on average, each organism produces 2 new organisms per year. However, any individual organism may produce more than 2, say 3 or 4, or less than 2, either 1 or 0. Now there may be deterministic reasons for these differences. But we can't figure them out. So instead, we develop probability distributions for these phenomenon.

When do we specifically deal with probabilities and when do we simply use averages and deterministic models?

For population modelling, we usually make this decision on the basis of population size. The larger a population is, the better we feel about using deterministic models. One important reason for this has to do with the probability of **extinction**. It turns out that as you let time go to infinity, the probability of a population becoming extinct in the absence of any other factors is:

$$\text{probability of extinction} = \left(\frac{d}{b}\right)^{N_o}$$

Therefore, we clearly see that as long as b is greater than d, the probability of extinction decreases as the initial size of the population increases. However, even with measured average values of b > d, there exists the possibility that due to stochastic (random) events, the population will actually decrease instead of increase and become extinct. Our deterministic model predicts extinction only when d > b. So there exist systems where our deterministic models will predict the wrong answer!

In practice, we usually need to worry about the probability of extinction only for very small populations, such as for endangered species. Nevertheless, the sheep ranchers south of the Dog Fence probably worry about stochastic events every day. What if a windstorm blew large sections of the fence down? What if a contagious sheep disease suddenly entered the flock? What if this year a severe drought occurs and not enough grass grows? The sheep ranchers will worry.

Later in the course we will prove that diversity at the ecosystem level leads to stability. Genetic diversity also exists at the species level. There are DNA differences between organisms within the same species. One organism may be more resistant to a specific disease than another, for example. A species containing genetically diverse individuals (i.e. individuals that have numerous differences in DNA) will be less susceptible to extinction than a species containing individuals that are less genetically diverse. Greater genetic diversity reduces the chance that a catastrophic disease, for example, will eliminate all the organisms – at least one organism (or mating pair) may have genetic resistance. Modern agriculture, however, has bred species with limited genetic diversity in order to maximize particular traits (growth rate, protein content, etc.) At the species level these organisms (whether they are plants like wheat or livestock like sheep) are much more susceptible to catastrophic loss, even if the population is large.

Example 15.2

For the conservation area in Examples 14.1 and 15.1, calculate the probability of extinction for deer population 5 years ago, today and 45 years from now. Use the populations predicted using the logistic equation.

$d = 0.88\ yr^{-1}$ and $b = 0.96\ yr^{-1}$ so:

$d / b = 0.9167$

N_o actually refers to the population at the time that we want to know the probability of extinction. This may seem funny, but remember that the probability of extinction is from some given point in time until infinity.

	5 years ago	Today	45 years from now
Deer population	25	37	889
Probability of Extinction	0.11	0.04	$2.5 \times 10^{-34} \cong 0$

As expected, the probability of extinction decreases substantially as the population increases. Nevertheless, even though the average birth rate is greater than the average death rate, there remains a chance, especially when the deer population is small, that the deer population in the conservation area could become extinct due to some random natural event.

Lecture 16 **Human Population Growth**

Population Growth

Human population growth in the last 300 years or so has been extraordinary. Between 1960 and 1999, for example, the human population doubled from 3 billion to 6 billion and growth continues at over 80 million per year. If the freeway or subway or movie theatre or restaurant all seem more crowded as time goes by it is because they are.

Textbooks suggest that the human growth rate has been exponential. Recall exponential growth equation from Lecture 14:

$$\mathbf{N = N_o exp(rt)}$$

We arrived at that expression by doing an organism balance. To achieve this expression, we assumed that r = constant. Although we examined this expression in some detail, we neglected to consider an important issue: doubling time.

What is a population doubling time?

Doubling time: **The length of time required to double the population**

What is the doubling time mathematically?

It is a function of the population growth model used. For exponential growth we can determine the doubling time as follows.

Let $\mathbf{N = 2N_o}$.

$$\mathbf{2N_o = N_o exp(rt_d)}$$

where: t_d = doubling time

$$\mathbf{2 = exp(r \cdot t_d)}$$

So: $\mathbf{t_d = \ln 2 / r}$

The initial population does not matter for the doubling time when the growth is exponential.

For exponential growth, the doubling time is:

1. A constant (because r is assumed constant)
2. A function only of the net specific growth rate (r)

We can readily calculate doubling times, then, for systems undergoing exponential growth. We can do it for other systems too, but we will have a different equation.

For human populations, the net specific growth rate is often reported as a percent. The conversion is as follows:

$$\mathbf{\%\ growth\ rate = 100r}$$

The units are organisms per 100 organisms per year (since year is usually the time unit used). Using % growth rate, it is very easy to estimate a doubling time.

$$\mathbf{t_d = \ln 2 / (\%\ growth\ rate / 100)}$$

$$\mathbf{t_d = 100 \ln 2 / (\%\ growth\ rate)}$$

$$\mathbf{t_d = 69.3 / \%\ growth\ rate}$$

Now let's see if human population growth has been simply exponential in that last several centuries by examining the following population numbers (Kormondy, 1996):

Human population grew	During the Period	t_d
from 0.75 billion to 1.6 billion	1750 to 1900	137 years
from 1.6 billion to 3.3 billion	1900 to 1965	62 years
from 3.3 billion to 7.0 billion	1965 to 2005?	37 years (predicted)
from 3.0 billion to 6.0 billion	1960 to 1999	39 years (actual)

The predicted t_d values were calculated by rearranging the exponential growth expression to solve for r:

$$r = \ln (N / N_o) / t$$

and then solving for t_d using the predicted r. For comparison, the 1994 growth rate was 1.6% which gives t_d = 43 years, pretty close to the predicted number of 37 years.

Is this simple exponential growth?

Not by our definition. Simple exponential growth as we have defined it requires a constant growth rate and provides a constant doubling time. These doubling time numbers show that:

1. The **doubling time** was **decreasing**!
2. Therefore, the **growth rate** was **increasing**!

In other words, human population growth has occurred faster than simple exponential growth.

Fortunately, data over the last 30 years indicate that the growth rate may be declining slightly after peaking in 1965 at approximately 2%. The growth rate may not go much below 1.6% in the near future, however. So after experiencing "super" exponential growth, we may now be experiencing only simple exponential growth.

Causes of Human Population Growth

We can examine human population growth from the same theoretical framework that we used for other organisms. For human populations:

$$\mathbf{r' = b' - d'}$$

where r' = net reproduction rate in units of people per 1,000 people per year
b' = birth rate (births per 1,000)
d' = death rate (deaths per 1,000).

The % growth rate for human populations using these definitions is:

% growth rate = r' / 10

r' has been increasing with time, at least until about 30 years ago. Let's see where those increases have come from.

Birth rate

Within the past 200 years and especially the past 100 years we have seen significant reductions in infant mortality due to better medical practices. It would seem from this, then, that birth rates would have increased. In fact, the opposite is true. Birth rates have declined significantly within the last 200 years. Consider these data:

World average b' in 1800 = 40 (births per 1,000 people)
1850, b' begins to drop in developed countries
1950, b' begins to drop in developing countries
Recent developed b' ≅ 15
Recent developing b' ≅ 27
Recent Africa b' ≅ 44
World average b' ≅ 26

Overall, b' has dropped, so increases in r' can not have been due to b' alone.

Death rate

r' is a function of b' **and** d'. Let's examine d':

World average d' in 1800 = 35 (% growth rate = 0.5%)
1850, d' began to drop in developed countries.
1880, d' began to drop in developing countries.
Recent developed d' ≅ 9-10 (% growth rate = 0.5 - 0.6%, t_d = 116 to 139 years)
Recent developing d' ≅ 8-10
Recent Africa d' ≅ 15
World average d' ≅ 10 (% growth rate = 1.6%)

Note that, particularly in developing countries, although death rates started to decrease in the late 1800s, birth rates didn't begin to decrease until about 1950. Because of this, even though birth rates have dropped significantly, r' is still approximately 3 times the growth rate 200 years ago.

Clearly, then, decreases in death rates have led to the tremendous population growth rates we see today. It is worthwhile to consider some of the reasons for these decreases in death rates because engineering activities are responsible for much of these decreases.

1) Better medical practices. This stems primarily from an understanding of what really causes disease: viruses, bacteria, protozoa and other organisms. This information began to become available starting in the early to mid 1800s. Specific items that have helped are:

(a) Improved diagnosis of disease (medical field). Includes engineers, however, to design modern diagnostic equipment.

(b) Improved treatment of disease (medical field). Includes chemical engineering, however, to mass produce new medicines and other engineering specialties to design modern treatment equipment.

(c) Improved prevention of disease (medical field). Here I am referring specifically to things like vaccines. We will see shortly that disease prevention has also been significantly improved directly by engineering activities.

2) Better nutrition.

(a) Increased food production (agricultural field. Definitely includes engineers) Starvation has been, and remains, a key cause of death. In 1798, Thomas Malthus predicted that food production would be a key limit to human population growth. For over 200 years, we have worked very hard to prove Malthus wrong. We can now produce much more food per land area than ever before due to mechanized agriculture, fertilizers, pesticides, genetic engineering (which has been practiced with food crops for a long, long time), and, in western societies, huge energy inputs. Not only have we managed to keep food production satisfactory, we have actually probably increased the amount of food produced per person, while using a much smaller percentage of people to do so (energy and mechanization have reduced the people requirement).

(b) Better distribution of food (civil engineering - transportation). You will still starve if the food never reaches you. Our transportation systems have been improved dramatically due to engineering effort. It is now possible in theory to distribute food anywhere it is needed. However, social and political problems still interfere.

(c) Better food storage (engineering). Because of refrigeration, chemical preservatives and aseptic packaging, among other things made useful at the large scale by engineers, food spoilage from bacteria, fungi, and insects is a significantly smaller problem. Storage allows cyclic production due to weather to be mitigated substantially.

Starvation still occurs in the world, but the reasons are political and economic, not technical. Worldwide, sufficient food is produced but it does not always get where it is needed.

3) Improved water quality. A major source of disease historically has been contaminated drinking water. Improving water quality, then, is a disease prevention activity.

(a) Wastewater segregation from drinking water sources (civil engineers). This occurred after it was recognized that cholera and typhoid, for example, are waterborne diseases. Engineers built collection systems to transport sewage away from the drinking water sources. While this problem is handled pretty well in developed countries, in developing countries the problem still exists.

(b) Wastewater treatment prior to disposal in drinking water sources (civil engineers and now other engineers). In most places anymore, it is impossible to actually transport the sewage far enough that it won't be in somebody's drinking water supply. Therefore, wastewater treatment was developed to remove disease causing agents prior to discharge.

(c) Water treatment, in particular disinfection (civil engineers) The final step was to recognize that water must still be treated prior to drinking to remove disease causing agents: viruses, bacteria, protozoa that may still be in the water.

Limits to Growth

We know that a population cannot grow forever due to mass and energy limitations. Are we anywhere near the ecological limits for human population? Are we anywhere near the social limits of human populations? Consider the following possible limits to human population size.

1. Carrying capacity limit due to food production.

Many experts try to predict a carrying capacity for humans. The number based on food production seems to be about 10 to 11 billion people. The likelihood is high that the human population will actually reach 10 to 11 billion when the demographics of the current 6.2 billion humans are considered. But that "expert" number is, in my opinion, unsustainably high if all factors are considered.

2. Carrying capacity limit due to water limits.

How much fresh water is available for human activities including drinking, agriculture and industry? How many humans can that water support? What are the implications to ecosystems if humans consume and/or redirect vast quantities of water?

Canada contains only 0.5% of the world's human population but 5.6% of the world's freshwater supplies. This has led to the belief that water is infinitely available and not a limit to growth. While perhaps true in the short term for Canada, this belief is incorrect for most of the world. Water will likely be the key limiting resource.

3. Carrying capacity due to life-support.

An ecological footprint is an estimate of the land area required to support the lifestyle of one human. The footprint includes the land (and ocean) requirement for food but also incorporates the land required for the products used by the individual and the land required to absorb the carbon dioxide released from fossil fuel combustion. Using ecological footprints, we can estimate how much land is required to support humans overall, not just to feed us.

As might be expected, people living in industrialized nations cast a much larger footprint than those in other countries. For example, the average footprint for a person living in the United States is over 10 times that for a citizen living in India. Current estimates indicate that the existing human population is already using 33% more resources than can be replenished sustainably. In other words, even 6.2 billion people is too many for our current average footprint. Logic would suggest, then, that we must somehow reduce our ecological footprint dramatically. So while simply on the basis of food production, the planet may be able to support 10-11 billion people, with other factors considered the number could be much, much lower.

4. Carrying capacity due to warfare.

Death rates have fallen dramatically. They will likely increase again as the population size continues to increase because as resources become limited, incidents of warfare will undoubtedly increase. When faced with the inevitable water limitations, for example, even the most peaceful countries will be forced to fight for this critical resource. Reasonable people will argue about whether the ecological carrying capacities for human populations have been met or exceeded – the data required to conclusively resolve carrying capacity questions are difficult to obtain. In the meantime, people will, if history is any judge, lead military campaigns against their neighbors to obtain the resources that are becoming limited. Judging by events occurring around the world today, we may be very close to our carrying capacity due to warfare, if we haven't already exceeded it.

My personal opinion…

The per capita environmental impact of humans varies with politics and economics but has been trending lower, at least in developed countries. The problem is that the environment responds to the total impact, which is the per capita impact multiplied by the number of humans. That total impact is increasing because the human population is growing faster than we can reduce our per capita impact.

An increasing environmental impact is unsustainable. While engineers and others work to reduce our environmental impact while still maintaining high standards of living, I don't think it will be enough unless the human population stabilizes, i.e. stops growing. We know what causes human populations to stabilize: education (especially for women), equal rights and equal pay (regardless of race, religion or sex), economic prosperity, and democratic governments that guarantee political freedom. So if we know these things, why do we appear to have done so little about it? In my opinion, the greatest threat to the planet today is the uncontrolled growth of our human population. The laws of mass and energy conservation that lead to carrying capacities for populations cannot be violated by humans either. Will we figure that out soon enough, or suffer the fate of any population of organisms that shoots past its carrying capacity – a dramatic population crash?

Lecture 17 **Competition and Coexistence**

By constructing the Dog Fence, the sheep ranchers significantly reduced the problem of sheep predation by dingoes. Earlier lectures examined mathematical techniques that could be used for sheep and kangaroo populations south of the fence. Both the exponential growth and logistic growth expressions assume there is no predation. As Examples 14.1, 15.1 and 15.2 indicate, the equations are also applicable to other populations where predation is not considered a problem. However, although we make simplifications when we can, nothing is really ever simple in a natural environment. The population equations presented only provide tools for making relatively rough estimates. One complicating factor that we have not yet considered is competition and coexistence.

The Dog Fence was erected to protect sheep. It also protects kangaroos. Dingoes also prey on kangaroos but with the fence, kangaroo populations south of the fence are booming. A problem for sheep ranchers now is competition. Kangaroos compete with sheep for water and grass. Competition is an important factor when trying to predict populations and as you should expect, mathematical models have been developed to deal with compeition.

Competition results when there are insufficient resources to support an unlimited population or populations of organisms. There are two classifications of competition:

Intraspecific: **Competition for resources between organisms of the <u>same</u> species**.

Interspecific: **Competition for resources between organisms of <u>different</u> species**.

We have already developed equations to model intraspecific competition: the logistic equation which uses a finite carrying capacity. Equations for interspecific competition, such as that between kangaroos and sheep, are developed in this lecture.

The classic equations for modeling interspecific competition are known as the **Lotka-Volterra equations**. The simplest forms of these equations are:

$$\frac{dN_1}{dt} = r_1 N_1 \left(\frac{(K_1 - \alpha N_2) - N_1}{K_1} \right)$$

$$\frac{dN_2}{dt} = r_2 N_2 \left(\frac{(K_2 - \beta N_1) - N_2}{K_2} \right)$$

where: N_1 = population of species 1

N_2 = population of species 2

r_i = net growth rate for species 1 or 2

K_i = carrying capacity of species 1 or 2 <u>in the absence of the other species</u>.

αN_2 = carrying capacity reduction for species 1 due to the presence of species 2

βN_1 = carrying capacity reduction for species 2 due to the presence of species 1

α units = organisms of species 1 per organisms of species 2

β units = organisms of species 2 per organisms of species 1

The assumptions implicit in these equations are:

1. Insignificant migration of either species (otherwise we would need migration terms in the equation).
2. Instantaneous effect of competition.
3. Competition is the only significant biological interaction (in other words, no predator/prey relationships between the organisms).

All three conditions reasonably apply to the sheep / kangaroo populations south of the Dog Fence.

Unlike the single organism growth models, these equations do not lend themselves readily to analytical solution. That doesn't bother us much, though, because systems of ordinary differential equations can be readily solved numerically on the computer. If you haven't yet learned how, you will before you graduate.

For this course we won't be attempting to determine the time-varying solutions to systems of differential equations (only simple ones that can be readily integrated by hand). Instead, we will be trying to understand the ecological processes that the equations represent. As is often the case, the mathematics can help improve our understanding by focussing our attention on a few key points.

For the ecological process of competition, we can examine the system at **steady state**. <u>What happens to our equations at steady-state</u>?

$dN_1/dt = dN_2/dt = 0$

because, by definition, at steady state there are no changes with respect to time.

Substituting zero for the derivative in the Lotka-Volterra equations and simplifying gives two linear equations:

$N_1 = K_1 - \alpha N_2$

$N_2 = K_2 - \beta N_1$

These two independent equations describe the relationship between the population of one species as a function of the population of the competing species at steady state.

There are four possible outcomes of these two equations based on the relative values of the constants to each other. Note that the constants must be determined using actual data. We cannot necessarily predict their relative values. The four cases we will consider are:

1. $K_1/\alpha > K_2$ and $K_2/\beta < K_1$
2. $K_1/\alpha < K_2$ and $K_2/\beta > K_1$
3. $K_1/\alpha > K_2$ and $K_2/\beta > K_1$
4. $K_1/\alpha < K_2$ and $K_2/\beta < K_1$

To examine these cases, we will plot N_2 versus N_1. This makes sense because at steady state, we have two linear expressions between N_2 and N_1. We will then pick an arbitrary starting set of values for N_2 and N_1 and attempt to predict the N_2 and N_1 values once the system reaches steady-state.

Case 1: **$K_1/\alpha > K_2$ and $K_2/\beta < K_1$**

Figure 17-1 shows the graphical solution for this case. Note several features in this figure. The lines represent the steady state solutions for the Lotka-Volterra equations. Notice that within the realistic quadrant of both populations being equal to or greater than zero, the lines do not cross. This makes determining a steady-state solution more challenging.

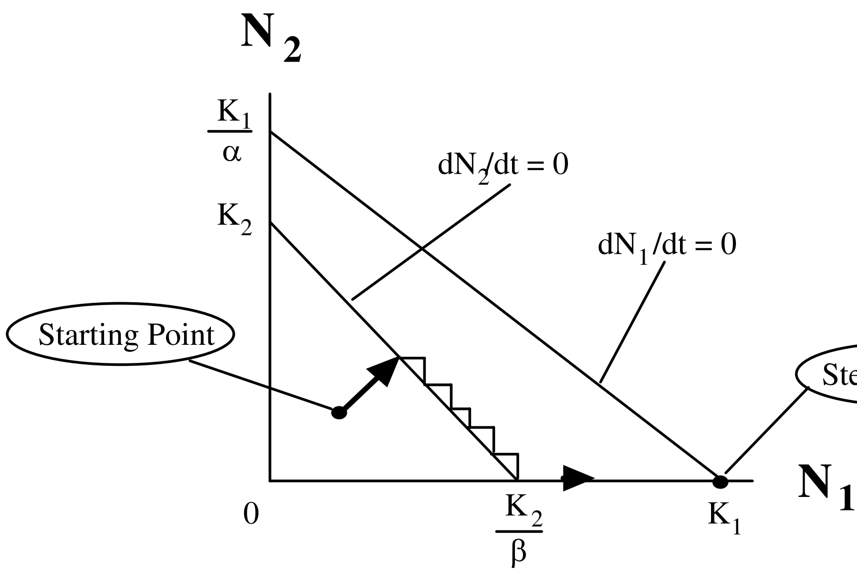


Figure 17-1 Case 1 Competition Steady State

To determine the steady-state populations, start with any point. In Figure 17-1 I have chosen an initial point where both N_1 and N_2 are below their individual carrying capacities. Both populations try to grow to reach their individual carrying capacities until they reach the first steady-state line (as shown). At this point, N_2 has no driving force to continue to grow as $dN_2/dt = 0$. N_1, however, continues to grow. This pushes the N_1/N_2 set off of the N_2 solution. There are now too many organisms in population 1 to support such a high N_2 so N_2 decreases until it reaches the steady-state line again (first stair-step along the dN_2/dt line). However, N_1 continues to increase. The process is repeated until at $N_1 = K_2/\beta$, N_2 becomes zero. Too many resources are being used by N_1 to allow survival of N_2. At this point, N_1 continues to increase to its carrying capacity K_1 (arrow on x-axis).

The steady-state populations are $N_2 = 0$ and $N_1 = K_1$. Species 1 outcompeted species 2 for the available resources and all of species 2 disappeared. As might be expected with the two non-intersecting steady-state solutions, only one population will survive.

Case 2: $\mathbf{K_1/\alpha < K_2}$ **and** $\mathbf{K_2/\beta > K_1}$

Figure 17-2 shows the graphical solution for this case. The lines showing how to move from the starting point to the steady-state point are not shown. Take the time to add them in.

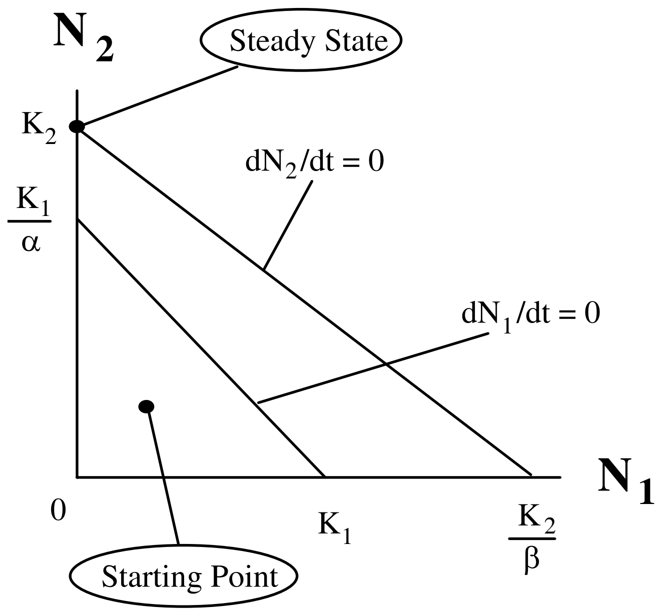


Figure 17-2 Case 2 Competition Steady State

Now the equilibrium populations are $N_1 = 0$ and $N_2 = K_2$. Species 2 outcompetes species 1.

Case 3: $\mathbf{K_1/\alpha > K_2}$ **and** $\mathbf{K_2/\beta > K_1}$

As can be seen in Figure 17-3, the steady-state solutions for this case actually intersect. The intersection point occurs at:

$$N_1 = \frac{K_1 - \alpha K_2}{1 - \alpha\beta}$$
$$N_2 = \frac{K_2 - \beta K_1}{1 - \alpha\beta}$$

In this case, the two species can actually coexist. You can test that by choosing different starting points and seeing how the system responds. The intersection point is stable.

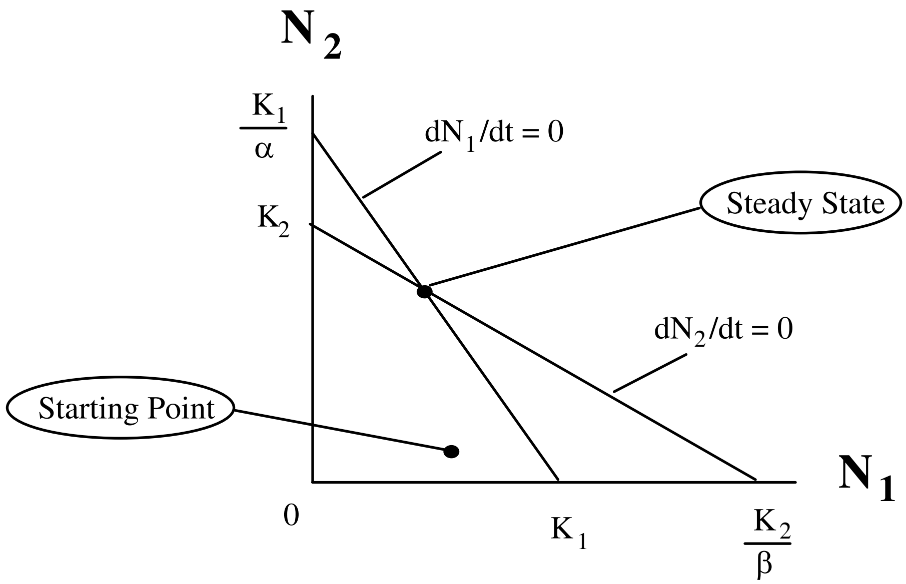


Figure 17-3 Case 3 Competition Steady State

Case 4: **$K_1/\alpha < K_2$ and $K_2/\beta < K_1$**

For Case 4, the steady-state lines also cross (Figure 17-4). The intersection is described by the same two equations as in Case 3. However, this intersection is not stable. Either of the two possible steady-state points on the axes are stable. Test this by choosing different initial starting points and determining where steady state will occur.

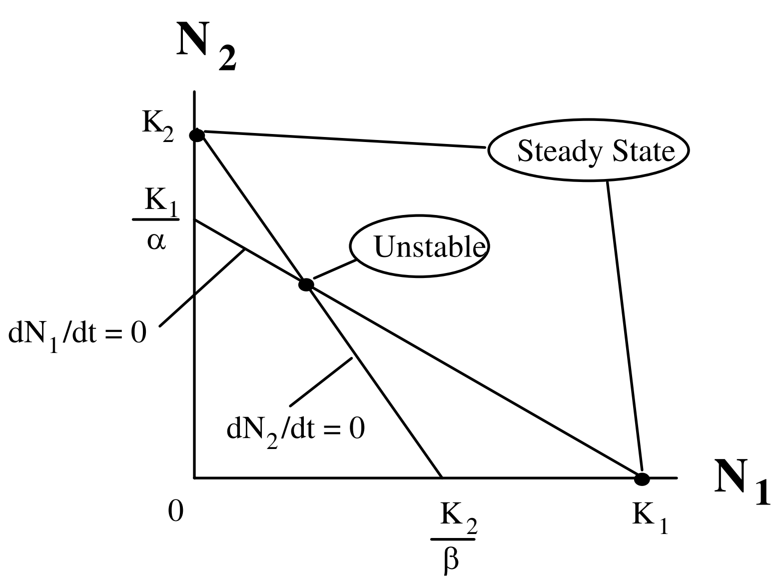


Figure 17-4 Case 4 Competition Steady State

In this case, the two possible stable steady-state solutions, either $N_2 = 0$ and $N_1 = K_1$ or $N_1 = 0$ and $N_2 = K_2$, depend entirely on where the system started.

The techniques we have just examined suggest that in the case of sheep and kangaroos south of the Dog Fence in Australia, it is probable that without some sort of intervention, one or the other will be outcompeted. Since the sheep ranchers can't afford to have the kangaroos outcompete the sheep, kangaroo populations are managed artificially with over 3 million kangaroos per year culled.

One of the simplest of products, a fence, can have profound implications on natural systems. As the Dog Fence example suggests, once actions are taken in one direction, it is virtually impossible to not take more actions.

Example 17.1:

Animals are not the only species to which ecological theory applies. This example considers two grasses: crested wheatgrass, which was introduced to the Canadian prairies 70 years ago and native prairie grasses. Under dry, drought conditions, crested wheatgrass is more competitive. However, crested wheatgrass is ultimately destructive to the prairie ecosystem.

Assume that crested wheatgrass has an $r_1 = 0.26\ yr^{-1}$, $K_1 = 90 + 1.5(P - 9)$ plants/m^2 (P = precipitation, cm/yr). Assume the native prairie grass has an $r_2 = 0.21\ yr^{-1}$, $K_2 = 45 + 3(P - 18)$ plants/m^2. $\alpha = 0.85$ and $\beta = 0.8$.

a. At what precipitation rate are the carrying capacities equal?

Set $K_1 = K_2$:

$90 + 1.5(P - 9) = 45 + 3(P - 18)$

$90 + 1.5P - 13.5 = 45 + 3P - 54$

$1.5P = 85.5$

$P = 57$ cm/yr

b. If the precipitation rate is 85 cm/yr, what are the steady-state populations of the two species?

$K_1 = 90 + 1.5(85 - 9) = 204$ plants/m^2

$K_1/\alpha = 204 / 0.85 = 240$ plants/m^2

$K_2 = 45 + 3(85 - 18) = 246$ plants/m^2

$K_2/\beta = 246/0.8 = 307.5$ plants/m^2 $= 308$ plants/m^2

Either remember which case this is (which I can never do) or plot it (Figure 17-5) and see which case it is.

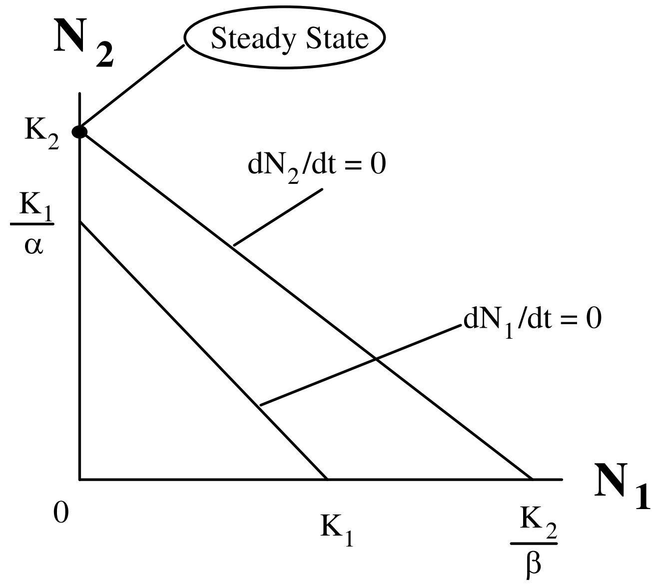


Figure 17-5   Example 17.1 Solution

At equilibrium:

N_1 (crested wheat grass) = 0

N_2 (native grass) = K_2 = 246 plants/m^2

Test your understanding of how to use these graphs by choosing a starting point and working to the steady-state solution.

Final Reality Check

For certain combinations of parameters, the competition equations predict that one species will completely dominate another competitive species, driving the second species to extinction within the system of interest. This idea lead's to **Gause's principle**:

> **At equilibrium, two species with identical resource requirements cannot occupy the same habitat.**

This principle may also be considered the ecological definition of a species. It is an observed, measurable fact. So our model agrees with observation on this important matter.

If no two species with identical resource requirements can occupy the same habitat, Why bother with dynamic competitive population growth models?

The reason is, **dynamics**. Steady-state solutions help us think about ecological facts. Dynamic solutions are actually required to solve problems.

Lecture 18 Mutualism

At the organism level, life is hard. As we saw in the previous lecture, two species will compete for the same resources. The species that is "most fit" often "wins" all of the resources. There is no prize for second place. Natural selection is a harsh, unbiased, and permanent process that has caused the extinction of many species that were not "fit enough." As we will see in the next lecture, competition is not the only challenge facing organisms. Predation is perhaps even more brutal than competition. Being "fit enough" to survive means being able to outcompete other organisms for a specific niche while somehow also avoiding complete consumption.

Nevertheless, there are numerous cases where species neither compete with each other nor cause each other harm. To the contrary, two species appear to work together for each other's mutual benefit. Such systems are considered mutualistic. This lecture will briefly examine mutualism and a related process called commensalism.

Mutualism: Relationship between two species that benefits both species.

Commensalism: Relationship between two species that benefits one species but does not affect the other species.

Table 18-1 shows where mutualism and commensalism fit in the spectrum of possible relationships between species that we examine in this course.

Table 18-1 Possible Relationships between Species

Type of Relationship	Species 1	Species 2
Competition	–	–
Mutualism	+	+
Commensalism	+	0
Predation	+	–

– = A negative effect to the species
+ = A positive effect to the species
0 = No effect.

As we saw earlier, competition occurs to the detriment of both species (at least until one of the species is successful). Predation occurs to the benefit of the predator (Species 1) but the detriment of the prey (Species 2). Mutualism, however, benefits both interacting species and commensalism benefits at least one species at no cost to the other species. Upon first glance, these beneficial relationships appear to disagree with the Darwinian theory of "survival of the fittest." Do they?

Types of Mutualism

Ecologists have identified a range of mutualistic behavior between species. **Commensalism** is the least restrictive to the organisms involved. In other words, the commensal organisms are not obligately dependent on each other. One type of commensal behavior is the dispersal of seeds by plants that don't produce fruits. Some plants, such as dandelions, use physical forces such as the wind to disperse their seeds. Other plants encase their seeds in sticky or barbed casings. These seeds stick to animal fur and feathers and are transported to another location for germination. On occasion the seed disturbs the animal but usually the animal conducts the disperal at no cost and with no notice. In cases such as these, the relationship between the species is very loose. The plant just needs an animal carrier – any animal will do. The evolution of this mechanism of seed dispersal by plants did not change the environment sufficiently to cause natural selection of another species in response.

Other examples of commensalism include sea anemones growing on hermit-crab shells. The crab neither benefits nor is harmed, but the sea anemone finds itself closer to a food source – the scraps that the crab does not eat. In this example, the benefit provided is more immediate than with seed dispersal. The individual sea anemone benefits daily from a more consistent food source. With seed disperal, the species as a whole benefits over a longer time and the individual organism that produced the seed does not benefit at all.

Obligate mutualism is more restrictive than commensalism. In these cases, the mutualistic organisms are dependent on each other for their survival. There are two types of obligate mutualisms:

1. **Non-Symbiotic Mutualism:** Mutualistic organisms live physically separate lives.
2. **Symbiotic Mutualism:** Mutualistic organisms live together in close physical association.

Perhaps the most common case of <u>non-symbiotic mutualism</u> is pollination. Many plants require pollination to reproduce. A wide variety of processes to facilitate pollination have been evolved, some depending entirely on physical processes such as the wind and others requiring movement of the pollen by other organisms via non-symbiotic mutualism.

The movement of pollen between flowers on a plant, say by a bee, is considered mutualistic because the plant benefits (pollen is moved to ensure reproduction) and the bee benefits (consumes the nectar produced by the plant specifically for the pollinator). Some plants are generalists and can be pollinated by a variety of pollinating insects. Other plants have become so specialized that their flowers have evolved to allow only one species of pollinating insect to be successful. Likewise, some pollinators are generalists and can pollinate a variety of plants while others have evolved to pollinate only one plant species.

Ants and plants are involved in a number of non-symbiotic mutualistic relationships. For example, a species of ants in Central America live in the swollen thorns of acacia trees. These thorns provide the ants shelter and food. The tree produces protein-rich nodules and sugar-secreting nectaries that provide most of the food needed by the ants. In return for such good treatment, the ants protect the tree. If herbivorous animals disturb the tree, the ants attack the intruder until it leaves. In Africa acacia trees and ants have a similar relationship, with the ants protecting the tree against defoliating insects. Experiments have shown that when the ants are removed, the tree suffers and can be killed.

Symbiotic mutualistic relationships are also relatively common and often important to the ecosystem in which the organisms live. Lichens, for example, are often discussed as if they were a single plant species, but in fact lichens consist of an algae species and a fungus species living symbiotically. Different lichens are composed of different combinations of algae and fungi. The algae species captures energy photosynthetically and "feeds" the fungus from material that leaks from its cells. The benefit provided by the fungus is primarily protection, although some ecologists have argued that the algae doesn't really benefit much. These ecologists have, in my opinion, missed the point. Lichens can grow in inhospitable environments, such as on the surface of rocks. Neither algae nor fungi appear to grow on these surfaces alone (at least not the rock surfaces I have hiked over). The mutualistic combination, however, allows these two organisms to now grow where they could not individually grow before. Apparently the fungus partner is required for this to happen, so the algae benefits by being able to thrive in an otherwise inaccessible niche.

Other examples of symbiotic mutualistic relationships are ruminant organisms such as cows and termites. In both cases, anaerobic microorganisms reside in the digestive tracks of the cow (in the rumen) or termite that can enzymatically degrade cellulose into sugars. Animals that survive by eating cellulose (grasses or wood, respectively) must be able to digest the cellulose and so the bacteria responsible provide a necessary benefit to the animal. The bacteria receive a steady source of food and also a "comfortable" environment that is mostly free of competitors and predators. In this case, the bacteria can live in other anaerobic (oxygen-free) environments and so are not entirely dependent on the ruminant or termite.

Why Mutualism?

As mentioned earlier, mutualism appears to contradict the premise of natural selection. This appearance arises from a superficial examination of these relationships. Some ecologists, in fact, have claimed that mutualistic relationships indicate that organisms work together to benefit each other. This interpretation is inappropriate. The organisms involved in mutualistic relationships have not chosen to do so. They are not humans capable of deciding to work together for the common good. They are typically not even intelligent life forms that could make decisions (the algae and fungi that form lichens, for example, are simple life forms while anaerobic bacteria found in ruminants are single-celled organisms). So if these organisms are not "choosing" to work together (which would indeed set a good example for humans if it were the case), why are they forming mutualistic relationships?

The answer is, as always with organisms, survival of the fittest. Mutualistic relationships benefit both organisms involved. These benefits make both organisms more fit, and hence more likely to survive. The part that confuses people is how these relationships initiated. If choice by the organisms wasn't involved, what was? The answer, in my opinion, is chance, the same force that motivates much natural selection. For example, a plant mutation could occur (by chance) such that its flower structure was more suited to one type of pollinator than another. At a given time, that mutation would provide the plant a benefit over another, perhaps by keeping out less useful pollinators. This plant will have a slight reproductive edge and slowly outcompete the other plants without this mutation. Additional mutations may occur, both in the plant and the pollinator, until the close mutualistic relationships that we see today developed.

Modeling Mutualism

Models for mutualistic relationships are beyond the scope of this class. Each mutualistic relationship is different. The specifics of each relationship must be understood and carefully quantified. General models such as we have investigated for competition (and will investigate for predator-prey relationships) are not applicable.

<u>Lecture 19</u> **Predator/Prey Dynamics #1**

Swainson's Hawk

(From: DiSilvestro1996).

Many birds migrate extremely long distances seasonally. We think of this occurring with Canada geese, for example. However, raptors (not the NBA team, but carnivorous birds) also migrate. One particular species is the Swainson's Hawk.

The Swainson's Hawk is found in North America in western Canada and the western U.S. They are rather large birds, 700 to 1,000 g and they live in North America during the spring and summer. When it starts to get cold in the fall, they head south to South America, where spring is just starting. Unfortunately, North American researchers observed a 90% drop in numbers since the 1940s. Because conditions in Canada and the U.S. are relatively favorable, researchers suspected the problem lay with either the migration or the South American destination. By tagging the birds and using satellite tracking, their southern destination was determined: Argentina (some birds were also found in Mexico and Panama, but the largest numbers were in Argentina). But when researchers flew to Argentina they found large numbers of dead hawks. Something in Argentina was killing hawks.

Swainson's Hawks love grasshoppers. A group of hawks would move into a field and eat grasshoppers until there were hardly any left. They would then fly to the next field and eat some more. Until about 1986, the La Pampa province in Argentina (which was a very popular destination for Swainson's hawks) was primarily cattle country. Grasshoppers didn't really cause any agricultural problems, and the hawks stuffed themselves. Then the area shifted to "industrial" crops, in particular sunflowers that are grown to make sunflower oil. Grasshoppers love sunflowers so, of course, farmers were determined to kill the grasshoppers.

This is a lecture on predator/prey dynamics. The predators in this example are Swainson's Hawks and the prey are grasshoppers. Before we develop any equations, let's think about the following question.

<u>Which alternative will minimize the grasshopper population for the least cost</u>?

1. Kill the grasshoppers with a cheap, non-selective pesticide.
2. Kill the grasshoppers with a more expensive but more selective pesticide.
3. Encourage Swainson's Hawks to eat as many grasshoppers as possible.

Before answering that question, consider what has actually been done. The farmers chose option 1 and blasted their lands with pesticides. One pesticide was particularly troublesome: **monocrotophus**. This pesticide is highly effective, on both grasshoppers <u>and</u> hawks. As little as a milligram can kill a golden eagle. The Swainson's Hawks were eating the killed grasshoppers and dying from pesticide ingestion.

What happens when Swainson's Hawk and other predators are killed by the poison in the prey?

The predators provide a natural removal mechanism for grasshoppers. When the predators are killed, there is reduced pressure on the prey populations and they will begin to increase. From a practical standpoint, the farmers would then have to use more pesticide to kill the same number of grasshoppers.

Option 1, chosen by the farmers, was inappropriate. Option 2 would be better. Other pesticides, such as **carbaryl**, are more selective and will not kill hawks. These more selective pesticides cost more per kilogram but may in fact cost less if cost is calculated on a per grasshopper basis. Certainly, a business opportunity exists to develop and produce a less destructive pesticide. Under Option 2, predators continue to assist with pest removal. Option 3 would be ideal ecologically. Whether or not it is feasible from an agricultural standpoint is unknown and should be investigated.

Basic Equations

We never really answered the question posed above: how to best minimize grasshopper populations. The reason is that we don't have sufficient data to conduct that analysis. Intuition suggests that there is an ecologically better way than the indiscriminate use of monocrotophus. Let's now develop the tools required to examine the question more rigorously, with less reliance on intuition.

Predator/prey interactions are fundamentally different from competition. In these interactions, prey are the resources for the predators.

There are four general predator/prey-type of relationships:

herbivory: animals eating plants

carnivory: animals eating other animals

parasitism: organisms sustaining themselves at the expense of other organisms not necessarily in the form of eating, and

cannibalism: a subset of carnivory where animals eat other animals of the same species.

In this course we will consider only carnivory. We don't have time to develop the biological background needed to model the other relationships.

As before, to model the system we must first conduct an "organism balance" over a selected system. Recall our simple system definition from Lecture 14 (Figure 19-1). As before, we will assume that migration in and migration out are negligible. However, we will definitely not assume that predation is not important.

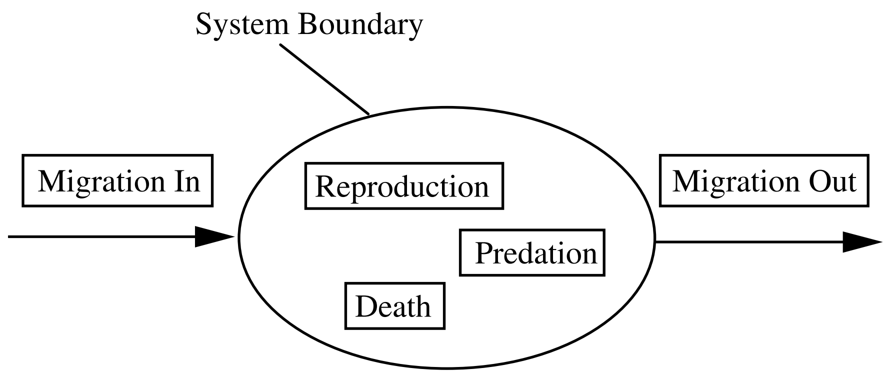


Figure 19-1 Simple System for Population Analysis

For predator/prey systems, we must conduct organism balances for both the predator and the prey. Let's consider the prey first:

accumulation = dN/dt

(as before)

reproduction rate = bN

(as before)

death rate = dN

(as before)

This will give us a net growth rate of:

net growth rate = rN

As a first estimate, this net growth rate expression may be used. However, you may also use the net growth rate expression associated with the carrying capacity, i.e., the logistic form of the net growth rate.

We also know that the prey population will be consumed by predators. So we need an expression describing the **predation rate**. Let's assume a simple predation rate:

predation rate = a'CN

where: **a'** = "searching efficiency" or "attack rate", $\text{carnivore}^{-1}\cdot\text{time}^{-1}$.

C = population of the carnivore, number of carnivores in the system of interest

Combining the predation rate with our simple net growth expression gives:

dN/dt = rN – a'CN

This can be rearranged to give:

dN/dt = N(r – a'C) = N(b – Σdeath terms)

where: **Σdeath terms = d + a'C**

Now consider the predator organism balance in the system. We see that we must have a value for the population of predators to solve the prey equation. For our closed system (no migration in or out) we start with the same basic expression:

dC/dt = growth rate – death rate

The predator is <u>growing because it is eating prey</u> so the predator growth rate must be related to the prey predation rate. This can be done simplistically as follows:

$$\text{growth rate} = \sum_{i=1}^{\text{number of prey}} f_i \left(\text{predation rate}\right)_i$$

where: f = the efficiency of conversion of prey into predators, units of carnivores per prey.

This expression allows us to account for the fact that most carnivores eat more than one type of prey. For a simple one prey / one predator system, assume the following expression:

growth rate = fa'CN

As with prey, the death rate should be the sum of all the things causing death to the carnivore including starvation due to lack of prey, illness, old age, injury, etc. Additionally, carnivores may be prey for higher trophic level organisms. For simplicity, we will assume there is not predation of the predator and that the overall death rate is:

death rate = q·C

where: q = specific mortality rate, time^{-1}.

Combining the growth and death rates, our predator equation becomes:

dC/dt = fa'CN – qC

As was the case with competition, we now have a pair of differential equations with interdependent terms. To obtain C and N as functions of time we need to solve both equations simultaneously. If we wanted to look at more than one trophic level, we would have even more differential equations to solve.

However, as before, we will examine the system at steady-state to assist us in understanding the ecological principles at work. This examination will also tell us if we have chosen reasonable expressions for our organism balances but will not provide the population dynamics.

At steady state, the rate of change of the prey population is equal to zero and the differential equation simplies to:

dN/dt = 0 = rN – a'CN

which can be rearranged and solved to provide:

C = r / a'

Similarly, at steady state, the rate of change of the carnivore population is equal to zero and the differential equation simplies to:

$$dC/dt = 0 = fa'CN - qC$$

This can be rearranged to give:

$$N = q / fa'$$

As we did with competition, we can plot the populations against each other, in this case C versus N. Specifically, I will plot the two lines obtained at steady-state / equilibrium.

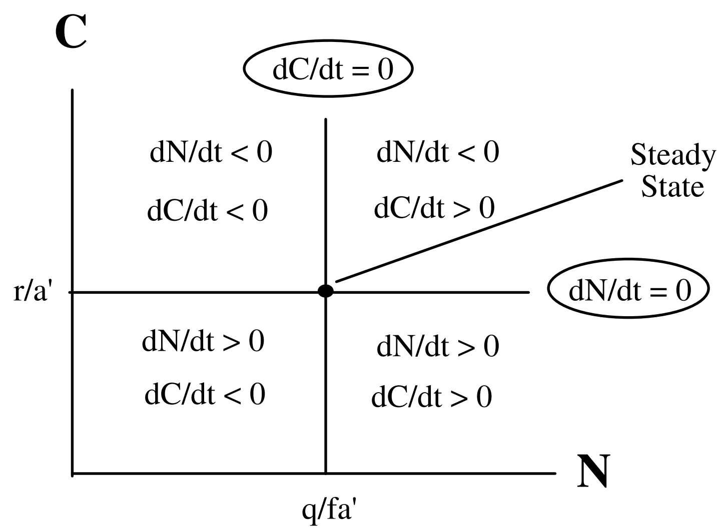


Figure 19-2 Predator/Prey Populations for Simple Expressions

Figure 19-2 shows that steady state should occur at one pair of predator and prey populations. This makes intuitive sense. We can use Figure 19-2 to qualitatively describe the populations if we start at some point besides equilibrium. For example, let's pick a point to the right of the dC/dt = 0 line and above the dN/dt = 0 line (see Figure 19-3). We note from our quadrants in Figure 19-2 that C will increase, because there are sufficient prey to provide a greater growth rate than death rate. However, N decreases, because there are too many carnivores. We reach point A, which is the maximum number of carnivores, but N is still decreasing, so we can't stay on this line. In the next quadrant, C is decreasing because there aren't enough prey. The prey are still decreasing because there are still too many carnivores. We reach point B, but C is still decreasing so we can't stay on this line. Using the same logic, we follow the circle on around to where we started.

We can also plot the time-varying N and C populations as well from our C versus N exercise. The system described in Figure 19-2 provides oscillations, as seen in Figure 19-4. Do the results in Figures 19-2, 19-3 and 19-4 seem reasonable?

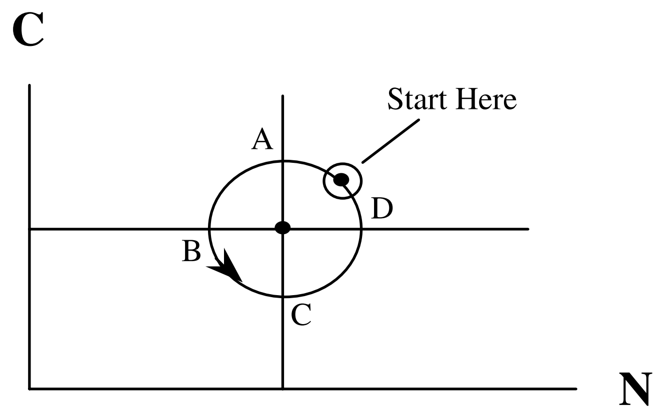


Figure 19-3 Variation of Populations when not at Steady State

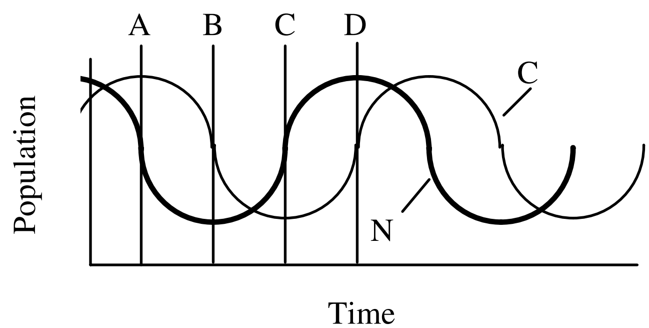


Figure 19-4 Variations of Populations with Time

What is reasonable? Our intuition suggests that the system should be moving toward steady state, just as it did for competitive systems. The system shown in the figures oscillates. In the real world, predator-prey systems can move toward equilibrium, they can oscillate stably about a "steady-state" point or the oscillations can diverge. Our intuition was too simplistic, as were the equations that we used. Developing useful models for natural predator-prey systems is a demanding task that requires a great deal of data. The approaches developed here are useful for thinking about these systems, but are likely too simple for real systems.

<u>Lecture 20</u> **Predator-Prey Dynamics #2**

Because predators often migrate when prey populations decrease in a geographical area, migration terms may be required for some predator-prey problems. Example 20.1 provides an illustration of how to incorporate migration terms into the appropriate organism balances.

Example 20.1

Your firm is designing a new 4-lane highway through a forest habitat. The forest supports a wolf population. The following relationships relating wolves and rabbits have been developed:

Wolf growth rate = fa'WR

Wolf death rate = qW

Wolf migration rate, in = 10[R/(R+1000)]

Wolf migration rate, out = 15[1 – exp(–1000/R)]

Rabbit reproduction rate = bR

Rabbit death rate = dR

Rabbit predation rate = a'WR

Rabbit migration rates, in and out = 0

Where W = wolf population, R = rabbit population, f = 0.005, a' = 0.05, q = 0.3, b = 5, and d = 4 with appropriate units as discussed earlier.

a) Write the differential equations describing the dynamic organism populations for both wolves and rabbits.

From an organism balance on wolves:

$$\frac{dW}{dt} = fa'WR - qW + 10\left(\frac{R}{R+1000}\right) - 15\left[1 - \exp\left(\frac{-1000}{R}\right)\right]$$

From an organism balance on rabbits:

$$\frac{dR}{dt} = bR - dR - a'WR$$

b) If the population of rabbits is at steady-state, what is the wolf population?

At steady state, dR/dt = 0. Substituting into the above expression for rabbits gives:

0 = bR – dR – a'WR

0 = b – d – a'W

so:

$$W = \frac{b-d}{a'} = \frac{5-4}{0.05} = 20 \text{ wolves}$$

c) If the population of wolves is at steady-state, what is the rabbit population?

At steady state, dW/dt = 0. So solve the dW/dt = 0 equation iteratively and you should get R = 1480 rabbits.

d) Prior to construction of the highway, a steady-state had been reached between wolf and rabbit populations. Studies suggest, however, that after construction of the highway, this steady state will be disrupted. The wolf specific death rate after construction, q_{new}, is predicted to be twice the current specific death rate, q. All other constants are expected to remain the same. Describe what will happen to the wolf and rabbit populations over time after construction of the highway.

Initially W will decrease due to the increased death rate. This will cause R to increase due to the decreased predation rate a'WR. However, as R increases:

(i) fa'WR will begin to increase, increasing the wolf population.

(ii) Wolf migration in will begin to increase (as R increases, R / (R+1000) goes to 1)

(iii) Wolf migration out decreases (as R increases, the 1 – exp term goes to 0)

Therefore, increases in R due to the initial drop in W will lead to increases in W, although perhaps not fast enough to support a healthy wolf population. If steady state can be reestablished, W will be the same as in part b), 20 wolves. R, however, will be larger, equal to 2,150 rabbits (if steady-state can be achieved).

More Than Two Trophic Levels

We have now examined the basic tools needed to examine populations in environmental systems. Hopefully, the impacts of different products on both organisms and populations is clear. We started the course with a product that had little environmental impact as a product, i.e., potato chips, but clearly other products that have been designed and manufactured by engineers and then USED AS DESIGNED have had an impact. The capital letters are important. The point is that environmental impact does not arise only from "pollution" or waste products, but also from products during their active product life.

The following example shows how predator-prey dynamics can impact multiple trophic layers. The engineering product involved is a chemical cousin of DDT called <u>dieldrin</u>. Dieldrin is a powerful insecticide that was used, in addition to DDT, to kill mosquitos that cause malaria.

In North Borneo (now part of Indonesia) malaria once infected 90% of the population. However, in 1955, to reduce the rate of malaria infection in North Borneo, the World Health Organization began spraying with dieldrin to kill mosquitoes.

<u>Knowing what we now know about populations, what happened</u>?

1. Mosquitoes were killed. This removed the pathway for transmitting the malaria protozoan to people and malaria infections decreased. This was the desired outcome.
2. Other insects such as flies and cockroaches were killed. This appeared initially to be an unplanned benefit.
3. Lizards ate the insects that were killed by dieldrin. The predator / prey relationship between lizards and insects was affected. Initially, this must have seemed beneficial. The lizards were cleaning up the dead insect debris in the villages.
4. Lizards began to die from dieldrin poisoning. This is not surprising to us, given the same type of response with Swainson's Hawks eating grasshoppers. However, it was an unplanned outcome. The dead lizards in villages would cause much more inconvenience than dead insects.
5. Cats ate the dead lizards. Now a third trophic level is involved. This helped clean up the dead lizard problem.
6. Cats began to die from dieldrin poisoning. This is also not surprising to us, given what we know now. Bioaccumulation was also at work as dieldrin moved up the food chain.

Before going any further, recognize that predator/prey dynamics work both ways. In other words, if a predator population decreases, prey populations will increase. With that in mind note that an important prey for the cats was rats.

7. Rat populations exploded. A natural limit to rat population has been removed, the predator. The rat population likely began to follow exponential growth, as we would expect when constraints are removed.

The next point to note is that rats carry fleas and fleas carry the organisms that cause human disease, such as typhus and plague.

8. Villagers started to suffer from typhus and plague. With so many more rats, the potential for contact between fleas and people increased tremendously. One obnoxious human pathogen (the protozoan that causes malaria) has been exchanged for other human pathogens.

As uncomfortable as the villagers are now, the problem is not yet over. Another predator population was inadvertantly killed, this one by direct toxicity from dieldrin. The organisms were caterpillar-eating wasps.

9. Caterpillar populations increased dramatically. Again, this is something we could predict using predator / prey modeling.

Another fact was that caterpillars eat thatch (the natural roofing material used by villagers).

10. Thatch roofs began to collapse due to overconsumption by caterpillars.

This story illustrates (Figure 20-1) how an apparently simple action can have extensive repercussions and how short-sighted some of our actions are. Most likely the situation was brought under control by:

1. Reducing dieldrin doses
2. Poisoning the rats, and
3. Providing tin roofs to the villagers.

However, the situation would have reached a different steady-state at some point had these additional actions not been taken. Hopefully, with experiences such as these to learn from, we won't make such errors in the future.

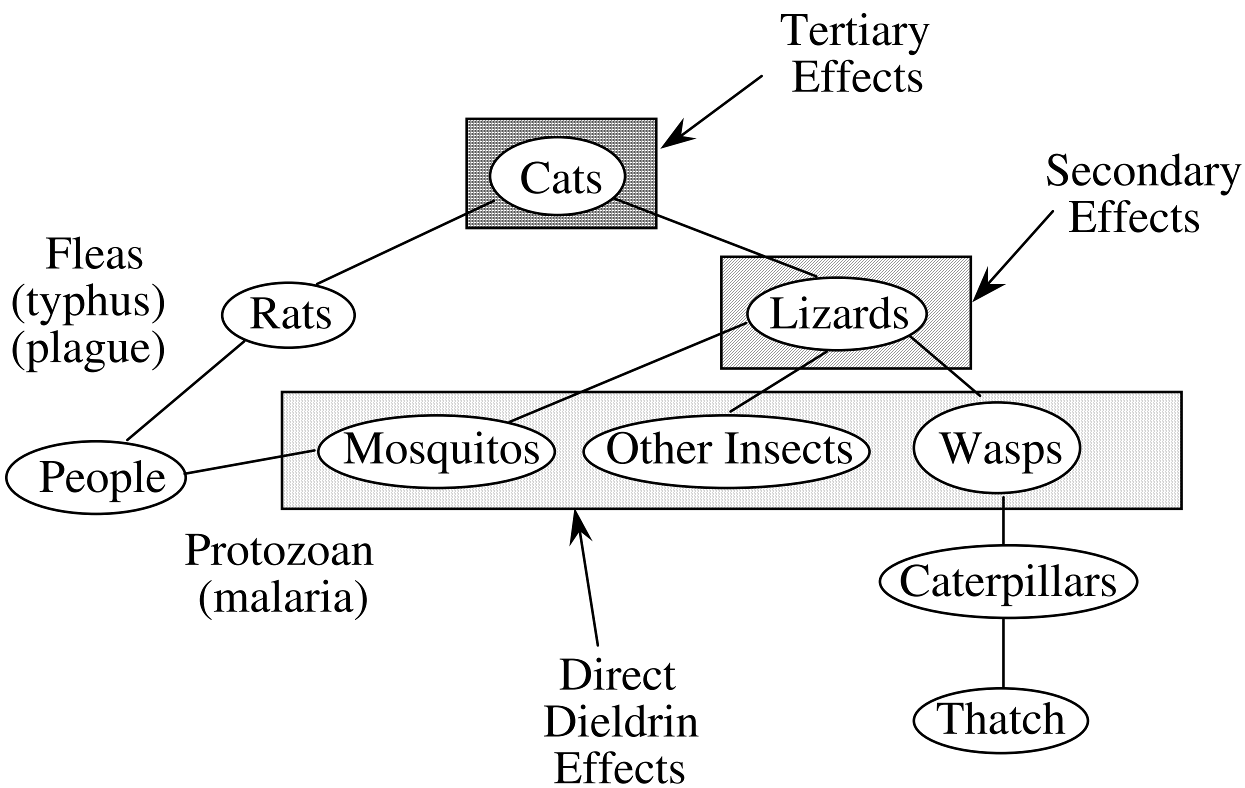


Figure 20-1 Summary of Interactions Arising from Dieldrin Usage

<u>Lecture 21</u> **Habitat Fragmentation**

Road construction, clear-cutting of forests, subdivision development and agricultural development are human activities that lead to habitat fragmentation.

Habitat fragmentation: **The breaking up of a larger continuous habitat into smaller, discontinuous pieces (or fragments)**

Does habitat fragmentation necessarily affect an ecosystem or can the individual fragments each perform satisfactorily? Is there any real reason an ecosystem must be a certain size and if so, how can we determine what that size should be? This lecture and the next will examine the issue of habitat fragmentation at the species level (this lecture) and the ecosystem level (next level).

Construction of Interstate 75 west from Miami, Florida, US

The Interstate highway system in the U.S. was started in the 1950s to link the country by road and allow easy mobility of people. My father grew up south of Cleveland, Ohio and worked at least one summer in the mid 1950s on Interstate 71. In particular, the federal government provided funding because the highway system was considered vital to national defence. The result is an impressive collection of north-south and east-west highways that criss-cross the country.

There are two major north-south interstate highways in the eastern and mid-western US:

- **I-95**, which runs from the state of Maine along the Atlantic coast through New York City and Washington, D.C., all the way to Miami.
- **I-75**, which runs from Michigan across from Sault Ste. Marie, through Detroit, Cincinnati, and Atlanta, into Florida, and now also ending in Miami.

To get to Miami, I-75, which runs down the center of the state and then the Gulf coast, must cross the northern part of the Everglades ecosystem of southern Florida. Before I-75 was constructed, it was called Highway 84 but its nickname was Alligator Alley. One of the challenges with constructing I-75 was that the Everglades are home to the Florida panther, an endangered organism, whose habitat included both sides of the planned highway. Ecologists predicted that panthers would be unlikely to successfully cross a 4-lane express highway without being hit by cars. Therefore, to improve the ability of the panther, and other organisms, to cross the road, portions of the road were elevated, leaving "tunnels" of natural habitat for panther crossing <u>underneath</u> the road. As we will see later, other alternatives to allow different organisms to cross habitat barriers have also been developed, including in Canada.

Constructing the tunnels and the fences along the road to help channel organisms to the tunnels added to the cost of constructing I-75. An important question, then, was whether the tunnels have worked? To answer that question, ecologists placed automated cameras in an underpass. Pictures of the wildlife passing throught the tunnel were then automatically taken.

As camera technologies have improved, this technique has become more commonly used by ecologists to gather field data. The pictures showed that indeed many organisms used the underpass, including panthers. Additionally a car, including the license plate number, was clearly photographed illegally driving through the underpass. Cars are not an endangered species and are in fact not allowed in the conservation areas on both sides of I-75. The owner received a note from the police informing him of that. Proof exists, then, that organisms do use the underpasses but whether that can help the panther population or not still remains to be determined. One remaining problem is that the Florida panther population is now also thoroughly isolated from other panther populations in North America. The genetic diversity of the population is becoming so limited due to interbreeding that the population is becoming very susceptible to extinction.

Camera Traps (a digression)

Throughout the course I have talked about the number of organisms in a population but have not suggested how that number can be determined. Camera traps are an important tool for counting the population of large animals in an area. The cameras automatically take a picture when the animals break an infrared beam "trigger" that has been set up.

Camera traps are particularly useful for counting tigers but there are difficulties too! Sorry, if you want to know more about camera traps, you will have to be in lecture.

(digression ends)

Metapopulations

When we conducted organism balances, we ignored the movement of organisms into or out of these systems. The assumption of no migration is invalid for cases of habitat fragmentation. To the contrary, migration is often a key issue for the population of interest. Therefore, to try to model these systems, we must either:

1. Allow migration into and out of the systems of interest, or
2. Examine larger systems where migration may still be ignored.

The first option, migration modeling, requires more data, such as the underpass data in Florida, and more sophisticated models than we developed (although still starting from an organism balance). The second option hides important information about the smaller areas within the system, but may still be useful. To use the second option, ecologists have defined:

Metapopulation: **a collection of smaller, physically separated populations of the same species.**

Metapopulations are useful mathematically because movement into and out of each of the small populations does not need to be modeled. Any individual small population may become extinct or thrive. However, if an isolated population becomes extinct or is close to becoming extinct, it may be <u>recolonized</u> by organisms from a nearby population, perhaps one that is thriving (see Figure 21-1). If we are trying to model the isolated population alone, we have to account for the recolonization activities. However, if we look at a metapopulation that includes both populations, we don't have to account for individual populations but can simply model the overall metapopulation. There are 4 basic types of metapopulations.

1. **Classic** (see Figure 21-2)
   a. Individual populations are far enough apart to actually become extinct.
   b. Individual populations are close enough together to allow recolonization.
   c. Direction of recolonization between individual populations is arbitrary.

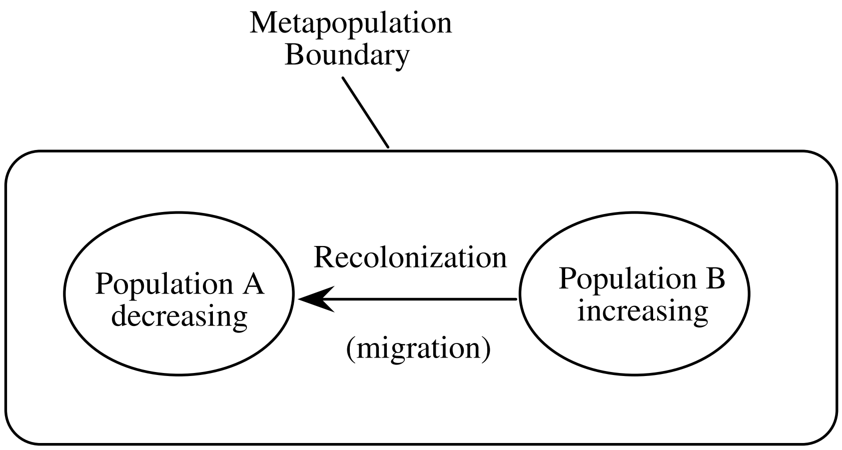


Figure 21-1 Recolonization occurring within Metapopulation A+B

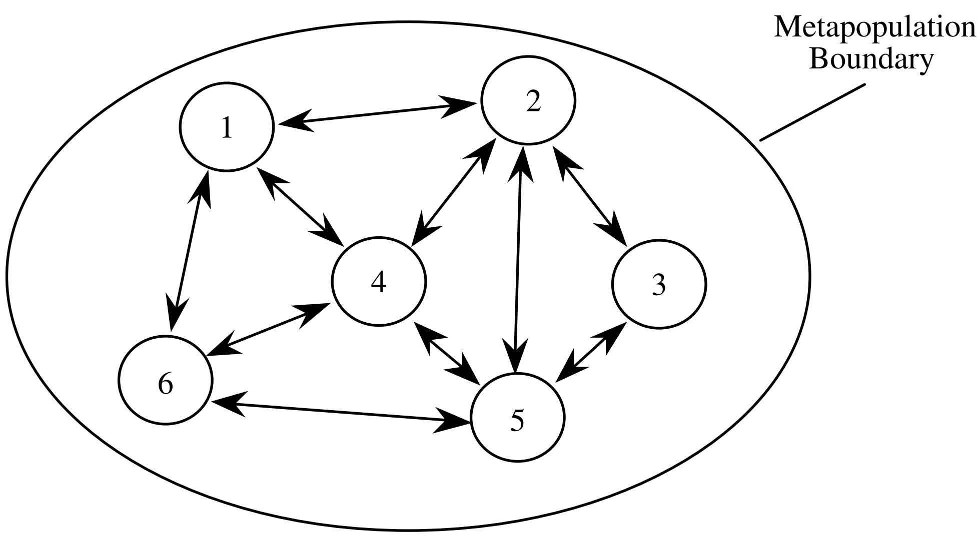


Figure 21-2 Classic Metapopulation

For example, if population 1 becomes extinct and is recolonized from population 2, population 1 may then serve as the recolonizing source for another population, including population 2, if it becomes extinct. The classic metapopulation approach may be applied to a forest that has <u>small</u> patches of clear cutting. The uncut forest would serve as sub-populations to recolonize other un-cut patches (and even cut patches) while the whole checkerboard area would be the metapopulation.

2. **Core/Satellite** (see Figure 21-3)
   a. Large core population is extinction-resistant (recall probability of extinction issues discussed earlier).
   b. Satellite populations are smaller and may become extinct.
   c. Colonization or recolonization occurs from core to satellite.

This could be similar to lumbering around a large protected forest. In this case, the clear cut areas would be "extinct" populations that would be recolonized by the main forest.

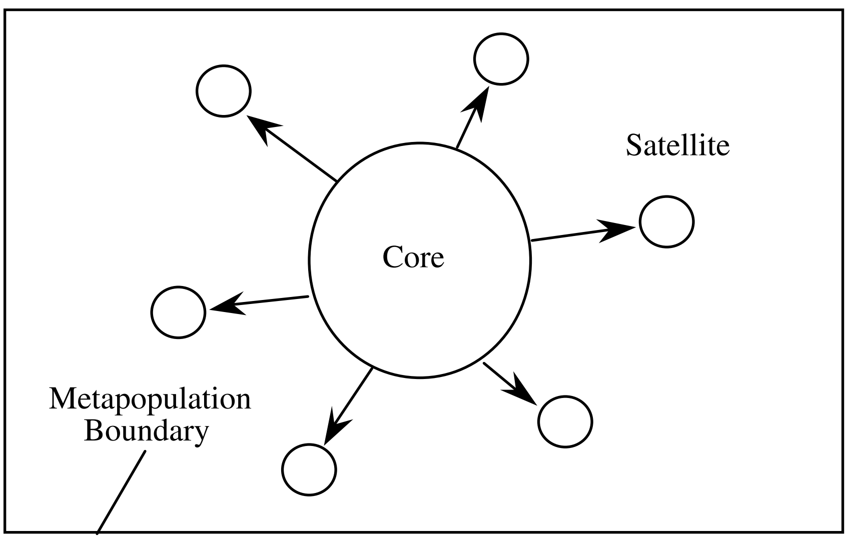


Figure 21-3 Core/Satellite Metapopulation

3. **Patchy**.
   a. Version of classic type
   b. Recolonization is so rapid no individual population becomes extinct
      - Colonies are close together
      - Organisms easily move across physical gap between colonies

This is considered a metapopulation, as opposed to a single population only because the physical distribution of organisms is not uniform.

4. **Nonequilibrium**.
   a. Another version of classic type.
   b. Individual populations are <u>not recolonized</u> after they become extinct because:
      - Physical barriers between colonies cannot be breached due to
        1) Distance
        2) Other obstacles, perhaps human activity.
      - Other colony populations are not productive enough to allow migration out.

A <u>typical cause</u> of nonequilibrium metapopulations is <u>habitat fragmentation</u> caused by human development. Perhaps there was originally a large stable population (or patchy metapopulation), but then human development cut off individual population patches from each other. Organisms could not move across the human barriers to recolonize separate patches. I-75 in Florida could have divided an already declining panther population into a nonequilibrium metapopulation. Massive clearcutting can do the same. The breach is too large for organisms to cross.

<u>Lecture 22</u> **Island Biogeography**

Metapopulations can be useful to examine the impacts of habitat fragmentation on individual species of organisms. To examine the impact of habitat fragmentation on ecosystems, another approach, called **island biogeography**, is required.

To understand island biogeography, let's first define

Island: **A geographically isolated area.**

This definition includes actual islands and also, <u>in theory</u>, areas on the continents that are geographically isolated for some reason, perhaps due to habitat fragmentation. Although isolated, an island **is not a closed system**. Migration of species onto and off of an island occurs. Additionally, an island has internal growth and death terms as well as in and out terms.

Now consider Figure 22-1 where an island is shown in relation to the mainland.

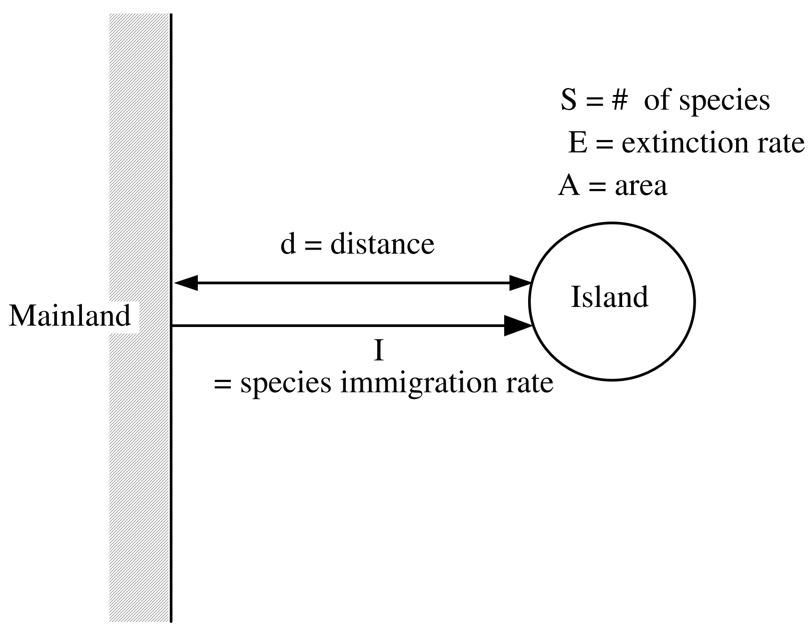


Figure 22-1 Schematic of Island and Mainland

The symbols shown in Figure 22-1 are defined as follows:

S = number of species on an island

S_{eq} = maximum equilibrium number of species on an island.

I = <u>new species</u> (not organism!) immigration rate to the island, number species/yr

E = <u>species</u> (not organism!) extinction rate on the island, number species/yr

A = island area, km^2

d = distance of island from mainland, km

A species balance around the island gives:

$$\mathbf{dS/dt = I - E}$$

where the rate of new species forming on the island due to mutations and natural selection is considered negligible (this could be a poor assumption in the long term).

The following postulates help to simplify island biogeography:

1. The number of species, S, on an island will increase to a maximum equilibrium value, S_{eq}.

This occurs when:

$$\mathbf{dS/dt = 0} \quad \text{so} \quad \mathbf{I = E}.$$

Note that at equilibrium, individual species may become extinct, but the total number of species at equilibrium, S_{eq}, remains constant.

2. S_{eq} is determined entirely by the island's area and position.
3. I has the following functionality:
   a. Increases as island area, A increases. Bigger islands provide bigger targets for new species.
   b. Decreases as distance from the mainland, d, increases. More species can travel a shorter distance than a longer distance.
   c. Decreases as S increases.

Item 3c is not necessarily intuitive. Remember that I is the **new** species immigration rate. So as the island gets more and more species, there are fewer species that are not already on the island. So the rate of new species immigration must decrease.

A possible mathematical expression for I that fulfills the above postulates could be:

$$I = f_1\left(\frac{A}{d}e^{-S}\right)$$

where f_1 is some function.

4. E has the following functionality:
   a. Decreases as island area, A, increases. Bigger islands will have larger populations, which are less susceptible to extinction.
   b. Increases as distance from the mainland, d, increases. This is due to the "rescue effect". If a species that is dying off on the island continues to get new organisms from immigration, it will not become extinct. However, as d increases, we know that I decreases so species won't be "rescued" by immigrating organisms of the same species.
   c. Increases as S increases. This means that the rate of extinction increases if there are more species simply because there are more opportunities for a species to become extinct.

A possible mathematical expression for E that fulfills the above postulates could be:

$$E = f_2\left(\frac{d}{A}S^2\right)$$

where f_2 is some function.

With mathematical functions for I and E, we can mathematically test the validity of the earlier postulates by rewriting the differential equation:

$$\frac{dS}{dt} = f_1\left(\frac{A}{d}e^{-S}\right) - f_2\left(\frac{d}{A}S^2\right)$$

Equilibrium is reached as $S = S_{eq}$ which gives:

$$f_1\left(\frac{A}{d}e^{-S_{eq}}\right) = f_2\left(\frac{d}{A}S_{eq}^2\right)$$

This equation cannot normally be easily solved for S_{eq}. However, we can see that S_{eq} is only a function of A and d. In fact, it turns out that when comparing islands of the same distance away from the mainland, S_{eq} is often simplified to the following function of A:

$$S_{eq} = cA^z$$

where: c = constant, determined experimentally

z = constant, determined experimentally

Is island biogeography useful for examining habitat fragmentation? Maybe, maybe not. But it can provide us a framework for examining systems that become geographically isolated.

Example 22.1

Easter Island, a 163 km^2 island 3,600 km off the coast of Chile, was deforested over 300 years ago by the islanders. San Cristóbal Island, one of the Galapagos Islands, has an area of 800 km^2 and is 1,000 km off the coast of Ecuador. Assume that the specific immigration rate, K_I, is the same for both islands. Additionally, assume that on Easter Island, the total species immigration rate has remained constant at 1.0 species per year and the number of species on the island has remained constant at 295 (A is km^2 and d is km). Use the following island biogeography equations:

$$I = \frac{K_I A^{0.1}}{d^{1.1}\cdot S} \qquad\qquad E = \frac{K_E d^{0.1}\cdot S}{A^{0.5}}$$

a) What is the specific immigration rate, K_I, for Easter Island?

$$I = 1 \text{ species/yr} = \frac{K_I A^{0.1}}{d^{1.1}\cdot S} = \frac{K_I(163)^{0.1}}{(3600)^{1.1}\cdot 295}$$

Rearranging for K_I gives: $K_I = 1.45 \times 10^6$

The units for K_I are species^2·yr^{-1}·km$^{0.9}$. These units are essentially meaningless because the exponents for A and d would be chosen to mathematically fit experimental data and are not necessarily physically meaningful.

b) What is the specific extinction rate, K_E, on Easter Island?

Because the total number of species on the island has remained constant, assume that equilibrium has been reached so dS/dt = I – E = 0. Therefore, I = E = 1 species/yr.

$$E = 1 \text{ species/yr} = \frac{K_E d^{0.1} \cdot S}{A^{0.5}} = \frac{K_E (3600)^{0.1} \cdot (295)}{(163)^{0.5}}$$

Rearranging for K_E gives: $K_E = 0.0191$ yr^{-1}·km$^{0.9}$

c) If the specific extinction rate, K_E, on San Cristóbal Island is 0.041, predict the equilibrium number of species on the island.

At equilibrium, I = E so:

$$\frac{K_I A^{0.1}}{d^{1.1} \cdot S_{eq}} = \frac{K_E d^{0.1} S_{eq}}{A^{0.5}}$$

Rearranging and solving for S_{eq} gives:

$$S_{eq}^2 = \frac{K_I A^{0.6}}{K_E d^{1.2}} = \frac{1.45 \times 10^6 (800)^{0.6}}{0.041 (1000)^{1.2}}$$

S_{eq} = 700 species

This is larger than on Easter Island which makes intuitive sense because the island is bigger and closer to the continent.

<u>Lecture 23</u> **Diversity and Stability**

Diversity and stability are key issues for ecosystems. The words are used extensively, but rarely properly because the concepts are widely misunderstood. In this lecture, we will attempt to define diversity and examine it within the context of energy flow.

One simple definition for ecological diversity used by ecologists is:

Species richness: The number of species in an ecosystem or region.

<u>How would you determine the species richness of an ecosystem</u>?

Count the number of species observed. The resulting count would be a function of:

1. <u>Size of geographic area</u> of interest. As Size ↑, Species Richness ↑.
   This makes intuitive sense: more area, more species.
2. <u>Length of time</u> spent counting. As Time ↑, Species Richness ↑.
   This is not necessarily intuitive.
3. <u>Total number of organisms</u> counted. As Total ↑, Species Richness ↑.
   This is also not necessarily intuitive.

To understand why the time spent counting and the total number of organisms counted affects the species richness measurement, let's conduct the following thought exercise.

You decide to count the species in a <u>specified geographical area</u>. You do this two different ways.

1. Count the number of species observed and number of organisms per species for 8 hrs.
2. Do the same as in 1. but for 16 hrs.

The results of the 8-hr count are:

S_1 = number of species

N_1 = total number of organisms counted where:

$$N_1 = \sum_{i=1}^{S_1} N_i$$

N_i = number of organisms per each species

The results of the 16-hr count are S_2 and N_2.

<u>What is the expected relationship between N_1 and N_2</u>?

$N_2 \geq N_1$. If you have more time to count, you will see organisms that you missed during the first counting period. This doesn't include those organisms that you accidentally double count.

<u>What is the expected relationship between S_1 and S_2</u>?

$S_2 = S_1$. The total number of species in a fixed geographical area should be constant, regardless of how long you count. However, your measurements will show $S_2 \geq S_1$. The reason for this is that your <u>measurement</u> is only an <u>estimate of the true number</u> of species. The probability that you will count a species increases as the number of organisms in that species increases and as the time you spend counting increases. The reason is practical – we are simply unable to find all the organisms in an ecosystem in a short period of time. The longer we count, the closer our measurement should come to the actual number of species in the ecosystem.

Ecologists recognized this counting problem and developed equations to normalize the number of species measured in an area by the total number of organisms measured. These equations allow you to compare species richness numbers from different studies on an equal basis.

One equation that does this is the **Hurlbert-Simberloff** equation:

$$E(S) = \sum_{i=1}^{S} \left\{ 1 - \left[\binom{N - N_i}{n} \div \binom{N}{n} \right] \right\}$$

Where: $E(S)$ = expected number of species in a standardized sample of size n (this is the species richness)

S = number of species measured in the actual sample

N = total number of organisms measured in the actual sample

N_i = the number of organisms of species i

n = the standardized sample size

$$\binom{N}{n} = \frac{N!}{n!(N-n)!}$$

$N!$ = factorial = $N(N-1)(N-2)...(1)$

Using this equation, we can take any data set from field study and determine the expected number of species E(S) for a standardized sample size and then compare species richness.

Diversity Indices

The species richness is only one way to measure diversity, and not necessarily the most useful. Diversity should consider both the number of species AND the number of organisms per species. Ecologists have developed two types of indices to measure diversity that consider both items.

1. **Dominance indices**
2. **Information statistics indices**.

Dominance indices provide a measure of diversity that gives more weight to common, or dominant, species. The **Simpson** dominance index is one simple example:

$$D = \sum_{i=1}^{S} p_i^2$$

Where: D = dominance measure

p_i = proportion of individuals of species i to the total number of individuals in the system, N_i/N

S = number of species in the system

This is a somewhat strange index. D can be interpreted as:

The probability of any two individuals drawn at random from an infinitely large community belonging to the same species.

This means that as D increases, diversity actually **decreases**! This index is simple to calculate, however, so to make intuitive use of it, use 1 – D or 1/D so that larger numbers mean greater diversity.

Information Statistics indices make more intuitive sense. As the index value increases, so does the diversity of the system. The **Shannon and Weaver** information statistics index is commonly used. It is:

$$H' = -\sum_{i=1}^{S} p_i \ln p_i$$

This index assumes all species are represented in the sample and that the sampling was random. The negative sign takes care of the negative arising from taking the natural log of a number less than 1.

This index is intuitive, i.e., it increases as diversity increases, it accounts for different abundance levels and it is maximized when all species are equally abundant. This also makes intuitive sense: that diversity increases not only as the number of species increases but also as the number of organisms of each species increases. The maximum diversity is:

$$\mathbf{H_{max} = \ln S}$$

which occurs when all species are equally abundant (p_is are all equal).

Biological Causes of Diversity

As we will see, there are thermodynamic reasons for diversity. However, thermodynamics only predicts what should happen. The following biological mechanisms help facilitate the thermodynamic reactions.

Competition.

There are limited resources in an ecosystem. Only the most competitive organisms will survive. Competition, then, works to decrease diversity as competitive organisms attempt to dominate the system. Unlike economic systems, however, there are not government bodies in ecosystems to regulate the dominance of the most competitive organisms. There are regulating influences, however, as mentioned next.

Predation.

Predation increases diversity because competitive species don't get the chance to dominate an area: predators eating them gives other organisms a chance. This theory gives rise to the concept of a keystone species.

Keystone species: A species that ensures the diversity of an ecosystem because of its predation on and/or other interaction with a number of species.

Removal of a keystone species can cause an entire ecosystem to collapse with only the most competitive prey remaining and a significant reduction in diversity.

The keystone species concept is important for predicting the effect of human activities. There are many endangered species on earth. Some of these species may be keystone species. If they are lost, we can expect significant changes in the remaining ecosystem. Should we save just the keystone species? No, because we don't know what the keystone species are in most ecosystems until after they are gone and the ecosystem collapses.

Stability

What do we mean by ecosystem stability?

1. **There appears to be no changes with time (steady-state)**.
2. **The ecosystem can resist change**.
3. **The ecosystem can return to the same state after a perturbance**.

These traits are also indicative of **chemical equilibrium**, so let's use chemical equilibrium as a model for ecosystem stability.

Recall that at chemical equilibrium, the reaction system **has reached the lowest possible free energy.** The equilibrium point can be changed only by adding energy to the system in some manner.

Proposal: Analogous to a chemical reaction system, an ecosystem will be considered stable when it has reached some lowest possible energy point for the configuration allowed.

We have a slight problem analyzing this proposal. Ecosystems are wide open to energy and mass input. In chemical systems, adding energy or mass changes the equilibrium state. Wouldn't the same be true in ecosystems? Yes. However, if the inputs and outputs are relatively constant, we can determine a steady-state pseudo-equilibrium state and assume that it has properties similar to a true equilibrium state.

Diversity Versus Stability: Entropy

Does diversity promote stability?

To answer that question, recall from chemistry the following equation:

$$G = H - TS$$

where:
- G = Gibbs free energy (same as earlier)
- H = enthalpy (essentially the thermal energy released or required by a reaction)
- S = entropy (in this case, not number of species)
- T = temperature (in Kelvin).

Equilibrium is achieved when G is minimized. Furthermore, it is thermodynamic fact that:

A spontaneous reaction must lead to a decrease in G.

Mathematically:

$$G_2 - G_1 = (H_2 - H_1) - T(S_2 - S_1) < 0$$

or $$(H_2 - H_1) - T(S_2 - S_1) < 0$$

However, during a spontaneous reaction, <u>H may increase or decrease</u>. In other words, spontaneous chemical reactions may either release thermal energy or consume thermal energy. Therefore, <u>for our equation to hold, S must always increase</u> as stated in the 2nd Law of Thermodynamics:

For every spontaneous reaction that occurs, entropy increases.

To understand this statement, we must define entropy. One useful definition is:

Entropy: A measure of the randomness of a system.

Mathematically, entropy has been defined as follows:

$$\mathbf{S = k\ln\Omega}$$

where: k = Boltzmann constant = 1.381×10^{-23} J/K

Ω = number of different, equally probable arrangements of the components of the system of interest.

Since k is a constant, <u>S increases when Ω increases</u>, or when the number of possible arrangements of the system increases. In other words:

During a spontaneous reaction the total number of possible arrangements in the system increases.

In a sense, species of organisms are simply how elements in an environmental system are arranged. If so, diversity is conceptually analogous to Ω. Then logically:

1. As ecosystem diversity increases,
2. Ecosystem free energy decreases, and
3. The ecosystem becomes more stable.

Diversity is critical for ecosystems because it leads to stability.

Another thermodynamic fact must be considered, however, to deal with the fact that ecosystems are open to energy input.

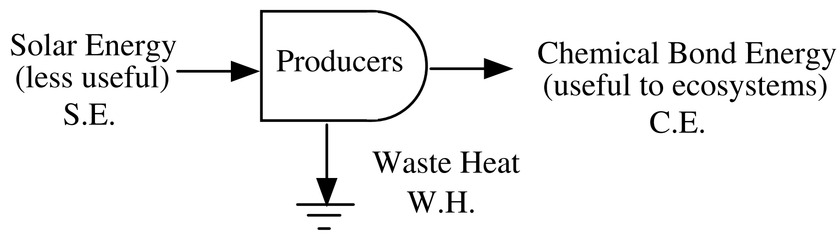
The entropy of a system can only be decreased by adding energy to the system.

So adding energy to an ecosystem, from sunlight, hurricanes, or glacial movement (gravity), etc., can reduce system entropy and therefore decrease diversity. For example, diversity is pretty low in an area that has just recently been covered with lava from a volcano. Energy from within the earth caused that diversity loss.

With this in minds, we may make one last postulate:

Ecosystems are constantly moving toward a state of greater diversity, but large energy inputs may disrupt the ecosystem and temporarily decrease diversity.

In earlier discussions we examined the issue of increasing the usefulness of energy. For example, plants take the less useful solar energy and convert it to more useful chemical bond energy. Figure 23-1 summarizes how that works from an energy standpoint. The key is that waste heat must be generated in the process as specified by the 2nd Law of Thermodynamics.



At Steady-State: S.E. = C.E. + W.H.

Figure 23-1 Energy Balance and the 2nd Law of Thermodynamics

This helps to explain an apparent contradiction. We would expect the greatest energy input into the tropics and large energy inputs can decrease entropy. Therefore, shouldn't the tropics be less diverse compared to other geographical regions that receive less energy? The answer is no – the tropics should be more diverse for two reasons.

1. More available energy will lead to a greater variety of photosynthetic organisms (or least, more variety is thermodynamically preferred – there may be reasons why any given ecosystem may have a reduced variety of photosynthetic organisms)
2. The more solar energy that is converted to useful chemical bond energy, the longer and more diverse the food chain must be.

In other words, a larger energy input produces more primary producers allowing the ecosystem to then "fall apart" via food chains as energy flows through the system. The 2nd Law was obeyed in accordance with Figure 23-1 when the primary producers first captured the energy and then was obeyed again via the food chain.

<u>Lecture 24</u> **Concepts of Industrial Ecology**

We are now done looking at "pure" ecology. Now we will try to take the concepts that we have learned and use them to help us better understand the impacts of engineering activities and also to help us be better engineers.

Consider the following equation:

$$EI = P \cdot SLpc \cdot EIpsl$$

where: EI = overall environmental impact of human activities in an area

P = human population in an area

SLpc = standard of living per capita

EIpsl = environmental impact per unit of standard of living

To reduce the overall environmental impact of our activities requires an understanding of each term and how, in particular, engineers affect each term.

<u>Population</u>:

As individuals, our personal impact on human population growth will be determined by our own personal choices. Ironically, as we saw in Lecture 16, engineers as a group have been part of the reason for explosive human population growth, and it has nothing to do with the average sexual prolificacy of engineers. At this point, all indications are that the human population of the planet will continue to increase exponentially. So until data begin to suggest otherwise, this term must be assumed to increase with time.

<u>Standard of Living per capita</u>:

Engineers have always worked to improve the standard of living of a society. Think of the basic things that many of us take for granted:

1. Clean drinking water.
2. Electricity.
3. Computers.
4. Transportation systems.
5. Leisure time.
6. etc.

The standard of living around the world is not uniform, however. Many people have a significantly lower standard of living per capita than we have in Canada. We may assume that those with a lower standard of living will want to increase their standard of living. We may also assume that those with a higher standard of living will also want to increase their standard of living. People, in general, want to live more comfortable lives.

So far two of the terms in our equation are expected to increase. Unless the third term decreases, we will see an overall increase in the environmental impact of human activities.

Environmental Impact per unit of Standard of Living:

If we want to decrease our overall environmental impact, we must decrease this term. Engineers have historically reduced this term, although the reason wasn't usually for environmental purposes. As discussed in Lecture 2, more efficient processes save money. Engineers have designed more efficient processes and as a side-effect have reduced environmental impacts. With the first two terms of the equation continuing to increase, however, engineers must accelerate efforts to decrease the environmental impact per unit of standard of living. Can we actually decrease EIpsl fast enough to account for P and SLpc increases?

Industrial Ecology

What is industrial ecology?

One useful definition is:

Industrial Ecology: An approach to the design of products and processes that evaluates such activities through the dual perspective of product competitiveness and environmental interactions.
(Graedel and Allenby, 1995)

In other words, industrial ecology can help us continue to decrease the environmental impact per standard of living.

Note a couple of points about this definition:

1. Product competitiveness is key. We must continue to produce the best products for the lowest cost.
2. Environmental interactions are important because:
    a) Ecological resources have an economic value > 0.
    b) The costs of damaging the environment increase product costs.
    c) Long-term sustainability of raw materials is required to maintain reasonable raw materials costs.

While this is the definition by the engineers who helped invent the field of industrial ecology and certainly wrote the book (literally), I like to think of industrial ecology as the application of ecological principles to engineered systems, in particular ideas like conservation of mass and energy, and designing systems to use the "waste" from one process as the raw material for another process. Also the ecological concepts that effects can arise far from where the cause occurred because of the interrelatedness of ecosystem activities. Applying these principals can significantly improve the quality of the engineering we do.

Life Cycle Assessment

Two important tools of industrial ecology are:

1. Pollution Prevention

2. Life Cycle Assessment (LCA)

We discussed Pollution Prevention in Lecture 2 so we will discuss LCA here. One **definition for LCA** is:

Examination of the entire life cycle of a product from raw material to disposal.

Consider Figure 24-1. It is a generalized version of Figure 2-1 for any given engineering process. We noted that environmental impacts could arise from the product, from raw material production, from energy production and from residuals disposal. Now expand the concept in Figure 24-1 to include the entire life cycle of a product, starting from the environment (the ultimate the source of all raw materials and energy) and ending with the environment (the ultimate disposal site for all products and residuals). Figure 24-2 presents a simplified version of a product life cycle. Notice that Figure 24-2 is essentially composed of a number of Figure 24-1-type processes linked together. The key point is that for LCA, we consider everything related to a product in both time and space.

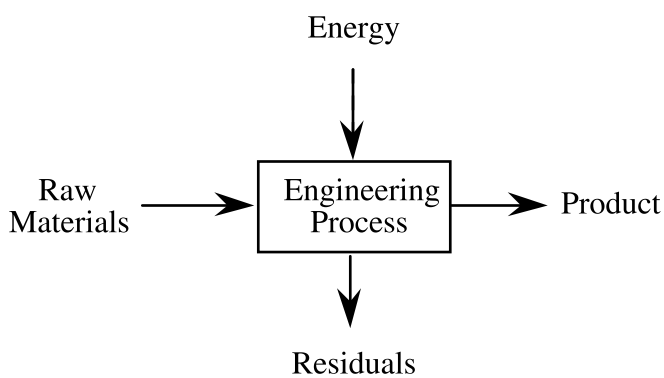


Figure 24-1 Generalized Schematic for Engineering Process

LCA consists of three stages:

1. Inventory analysis.
2. Impact analysis.
3. Improvement analysis.

Inventory Analysis.

This stage consists of conducting **mass** and **energy** balances for the product over **its entire life cycle**. Conduct an inventory analysis as follows:

1. Clearly identify the final product of interest.

Potato chips, roads, chemicals, buildings, clothing, etc. **LCA can be applied to any engineered product.**

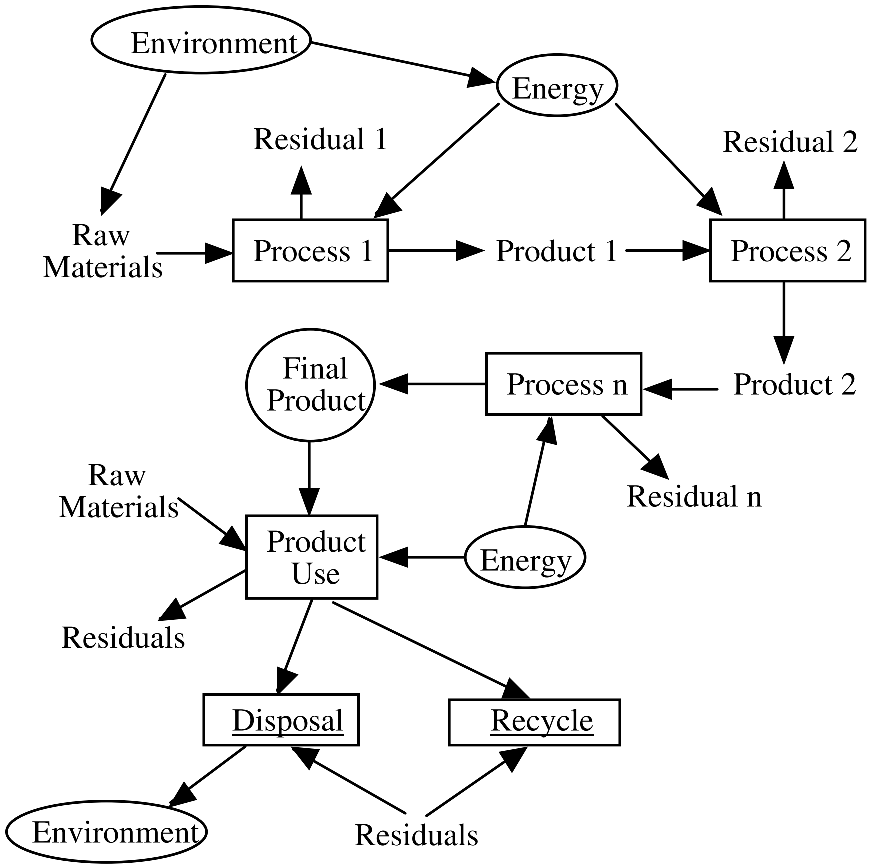


Figure 24-2 Generalized Life Cycle for a Product

2. <u>Identify</u> all of <u>the processes</u> involved in <u>producing</u> this product and the mass and energy requirements of production.

Go all the way back to the virgin materials and basically develop a detailed Figure 24-2.

3. <u>Identify</u> the <u>mass and energy requirements</u> of the product <u>throughout its life</u>.

This means examining the product use section of Figure 24-2. For example, consider a building. A series of engineering processes are required to convert raw materials into a building. The building as a product has a certain life. During its life, energy is certainly required for a building. Additional raw materials are also required for maintenance (paint, floor wax, cleaning materials, etc.) In this section of the inventory analysis, you will identify the mass and energy required to properly use the product (in this case a building) throughout its useful life.

At this point, pay particular attention to the residuals. The residuals are certainly not the only aspect of the life cycle that will cause an environmental impact. We have seen several examples where product use as intended caused problems, as did product disposal after use. But residuals provide opportunity for pollution prevention (produce fewer residuals) and developing systems to use residuals from one process as a feedstock for another.

4. Identify the ultimate fate of the product.

What happens to the product after it is used?

  a. Consumed?
  b. Disposed? If so how?
  c. Recycled? If so how?

Consider a building again. What happens to a building when it is demolished to make way for another building? Do its parts end up in a landfill (disposed), or was the building designed so that its parts could be recovered and reused in another application, or even building (recycled)?

Impact Analysis

Impact analysis basically consists of answering two difficult questions:

  1. How can the environmental impact of a product be determined?

This requires a knowledge of ecology and toxicology as well. You should have an appreciation of how difficult determining the environmental impact will be. We now have plenty of examples of where to look for impacts which we should apply to new products, but we continue to learn more about ecosystem complexity and function, and how our impacts to one part of the ecosystem may extend far beyond our original expectation.

  2. How can different environmental impacts be compared?

How do you compare, for example, the impact of discharging contaminants into a water body with the impacts caused by the treatment process that removes contaminants? At what point does the impact of improved treatment outweigh the benefit of the reduced discharge concentration?

Impact analysis is rarely done by engineers alone. Specialists in ecology, biology, toxicology, risk assessment, etc. must also be involved.

Improvement Analysis

Improvement analysis consists of determining and taking the steps needed to minimize the overall impact of the product. Another name for the activities conducted at this point is **Design for the Environment (DFE)**. This goes beyond pollution prevention. The types of questions to be asked and answered at this stage include:

1. Can the product be made with less toxic, recyclable, and/or renewable materials?
2. Can the product be made with less material?
3. Can extractions be conducted more efficiently?
4. Can the product be designed to be recycled after use?
5. Can residuals serve as raw materials for other processes?
6. Can the nature of the residuals be changed so that they can serve as raw materials for other processes?

7. etc.

Improvement analysis, like inventory analysis, is conducted by engineers. For example, who but a structural engineer can decide whether a new, environmentally friendly building material (such as pressed-sawdust beams or bricks made from incinerator ash) will meet load requirements? Who but a chemical engineer can decide whether a less toxic paint formulation will provide appropriate rust protection? Improvement analysis is where the really creative opportunities in engineering arise.

Lecture 25 Infrastructure

An important product of engineering activities: **infrastructure**.

What is infrastructure?

Infrastructure: Physical systems supporting human activities.

Examples of engineered infrastructure include:

a. Transportation systems. Roads, bridges, rails, canals.
b. Structures. Houses for people, buildings for industrial and other activities.
c. Water collection, treatment and distribution systems.
d. Wastewater collection and treatment systems.
e. Stormwater collection and flood control systems.
f. Solid waste disposal facilities.
g. Dams for water storage, power generation, and flood control.
h. Power generation and distribution facilities.

Infrastructure is required by human populations to do the following things:

1. Improve quality of life (houses, electricity, reduced disease, etc.)

   All of the examples listed above improve quality of life.

2. Support industrial activities and the economy.

   Items a, b, c, g and h directly support industrial activities. However, d, e and f indirectly support industrial activities by removing wastes or excess water from industrial sites.

3. Protect the environment.

   Items d and f directly protect the environment, although the treatment of stormwater prior to disposal also protects the environment. The rest of the items can significantly impact the environment, depending on how they are implemented. This shouldn't be a surprise – if the environment provided everything exactly suitable for human use, there would be no need for constructed infrastructure.

Why Environmental Protection is Important

Most engineered infrastructure is constructed entirely for the benefit of humans. Even those infrastructure items that protect the environment were originally constructed to protect humans. Raw wastewater running through the city streets poses a tremendous health hazard – hence the need to collect wastewater to be discharged elsewhere. Wastewater discharged into waters used as drinking water supplies poses another human health hazard – hence the need to treat wastewaters before discharge. Even wastewaters that do not appear to have toxic contamination may sufficiently disrupt the receiving water ecosystem that fish are killed, fish that otherwise would have been human food – another reason to treat wastewaters before discharge.

Constructed infrastructure that deliberately protects the environment makes good sense – we are really protecting ourselves. Reducing the environmental impact of all infrastructure is critical, however, to continue to protect ourselves. This is because the environment provides a natural infrastructure that is crucial to supporting human activities.

While the engineered infrastructure noted supports modern human populations, **life-support systems** are nevertheless also required. Buildings, roads and electricity are not readily digested by humans. Food must be produced from agricultural systems. While not typically thought of as engineered infrastructure, modern agriculture is highly energy intensive and depends on the extensive use of engineered products such as pesticides, fertilizers and mechanical equipment. The sustainability of suitable agricultural lands depends primarily on the agricultural practices used, but also depends on how well the environment is protected.

Natural environments also provide important necessities of our human life-support system. Current engineered infrastructure for treating waste materials does not return the material to pristine condition. For example, even with catalytic converters, automobiles emit significant masses of pollutants. Most wastewater treatment plants remove only a fraction of the incoming pollutants (the fraction is typically high, >90%, but that still leaves pollutants in the water). We implicitly assume that the natural environment will finish treating the air and water for us. Additionally, we depend on the natural environment to recycle water (through the hydrological cycle) as well as carbon, nitrogen and other important compounds (via the biogeochemical cycles).

Since the beginning of the Industrial era we have routinely ignored the value of natural environments to supply human necessities, but nevertheless depended on natural environments to continue to provide these necessities. The non-engineered, hidden infrastructure of natural environmental systems is admittedly difficult to understand and quantify, as should be even clearer now that we have applied quantitative techniques to try to describe natural ecosystems. That does not make it less valuable. Engineered infrastructure, even if constructed only to benefit humans, must also consider environmental protection. Inadvertent destruction of natural systems decreases the life-support capacity for human activities, and that is not beneficial.

Examining Infrastructure from an Industrial Ecology Standpoint

Although underpinning all of modern society, constructed infrastructure has only recently been approached from an industrial ecology standpoint. Certainly, the environmental impacts of dams and flood control structures, the emissions from transportation systems and coal-fired electricity generating stations, and the habitat destruction of housing developments and industrial facilities have been identified. But industrial ecology goes beyond simply identifying what is undesirable. It provides techniques for reducing the environmental impact, while also saving money.

Construction is a universal engineering process required to produce infrastructure. Figure 25-1 shows a schematic of the construction process with the raw materials and energy requirements. This simple schematic shows that the engineering processes required to construct infrastructure can have significant impacts on the environment. The raw materials must be mined, which can be very disruptive to the environment if not conducted thoughtfully. The processes that convert the raw materials to useful feed products: iron ore to steel, for example, use tremendous amounts of energy and produce large quantities of residuals. Once the feed products are produced, they must be transported to the construction site.

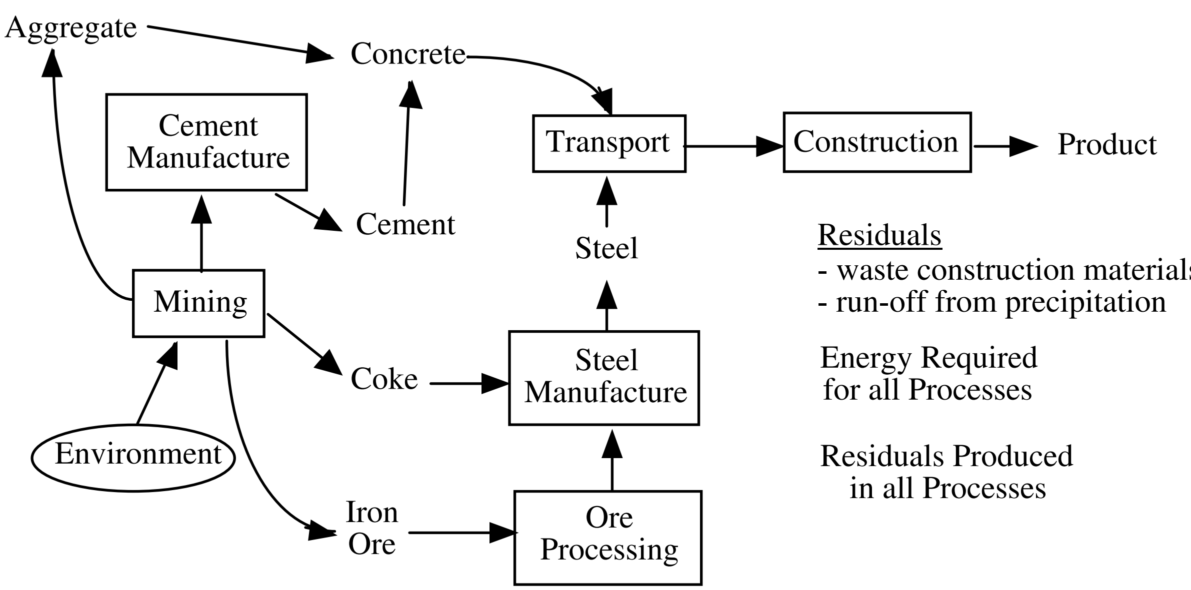


Figure 25-1 Schematic of Engineering Processes: Construction

Significant impacts to the environment occur during construction too. The ground surface is usually greatly disturbed. Precipitation can then lead to significant erosion, which removes a valuable resource (soil) while damaging the construction site environment as well as locations downstream where the soil is redeposited. Furthermore, all waste materials that are generated must be disposed.

A complete LCA inventory analysis on the construction process will show that many materials are needed, much energy is used and many residuals are produced. The environmental impact component will show the potential for large environmental impacts. The improvement analysis, however, can show the potential to greatly reduce impacts. The habitat destruction caused by mining, for example, can be temporary if restoration is planned for the mine from the beginning. The tailings produced during mineral processing can be used to produce "paste" – a product that can be used to provide structural support in the mine itself. The large quantities of residuals formed and large amounts of energy needed can be minimized by using the most efficient processes possible.

Additional possibilities for improvement include identifying other industries and activities that would use the residuals produced as raw materials. Furthermore, we should carefully look to the residuals of others industries to see if these can be used as <u>raw materials</u> for construction. Fly ash from electricity generating facilities, for example, can be used in the manufacture of high performance concrete. Many other residuals are also being evaluated for use as raw materials for construction processes, following the ecological principle that mass is conserved and recycled.

Lecture 26 **Water and Humans**

The next number of lectures will examine water. There are three reasons for this. First, water is a key component of every ecosystem and also an entry point for environmental impact in many ecosystems. Second, the infrastructure we use for water provides some excellent opportunities to conduct improvement analysis using industrial ecology principles. Finally, my research is in the water area and I find it interesting (perhaps you will too).

Natural Hydrological Cycle

A schematic of the natural hydrological cycle is shown in Figure 26-1. The boxes indicate forms of water and the arrows indicate processes that move water and direction. A key point is that water moves uphill – without pumps.

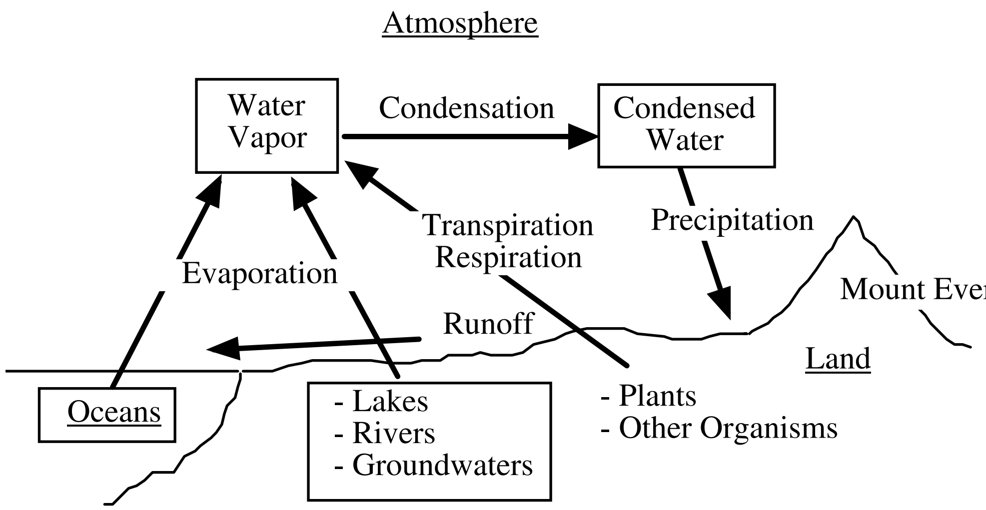


Figure 26-1 Schematic of Natural Hydrological Cycle

Example 26.1

a. How much energy is required to move 1 kg of water uphill, from sea level to the top of Mount Everest, at over 8,800 m above sea level?

The energy required is equal to the potential energy that water has at the top of Mount Everest versus the potential energy of water at sea level. For convenience, define the potential energy of 1 kg of water at sea level as 0 J. At the top of Mount Everest:

P.E. = mass x acceleration x distance

Assume that the acceleration due to gravity is 9.81 m/s^2 (true at sea level, but not at the top of Mount Everest) and that the distance traveled is 8,800 m. Then:

P.E. = 1 kg x 9.81 m/s^2 x 8,800 m = 86,328 J = 86.3 kJ

b. If the water must be moved by the natural hydrological cycle, how much energy is required?

The only way to move water uphill naturally is to evaporate it. The energy required to evaporate 1 kg of water is approximately 2,255 kJ, over 26 times that needed to simply move water 8,800 m straight up. The 86.3 kJ is still required as well.

Example 26.1 suggests that a tremendous amount of solar energy is required to move water uphill. Much of the energy required for evaporation is recovered, however, when the water condenses. Condensation releases the same amount of energy as required for evaporation. The energy released when water vapor condenses over Mount Everest is not directly available for evaporating more water at sea level, however. So, from a practical standpoint, the full energy requirement is needed at the point of evaporation.

Huge amounts of water are moved. Niagara Falls, for example, is approximately 50 m high. Water at the top of the falls has a potential energy of 490 J/kg compared to water at the bottom. Approximately 5,000 kg of water must fall over Niagara Falls to provide the energy needed to evaporate 1 kg of water (assuming 100% energy efficiencies). The actual flow over the falls is approximately 5.7×10^6 kg/s, providing plenty of potential energy to evaporate over 1,000 kg of water per second. On the other hand, all of that water was first 'pumped' up hill using solar energy.

Solar energy drives ecosystems as we discussed earlier in the course. Solar energy also drives the physical processes, such as water movement, required for ecosystems to function in addition to the physical processes that humans have harnessed directly for our own use.

Human Hydrological Cycle

The traditional human hydrological cycle is shown in Figure 26-2. Solar energy still moves water upstream, but is not shown because it occurs naturally under no influence of human technology. The production of hydroelectric power is not shown in Figure 26-2. That occurs by interrupting the runoff process shown in Figure 26-1. Where possible, we take advantage of gravity to move water, but that can only be done when we are moving water downhill. To fully meet our needs, we have to input energy to pump the water to where we need and want it.

Water has many uses, but one that is key is for drinking. Drinking water must be free of contaminants that could be deleterious to human health. Historically, the most important contaminants were pathogenic organisms. Bacteria such as *Vibrio cholera* and *Eschericia coli* O157:H7 are waterborne and deadly. Other pathogenic organisms include viruses and protozoa. Although all pathogens are naturally occurring, the concentration of these organisms in a water will depend strongly on human activities.

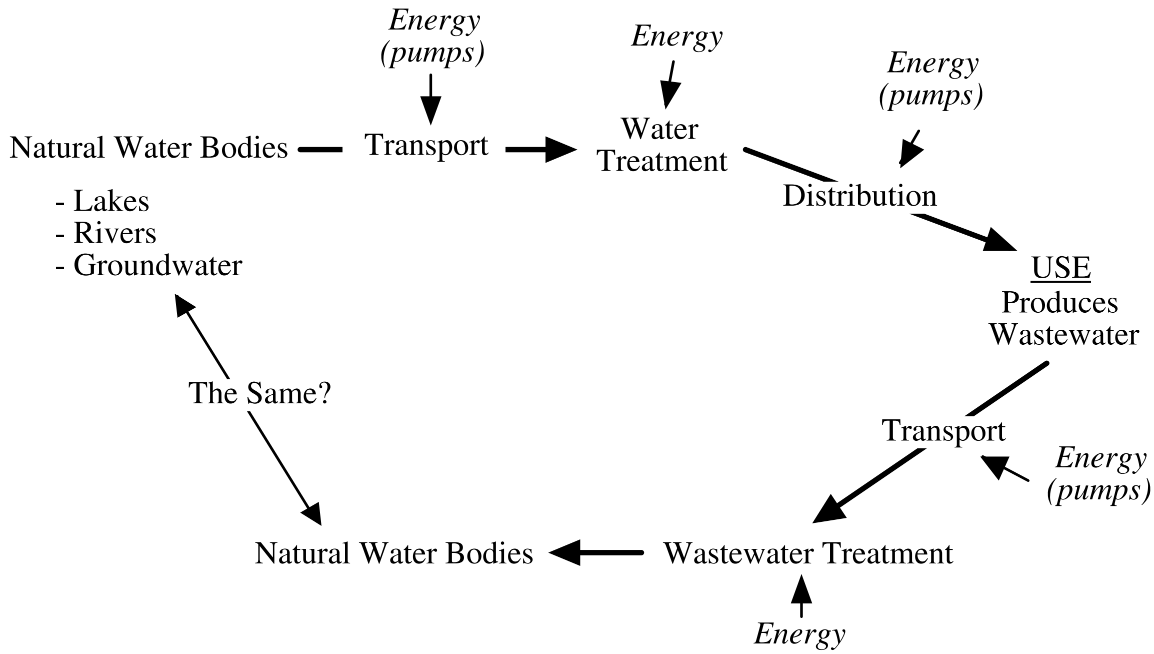


Figure 26-2   Human Hydrological Cycle

Other contaminants of concern in drinking water include metals, toxic organic compounds, and most recently, endocrine-disrupting compounds. Although some of these contaminants occur naturally, most end up in water supplies due to human activities.

Historically, our sources of drinking water are natural water bodies, as shown in Figure 26-2. To achieve drinking water quality at the USE stage, we must treat the water, as indicated. A number of processes are used for treating water to be used for drinking including sedimentation, filtration, membranes and disinfection. These processes are discussed in much greater detail in the fourth year class CIV540. Although gravity is used extensively in water treatment (settling for example), energy will always be required to achieve drinking water quality standards.

Figure 26-2 shows that wastewaters are discharged to natural water bodies. These are the same natural water bodies from which we obtain the water that we will use for drinking. It is no surprise, then, that natural waters must be treated before we drink them. Typical municipal wastewaters contain BOD, nitrogen and phosphorus. Municipal wastewaters also contain human pathogens, metals, toxic organics, and endrocrine disruptors. Wastewaters are classic residuals where for the most part we treat them sufficiently to throw them away. This using violates the principles of industrial ecology. We can do much better.

Lecture 27 **Biochemical Oxygen Demand**

Wastewaters typically contain concentrations of organic constituents. Often, these constituents are not inherently bad for the environment. For example, humans and other organisms have always excreted their waste materials into the environment and natural processes, typically involving detrivores, recycle these materials. So what is the big deal with non-toxic organic constituents in wastewater anyway? The issue, once enough humans are living together in one spot and discharging wastes into limited waterways is:

Biochemical Oxygen Demand (BOD)

Definition:

The amount of oxygen required to biodegrade a given quantity of dissolved material by aerobic microorganisms living in receiving water bodies.

Units = mg O_2 per liter.

Note that the microorganisms consuming the biodegradable material are natural parts of the ecosystem doing what such detrivores do – converting another organism's waste into something useful.

BOD does not measure one specific compound, but rather the sum of all the biodegradable compounds in a wastewater. Additionally, BOD is reported in units of mg O_2 per liter because, as we will see next lecture, dissolved oxygen is a constituent of great concern in the many receiving waters.

Some, perhaps most, wastewaters contain specific contaminants that are particularly troublesome in the environment. Measurements for these contaminants must be conducted in addition to BOD. BOD is used primarily to describe as one unit all of the non-toxic organic compounds that may be dissolved in a wastewater. A contaminant does not have to be toxic, however, to significantly impact the environment. If all the dissolved oxygen in a receiving water is used to consume BOD, there will be none left for the other organisms in the ecosystem, such as fish.

Theoretical BOD

If we know the chemical formula of the compound of interest, we can calculate the BOD theoretically. The theoretical oxygen demand or ThOD requires only a balanced chemical reaction.

Example 27.1

Calculate the BOD of glucose in solution at 500 mg/L. The balanced equation is:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

This equation tells us that 6 moles of oxygen are required to degrade 1 mole of glucose. To determine ThOD:

$$\frac{500 \text{ mg glucose}}{\text{liter}} \times \frac{1 \text{ mmol glucose}}{180 \text{ mg glucose}} = 2.78 \text{ mmol glucose/liter}$$

$$\frac{2.78 \text{ mmol glucose}}{\text{liter}} \times \frac{6 \text{ mmol } O_2}{1 \text{ mmol glucose}} = 16.7 \text{ mmol } O_2\text{/liter}$$

$$\frac{16.7 \text{ mmol } O_2}{\text{liter}} \times \frac{32 \text{ mg } O_2}{\text{mmol } O_2} = 533 \text{ mg } O_2\text{/liter}$$

So 500 mg glucose/liter requires 533 mg oxygen/liter to be consumed. Therefore, the ThOD, is 533 mg/L.

Example 27.2

Calculate the theoretical BOD for X mg/L of sewage if the general formula for organics in domestic wastewater can be assumed to be $C_{10}H_{19}O_3N$. Use the following balanced equation.

$$2\ C_{10}H_{19}O_3N + 25\ O_2 \rightarrow 18\ CO_2 + 2\ NH_4^+ + 2\ HCO_3^- + 14\ H_2O$$

The theoretical BOD would be:

$$\frac{X \text{ mg } C_{10}}{\text{liter}} \times \frac{1 \text{ mmol } C_{10}}{201 \text{ mg } C_{10}} = 0.005X \text{ mmol } C_{10}\text{/liter}$$

$$\frac{0.005X \text{ mmol } C_{10}}{\text{liter}} \times \frac{25 \text{ mmol } O_2}{2 \text{ mmol } C_{10}} = 0.062X \text{ mmol } O_2\text{/liter}$$

$$\frac{0.062X \text{ mmol } O_2}{\text{liter}} \times \frac{32 \text{ mg } O_2}{\text{mmol } O_2} = 1.99X \text{ mg } O_2\text{/liter}$$

The ThOD is 1.99X mg/L.

From a practical standpoint, how would X be determined? It must be measured. Since a measurement is required, why not measure BOD directly?

Examples 27.1 and 27.2 are for <u>theoretical</u> BOD. The actual measured BOD will be less than the ThOD because:

1. Organisms do not oxidize every molecule completely. Some of the carbon is used to synthesize new cells and isn't oxidized
2. Some organic material is not readily biodegradable, e.g., lignin and cell wall material.

Measuring BOD

BOD is unlike many contaminants of environmental concern because it is not measured directly. Instead, oxygen consumption is measured and BOD is reported from that measurement. Perhaps the easiest way to understand this is by considering the traditional BOD measurement technique.

Traditionally, BOD was measured by taking a sample of the wastewater of interest, placing it into what is called a BOD bottle (which is approximately 300 mL in volume), and filling the bottle all the way to the top with dilution water. The dilution water contains some nitrogen and phosphorus needed by microorganisms for growth and a small inoculation of bacteria that will actually consume the BOD. The dissolved oxygen concentration of the diluted sample is measured and then the bottle is closed, leaving absolutely no air bubbles. The bottle is incubated in the dark at 20°C for 5 days after which the top is removed and the dissolved oxygen concentration is measured again.

<u>What is happening in the bottle during the 5-day incubation period</u>?

Figure 27-1 shows an idealized schematic of what happens to the BOD (written as L).

L: another term for BOD, mg O_2/L

The initial BOD (L_o) is consumed with time by the bacteria that were added with the dilution water. The removal of BOD in this bottle can be modeled with an exponential decay function as:

$$L = L_o\,[\exp(-k_1 t)]$$

where k_1, the decay constant, is in units of day^{-1}.

The rate of BOD removal, which is the slope of the L curve in Figure 27-1, can be determined by taking the derivative of L with respect to time:

$$\frac{dL}{dt} = -k_1 L$$

Recall that the dissolved oxygen concentration is measured, not L. To determine BOD, we must relate oxygen consumption to L. Figure 27-1 shows the curve representing the oxygen consumed during the BOD test (y)

y: the amount of oxygen that has been consumed at any time, mg O_2/L

Because both y and L are in the same units, y is related to L as follows:

$$y = L_o - L$$

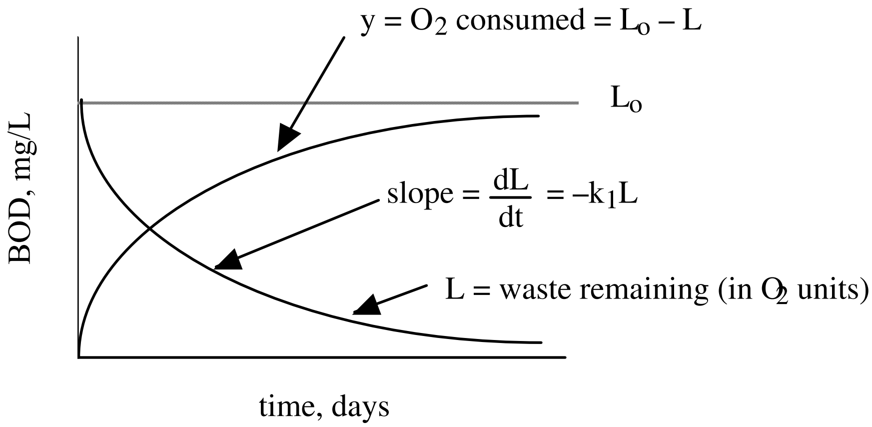


Figure 27-1 BOD Removal and Oxygen Consumption in BOD Bottle

Substituting from our equation for L we get:

$$y = L_o\,[1 - \exp(-k_1 t)]$$

The rate of oxygen consumption in the BOD bottle can be calculated from the derivative:

$$r_{O_2,\,BOD} = \frac{dy}{dt}$$

Differentiating the y equation with respect to time gives:

$$r_{O_2,\,BOD} = \frac{dy}{dt} = k_1 L_o \exp(-k_1 t)$$

$$= k_1 L$$

Both k_1 and L_o can be determined experimentally from measurements of y and time. Additionally, k_1, can be adjusted for temperature using the following equation:

$$k_{1,\,T_2} = k_{1,\,20}\,\theta^{T_2 - 20}$$

where $\theta = 1.047$ (most common) and T is the temperature in degrees C.

<u>How is BOD calculated from the dissolved oxygen measurements in the BOD bottle</u>?

The dissolved oxygen measurements actually provide the oxygen consumed in the BOD bottle, or y, using the following equation:

$$y = \frac{(DO_i - DO_f)V_b}{V_s}$$

where DO_i = initial dissolved oxygen concentration in the bottle, mg/L

DO_f = dissolved oxygen concentration in the bottle at 5 days, mg/L

V_b = bottle volume for incubation, mL (standard is 300 mL)

V_s = sample volume used, mL

To find the BOD in the sample, L_o, which is the meaningful value for predicting environmental impacts, we rearrange our relationship between y and L_o to give:

$$L_o = \frac{y}{1 - \exp(-k_1 t)}$$

Practical Problem

There is nothing really conceptually difficult about BOD. It is simply a technique to report organic contamination in terms of how much oxygen will be consumed if the contaminants are discharged into the environment. Unfortunately, in practice, the term BOD is often given another, technically erroneous meaning. In the wastewater treatment industry, the 5-day y value is typically called the "BOD_5" or worse simply "BOD". As indicated above, the y-measurement is not the same as BOD.

Example 27.3

30 mL of waste are diluted into a 300 mL BOD bottle. The initial dissolved oxygen concentration is 8.5 mg/L. After 5 days of incubation at 20°C, the dissolved oxygen concentration is 2.0 mg/L.

1. What is BOD_5 (y)?

   DO_i = 8.5 mg/L

   DO_f = 2.0 mg/L

   V_b = 300 mL

   V_s = 30 mL

   $$BOD_5 = y = \frac{(8.5 - 2.0 \text{ mg/L})300 \text{ mL}}{30 \text{ mL}}$$

   = 65 mg/L

2. If $k_1 = 0.2$ days^{-1} at 20°C, what is L_o (the true BOD)?

   $y = L_o[1 - \exp(-k_1 \cdot t)]$

   Rearrange to get:

   $$L_o = \frac{y}{1 - \exp(-k_1 t)}$$

   $$L_o = \frac{65 \text{ mg/L}}{1 - \exp(-0.2 \times 5)}$$

   L_o = 103 mg O_2/L

   = concentration of organic compounds in the wastewater in oxygen units.

<u>Lecture 28</u> **Oxygen Sag Curve**

The calculations and discussion in the previous lecture are interesting but are particularly useful for one specific activity: to calculate the dissolved oxygen concentration in a receiving water body. Consider, for example, the situation in Figure 28-1. A river is receiving a discharge of wastewater. The wastewater may be from a municipal wastewater treatment facility treating domestic wastewater or it could be from an industrial wastewater treatment facility treating industrial wastewater. The wastewater contains BOD. The BOD in the wastewater will be consumed by microorganisms in the river. While consuming the BOD, the microorganisms will also consume oxygen. Will the oxygen concentration in the river drop sufficiently to be unacceptable to larger organisms?

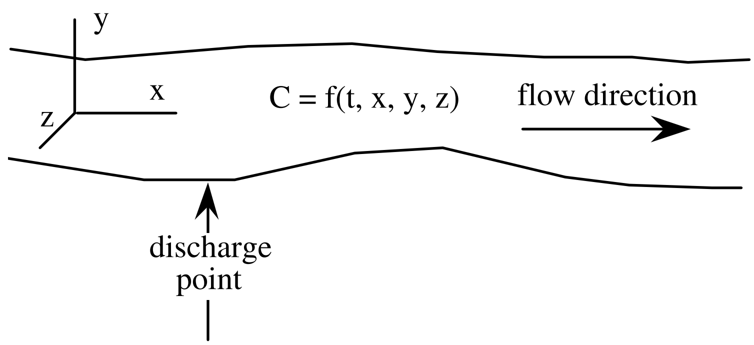


Figure 28-1 Schematic of a River Receiving a Wastewater Discharge

To answer this question, we will use the equation called the **Oxygen Sag Curve** or the **Streeter-Phelps equation** (after the two individuals who originally developed it in 1925). We will derive the sag curve ourselves starting with a general mass balance for oxygen in a river.

A general, 1-dimensional continuity equation (mass balance) for a constituent in a river is:

$$\frac{\partial C}{\partial t} = \overline{D}_x \frac{\partial^2 C}{\partial x^2} - \overline{v}_x \frac{\partial C}{\partial x} + \Sigma\text{reactions}$$

where: C = concentration of the constituent of interest, $g \cdot m^{-3}$

$\overline{D}_x$ = average dispersion coefficient, $m^2 \cdot day^{-1}$

$\overline{v}_x$ = average flow velocity of water in the river, m/day

t = time, day

x = distance downstream from a discharge point, m

Note that no y and z dimensions are considered. We are assuming that mixing across the width and depth of the river is complete and that there are no concentration gradients in those dimensions.

For the oxygen sag curve, we are concerned about the oxygen concentration, so C equals the concentration of dissolved oxygen at any time and place. To avoid solving a 2nd order partial differential equation, let's make some additional simplifying assumptions.

Assumptions

1. Continuous input of wastewater with BOD.
2. Dispersion is negligible (plug-flow) so $\overline{D}_x = 0$. This gives us:
   $$\frac{\partial C}{\partial t} = -\overline{v}_x \frac{\partial C}{\partial x} + \Sigma\text{reactions}$$
3. Steady state so $\frac{\partial C}{\partial t} = 0$. This gives us:
   $$\overline{v}_x \frac{\partial C}{\partial x} = \Sigma\text{reactions}$$
4. Let $dx = \overline{v}_x d\theta_H$ so we can write everything in terms of θ_H. This gives us:
   $$\frac{dC}{d\theta_H} = \Sigma\text{reactions}$$

Assumption 4 is simply a rewriting of the x component in terms of flow time (hydraulic time). The time, θ_H, that a packet of fluid spends in a given volume can be determined by dividing the volume, V, by the flow rate, Q:

$$\theta_H = \frac{V}{Q}$$

Rewriting this equation in terms of velocity and distance:

$V = xA$ where A is the cross-sectional area

and

$Q = \overline{v}_x A$

giving: $$\theta_H = \frac{xA}{\overline{v}_x A} = \frac{x}{\overline{v}_x}$$

So θ_H is also the time required by a fluid packet to travel a given distance when traveling at a given velocity. We can convert dx, then, into $d\theta_H$ as follows:

$d\theta_H = (1/\overline{v}_x)dx$ (because $\overline{v}_x$ is constant with respect to x)

or $dx = \overline{v}_x d\theta_H$

All we have to do now is determine the reaction terms and the equation can be "easily" solved.

Possible Reactions for Oxygen in a River

Oxygen in a river is subject to many different reactions. Five common reactions are:

1. Oxygen consumption due to BOD consumption, call it r_{O2}.
2. Gas transfer (reaeration), call it r_R.

3. Oxygen generation by photosynthesis. This is actually the difference between the rate of oxygen production, r_{AP}, in the day and the rate of oxygen consumption by photosynthetic organisms, r_{AR}, in the night. In a healthy system, the difference $r_{AP} - r_{AR} > 0$, but they occur at two different times of the day.
4. Oxygen consumption by sludge deposits (benthic demand), call it r_B.
5. Oxygen consumption by nitrogenous oxygen demand (NOD), call it r_N.

Summing:

$$\Sigma\text{reactions} = -r_{O2} + r_R + (r_{AP} - r_{AR}) - r_B - r_N$$

If you need to examine a system in detail, use this equation or something similar. However, we will examine a simplified set of reactions. Assume that the effects of photosynthesis, sludge deposits and NOD can be negligible. The effects of these, if they are present, are difficult to predict and may vary widely from river to river. This leaves us with only 2 reaction terms: BOD consumption and reaeration.

BOD Consumption

In the previous lecture we derived what we need for BOD consumption. We already have an expression for r_{O2}:

$$r_{O_2} = \frac{dy}{dt} = k_1 L_o \exp(-k_1 t)$$

Because we are dealing with flow systems now instead of a batch system, we will define t as the time required to move from x = 0 to x = x when traveling at a velocity $\bar{v}_x$, or:

$$t = \frac{x}{\bar{v}_x} = \theta_H$$

Substituting:

$$r_{O_2} = k_1 L_o \exp(-k_1 \theta_H)$$

or $\quad r_{O_2} = k_1 L$

where: $\quad L = L_o \exp(-k_1 \theta_H)$

Note that now we are applying this equation to a real system, not a BOD bottle, θ_H is not defined to be 5 days, but varies with the distance of interest. k_1 may also be different because the rate of BOD removal in a natural system would likely be different than in a bottle in the lab. L_o is the actual BOD concentration in the river at the discharge point, not the BOD concentration in the wastewater.

Reaeration

The rate of oxygen transfer (reaeration) from the atmosphere into the water can be assumed to be:

$$r_R = k_2 (C_s - C)$$

where: k_2 = reaeration constant, day^{-1}

C_s = saturation concentration of dissolved oxygen in the river, mg/L

C = actual dissolved oxygen concentration at any time or place in the river, mg/L

Substituting into the simplified continuity equation gives:

$$\frac{dC}{d\theta_H} = k_2(C_s - C) - k_1 L_o \exp(-k_1\theta_H)$$

This can be solved as is, but traditionally, one more substitution is made. This requires us to define a term called the oxygen deficit

Oxygen deficit = D = C_s – C

Taking the derivative with respect to θ_H of both sides gives:

$$\frac{dD}{d\theta_H} = -\frac{dC}{d\theta_H}$$

Now making these substitutions and rearranging gives:

$$\frac{dD}{d\theta_H} = k_1 L - k_2 D$$

which can be rearranged to:

$$\frac{dD}{d\theta_H} + k_2 D = k_1 L_o \exp(-k_1\theta_H)$$

which is a simple, linear, 1st-order differential equation. It is solved to give:

$$D = \frac{k_1 L_o}{k_2 - k_1}\left(\exp[-k_1\theta_H] - \exp[-k_2\theta_H]\right) + D_o \exp[-k_2\theta_H]$$

where D_o is the oxygen deficit at the point of waste discharge and D is at any point downstream.

Example 28.1

Consider the schematic in Figure 28-2. If C refers to oxygen concentration, what is D_o, the initial deficit? Q refers to flow rate (m^3/day).

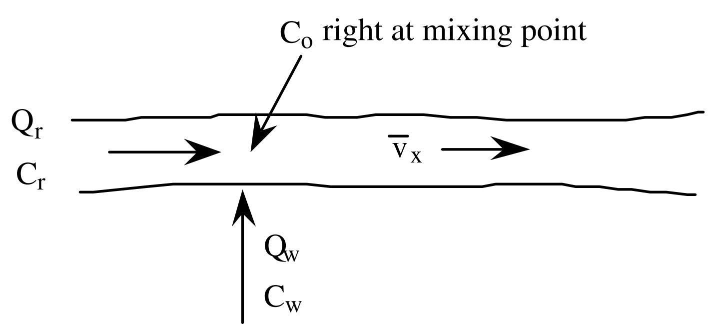


Figure 28-2 Schematic for Example 28.1

Assume that where waste is discharged, it instantaneously mixes with the river. A point mass balance gives:

$$Q_r C_r + Q_w C_w = (Q_r + Q_w) C_o$$

where: Q_rC_r = dissolved oxygen mass flow from upstream, g/day

Q_wC_w = dissolved oxygen mass flow in the wastewater, g/day (probably near 0)

$(Q_r + Q_w)C_o$ = dissolved oxygen mass flow downstream from the point of discharge, g/day

Solving for C_o gives:

$$C_o = \frac{Q_rC_r + Q_wC_w}{Q_r + Q_w}$$

where: C_o = dissolved oxygen concentration at the mixing point in the river.

The initial deficit, then, is:

$$D_o = (C_s - C_o)$$

Important: you cannot calculate D_o directly from a balance on deficits because a deficit is not a mass! You must do the balance on C.

Sag Curve

A typical sag curve is shown in Figure 28-3. It is appropriately named. As shown, at some point downstream of the discharge, the dissolved oxygen concentration will reach a minimum value, or "sag point". At and around this point, the stream is most susceptible to having oxygen concentrations below those required by aerobic organisms living in the stream. This point is called the critical point.

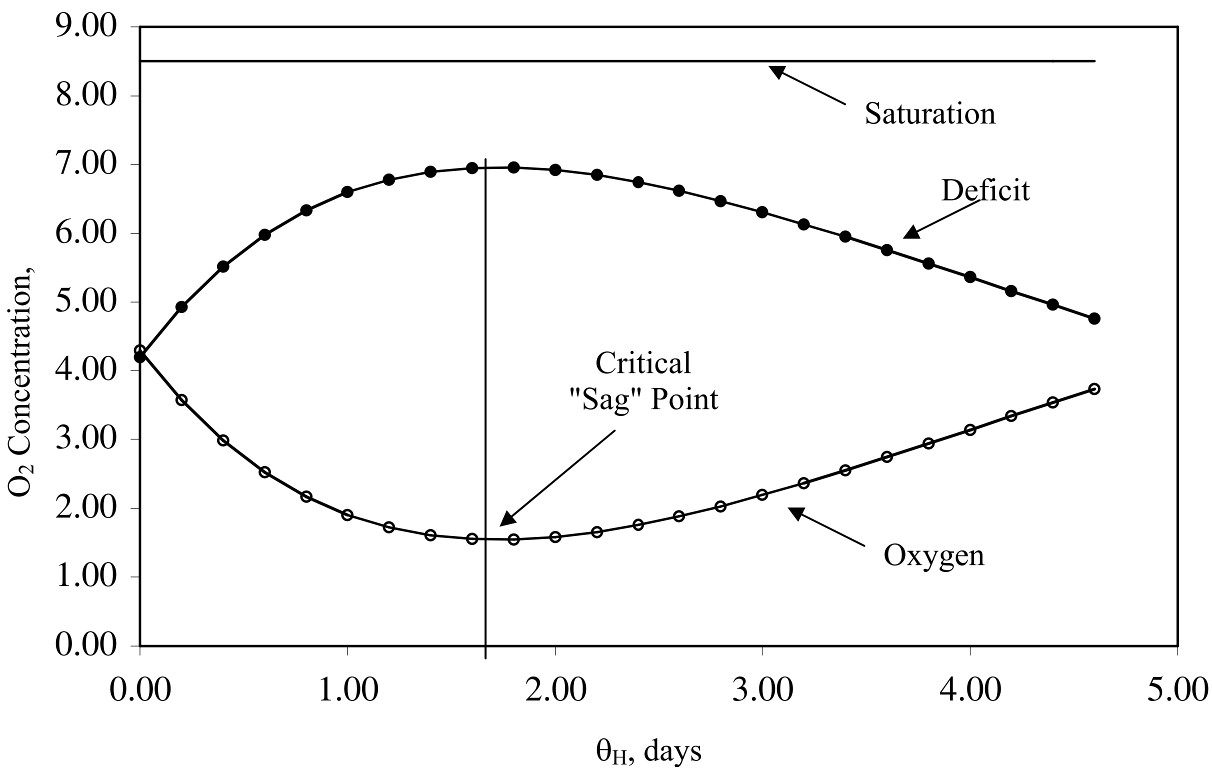


Figure 28-3 Typical Sag Curve

We usually want to know 2 things about the oxygen sag curve:

1. Where is the sag point (critical point)?
2. What is the oxygen concentration at the critical point?

Because we are looking for a maximum deficit, we can easily find D_c, the deficit at the critical point by differentiating our equation with respect to θ_H and setting it equation to 0.

$$\frac{dD}{d\theta_H} = k_1 L_o \exp[-k_1\theta_H] - k_2 D$$

When $\frac{dD}{d\theta_H} = 0$

$$D_c = \frac{k_1}{k_2} L_o \exp[-k_1\theta_H^*]$$

where θ_H^* = flow time required to reach the critical point. To solve this equation, then, we must determine θ_H^*. We do this by recognizing that our equation for D holds at the critical point as well to give:

$$D_c = \frac{k_1 L_o}{k_2 - k_1}\left(\exp[-k_1\theta_H^*] - \exp[-k_2\theta_H^*]\right) + D_o \exp[-k_2\theta_H^*]$$

Substituting into the other D_c equation and rearranging, we obtain:

$$\theta_H^* = \frac{1}{k_2 - k_1} \ln\left[\frac{k_2}{k_1}\left(1 - \frac{D_o(k_2 - k_1)}{k_1 L_o}\right)\right]$$

To find the critical point deficit, solve for θ_H^* directly and then substitute into the simple D_c equation. Find the oxygen concentration at the critical point by remembering the definition of a deficit.

Example 28.2

During the summer dry season, the effluent from a community's wastewater treatment plant accounts for 50% of the total flow of the receiving stream. The treated effluent flow is 4.6 m^3/s with a dissolved oxygen concentration of 1 mg/L. The maximum allowable BOD_5 in the wastewater is 25 mg/L. Upstream of the effluent discharge point in the stream, the dissolved oxygen concentration is 7.6 mg/L and the BOD_5 is 5 mg/L. The stream reaeration coefficient (k_2) is 0.54 day^{-1} at ambient temperature and the deoxygenation rate coefficient (k_1) is 0.30 day^{-1} at ambient temperature and 0.25 day^{-1} at 20°C. The saturation oxygen concentration in the stream at ambient temperature is 8.5 mg/L. Determine the minimum dissolved oxygen concentration expected in the stream.

<u>Solution</u>

The worst case situation occurs in the summer dry season when 50% of the river flow is due to wastewater discharge and the maximum allowable BOD_5 is in the wastewater.

Wastewater flow, $Q_w = 4.6\ m^3/s = 0.5Q_t$ (Q_t = total river flow)

$Q_w + Q_u = Q_t$ (Q_u = upstream river flow)

$Q_t = 4.6 / 0.5 = 9.2\ m^3/s$

$Q_u = 9.2 - 4.6 = 4.6\ m^3/s$

From Example 28.1, find C_o:

$C_o = [(1\ mg/L \cdot 4.6\ m^3/s)+(7.6\ mg/L \cdot 4.6\ m^3/s)] / (9.2\ m^3/s)$

$C_o = 4.3$ mg/L

Using the definition of deficit, find D_o:

$D_o = C_s - C_o$

$D_o = 8.5 - 4.3 = 4.2$ mg/L

Using the equation from Example 28.1, find $BOD_{5,o}$:

$BOD_{5,o} = [(25\ mg/L \cdot 4.6\ m^3/s)+(5\ mg/L \cdot 4.6\ m^3/s)] / (9.2\ m^3/s)$

$BOD_{5,o} = 15$ mg/L

Find L_o using approach from Example 27.3 (remembering that $BOD_5 = y$):

$L_o = 15\ mg/L / [1 - \exp(-0.25 \cdot 5)]$

(remember that the BOD test is done at 20°C and for 5 days)

$L_o = 21.0$ mg/L

Now find θ_H^* using:

$$\theta_H^* = \frac{1}{k_2 - k_1} \ln\left[\frac{k_2}{k_1}\left(1 - \frac{D_o(k_2 - k_1)}{k_1 L_o}\right)\right]$$

$$\theta_H^* = \frac{1}{0.54 - 0.3} \ln\left[\frac{0.54}{0.3}\left(1 - \frac{4.2(0.54 - 0.3)}{0.3 \cdot 21.0}\right)\right]$$

$\theta_H^* = 1.72$ day

Now find the critical deficit using:

$$D_c = \frac{k_1}{k_2} L_o \exp\left[-k_1 \theta_H^*\right]$$

$$D_c = \frac{0.3}{0.54} 21.0 \exp\left[-0.3 \cdot 1.72\right]$$

$D_c = 7.0$ mg/L

Therefore, using the definition of a deficit again:

$C_{min} = C_s - D_c$

$C_{min} = 8.5 - 7.0 = 1.5$ mg/L

This is very low for environmental systems. Many organisms in the river will become oxygen-starved. The wastewater treatment plant must do a better job of removing BOD.

The minimum dissolved oxygen concentration occurs 1.72 days downstream, where the time refers to the hydraulic time. To convert this to a distance, the river velocity must be determined which requires a cross-sectional area (not given). Then use $x_c = \bar{v}_x \theta_H^*$ to determine the critical distance. Also, the deficit at other hydraulic times may be readily calculated using the general equation for the deficit:

$$D = \frac{k_1 L_o}{k_2 - k_1}\left(\exp[-k_1\theta_H] - \exp[-k_2\theta_H]\right) + D_o \exp[-k_2\theta_H]$$

The sag curve for this example was plotted in Figure 28-3.

<u>Lecture 29</u> Eutrophication, Nitrogen and Phosphorus

Wastewaters usually contain nutrients in addition to BOD. Nutrients are defined as elements that are needed for organism growth in addition to carbon compounds. The two most common required elements are nitrogen (N) and phosphorus (P). Other nutrients are also needed, including sulfur (S) and many metals, but the amounts needed are much lower than for N and P.

Nutrients are needed for biological activity. This is important to remember. While certain molecules that contain nutrients may be toxic to organisms, such as ammonia (NH_3), the nutrient element itself is still necessary in a different chemical form. Nevertheless, there is often great concern over excessive nutrients in water bodies. The reason is <u>eutrophication</u>.

Eutrophication: **The process by which the biological activity of a water body increases with time as nutrients enter the water body**.

Eutrophication is a natural process. Material from the land runs off into surrounding water bodies. When that material contains nutrients, usually from dead organisms growing on the land, eutrophication occurs. In some areas, eutrophication can occur relatively rapidly without any human assistance.

Eutrophication is accelerated by anthropogenic (human-produced) nutrients. This accelerated process is called **cultural eutrophication**. Large sources of anthropogenic nutrients are run-off from fertilized agricultural fields and from animal grazing areas. Domestic wastewater also contains nutrients that are found in human wastes.

The problem with eutrophication can only be appreciated by considering limits to ecosystem activity. As discussed previously, energy flows through ecosystems, entering as solar electromagnetic radiation and leaving as low-grade thermal energy (waste heat). The rate at which this energy flow occurs depends on the mass and activity of the biomass present. Therefore, limits to ecosystem activity are really limits on biomass quantity.

<u>Limit 1: Solar radiation</u>

The maximum total amount of biomass that can be present in an ecosystem will depend on the amount of solar electromagnetic energy that enters the system and can be used by photosynthetic organisms. There is less energy available at higher latitudes than at lower latitudes. Therefore, less solar energy can be stored as organic compounds through photosynthesis. This leads to ecosystems with less total biomass.

<u>Limit 2: Water</u>

As was indicated in Figure 7-2, water is required for photosynthesis to occur. Water is also required for non-photosynthetic organisms. Ecosystems in climates with lower precipitation levels will have less total biomass than ecosystems at the same latitude with greater precipitation levels.

Limit 3: Nutrients

Many photosynthetic organisms obtain their carbon from atmospheric carbon dioxide. Nevertheless, adequate sunshine and water will still lead to barren ecosystems without nutrients. The open ocean is a good example that was discussed earlier. The reason for this is all organisms also require nitrogen for amino acids, phosphorus for ATP and phospholipids, sulfur for amino acids, etc. Although nitrogen is plentiful in the atmosphere, as we will see shortly, that nitrogen is mostly unavailable to organisms. The overall biomass level of an ecosystem will depend on how available nutrients are.

Adding more nutrients to an ecosystem will allow it to support more biomass. The desirability of this depends on the ecosystem. We want more biomass produced from agricultural lands so we add nutrients in the form of fertilizer. On the other hand, although water ecosystems are often nutrient limited, we may not want greater productivity. Adding more nutrients to a water ecosystem will lead to increased growth of algae at the bottom of the food chain. This will allow the production of more organisms, such as fish for harvesting, at the upper end of the food chain. However, predicting which fish will be present after nutrient addition is extremely difficult. Our earlier calculations of population changes due to competition and predator/prey cycles were overly simplistic. To use them in a real ecosystem, we must identify equations for ALL of the relevant organisms and then solve them simultaneously.

There are at least three reasons why we do not want cultural eutrophication to cause excessive biomass in water ecosystems.

1. Aesthetics

The first thing to grow when extra nutrients enter an ecosystem are photosynthetic organisms, usually in the form of algae. The algae may cover the surface of the water body, look disgusting and interfere with boating and swimming.

2. Drinking water impacts

Another reason to limit biomass production in water ecosystems is the impact on drinking water quality. The byproducts of algae in particular can be troublesome. For example, the drinking water in the Toronto area periodically tastes terrible due to geosmin produced by algae blooms. The blooms are due in part to eutrophication.

3. Dissolved oxygen concentration

Unlike natural eutrophication, cultural eutrophication occurs more rapidly than the receiving ecosystem can adapt. Much of an algae bloom that may be caused by cultural eutrophication will not be consumed by herbivores because there has not been enough time for the herbivore populations to increase. So the algae bloom dies. The algae decompose as they settle to the bottom of the water body. This decomposition is facilitated by detrivores which require oxygen. Another way to look at it is that the nutrient addition was converted to a BOD addition by the processes of photosynthesis and death. If the algae bloom is sufficiently large, the dissolved oxygen concentration at the bottom of the water body may be completely depleted. The result is the same as a direct BOD discharge. Organisms that require dissolved oxygen must either leave the depths or die. This can lead to dead zones such as occur in the Gulf of Mexico offshore of New Orleans.

Nitrogen Cycle

Nitrogen is one of the key biological nutrients. It is found in domestic wastewaters, in the run-off from agricultural areas, and surprisingly, in rain. Examination of the biogeochemical cycle for nitrogen (Figure 29-1) provides us a better understanding of how nitrogen may move through ecosystems.

The primary pool of nitrogen on earth is the atmosphere. Before any biological activity can occur, that nitrogen has to be converted from N_2 (in the lower right hand corner of Figure 29-1) to something biologically useful, such as ammonia (NH_3). This is done by a process called **Nitrogen fixation**.

Nitrogen fixation occurs in one of four ways. The first two are shown next to the "Nitrogen Fixation" process box in Figure 29-1, directly above the N_2 pool.

1. Biological fixation.

This process is conducted only by certain bacteria, primarily cyanobacteria and some soil bacteria that live symbiotically with plant roots, in particular legume roots. N_2 is converted to NH_3. This is the only biological process that converts N_2 to a biologically useful form.

2. Chemical processes.

The industrial production of nitrogen compounds from N_2. This is a famous chemical process that all chemical engineers learn about. When it was first developed the process required high temperature and pressures which meant energy. The production of modern fertilizers and many modern organic polymers that contain nitrogen first requires chemically produced NH_3.

The next two methods of nitrogen fixation are shown in the left bottom corner of Figure 29-1 near the "Oxidation" process box.

3. Lightning.

Lightning is the other natural process for converting N_2 to a biologically useful form, in this case oxidized nitrogen compounds that will be converted to nitrate, NO_3^-. The oxidation of N_2 requires the high temperatures which are provided by the lightning flash.

4. Fossil fuel combustion.

The other oxidation process that converts N_2 to oxidized compounds is fossil fuel combustion. Because most fossil fuel combustion occurs using air and not pure oxygen, there is

plenty of opportunity for the N_2 that makes up approximately 79% of air to be oxidized during combustion.

Once nitrogen is converted to biologically available forms, it can be converted to organic compounds containing nitrogen, amino acids for example. The pool of biological nitrogen is shown at the top of Figure 29-1 and has two processes, "Assimilation" and "Assimilatory Reduction" leading to it and one process, "Ammonification" leading from it. These processes are complex biochemical processes that may be facilitated by many organisms. Once organic N is produced, it may be used by many organisms via the food chain.

Two other processes are shown in Figure 29-1: "Nitrification" and "Denitrification". These processes are mediated only by bacteria and ultimately convert biologically available nitrogen back to N_2. Nitrification requires oxygen while denitrification occurs only in the absence of oxygen and the presence of a source of electrons as shown.

$NH_3 + 2\ O_2 \rightarrow HNO_3 + H_2O$ Nitrification

$6\ HNO_3 + 5\ CH_3OH \rightarrow 3\ N_2 + 5\ CO_2 + 13\ H_2O$ Denitrification using methanol

From the standpoint of improving the productivity of an ecosystem, these processes may be considered detrimental because they convert biologically useful nitrogen in the form of ammonia (NH_3) into biologically unusable nitrogen (N_2 gas). From the standpoint of removing nitrogen from wastewaters these processes are desireable. Indeed, many municipal wastewater treatment plants now include these processes as the most cost-effective method for removing nitrogen. However, while removing nitrogen from wastewaters is desirable, why convert it back to N_2? Our society needs NH_3. Perhaps we should be looking for ways to recover NH_3 directly from wastewaters, instead of expending large amounts of energy to produce it from N_2.

Notice that in Figure 29-1 there is no indication of where in the environment the different forms of nitrogen are found. Figure 29-1 contains only transformation processes for nitrogen. Figure 29-2, on the other hand, presents a simplified N cycle that shows the movement of nitrogen between the atmosphere, the ocean and the terrestrial ecosphere (adapted from Kinzig and Socolow, 1994). This diagram compares what has happened in the last 200 years because of human activities. Look at the amount of N entering and leaving each pool. Before industrialization, N fixation into the terrestrial pool was 100 Tg/yr (Tera = 10^{12}) and denitrification was 80 Tg/yr. The difference was run-off to the oceans, 20 Tg/yr. In the oceans, fixation was 30 Tg/yr and denitrification was 50 Tg/yr. So a mass balance over the terrestrial and ocean gives:

$$\text{accumulation} = (100 - 80 - 20)_{\text{terrestrial}} + (20 + 30 - 50)_{\text{ocean}} = 0.$$

What is occurring now? Now terrestrial fixation is 250 Tg/yr! The 150% increase is due to fixation by humans:

a. Fertilizer = 90 Tg/yr

b. Planted leguminous crops = 40 Tg/yr (from bacteria that live in the roots)

c. Combustion of fossil fuels = 20 Tg/yr, most from combustion of N_2.

Terrestrial denitrification has increased to 130 Tg/yr and runoff has increased to 40 Tg/yr. N-fixation in the ocean has not changed, but denitrification has increased to 70 Tg/yr. What does our mass balance say:

$$\text{accumulation} = (250 - 130 - 40)_{\text{terrestrial}} + (40 + 30 - 70)_{\text{ocean}} = +80 \text{ Tg/yr !}$$

So, now because of human activities, the terrestrial environment is accumulating 80 Tg/yr. Certainly it will be long, long time before the stock of atmospheric nitrogen is depleted at this rate. And it will be a long time before there is a significant increase in total terrestrial nitrogen. Nevertheless, the balance has been changed. What impact will that have on terrestrial ecosystems and in particular, lake and river ecosystems?

Phosphorus Cycle

Phosphorus is another key nutrient. A simplified biogeochemical cycle for phosphorus is shown in Figure 29-3. The source of P for the ecosphere is the lithosphere, or rather, rocks. This inorganic pool is shown in the bottom right corner of the figure. Most of the processes shown are physicochemical: dissolution, precipitation (back to solid, not in rain), sedimentation and geological processes, for example. The biological component is shown at the top of the figure. Phosphorus, primarily in the chemical form of phosphate, is incorporated into organic compounds such as ATP (adenosine triphosphate) and phospholipids. Once in organic form, P can be transmitted through an ecosystem via food chains. Dead organisms are recycled and phosphate is released ("Degradation") or settle to the bottom of water bodies and are ultimately recycled by geological processes.

The primary human impact has been mining. Phosphorus is mined for a number of reasons, including, importantly, to be used as a fertilizer. When used as a fertilizer, several things can happen to phosphorus:

1. Run-off directly into nearby water bodies. This happens when too much fertilizer is used or appropriate run-off controls are not used. The result can be cultural eutrophication of receiving water bodies.
2. Precipitate to an immobile chemical compound in the soil. This defeats the whole point of fertilization, although it does minimize eutrophication due to run-off.
3. Incorporated by plants, eaten by people and eventually discharged to water bodies from sewage treatment facilities (think food chain).

Lecture 30 Wastewater Treatment

Wastewater treatment is one of the few engineering processes developed specifically to protect the environment. If we take an industrial ecology approach, we would say that the product of a wastewater treatment plant, treated effluent, has a reduced environmental impact than the untreated wastewater. Ironically for a process that is designed to protect the environment, wastewater treatment has rarely been subjected to industrial ecology approaches. Therefore, the next several lectures will examine this important engineering process from an industrial ecology standpoint.

To provide a baseline for comparison, consider the schematic for a modern municipal wastewater treatment plant (Figure 30-1). This facility removes large items from the wastewater at the screens, producing a solid waste. The grit chamber is then used to remove grit that could damage pumps later in the process. Primary clarification uses gravity to settle suspended solid material in the wastewater. The primary sludge is typically 97-98% water, with the rest suspended solid material.

The next process is a complex biological nutrient removal process. The anaerobic zone is required to provide conditions that are suitable for phosphorus accumulating organisms. In the anoxic zone, denitrification occurs, consuming some BOD and converting NO_3^- to N_2 gas. In the aerobic zone, air is bubbled through the system so that aerobic bacteria can convert BOD to CO_2, H_2O and more cells, nitrifying bacteria can convert NH_3 to NO_3^- and phosphorus accumulating organisms can accumulate excess phosphorus in their cells. The internal recycle streams move the organisms to where they need to be. The secondary clarifier settles the organisms, leaving a clarified effluent. Secondary sludge is typically 98.5-99.5% water with the rest being excess microorganisms (those that aren't recycled). The phosphorus is contained in the phosphorus accumulating organisms and is removed with the secondary sludge.

The biological nutrient removal process requires a significant input of energy to operate the blowers that provide aeration. Much of the chemical bond energy contained in the BOD is lost when the organic compounds are oxidized to CO_2.

To further remove suspended solids remaining in the clarified effluent, a filter may be added. This is often followed by a disinfection process which inactivates most of the remaining pathogens (as suspended solids, many pathogens are removed in the different settling processes). Chlorine disinfection was commonly used but more and more facilities now use ultraviolet light.

While a lot of money and energy have been spent to treat the wastewater, the treated effluent is still far from drinking water quality and still lower quality than most natural waters.

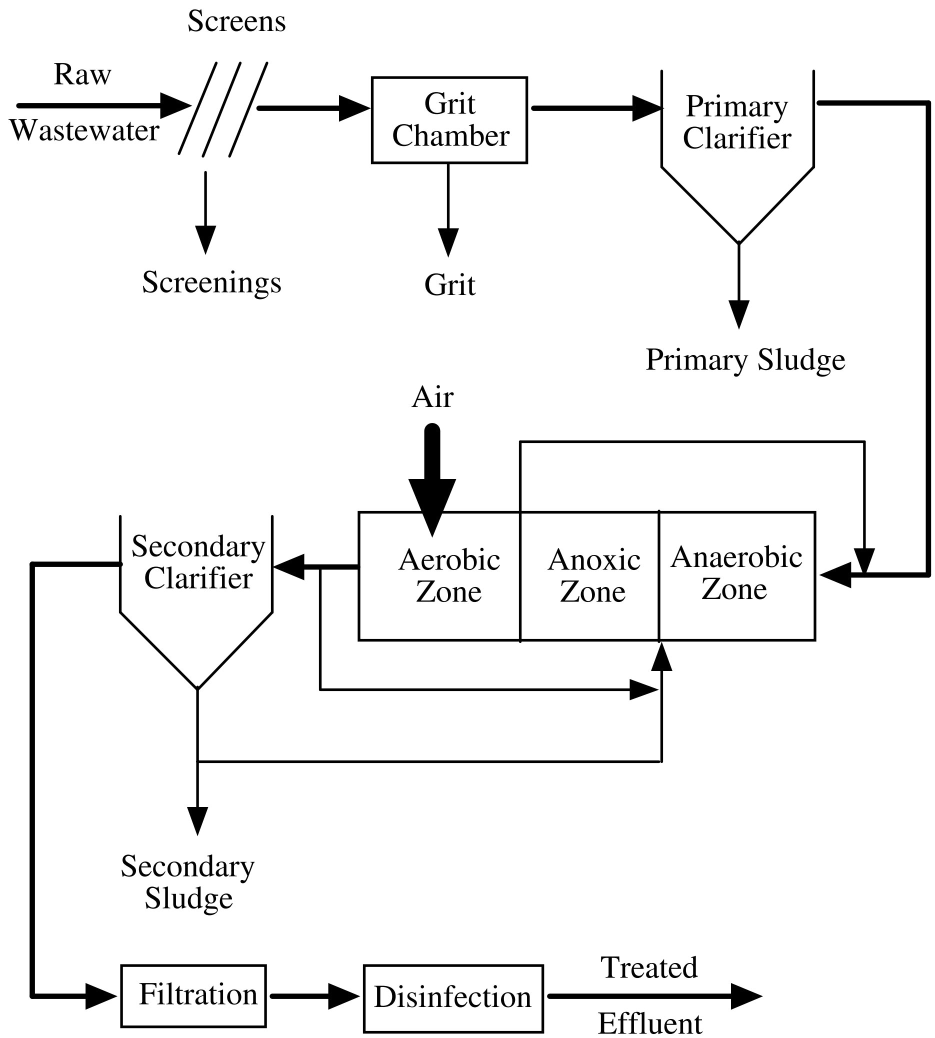


Figure 30-1 Schematic of a Modern Wastewater Treatment Plant

Figure 30-2 provides a schematic of a typical solids treatment train for treating the waste solids that have been separated from the wastewater. A thickening process is used to remove water. Depending on the process used, the water content leaving the thickener will have been decreased to 94-96%. This may not seem like much, but it reduces the volume of sludge to be treated by at least a factor of 2 and so reduces the capital cost to build the sludge treatment processes. The water is sent back to the wastewater treatment process, typically added back right before the primary clarifiers.

Anaerobic digestion can then be used to process the solids. In the absence of oxygen, anaerobic microorganisms convert the organic compounds present in the solids to methane and CO_2. The methane produced may be used to produce energy, either via combustion or after

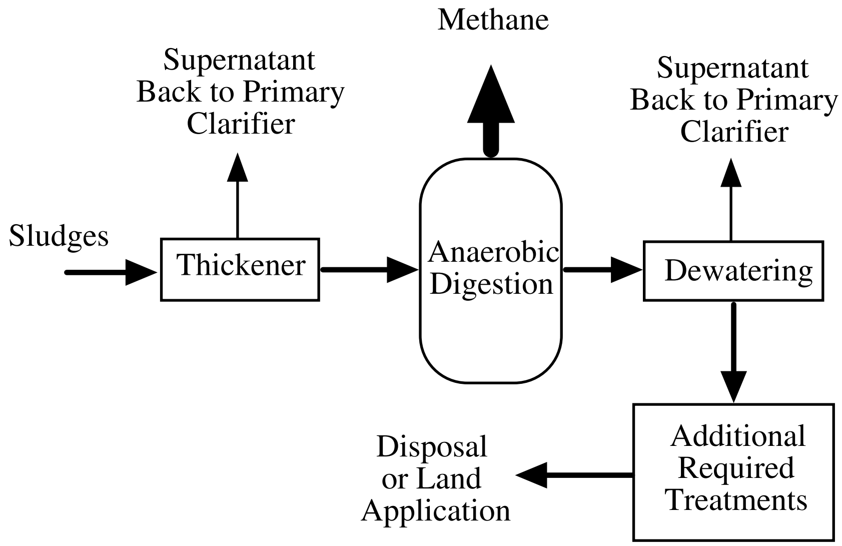


Figure 30-2 Schematic of Sludge Treatment Train

reforming it to hydrogen which can be used in a fuel cell. The digested solids are then dewatered which decreases the water content to about 65-75%. Although that stills seems like a lot of water, the solids can now be managed as a solid instead of as a liquid. Depending on how the treated sludge, now called biosolids, will be ultimately used, additional treatments may be required such as composting. Often, the biosolids are land applied as a soil amendment or disposed in a landfill. If incineration is used, the ash is typically disposed in a landfill. More productive uses for solids have been examined but are not widely implemented.

One product of the processes described in Figures 30-1 and 30-2 is an effluent that while much cleaner than the starting wastewater is still not clean enough for most human uses (let alone drinking). Natural environmental processes finish removing the contaminants after discharge. Biosolids are another product. These are typically a disposal hassle although some jurisdictions have successfully sold them as fertilizer. The methane produced would be a product, but the energy produced is not even sufficient to operate the blowers used for aeration. The wastewater treatment process as noted above is a net energy consumer. The opportunity to apply improvement analysis using industrial ecology principles is tremendous.

<u>Lecture 31</u> Natural Wastewater Treatment

Before there were modern engineered wastewater treatment plants like the one discussed in the previous lecture, human wastewaters were treated by completely natural processes. Natural processes are still capable of treating wastewaters to some extent. In particular, in recent years the use of **wetlands** to treat wastewaters has been a subject of intensive research. Wetlands are an interesting application of improvement analysis because the residual, the treated wastewater, is used to produce an entire ecosystem.

Wetlands: Basics

What is a wetland?

Wetland: **"Land area that is wet during part or all of the year because of its location"** (Kadlec and Knight, 1995)

That is pretty vague. All land is "wet" at some point during the year, e.g., after it rains. The key here is how "wet" is defined. To classify a land area as a wetland requires a look at the soil of the land area, and in particular, the soil saturation, the depth of saturation and the time of saturation.

Soil is composed of primarily three phases:

1. **solid** (soil particles)
2. **gas** (air spaces between soil particles)
3. **liquid** (water or other liquid that replaces air in the spaces between soil particles)

Saturation of soil is determined by how much of the **void** volume is liquid, where:

Void volume = total volume – solid volume
= gas volume + liquid volume

A **saturated** soil exists when the entire void volume is filled with **water**. Specifically, for the case of wetlands, the soil saturation extends to the ground surface (there also may be a free water surface above the soil in some wetlands).

Wetlands are not required to have saturated soils all of the time. The driest wetland will be completely saturated or flooded for at least 7 to 30 days each year. The minimum saturation time is that required to cause sufficient changes to the soil, in particular oxygen depletion, so that only wetland plants can thrive. This minimum time will vary from location to location depending on the climate and soil properties.

At the other end of the spectrum, wetlands can be completely flooded all of the time. At some water depth, typically 1 to 2 m, the area would no longer be considered a wetland but instead would be an aquatic ecosystem. The ecological difference between the two ecosystems is that rooted plants can survive in a wetland while they cannot in an aquatic ecosystem. The water depth at which this occurs will vary from location to location.

There are both freshwater and saltwater wetlands. Natural (i.e. not man-made) freshwater wetlands generally fall into two groups:

1. **Marshes:** intermittent to continuous flooding, vegetation is dominated by emergent plant species.
2. **Swamps:** infrequent to prolonged flooding, vegetation dominated by tree species.

Wetlands used for treatment may be either type, or modified man-made versions.

Historically, wetlands have been considered **barriers to** the **development** of infrastructure and human activity. Farmers don't like wetlands because you can't grow many crops in wetlands (except, notably, rice). Civil engineers don't like wetlands because construction on wetlands is expensive. Both farmers and civil enginers have historically tried to **drain and fill** as many wetlands as possible.

Hydraulically, wetlands are great places to **store water**. They act as big sponges. If there is a lot of precipitation in an area, for example, wetlands will absorb the water and reduce the amount of flooding downstream. During dry spells, wetlands will continue to release water slowly, providing downstream flow. When wetlands are drained and filled, there is a reduction of hydraulic storage capacity of an area. This leads to greater flooding potential.

Wetlands are great places to **treat water**. Because water typically moves through wetlands very slowly, there is plenty of time for contaminants to be removed by:

1. Settling of suspended particles
2. Precipitation of dissolved inorganic compounds
3. Biodegradation of organic compounds
4. Adsorption of inorganic and organic compounds
5. Uptake (by plants) of nutrients and other compounds.

Ecologically, wetlands are great places for environmental **diversity**. Because they contain a lot of water and because they trap much of what enters them, such as nutrients, wetlands tend to contain a tremendous variety of plants and animals. Such diversity is important ecologically but also for treatment.

Wetlands: Treatment

Wetlands are being intensively used for wastewater treatment for a number of reasons.

1. The natural <u>processes</u> noted above are <u>known to exist in wetlands</u> for removing contaminants.
2. <u>Wetlands are</u> relatively <u>inexpensive to construct</u> compared to fully engineered systems. Note, many wetlands used for treatment are also engineered, but not to the same level as the system presented in the previous lecture.
3. <u>Wetlands are</u> very <u>inexpensive to operate</u> compared to a fully engineered system.

4. Because they provide habitat for many organisms and have been systematically destroyed in the past, wetlands appeal to non-engineers who do not appreciate the complexity of wastewater treatment challenges.

Either natural or constructed wetlands may be used for wastewater treatment. The **capacity of natural wetlands** to treat wastewaters **is much less than that of constructed wetlands** for the following reasons.

1. The flow patterns of natural wetlands are uncontrolled and may provide a very wide range of hydraulic retention times. Some entering wastewater may stay in the wetland only a short time and not receive complete treatment.
2. The soils of natural wetlands are uncontrolled. Soil characteristics are very important to the ecological functioning of a wetland. The introduction of wastewater constituents may adversely change the soil characteristics.
3. The vegetation of a natural wetland is uncontrolled. The vegetation may not be optimal for transferring oxygen into the soil through the roots, for example, or for adsorbing and taking up nutrients. As a consequence, natural wetlands are often used for "polishing" wastewaters prior to discharge to a water body. The bulk of the contaminants will be removed in a fully engineered facility, with the wetland removing the remaining contaminants to low concentrations.

Constructed wetlands can be designed to address each of the deficiencies of natural wetlands. Hydraulic design is conducted by engineers and soil selection is conducted by soil scientists and engineers. Vegetation is specified by a wetlands biologist or ecologist. Organisms will be selected that are suitable for the wastewater to be treated.

There are two primary types of constructed wetlands: **surface flow or open-water wetlands** and **subsurface flow wetlands**. Open-water wetlands range from continuously-flooded areas receiving relatively steady flows of wastewater to periodically flooded areas due to surges in wastewater. The latter is primarily the case for open-water wetlands used to treat storm run-off. Open water wetlands are primarily suitable for warmer climates, but can be used in cold climates if the the entire water depth does not freeze.

Subsurface flow wetlands route wastewater flow entirely through the subsurface. To allow this to occur at a reasonable flow rate, the subsurface in these systems is usually gravel or some other medium with a high hydraulic conductivity. Wetland vegetation is planted above the gravel bed. Because the wastewater is below the surface, possible issues of odors are reduced. Subsurface flow wetlands can be readily used in colder climates, as long as the flow rate and temperature of the wastewater are sufficient to prevent freezing in the bed.

Construction of a wetland requires a good hydraulic design, earth moving equipment and some mechanisms to balance flow entering and within the system. This is significantly less effort than the construction of a fully engineered system where the earth moving function simply clears the site for construction and is not the final step. Operation of a wetland requires no significant energy input and essentially no human interaction. Currently, fully engineered systems require large energy inputs and typically numbers of human operators.

Given these attributes, wetlands appear to be the perfect wastewater treatment technology. As an "engineered" process, they have little of the environmental impact associated with a fully engineered plant (think about the impact due to energy usage and construction of the plant discussed in the previous lecture). If they are so wonderful, why isn’t all wastewater treatment done using wetlands?

1. Large land area required. Wetlands cannot remove contaminants at the same rate as fully engineered systems. Therefore, to achieve the same level of treatment, much larger areas are required. From a practical standpoint, then, wetlands are limited to smaller wastewater flows because of the availability of suitable land.
2. Oxygen Transfer Limitations. One of the defining features of a wetland, as opposed to a "dryland" is the depletion of oxygen in the soil. This means that biochemical oxygen demand (BOD) removal rates are reduced because oxygen transfer is limited. Recall the earlier discussion of the oxygen sag curve. The aeration systems of a fully engineered system are specifically designed to maximize the transfer rate of oxygen into water. From a practical standpoint, then, wetlands are only suitable for relatively dilute wastewaters, such as stormwaters and treated municipal wastewaters. If the flows are low enough, a properly designed wetland may be usable for an untreated municipal wastewater. Interestingly, wetlands are also good for treating acid mine drainage where an oxygen-depleted environment will faciliate removal of sulfuric acid due to sulfate reduction to sulfide.
3. Contaminants in the Environment. A wetland, even a constructed wetland, is an ecosystem. Any contaminants that cannot be degraded, such as heavy metals, will accumulate and may enter the food chain. Pathogenic organisms in municipal wastewater also may be troublesome, although hopefully they will be sufficiently removed. Practically, then, a wetland should treat wastewaters that do not contain bioaccumulating compounds, unless those compounds will be sufficiently sequestered to not enter food chains.

Summary

Even given their limitations, wetlands can be an important wastewater treatment approach. Careful engineering evaluation is required, in particular looking at the contaminants to be treated and the flow characteristics of the wetland (natural or constructed). Wetlands are also appealing because a working ecosystem is produced. Additionally, wetlands provide a model for how fully engineered systems can be designed to minimize environmental impact.

Lecture 32 **Water From Wastewater**

Although specifically designed and constructed to protect the water environment, most wastewater treatment processes have not been subjected to a complete life cycle assessment. The product of interest – treated wastewater – has been identified and inventory analyses have been done in many cases. The impact analysis, however, has been done only for the water that is discharged to the environment. For a typical modern engineered wastewater treatment plant, there will be additional impacts due to processing and disposal of residual solids and due to the energy used by the plant. One advantage of a treatment wetland is the reduced impact (hardly any energy required, solids disposal occurs in the wetland via natural processes), nevertheless products of economic value are not readily recovered, although a produce of environmental value, the wetland itself, is produced. Improvement analyses have been done historically, but because the full impacts have not been identified, these analyses have produced very limited results from an environmental standpoint, although cost savings have been achieved. Better life cycle assessments are required for wastewater treatment facilities.

Impact and Improvement Analyses

Because wastewater treatment processes with inventory analyses exist (at least in principle – it takes a bit of research to find this type of information for any given facility), we will continue the LCA at the impact analysis stage. Recall the two questions associated with an Impact Analysis:

1. How can the environmental impact of a product be determined?
2. How can different environmental impacts be compared?

As engineers, we often can't answer these questions directly. However, for any given process of interest, we can identify linkages to impact. For the wastewater treatment plant we can make the following statements:

a. The impact of the treated wastewater on the receiving water will decrease as the amount of contaminants discharged to the receiving water decreases.
b. The impact of the residual solids on the environment will decrease as the amount of residual solids produced decreases.
c. The impact of the energy generation processes (typically not even located at the wastewater treatment plant) decreases as the amount of energy used decreases.

Making these statements does not calculate the environmental impact of the wastewater treatment process. However, these statements do allow us to conduct comparisons between different wastewater treatment processes and to rank the environmental impact of the different processes with respect to water quality, residual solids disposal and energy usage.

The purpose of the improvement analysis is to identify whether the product and/or its production process can be redesigned to reduce the environmental impact. Recall the questions posed in Lecture 24:

1. Can the product be made with less toxic, recyclable, and/or renewable materials?
2. Can the product be made with less material?
3. Can extractions be conducted more efficiently?
4. Can the product be designed to be recycled after use?
5. Can residuals serve as raw materials for other processes?
6. Can the nature of the residuals be changed so that they can serve as raw materials for other processes?

Another question that arises when considering wastewater treatment is:

7. Can additional products be produced from the same raw material?

To answer these questions "yes" implies that new processes are required. These processes must be designed and then subjected to the impact analysis to determine whether a reduction in environmental impact is observed. From our standpoint as the engineers, the LCA becomes iterative and closely tied to design.

Reducing Impact to Water Environment

As treated wastewater is currently the primary product of wastewater treatment plants, let's focus on water for now. One key way to reduce the impact of treated wastewater on the environment is to decrease the amount of contaminants discharged to the receiving water (as noted). There are several ways to do this:

1. Produce less wastewater and treat to the existing product specifications.
2. Treat water to remove more contaminants (in other words, make the product specifications more stringent).
3. Decrease the amount of water discharged by reusing it earlier in the human hydrologic cycle (Figure 26-2 in Lecture 26).
4. Combinations of items 1-3.

Item 1 is important, but it is beyond the scope of the engineer designing the wastewater treatment plant. Upstream processes that produce wastewater must be redesigned. Items 2 and 3 are related. If we treat water to remove more contaminants, we might as well treat it sufficiently that we can reuse it. In this case, **water becomes a product with economic value**, not just something to be thrown away. A revised human hydrological cycle incorporating this idea is shown in Figure 32-1. In addition to reducing the impact of discharging treated wastewater, recycling water reduces the amount of water that needs to be taken from natural sources. This minimizes the impact of water withdrawal at these sources.

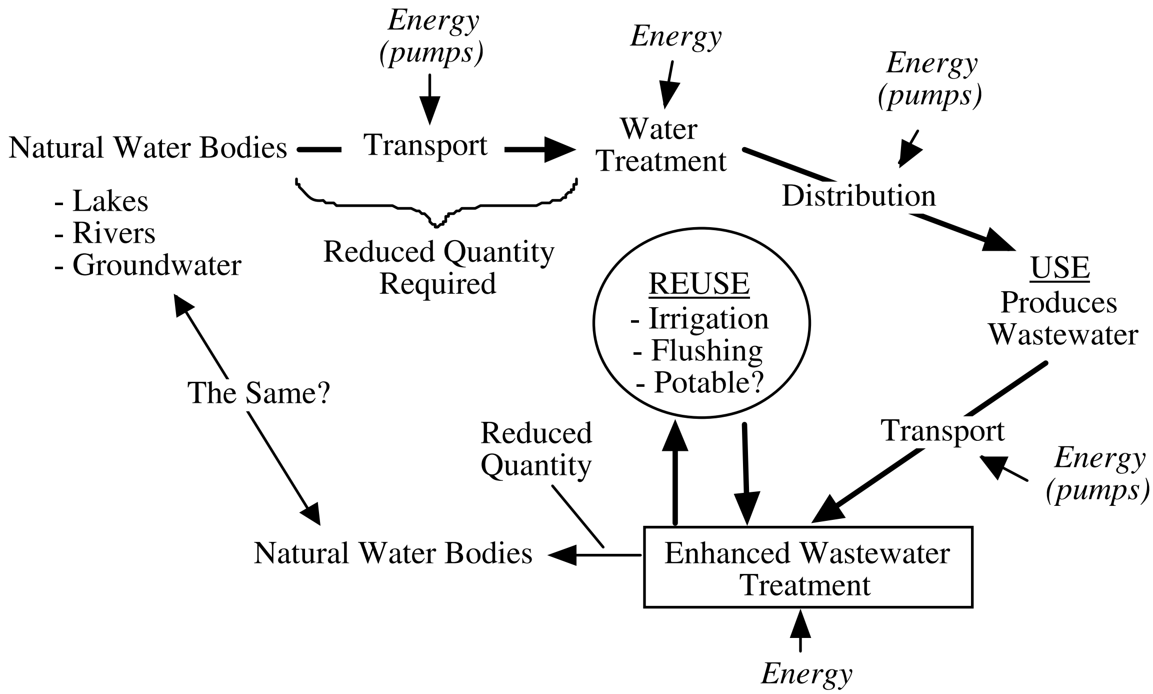


Figure 32-1 Modified Human Hydrological Cycle Including Reuse

Before we can examine processes to treat water sufficiently for reuse, we must define the product specifications. These will depend on the use. Typically, these specifications are now prepared by government agencies. Because specifications vary between jurisdictions, the following generalizations can be made:

a. Water to be reused for irrigation and other non-human ingestion purposes should be at least as clean as the a natural water body used as a drinking water source. Note that water used as a drinking water source is typically not drinkable without further treatment (see Water Treatment process in Figure 32-1).
b. Water to be ultimately reused for human ingestion must at a minimum achieve drinking water standards. For safety, this water will likely be further treated prior to drinking.

Detailed specifications can be found in appropriate government documents. The Ontario Ministry of the Environment (MOE) has drinking water standards that can be found by starting at the MOE web site at http://www.ene.gov.on.ca/ while the U.S. Environmental Protection Agency has drinking water standards which can be found by going to http://www.epa.gov/ and working your way to Title 40 of the Code of Federal Regulations (CFR) Part 141 (may also be able to start at http://www.gpoaccess.gov/ecfr/). Water reuse standards are typically set by local authorities. With the specifications identified, the next step is to determine what is in wastewater and how to remove it. Table 32-1 summarizes that information for typical municipal wastewater. Industrial wastewaters will have different compositions depending on the industry.

Lecture 30 presented a process schematic that could achieve current discharge standards (which are not sufficient for reuse). Components of this schematic may be useful, but before selecting those components, we should step back and look at the processes on the basis of how they work. As shown in Figure 32-2, there are two groups of processes:

1. **Processes that remove non-dissolved constituents**
2. **Processes that remove dissolved constituents**

Non-dissolved constituents are considered either settleable or non-settleable. Settleable constituents can be removed by allowing them to settle out of the water. Because gravity is free, the cost of settling processes is due to the cost of construction. The grit chamber, primary clarifier, and secondary clarifier shown in Figure 32-3 are settling processes.

Most non-settleable constituents can, in theory, settle given enough time and proper chemical preparation. As a practical matter, however, these particles settle too slowly for cost-effective settling. The settling tanks would have to be too big. Therefore, non-dissolved, non-settleable constituents are removed by different processes including filtration (shown in Figure 30-1) and membranes. Pathogenic organisms, which are non-dissolved and both settleable and non-settleable depending on the water chemistry conditions, can also be inactivated with disinfection processes (shown in Figure 30-1).

To reliably remove sufficient non-dissolved constituents for water reuse, the settling processes shown in Figure 30-1 must be augmented with membrane processes. Microfiltration is the largest membrane process that will remove micoorganisms, while ultrafiltration removes smaller particles and nanofiltration removes very small particles. If micro- or ultra-filtration are used, the secondary clarifier and filtration unit shown in Figure 30-1 may be replaced with these processes. If nano-filtration is used, another solids separation process must be used in advance to minimize plugging.

Dissolved constituents are either biodegradable or non-biodegradable. Biodegradable constituents are converted to other compounds such as CO_2, H_2O, methane (CH_4), H_2 and N_2 as well as to biomass due to the growth of organisms conducting the biodegradation. The anaerobic/anoxic/aerobic processes in Figure 30-1 represent biological processes for removing BOD, nitrogen and phosphorus. The gaseous products escape to the atmosphere or are collected for use. The biomass must be separated, with a secondary clarifier, as shown in Figure 30-1, or using other processes as indicated earlier for non-dissolved constituents.

Table 32-1 Constituents in Municipal Wastewater

Constituent	Typical Concentration	Classification	Removal Mechanism
BOD	220 mg/L	D, B	Biological Oxidation to CO_2 Biomass Incorporation Biological Conversion to CH_4, H_2
Suspended Solids	220 mg/L	n-D, S and n-S	Settling Filtration Membranes
Nitrogen (NH_3)	40 mg/L	D, B	Biological Oxidation to NO_3^- Air stripping Biomass incorporation
Nitrogen (NO_3^-)	0 mg/L	D, B	Biological Reduction to N_2 Biomass incorporation
Phosphorus (P)	8 mg/L	D, n-B	Precipitation Biomass incorporation Biomass excess accumulation
Metals	Variable	D, n-B	Precipitation Adsorption Reverse Osmosis
Pathogens	Variable	n-D, S and n-S	Settling Filtration Membranes Disinfection
Organic Toxicants	Variable	D, B and n-B	Biodegradation Adsorption Nanofiltration or Reverse Osmosis
Endocrine Disruptors	Variable	D, n-B	Reverse Osmosis?
Salts (Na^+, K^+)	Variable	D, n-B	Evaporation Reverse Osmosis
Salt anions (Cl^-, SO_4^{2-})	Variable	D, n-B	Evaporation Reverse Osmosis

D = dissolved, B = biodegradable, n-B = non-biodegradable
n-D = non-dissolved, S = settleable, n-S = non-settleable

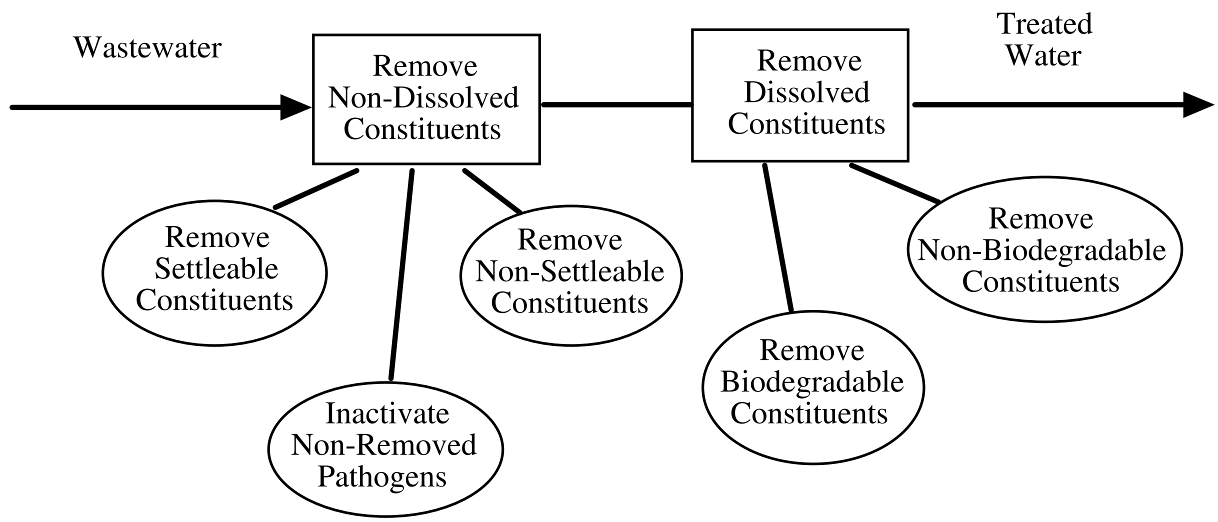


Figure 32-2 Classifications of Treatment Processes

Some non-biodegradable dissolved constituents can be converted to solid form and removed with the non-dissolved material (for examples, metal ions may be precipitated). Other processes may also be used (see Table 32-1). A subset of non-biodegradable dissolved constituents, such as salts, are difficult to remove economically. These constituents can be removed with reverse osmosis (another membrane process with a very small pore size) or physical processes such as evaporation. To achieve the standards needed for irrigation, salts may or may not have to be removed depending on the concentration, the resilience of the crop being irrigated, the climate, and soil conditions. To achieve drinking water standards, a fraction of the salts must typically be removed.

Figure 32-3 shows a schematic of a wastewater treatment plant that will produce very high quality water – much better than many natural waters and probably achieving drinking water quality standards. Note that simply because this water would probably meet drinking water standards, it should not be ingested by humans without further processing. When designing water reuse systems, every other use besides potable reuse must be examined first and only when those needs are met and the natural water supplies are still insufficient for the needs of the population should potable reuse even be considered.

This schematic is only one possible alternative for producing very high quality water as a product. This reduces the impact associated with water discharge, possibly to zero if all of the water is reused, but not the impacts associated with residuals or energy use. To the contrary, an inventory analysis will show that there will be more residuals produced and more energy required to operate the membrane processes. Before trying to assess these impacts, additional improvement analysis should be done to see if the residuals production and energy requirement can be reduced. We have now completed one full iteration of the LCA process from where we were – recommended improvements (to produce higher quality water), estimated the inventory analysis and predicted relative environmental impacts. Another iteration will be conducted in Lecture 33.

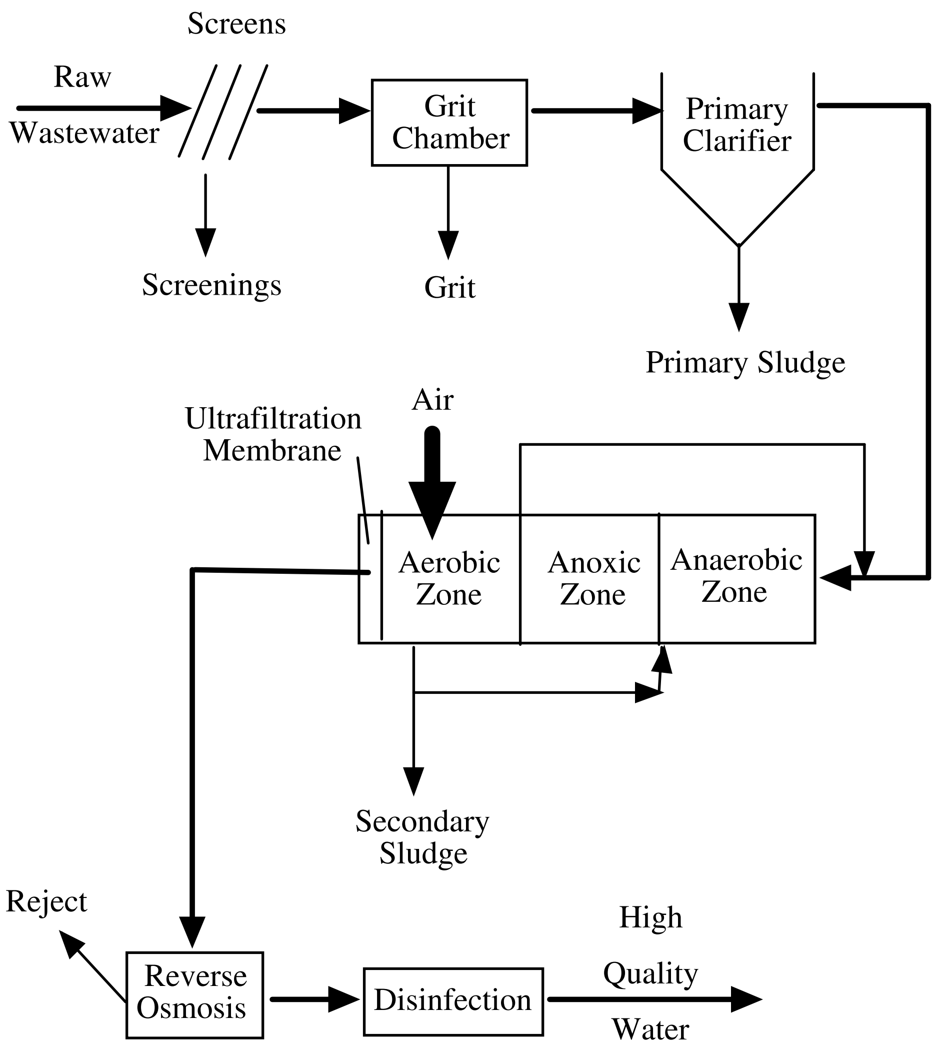


Figure 32-3 Schematic of Process to Produce High Quality Water

Lecture 33 Other Products of Wastewater

By considering water to be a product of wastewater treatment, we significantly reduced the impact of water on the environment and also reduced the impact of taking water from the environment (because we take less). The key technology proposed to do that was the addition of membrane processes after biological treatment. The challenge now is to identify whether the impacts due to residuals production and energy use can be reduced, while keeping water as a product.

Energy as a Product

Consider energy first. Figure 33-1 shows an overall energy balance for the plant shown in Figure 32-3, using the sludge treatment train shown in Figure 30-2. For the schematic shown in Figure 32-3, the blowers used to aerate the biological treatment system consume the largest fraction of energy (if different technologies are used for aeration, the fraction of energy used may decrease). The anaerobic digester for sludge treatment in Figure 30-2 requires energy for heating and mixing (these systems are typically operated at 35°C) but methane is produced. This process, then, is the only energy producing process in the entire plant.

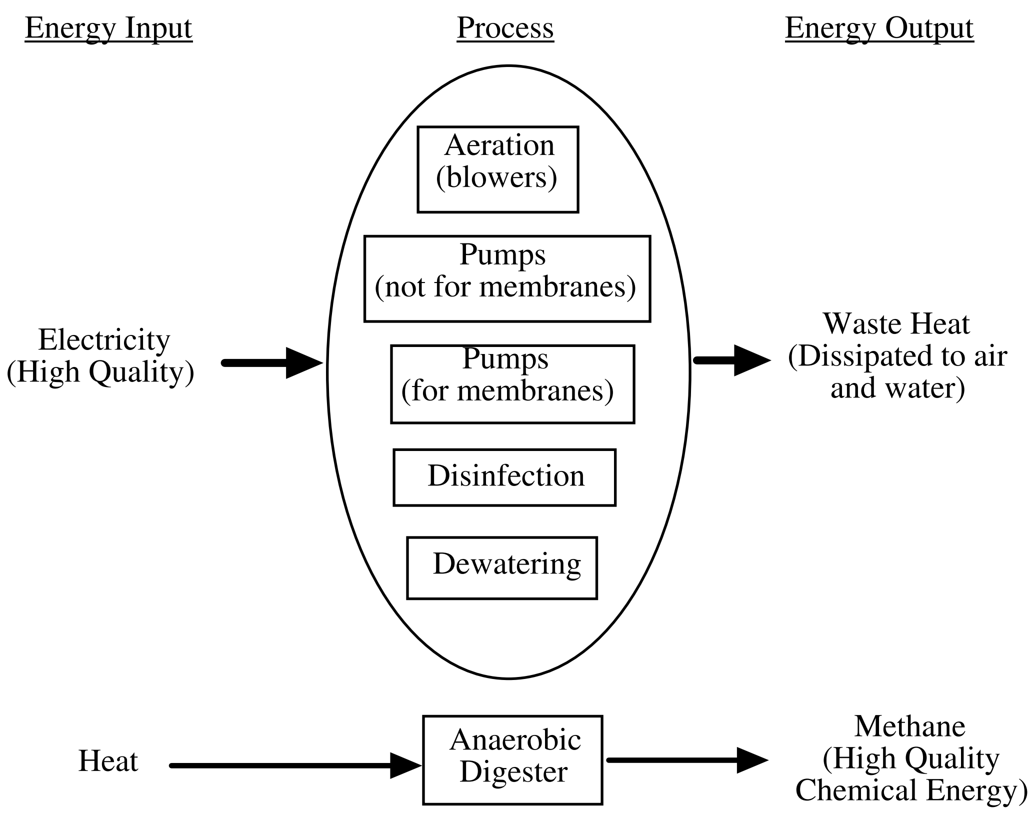


Figure 33-1 Energy Balance over Treatment Plant

Question #1: Does the plant produce enough energy through anaerobic sludge digestion to be energy self-sufficient (not require external energy sources)?

Answer #1: No, although a large fraction can be recovered.

Reason #1: Activated sludge treatment has two inherent energy penalties. First, energy is required to blow air into the treatment system. Second, about 50% of the energy contained in the organic material in the wastewater is lost to waste heat when the carbon is oxidized to CO_2. The other 50% is rearranged into microorganisms, from which methane can be recovered during anaerobic digestion.

Question #2: Does the potential exist for the plant to produce enough energy from the organic constituents in the wastewater to be energy self-sufficient?

Answer #2: YES. The potential energy in the organic constituents of municipal wastewater is approximately 1.76 kWh/m^3 wastewater (Shizas and Bagley, 2004). The electricity required to run a plant without reverse osmosis is approximately 0.2-0.4 kWh/m^3 wastewater. So with the right design, a wastewater treatment plant should become at least energy self-sufficient.

Question #3: Can the design be modified to reduce the energy consumption?

Answer #3: Yes, using the following improvement analysis strategies:

1. Design more efficient mechanisms for dissolving oxygen into water (ongoing).
2. Design more efficient primary clarifier to remove more suspended solids (onging).
3. Increase the digestion effectiveness of the anaerobic digester (ongoing).
4. Increase the efficiency of energy production from the methane-containing digester gas (onging – includes the use of fuel cells for direct electricity production).
5. Design an anaerobic process for treating the wastewater that doesn't require aeration and doesn't "throw away" 50% of the incoming energy content (conceptual).

Strategies 1, 2 and 5 will save energy. In other words, the amount of electricity required will decrease below 0.2-0.4 kWh/m^3 wastewater. Additionally, strategies 2-5 will lead to increased production of energy. In other words, strategies 2-5 will increase the fraction of the potential 1.76 kWh/m^3 wastewater that is converted to usable electricity. The combination of reduced energy use and increased energey production should lead to **energy becoming a product with economic value**. If the wastewater treatment plant is completely energy sufficient and selling excess energy, the impact due to the external energy generation processes becomes zero (and may be even further improved if there is a lot of excess energy available).

One possible process that achieves the same water quality criteria as that in Figure 32-3 but decreases energy requirements significantly is shown in Figure 33-2. Nitrogen is still

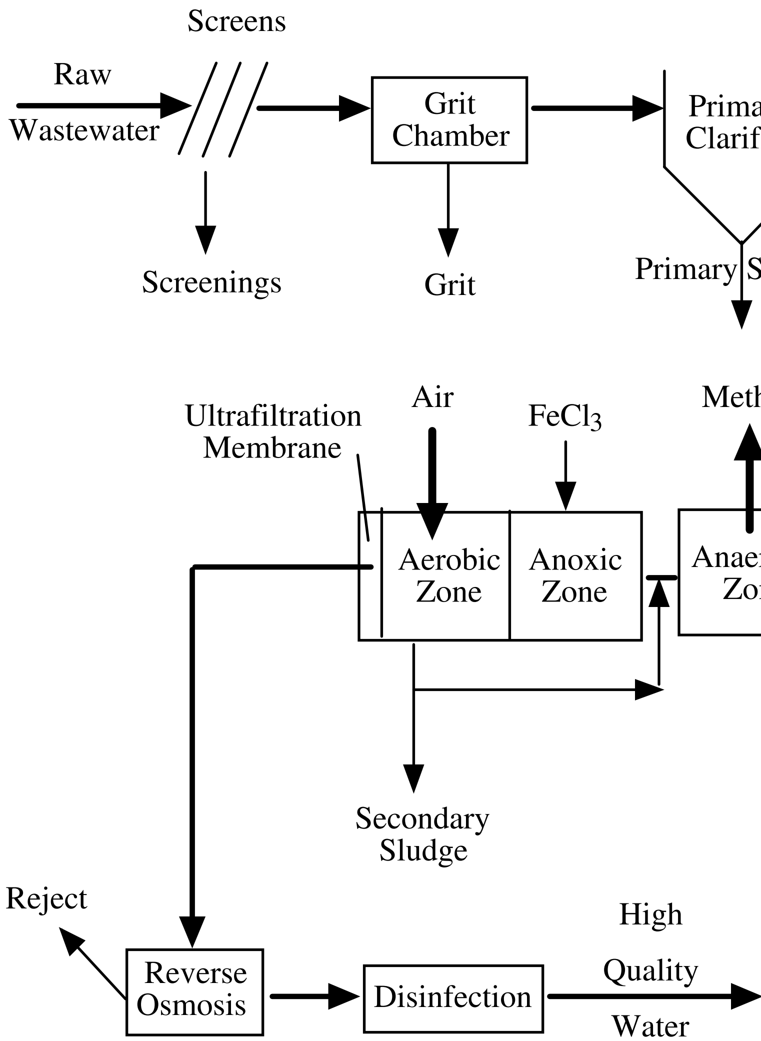


Figure 30-2 Schematic to Produce Water and Energy

removed by converting it first to NO_3^- (which requires oxygen) and then to N_2. Phosphorus is now removed by precipitation with $FeCl_3$.

Products from Residuals

With the further modifications suggested above, the environmental impact due to energy generation may be significantly reduced, perhaps producing energy as a product, while also keeping water as a product. The remaining principal source of environmental impact is the residuals.

<u>What are the residuals</u>?

1. Anaerobically treated sludge (biosolids). The biosolids contains organic carbon, nitrogen, phosphorus, metals, pathogens, endocrine disruptors, etc.

2. Rejects (principally concentrated salt solutions) from the membrane processes.
3. Gases such as N_2 (from denitrification) and CO_2 (from carbon oxidation, both biologically and during combustion of methane).

<u>What can be done with the residuals</u>?

This is a multi-billion dollar question. Often, the biosolids are further treated to decrease the pathogen content (by biological reaction at 55-60°C for specified times) and then they can be land applied as a soil amendment. This works if the metal concentration isn't too high, the odors aren't too offensive, and there is plenty of land available relatively close to the treatment facility that can accept the biosolids. If land is not close by, the environmental impact of biosolids transportation can become important.

Another option for biosolids disposal is incineration in a fluidized bed incinerator. Incineration arouses public concern because everybody nearby can see the stack and the plume. The public is typically very poorly informed with technical information. For example, the visual plume from a biosolids incineration stack in the winter is caused by the condensation of pure water produced during the incineration process. The lack of appropriate technical information will not stop the public and their elected politicians from fighting incineration, in particular in Toronto where there is a very well organized, politically active group prepared to do almost anything to stop incineration in the city. The sad fact is that historically incineration technologies were not clean and so even though far superior technology is now available, overcoming the legacy of inappropriate technology used in the past is very difficult.

All that remains after incineration are the metals in the ash, which typically are landfilled although they could be used as a raw material for construction processes, like fly ash from electricity generation facilities often is. Although not widely done (too expensive with current rates), electricity generation from the incinerator is also a possibility.

Using the industrial ecology approach, other options to use biosolids as a feedstock for another industry should be examined. Land application and incineration are still primarily disposal options, not use options. The challenge is economic – if other feedstocks are cheaper, then who will use biosolids as their raw material? As with most economic challenges, research is necessary to develop technologies that cost less.

Membrane processes are not yet widely used and so at present little information about the disposal of reverse osmosis rejects is available. This presents a major opportunity for technology development.

Note that the proposed anaerobic process for energy generation also reduces the amount of residuals produced (and thus simplifies challenges with residuals). This occurs because anaerobic microorganisms cannot transform as much carbon into biomass as aerobic microorganisms can. Instead, they "throw away" the energy needed to do that as methane.

A "Crazy" Idea

By creating reusable water, producing energy, and reducing residuals production, the proposed wastewater treatment system has significantly reduced its overall impact on the environment. Because products are being produced, the capital cost to make these changes may be offset by the income from selling the products. Nevertheless, the residuals are still troublesome. In a natural system, the residuals would be ultimately recycled so why not in our engineered system?

What if the following schematic (Figure 33-3) could be constructed? All of the wastewater would be anaerobically treated (with a small aerobic basin to help polish BOD removal, but not cause nitrification) and then passed through membranes. The amount of excess sludge would be very small compared to current, leaving the rejects from the membrane processes as the principal residuals. Because no aerobic processing was conducted, the nitrogen would be in the form of NH_3, which is the form needed for fertilizer. Perhaps the NH_3 and phosphorus could then be recovered from the membrane reject streams and converted directly into high-quality fertilizer (as opposed to the low-quality fertilizer of biosolids). This provides another high quality product from the wastewater.

The remaining material in the rejects will be metals, undegraded organic compounds, and salts. Perhaps if the sufficiently concentrated, the metals could be recovered as well as the salts, leaving only the undegraded organic compounds. Someone must be able to think of a way to reuse this material.

These ideas are just that – ideas. While components of the technology needed to do this may actually exist, few have tried to put them to this use. One reason is relative cost. We can produce fertilizer from virgin phosphate rock and N_2 gas more cheaply than we can recover it from waste, at least using our current economic principles. If the full environmental costs are incorporated, a "crazy" idea like the one in Figure 33-3 may indeed be cost-effective. This looks like a great engineering challenge to me.

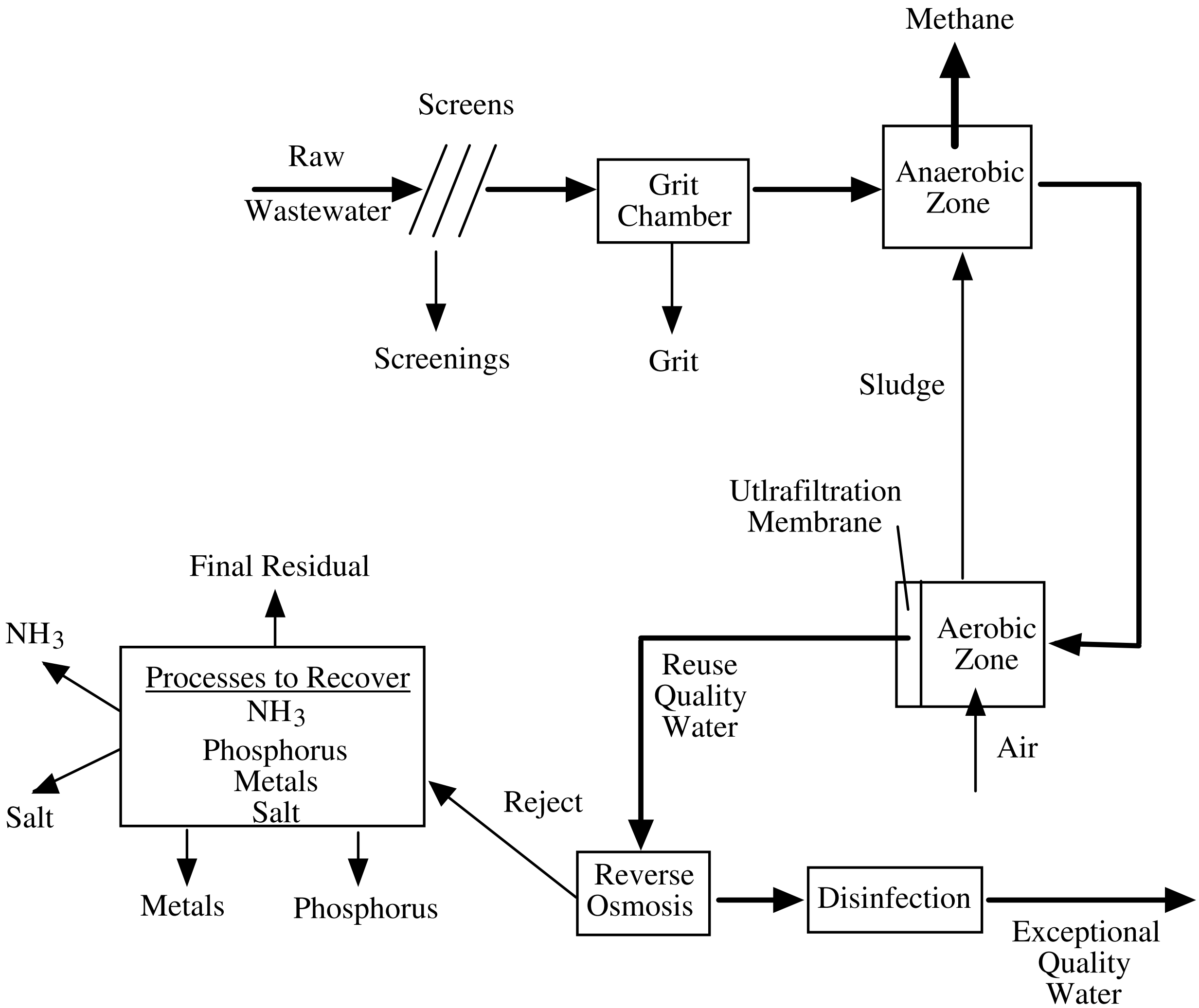


Figure 33-3 A "Crazy" Idea for Wastewater Treatment

Lecture 34 **Sustainability**

The phrase Sustainable Development is now commonly used by everyone from technical experts to the public press. What is it?

Sustainable Development: The prudent use of existing, irreplaceable natural resources in order to assure their continued availability for future generations.

The key points of this definition are:

1. Irreplaceable natural resources. Resources that, once used or destroyed, cannot be replaced, ever.

Which of the following are irreplaceable resources?

a. Minerals?
b. Fossil fuels?
c. Organisms?
d. Ecosystems?

Minerals From our discussions of ecosystems, we know that mass on earth is limited. Therefore, the quantity of minerals available must be limited. But we also know that in ecosystems mass is constantly recycled. The same is true of minerals. As long as we can develop technologies to recycle them, **minerals are not irreplaceable**. From an engineering standpoint, we should be thinking of ways to use minerals so that they can be efficiently reused or recycled.

Note that I am not claiming that recycling minerals after we have used them is economically attractive, yet. Because engineers are responsible for the practical application of technology to solve problems, economics is usually important. I will examine economics shortly. An important distinction exists, however, between technical viability and economic viability; a distinction that many engineers often forget. We know, for a fact, that mass is conserved and so we should be able to find it again after we use it. We may not yet have the technology to recycle mass after we have used it, but even when we do, the technology may be very expensive. In this case, we would have a technically feasible process that is not economically feasible. To be practically useful, the technology must be technically and economically feasible. While further technical development is often required to improve economic feasibility, that is not always the case, and certainly won't be the case when we begin to push the limits of sustainability. Technical feasibility and economic feasibility are separate issues, and their difference must be understood to make appropriate engineering decisions.

Fossil fuels The quantity of these is also limited and we are constantly converting them into CO_2 and H_2O. The natural replacement rate is very slow because photosynthesis must first convert CO_2 back into organic matter and then geological processes must convert the organic matter into fuel. Because the value of fossil fuels is not their mass, but instead their energy content, and because energy cannot be recycled, fossil fuels **are irreplaceable** in the time frame within a reasonable time frame. The more relevant question, however, is whether the energy provided by fossil fuels is replaceable. In other words, can we directly convert solar energy into high quality energy for use by humans? If so, then the **energy currently provided** by fossil fuels **is not irreplaceable**. As discussed earlier, the challenge is to develop appropriate sources of renewable energy.

As with the recycling of minerals, I am not claiming non-fossil fuel energy sources are necessarily economically feasible at this time. The deregulation of electricity prices in California several years ago shows clearly, however, how economic feasibility can change without technical development. For example, many wastewater treatment plants in California have added processes to produce electricity from the biogas they produce from anaerobic sludge digestion. They are using existing technology: technical feasibility existed before deregulation but wasn't being used. These efforts became economically feasible simply because the price of electricity increased enough that the cost to buy the equipment could be recovered quickly in savings.

<u>Organisms</u> There is a common belief that organisms are renewable. This belief arises from our knowledge that organisms reproduce. We take advantage of that by farming: crops, livestock, lumber, fish, etc. But consider the following equation:

d(resource)/dt = replacement rate – usage rate

<u>What happens when the usage rate > replacement rate</u>?

The resource is consumed. In the case of organisms, if all the organisms of a species are lost (extinction), the DNA (information) that identifies that species is also lost. Fifty years ago, if a species became extinct, the information was lost forever. Today, if a species becomes extinct, the information is lost forever unless we happened to preserve its DNA. But even so, we can't do anything with the information. Fifty years from now, perhaps, we will have developed libraries of DNA for every organism on earth. Maybe we will also have learned how to create functional, living organisms starting only from their DNA. If so, then when a species becomes extinct in the wild, we could simply produce another one. The religious implications of this aside, if we could do it, perhaps organisms would be replaceable. Until then, however, **organisms are irreplaceable resources**.

<u>Ecosystems</u> The information required to construct functioning ecosystems is immense. So far, we have failed to construct all but the simplest artificial functioning ecosystems. Having all the genetic information for every organism in a given ecosystem is not sufficient to reconstruct an ecosystem that has been destroyed. Reconstructing all of the organisms does not ensure the success of the ecosystem because the physicochemical boundaries must also be

known. While work continues to map out the information content of important ecosystems, **ecosystems must be considered irreplaceable** at the present.

2. For future generations. This forces us to consider not only the present, and the economic benefit to arise from our current activity, but also the future. Fifty generations from now, will there be sufficient biological diversity for people to enjoy the standard of living that we enjoy today?

Can we answer that question now? We can, but only if we consider cases.

Case 1 – Human population growth continues at current rate:

This is easy. The answer is unequivocably NO. Sustainable development is impossible under these conditions. Indeed, this case is so unsustainable that human population growth could not even continue to grow at its current rate for fifty generations. Recall the exponential growth of the human population. At a 1.6% growth rate and taking a generation to be 18 years, in 50 generations there would be 1.1×10^{16} people on the planet, or 1.8 million times as many as today's 6.2 billion people.

Case 2 – Human population growth naturally stops at some time in the future, but we continue our current consumption habits:

This is also easy – sustainable development is impossible here too! Estimates of the ecological footprint of the current human population today indicate that with the current 6.2 billion, we already need more land than exists on earth. Adding more people, even only another 5 billion or so, will just make the situation worse.

Case 3 – Same as Case 2 BUT we change our consumption habits and technology:

Maybe sustainable development can be achieved. Not only is technology required, which is in the realm of engineering, but also changes in society. A tremendous challenge.

Case 4 – Human population stabilizes quickly and we change our consumption habits and technology:

Yes, I think sustainable development is achievable under these conditions.

My point here is that unless the human population gets under control soon, all the technological advances to improve sustainability will simply be crushed under the weight of our human needs.

Economics (may be review for those who have taken APS111)

Most arguments against sustainable development are presented by individuals who are making a lot of money following our historical, non-sustainable practices. The validity of these arguments is therefore usually suspect. Economic issues are nevertheless extremely important and the question that must be answered is:

Is Sustainable Development economically sound?

To answer that question, consider the following simple statements:

1. Economic activity is motivated by profit.
2. Profit centers try to maximize profit.

To understand the relationship to sustainable development, some definitions are required. First, a **profit center** is any entity (person, organization) that does something, produces a product, creates a service, etc., that can be sold to provide revenue. Non-profit centers may also do this, but differ in that they are not motivated by profit; they have other motivations for conducting their activities.

Second, there are two types of profit:

Accounting Profit = Total Revenue – Internal Costs

where:

Total Revenue (TR) = Sale Price per item (P) x **Number of items sold**

Internal Costs = Those costs actually paid by the profit center. For example, labor and raw materials are internal costs.

and:

True Profit = Accounting Profit – External Costs

True Profit = Total Revenue – Internal Costs – External Costs

where:

External Costs = **The costs of the producing the product that somebody besides the profit center pays.**

For example, health care costs due to air pollution arising from automobile use are not paid by the automobile manufacturer, even those these costs arise from their product. Society pays these costs.

Because external costs are not paid directly by the profit center, most profit centers try to maximize Accounting Profit.

Maximizing Profit

So this is easy, right? To maximize accounting profit, simply maximize total revenue and minimize internal costs! The apparent simplicity of the total revenue equation is misleading, however. The equation makes it look like price is a fixed value and so the more items that are sold, the greater will be the total revenue and vice-versa. Is that really the case?

Law of Supply: **The quantity of product produced by suppliers tends to increase when the price increases, and decrease when price decreases, all else being equal.**

A simple linear supply versus price curve, S = nP + c where c = 0, and S is the number of items produced (supplied) can be used to examine this law (Figure 34-1).

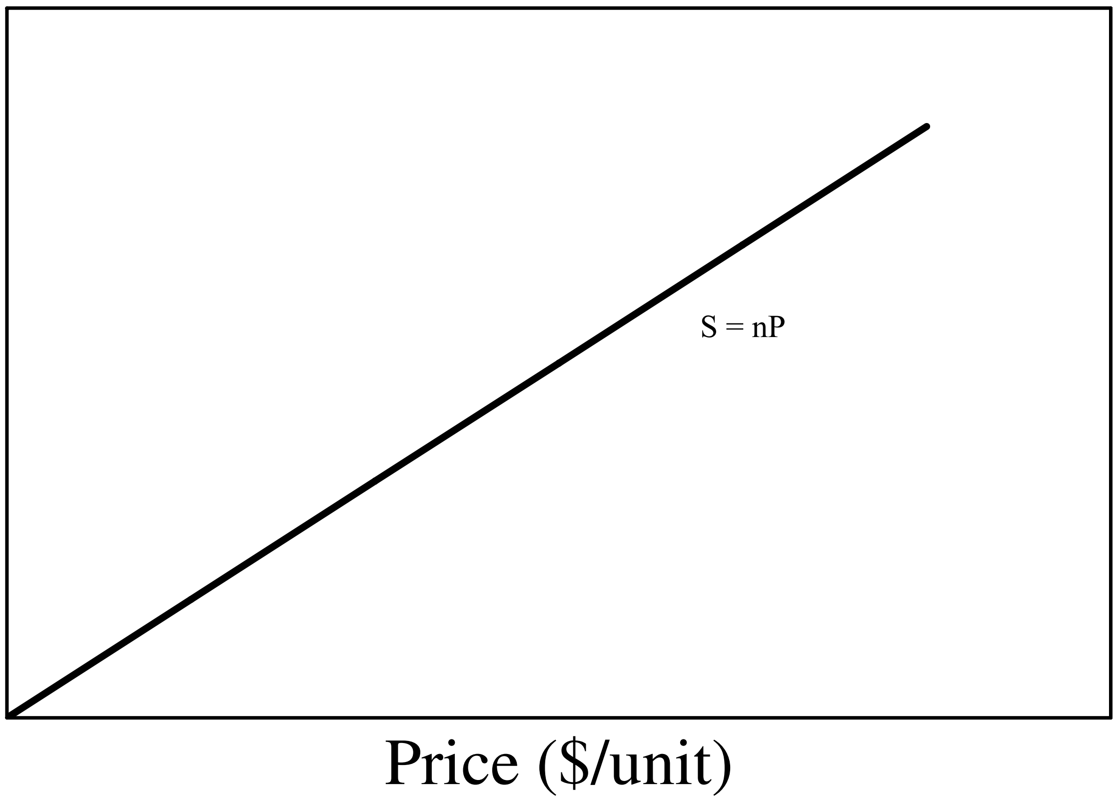


Figure 34-1 Supply versus Price Example

Now substitute the supply curve into the total revenue equation to get:

TR = P x number of items sold = PS

TR = nP^2

This is shown in Figure 34-2.

For this simple system:

What is the price that will maximize total revenue? Infinite

What is the supply that will maximize total revenue? Infinite

So the total revenue equation was correct – when price goes up, suppliers produce more, supply goes up and total revenue goes up! Right?

When something sounds too good to be true, it usually is.

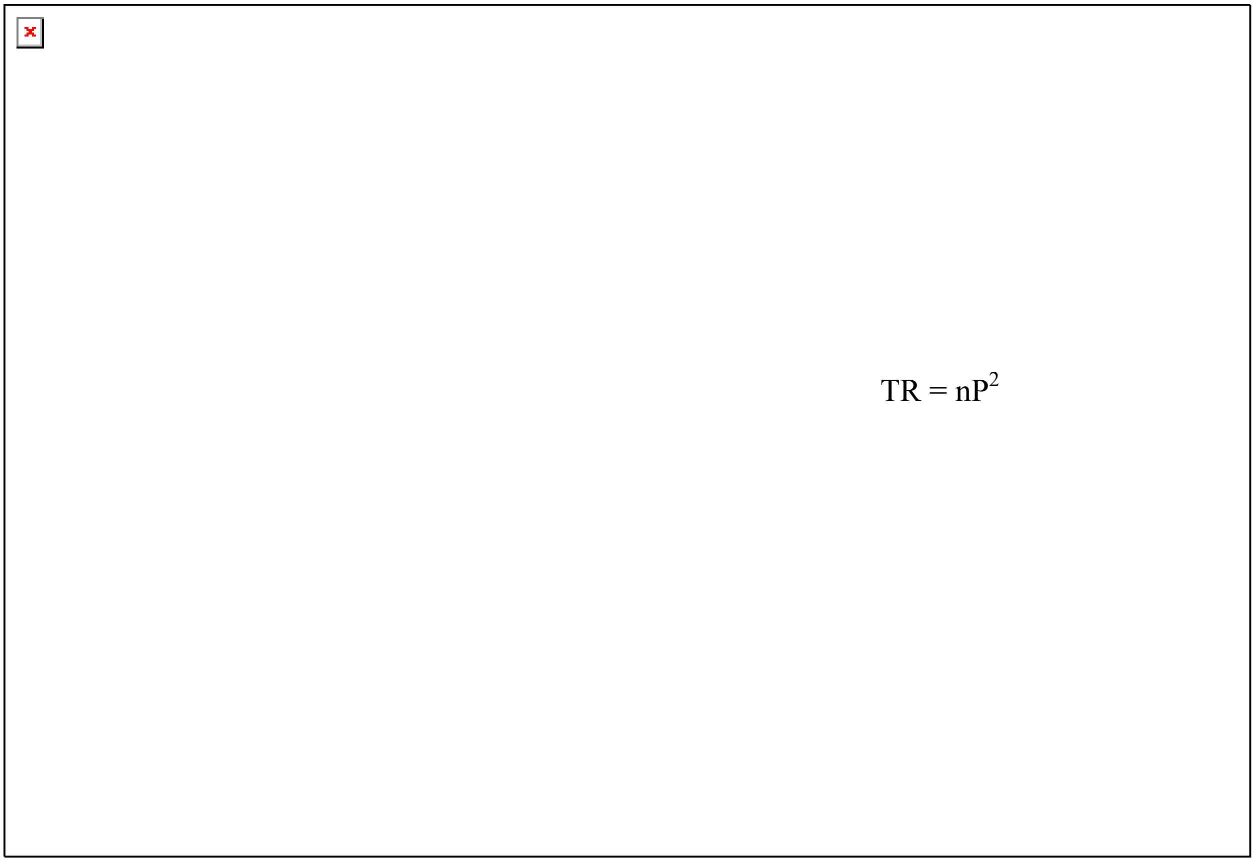


Figure 34-2 Total Revenue when Sold = Supply

What key assumption did I make that led us to the very rosy picture about total revenue?

I assumed that the number of items sold = supply

Is that assumption valid?

Not necessarily. Examining supply only does not present enough information.

So what must also be considered?

Demand.

Law of Demand: The quantity of product demanded by users/consumers tends to increase when price decreases and decrease when price increases, all else being equal.

A simple, linear demand versus price curve is $D = -mP + b$ where D is the number of items that the market will actually buy (Figure 34-3).

How does this relate to total revenue? Let the number of items sold equal demand:

$TR = P \times \text{number of items sold} = PD$

$TR = -mP^2 + bP$

This is shown in Figure 34-4.

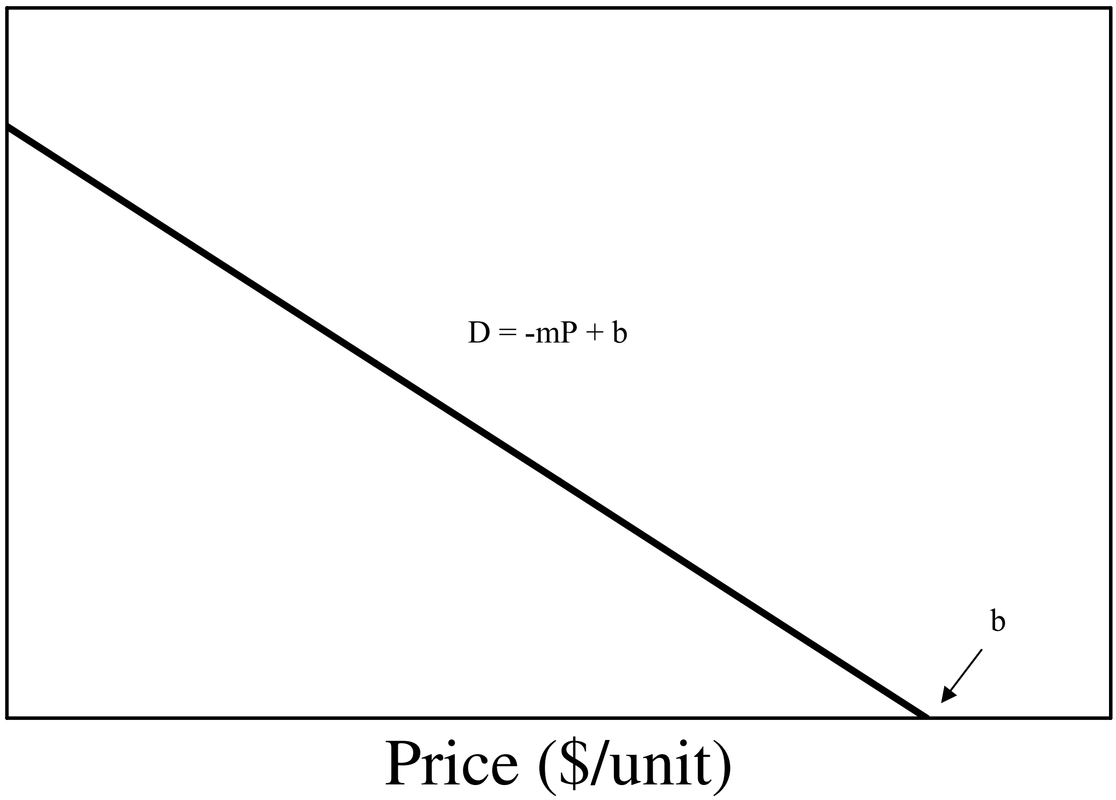


Figure 34-3 Demand versus Price Example

What is the price that will maximize total revenue? It is the top of the curve.
How can I determine the price that will maximize total revenue?

From calculus, the maximum (or minimum) can be readily determined by taking the derivative:

$$d(TR)/dP = -2mP + b$$

and solving for P that sets the derivative equal to zero:

$$P = b/2m$$

So the maximum total revenue will not occur at the maximum price or the maximum demand. Total revenue will decrease if the price is lower than above, even though more will be sold and total revenue will decrease if the price is higher because fewer items will be sold.

Interaction of Supply and Demand

Clearly, the supplier has a tough decision to make.

Should the total revenue equation be based on supply or on demand?

That is the wrong question. A better question is:

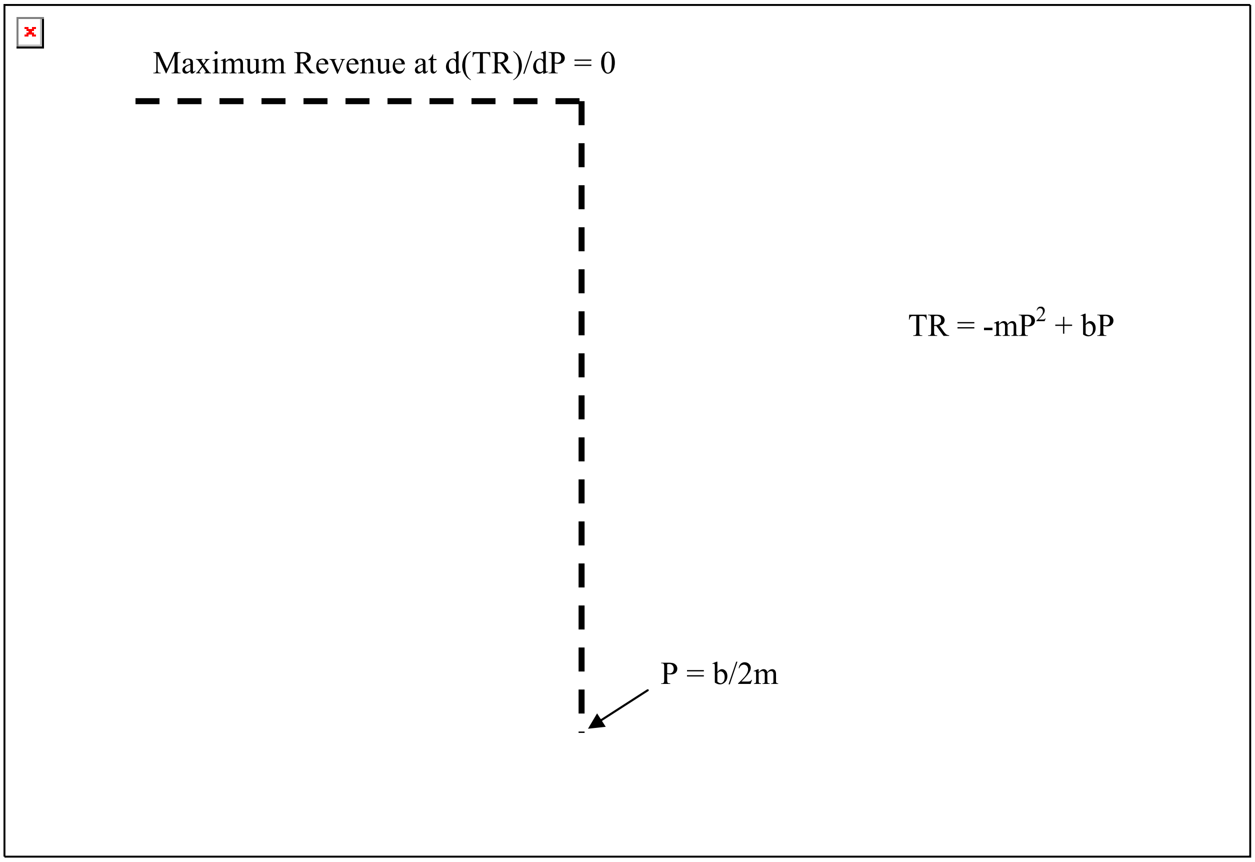


Figure 34-4 Total Revenue when Sold = Demand

<u>Does the supplier have any choice</u>?

Not really. Consider a plot of the supply and demand curves on the same graph (Figure 34-5) and three situations:

1. <u>The price is less than that of the intersection.</u>

In this case, the supply is much lower than the demand. This means that consumers are prepared to pay more. This is great for suppliers who want to sell more, and can do so at a higher price. So a price below the intersection point is unstable – price will increase, supply will increase and demand will decrease.

2. <u>The price is greater than that of the intersection</u>.

In this case, the supply is greater than the demand. This means that too few consumers are prepared to pay this price to meet the amount produced. The suppliers will be in big trouble if they continue this practice. The price must decrease. As it does, the demand increases but the supply decreases because suppliers have less incentive. As before, the price above the intersection point is unstable – price will decrease, supply will decrease and demand will increase.

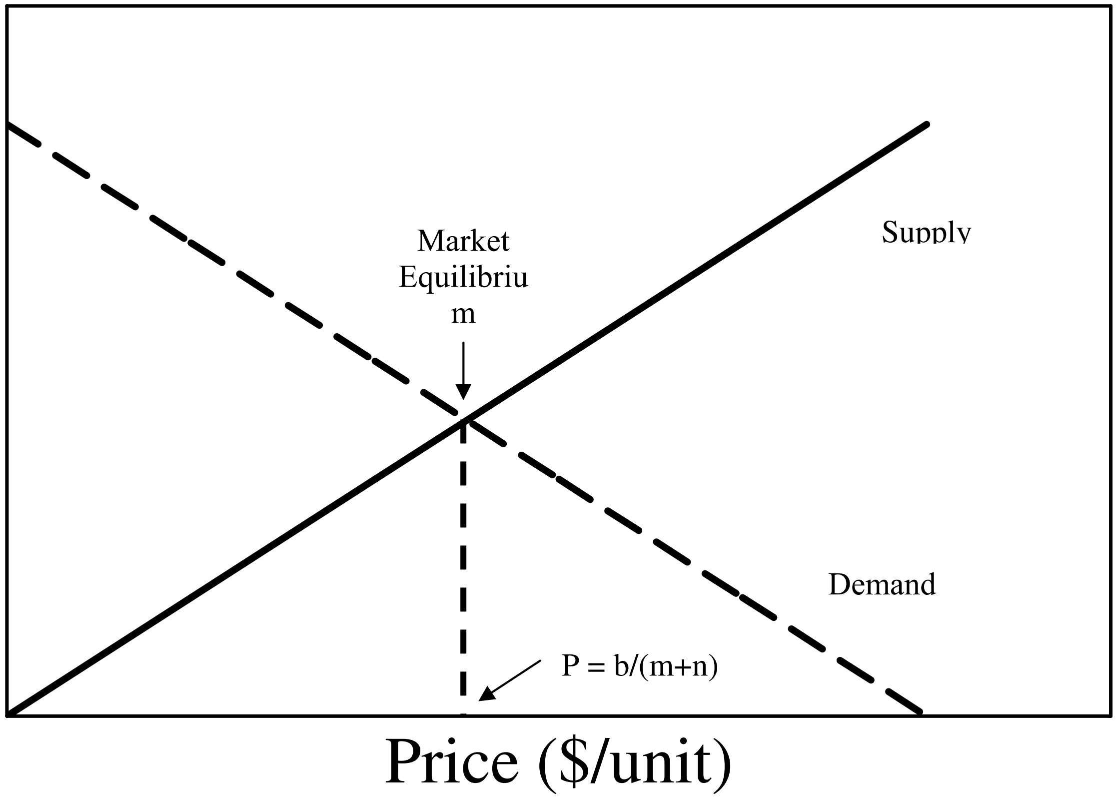


Figure 34-5 Supply and Demand versus Price

3. <u>The price is equal to that of the intersection</u>.

In this case, the system is stable. If the price is raised, the second option will occur, bringing the price back down. If the price is decreased, the first option will occur, bringing the price back up.

The marketplace, then, puts pressure to reach this stable point. How close is this to the point where the supplier achieves maximum total revenue? Solve for P at the intersection point:

$$-mP + b = nP$$

$$P = b/(m+n)$$

Recall that the maximum total revenue when demand was used as the number of items sold occurred when $P = b/2m$. So if $n = m$ then the supplier achieves maximum total revenue but otherwise the supplier does not.

Relevance

<u>Does the real world follow the laws of supply and demand</u>?

Yes, and no. The real world will follow these laws when the marketplace is 'suitable.' That is a pretty slushy definition and it should be driving you nuts. What does 'suitable' mean? Among other things it means:

1. The cost to enter the marketplace is not excessive. The supply curve depends on more supply being produced as the price increases. This may not happen. If the cost to produce more supply is too high, either more suppliers will not enter the marketplace and/or existing suppliers will not increase their supply.
2. Demand is <u>elastic</u>. The demand curve depends on consumers being ready and able to change their consumption habits as a function of price. When demand is inelastic, increasing or decreasing the price has little impact on demand. Typically, products like electricity and gasoline have relatively inelastic demand. Both are crucial to modern lifestyles so the demand will not change much as the price goes up.
3. There is not too much, or too little government regulation. Marketplaces that are perfectly unfettered by regulation are susceptible to suppliers who are prepared to act unethically to drive out competition. Too much regulation, on the other hand, can lead to inelastic demand or excessive cost to enter the marketplaces (items 2 and 1 above). The amount of regulation must be 'just right.'

So if supply and demand are only partly relevant, why did I spend so much time on it? Because even with the imperfections of these laws the following is clear:

If the supply of a crucial resource becomes limited, its price will rise dramatically.

The idea of sustainable development is to assure the availability of irreplaceable resources into the future. Doing this helps assure that the <u>supply</u> of these resources will remain stable, which will stabilize long-term pricing. In other words, by ensuring that raw materials will always be available, sustainable development ensures that economic activity as we know it can continue. Therefore, in the long-term **sustainable development is the only economically sound development**. Most of the short-term practices used today are neither sustainable nor economically sound, although these practices do enrich the personal wealth of a small number of individuals dramatically.

Costs

The laws of supply and demand govern the total revenue component of the profit equation. The reason sustainable practices are often not currently practiced, however, is often the cost side of the profit equation.

<u>Classification of Costs</u>

As mentioned earlier, there are internal and external costs. Most profit centers, at least currently and in the near future, will likely focus primarily on internal costs. These can be classified as follows:

1. <u>Capital costs</u>. These are the upfront, 'one-time' costs required to implement new technology. Typically, implementation of sustainable approaches will have upfront capital costs.

2. Operating costs. These are ongoing costs that are incurred repeatedly. Labor to operate a facility, maintenance to keep the major parts working, raw materials to produce the product, etc. are examples of operating costs.

Although both are called costs, capital costs and operating costs are not in the same units. Capital costs are in units of dollars while operating costs are in units of dollars per time. I left the profit equation in units of dollars. So for the profit equation as I wrote it, the operating costs must be multiplied by the appropriate time, corresponding to the time required to produce the number of items sold. I could have written the profit equation in units of dollars per time, in which case I would somehow have to convert the capital costs into those units. You can see that dealing with costs quickly becomes very complicated. In 3rd year, you will receive a course in engineering economics where you will learn how to manage these types of issues.

Regardless of the units, we know that the internal costs will be minimized when there is no production. In other words, if you spend no capital to make something you will have no need for operating expenses and your internal costs will be close to zero (zero if you spend no time at all thinking about this).

Will profit be maximized when costs are minimized?

No! Profit requires revenue! If no costs are incurred, then no revenues will be generated and so profit will be zero – definitely not maximized.

When will profit be maximized?

When the difference between total revenue and costs is maximized. Mathematically, you can take the derivative of the profit equation with respect to the variable of interest, solve for zero, and from that determine the maximum profit with respect to the variable of interest. This may occur at neither maximum total revenue nor minimum cost (indeed, I just proved why it won't occur at minimum cost!)

Can increasing capital costs decrease operating costs?

Absolutely! When considering only internal costs, the key question to be answered is whether spending money (as capital costs) to improve sustainability will sufficiently decrease operating costs so that the savings end up paying for the capital costs. As I mentioned earlier, this was exactly the case in California when electricity prices increased – wastewater treatment plants found that by spending capital costs to implement onsite electricity production, they saved enough in operating costs to pay for it.

Sustainability and External Costs

There are numerous external costs that are not paid directly by the profit center. The cost of environmental damage is a huge external cost that has been missed historically in economic thought. Currently, there is an increasing recognition that ecosystems have an inherent economic value and therefore their loss incurs a cost. Economists and engineers are working to assign value to environmental systems so that the costs of environmental damage can be properly incorporated into human activities. Similarly, societal costs due to poor health caused by everything from environmental damage to poor working conditions are enormous and missed in conventional economic thought.

The problem is how to internalize external costs so that they become part of the Accounting Profit picture. We know profit centers won't worry about things that they don't have to pay for, so external costs are just missed. The internalization of external costs will significantly help our economic systems move toward sustainability. Decisions will then be made based on True Profit, and the capital costs required to implement sustainable approaches will be more readily recovered because they will offset external operating costs. The challenge here isn't really engineering, though. The challenge is to transform an economic system based entirely on growth, where the physical laws of conservation of mass and energy are ignored to one based on ecological principles where the physical laws are followed. While this is occurring, engineers can nevertheless improve sustainability by working within the current economic structure. Indeed, as demonstrated with supply and demand, <u>sustainability is required</u> to keep the current system running.

<u>Lecture 35</u> Postlude – Grizzly Bears

(The material for this lecture was compiled from Marty, 1997; Backhouse, 1999; Payton, 2001; and Chadwick, 2001.)

Grizzly Bear Basics

The grizzly bear, *Ursus arctos horribilis*, is the second largest land predator in North America, behind the polar bear. It is a sub-species of the brown bear species *Ursus arctos* which includes the European and Asiatic brown bears as well as the Kodiak bear, *Ursus arctos middendorffi*, which is found only on three islands in Alaska. As a top predator, the grizzly bear can be considered a keystone species for the ecosystems it inhabitats. Therefore, examining the health of grizzly bear populations in North America can provide an indication of the health of the ecosystems. If the grizzly bear population is not robust in an ecosystem, the reasons can be identified and possibly addressed.

The worldwide brown bear population is estimated to be between 125,000-180,000. At least 65,000 and possibly 100,000 are estimated to live in the area of the former Soviet Union. Remnant populations of less than 100 are estimated in Spain, France and Italy. Approximately 58,000 brown bears (grizzly bears) remain in North America with about 32,000 in Alaska, 25,000 in Canada and 1,100 scattered in only 5 remaining ecosystems in the continental United States. In Canada, there are an estimated 5,000- 9,000 grizzly bears in the Yukon, 4,000-5,000 in the Northwest Territories, 700 in Alberta (down from about 6,000 in the early 1900s), with the remaining bears in British Columbia. Conservationists estimate the number of grizzly bears in BC to be about 5,000 – well below the official BC government estimate of 10,000-13,000 bears which is used to set provincial quotas for hunting the bears. There are believed to have been well over 100,000 grizzly bears in North America in the early 1800s.

The adult male grizzly bear ranges in mass from 135-390 kg depending on the habitat in which it lives. The biggest bears, typically over 300 kg, live on the west coast of BC and Alaska. The adult female grizzly bear is smaller, ranging from 95-275 kg. As with the males, the largest female bears, typically over 200 kg, live on the west coast of BC and Alaska. The bears living in the Rocky Mountain region are the smallest. For example, female bears living in the Banff area of Alberta are typically only 90-114 kg. When on all four legs, the bears are about 1 m tall but can be up to 2.6 m long overall.

Female grizzly bears bear live young with a mass of about 0.5 kg once every 3 to 4 years, depending on the quality of the food supply (3 years with a good food supply, 4 years in poorer habitat). There are typically 2 cubs per litter, although the litter size can range from 1-4 cubs. If the cubs can survive their first year, their natural life expectancy is 10-20 years, with the males reaching maturity at 8-10 years and the females reaching maturity at 4.5-7 years.

Diet and Energetics

Grizzly bears are omnivores, meaning that they will eat just about anything suitable, and even things that aren't suitable such as human garbage. The key energetic issue for grizzly bears is to store enough energy (as fat) to survive the winter hibernation which can last up to 6 months. During hibernation, an adult male grizzly bear may lose over 68 kg of fat. To prepare for hibernation, grizzly bears eat as much as they possibly can, especially in the late summer and fall, of material with the highest calorie content that they can find. Grizzly bears are also looking for the highest calorie content in the spring when they end their hiberation and are quite hungry.

The specific foods eaten by grizzly bears depend on the ecosystem in which they live. In the Khutzeymateen Grizzly Bear Sanctuary in British Columbia (a 44,300 ha refuge that contains about 60 grizzlies), the bears eat fish (salmon especially during the salmon run), insects, sedge, skunk cabbage, beach lovage, cow parsnips, nettles, ferns and berries. About 80% of their diet is vegetable. In the spring when hiberation ends, a particularly popular food is Lyngby's sedge (*Carex lynbgyei*), a grasslike plant. The fresh greenshoots and blades of the spring contain up to 28% protein making this a good food source for hungry bears. The high protein content is important because bears, somewhat like humans, have a relatively short digestive system and do not have multi-chambered foreguts like ruminants (such as cattle) that allow the digestion of cellulose. Therefore, when eating sedges, bears must consume 25-45 kg/day, the undigestible part of which will later be excreted.

In Banff National Park in Alberta, bears do not have access to salmon but eat other things including showy locoweed, ants, and berries. Some bears also find, unfortunately, the garbage that humans in Banff and other parts of the Bow River valley generate. In parts of the Rocky Mountains in the United States, such as the Yellowstone National Park ecosystem in Wyoming, bears eat everything from elk, hornet larvae, roots and bulbs stored in pocket gopher burrows, pocket gophers, to Army cutworm moths, berries and buffalo calves. The Army cutworm moth, with abdomens about the size of jelly beans, arrive in the alpine Yellowstone ecosystem in June/July from the prairies, as far away as Nebraska. When they arrive, they are about 40% fat. By late August, after eating nectar from alpine flowers during the night and hiding in rock crevices during the day, the moths are about 72% fat giving them the highest calorie per gram content of any bear food in the ecosystem (including deer and elk). The result is that big adult male grizzlies eat up to 2,500 moths per hour, or 40,000 moths per day and certain hot spots with a lot of moths may contain up to 23 grizzlies at a time eating these little balls of fat. At these times, the grizzly dung is mostly the hard little legs and compressed shiny wing parts that aren't digested.

Although grizzlies may eat up to 70,000 berries a day when in season, in parts of the Yellowstone ecosystem where perhaps moths and berries are less plentiful, researchers suggest that adult males may receive up to 70% of their energy from the meat of hoofed mammals. In Arctic ecosystems, arctic ground squirrels, which themselves grow fat on tundra herbs, make up a large portion of the grizzly bear diet.

To meet their energy needs, grizzly bears typically require a large amount of space. On average an individual male bear requires approximately 500 to 1,300 km^2 but may require up to 2,000 km^2 in less rewarding habitat. Female bears require less space, from about 130 to 750 km^2, again depending on the quality of the habitat with respect to food. As the range decreases, more bears can be found in the same area. For example, the rich Khutzeymateen Grizzly Bear Sanctuary contains 60 grizzlies in 443 km^2 for a density of 0.14 bears per km^2. Parts of the Alaska peninsula, also very rich habitat, contain 1,500 bears in 2,600 km^2, a density of 0.58 bears per km^2. On the other hand, on Alaska's north slope, only 4-5 bears live in the same 2,600 km^2, a density of 0.002 bears per km^2 and in Banff National Park, between 60-100 bears live in 6,641 km^2, giving a density of 0.009-0.015 bears per km^2. One issue in Banff is that only about 3% of the park's area is critical montane habitat – valley bottom and open forests, so much of the area is not suitable for the bears.

The Impact of Grizzly Bears on the Environment

Grizzly bears benefit the ecosystems in which they live. In the alpine ecosystems, bears are the main earth movers, digging up the soil with their claws when looking for roots to eat. This digging facilitates the planting of seeds and releases nitrogen in the subsurface to be used by plants. Bears also serve as a prime mover of berry seeds, which are principally excreted by bears in their dung.

A more recent impact of bears has been determined. Nitrogen is a key limiting nutrient in Pacific temperate rain forests along the west coast of North America. These forests receive up to 3 m of rain per year and produce more biomass per hectare than a tropical rain forest, making them one of the most ecologically productive ecosystems on the planet. Grizzly bears are an important source of the nitrogen in these ecosystems, albeit indirectly. On their return from the ocean to spawn in the freshwater rivers where they were born, salmon bring a tremendous source of nitrogen that they accumulated from another ecosystem (the open ocean) - themselves. During the salmon run, bears eat a great number of salmon, but only about 50% of the fish – the brain, dorsal muscles and, if present, eggs. The rest is left on the forest floor where scavengers, including gulls, crows, ravens, eagles and martens take what they want. Finally, ground beetles and fly larvae in addition to other detrivores finish decomposing the left over fish. Within a 45-day feeding frenzy near Bag Harbour on the Queen Charlotte Islands, bears left behind 4,800 rotting fish and many piles of bear dung. This "waste" accounts for 10-25% of the total available nitrogen in the forest within 400 m of the river. Some estimates indicate that trees in this area grow 60% faster than the same tree species in areas not fertilized by the activities of grizzly bears.

The Impact of Humans on Grizzly Bears

Humans have been tough on grizzly bears. Until the mid-20th century, grizzly bears were routinely killed because they were big, aggressive when threatened (but otherwise typically trying to avoid humans) and apparent killers of livestock (on average fewer than 50 cattle are killed per year in the lower 48 states due to grizzlies). Bears are still legally killed in B.C. (300 per year) and Alaska (1,000-1,600 per year) and illegally poached (up to 300 per year in B.C. alone). Bears are also killed in other jurisdictions where they have become habituated to humans (no longer afraid, in part because human garbage is not properly secured and in part because tourists continue to insist on feeding bears, although much less so than 50 years ago) and therefore a true hazard.

A subtler effect of humans on grizzly bears is habitat fragmentation. Given their large ranges, grizzly bears move around a lot. In fact, movement and intermingling of populations is important for maintaining genetic diversity of the species. Habitat fragmentation effectively isolates the Yellowstone bear population from others in North America. The Trans-Canada highway, Highway 1, dramatically isolates populations on the north and south side of the highway in the Bow River valley of Alberta, as does the development occuring in the valley and up to the town of Banff. Prior to constructing wildlife overpasses, very few bears could cross the 4-lane highway that had over 21,000 vehicles per day in the summer traveling at 100 km/hr or more. In 1996, only 4 male grizzly bears dared to cross the road. Female bears refused. The construction of wildlife overpasses should help, although there is concern that female bears may still refuse to cross.

Another important effect of humans on grizzly bears is the destruction of prey species. Salmon stocks have plummetted due to overfishing on the Pacific coast. This will lead to the decrease of bear populations in coastal areas where the salmon spawning runs provide a major source of nutrients. This may also lead to a decrease in productivity of the surrounding forest, as the amount of nitrogen introduced due to salmon remains and bear dung decreases. More subtle links may also exist, such as the one between Army cutworm moths and bears. If increased non-discriminate pesticide use occurs in the American prairies, say Nebraska which is a heavily agricultural state, will this decrease the number of moths that fly to the Yellowstone ecosystem, thus decreasing one of the richest sources of fat for bears in that area?

Conclusion

Grizzly bears clearly demonstrate the complex interrelatedness of environmental systems and provide an indicator of our impact on these systems. As engineers we shouldn't forget that something as apparently insignificant as bear dung in the woods may be critically important to ecosystem health and productivity, and ultimately to the health and productivity of our own human systems.

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