Boston University Global Development Policy Center
Economics in Context Initiative

Microeconomics and the Environment

By Brian Roach, Erin Lennox, and Anne-Marie Codur

An ECI Teaching Module on Social and Environmental Issues in Economics

Global Development Policy Center
Boston University
53 Bay State Road
Boston, MA 02155
bu.edu/gdp

Economics in Context Initiative, Global Development Policy Center, Boston University, 2024.

Suggested citation: Roach, Brian, Erin Lennox, and Anne-Marie Codur. 2024 “Microeconomics and the Environment.” An ECI Teaching Module on Social and Environmental Issues in Economics, *Economics in Context Initiative*, Global Development Policy Center, Boston University.

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Economics in Context Initiative
Global Development Policy Center
Boston University
53 Bay State Road, Boston, MA 02215
http://www.bu.edu/eci/

Email: eci@bu.edu

NOTE – terms denoted in **bold face** are defined in the **KEY TERMS AND CONCEPTS** section at the end of the module.

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1. INTRODUCTION

Environmental policies are often controversial. For example, should oil drilling be permitted in sensitive wildlife habitats? Should fossil fuel taxes be raised? Should society invest heavily in renewable energy to limit global climate change? Resolving these controversies requires us to draw upon various academic disciplines, such as ecology, political science, ethics, and sociology. Increasingly, the discipline of economics is at forefront of many environmental debates.

A common viewpoint is that economic goals generally conflict with environmental goals. But, as we will show in this module, this is not necessarily true. In fact, often a strong *economic* case can be made for environmental protection. The Nobel prize-winning economist Paul Krugman has written that:

> …my unscientific impression is that economists are on average more pro-environment than other people of similar incomes and backgrounds. Why? Because standard economic theory automatically predisposes those who believe in it to favor strong environmental protection.[1]

The module is organized into five subsequent sections:

- In the second section, we present key economic perspectives on environmental issues. Different economists approach the analysis of environmental issues in different ways. An understanding of these differences is important to gain insight into why economists sometimes disagree about environmental policies.
- Next, we explore the main ways standard economic theory is applied to environmental issues. One application is the theory of environmental externalities. The other applications concern the management of common property resources and public goods. In all these cases, we'll see that unregulated markets fail to produce the best outcomes for society, and that some form of government regulation is necessary to increase social welfare.
- In the fourth section, we study how economists "value" the environment in monetary terms. Through the technique of cost-benefit analysis, economists seek to determine which policies provide the greatest overall benefits to society. We consider both the advantages and limitations of this approach for guiding policy decisions.
- In the fifth section, we summarize different environmental policy options. We'll see that there is no universal "best" approach to regulating the environment. Different approaches are needed for different situations.
- Finally, we apply the economic concepts discussed in the module to three important policy issues: fisheries management, agriculture, and climate change. In each case, we'll see that economic policy tools can be used to promote more environmentally sustainable outcomes.

[1] Krugman, 1997.

2. ECONOMIC PERSPECTIVES ON THE ENVIRONMENT

Economic analysis of environmental issues can be approached from two different (though sometimes overlapping) perspectives: environmental economics and ecological economics. **Environmental economics**[2] applies insights from traditional economics to environmental issues. We will explore several of these topics in Section 3 of this module. Environmental economists recognize that the environment has value but tend to focus on environmental values in human terms, specifically those that can be measured monetarily. **Ecological economics** places greater emphasis on ecosystem integrity, stressing that all economic activity occurs within the broader biological and physical systems that support life. Thus, ecological economists are more likely to see the value of nature as something extending beyond any monetary estimates. We next explore the differences between these two approaches by considering how they address three important topics: defining sustainability, defining value, and assessing limits to growth.

2.1 Defining Sustainability

While the importance of sustainability is widely acknowledged, there is no universally accepted definition of it. According to a standard environmental economics approach, sustainability is typically defined as providing future generations of humans the capacity to be at least as well-off as the current generation. This perspective of sustainability, sometimes referred to as **weak sustainability**, seeks to maintain a constant (or improving) level of overall human well-being over time. According to weak sustainability, **natural capital** (such as the quality of air and water, the amount of wildlife habitat, and effective nutrient cycling) is largely substitutable with **produced capital** (such as factories, roads, and schools) and **human capital** (such as knowledge and productive skills). As long as the overall level of capital is maintained over time, weak sustainability is achieved.[3]

So, for example, in this perspective the loss of a wetland area (a reduction in natural capital) can potentially be offset by an increase in other types of capital (such as building a new hospital or increasing educational opportunities). Another way to view weak sustainability is that human well-being depends on the environment, but also depends on many other factors. Well-being can be maintained despite a reduction in natural capital as long as equivalent compensation is provided. Compensation may be something physical, such as a road or building, or it can be something intangible such as knowledge.

Note that weak sustainability implies that we need a metric for comparing different types of capital. For example, how do we know if building a new hospital is sufficient compensation for the loss of 100 acres of wetlands? Environmental economics tends to rely upon money value as a metric to compare different types of capital. Thus, techniques are required for converting environmental benefits into monetary units. We will discuss some of these techniques in Section 4.

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[2] Bolded key terms are defined at the end of the module.

[3] The use of terms such as “weak” and “strong” does not imply that one is better than the other. These terms refer to the specific assumptions made in defining different concepts of sustainability.

Ecological economics tends to advocate for **strong sustainability**, which does not consider natural capital substitutable with other types of capital. Instead, the objective of strong sustainability is to maintain the overall level of natural capital over time. Different types of natural capital may be considered substitutes, but only if important ecological functions can be adequately maintained. For example, cutting down a forest or filling a wetland may be consistent with strong sustainability as long as new trees of equivalent ecological value are planted or new wetlands are created elsewhere.

Like weak sustainability, strong sustainability requires a metric that will indicate whether compensation is sufficient. While natural capital can be measured in monetary terms for purposes of weak sustainability assessment, ecological economists often favor physical measures in assessing strong sustainability. For example, the biological productivity of natural habitats is sometimes used to measure their ecological value. Based on this approach, habitats such as wetlands and tropical rainforests are particularly productive, while tundra and deserts are less productive.

2.2 Defining Value

The differences between environmental and ecological economics in defining sustainability translate to different conceptions of "value." As environmental economics defines sustainability based on human well-being, the environment has value only to the extent that it is useful to humans. Some of these uses may involve extracting natural resources, such as harvesting trees or fish, but humans may also place value on passive uses of the environment such as watching a sunset or knowing that unspoiled places exist in the world.

The key concept in defining value according to environmental economics is the **willingness-to-pay (WTP) principle**. This states that the economic value of something is equivalent to the maximum amount of money people are willing to pay for it. If I am willing to pay, say, a maximum of $50 to ensure the protection of an endangered species, then $50 is the value of that species to me. In some cases, natural resources are sold in markets, and we can ascertain their economic value by studying such markets. But there are no markets for such things as clean air, endangered species, or National Parks. Environmental economists have developed various techniques for measuring economic values in these instances, as we'll discuss further in Section 4.

An advantage of the willingness-to-pay principle is that it allows economists to compare the relative value of different uses of a natural resource, such as whether a forest should be managed for timber harvesting or recreation. The willingness-to-pay principle can also be considered democratic in the sense that the values of all affected individuals should be elicited when making policy decisions. As long as someone is willing to back up his or her preferences with a willingness to pay amount, then their WTP is included in an economic analysis. However, we need to recognize that one's willingness to pay is directly related to one's ability to pay. So instead of operating under the democratic principle of "one person, one vote," the willingness-to-pay principle is based on "one dollar, one vote."

Some ecological economists also assess the value of natural capital using the willingness-to-pay principle. But ecological economists are also more likely to emphasize the limitations of this approach. Some kinds of natural capital such as ecosystems and species may have **inherent value** – a value that exists regardless of whether humans are willing to pay for it. Inherent value may derive from an ethical foundation of natural rights. Some ecological economists argue that each species has an inherent right to exist, and that driving a species to extinction, regardless of the potential economic benefits, is never justifiable. More broadly, the functions of complex ecosystems are essential to maintain life on earth, and degrading these ecosystems threatens to undermine any short-term monetary gains. These crucial ecosystem functions are unlikely to be captured by a willingness-to-pay metric.

Of course, inherent value and ecological complexity are difficult, if not impossible, to measure in a quantitative sense. Inherent value is also a subjective concept, based on individual notions of rights and fairness. A strictly economic principle would be to choose policy options that provide the maximum human benefits over time, based on the willingness-to-pay principle. But ecological economists tend to advocate for policies that maintain important ecological functions or satisfy certain ethical criteria such as providing basic needs and reducing inequality. These issues become more pressing in the light of the next topic: limits to economic growth.

2.3 Limits to Growth

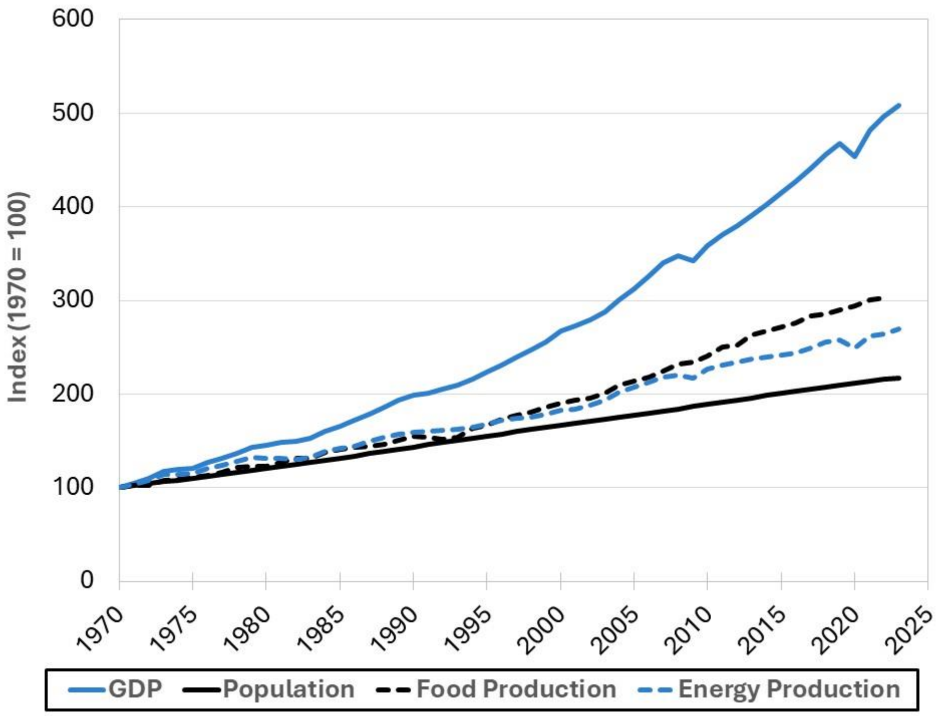
The final difference we'll consider between environmental and ecological economics concerns whether there are limits to economic growth. We can see in Figure 1 that global economic production, measured as total GDP and adjusted for inflation, has increased by a factor of more than 5 since 1970. Can such growth continue without approaching or exceeding ecological limits?

In 1798 the British economist Thomas Malthus published his famous *Essay on the Principle of Population*, in which he theorized that human population growth would tend to exceed food supplies, keeping the majority of people in a continual state of poverty. However, the original **Malthusian hypothesis** proved to be incorrect – in general, food production in Europe grew faster than population, contributing to an overall increase in average living standards.

More recently, starting in the 1960s, some researchers warned of a new version of the Malthusian hypothesis, in which natural resource constraints and ecological degradation threaten to slow or even reverse centuries of economic progress. But as we see in Figure 1, not only has economic production continued to outpace population growth, but per capita food and energy consumption are higher now than at any time in human history.

While Figure 1 does not support the Malthusian hypothesis, we cannot assume that continued growth and prosperity is assured. The data in Figure 1 do not include issues such as pollution levels, biodiversity loss, or global climate change, which could eventually limit further economic growth. The data also do not reflect the uneven distribution of economic prosperity, food production, and energy resources across the globe.

Figure 1. *Change in Global Economic Production, Energy Production, Food Production, and Population, 1970-2023*



Sources: World Bank, World Development Indicators online database (GDP and population); Food and Agriculture Organization of the United Nations, FAOSTAT (food production); Energy Institute, Statistical Review of World Energy (energy production).

As we mentioned above, environmental economics considers natural capital to be largely substitutable with produced and human capital. So even as some natural resources have been degraded over time, advances in technology have fostered more efficient resource use and invented substitutes (for example, fiber optics replacing copper wire). This process continues today, as fossil fuels are increasingly being replaced by renewable energy sources such as wind and solar.

Ecological economists are more concerned about the overall scale of human economic activities and their impact on the environment. The late Herman Daly, widely considered to be the founder of ecological economics, noted that an economic system designed for continual growth is fundamentally incompatible with a fixed biosphere. He has written that "as long as our economic system is based on chasing economic growth above all else, we are heading for environmental, and economic, disaster."[4]

[4] Daly, 2008.

Some ecological economists have devised methods for assessing the sustainability of humanity's ecological impacts. One such measure, the **ecological footprint**, suggests that we are already in a state of global "overshoot," in which humanity now requires the equivalent of 1.7 Earths to supply its resources and adequately assimilate its wastes.[5] This not only implies that further economic growth based on expanded resource use is unsustainable, but also that humanity's footprint needs to be scaled back significantly from current levels. Thus, ecological economists are more likely to accept the idea that natural resource constraints imply limits to economic growth, including the limited availability of nonrenewable resources, land, and the absorptive capacity of the atmosphere.

Finally, ecological economists are more likely to support policy action even when full information on whether a failure to act could result in catastrophic environmental impacts is lacking. Referred to as the **precautionary principle**, this approach implies that policy should err on the side of caution, even when the risks of a catastrophic outcome appear to be low. For an example of how the precautionary principle has been applied, see Box 1.

3. APPLICATIONS OF ECONOMIC THEORY TO THE ENVIRONMENT

Standard economic theory demonstrates that under certain assumptions unregulated markets, guided by the forces of supply and demand, allocate resources in an efficient manner. In other words, market outcomes maximize the total net benefits obtained by buyers and sellers. But when we consider the environmental impacts of market activity, the conclusion that unregulated outcomes are efficient is no longer valid. Using standard economic theory, we will show below how government intervention in markets can actually increase economic efficiency while also reducing environmental impacts.

In this section we also analyze the management of natural resources that tend to not be privately owned, such as ocean fisheries, groundwater, or the atmosphere. We'll see that market forces generally lead to over-exploitation of these resources. In these cases, a solution that is both economically efficient and ecologically sustainable normally requires a policy intervention.

3.1 Environmental Externalities

The concept of **externalities** is central to environmental economics. In economic terms, a market transaction creates an externality when it impacts someone other than the buyer and the seller.[6] For example, a firm which pollutes a river while manufacturing paper harms those who use the river for fishing, swimming, or drinking water. This **negative externality** might be measured in monetary terms – for example, the lost revenues of commercial fishers. Some damages may be more difficult to measure but no less important – for example, health costs caused by toxins in the water or the loss of enjoyment by those who can no longer swim in a polluted river.

[5] Global Footprint Network, 2024.
[6] For this reason, sometimes externalities are referred to as "third-party effects."

BOX 1. THE PRECAUTIONARY PRINCIPLE AND CHEMICALS POLICY

The United States Congress passed the Toxic Substances Control Act (TSCA) in 1976 to regulate the production and sale of chemicals. At the time, there were approximately 62,000 chemicals in commercial use in the country. TSCA effectively allows the continued use of these chemicals unless the U.S. Environmental Protection Agency (EPA) can prove, on a case-by-case basis, that a particular chemical is unsafe. Chemical manufacturers were not required to provide the EPA with any data regarding a chemical's toxicity unless requested. While the EPA has expressed concerns about the safety of 16,000 chemicals, due to resource limitations the agency has reviewed the risks of only a couple of thousand, and fully tested only about 200.

For the approximately 23,000 new chemicals introduced since the passage of TSCA, manufacturers are required to notify the EPA of their intention to produce the chemical, and to provide any toxicity data that are available. But as there are no minimum data requirements, the law creates an incentive for manufacturers to avoid rigorous testing of new chemicals. Under TSCA, the burden of proof is clearly upon the EPA to demonstrate a chemical is unsafe.

In sharp contrast to chemicals policy in the United States, the European Union's ambitious chemicals policy, REACH (Registration, Evaluation, Authorization, and Restriction of Chemical Substances), went into effect in 2007, and was phased in over an 11-year period. According to the text of REACH, the law is "underpinned by the precautionary principle."

Under REACH the burden of proof regarding a chemical's safety is on the chemical manufacturer, not the regulating agency. If a manufacturer cannot demonstrate the safety of the chemical, its use may be restricted or banned. REACH's requirements apply to all chemicals produced in or imported into the EU. The initial focus has been on testing those chemicals produced in high volumes (greater than 1000 metric tons per year) or of the greatest concern. By 2018 all chemicals produced in excess of one metric ton annually were required to be registered, evaluated for safety, and approved for manufacture.

Sources: Wilson and Schwarzman, 2009; European Commission, 2006.

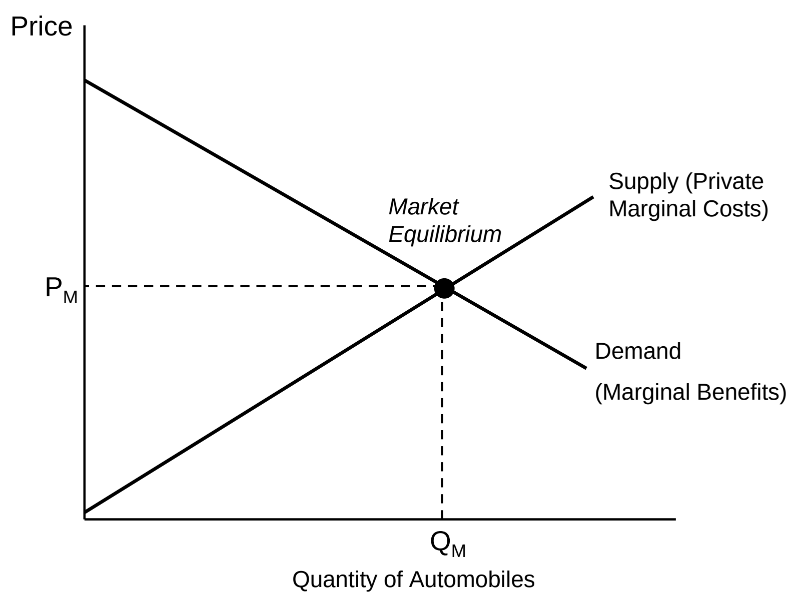
Some economic activities may bring benefits to people other than those involved in the activity. These third parties benefit from what economists call **positive externalities**. An example of a positive externality is the case of beekeeping. A honey farmer raises bees for his or her own benefit – in order to sell the honey they produce. This is a private activity with private benefits and costs. However, bees contribute to the pollination of flowers in the gardens and orchards of other people in the area, who benefit freely from this positive externality. The owners of these gardens receive an external benefit from the fact that their neighbor produces honey.

3.2 Economic Analysis of Negative Externalities

In a basic economic analysis of markets, supply and demand curves represent costs and benefits. A supply curve tells us the private **marginal costs** of production—in other words, the costs of producing one more unit of a good or service. Meanwhile, a demand curve can be considered a private **marginal benefits** curve because it tells us the perceived benefits consumers obtain from consuming one additional unit. The intersection of demand and supply curves indicates the **market equilibrium**, as shown in Figure 2 which presents a hypothetical market for automobiles. Notice that at the equilibrium price (P_M) the marginal benefits just equal the marginal costs. This equilibrium represents a situation of **economic efficiency** since it maximizes the total benefits to the buyers and sellers in the market – if there are no externalities.[7]

But this market equilibrium does not tell the whole story. The production and use of automobiles create numerous negative externalities. Automobiles are a major contributor to air pollution, including both urban smog and regional problems such as acid rain. In addition, their emissions of carbon dioxide contribute to global warming. Automobile oil leaked from vehicles or disposed of improperly can pollute lakes, rivers, and groundwater. The production of automobiles uses toxic materials which may be released to the environment as toxic wastes. The road system required for automobiles paves over many acres of rural and open land, and salt runoff from roads damages watersheds.

Figure 2. *The Market for Automobiles*



[7] Benefits to buyers are known as **consumer surplus** and benefits to sellers are called **producer surplus.**

Where do these various costs appear in Figure 2? The answer is that they do not appear at all. Thus, the market overestimates the net social benefits of automobiles because the costs of the negative externalities are not considered. We need to expand our analysis so it includes all the costs and benefits of automobiles, not just the market benefits.

In order to incorporate a negative externality into our market graph, it needs to be represented in monetary terms. Yet assigning a monetary value to environmental damages is not a straightforward task. How can we reduce the numerous environmental effects of automobiles to a single dollar value? There is no clear-cut answer to this question. In some cases, economic damages may be identifiable. For example, if road runoff pollutes a town's water supply, the cost of water treatment gives at least one estimate of environmental damages. This measure, however, doesn't include less tangible factors such as damage to lake and river ecosystems.

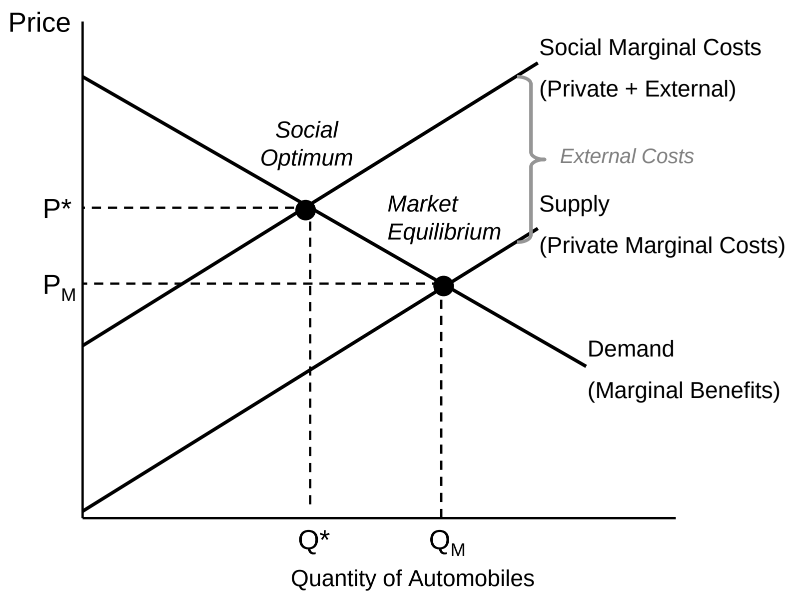
If we can identify the human health effects of air pollution, the resulting medical expenses will give us another monetary damage estimate. But we should also include the aesthetic damage done by air pollution. Smoggy air limits visibility, which reduces people’s welfare even if it doesn’t have a measurable effect on their health. While issues such as these are difficult to monetize, if we don't assign some monetary value to them the market will effectively assign a value of zero, as none of these issues are reflected in consumer and producer decisions about automobiles. We will discuss techniques economists use to estimate such value in Section 4.

Assuming we have a reasonable estimate of all external costs, how can these be introduced into our supply and demand analysis? Recall that a supply curve tells us the marginal costs of producing a good or service. The supply curve in Figure 2 shows what it costs automobile companies to produce vehicles. But in addition to the normal private production costs, we also need to consider the environmental costs—the costs of the negative externalities. We can add externality costs to the production costs to obtain the total *social* costs of automobiles. This results in a new cost curve which we call a **social marginal cost** curve, shown in Figure 3.

The social marginal cost curve is above the original market supply curve because it now includes the externality costs. Note that the vertical distance between the two cost curves is our estimate of the externality costs of automobiles, measured in dollars. In this simple case, we have assumed that the external costs of automobiles are constant. Thus, the two curves are parallel. This assumption helps to simplify our analysis, but in reality, the marginal external costs of automobiles may change depending on the number of automobiles produced. Specifically, the external costs of an additional automobile are likely to increase when more automobiles are produced as air pollution exceeds critical levels and congestion becomes more severe. This would be represented by a social marginal cost curve that slopes upward more steeply.

Considering Figure 3, is our market equilibrium still the economically efficient outcome? It is definitely not. To understand why, you can think of the social decision to produce each automobile as a comparison of marginal costs and benefits. If the marginal benefit exceeds the marginal cost, considering all benefits and costs, then from the social perspective it makes sense to produce that automobile. But if the costs exceed the benefits, then it doesn’t make sense to produce that automobile, as net benefits would decline.

***Figure 3**. The Market for Automobiles with Negative Externalities*



In Figure 3 we can see that it makes sense to produce the first automobile because the demand curve (reflecting the marginal benefits) is above the social marginal cost curve (reflecting the production and externality costs). Even though the first automobile creates some negative externalities, the high marginal benefits justify producing that first automobile. This is true for each automobile produced up to a quantity of Q*. At this point, the marginal benefits equal the social marginal costs. But then notice that for each automobile produced beyond Q*, the social marginal costs exceed the benefits. In other words, for each automobile produced above Q*, society is becoming worse off!

According to this analysis, the unregulated market outcome, at Q_M, results in a level of automobile production that is too high. We should only produce automobiles as long as the marginal benefits are greater than the social marginal costs. The optimal level of automobile production is thus Q*, not the market outcome of Q_M. Rather than producing the maximum benefits for society, the equilibrium outcome is inefficient in the presence of a negative externality. We can also see in Figure 3 that from the perspective of society, the market price of automobiles is too low—that is, it fails to reflect the true costs including the environmental impacts of automobiles. The efficient price for automobiles is P*, not the market price of P_M.

3.3 Internalizing a Negative Externality

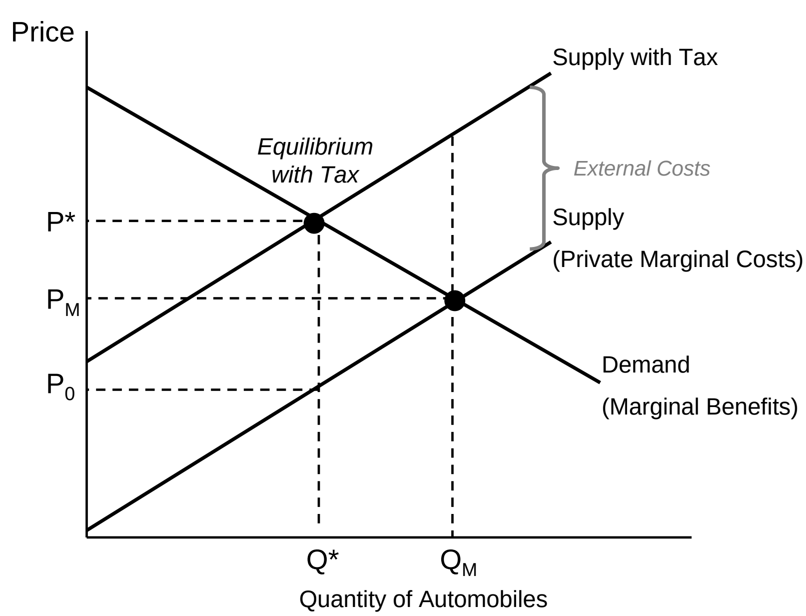
What can we do to correct this inefficient market outcome? The solution lies in getting the price of automobiles "right." The unregulated market fails to send a signal to consumers or producers that further production past Q* is socially undesirable. While each automobile imposes a cost upon society, neither the consumers nor the producers pay this cost. We need to "internalize" the externality so that these costs now enter into the market decisions of consumers and producers.

The most common way to internalize a negative externality is to impose a tax, known as a **Pigovian tax**, after the British economist Arthur Pigou. This approach is also known as the **polluter pays principle**, since those responsible for pollution pay for the damages they impose upon society.

For simplicity, assume that the tax is paid by automobile manufacturers.[8] For each automobile produced, they must pay a tax to the government. But what is the proper tax amount? By forcing manufacturers to pay a tax for each automobile produced, we've essentially increased their marginal production costs. A pollution tax thus has the effect of shifting the private marginal costs upwards. The higher the tax, the more we would shift the cost curve upwards. If we set the tax exactly equal to the externality damage associated with each automobile, then the new marginal cost of production would equal the social marginal cost curve in Figure 3. This is the "correct" tax amount—the tax per unit should equal the externality damage per unit.[9] In other words, those responsible for pollution should pay for the full social costs of their actions.

In Figure 4, the new supply curve with the tax is the same curve as the social marginal cost curve from Figure 3. It is the operative supply curve when producers decide how many automobiles to supply, because they now must pay the tax in addition to their manufacturing costs.

Figure 4. *Automobile Market with a Pigovian Tax*



[8] If we impose the tax on the consumer instead of the producer, we would reach the same result as we'll obtain here.
[9] Note that in our example, the externality damage is constant per automobile produced. If the externality damages weren't constant, we would set the tax equal to the marginal externality damage at the optimal level of production.

The new equilibrium results in a higher price of P* and a lower quantity of Q*. The tax has resulted in the optimal level of automobile production. In other words, automobiles are produced only to the point where the marginal benefits are equal to the social marginal costs. Also note that even though the tax was levied on producers, a portion of the tax is passed on to consumers in the form of a price increase for automobiles.[10] This causes consumers to cut back their automobile purchases from Q_M to Q*.

From the point of view of achieving the socially optimal equilibrium, this is a good result. Of course, neither producers nor consumers will like the tax, since consumers will pay a higher price and producers will have lower sales and profits, but from a social point of view we can say that this new equilibrium is optimal, or efficient, because it accurately reflects the true costs that automobiles impose on society. Society as a whole is better off with the tax because externality damages are reduced, and tax revenues can be used for socially beneficial investments.

Our story tells a convincing argument in favor of government regulation in the presence of negative externalities. Pigovian taxes are an effective policy tool for producing a more efficient outcome for society. But should the government always impose a tax to counter a negative externality? The production of nearly all goods or services results in some pollution damage. Does this mean that the government should tax *all* products on the basis of their environmental damage?

Determining the appropriate tax on every product that causes environmental damage would be a monumental task. For example, we might impose a tax on shirts because the production process involves growing cotton, using petroleum-based synthetics, applying toxic dyes, etc. But we would theoretically need to set a different tax on shirts made with organic cotton, or those using recycled plastics, or even shirts of different sizes!

Rather than looking at the final consumer product, economists generally recommend applying Pigovian taxes as far "upstream" in the production process as possible. An **upstream tax** is imposed on raw materials and other inputs into production processes, such as the crude oil or raw cotton used to make a shirt. If we determine the appropriate Pigovian tax on cotton, then this cost will translate to a higher final selling price of a shirt. We could focus our taxation efforts on those raw materials that cause the most ecological damage. Thus, we might tax fossil fuels, various mineral inputs, and toxic chemicals. This limits the administrative complexity of tax collection and avoids the need for estimating the appropriate tax for a multitude of products.

3.4 Positive Externalities

Just as it is in society's interest to internalize the social costs of pollution using Pigovian taxes, it is also socially beneficial to internalize the social benefits of activities that generate positive externalities. Just as with a negative externality, the free market will also fail to maximize social welfare in the presence of a positive externality. And for the same reason, a policy intervention can be used to reach an efficient outcome.

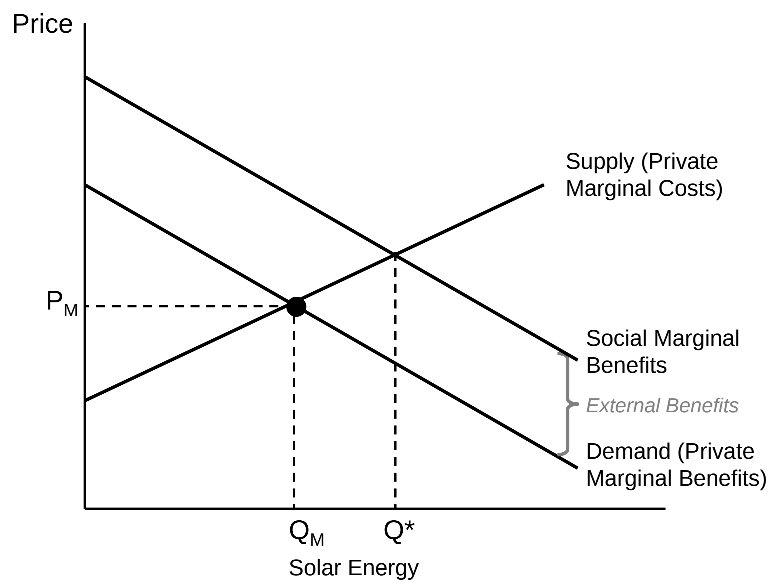
[10] Note that the price of automobiles did not rise by the amount of the tax. In Figure 4 the vertical distance between P_0 and P* equals the per-unit tax. But the price only rose from P_M to P*. So, while some of the tax was passed on to consumers, automobile manufacturers also bear some of the burden of the tax in terms of lower profits.

A positive externality is an additional social benefit from a good or service above the private, or market, benefits. Since a demand curve tells us the private marginal benefits, we can incorporate a positive externality into our analysis as an upward shift of the demand curve. This new curve represents the total social benefit of each unit.

Figure 5 shows the case of a good that generates a positive externality—solar panels. Each solar panel installed reduces emissions of carbon dioxide, and thus benefits society as a whole. The vertical distance between the market demand curve and the **social marginal benefits** curve is the positive externality per solar panel, measured in dollars. In this example, the social benefits are assumed to be constant per panel, so the two benefit curves are parallel.

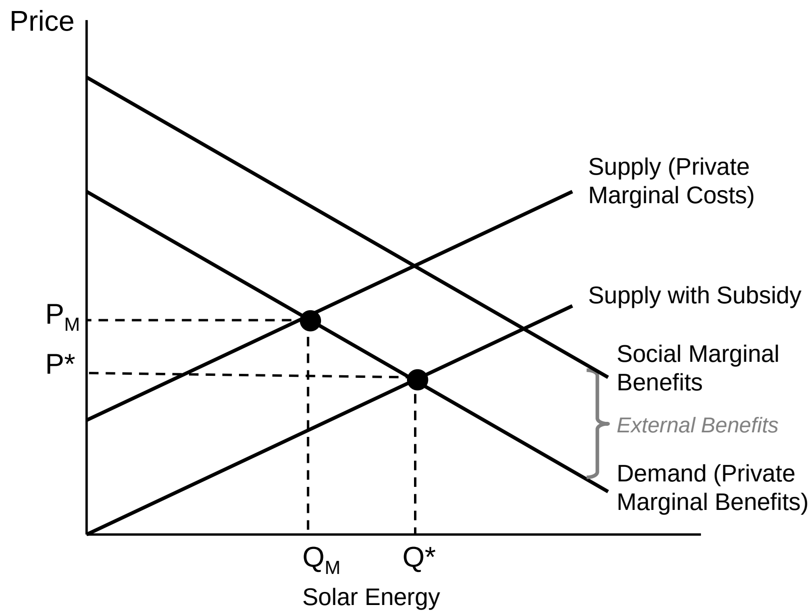
The unregulated market equilibrium price is P_M and quantity is Q_M. But notice in Figure 5 that between Q_M and Q*, marginal social benefits exceed the marginal costs. Thus, the optimal level of solar energy is Q*, where social marginal benefits just equal the marginal costs, not Q_M. We can therefore increase net social benefits by increasing the production of solar energy.

Figure 5. *The Market for Solar Energy with Positive Externalities*



In the case of a positive externality, the most common policy to correct market inefficiency is a subsidy. A **subsidy** is a payment to producers, normally a set amount per unit, to provide an incentive for them to produce and sell more of a good or service. The way to illustrate a subsidy in our market analysis is to realize that a subsidy effectively lowers the cost of producing something. A subsidy lowers the supply curve by the amount of the per-unit subsidy. In essence, a subsidy makes it cheaper to produce solar panels. The "correct" subsidy shifts the supply curve such that the new market equilibrium will be at Q*, which is the socially-efficient level of production. This is illustrated in Figure 6. The principle mirrors the use of a tax to discourage economic activities that create negative externalities—except that in this case we want to encourage activities that have socially beneficial side effects.

Figure 6. *Market for Solar Energy with a Subsidy*



3.5 Public Goods and Common Property Resources

The above analysis shows that unregulated markets are not efficient in the presence of externalities. While private goods, such as automobiles, apples, and computers, are normally distributed through markets, economic analysis of other goods requires different models. In this section, we consider the allocation of **common property resources** and **public goods**.

Private goods are **excludable**, meaning that the legal owners of them can prevent other people from enjoying the goods' benefits. For example, if I am the owner of an automobile, I can legally prevent anyone else from using it. But many natural resources are **nonexcludable**, meaning that the benefits of these resources are available to anyone. For example, in absence of regulation an ocean fishery can be accessed by anyone, or the atmosphere is freely available to all as a repository of pollution.

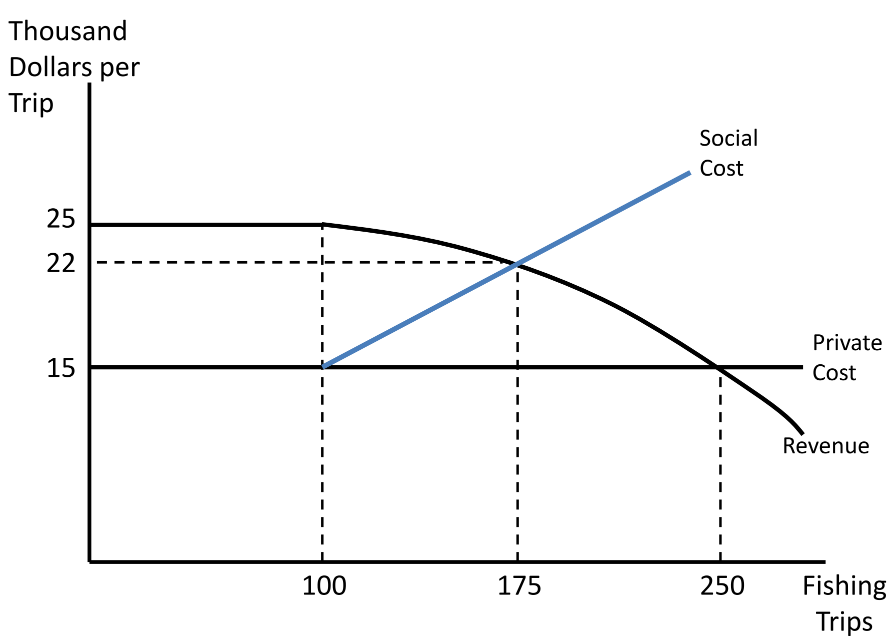
Economists differentiate between public goods and common property resources. While both of these are nonexcludable, they differ in terms of whether multiple people can benefit from them at the same time. Public goods are **nonrival**, meaning that many people can enjoy these goods at the same time, without affecting the quantity or quality of the good available to others. An example of a public good is national defense – the benefits I get from national defense do not diminish the benefits others receive. Common property resources are typically **rival**, meaning that use of the resource by one person reduces the quantity or quality of the resource available to others. An example of a common property resource would be groundwater. If I withdraw some groundwater, that water is not available for others to use.

3.6 Management of Common Property Resources

This section considers whether regulation is desirable in the case of a common property resource, using the example of an ocean fishery. Initially, assume that the fishery is not regulated, so that anyone who wants to can access the fishery. If only a few people access the fishery, then adding one more fisher is unlikely to affect the catch of anyone else. But as total fishing pressure increases, eventually adding more fishers will begin to harm the health of the fishery, thus reducing the catch of each fisher. We can think of this situation as similar to a negative externality – in an already crowded fishery an additional fisher imposes a cost on all other fishers. But as each fisher only considers his or her own profits, this external cost does not enter into their fishing decision.

Figure 7 illustrates this situation. Suppose that it costs $15,000 to operate a fishing trip, including the cost of labor, fuel, and supplies. If there are only a few fishing trips occurring in the fishery, each boat trip yields $25,000 in revenues, and thus a $10,000 profit.[11] This is true as long as the total number of fishing trips is less than 100, as shown in the figure.

Figure 7. *Common Property Model of a Fishery*



[11] In this simple example we assume that all fishing trips are the same. Thus, the cost of each trip is constant at $15,000 and the revenue per trip does not vary for different fishers.

But once the fishing pressure exceeds 100 trips, the amount of fish caught per trip begins to decline as the health of the fishery is impaired. With less fish caught, revenue per trip also declines. Each additional fishing trip above 100 trips further reduces the revenue per trip for everyone – the fishery has become rival.

While the fishers will notice the decline in their revenues, as long as each one is still making a profit they will continue to fish. In the figure, we see that the revenue per trip exceeds cost per trip up to 250 fishing trips. As long as there are less than 250 trips, there is an incentive for more trips to occur as each trip will be profitable. Only when we get to 250 trips does the revenue per trip equal the cost per trip, and there is no further incentive for more trips. Thus 250 trips is the eventual outcome in the fishery without any regulation.

Is this outcome optimal from the perspective of the fishery as a whole? When only 100 trips were being taken, each fisher was earning a $10,000 profit per trip. But at 250 trips, each fisher is barely covering his or her costs. So from the industry perspective, 250 trips are clearly not optimal as total profits have essentially been eliminated. Further, from an ecological perspective the health of the fishery is likely to further decline as it is being overfished. This outcome is known as the **tragedy of the commons**, in which individuals acting in their own self-interest tend to exploit a common property resource, leading to a sub-optimal social outcome and resource degradation.

We can determine the optimal social outcome using the same principle that we applied when internalizing a negative externality. The blue Social Cost line in Figure 7 adds to the private cost of fishing the amount that each additional fishing trip reduces the profits of all other fishers. In other words, the Social Cost line represents the $15,000 private cost of operating a boat trip plus the external cost equal to the reduction in others' profits.

The socially efficient level of fishing trips is 175 in Figure 7. Up to this point the revenue per fishing trip exceeds the social cost. This level of fishing maximizes the profits in the fishing industry. Also, this lower level of fishing effort is more likely to be ecologically sustainable.

One solution to avoid the tragedy of the commons is to institute a fee for each fishing trip, much like a Pigovian tax. At 175 trips, the external cost of an additional fishing trip is $7,000 (the difference between the social cost and the private cost). So if the fee for a fishing trip were $7,000, then there would be no incentive for fishers to take additional trips beyond 175 trips. Above 175 trips, the total cost of a fishing trip would be $22,000 (the $15,000 private cost plus the $7,000 fee) but the revenue would be less than $22,000.

Another solution is to institute **individual transferable quotas (ITQs)**. With this approach a government sets the total allowable fishing effort – in this case, 175 trips – and then permits for each trip are allocated either for free or at auction to the highest bidders. Holders of ITQs can use these permits to fish or sell them to interested parties. In principle, the value of a permit would equal the potential profits to be made from a fishing trip. The price of ITQs are not set by the government, but allowed to vary based on supply and demand. ITQ programs for ocean fisheries have been established in several countries, including Australia, Canada, Iceland, and in some United States fisheries.

3.7 Management of Public Goods

Public goods are both nonexcludable and nonrival. So even if everyone in society benefits from a public good, degradation of the good is not a potential problem. Instead, the problem with public goods is that they tend to be under-supplied by private markets, if they are supplied at all. With a private good, the fact that people must pay the market price for it in order to receive its benefits allows sellers to make profits. But with a public good, people can obtain the benefits of the good *without paying*.

Consider national defense as an example of a public good. Could we rely upon some mega-corporation to provide national defense in a market setting? No, because there would be no way for the corporation to sell the product to individual buyers. No individual would have an incentive to pay because they could receive essentially the same level of benefits without paying. Thus the "equilibrium" quantity of public goods in a market setting is normally zero, as no company would want to produce something that no one is willing to pay for.

Perhaps we could rely on donations to supply public goods. This is done with some public goods, such as public radio and television. Also, some environmental groups conserve habitats that, while privately owned, can be considered public goods because they are open for public enjoyment. Donations, however, generally are not sufficient for an efficient provision of public goods. Since public goods are nonexclusive, each person can receive the benefits of public goods regardless of whether they pay. For example, some people are willing to donate money to public radio but many others simply listen to it without paying anything. Those who benefit from public goods but do not pay are called **free riders**.

While we cannot rely on private markets or voluntary donations to fund the provision of public goods, their adequate supply is of crucial interest to the whole society. In democracies, decisions regarding the provision of public goods are commonly decided in the political arena. This is generally true of national defense. A political decision must be made, taking into account that some citizens may favor more defense spending, others less.

Similarly, decisions on the provision of environmental public goods are made through the political system. The U.S. Congress, for example, must decide on funding for the National Park system. Should more land be acquired for parks? Should some existing park areas be sold or leased for development? We may obtain information on whether the current supply of certain public goods is too high or too low based on opinion surveys. Or we may rely upon elected officials to make public goods decisions on behalf of their constituents. Once the appropriate level of public goods provision is determined, the necessary funds are obtained through taxes.

Paying for public goods using taxes effectively avoids the free rider problem. However, issues of fairness may arise, as the structure of the tax system determines who pays for public goods, and how much. Inevitably, some people will feel they are taxed too heavily, or that they are paying for public goods from which they do not benefit personally. Resolving these issues demonstrates that management of public goods is as much a political problem as an economic problem.

4. VALUING THE ENVIRONMENT

As we discussed in Section 2, environmental economics measures value according to the willingness-to-pay principle. Ecological economics is more likely to consider the inherent value of natural capital. In either case, economists recognize that the environment has value beyond just its market uses, such as supplying timber, fish, and agricultural land. Policy makers need to determine whether natural resources should be used for market uses or non-market benefits, including:

1. **Recreation**: natural sites provide places for outdoor recreation including camping, hiking, fishing, hunting, and viewing wildlife.
2. **Ecosystem services**: these are tangible benefits obtained freely from nature as a result of natural processes, including nutrient recycling, flood protection by wetlands, waste assimilation, carbon storage in trees and soils, water purification, and pollination by bees.
3. **Nonuse benefits**: these are non-tangible benefits that we obtain from nature. Nonuse benefits include the psychological benefits that people gain just from knowing that natural places exist, even if they will never visit them. The value that people get from knowing that ecosystems and species will be available to future generations is another type of nonuse benefit.

The **total economic value** of a natural system is the sum of all the benefits people are willing to pay for. Thus, the total economic value of a National Forest would be the sum of any profits obtained from timber harvesting, the willingness to pay of all those who recreate in the forest, the value of the ecosystem services such as soil erosion prevention and carbon storage, and the nonuse benefits people obtain by simply knowing the forest exists.

It is important to realize that in calculating total economic value priority is not given to any particular use of the forest. When uses are incompatible, such as deciding whether a particular tract of forest should be clear cut or preserved for recreation and wildlife habitat, economic analysis can help to determine which use provides the highest overall value to society.

4.1 Nonmarket Valuation Methodologies

If we are to estimate total economic value, we need techniques to estimate such values as recreation benefits, ecosystem services, and nonuse values. In addition, we need a measure of the damages caused by negative environmental externalities. These techniques are referred to as **nonmarket valuation**, because they produce benefit estimates for goods and services that aren’t directly traded in markets. There are four main types of nonmarket valuation techniques:

1. Cost of illness method
2. Replacement cost methods
3. Revealed preference methods
4. Stated preference methods

Each of these methods has advantages for analyzing particular issues, and also has some disadvantages and limits, as summarized below.

4.2 Cost of Illness Method

The **cost of illness method** is used to estimate the damages from reductions in environmental quality that lead to human health consequences. Conversely, it can be used to estimate the benefits of improvements in environmental quality (i.e., the avoided damages). This method estimates the direct and indirect costs related to illnesses attributed to environmental factors. The direct costs include medical costs such as office visits and medication paid for by individuals and insurers, and lost wages due to illness. Indirect costs can include decreases in human capital (such as a child missing a significant number of school days due to illness), welfare losses from pain and suffering, and decreases in economic productivity due to work absences.

The cost of illness method generally only provides us with a **lower-bound estimate** of the willingness to pay to avoid illnesses. The true WTP could be greater, since the actual expenses may not capture the full losses to individuals or society from illness. But even a lower-bound estimate could provide policy guidance. A 2019 study estimated that the direct medical costs of asthma in the United States will be about $300 billion over 2019-2038.[12] When the value of lost economic productivity is also included, the costs rise to more than $960 billion. While the study did not value losses from pain and suffering or reduced human capital, these estimates still provide a starting point to determine whether efforts to reduce asthma cases are economically efficient.

4.3 Replacement Cost Methods

Replacement cost methods can be used to estimate the value of ecosystem services. These approaches consider the cost of actions that substitute for lost ecosystem services. For example, a community could construct a water treatment plant to make up for the lost water purification benefits from a forest habitat. The natural pollination of plants by bees could, to some extent, be done by hand or machine. If we can estimate the costs of these replacement actions, in terms of construction and labor costs, these may be considered an approximation of society's willingness to pay for these ecosystem services.

While replacement cost methods are often used to estimate ecosystem service values, they are not necessarily measures of WTP. Suppose a community could construct a water treatment plant for $50 million to offset the water purification services of a nearby forest. This estimate doesn't tell us whether the community would actually be willing to pay the $50 million should the forest be damaged. Actual WTP could be greater or less than $50 million. For example, if the community actually pays $50 million for the water treatment plant, then $50 million would represent a lower-bound estimate of their maximum WTP.

[12] Yaghoubi *et al*., 2019.

4.4 Revealed Preference Methods

While markets don't exist for many environmental goods and services, we can sometimes infer the values people place on them through their behavior in other markets. **Revealed preference methods** are techniques that obtain nonmarket values based on people's decisions in related markets. While economists generally prefer deriving nonmarket values based on actual market behavior, there is a limited category of environmental benefits that can be estimated using revealed preference methods.

One common type of revealed preference method is **travel cost models**. These models are used to estimate the economic benefits people obtain by recreating at natural sites such as National Parks or lakes. Even if the recreation site doesn't charge an entry fee, all visitors must pay a "price" equal to their costs to travel to the site, such as gas, plane tickets, accommodations, and even the time required to travel to the site. As visitors to a recreation site from different regions effectively pay a different price, economists can use this information to derive a demand curve for the site using statistical models, and thus estimate **consumer surplus** – the net benefit derived by consumers from recreation at this site. Travel cost models are most applicable for recreation sites that attract visitors from distant places, in order to provide enough variation in travel costs to estimate a demand curve.

Numerous travel cost models have estimated the recreational benefits of natural sites. For example, a 2024 study of visitors to the Baltic Sea found that total recreational benefits to nine coastal countries were over €27 billion annually, and that improvements in water quality and infrastructure could boost annual benefits by €6 billion.[13] Other recent travel cost analyses have estimated the benefits of wetland restoration in China[14], damages from coral reef degradation due to climate change in Hawaii[15], and the recreational benefits of Awash National Park in Ethiopia.[16]

Another type of revealed preference method is the **defensive expenditures approach**. In some situations people are able to take actions to reduce their exposure to environmental harms. For example, people with concerns about their drinking water quality may choose to purchase bottled water or install a water filtration system. These expenditures may reflect their willingness to pay for water quality. A 2018 study in China used expenditures on particulate-filtering facemasks to infer the potential benefits of improved air quality.[17]

A limitation of the defensive expenditures approach is that people may be taking defensive actions for a variety of reasons, some unrelated to environmental quality. For example, other reasons for buying bottled water may include convenience or status. Thus, attributing the entire cost of bottled water as a measure of concern about drinking water quality would not be appropriate in such cases. It also suffers from the inherent problem of any market valuation: the preferences of the rich weigh much more heavily than the preferences of the poor. Plenty of people around the world who are

[13] Czajkowski *et al.*, 2024.
[14] Dai *et al.*, 2022.
[15] Fezzi *et al.*, 2023.
[16] Ashim and Shete, 2022.
[17] Zhang and Mu, 2018.

actually suffering from the health effects of impure water may not be able to afford to buy bottled water; thus their willingness to pay is made invisible by their inability to pay.

In addition to the problem of unequal ability to pay, revealed preference approaches generally cannot be used to obtain benefit estimates for many ecosystem services and nonuse values. We next consider a valuation technique that can theoretically be used to value any environmental service or natural resource.

4.5 Stated Preference Methods

The final nonmarket valuation technique we consider is the most used, as well as the most controversial. **Stated preference methods** use surveys to obtain information about people's preferences in a hypothetical scenario. The most common stated preference method is **contingent valuation**, in which survey respondents are asked questions about their willingness to pay for hypothetical outcomes.

The main advantage of contingent valuation is that surveys can be designed to ask respondents about *any* type of environmental benefit. For example, a 2022 study in Spain asked people about the price premium they would pay for beef that is raised without the use of burning to clear grazing land.[18] A 2023 paper asked Egyptians about their willingness to pay to improve air quality in the Cairo metro area.[19]

While hundreds of contingent valuation studies have been conducted over the last several decades, the validity of the results remains highly controversial. Given that respondents' preferences are based on a hypothetical scenario, and they don't have to actually pay anything, some economists consider the results flawed due to various biases. For example, a respondent who generally favors environmental quality improvements may have an incentive to overstate his or her actual WTP in order to influence the policy process. Some respondents may not accurately consider their income limitations when stating WTP values; this gets around the "ability to pay" problem but does not produce the kind of WTP estimates that economists consider valid.

Some of the problems associated with contingent valuation can be avoided by using **contingent ranking**, another stated preference method. With contingent ranking, respondents are asked to simply rank various hypothetical scenarios according to their preferences. Thus there is no potential for respondents to exaggerate their willingness to pay.

4.6. Cost-Benefit Analysis

The nonmarket valuation methods discussed above can be used to estimate the positive and negative externalities associated with different products. They can also provide guidance on appropriate public policies. For example, consider how we might evaluate a proposed law to increase air quality standards. We might ask whether the benefits of the policy exceed its costs. Environmental economists use the technique of **cost-benefit analysis** (CBA) to estimate the net

[18] Deely *et al*., 2022.
[19] Ganhem *et al*., 2023.

benefits (i.e., the benefits minus the costs) of proposed projects or policies, measuring impacts in monetary units.

In theory, measuring all impacts in dollars (or some other currency) produces a "bottom-line" result (i.e., a single number) so we can choose which option results in the greatest net social value. In practice, however, cost-benefit analyses are often incomplete. The results are often dependent on specific assumptions. Sometimes one side of the analysis—the costs or the benefits—may be much more fully developed than the other, making it difficult to obtain an objective recommendation.

The basic steps of a cost-benefit analysis are relatively straightforward:

1. List all costs and benefits of the project or policy proposal. Typically, this is done for several different scenarios including a baseline, or status quo, scenario.
2. Convert all costs and benefits to monetary values, if possible. Some values can be obtained based on market analysis, while other values will require nonmarket valuation.
3. Add up all the costs and benefits to determine the net benefits of each scenario. Sometimes the results are expressed as a ratio (i.e., benefits divided by costs).
4. Choose the scenario that is the most economically efficient.

Perhaps the most appealing feature of CBA is its seeming objectivity. It also presents a way to argue for environmental protection in economic terms, rather than on ethical or ecological terms. Many CBAs have shown that the willingness to pay for environmental protection can be quite large.

Of course, all the problems with the nonmarket valuation techniques discussed earlier can complicate cost-benefit analysis. Further, two additional issues often arise in environmental CBAs: how to value costs and benefits that occur in the future, and how to value human lives. We consider these two issues next.

4.7 Discounting the Future

Many environmental policies involve paying costs in the short term, while the benefits arise further in the future. For example, the cost of installing pollution control equipment is an upfront cost, while the health benefits of reduced cancer rates will only be realized decades in the future. Thus, we need a way to compare impacts that occur at different times.

There is a natural human tendency to focus on the present more than the future. Most people would prefer to receive a benefit now than a similar benefit in the future. This may be a simple matter of personal preference, or it may be based on the economic logic that having resources in the present allows for investment to receive greater benefits in the future.

Economists incorporate this concept into CBA through **discounting**. Discounting effectively reduces the weight placed on any cost or benefit that occurs in the future, relative to the same impact occurring now. The further the cost or benefit occurs in the future, the less weight is given to that impact. To compare an impact that occurs in the present to an impact that occurs in the future, the future impact must be converted to a **present value** using the following formula:

$$PV\ (X) = X / (1 + r)^n$$

where X is the monetary value of the cost or benefit, n is the number of years in the future the impact occurs and r is the **discount rate**—the annual rate by which future impacts are reduced, expressed as a proportion (i.e., r=0.03 for a 3% discount rate).

A simple example will illustrate how discounting works. Suppose we are analyzing a proposal to improve air quality. Assume that the cost of this proposal, including the installation of new pollution control equipment, is $10 million, to be paid right now. The benefits of cleaner air are estimated to be $20 million, but these benefits will occur 25 years in the future.[20] Should we proceed with this proposal?

To obtain the present value of the $20 million future benefit, we need to choose a discount rate. Suppose we apply a discount rate of 5%. The present value of the benefits would be:

$$PV = \$20{,}000{,}000 / (1.05)^{25} = \$5{,}906{,}055$$

As the present value of the $20 million benefit is only about $6 million, it does not make economic sense to pay $10 million now to obtain this benefit. But suppose that we instead apply a discount rate of 2%. In this case the present value of the benefits is:

$$PV = \$20{,}000{,}000 / (1.02)^{25} = \$12{,}190{,}617$$

In this case the net benefits of the proposal are positive (i.e., the present value of the benefits exceeds the costs by about $2 million). At the lower discount rate, the proposal makes economic sense. This example illustrates the importance of the choice of a discount rate. We will see later in the module that this is particularly true when we discuss analyses of global climate change.

One approach for choosing a discount rate is to set it equal to the rate of return on low-risk investments such as government bonds. The rationale behind this is that any funds used for a beneficial public project could otherwise be invested to provide society with greater resources in the future. In mid-2024 the nominal rate of return on long-term U.S. Treasury bonds was about 4.7%.[21] However this rate has varied considerably over time, from less than 2% in 2020 to over 15% in the early 1980s. Some economists question whether we should base the valuation of long-term environmental impacts upon an interest rate subject to the whims of financial markets.

Other approaches for choosing a discount rate consider the ethical dimension of valuing future impacts. In some sense, a positive discount rate implies that future generations count less than the current generation. While nearly all economists believe in the principle of discounting, ecological

[20] In reality the benefits would occur over numerous future years. Here, for simplicity, we assume all the benefits occur in a single year, 25 years from now.

[21] U.S. Department of the Treasury. Daily Treasury Long-Term Rates.

economists tend to argue for lower discount rates to incorporate concerns about severe long-term environmental damages. [22]

4.8 Valuing Human Lives

Another controversial aspect of CBA is analyzing policies that affect human mortality rates. In a CBA framework, we seek to convert all benefits to monetary values to make them directly comparable to the costs. Suppose we are analyzing a policy that will improve air quality at a cost of $500 million but reduce the number of deaths associated with air pollution by fifty per year. Is such a policy "worth it" to society?

While economists don't value any particular person's life, they instead estimate how people value relatively minor changes in mortality risk and use this information to infer the **value of a statistical life (VSL)**. A VSL estimate, in theory, indicates how much society is willing to pay to reduce the number of deaths from environmental pollution by one, without any reference to whose death will be avoided.

An example illustrates how a VSL is estimated. Let's assume we conduct a contingent valuation survey asking people how much they would pay to improve air quality such that the number of deaths from air pollution would decline by fifty per year. Each respondent's risk of dying from air pollution would decline slightly as a result of the policy. Suppose the survey results indicate that the average household is willing to pay $10 per year for this policy. If society comprises 100 million households, then the total willingness to pay for the policy would be:

100 million * $10 = $1 billion/year

Since this is the WTP to reduce deaths by fifty, the VSL would be:

$1 billion / 50 = $20 million

Some people object to valuing human lives on ethical grounds. Others counter that we must explicitly or implicitly analyze the tradeoffs between public expenditures and health benefits. According to statutory law, major environmental policy proposals in the United States must be reviewed using cost-benefit analysis, and thus government agencies must often apply a VSL. The VSLs used by government agencies have varied but generally increased over time, from around $2 million in the 1980s to over $10 million more recently. In other words, regulations that can reduce environmental deaths at a cost of less than $10 million per avoided death would be considered economically efficient.

[22] Nearly all economists justify some discounting on the assumption that future generations will have higher incomes and better technology, and will thus be better equipped to deal with problems created in the present. However some economists suggest that the effects of climate change and other environmental problems could lead to a decline in living standards, which would reverse the logic of discounting, giving greater weight to future damages and therefore making preventive action today more urgent.

4.9 Other Issues with Cost Benefit Analysis

Most environmental cost-benefit analyses are further complicated by several other issues. These include:

1. Analysis of uncertainty
2. Missing monetary values
3. Sensitivity to assumptions

Consider a proposal to build a large dam for flood protection. The benefits of flood protection depend somewhat on future climate conditions, which are difficult to predict with a high degree of certainty. There may also be a small chance that the dam will fail, perhaps causing catastrophic damage.

Another example would be analyzing the risk of a major oil spill. Incorporating such uncertainty into a CBA may be possible if we have some idea of the probability of various outcomes, but some risks are fundamentally difficult to predict. In such cases, some economists advocate applying the precautionary principle discussed earlier—that policies should err on the side of caution when there is a risk of a catastrophic outcome.

In almost any environmental CBA we will be unable to estimate all impacts in monetary terms. For example, how can we estimate the benefits of a proposed National Park if the park doesn't exist yet? We may be able to "transfer" an estimate from an existing similar park, but we can't be sure the transferred estimate is valid for the new site. Also, government agencies frequently don't have the resources to fund original studies to estimate all needed values. We may be able to make an educated guess about certain missing values, but this obviously reduces the objectivity of a CBA.

Finally, the recommendations of many CBAs are highly dependent upon various assumptions. As we saw earlier, the choice of a discount rate may determine whether a particular policy is recommended or not. Other assumptions may have to do with how risk is analyzed, or how contingent valuation results are interpreted. Ideally, a CBA should consider a broad range of realistic assumptions. Of course, if different assumptions produce different results, then we must make a subjective decision about which result we should rely upon. Again, this issue implies that CBA may not be as objective as it may seem at first.

5. ENVIRONMENTAL POLICY ALTERNATIVES

In devising policies to internalize environmental externalities, a Pigovian tax is just one type of environmental policy. Decision-makers generally have other policy options, and which one is appropriate depends on the particular context. The four basic environmental policy options are:

1. Pollution standards
2. Technology-based regulation

3. Pigovian (or pollution) taxes
4. Tradable pollution permits

5.1. Pollution Standards

Pollution standards regulate environmental impacts by setting allowable pollution levels or specifying the acceptable uses of a product or process. Many people experience pollution standards at an annual automobile inspection. Cars must meet certain standards for tailpipe emissions; if your car fails, you must correct the problem before receiving an inspection sticker.

The clear advantage of standards is that they can specify a definite result. This is particularly important in the case of substances that pose a clear hazard to public health. By imposing a uniform rule on all producers, we can be sure that no factory or product will produce hazardous levels of pollutants. In extreme cases, a regulation can simply ban a particular pollutant, as has been the case with DDT (a toxic pesticide) in most countries.

However, requiring all firms or products to meet the same standard is often not cost-effective. The overall cost of a regulation can be lowered if firms that can reduce pollution at low marginal costs reduce pollution more than firms that have high marginal reduction costs. Requiring all firms to reduce pollution by the same amount, or to meet the same standard, is not the least-cost way to achieve a given level of pollution reduction. Another problem with standards is that once firms meet the standard they have little incentive to reduce pollution further.

5.2. Technology-based Regulation

A second approach to environmental regulation is to require that firms or products use a particular pollution-control technology. For example, in 1975 the United States required that all new automobiles include a catalytic converter to reduce tailpipe emissions. While auto manufacturers are free to design their own catalytic converters, each must meet certain emissions specifications.

Perhaps the main advantage of technology-based regulation is that enforcement and monitoring costs are relatively low. Unlike a pollution standard, which requires that firms' pollution levels be monitored to ensure compliance, a technology-based approach might only require an occasional check to ensure that the equipment is installed and functioning properly.

Technology-based approaches may not be cost-effective, because they do not provide firms the flexibility to pursue a wide range of options. Technology-based approaches may, however, offer a cost advantage due to standardization. If all firms must adopt a specific technology, then widespread production of that technology may drive down its production costs over time.

5.3. Pigovian (or Pollution) Taxes

Pollution taxes, along with tradable pollution permits, are considered **market-based approaches** to pollution regulation because they send information to polluters about the costs of pollution without mandating that firms take specific actions. Individual firms are not required to reduce pollution under a market-based approach, but the regulation creates a strong incentive for action.

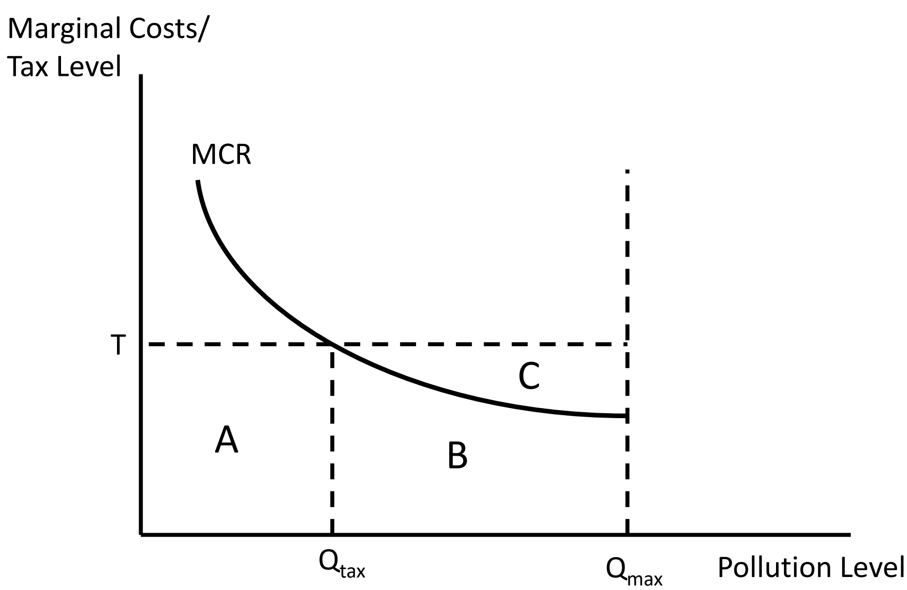
As we saw earlier in the module, a pollution tax reflects the principle of internalizing externalities. If producers must bear the costs associated with pollution by paying a tax, they will find it in their interests to reduce pollution so long as the marginal costs of reducing pollution are less than the tax.

Figure 8 illustrates how an individual firm will respond in the presence of a pollution tax. Q_{max} is the level of pollution emitted without any regulation. The curve MCR shows the marginal cost of pollution reduction for the firm. Note that the MCR curve slopes upward moving away (to the left) from Q_{max} because the firm would first implement those options that reduce pollution at the lowest marginal cost before moving to more expensive options.

If a pollution tax equal to *T* is imposed, the firm will be motivated to reduce pollution to level Q_{tax}, at a total cost of B (equal to the area under their MCR curve between Q_{tax} and Q_{max}). If the firm maintained pollution at Q_{max} it would have to pay a tax of (B + C) on these units of pollution. Thus the firm saves area C by reducing pollution to Q_{tax}.

After reducing pollution to Q_{tax}, the firm will still need to pay a tax on its remaining units of pollution, equal to area A. The total cost to the firm from the pollution tax is the sum of its reduction costs and tax payments, or areas (A + B). This is less than areas (A + B + C), which is what they would have to pay in taxes if they undertook no pollution reduction. The firm's response to the tax is cost-effective, as any other level of pollution different from Q_{tax} would impose higher costs.

Figure 8. *A Firm's Response to a Pollution Tax*



All other firms in the industry will determine how much to reduce their pollution based on their own MCR curve. Assuming that each firm is acting in a cost-effective manner, the total cost of pollution reduction is minimized. Those firms that can reduce pollution at low marginal costs will reduce pollution more than firms that face higher costs. This is the main advantage of market-based approaches to pollution regulation—they achieve a given level of pollution reduction at the lowest overall cost. In other words, they are economically efficient compared to pollution standards or technology-based approaches.

5.4. Tradable Pollution Permits

Economic efficiency in pollution control is clearly an advantage. One disadvantage of pollution taxes, however, is that it is difficult to predict the total amount of pollution reduction a given tax will produce. It depends on the shape of each firm's MCR curve, which is usually not known to policymakers.

An alternative is to set up a system of **tradable pollution permits**. The total number of permits issued equals the desired target level of pollution. These permits can then be allocated freely to existing firms or sold at auction. Once allocated, they are fully tradable, or transferable, among firms or other interested parties. Firms can choose for themselves whether to reduce pollution or to purchase permits for the pollution they emit—but the total volume of pollution emitted by all firms cannot exceed a maximum amount equal to the total number of permits.

Those firms with higher MCR curves will generally seek to purchase permits so they don't have to pay high pollution reduction costs. Firms that can reduce pollution at lower cost may be willing to sell permits, as long as they receive more money for the permits than it would cost them to reduce pollution. With this system private groups interested in reducing pollution could also purchase permits and permanently retire them, thus reducing total emissions below the original target level. Pollution permits are normally valid only for a specific time period. After this period ends, the government can choose to issue fewer permits in the following time period, resulting in declining pollution over time.

A detailed analysis of tradable permits, which we don't present here, demonstrates that a given level of pollution reduction is achieved at the same total cost as a tax.[23] Thus whether one prefers pollution taxes or tradable permits depends on factors other than pollution reduction costs (however, the administrative costs of the approaches may differ). Taxes are generally easier to understand and implement. But taxes are politically unpopular, and firms may prefer a permit system if they believe they can successfully lobby to receive the permits for free.

The main difference between the two approaches is where the uncertainty lies. With pollution taxes, firms have certainty about the cost of emissions, which makes it easier for them to make decisions about long-term investments. But the resulting level of total pollution with a tax is unknown in advance. If pollution levels turn out to be higher than expected, then the government might have to take the unpopular step of raising taxes further.

[23] For a more detailed analysis, see Harris and Roach, 2022.

With a permit system, the level of pollution is known because the government sets the number of available permits. But the price of permits is unknown, and permit prices can vary significantly over time. This has been the case with the European permit system for carbon emissions. The price of permits initially rose to around €30/ton in 2006, shortly after the system was instituted. But then prices plummeted all the way down to €0.10/ton in 2007 when it became evident that too many permits had been allocated. After some changes to the system, prices rose back to over €20/ton in 2008, fell again down to less than €3/ton in 2013, but eventually peaked at over €100/ton in 2023. Such **price volatility** makes it difficult for firms to decide whether they should make investments in technologies to reduce emissions.

6. ECONOMIC ANALYSIS OF CURRENT ENVIRONMENTAL POLICY ISSUES

We now apply the lessons from this module to three current environmental policy issues: fisheries management, agriculture, and climate change. We'll present relevant data for each issue, focusing on historical trends and projections. In each case we'll see how the insights from environmental and ecological economics can help design policies that promote sustainability.

6.1 Fisheries Management

As we have seen earlier, without sufficient regulation ocean fisheries are likely to be subject to the tragedy of the commons. Individual fishers have little incentive to practice conservation, for they know that if they do not catch the available fish, someone else probably will. Technological improvements that make it easier to find and catch fish only make matters worse, since intensive fishing operations can easily wipe out existing fishing stocks.

Fisheries are examples of **renewable resources**, which regenerate over time through natural processes. One basic rule for renewable resource management derived from ecological principles is that harvest levels should be kept below the **maximum sustained yield (MSY)**. In other words, the annual harvest of the resource should be no more than what is regenerated annually through natural processes.

The world's fisheries are classified into the categories, roughly based on a comparison between harvest levels and the MSY[24]:

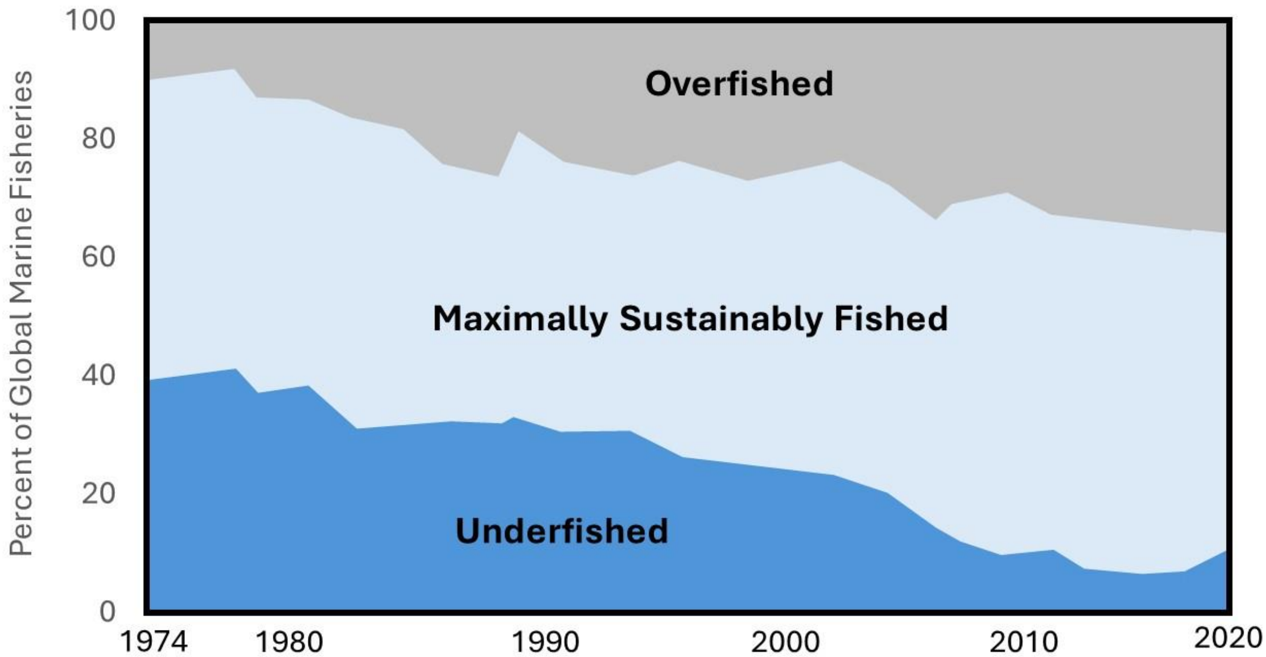
1. *Underfished:* Fisheries with harvest levels below their MSY. A potential may exist to increase harvest levels.
2. *Maximally sustainably fished:* Fisheries with harvest levels approximately equal to their MSY. Increasing production is not ecologically sustainable.
3. *Overfished:* Fisheries with harvest levels above their MSY. Strict management plans are needed to improve the biological health of these fisheries (although such plans are

[24] Fishery classification from the FAO (Food and Agriculture Organization of the United Nations).

normally not currently in place).

As shown in Figure 9, the world's fisheries are becoming more exploited over time. In recent decades the percentage of fisheries classified as overfished has approximately tripled. Meanwhile, the percentage of fisheries that are underfished, with the potential for expanded harvest, has decreased from about 40% to 12%. The depleted state of fisheries is due to overfishing and increasing habitat degradation.

Figure 9. *State of the World's Fish Stocks, 1974-2021*



Source: FAO. 2024.

6.2 Global Fish Production and Consumption

People in developed countries currently consume approximately 20 percent of the global fish catch; the other 80 percent is consumed in the developing world, where fish is an important protein source.[25] Increasing population and income in developing countries will likely produce steady growth in the global demand for fish and fish products, but supply expansion, at least from wild fisheries, may be close to its limits.

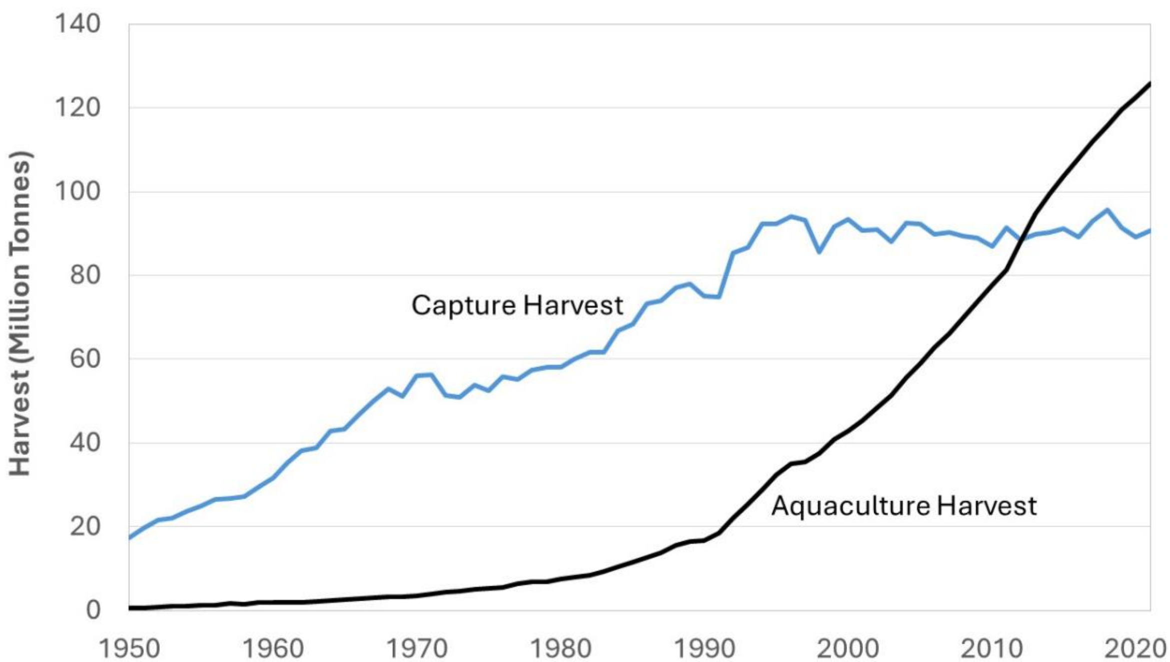
Figure 10 shows global fish production from 1950 to 2021. World fish harvest of naturally occurring stocks steadily increased from 1950 until the mid-1990s. Since then the wild catch has

[25] Sarkodie and Owusu, 2023.

leveled off at about 90 million tons annually. This is consistent with the decline in underfished stocks shown in Figure 9. But the global fish harvest has continued to increase as an increasing share of the total catch is produced using aquaculture – essentially fish farming. In recent years the fish total harvest from aquaculture has exceeded the harvest from wild capture fishing. While aquaculture has provided a means to meet the growing global demand for fish, a challenge is to reduce the environmental impacts associated with aquaculture, as discussed in Box 2.

Per-capita fish consumption has doubled globally since the 1960s. The greatest growth has occurred in developing countries, driven by population growth, higher incomes, and improved distribution infrastructure. However, the expansion of fish consumption has been highly uneven. China has been responsible for most of the increase in global fish consumption, while many countries in Sub-Saharan Africa have seen fish consumption remain constant or even decrease.

Figure 10. *Global Fish Production, 1950-2021*



Source: FAO. 2024.

BOX 2. REDUCING THE ENVIRONMENTAL IMPACT OF SALMON AQUACULTURE

As shown in Figure 10, global aquaculture production has increased significantly over the last few decades. A farm-raised species that has seen particular growth is salmon. According to the environmental group WWF, salmon farming is the fastest growing food production system in the world.[26] About 80 percent of the global salmon harvest now comes from aquaculture, with Norway, Chile, Scotland, and Canada being the top producers.[27]

A set of standards for sustainable salmon farming was established in 2010 by the Aquaculture Stewardship Council (ASC). Among the ASC standards are limits on the proportion of escaping salmon, a prohibition on genetic engineering, limits on antibiotics, and guidelines on the food that is fed to salmon. Farms that meet these standards are given the ASC's "responsibly farmed" eco-label. Over half of all farm-raised salmon now meet ASC standards.[28]

While ASC certification has reduced the negative environmental impacts of salmon aquaculture, significant challenges remain. One problem is that aquaculture concentrates waste products which can seep into surrounding areas, harming other species. Producing one pound of salmon using aquaculture creates over 100 pounds of nitrogen and phosphorus waste.[29] Another problem is that high fish density can lead to rapidly spreading diseases, not only harming salmon but the broader marine environment. A 2021 study found that the global environmental damage from salmon aquaculture amounted about $50 billion over 2013-2019.[30] A 2024 *Nature* paper finds that the growth of salmon aquaculture has been associated with an increase in mass mortality events where large numbers of fish die in a short time.[31] These mortality events can create large "dead zones" from oxygen depletion.

Proposed policies that could reduce the environmental impacts of salmon aquaculture include:[32]

- Moving salmon farms to onshore facilities such as large tanks to prevent negative interactions with the marine environment.
- Reducing waste runoff using filters and collection systems
- Implementing a waste tax—a charge per unit of waste that migrates into the marine environment
- Reducing fish disease incidence by lowering fish densities and providing healthier feed

[26] WWF, Farmed Salmon, Overview.
[27] Mowi ASA, 2023.
[28] Anonymous, 2022.
[29] Brumby *et al.*, 2019.
[30] Harvey, 2022.
[31] Singh, *et al.*, 2024.
[32] Brumby *et al.*, 2019.

6.3 Sustainable Fisheries Policies

Clearly the open-access outcome described in Section 3 is not consistent with environmental sustainability. In the case of a common property resource such as a fishery, economic incentives work in a perverse way. In response to declining yields, operators increase their effort, often investing in more efficient equipment, which accelerates the decline of the fishery.

Open-access fisheries pose additional ecological problems because modern fishing methods often cause a high death rate among non-target species. Also, many target species fish are discarded after being caught, because they are either undersized or nonmarketable. This wasted portion of the global harvest is called bycatch. Estimates of the magnitude of global bycatch vary – a 2019 United Nations analysis estimated bycatch as 11% of total harvest while other research finds bycatch to be as high as 40% of harvest.[33] Regulations that reduce bycatch include seasonal closures of ecologically sensitive fishing areas, bycatch and harvest quotas, and fish gear requirements (particularly fishing net standards).

Identifying the maximum sustainable yield for a fishery can help maintain an individual species, but issues of ecological sustainability are more complex. Depleting one species may lead to an irreversible change in ocean ecology as other species fill the ecological niche formerly occupied by the harvested species.[34] For example, dogfish and skates have replaced overfished cod and haddock in major areas of the North Atlantic fishery, and are now themselves threatened with overfishing.

Fishing techniques such as trawling, in which nets are dragged along the bottom of the ocean, are highly destructive to all kinds of benthic (bottom-dwelling) life. In large areas of the Atlantic, formerly productive ocean floor ecological communities have been severely damaged by repeated trawling.

The World Bank and FAO stress the critical need to reform fisheries management:

> The most critical reform is the effective removal of the open access condition from marine capture fisheries and the institution of secure marine tenure and property rights systems. Reforms in many instances would also involve the reduction or removal of subsidies that create excess fishing effort and fishing capacity. Rather than subsidies, the World Bank has emphasized investment in quality public goods such as science, infrastructure, and human capital, in good governance of natural resources, and in an improved investment climate.[35]

A 2023 article notes that approximately two-thirds of global fisheries subsidies are classified as harmful, encouraging harvest above MSY levels.[36] These perverse subsidies lead to "a cascade

[33] Pérez Roda, *et al*., 2019; Davies, *et al*., 2009.
[34] See, for example, Ogden, 2001.
[35] World Bank and FAO, 2009, p. xxi
[36] Hollander, 2023.

of negative ecological consequences," including "overfishing due to overcapacity and artificially low costs, habitat damage, climate change, and equity issues."

From an economic point of view, the tragedy of the commons occurs because important productive resources—fisheries in this case—are treated as free resources, and are therefore overused. One potential solution is to privatize fisheries, in the hopes that owners would manage fisheries for sustainable profitability. Ocean fisheries, however, are not conducive to private ownership from a practical and legal perspective.

The oceans have been called a common heritage resource—they belong to everyone and no one. But under the 1982 Law of the Sea treaty, agreed to under United Nations auspices, nations can claim territorial rights to many important offshore fisheries. They can then limit access to these fisheries by requiring a fishing license within their Exclusive Economic Zones (EEZs), which normally extend 200 miles from their coastlines.

Within each country's EEZ, they can implement the economic policies we discussed in Section 3, including charging fishing license fees or instituting individual transferable quotas. To determine the maximum sustainable yield, policymakers can defer to marine biologists. Once ecological sustainability has been assured, the ITQ market will promote economic efficiency. Those who can fish most effectively will be able to outbid others to acquire the ITQs.

A more difficult problem concerns species that are highly migratory or are principally located outside of any nation's EEZ. Tuna and swordfish, for example, continually travel between national fishing areas and the open ocean. Even with good policies for resource management in national waters, these species can be harvested as an open-access global resource, which almost inevitably leads to stock declines. Only an international agreement can solve an issue concerning global commons.

In 1995, the first such international agreement was signed – the Straddling Fish Stocks Agreement.[37] This treaty embodies the precautionary principle, discussed in Section 2. For example, the treaty states that the "absence of adequate scientific information shall not be used as a reason for postponing or failing to take conservation and management measures."[38]

Changes in human consumption patterns are also important. Public education campaigns that identify fish and seafood produced with environmentally damaging techniques may lead consumers to avoid these species. **Ecolabeling**, which identifies products produced in a sustainable manner, has the potential to encourage sustainable fishing techniques. Products of certifiably sustainable fishing practices can often command a higher market price. A 2022 meta-analysis found that consumers are willing to pay significantly more ($2—$5 per pound extra) for fish that meets environmental certification standards.[39]

Governments can also institute subsidies when certain activities create positive externalities, as

[37] A straddling fish stock is one that migrates through or occurs in more than one EEZ.
[38] United Nations, 1995, p. 6.
[39] Smetana, *et al.*, 2022.

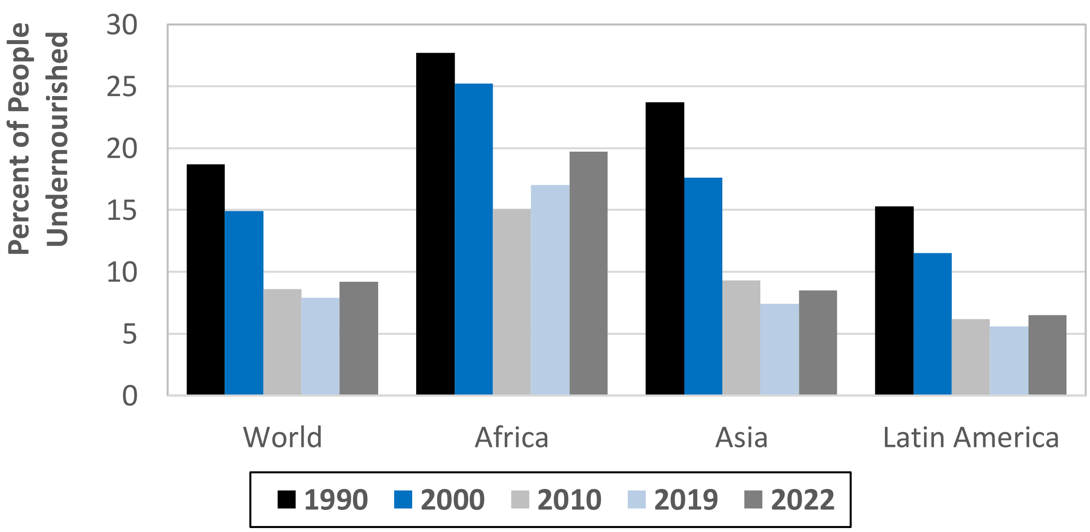
discussed in Section 3. For example, subsidies can assist in developing or acquiring equipment designed especially to release bycatch, or to avoid major disturbances of the seabed. This may moderate political opposition from fishing communities to government intervention aimed at eliminating destructive fishing practices. Unfortunately, as noted above most current fishery subsidies are counterproductive, increasing economic incentives for overfishing.

6.4 Sustainable Agriculture

We saw in Section 2 that predictions indicating that humanity will be unable to feed itself have been proven wrong. On average, food consumption per capita has steadily increased, as shown in Figure 1 (i.e. food consumption has grown faster than population). Among the Sustainable Development Goals set by the United Nations in 2015 is the goal of zero hunger globally by 2030. Overall, progress has been made on this front, with a decline in the percentage of people suffering from undernourishment globally from near 20% in the 1990s to 7.9% in 2019.[40] However, the COVID-19 pandemic and the war in Ukraine (Ukraine and Russia are major food producers) have pushed the percentage of undernourished globally back up to over 9% in 2022.[41]

Progress on reducing hunger has been uneven across global regions. As shown in Figure 11, the greatest progress has occurred in Asia and Latin America, where the percentage of people undernourished has fallen below 10%. Meanwhile, the prevalence of hunger in Africa has increased since 2010, with a large increase due to the COVID-19 pandemic and other food supply shocks. Despite an overall decline in the percentage of undernourished people in Africa since 1990, the actual number of undernourished people in Africa has increased by about 100 million due to population growth.

Figure 11. *Percentage of Undernourished People, by Region, 1990-2022*



Sources: FAO, 2014; FAO 2023.

[40] FAO, FAOStat, Food Security Indicators online database.
[41] FAO *et al*., 2023.

The global reduction in malnourishment over the past three decades is not only attributed to increased food production, but also to higher incomes and wider food availability. One factor that hasn't contributed to the increase in the global food supply is an expansion of agricultural land – according to the World Bank global agricultural land area has remained relatively constant since the early 1990s.[42] Instead, improvements in agricultural technology and efficiency have been the drivers leading to a larger food supply.

The United Nations projects that the human population will increase to 9.7 billion by 2050,[43] nearly a 20% increase over 2024. However, with rising incomes the UN expects that global food production will need to increase by more than 50% to meet 2050 demand.[44] Most researchers conclude that that such an expansion of global agriculture is feasible.[45] But there are several important caveats to this conclusion:

1. *Biofuel expansion:* **Biofuels** are fuels made from living organisms, most commonly crops such as corn and sugar cane. Currently, less than 10% of the world's crops are used for biofuels and other industrial uses.[46] While some expansion of biofuels is expected, a significant reallocation of crops away from human consumption toward biofuels could reduce the ability to meet future food demands.
2. *Climate change:* The impact of climate change on agricultural production is not precisely known. While production could increase in some areas due to an expansion of the growing season, such as in Canada and Russia, the net impact of long-term climate change on global food production is expected to be negative. Further, the increasing incidence of extreme weather events and climate-related disasters is already reducing food security in many regions. In 2024, UN Secretary-General António Guterres emphasized that climate change increases the likelihood of armed conflicts due to resource shortages, with both factors contributing to recent famines in countries such as Syria and Myanmar.[47]
3. *Environmental damage:* While total agricultural production may rise, this may mask long-term damage to water, soil, and ecological systems. We address these issues in the next section.

6.5 Environmental Impacts of Modern Agriculture

In addition to being affected by a changing environment, modern agricultural practices impact the environment on local and global scales. We consider four environmental impacts in this section:

1. Deforestation
2. Soil erosion

[42] World Bank, World Development Indicators database.
[43] United Nations, 2024.
[44] Da Silva, 2012.
[45] Wise, 2013.
[46] Anonymous, 2023.
[47] Anonymous, 2024.

3. Use of chemical inputs
4. Emissions of greenhouse gases

While the overall land area devoted to agriculture globally has not significantly changed recently, new lands are constantly brought into agricultural production as the productivity of existing plots decline. Through the practice of **slash-and-burn agriculture**, primarily practiced in tropical regions, land is cleared for farming by first cutting and burning the existing vegetation. The remaining ash infuses the soil with nutrients, which are then used to support agriculture. However, the soils in tropical forests tend to be nutrient-poor. Once the nutrients from the burnt vegetation are depleted, often in a matter of a few years, farmers must move on to new lands and repeat the cycle.

While slash-and-burn agriculture has primarily been practiced on a small scale by subsistence farmers, increasingly deforestation is occurring as a result of large-scale commercial agriculture, including crops and livestock. According to a 2021 United Nations analysis:

> Agricultural expansion drives almost 90 percent of global deforestation – an impact much greater than previously thought … Worldwide, more than half of forest loss is due to conversion of forest into cropland, whereas livestock grazing is responsible for almost 40 percent of forest loss … The new data confirms an overall slowdown in global deforestation while warning that tropical rainforests, in particular, are under high pressure from agricultural expansion.[48]

The causes of deforestation by global region are presented in Figure 12. Global annual deforestation is about 8 million hectares (about the size of Panama), with 36% occurring in South America, 30% in Africa, and 25% in Asia. We see that deforestation in South America is driven primarily by livestock grazing, particularly for beef—cattle grazing is responsible for about 80% of deforestation in the Amazon rainforest. The primary cause of deforestation in Africa is small-scale subsistence slash-and-burn agriculture. In Asia, the expansion of large-scale palm oil plantations in Malaysia and Indonesia is a main cause of deforestation.

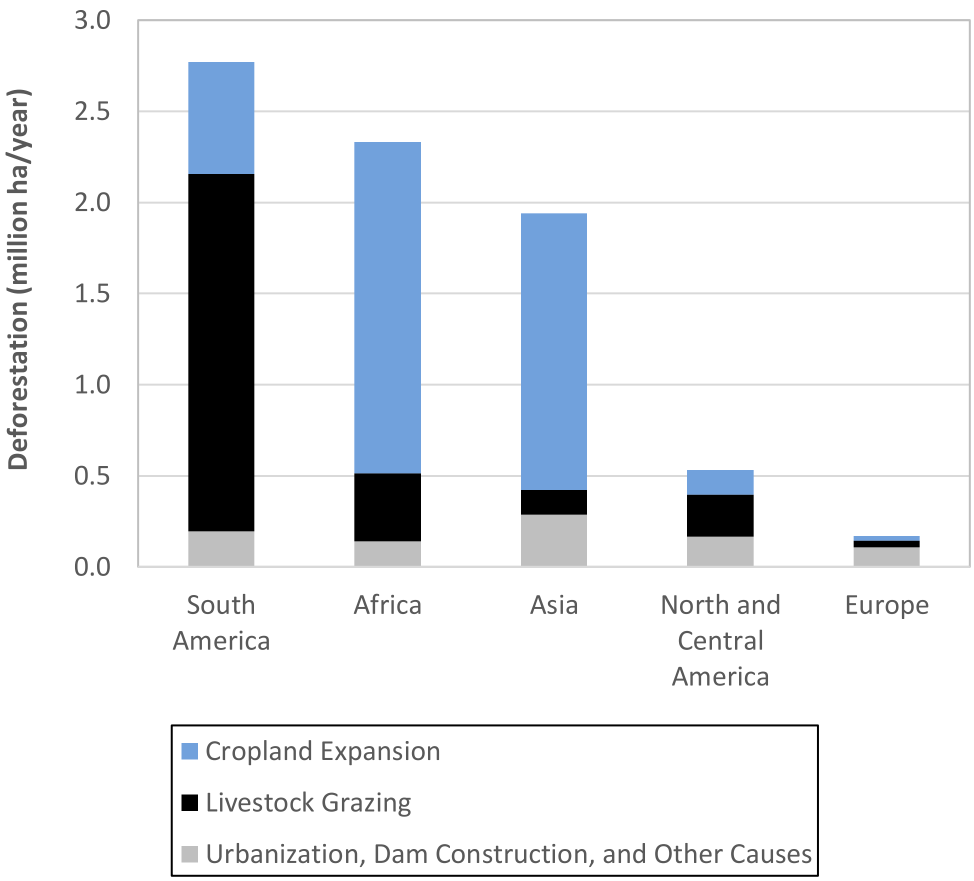
Over 90% of deforestation occurs in tropical forests, which are the most biodiverse ecosystems on the planet. While rates of deforestation in the topics have generally declined in recent decades, it appears increasingly evident that the goal of halting forest loss by 2030, agreed upon by 145 countries at the 2021 UN climate change conference in Glasgow, will not be met.

As we have seen before, economic theory can provide insight into both the nature of the problem and potential solutions. Farmers, small- or large-scale, tend to only consider their own financial situation when making decisions, failing to account for social costs. Thus, even if sustainable uses of forests provide society with the greatest net benefits, forests will still be converted to agriculture if the private benefits exceed the private costs. The challenge is:

[48] FAO, 2021.

to make users internalize all the social costs associated with converted forests. This will both increase the price and cost of the converted forest, and will also reduce the net marginal benefits of converted forest.[49]

Figure 12. *Causes of Deforestation, 2000-2018*



Source: FAO, 2022.

Another environmental impact of modern agriculture is excessive soil erosion. Soil is a natural resource that regenerates over very long time periods – the median rate of soil formation is only one centimeter every 370 years.[50] Yet soil can be eroded at much higher rates when it is left exposed to rain and wind, commonly 10-40 times the rate of natural formation.[51]

Soil erosion results in economic losses as agricultural land becomes less productive. A 2019 journal article estimated the global loss from soil erosion to be $8 billion, causing an increase in

[49] Benhin, 2006, p. 15.
[50] Stockmann *et al*., 2014.
[51] Dror *et al*., 2022.

food prices by 0.4-3.5%.[52] Soil erosion also results in environmental problems. For example, when eroded soil is deposited into rivers and lakes it can harm the health of these ecosystems. The siltation of rivers in the United States due to soil erosion is considered the second leading cause of water quality impairment in the country.[53] Soil erosion can also contribute to air pollution when winds carry off exposed soils.

Rates of soil erosion can be significantly reduced by implementing good agricultural practices that minimize soil disturbance, reduce soil exposure to the elements, and slow down water runoff. For example, rather than intensively tilling the soil prior to planting, in which nearly all plant residue is buried below the surface, the practice of conservation tillage leaves at least 30% of these residues on the soil surface in order to reduce soil exposure and slow runoff. Conservation tillage also promotes carbon storage in soil, reducing climate change.[54]

A third environmental impact of agriculture is the release of numerous chemicals into the environment. The widespread use of pesticides, herbicides, fertilizers, and other chemicals has clearly increased agricultural productivity and reduced global hunger. But this has come at an environmental cost.

The negative impacts of these chemicals first came to light in the 1960s, most famously with the publication of Rachel Carson's *Silent Spring*. Carson documented the problem of bioaccumulation, whereby pesticides stored in the fat tissue of animals become more concentrated further up the food chain. Top predators such as bald eagles are particularly susceptible to high concentrations of toxic chemicals, leading to eggshell thinning and increased mortality. Agricultural fertilizers can run off into waterways and promote algal blooms (a process known as eutrophication) that can kill fish and other aquatic animals. A 2021 study by the UN assessed the environmental and human health impacts of agricultural chemicals, finding that about 11,000 people die each year from such chemicals and concluding that "current and projected patterns of global pesticide and fertilizer use are not sustainable."[55]

Once again, this issue can be framed as a negative externality. As long as chemical manufacturers and farmers do not pay for the external costs of agricultural chemicals, these chemicals will be overused from the viewpoint of economic efficiency. Thus, a tax is one economic instrument that could reduce chemical use toward an economic optimum. Denmark is one of a handful of countries (including France, Norway, and Sweden) that have instituted taxes on agricultural chemicals. When the tax was first implemented in the mid-1980s, all pesticides were taxed at the same rate. In 2013 the program was restructured so that the most harmful chemicals are taxed at higher rates to particularly discourage their use.[56]

The final environmental impact of modern agriculture that we consider is its contribution to global climate change. Agriculture directly contributes to climate change by releasing various gases into

[52] Sartori *et al.*, 2019.
[53] Kertis and Iivari, 2006.
[54] Liu *et al.*, 2023.
[55] UN Environment Programme, 2021.
[56] Ministry of Environment and Food of Denmark, 2017.

the atmosphere. According to the United States Environmental Protection Agency, agriculture accounted for 11% of U.S. emissions in 2021, primarily from the release of methane and nitrous oxide.[57] But other estimates suggest that agriculture's contribution to climate change is much greater when indirect impacts are considered, including deforestation, soil erosion, transportation, and food waste. A 2019 UN report estimated that the global food system is responsible for 21-37% of total greenhouse gas emissions.[58] The final section of the module will discuss climate change in more detail.

6.6 Making Agriculture Sustainable

Traditional economic analysis has considered agricultural production as a process of combining inputs, including land, water, fertilizer, and pesticides to maximize output (measured as yields or profits). Environmental economics focuses on the negative externalities associated with agriculture, such as soil erosion, deforestation, toxic chemicals, and greenhouse gases as described above. These externalities can be addressed with economic policies such as taxes and subsidies.

From an ecological economics point of view, the crux of the problem with modern large-scale agriculture is that it runs counter to the equilibrium that is found in natural ecosystems. Through natural processes, important nutrients are cycled through an ecosystem as plants die, decompose, enrich the soil, and then provide nutrients for the next generation of plants. Different plants may serve different purposes in an ecosystem. For example, certain plants "fix" nitrogen, a process by which nitrogen in the atmosphere is converted into a form that is usable by other plants in the soil. The diversity of natural ecosystems also makes them highly resilient – able to bounce back in the presence of disturbances such as disease or extreme weather.

Industrial agriculture is normally a monoculture – meaning that a single plant species is grown exclusively on a plot year after year. Unlike natural systems, monocultures tend to be more vulnerable to diseases and pests, require the constant input of nutrients, and degrade the soil. An ecological view of agricultural production sees crop output as one part of a diverse agroecological system, which aims to maintain natural processes and nutrient cycles. To achieve long-term sustainability, cultivating practices must minimize chemical inputs and rely more on organic techniques, which return nutrients to the soil, control pests by natural methods, and are not harmful to other species.

A sustainable agricultural system is defined here as one that produces a stable level of output without degrading the environmental systems that support it. In economic terms, this means no significant uninternalized externalities or excessive depletion of common property resources. From an ecological point of view, a sustainable system minimizes disruption to natural cycles. More recently, the term **regenerative agriculture** has been used to describe agricultural systems that are not only sustainable but aim to restore degraded productivity levels and increase carbon storage in plants and soils to mitigate climate change.

[57] U.S. EPA., 2023.
[58] Mbow *et al.*, 2019.

Production techniques such as organic fertilization by recycling of plant and animal wastes, crop rotation and intercropping of grains and nitrogen-fixing legumes help to maintain the soil's nutrient balance and minimize the need for artificial fertilizer. The use of reduced tillage, terracing, fallowing, and agroforestry (planting trees in and around fields) all help to reduce erosion and increase carbon storage. Integrated pest management (IPM) uses natural pest controls such as predator species, crop rotation, and labor-intensive early pest removal to minimize use of chemical pesticides. Efficient irrigation techniques and the use of drought- and salt-tolerant crop varieties can reduce water use. Species diversity is promoted by multiple cropping (planting several different crops in the same field) rather than monocultures.

The traditional view has been that sustainable and regenerative agricultural methods are less profitable than industrial agriculture. Recent research suggests that this may not be true over the long run, particularly when one considers that organic agricultural products sell at a price premium. In a 2011 study conducted in Minnesota over 18 years, researchers compared the profitability of several of the main U.S. grain crops (corn, soybeans, oats, and alfalfa) using both organic and chemical-intensive methods.[59] The paper concludes:

> These results show that with current price premiums, an organic crop farm in the Upper Midwest can earn greater per-hectare profits … than a conventional farm using [the practices that are] predominant in the region. [Further,] organic premiums could decline in the future without necessarily causing organic production to lose its profitability advantage over conventional, [chemically intensive] cropping systems.[60]

A 2015 meta-analysis of studies of organic and conventional farming that included 55 crops on 5 continents showed similar results, finding organic agriculture to be significantly more profitable while also benefiting human health, the environment, and helping to achieve socioeconomic objectives.[61] A 2023 report studying wheat farming in Kansas found that the transition from conventional to regenerative farming takes about 3-5 years, during which profitability is likely to decline slightly. However, in the longer-term regenerative agriculture can increase profitability by as much as 120%.[62]

Still, the barriers to implementing organic and regenerative agriculture in the U.S. and worldwide are considerable. One major problem is access to information. Sustainable techniques tend to be both labor-intensive and information intensive. Many farmers are not sufficiently knowledgeable about the complex techniques of organic and low-input agriculture to be able to make them pay. It is often much easier to read the instructions on a bag of fertilizer or a canister of pesticide. In developing countries, traditional low-input farming systems have often been displaced by modernized "Green Revolution" techniques, which are advocated by large agricultural companies and many governments.

[59] Delbridge *et al*., 2011.
[60] Ibid., p. 1381.
[61] Crowder and Reganold, 2015.
[62] Petry *et al*., 2023.

In recent years, organic agriculture has expanded rapidly. A 2023 report by the U.S. Department of Agriculture found that total acreage for growing organic crops and livestock in the U.S. increased by over 170% from 2000-2021, with revenues increasing by more than 450%.[63] A 2024 report found even greater growth for organic agriculture at the global level.[64] From 2000 to 2022, total organic acreage worldwide increased by 540% and revenues increased nearly 800%. Despite this growth, organic products still only account for about 5% of food sales in the U.S.[65] and a smaller market share at the global level. Government policies, such as the establishment of organic standards, reform of agricultural subsidy policies, and internalization of externalities will have an important influence on the future of organic and regenerative farming.

6.7 Global Climate Change: Introduction

Global warming, more accurately described as **climate change**, has become a major environmental and economic issue in recent decades. The vast majority of scientists (more than 99%) concur that global climate change[66] is primarily caused by human actions, in particular the increased emissions of various **greenhouse gases** (GHGs).[67] These gases act much like the glass in a greenhouse—allowing solar radiation to penetrate, but then trapping it and increasing temperatures.

While most greenhouse gases exist naturally in the earth's atmosphere and make life possible on earth, human activities have increased the concentration of many of these gases, as well as introduced entirely new greenhouse gases into the atmosphere. The most important greenhouse gas emitted by humans is carbon dioxide (CO_2), which is formed when fossil fuels (coal, oil, and natural gas) are burned. Other greenhouse gases include methane, nitrous oxide, and chlorofluorocarbons (CFCs).[68] While these gases warm the atmosphere much more per ton of emissions than CO_2, we emit much lower quantities of them. Considering the different warming potential of each GHG, CO_2 accounts for about 75% of human emissions of GHGs.

As atmospheric concentrations of GHGs increase, the world is expected to become warmer, on average, though not all regions will warm equally and some regions may actually become cooler. Climate change is also expected to result in more frequent and more intense tropical storms and droughts. The melting of polar ice caps and glaciers will contribute to rising sea levels. Among the ecological and human effects climate change are higher rates of species extinctions, lower average agricultural production, reduced freshwater availability, and higher rates of tropical diseases.[69]

Climate change is already having an impact on all countries, particularly lower-income countries which tend to lack the resources to adapt to a changing climate. Many lower-income countries are

[63] Carlson *et al*., 2023.
[64] Willer et al., 2024.
[65] Carlson and Skorbiansky, 2023.
[66] We use the term "climate change" instead of "global warming" because in addition to warmer average temperatures there are numerous other effects of this hugely complex system change—sometimes even including colder than normal temperatures in certain locations.
[67] Lynas *et al*., 2021.
[68] CFCs have also been implicated as ozone depleting substances. It is important to note that the degradation of the ozone layer, while serious, is an issue almost entirely unrelated to global climate change.
[69] IPCC, 2022.

in tropical or sub-tropical regions that will see the greatest impacts from extreme weather, rising seas, droughts, and disease spread. The World Bank estimates that declining agricultural yields in Africa related to climate change will increase the number of people in poverty by 43 million by 2030.[70] A 2019 paper finds that climate change is responsible for increased migration, not only directly due to crop failures, water scarcity, and extreme weather, but also indirectly as climate change increases the probability of armed conflicts.[71]

At the 2015 international climate meeting in Paris, participating nations set a target of limiting the eventual global temperature increase to no more than 2° Celsius (3.6°F), relative to pre-industrial levels, and to pursue "efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change."[72]

In order to meet these targets, global emissions of greenhouse gases will need to decline significantly, which will require a transformation of how humans obtain energy. Currently the world economy obtains over 80 percent of its energy from fossil fuels (coal, oil, and natural gas).[73] At the 2023 international climate meeting in Dubai, United Arab Emirates, nations called for a "transition away from fossil fuels" including "a tripling of renewable energy capacity, doubling energy efficiency improvements by 2030, accelerating efforts towards the phase-down of unabated coal power, phasing out inefficient fossil fuel subsidies, and other measures to drive the transition away from fossil fuels in energy systems."[74]

As shown in Figure 13 global emissions of greenhouse gases have increased significantly over the last few decades—up 48% between 1990 and 2023. China is the world's top emitter of GHGs (responsible for 29% of global emissions), followed by the United States (11%), India (7%), and Russia (5%).[75] Figure 13 also presents different projections for global GHG emissions to 2050, from top to bottom:

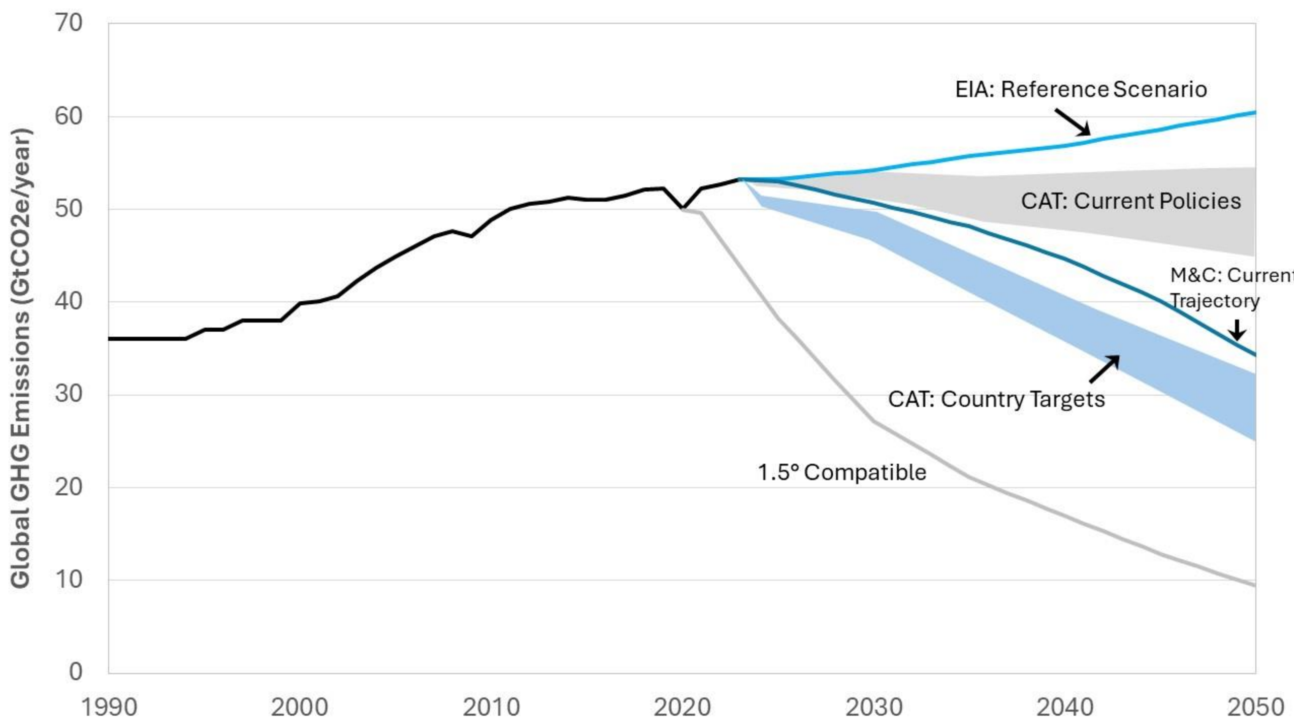
- The U.S. Energy Information Administration (EIA) projects under their "reference scenario" that GHG emissions will continue to increase in the future. This scenario assumes that no new policies will be implemented and that existing policies with expiration dates will not be renewed. This scenario is the most pessimistic case and would lead to warming of about 3°C by the end of the 21st century.
- Climate Action Tracker (CAT), an independent non-profit, projects that under existing national policies global GHG emission will remain approximately constant over the next few decades. Similar to the EIA case above, this scenario assumes no new policies. CAT estimates that this scenario would lead to warming of about 2.7°C by 2100.
- McKinsey & Company, a private consulting firm, projects a "current trajectory" scenario that considers existing policy momentum and further cost declines for renewable energy. Global GHG emissions decline by 36% over 2023-2050. However, the Paris Climate

[70] World Bank, 2022.
[71] Abel *et al*., 2019.
[72] United Nations, 2015.
[73] Energy Institute, 2024.
[74] United Nations Climate Change, 2023.
[75] European Commission, 2023.

Agreement target of limiting warming to 2°C is still not met in this scenario, with warming of 2.4°C expected.

- CAT also provides a scenario in which countries meet their current targets for emissions reductions. Under this scenario, global GHG emissions in 2050 would be 40-53% lower than in 2023. If countries meet their current emissions targets, limiting warming to the Paris 2°C target is possible, with about 2.1°C of warming expected.
- The lowest projection (also from CAT) estimates the emissions path necessary to meet the 1.5°C Paris target. As shown in the figure, global emissions would have already started to decline in this case, with emissions decreasing by about 80% over 2020 to 2050. In reality, meeting the 1.5°C target may no longer be possible—as of mid-2024 the global average temperature exceeded this target for 12 consecutive months.[76]

Figure 13. *Past and Projected Global Emissions of Carbon Dioxide, 1990-2050*



Sources: U.S. EIA, 2023; Climate Action Tracker, 2023; McKinsey & Company, 2022a.

These scenarios illustrate the considerable uncertainty in future emissions and temperatures. Avoiding the worst impacts of climate change will require more aggressive policies to reduce fossil fuel consumption, expand renewable energy capacity, and increase energy conservation. We next turn to an economic perspective on climate change, before considering policy options in Section 6.9.

[76] Smith, 2024.

6.8 Economic Analysis of Climate Change

Most of the topics discussed in Sections 2 through 5 of this module are relevant to the economics of global climate change. Environmental economists tend to view climate change within a traditional cost-benefit analysis framework, applying the standard techniques of economic valuation and discounting. Ecological economists are more likely to view climate change from a strong sustainability perspective, arguing for policy action on the basis of ecological and ethical, as well as economic, justifications.

Virtually all economists agree that carbon emissions, as a negative externality, should be internalized through market mechanisms such as a Pigovian tax or a tradable permit system. Either a tax or permit system effectively puts a price on emitting CO_2 and other GHGs, commonly referred to as the **social cost of carbon**, reflecting the long-term discounted damages. There is a lively debate among economists about the appropriate social cost of carbon, with a low price implying a relatively modest response to climate change while a high price indicates a more aggressive approach.

In a 2023 paper, William Nordhaus (who received the 2018 Nobel Memorial Prize in economics for his climate change analyses) estimated that the social cost of carbon should start at around \$6/ton of CO_2 in 2022, rising to \$90/ton in 2040 under an "optimal" scenario.[77] Other economists propose that the social cost of carbon should be significantly higher, noting that Nordhaus' recommendations would result in unacceptable warming of nearly 3 degrees Celsius (relative to the pre-industrial average) by 2100. A 2021 paper co-authored by Nobel-prize winning economist Joseph Stiglitz suggests a social cost of carbon of \$100-\$125/ton.[78] A 2022 article in the journal *Nature* produced a social cost of carbon estimate of \$185/ton, based on recent scientific research regarding the potential damages of climate change.[79] An even higher estimate of over \$1,000/ton comes from a 2024 paper that estimates warming damages based on the historical relationship between temperatures and country-level macroeconomic performance.[80]

The different values for the social cost of carbon are largely a function of the discount rate used in the analysis. William Nordhaus recommends a discount rate of around 4 percent, which produces his relatively low current social cost of carbon of \$6/ton discussed above. In contrast, the \$185 and \$1,000/ton values rely on a lower discount rate of 2 percent. Economics cannot determine which discount rate is "correct", although a survey of nearly 200 experts on discounting revealed an average preferred rate of 2.25 percent, with two-thirds of respondents preferring a rate from 1 to 3 percent.[81]

From an economic perspective, the costs of action to mitigate the effects of climate change, such as investments in renewable energy and energy efficiency, should be weighed against the benefits, measured as the future reduction in damages from severe storms, crop losses, tropical diseases,

[77] Barrage and Nordhaus, 2023.
[78] Stern and Stiglitz, 2021.
[79] Rennert *et al*., 2022.
[80] Bilal and Känzig, 2024.
[81] Drupp *et al*., 2015.

and other impacts. Various economic analyses have estimated that the additional investment needed to limit warming to no more than 2ºC will cost between 0.4 and 2 percent of world GDP annually.[82]

Nearly all recent analyses conclude that the benefits of strong action to mitigate climate change far exceed these costs. For example, a 2021 analysis by Swiss Re (one of the world's largest insurance companies) estimates that without strong mitigation policies the economic costs from additional climate change would be between 7 and 14 percent of the world economy by 2050.[83] A 2022 study estimates that measures to meet the Paris climate targets will result in a net benefit to the world economy of $43 trillion over 2021-2070, and that "the status quo is the costlier choice."[84]

Similarly, a 2022 paper by the International Monetary Fund concludes that "the costs of action are small relative to the costs of inaction."[85] Finally, a 2023 analysis sponsored by over 100 of the world's central banks found that efforts to reduce global carbon emissions to net zero by 2050 would result in global GDP being 7 percent higher as compared to current policies ("net zero" means that remaining emissions would be fully offset by increased carbon removal from forests, improved agricultural practices, and other actions).[86]

6.9 Climate Change Policy

A sufficient response to climate change will require a range of policies at the local, national, and international levels. As discussed in Section 5, economists tend to focus on market-based policies to address environmental problems—in this case, carbon taxes and permit systems. Other policies, including emissions standards, technological requirements, and other policies can also be effective at reducing GHG emissions. Some of these policies include:

- *Reducing or eliminating fossil fuel subsidies.* While economic efficiency would suggest taxing fossil fuels, most countries instead encourage fossil fuel development and consumption through subsidies. For more on fossil fuel subsidies, see Box 3.
- *Renewable energy targets.* More than 60 countries have announced targets to obtain a given amount of their energy (or electricity) from renewable sources by a specific date. For example, in 2023 the European Union announced that it intends to obtain 42.5% of its energy from renewable sources by 2030.[87] China's target is to obtain 35% of its electricity from renewables by 2030.[88] Sweden intends to obtain 100% of its electricity from renewable sources by 2040.[89]
- *Efficiency standards.* These policies mandate minimum efficiencies for appliances, automobiles, buildings, lighting, and other products. For example, the 2024 Corporate Average Fuel Economy standard in the U.S. is 43.5 miles per gallon for cars and light

[82] For the low estimate, see: Black *et al*., 2022. For the high estimate, see: McKinsey & Company. 2022b.
[83] Swiss Re Institute, 2021.
[84] Deloitte, 2022.
[85] Black, *et al*., 2022.
[86] Mehrhoff, 2023.
[87] European Union. Renewable Energy Targets.
[88] Bloomberg News Editors, 2018.
[89] Climate Council, 2022.

trucks, with penalties for manufacturers who fail to meet this standard.

- *Technology transfer*. Most of the projected growth in energy consumption and carbon emissions will occur in lower-income countries. Richer countries should ensure that other countries have affordable access to clean energy technologies.

BOX 3: FOSSIL FUEL SUBSIDIES

Fossil fuels are subsidized by governments around the world in numerous explicit and implicit ways. Beyond reducing suppliers' production costs through direct subsidies, implicit subsidies include the failure to institute appropriate Pigovian taxes on fossil fuels for air pollution and climate change damages. According to the International Monetary Fund, global fossil fuel subsidies were $7 trillion in 2022, equal to 7.1 percent of global GDP. [90]

About 60 percent of total subsidies were attributed to a failure to internalize the externalities associated with carbon emissions and local air pollution. The IMF notes that fossil fuel subsidy reforms raising fuel prices to their economically efficient levels would reduce global carbon emissions by 43 percent by 2030—a reduction that is consistent with meeting the Paris Climate Agreement targets of a maximum 1.5-2.0°C temperature increase.

The IMF concludes that subsidy reform would generate an additional $3 trillion in government revenues in low- and middle-income countries, allowing them to meet UN targets for poverty alleviation. However, fossil fuel subsidy reforms remain politically challenging, as the IMF notes:

> … many countries have had difficulty reforming subsidies despite the potential gains. When reforms are made, prices increase, and this can lead to social unrest. The absence of public support for subsidy reform is in part due to a lack of confidence in government's ability to compensate the poor and middle class for the higher energy prices they face.[91]

Another factor hampering the reform of inefficient fossil fuel subsidies is the enormous amount of political and financial power harnessed by the companies which benefit from these subsidies. According to a 2023 analysis, the oil and gas industry spent over $2 billion on political activities in the U.S. over 2008-2018, outspending clean energy advocates by a factor of 27. [92]

[90] IMF, 2024.
[91] IMF, https://www.imf.org/en/Topics/climate-change/energy-subsidies.
[92] Downie and Brulle, 2023.

Market-Based National and Regional Climate Policies

Both carbon taxes and permit systems have been used by a number of countries. Approximately 30 countries have implemented carbon taxes, including Japan, Chile, Colombia, and Switzerland. These taxes, however, are generally too low to fully internalize the externalities associated with greenhouse gas emissions. For example, Mexico's carbon tax is about $4 per ton of CO_2 while Japan's is only $2.40 per ton—well below the social cost of carbon values discussed earlier.[93]

The most extensive permit system is the European Union's Emissions Trading System, which has been in place since 2005. The system covers about 10,000 power stations and manufacturing plants, amounting to nearly half of all greenhouse gas emissions in the EU.[94] The system also covers air transport and (as of 2024) marine vessels. The price of permits in the EU system has varied significantly, ranging from more than €100/ton to less than €1/ton, depending on economic conditions and the allocation of permits.

California has also instituted a carbon trading system and has partnered with Canadian provinces to expand it. South Korea implemented a cap-and-trade system in 2015, initially freely allocating all permits but gradually increasing the share of permits that are auctioned.[95] In 2017, China initiated a nationwide carbon permit system, effectively doubling the proportion of the world's carbon that is subject to pricing.[96]

International Climate Policy

As climate change is a global problem, international cooperation is critical in mounting an adequate response. The first international treaty to address climate change, the 1997 Kyoto Protocol, specified emissions targets only for richer nations, with penalties planned for those that failed to meet their targets. When the treaty expired in 2012, some countries achieved their targets, while others did not (the United States never ratified the treaty), but no penalties were ever enforced.

In order to bring nearly all nations into the process, the 2015 Paris Climate Agreement let each country set their own targets on a voluntary basis, referred to as Nationally Determined Contributions (NDCs), without enforceable penalties. It is left to each country to decide what national policies they will enact to meet their NDC, whether these policies be taxes, permits, or other regulations. As mentioned earlier, the goal of the Paris Climate Agreement is to limit warming to "well below" an increase of 2°C above pre-industrial levels and to pursue efforts to limit warming further to no more than a 1.5°C increase. Nearly all nations, representing over 98 percent of global carbon emissions, have ratified the Paris Agreement.

Given the voluntary nature of the Paris Climate Agreement, some nations' NDCs are more ambitious than others. The organization Climate Action Tracker, which presents independent

[93] Letourneau, 2023.
[94] European Commission, 2024.
[95] Environmental Defense Fund, 2015.
[96] Harvey, 2017.

scientific analysis on climate issues, has rated the NDCs of 39 nations and the European Union.[97] Countries receiving their highest rating ("almost sufficient": compatible with the 2°C target but not the 1.5°C target) include Bhutan, Costa Rica, Ethiopia, and Norway. Countries with "insufficient" NDCs include Brazil, Japan, the EU, and the United States. Eighteen countries have "highly" or "critically insufficient" NDCs, including Canada, China, India, Russia, and Saudi Arabia.

As discussed earlier, meeting the more stringent 1.5°C Paris target appears unlikely but meeting the 2°C goal is a distinct possibility if countries meet their existing emissions targets. The Paris Climate Agreement calls on nations to submit more ambitious targets over time as the potential effects of climate change become more evident and technologies for renewable energy and energy efficiency improve, which would make meeting the 2°C goal even more likely.

The outlook for climate change includes a mix of pessimistic and optimistic perspectives. The International Energy Agency's 2023 *World Energy Outlook* projected that global CO_2 emissions will peak in 2024 or 2025, and thereafter start to decline—but this decline will need to be rapid to meet the 2°C Paris target.[98] The 2023 international climate summit in Dubai, UAE, concluded that "implementation of the Paris Agreement is lacking across all areas and not where it should be."[99]

The main reason for optimism about climate change is the dramatically declining cost of renewable energy. The U.S. Department of Energy found that the cost of "utility-scale" solar energy declined by 82 percent from 2010 to 2020,[100] with costs continuing to decline about 10 percent per year.[101] Considering the life-cycle cost of new energy installations without any subsidies, utility-scale solar and wind are currently the two cheapest energy sources globally, on average.[102] Consequently, about 85 percent of new energy installations globally now rely on non-fossil fuel sources, mainly wind and solar.[103] The International Energy Agency concludes that renewables will "dominate the growth of global electricity supply" and, along with nuclear energy, provide over half the world's power generation by 2026.[104] A global transition toward clean energy sources is already well under way, and is expected to gain further momentum, driven by economic logic and policy support.

[97] climateactiontracker.org/.
[98] Kharas et al., 2023.
[99] United Nations, Climate Change. 2024.
[100] NREL, 2021.
[101] Timmer, 2022.
[102] Lazard, 2024.
[103] NREL, 2023.
[104] International Energy Agency, 2023.

KEY TERMS AND CONCEPTS

Biofuels: fuels derived from recently-living biological sources, normally plant matter.

Bycatch: fishery catch that is discarded because it is undersized or non-marketable.

Climate change: changes in the earth's climate, such as warmer average temperatures and shifting precipitation patterns, attributed to either natural or human causes.

Common property resources: a resource that is not subject to private ownership and is available to all, such as a public park or the oceans.

Consumer surplus: the benefits consumers receive from a product in excess of the amount they pay for it.

Contingent ranking: a survey method whereby respondents are asked to rank a list of alternatives.

Contingent valuation: an economic tool that uses surveys to question people regarding their willingness to pay for a good or service such as the preservation of hiking opportunities or air quality.

Cost of illness method: an approach for valuing the negative impacts of pollution by estimating the cost of treating illnesses caused by the pollutant.

Cost-benefit analysis: a tool for policy analysis that attempts to monetize all the costs and benefits of a proposed action to determine the net benefit.

Cost-effectiveness analysis: a policy tool that determines the least-cost approach for achieving a given goal.

Defensive expenditures approach: a pollution valuation methodology based on the expenditures households take to avoid or mitigate their exposure to a pollutant.

Discount rate: the annual rate that future benefits or costs are discounted relative to current benefits or costs.

Discounting: the concept that future benefits or costs should not count as much as current benefits or costs.

Ecolabeling: a label on a good that provides information concerning the environmental impacts that resulted from the production of the good.

Ecological economics: a economic perspective that views the economic system as a subset of the broader ecosystem and subject to biophysical laws.

Ecological footprint: a measure of individual or national environmental impact in terms of land and resource use.

Economic efficiency: an allocation of resources that maximizes net social benefits; perfectly competitive markets in the absence of externalities are efficient.

Ecosystem services: beneficial services provided freely by nature such as flood protection, water purification, and soil formation.

Environmental economics: economics that applies the techniques of economic analysis, such as valuation and cost-benefit analysis, to environmental and resource issues.

Excludable: the characteristic goods where use of the good by one person excludes the potential for use by others.

Externalities: effects of market transactions that change the utility, positively or negatively, of those outside of the transaction.

Free rider: someone who avoids paying for a resource when the benefits they obtain from the resource are unaffected by whether they pay; results in the undersupply of public goods.

Greenhouse gases: gases such as carbon dioxide and methane whose atmospheric concentrations influence global climate by trapping solar radiation.

Human capital: the knowledge, skills, and abilities of the labor force, reflecting investments in education and training.

Individual transferable quotas (ITQ's): tradable rights to harvest a resource, such as a permit to harvest a particular quantity of fish.

Inherent value: the value of an organism, species, habitat, or other natural system independent of its economic value.

Lower-bound estimate: an economic estimate that provides the lowest possible value for some cost or benefit.

Malthusian hypothesis: the theory proposed by Thomas Malthus in 1798 that population would eventually outgrow available food supplies.

Marginal benefits: the benefits of producing or consuming one more unit of a good or service.

Marginal costs: the costs of producing or consuming one more unit of a good or service.

Market equilibrium: the market outcome that results from the interaction of supply and demand, i.e., the point where the supply and demand curves intersect.

Market-based approaches: economic regulations that create market incentives for behavioral change among participants (buyers and sellers), including taxes and tradable permits.

Maximum sustainable yield: the maximum quantity of a natural resource that can be harvested annually without depleting the stock or population of the resource.

Natural capital: the available endowment of land and resources including air, water, soil, forests, fisheries, minerals, and ecological life-support systems.

Negative externalities: harmful side effects, or unintended consequences, of economic activity that affect persons, or entities (such as the environment) that are not among the economic actors directly responsible for the activity.

Nonexcludable: a characteristic of goods where the one person's use of the good does not prohibit others from using the good also.

Nonmarket valuation: economic valuation of goods and services not traded in markets.

Nonrival: goods that can be used by more than one user at a time.

Nonuse benefits: benfits people obtain without actually using a resource; nonuse benefits include existence and bequest values.

Pigovian tax: a per-unit tax set equal to the external damage caused by an activity, such as a tax per ton of pollution emitted equal to the external damage of a ton of pollution.

Polluter pays principle: the view that those responsible for pollution should pay for the associated external costs such as health costs and damage to wildlife habitats.

Positive externalities: the positive impacts of a market transaction which affect those not involved in the transaction.

Precautionary principle: the view that policies should account for uncertainty by taking steps to avoid low-probability but catastrophic events.

Present value: the current value of a stream of future costs and/or benefits; a discount rate is used to convert future costs and/or benefits to present values.

Price volatility: large or frequent changes in the price of a good or service.

Produced capital: productive physical resources that are manufactured by humans, such as buildings, roads, and computers.

Producer surplus: the excess (summed over all the sellers in a market) of the amounts sellers actually receive, over the amounts that would make them just willing to supply the good or service.

Public goods: goods that are available to all (non-exclusive) and whose use by one person does not reduce their availability to others (non-rival).

Regenerative agriculture: agricultural systems that restore degraded productivity levels using ecologically sustainable techniques while increasing carbon storage in plants and soils to mitigate climate change.

Renewable resources: resources that are supplied on a continuing basis by ecosystems; renewable resources such as forests and fisheries can be depleted through exploitation.

Replacement cost methods: an approach to measuring environmental damages that estimates the costs necessary to restore or replace the resource, such as applying fertilizer to restore soil fertility.

Revealed preference methods: methods of economic valuation based on market behaviors, including travel cost models, hedonic pricing, and the defensive expenditures approach.

Rival: goods whose use is limited to one user at a time.

Slash-and-burn agriculture: agricultural production technique where existing vegetation is cut then burned to allow for the planting of crops, typically at a subsistence level.

Social cost of carbon: a monetary estimate of the discounted long-term damages from emitting a ton of CO_2.

Social marginal benefits: the additional benefits obtained by everyone in society by the provision of an additional unit of a good or service.

Social marginal costs: the additional costs that must be borne by all members of society associated with the production of an additional unit of a good or service.

Stated preference methods: economic valuation methods based on survey responses to hypothetical scenarios, including contingent valuation and contingent ranking.

Strong sustainability: the view that natural and human-made capital are generally not substitutable and, therefore, natural capital levels should be maintained.

Subsidy: government assistance to an industry or economic activity; subsidies can be direct, through financial assistance, or indirect, through protective policies.

Total economic value: the value of a resource considering both use and non-use values.

Tradable pollution permits: tradable permits that allow a firm to emit a certain quantity of a pollutant.

Tragedy of the commons: the tendency for common property resources to be over-exploited because no one has an incentive to conserve the resource while individual financial incentives promote expanded exploitation.

Travel cost models: the use of statistical analysis to determine people's willingness to pay to visit a natural resource such as a National Park or river; a demand curve for the resource is obtained by analyzing the relationship between visitation choices and travel costs.

Upstream tax: a tax to regulate emissions or production as near as possible to the point of natural resource extraction.

Value of a statistical life (VSL): the willingness to pay of society to avoid one death based on valuations of changes in the risk of death.

Weak sustainability: the view that natural capital depletion is justified as long as it is compensated for with increases in human-made capital; assumes that human-made capital can substitute for most types of natural capital.

Willingness to pay principle: the maximum amount of money people are willing to pay for a good or service that increases utility.

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DISCUSSION QUESTIONS

1. Which definition of sustainability, strong or weak, do you think is the most appropriate? Based on the material discussed in this module, how would you quantitatively measure whether your preferred definition of sustainability is being achieved?

2. Explain in your own words why an unregulated market outcome will not be economically efficient in the presence of a negative externality. Then explain how the market can achieve efficiency through the internalization of the externality.

3. Discuss how the global atmosphere can be considered a common property resource. Do you think the atmosphere is suffering from the tragedy of the commons? If so, what policy solutions would you recommend?

4. Do you think contingent valuation produces valid economic estimates of the benefits of environmental resources? Can you think of ways to ask contingent valuation questions in order to improve the validity of the responses?

5. What do you think is the main advantage of cost-benefit analysis? What do you think is its main disadvantage? Do you think cost-benefit analysis should be the basis for choosing environmental policy options? Why or why not?

6. List the main advantage and main disadvantage of each of the four environmental policy options discussed in this module: pollution taxes, tradable pollution permits, pollution standards, and technology-based regulation. Then for each of the four options discuss one pollution scenario for which you think it would be the best policy option to regulate pollution.

7. Do you think a carbon tax or a tradable permit system is the best approach for regulating the emissions of greenhouse gases? Explain your choice. What other policies might be effective as well as politically acceptable?