MODULE 3
The economics of climate change

1 Introduction

Module 1 showed that economic activities can influence the climate because the economy and the environment are interdependent. Module 2 explained the climate science behind climate change and showed how human activities contribute to change the climate. This module shows how economic theory explains the occurrence of transboundary environmental problems, such as climate change, and clarifies why it can be so difficult to implement solutions to these problems even though those solutions are well known.

Neoclassical economic theory stipulates that markets allocate resources in an optimal, i.e. efficient, way. At the same time, however, economic behaviour leads to important negative effects on the environment such as climate change. If markets allocate resources efficiently, how is it possible that severe environmental problems like climate change exist? Sections 2 and 3 of this module aim to answer this question.

Section 2 reviews the basic concepts of economic theory on markets and optimal allocations. It introduces the standard theoretical model describing market economies and the concept of Pareto efficiency used to evaluate whether resources are allocated efficiently. It shows that, in theory, fully competitive markets allocate resources in a Pareto-efficient way and thus optimally from a social point of view. However, this theoretical result only holds up provided that certain assumptions are satisfied; if these assumptions are not met, markets fail and generate outcomes that are not socially optimal. This is what is called a "market failure."

Section 3 shows that climate change is the result of such a market failure occurring because two assumptions are not met. First, contrary to the assumption of all commodities being private goods, the atmosphere is an open-access resource (see Section 3.1). As such, there are no legal constraints on its use, and therefore any country can release any amount of greenhouse gases into the atmosphere at any time. Open-access resources cannot be "efficiently" exploited in market economies because countries tend to overuse them. Second, GHG emissions are negative externalities (see Section 3.2). Negative because they detract from social welfare and externalities because they are external to any accounting within the economic system. Economic agents do not take negative externalities into account when making their decisions, and consequently over-emit greenhouse gases into the atmosphere. Due to the combination of these two factors, markets fail to generate a Pareto-optimal situation. This gives rise to climate change, considered to be the biggest market failure in human history.

Since markets have failed, policy interventions are needed to mitigate climate change. Even though it has been known for some time how policy interventions could mitigate climate change, the international community has been struggling for decades to solve the issue. Section 4 investigates how economic theory explains the inability of governments and societies to mitigate climate change. It shows that climate change mitigation is a global "public good" that has non-rival and non-excludable benefits (see Section 3.1). As no country can single-handedly take actions to eliminate the threat of climate change, international cooperation is needed. However, such cooperation is extremely difficult to achieve when dealing with a global public good. To illustrate this difficulty, the section introduces game theory concepts that are used to analyse strategic interaction among countries. It shows that the main cause of the failure of collective action is that countries have strong incentives to free-ride and not contribute to reducing emissions. This leads to an outcome that is not socially optimal. The section concludes by drawing several lessons from game theory models that allow us to identify ways to foster cooperation among countries.

At the end of this module, readers should be able to:

- State the implications of the first welfare theorem;
- Understand the conditions under which the first welfare theorem does not hold and define market failures;
- Explain why the atmosphere is considered to be an open-access resource;
- Explain why greenhouse gas emissions are negative externalities;
- Discuss why climate change is considered to be the biggest market failure in human history;
- Use game theory tools to analyse how economists explain the fact that the international community has been struggling to implement climate change mitigation policies.

To support the learning process, readers will find several exercises and discussion questions in Section 5 covering the issues introduced in Module 3. Additional reading material can be found in Annex 1.

2 The competitive markets model and Pareto efficiency

Neoclassical economic theory stipulates that markets allocate resources efficiently. If this is indeed the case, then why do markets sometimes fail to do so, producing highly inefficient outcomes leading to environmental problems such as climate change? To answer this question we first have to understand why economic theory concludes that markets produce efficient outcomes, in particular, understand (a) how economists conceptualize market economies, and (b) how economists evaluate the efficiency of market economies. This section clarifies these two points and shows that, given certain conditions, economic theory predicts that markets indeed produce efficient outcomes. Section 3 subsequently shows that in the context of climate change, some of these conditions are violated, and therefore markets fail to achieve efficient outcomes.

2.1 A simple model of market economies

Economic processes are inherently complex and difficult to understand. Economists thus rely on theoretical models of the economy to improve their understanding of these processes. Economic models are theoretical constructs that aim to represent different aspects of economic processes in a simplified way. They therefore rely on assumptions that might not necessarily hold in reality. Nevertheless, the models are very useful tools because they shed light on complex economic mechanisms and their relationships with the environment. Market economies, currently the dominant form of economic organization (Cohen, 2009), have been extensively studied and modelled. Economists have developed a standard model of a competitive market economy,[41] which we will now briefly introduce and which will serve as a starting point to understand how economic theory explains the occurrence of climate change.

In this standard model, the economy is assumed to be composed of economic agents (firms and households) acting purely in their own self-interest – i.e. trying to optimize their behaviour to achieve the outcome that is best for them. In other words, firms try to maximize their profits while households try to maximize their utility (i.e. consume a mix of goods and services that makes them as satisfied as they can be on a given budget). The model assumes that there are many different markets, one for each commodity. Each competitive market connects demand (how much households are willing to pay for the commodity) and supply (how much firms want to be paid to produce the commodity), thereby determining how much of the specific commodity is produced. In such a competitive market, the price of a commodity adjusts until demand equals supply. This is called equilibrium. Put differently, a market is in equilibrium if the sum of the quantities of commodities that households want to buy at current prices equals the quantities of commodities that firms want to produce at current prices (see Box 12 for a graphical illustration of an equilibrium in a single competitive market).

[41] Going into the details of the microeconomic foundations of the competitive market model is beyond the scope of this material. Interested readers may refer to standard microeconomic textbooks such as Varian (2010). Additional readings can also be found in Annex 1.

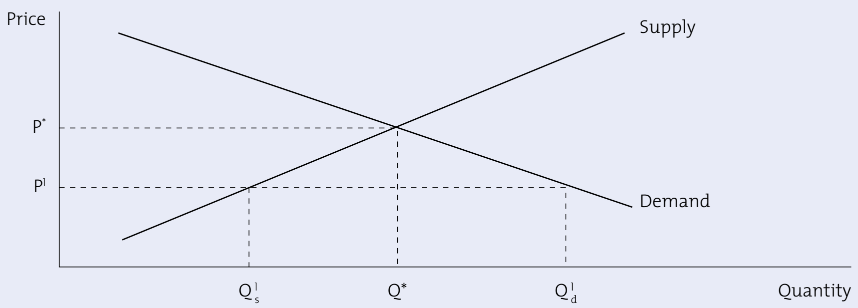
Box 12

Equilibrium in a single competitive market

Figure 30 displays a single competitive market for a normal good and shows the demand and supply curve for this particular good. The demand curve relates the quantity demanded by consumers to the market price. It is downward sloping, meaning that the cheaper the good, the more of it consumers are willing to buy. The supply curve relates the quantity supplied to the price and is upward sloping, meaning that the higher the price firms can charge, the more they are willing to supply. The market is in equilibrium at price P^* and corresponding quantity Q^*, as this is the only point where demand equals supply. Note that given the supply and demand curves, this is the only equilibrium in this particular market. For any other price, supply does not equal demand. To see this, look for instance at price P^l: at this price, consumers demand Q^l_d, but producers are only willing to supply Q^l_s. This situation is clearly not an equilibrium, as the quantity demanded is higher than the quantity supplied.

Figure 30

Equilibrium in a single competitive market



Source: Author.

If all firms maximize their profits, all consumers maximize their utility given their budget constraints, and all individual commodity markets are in equilibrium, then the resulting allocation of commodities and the corresponding set of prices is called a competitive equilibrium. Put differently, in this state, the whole market economy, and not only a single commodity market, is in equilibrium.

While the model allows us to understand how market economies allocate resources, it remains silent about how efficient those economies are in allocating these resources. This is important to know, however, as resources are scarce and allocating them improperly is costly. Economists have tried to answer this question by using the competitive market model and a very specific concept of efficiency – Pareto efficiency – introduced in the next section.

2.2 Pareto efficiency

Various conceptual tools are used to evaluate different allocations of resources. The most commonly used tool is called Pareto efficiency,[42] named after the 19th century Italian economist Vilfredo Pareto. An allocation of resources in which one can find a way to make one or more persons better off without making another person worse off is called a Pareto-inefficient allocation. If there is no way to make one or more persons better off without making another person worse off an allocation is called a Pareto-efficient allocation.

Pareto-inefficient allocations are a priori not desirable. After all, if you could improve the situation of at least one person without deteriorating the situation of another person, i.e. if you could "Pareto-improve" a situation, why not do it? When all such Pareto improvements have been made and no more are available, the allocation of resources is said to be Pareto-optimal.

While the Pareto-efficiency criterion is useful as a benchmark for evaluating whether or not an allocation is efficient, it has its limits. If two allocations are Pareto-efficient, the criterion is unable to evaluate which of the two allocations is preferable. Amartya Sen (1970: 22) made this point explicit by writing that an economy may be Pareto-efficient "even when some people are rolling in luxury and others are near starvation, as long as the starvers cannot be made better off without cutting into the pleasures of the rich... [A]n economy can be Pareto optimal and still be perfectly disgusting." Thus, Pareto efficiency does not allow us to identify allocations that optimize justice or equality. The criterion can only determine whether a society is allocating resources wastefully or not (Mas-Colell *et al.*, 1995) and whether allocations can be changed in a way that unambiguously improves the welfare of a society.

2.3 Competitive market equilibria and Pareto efficiency

Despite its limitations, Pareto efficiency allows for evaluating whether market economies, as modelled by the competitive market model, allocate resources efficiently. According to neoclassical economic theory, this is indeed the case. The first welfare theorem states that, as long as some conditions are satisfied, competitive markets' equilibria are Pareto-efficient allocations.[43] The first welfare theorem thus formalizes Adam Smith's conjecture in *The Wealth of Nations* in 1776 of an "invisible hand," and is one of the most central theoretical results in economics. It implies that markets composed of economic agents acting purely in their own self-interest will achieve an allocation of resources that constitutes a social optimum from which nobody's position can be improved without harming someone else. Box 13 illustrates this through the example of production in a single market.

[42] Pareto efficiency is sometimes also referred to as economic efficiency or Pareto optimality.

[43] Lerner (1934, 1944) was the first economist to (graphically) prove the existence of the first welfare theorem. Lerner (1944) also outlined the foundations of the second welfare theorem, stating that any Pareto-efficient equilibrium can be achieved by a market after lump-sum transfers of the initial wealth endowment, a theorem that was first formally proved by Arrow (1951).

Box 13

A Pareto-efficient level of production in a single market

Let us take an intuitive look at why market equilibria can be considered Pareto-efficient, using the example of production output in a single market. Figure 31 displays supply and demand curves of a normal good in a competitive market. As we have already seen, competitive markets determine the total quantity produced by taking into account how much consumers are willing to pay for the good and how much suppliers have to be paid to produce the good. In an equilibrium, demand and supply are balanced so that the willingness of consumers to pay an amount P^* for an extra unit is equal to the willingness of suppliers to be paid the amount P^* to supply an extra unit.

Why is the resulting equilibrium production amount considered to be Pareto-efficient? Suppose that instead of producing the equilibrium quantity Q^*, suppliers would produce less, say, Q^I. Then some producer would be willing to produce an additional unit and sell it at a price slightly above P^I_s, but well below the price that someone would be willing to pay for an extra unit (which would be a price slightly below P^I_d).

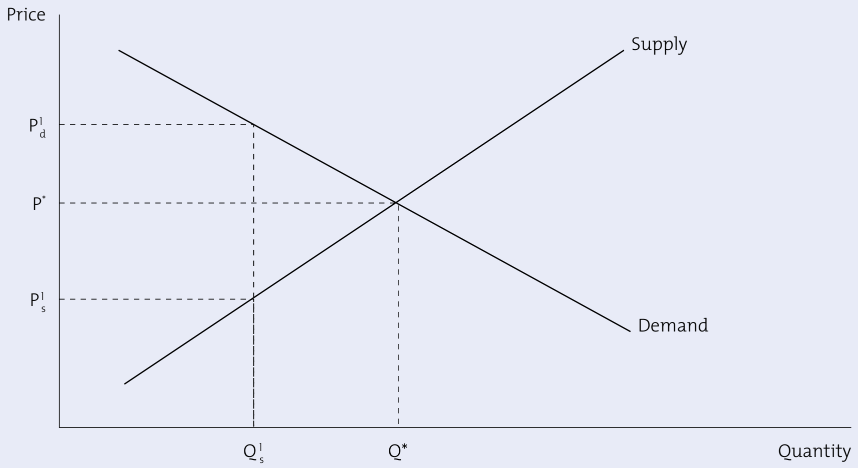
Box 13

A Pareto-efficient level of production in a single market

This would clearly be a win-win scenario, as by producing and exchanging that additional unit, at least these two persons would be better off. The same holds for all quantities below *Q. Thus as long as less than *Q** is produced, at least one person could be made better off by increasing total production. Would producing a quantity greater then *Q** also be a Pareto improvement? The answer is no. As the price any supplier asks for an extra unit produced would be higher than any consumer's willingness to pay for that unit, nobody would buy this extra unit, and thus no person would be better off. At the same time, the supplier producing the extra unit that cannot be sold would be even worse off. Therefore, only the market equilibrium allocation *Q** with the corresponding price *P** can be considered to be a Pareto-efficient allocation. This is an intuitive illustration of the claim that competitive markets determine a Pareto-efficient amount of output.**

Figure 31

A Pareto-efficient level of output in a single competitive market



Source: Author's elaboration based on a similar discussion in Varian (2010: 310–12).

The first welfare theorem depends, however, on a series of assumptions that Perman *et al*. (2011: 103) call "institutional arrangements." These arrangements have to be satisfied or the first welfare theorem does not hold and competitive markets do not produce socially optimal situations. These assumptions require that (a) markets exist for all goods and services; (b) these markets are perfectly competitive (no agent can influence the price); (c) all agents have full information on current and future prices; (d) private property rights exist for all resources and commodities; (e) there are no externalities; and (f) all commodities are private goods.[44, 45] In reality, these assumptions are often violated (Sandler, 2004). Consequently, markets fail to achieve Pareto-efficient allocations and economists speak of market failures, which can potentially have devastating consequences and lead to situations that are not socially optimal. As we will see in Section 3, climate change is the result of such a market failure. Some have even argued that climate change is the biggest market failure in human history (Stern, 2007).

Short summary

Section 2 reviewed basic elements of economic theory that are needed to understand how economic theory explains climate change. The section started by introducing the standard model of a competitive economy and discussed the concept of market equilibrium. It then briefly introduced the Pareto-efficiency criterion used to evaluate different allocations of resources. Finally, it showed that markets allocate resources in a Pareto-efficient way provided that certain conditions are satisfied, but fail to do so if these conditions are not met. These so-called market failures are at the heart of economists' explanations of the occurrence of climate change and are analysed in greater detail in the following sections.

[44] In addition to the assumptions highlighted in this section, there is an additional technical assumption on consumer preferences called local nonsatiation of preferences, which also has to be satisfied for the first welfare theorem to hold (Mas-Colell *et al*., 1995: 549–50).

[45] Note that, strictly speaking, assumptions (e) and (f) are already implied by assumption (d). If enforceable private property rights for all resources and commodities do exist, then all benefits and/or costs accrue to the agent holding the property right for the commodity or resource. This implies that there would not be any externalities and only private goods. However, we follow Perman *et al*. (2011) and list these assumptions separately for the sake of clarity, as we will discuss assumptions (e) and (f) extensively in sections 3.1 and 3.2.

3 Climate change: The greatest market failure in human history

Section 2 of this module showed that, according to the first welfare theorem of neoclassical economic theory, markets composed of economic agents acting purely in their own self-interest allocate resources in a Pareto-efficient way, i.e. produce a socially optimal situation in which no one's welfare can be improved without harming someone else's welfare. In this ideal theoretical world, human-induced climate change would not occur.

However, current empirical evidence points towards the existence of such human- induced climate change (IPCC, 2014a). Economists maintain that this empirical finding is due to the violation of two underlying assumptions of the first welfare theorem. The first of these assumptions, assumption (f), is that all goods have to be private goods. But since the atmosphere is an open-access resource (see Section 3.1), this assumption is violated. As we will see, open-access resources are very different from "normal" private goods, and markets cannot Pareto-efficiently handle the former. The second violated assumption, assumption (e), concerns the absence of any externality. As we will see in Section 3.2, GHG emissions are an example of a negative externality that again leads to a Pareto-inefficient outcome.

Because these two assumptions are violated, the first welfare theorem does not hold up, markets fail, and economic agents over-emit greenhouse gases, leading to growing GHG accumulation in the atmosphere that exacerbates climate change. In Sections 3.1 and 3.2, we discuss both violations in detail and show why climate change is considered to be the result of a major market failure.

3.1 The atmosphere: An open-access resource

Theory tells us that markets achieve Pareto-optimal allocations if they deal with private goods, but tend to fail if market systems involve non-private goods. This section will show that the atmosphere, in its function as a GHG repository, is not a private good. The section will then help us understand the consequences of this fact.

Goods can be classified as private or public using two criteria that characterize the benefits of their consumption: rivalry and excludability (Sandler, 2004; Perman *et al.*, 2011).[46] Benefits of consumption are rival when a unit of a good can only be consumed by one individual, meaning that one individual's consumption is at the expense of somebody else's consumption. Benefits of consumption are excludable when one can prohibit another person from consuming the good. Pure private goods are defined as having completely rival and excludable benefits. To illustrate the concept, let us look at a particular pure private good: bread. If an individual eats a loaf of bread, the loaf is destroyed and cannot be eaten by anybody else. Thus, the benefits of consuming a loaf of bread are completely rival. At the same time, consuming bread is completely excludable, as bread comes in separable units and one can identify who owns a specific unit and thus has the right to consume it. The right to consume the loaf can be traded or gifted, but everything else is considered stealing and is punishable by law. This means that any individual not owning the right to consume the loaf can be excluded from eating a particular loaf of bread; in other words, the benefits of consuming the loaf are excludable. Bread, similar to most goods we consume in our daily life, is therefore a pure private good.

The opposite of pure private goods are pure public goods. These types of goods were first described in 1954 by the American economist Paul Samuelson (1954). The benefits of pure public goods are non-rival and non-excludable. Non-excludability means that nobody can be excluded from consuming the good, and consumption entitlements can be neither identified nor traded or gifted. Non-rivalry means that an individual can consume a particular unit of the good without affecting the possibility of another individual consuming the same unit. Let us illustrate this with a classical example of a pure public good: national defence. Once a certain level of defence is provided by the military, no citizen who is living within the country can be excluded from being protected by the military (in other words, from consuming the benefits of the provided defence level). Hence, the benefits of national defence are non-excludable. If a citizen consumes the provided defence level, he or she does not diminish in the slightest the possibility of another citizen consuming the same level of defence. Thus, the benefits of national defence are also non-rival.

The economics governing pure private and pure public goods are thus very different. Within these two extreme cases, the literature identifies a variety of goods with different degrees of rivalry and excludability, or in other words, with different degrees of publicness (Perman *et al.*, 2011).[47] For our purpose, we will not discuss all these different types of goods,[48] but rather concentrate on one particular type – open-access resources – to which the atmosphere belongs.

Open-access resources are part of a larger class of goods called common-pool resources. They are

[46] Note that some scholars (e.g. Tietenberg and Lewis, 2012) use the term "divisibility" as an equivalent of "rivalry."

[47] It is important to understand that the attribute "public" refers to the publicness property of rivalry and excludability, not to the way a good is produced (by public or private agents). It is possible that a public good is privately produced and/or a private good is publicly produced.

[48] See Sanders (2004) for an overview on the different types of these goods.

defined by Tietenberg and Lewis (2012: 629) as "common-pool resources with unrestricted access." Because scholars are still struggling to unambiguously define common-pool resources, we will follow Ostrom (2008: 11) who defines them as "sufficiently large that it is difficult, but not impossible, to define recognized users and exclude other users altogether. Further, each person's use of such resources subtracts benefits that others might enjoy." Thus, the benefits of consuming common-pool resources are rival (which distinguishes them from pure public goods) but excludable only with difficulties. If no individual or group owns a common-pool resource or is able to exercise full control over such a resource, the resource is called an open-access resource. Examples of such open-access resources are fisheries, forests, or the atmosphere.

To be specific, the atmosphere is an open-access resource with respect to its function as a repository of GHG emissions. Everybody can use the atmosphere to dump their GHG emissions free of charge, and it is difficult (although not impossible) to restrain this usage. Thus, the benefits of using the atmosphere's function as a GHG repository are only partly excludable. Moreover, if firms and individuals use the atmosphere as a GHG repository, other firms and individuals cannot do the same without causing serious negative environmental consequences like climate change. In that sense, the benefits of using the atmosphere as a GHG repository are rival.

Considering that the atmosphere is an open-access resource and not a pure private good, economic theory tells us that it cannot be efficiently exploited by a market economy. If market economies exploit open-access resources such as the atmosphere, they tend to overuse these resources. The resulting market failure then leads to outcomes that are not socially optimal. The main reason for this overuse is the open access to the resource. As no individual or group is able to control who is dumping greenhouse gases into the atmosphere, economic actors adopt a "use it or lose it" mentality and use the GHG repository function of the atmosphere on a "first come, first serve" basis, thereby collectively overusing the resource (Tietenberg and Lewis, 2012) by dumping massive amounts of greenhouse gases into the atmosphere. This problem is widely known as the "tragedy of the commons,"[49] and is at the heart of economists' explanation of the occurrence of climate change.

As we will see in Section 3.2, the overuse induced by the open-access problem is made worse by what economists call negative externalities: economic agents make their decisions to exploit the atmosphere's GHG repository function solely on the basis of their own benefits and costs. By doing so, they ignore the negative impact their GHG emissions have on others. This leads to a situation in which no agent has an incentive to reduce its GHG dumping activities and to conserve the atmosphere's capacity to absorb greenhouse gases.

3.2 Greenhouse gas emissions: A negative externality problem

Section 3.1 showed that market economies overuse the GHG repository function of the atmosphere because they cannot efficiently manage open-access resources. In addition to the open-access problem, there is a second related factor contributing to the overuse of the atmosphere's GHG repository function: emitting greenhouse gases is a negative externality problem. This is an additional reason why markets fail and hence climate change occurs.

An externality exists if actions by one economic agent unintentionally affect other agents. To be more precise, according to Perman *et al.* (2011: 121), an externality occurs if "the production or consumption decisions of one agent have an impact on the utility or profit of another agent in an unintended way, and when no compensation/payment is made by the generator of the impact to the affected party." A priori, externalities can be positive or negative.[50] Whereas positive externalities have a positive unintended effect on other agents, negative externalities have a negative unintended effect on others. Vaccinations are examples of positive externalities. They protect the vaccinated person as intended, but also have a positive unintended external effect, lowering the probability that other non-vaccinated persons catch the disease. GHG emissions are a typical example of negative externalities. While they are the by-product of an intended production process, they have a negative unintended effect on others by contributing to climate change.

Markets fail in the presence of externalities because agents do not take these effects into account when making their decisions. The reason why they do not take them into account is that, by definition, these effects are unintended and hence, there is no monetary reward or penalty to the agent generating the externality. Thus, in the case of positive externalities, generating the positive effect, in itself, is not sufficiently encouraged as there is no reward for doing so. In the case of negative externalities the opposite happens: as there is no monetary punishment for generating

[49] Actually, as noted by Common and Stagl (2004), the expression "tragedy of the commons" – introduced in a famous article by Garrett Hardin in 1968 – is misleading because the problem is not related to common property rights, but to the open access to the common property. Thus, as Common and Stagl suggest, the tragedy should have been labeled "the open-access tragedy."

[50] Note that there are various ways to classify externalities. Besides classifying externalities into positive and negative, one can also classify them by the economic activity in which they originate (production or consumption) and by the economic activity that they affect (production or consumption). See Perman *et al.* (2011) for an overview on classifications of different externalities.

negative effects, agents are not sufficiently discouraged from generating them. Consequently, markets produce too much of the negative externality, thereby exacerbating the negative external effect. As we will see, this is exactly what happens in the case of GHG emissions.

Human beings produce greenhouse gases as by-products of production processes (e.g. by burning fossil fuels to produce energy, by raising cattle, and through a very wide variety of other activities). Emitting large quantities of greenhouse gases into the atmosphere causes climate change and thus indirectly imposes costs on present and future generations. These costs are not borne by the emitting firms or consumers of goods whose production emits greenhouse gases, but rather by all people across the planet, and by future generations. Thus, when making a production and/or consumption decision involving GHG emissions, economic agents only take their personal costs and benefits into account, ignoring the additional costs they impose on others. Consequently, they emit more than what is socially optimal. To clarify this, let us look at Figure 32 for a graphical illustration of the case of production decisions involving greenhouse gases.[51]

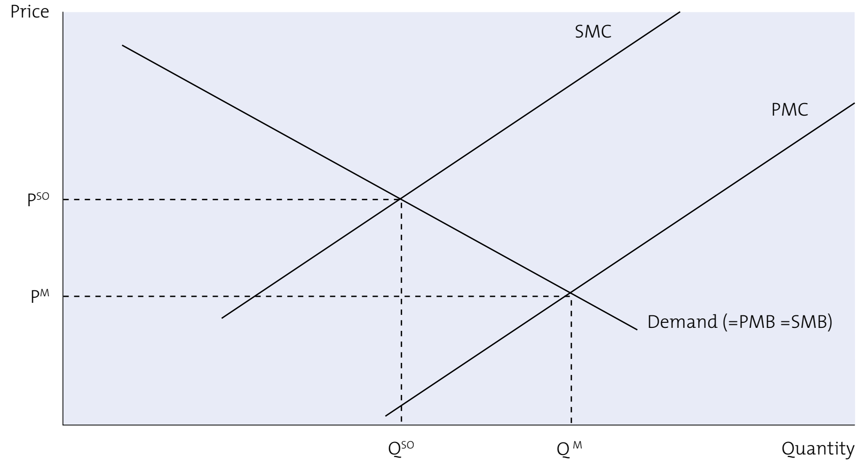
Figure 32 displays a market for a given good from the point of view of a specific firm that emits greenhouse gases during its production process. The x axis displays the quantity produced and the y axis the price of the good. The demand curve represents consumers' demand for the good. As usual, the lower the price, the more of the good people want to buy. Note that the demand curve also represents the firm's private marginal benefits (PMB). A firm's private marginal benefit corresponds, loosely speaking, to the price the firm can charge per unit produced. For simplicity, we shall assume here that there are no consumption-related externalities, and thus private marginal benefits equal social marginal benefits (SMB).[52]

[51] The following example of a negative production externality closely follows the discussion in Common and Stagl (2004: 327–29).

[52] Consumption-based externalities would drive a wedge between the marginal benefits perceived by a firm (PMB) and the marginal benefits perceived by society (SMB).

Figure 32

Greenhouse gas emissions: A negative production externality problem



Source: Author's elaboration based on Common and Stagl (2004: 327).

Figure 32 also displays a second curve labeled *PMC*, which stands for the firm's private marginal costs. This curve indicates, loosely speaking, the costs the firm incurs for producing the last unit of its total production output. These costs are also used by the firm's managers to decide how much the firm will produce. In order to maximize the firm's profits, the manager will equate the firm's PMCs with the firm's *PMBs* (represented by the demand curve). Thus, the firm will produce the quantity Q^M, selling each unit at the price P^M, as this is the only point where *PMC* equals *PMB*. The problem is that this allocation is not Pareto-efficient and thus not optimal from society's point of view. Why is this the case?

As mentioned earlier, the firm emits greenhouse gases during the production process and thus contributes to climate change. The costs associated with emitting greenhouse gases (i.e. the costs of climate change) are, however, not borne by the firm, but by the rest of the society.[53] From the point of view of the society, these are additional costs associated with the production of the good that have to be taken into account. Therefore, the social marginal costs of producing the good (*SMCs*) are higher than the firm's private marginal costs (*PMCs*). The difference between the social marginal cost and private marginal cost is known as the external marginal cost and is given by *EMC = SMC-PMC*. In our example, the external margin-

[53] To be precise, it is possible that the firm bears some of the costs of climate change, but the bulk of these costs accrue either to other individuals on the planet or to future generations.

al costs correspond to the climate change-related costs occurring as a result of greenhouse gases emitted during the production of the good. The Pareto-efficient point of production would thus not be the production level the firm chooses, but the pair Q^{SO} and P^{SO}, where social marginal benefits equal social marginal costs. We thus see in Figure 32 that the firm produces too much of the good (Q^{M} instead of Q^{SO}) and sells the good at a price that is too low (P^{M} instead of P^{SO}) because it ignores the climate change-related costs it imposes on others. The existence of the negative production externality therefore leads to a market failure due to which the firm emits too much greenhouse gases into the atmosphere compared to a Pareto-efficient situation. This example can be generalized and extended to also include negative consumption externalities, such as the pollution created by using cars.

In conclusion, as GHG emissions are negative externalities and the atmosphere can be used as an open-access resource to dump them, markets fail to achieve Pareto-optimal situations. Instead of optimally allocating resources, market economies dump unprecedented quantities of GHG emissions into the planet's atmosphere, and are thereby changing the climate of the earth. This massive market failure represents a danger for present and future generations and as such has been identified by Stern (2007) as the biggest market failure in the history of humankind.

Short summary

Sections 2 and 3 showed that while markets theoretically achieve Pareto-efficient outcomes, they fail to do so if some conditions are not satisfied. The occurrence of climate change is an example of such a failure, identified by some influential authors as the biggest market failure in human history. As shown in Section 3, this failure has two causes. First, the atmosphere's function as a GHG repository is an open-access resource and is therefore overused by economic actors because, unlike pure private goods, open-access resources cannot be efficiently dealt with by market economies. Second, greenhouse gas emissions are negative externalities. Economic actors do not directly bear the climate change-related costs associated with the emissions that they can dump free of charge into the atmosphere; consequently, they emit too much greenhouse gases. Together, these two reasons explain why markets fail and, hence, why climate change occurs.

4 Why is it so hard to solve the climate change problem?

As shown in Section 3, climate change occurs because markets fail and do not achieve Pareto-optimal allocations. As we have seen, rational economic agents, pursuing their own self-interest in an uncoordinated way, overexploit the atmosphere's GHG repository function and ignore the costs they impose on others. Consequently, they emit too much greenhouse gases into the atmosphere and cause climate change. Therefore, to solve the problem one cannot simply rely on a market system, as it is precisely this system that fails and which is at the root of the problem.

Climate change can only be fixed by a policy intervention that corrects the market failure. A priori, the solution is simple: if humans emitted less greenhouse gas into the atmosphere, they could stop or at least considerably slow climate change. If each country's politicians decided to cut GHG emissions, climate change could be mitigated or even avoided altogether. Thus, where is the problem? Why is humankind still struggling to implement this solution on a global scale? Since Mancur Olson's now-famous work in 1965, *The Logic of Collective Action*, economists have been working on a theory to explain this puzzling situation. Section 4 will show how economic theory explains the fact that the international community has been struggling for decades to solve the climate change problem despite the fact that the apparently simple solution has long been known. As we will see, much of the problem is related to the fact that solving global environmental problems like climate change requires cooperation among countries, which is not necessarily easy to achieve.

4.1 Mitigating climate change: A global public good

Mitigating climate changes requires reducing anthropogenic GHG emissions (IPCC, 2014b). Economists conceptualize climate change mitigation as a good that can be supplied and consumed. To supply the good, efforts have to be taken to reduce GHG emissions. Consumption of the good is passive: everybody can reap the benefits of climate change mitigation by living in a world that is not affected by the potentially catastrophic effects of a changing climate (IPCC, 2014a). However, climate change mitigation is not a "normal" good, i.e. it is not a pure private good like most of the commodities we consume in our daily lives.[54] From an economist's point of view, climate change mitigation is a so-called global public good (Ferroni *et al.*, 2002; IPCC, 2001; Per-

[54] See Section 3.1 for a definition of pure private goods.

man *et al.*, 2011; Sandler, 2004). The public-good nature of climate change mitigation is at the heart of economists' explanation for the inability of the international community to solve the climate change problem. As we will see in the sections that follow, supplying global public goods in sufficient quantities is difficult and involves several problems that are hard to overcome.

Section 3.1 introduced pure public goods and defined them as those having non-excludable and non-rival benefits. As we explained, non-excludability means that nobody can be excluded from consuming the good, i.e. once the goods are supplied, their benefits are instantly available to everybody. Non-rivalry means that a particular unit of the good can be consumed by an individual or group without affecting the possibility of another individual or group consuming the same unit. Sandler (2004) compares this property of global public goods to magic, stating that, like magic, a unit of a public good can be consumed by any number of individuals without any degradation in quality or quantity of that unit.

Climate change mitigation has exactly these two properties and is thus considered to be a public good. If a country decides to reduce its GHG emissions, the benefits are instantly available to all humans worldwide. Cutting a country's GHG emissions directly lowers the global GHG concentration in the atmosphere and thereby slows climate change compared to a business-as-usual scenario. Thus all countries gain from such a reduction. For the country that cuts its emissions, it is impossible to limit the benefits of its GHG reductions only to itself. The benefits of climate change mitigation are therefore non-excludable. Moreover, the benefits of climate change mitigation are also non-rival. The benefit a country obtains from reducing its GHG emissions does not reduce in the slightest the benefits other countries obtain from this reduction. Thus, consuming the benefits of GHG reductions does not affect the possibility of other nations enjoying these benefits. As the benefits are both non-rival and non-excludable, GHG reductions are considered to be pure public goods. Moreover, given that the benefits of a country's GHG reduction can be consumed by all countries on the globe, the literature has labelled climate change mitigation a "global public good" (Ferroni *et al.*, 2002; Perman *et al.*, 2011; Sandler, 2004).

Supplying global public goods such as climate change mitigation is a challenge. As shown in Section 3, markets cannot efficiently supply this type of good because they cannot deal with non-private goods. Policymakers therefore need to intervene and correct this market failure. But also nations struggle to supply global public goods. No country can single-handedly solve the problem, as no single country can by itself change the composition of the world's atmosphere and mitigate climate change (IPCC, 2001). Countries therefore need to collaborate in order to mitigate climate change. As we will see, many of the problems associated with supplying global public goods come from the fact that the costs and benefits for one country do not only depend on that country's actions, but also on the actions – or lack thereof – of other countries. This makes supplying (global) public goods what is called a "collective action problem" (Sandler, 2004). This type of problems often result in collective action failures that occur when rational decisions by individual countries result in an inefficient outcome that a single country cannot change (Sandler, 2004). As we will show, the non-excludability of climate change mitigation has a devastating implication for the supply of such a good: instead of supplying the good by reducing GHG emissions, countries might just wait for other countries to supply the good and then, as they cannot be excluded from receiving the benefits, benefit from the result. This is a behaviour that the literature calls "free-riding." As every country can make the same reasoning, it is quite possible that at the end of the day no country will actually be reducing its emissions.

Section 4.2 introduces basic theoretical elements of game theory, a theoretical tool that allows for systematically analysing the problems associated with the strategic interactions between countries trying to mitigate climate change.

4.2 Basic game theory notions and concepts[55]

In order to understand why countries struggle to reduce their GHG emissions, or in other words, why countries struggle to supply the global public good of climate change mitigation, we have to introduce basic game theory tools. Using these tools will enable readers to understand the nature of the problem at stake and grasp different important concepts like free-riding. Game theory is a theoretical apparatus that allows for studying any form of strategic interaction among individuals, groups, or countries (Varian, 2010). Widely used to study political negotiations and economic behaviour, it is particularly useful to analyse the issues involved in collective action problems such as climate change mitigation. Before we start with the analysis of climate change mitigation, we will introduce basic game theory notions and concepts that allow for analysing strategic interactions among countries.[56]

[55] Note that this short review only covers the essential concepts and notions needed for the analysis of climate change mitigation. Annex 1 provides additional readings on game theory.

[56] The presentation of basic notions of game theory in this section draws on Chapter 28 of Varian (2010).

Strategic interactions involve at least two individuals or groups called "players." A priori, any strategic interaction can involve many players and each player can have a large set of different strategies. An example of a strategic interaction would be climate change mitigation negotiations among different countries (the players), with each country pursuing its own strategy. A country's strategy could be, for instance, to reduce GHG emissions or to not reduce GHG emissions. A formal representation of such strategic interactions is called a "game." Games are the game theorist's tool to formally capture situations in which individuals or groups interact in a context where their welfare not only depends on their own actions, but also on the actions of others (Mas-Colell et al., 1995). To introduce the basic game theory notions and concepts we limit ourselves for now to strategic interactions with only two players. This kind of game can be represented in what is called a "payoff matrix." To illustrate how to represent a game in a payoff matrix, we use an example by Varian (2011: 522).

Suppose you have two players (player A and player B) playing a game. Each player has a sheet of paper and has to write one out of two words on his or her sheet. Player A can either write "Top" or "Bottom." Simultaneously, player B can choose to write "Left" or "Right." Player A does not see what player B is writing and vice versa. Each player will obtain a payoff that depends not only on his or her actions, but also on the actions of the other player. And each player has been informed about the potential payoffs he or she could get before playing the game. In the game theory terminology, the players' options to play the game are called "strategies." Thus in this game, each player has two strategies: player A's strategies are "Top" and "Bottom," and player B's strategies are "Left" and "Right."[57] After both players have written down their word, the sheets of paper are examined and the players receive their payoffs. These payoffs are listed in a payoff matrix. The payoff matrix of this simple game is displayed in Figure 33. It shows the payoffs to each player for each combination of strategies, and it is known to each player before they start to play the game.

[57] Actually, this is not completely accurate. Formally, strategies are defined to be a "complete contingent plan, or decision rule, that specifies how the player will act in every possible distinguishable circumstance in which she might be called upon to move" (Mas-Colell *et al.*, 1995: 228). However, as the game we are currently looking at consists of only one move (writing down the word) and the players have to write down the word simultaneously, and because we exclude the possibility of mixed strategies, the choices "Top" and "Bottom" are the two strategies of player A, while the choices "Left" or "Right" are the two strategies of player B.

Figure 33

Payoff matrix of a two-player game with a dominant strategy equilibrium

		Player B	
		Left	Right
Player A	Top	2,3	1,2
	Bottom	4,2	2,1

Source: Author's elaboration based on Varian (2010: 523).

As an example, if player A plays the strategy "Top" and player B plays the strategy "Right," we examine the upper right field of the payoff matrix that contains the payoffs for this combination of strategies. If the players play in this way, player A will receive a payoff of 1 (the first entry in the upper right box), while player B will receive a payoff of 2 (the second entry in the upper right box). Similarly, if player A plays "Bottom" and player B plays "Left," we see in the lower left box of the matrix that player A will receive a payoff of 4 while player B receives a payoff of 2.

Having understood how one reads a payoff matrix, we can now ask ourselves what happens if these two players actually play this game. Player A has a strong incentive to always play "Bottom," because the payoffs from playing "Bottom" (4 and 2) are always higher compared to the corresponding payoffs of playing "Top" (2 and 1). Player B has a strong incentive to always play "Left," as the payoffs from playing "Left" (3 and 2) are always higher than the corresponding payoffs of playing "Right" (2 and 1). Thus, we expect that in equilibrium we end up in the lower left box of the matrix, as player A will always play "Bottom" and player B will always play "Left."

We have been able to quickly find the solution to this game because each player has what is called a "dominant strategy," which is a player's best strategy regardless of what the other player plays (Mas-Colell *et al.*, 1995).[58] Here, player A's "Bottom" strategy dominates his or her "Top" strategy, as the player will get a higher payoff playing "Bottom" no matter what player B chooses. On the other hand, player B's dominant strategy is playing "Left" because no matter what

[58] Note that this kind of strategy is called "strictly dominant" as opposed to "weakly dominant," but for the sake of simplicity we will not discuss this difference as it is not needed to understand our main point. For more information see the additional readings listed in Annex 1.

player A plays, he or she will get a higher payoff if he or she plays "Right." The resulting equilibrium is therefore called a "dominant strategy equilibrium."

As Varian (2010) points out, dominant strategy equilibria are simple to find, but do not happen often. Let us look at a game with the same rules but a different payoff structure displayed in Figure 34. As one can see, this game has no dominant strategies. If player A chooses "Top," then player B wants to choose "Left," but if player A chooses "Bottom," then player B wants to choose "Right." Thus there is no dominant strategy for player B (or for player A, as you can easily verify) and therefore also no dominant strategy equilibrium.

Figure 34

Payoff matrix of a two-player game with two Nash equilibria

		Player B	
		Left	Right
Player A	Top	4,2	0,0
	Bottom	0,0	2,4

Source: Author's elaboration based on Varian (2010:524).

In real-life strategic interactions, players frequently do not have dominant strategies. Game theorists therefore developed alternative concepts that allow for analysing strategic interactions. One of these concepts, called the Nash equilibrium, was introduced in 1951 by John Nash, an American economist and Nobel Prize laureate.[59] Instead of requiring that a player's strategy be optimal for all possible choices of the other player, this concept only requires that a player's strategy be optimal given optimal strategies of the other player (Varian, 2010). In other words, in a Nash equilibrium, each player's strategy choice is the best strategy that the player can choose, given the strategy that is actually played by the other player. In that sense, Nash equilibria are weaker solution concepts than dominant strategy equilibria: each dominant strategy equilibrium is also a Nash equilibrium, but not each Nash equilibrium is a dominant strategy equilibrium.

In Figure 34, "Top"/"Left" would be such a Nash equilibrium: if player B plays "Left," the best strategy player A can choose is to play "Top." At the same time, if player A plays "Top," the best strategy player B can choose is "Left." Thus, "Top"/"Left" is a Nash equilibrium.[60] Of course, neither of the two players knows what the other player will play before they make their move, but each player might have some idea about what the other player's choice will be. A Nash equilibrium can thus be interpreted as "a pair of expectations about each person's choice such that, when the other person's choice is revealed, neither individual wants to change his behavior" (Varian, 2010: 525). For instance, if player A expects player B to choose "Left," player A will choose "Top," and if player B expects player A to choose "Top," player B will choose "Left" and the game ends in the Nash equilibrium "Top"/"Left." From this Nash equilibrium no player would want to unilaterally change his or her strategy if he or she had the opportunity, as the player could only lose. While the concept of the Nash equilibrium has several problems,[61] it is a very useful concept to analyse strategic interactions.

Having covered the basic notions and concepts of game theory, we now have the necessary tools to analyse why countries struggle to reduce GHG emissions and solve the global climate change problem. Climate change mitigation involves a strategic interaction among countries, as a coordinated effort by different countries is needed to mitigate climate change. Using the game theory tools introduced above, we will analyse this strategic interaction, showing what goes wrong and highlighting the reasons for the failure of the international community to mitigate climate change so far.

4.3 Climate change mitigation: A game theory perspective

We now turn our attention towards the analysis of the decade-long failure of the international community to mitigate climate change. To do so we use game theory tools to model a strategic interaction among countries trying to supply the global public good of climate change mitigation.

[59] The game theory work of Nash was popularized in Ron Howard's 2001 biographical movie "A Beautiful Mind."

[60] As you can verify, using similar reasoning, "Bottom"/"Right" is a second Nash equilibrium in this game

[61] One of the problems is that it is possible that a game has more than one Nash equilibrium, as illustrated by the game in Figure 34. Another problem is that some games might not have a Nash equilibrium if one considers only so-called "pure strategies." Pure strategies are the ones we have looked at so far and which consist of choosing an option once and for all. Instead of choosing an option and playing this option with 100 per cent probability, players can also randomize their choices. If they do so, game theorists speak of "mixed strategies" or "randomized strategies." When players play mixed strategies they assign probabilities to each of their choices and play the choices according to the probabilities assigned (Varian, 2010). If one takes mixed strategies into account, one can show that Nash equilibria exist for a fairly broad range of games, making the concept very popular (see Chapter 8 in Mas-Colell et al., 1995, for a discussion on this topic). We will not further discuss mixed strategies in this teaching material as we do not need them to analyse climate change mitigation.

4.3.1 Climate change mitigation in a world composed of two countries

We start our investigation of this strategic interaction by making a simplifying assumption. We suppose that the world is composed of two identical countries that try to mitigate climate change: country A and country B. Each individual country can play two strategies: it can choose to either reduce its GHG emissions by 20 per cent, or not to reduce its GHG emissions at all.

If the country chooses not to reduce its emissions, it does not bear any costs but also does not receive any benefit. If the country chooses to reduce its emissions, it has to pay a cost of 12 in order to finance the GHG reduction. At the same time, the emission reduction yields a benefit of 10 for the country, as it reduces the negative effects of climate change. While these cost and benefit numbers have been chosen arbitrarily, they reflect an important property of climate change mitigation. As the climate is the product of the behaviour of all nations on the planet, no single country can change the composition of the atmosphere alone and mitigate climate change single-handedly (IPCC, 2001). The benefits of a single country reducing GHG emissions will therefore be relatively small compared to the costs the country incurs in doing so. Hence, the cost of financing the GHG reduction for a single country (12) has been chosen to be bigger than the benefit (10) the country obtains from single-handedly reducing its emissions.

As mentioned in Section 4.1, climate change mitigation is a global public good, meaning that the benefits of abating are non-rival and non-excludable. This implies that if country A chooses to abate – paying the cost of 12 and receiving the benefit of 10 – country B also receives a benefit of 10 without doing anything whatsoever. This is a crucial point one has to understand. Country B receives a benefit from the emission reductions made by country A, because country A's emission reductions lower global concentrations of atmospheric emissions. Country A's efforts thereby slow climate change, which positively affects country A and country B. This leads to the payoff matrix displayed in Figure 35.[62]

Figure 35

Reducing greenhouse gas emissions in a world composed of two countries

		Country B	
		Not reduce	Reduce
Country A	Not reduce	0,0	10,-2
	Reduce	-2,10	8,8

Source: Author.

As can be seen in Figure 35, if both countries decide not to reduce their emissions, nothing will happen: country A and country B both obtain a payoff of 0 as there are neither mitigation costs nor mitigation benefits associated with inaction. If country A decides to reduce its emissions while country B decides not to reduce, country A obtains a payoff of -2 (the benefits it produces (10) minus its costs of doing so (12)) while country B receives a payoff of 10. Similarly, if country B decides to reduce while country A decides not to reduce, country B receives a payoff of -2 and country A receives a payoff of 10. Finally, if both countries decide to reduce, each country obtains a payoff of 8 (country A receives the benefit produced by itself (10) plus the benefit produced by country B (10) and pays its reduction costs (12); the same goes for country B).

Clearly, from the point of view of the whole planet, the best outcome of the game would be that both countries reduce their emissions and thereby contribute to mitigating climate change. This would yield an overall benefit of 16 (8+8), which is the highest possible payoff for the whole planet in the game.[63] Thus, "Reduce"/"Reduce" is a so-called "social optimum." But in this game, the social optimum is not the likely outcome. Or stated differently, "Reduce"/"Reduce" is not a Nash equilibrium because the best choice country A could make given that country B reduces its emissions is not to reduce its emissions. In that case, country A would receive a payoff of 10, which is greater than the payoff of 8 the country would obtain by also reducing its emissions. The exact same reasoning applies for country B. This free-riding behaviour is the main problem associated with

62 In game theory, this game structure is called a "prisoner's dilemma" and is probably the best-known application of game theory. This game was introduced by Merrill Flood and Melvin Dresher in 1952. Albert Tucker used a fictive interaction between two prisoners as an illustrating anecdote, which gave the game its name (Poundstone, 1992). Varian (2010: 527) outlines Tucker's original story as follows: "[T]wo prisoners who were partners in a crime were being questioned in separate rooms. Each prisoner had a choice of confessing to the crime, and thereby implicating the other, or denying that he had participated in the crime. If only one prisoner confessed, then he would go free, and the authorities would throw the book at the other prisoner, requiring him to spend 6 months in prison. If both prisoners denied being involved, then both would be held for 1 month on a technicality, and if both prisoners confessed they would both be held for 3 months." This game has a similar payoff matrix as in Figure 35, leading both rational prisoners to confess, while they would have been better off denying the crime.

63 The other options yield planetary payoffs of 0 (0+0), 8 (-2+10), and 8 (10-2), respectively.

the provision of public goods like climate change mitigation. Actually, the best payoff a country could hope for in the whole game (10) is obtained if the country free-rides, that is, if it lets the other country take action and benefits from these actions without doing anything by itself.

So what is the likely outcome of the game? One can easily see that country A's dominant strategy in this game is not to reduce its emissions: country A will be better off by not reducing, no matter the choice of country B. The same holds true for country B: for both choices of country A, country B obtains a higher payoff if it does not reduce its emissions. Hence "Not reduce"/"Not reduce" is the dominant strategy equilibrium and at the same time also the Nash equilibrium of the game. At this equilibrium, neither country A nor country B has an incentive to alter its choice unilaterally if given the opportunity. If a country were to unilaterally alter its choice in the Nash equilibrium, it would obtain a payoff of -2 instead of 0. The game thus predicts that no country will reduce its emissions, as both prefer to free-ride. At the same time, the whole planet would clearly be better off if both countries simultaneously decided to reduce their emissions and thereby mitigate climate change.

Although the game is very simple, it perfectly illustrates the problem underlying all collective action failures: "individual rationality is not sufficient for collective rationality. That is, individuals [or countries] who abide by the tenets of rationality may make choices from which the collective is left in an inferior position" (Sandler, 2004: 18). Instead of contributing to mitigating climate change by reducing emissions, countries have strong incentives to free-ride; climate change will thus not be mitigated.

4.3.2 Climate change mitigation in a world composed of n countries [64]

[64] This section draws on the presentation of the n country prisoner's dilemma in Sandler (2004) and Perman *et al.* (2011).

So far we have analysed a strategic interaction in a world composed of two countries. Given that there are considerably more than two countries in the world, we relax this restrictive assumption and generalize the collective action problem to incorporate any number of countries.

To do so, suppose the planet consists of a total of *n* identical countries. Each country can choose between two strategies: to reduce GHG emissions by 20 per cent or not to reduce GHG emissions. Suppose further that for a given country *i*, the cost of reducing its GHG emissions by 20 per cent equals c_i. By reducing its greenhouse gases by 20 per cent, the country produces a non-rival and non-excludable benefit of b_i (whereas $c_i > b_i$), benefiting it and each of the other *n-1* nations. Table 5 displays the payoffs of this game from the perspective of country *i*. The rows show the two strategies of country *i* while the columns indicate the actions of the other *n-1* countries. The top row displays the free-rider payoffs for country *i*: if one other country reduces its emissions, country *i* receives a benefit of b_i, if two other countries reduce their emissions, country *i* obtains $2b_i$, etc. The bottom row shows the payoffs for country *i* when it does reduce its emissions: if no other country contributes, country *i* obtains a payoff of b_i-c_i, if one other country contributes, country *i* receives $2b_i$-c_i, etc.

Table 5

Reducing greenhouse gas emissions in a world of *n* countries

	Number of greenhouse-gas-reducing countries other than country *i*				
	0	1	2	(...)	*n-1*
Country *i* does not reduce GHG emissions by 20 per cent	*0*	b_i	$2b_i$	(...)	$(n-1)b_i$
Country *i* does reduce GHG emissions by 20 per cent	b_i-c_i	$2b_i$-c_i	$3b_i$-c_i	(...)	nb_i-c_i

Source: Author's elaboration based on Figure 2.2 in Sandler (2004) and Table 9.1 in Perman *et al.* (2011).

As one can see, even if n-1 countries reduce their emissions, country *i*'s dominant strategy is to free-ride because the payoffs in the upper row exceed the payoffs in the bottom row by c_i-b_i, no matter how many other countries contribute. As the same holds for all other countries, the unique Nash equilibrium of the game is that nobody reduces its emissions. Given that nobody has an incentive to take action, the aggregated planetary payoff in the Nash equilibrium is 0.

The Nash equilibrium is clearly not a socially optimal outcome. The socially optimal outcome of the game occurs when all countries limit their emissions, leading to a maximized planetary payoff of n^2b_i-nc_i. Again, we want to emphasize that this social optimum is not a stable solution. Even if all other *n-1* countries contribute, country *i* always has an incentive to free-ride because it will obtain $(n-1)b_i$, which is greater than nb_i-c_i. As the free-rider payoffs are higher for all countries no matter how many other countries contribute, the world ends up in the unique Nash equilibrium with nobody reducing its emissions.[65]

Hence, the modified game structure does not result in a different prediction. Even in a world composed of many countries, rational countries would still free-ride and not contribute to mitigating climate change. While the game theory approach reveals the essential nature of the problem (free-riding), things are even more complicated in reality. Countries are not identical as we assumed in the games above: they vary in terms of size, wealth and technology. Costs and benefits of mitigation also differ widely among countries and are only imperfectly known (Common and Stagl, 2004; Perman *et al.*, 2011; Sandler, 2004; Stern, 2007). Countries are not equally affected by the consequences of climate change, thus they would not equally benefit from mitigation efforts. Mitigation costs and opportunities also differ between countries. Finally, there is the issue of international and intergenerational justice affecting negotiations about the financing of climate change mitigation (see the discussion on the principle of common but differentiated responsibilities in Module 4). All these factors further complicate the collective action problem and influence the likely outcome (or prognoses) of strategic interactions.[66]

In addition to factors related to the global public good nature of climate change mitigation and their game theory implications, there are other factors that can influence the outcome of collective action. Box 14 illustrates this issue by showing the vastly different outcomes of two, at first sight similar, collective action problems – mitigation of ozone-shield depletion and mitigation of climate change.

Box 14

Different collective action outcomes for identical collective action problems

Sandler (2004) highlights that seemingly identical collective action problems like the provision of a global public good can have vastly different collective action outcomes. To illustrate his point, he compares the collective action outcome of two pollution problems. One the one hand, the international community has been rather efficient in mitigating stratospheric ozone shield depletion caused by chlorofluorocarbons (CFCs) and bromide-based substances. On the other hand, it is still struggling with mitigating climate change caused by the accumulation of greenhouse gases in the atmosphere. Mitigating CFCs and mitigating greenhouse gases are both global public goods. Moreover, both problems are pollution problems and their solution requires international cooperation to reduce emissions. In the CFC case, humankind succeeded, while efforts to reduce GHG emissions have not been successful to date. Sandler explains this difference in the outcomes of collective action by the differences listed in Table 6. All these factors make finding a collective action solution more difficult in the case of climate change as compared to ozone-shield depletion.

Table 6

Factors affecting outcomes of collective actions

Ozone-shield depletion	Climate change
Emissions concentrated in relatively few countries	Emissions are added by virtually every country
Every country loses from a thinning ozone layer	There are winners and losers from global warming
There are substantial commercial gains from CFC substitutes	Uncertainty about substantial commercial gains from GHG substitutes
Uncertainty in terms of process and consequences has been resolved	Uncertainty remains in terms of process and consequences
Dominant strategy for some key polluters is to curb emissions, since b_i-c_i>0	Dominant strategy for most key polluters is not to curb pollutants, since b_i-c_i<0
Leadership by key polluters	Lack of leadership by key polluters
Intertemporal reversibility within 50 years	No intertemporal reversibility within 50 years
Decision makers were more informed about benefits than costs	Decision makers were more informed about costs than benefits
Relatively few economic activities add to ozone-shield depletion	Many economic activities add to global warming

Source: Table 10.4 in Sandler (2004), updated by the author.

Consequently, as Sandler (2004: 213) states, "the contrast between global collective action and inaction hinges on factors that go beyond the non-rivalry and non-excludability of these global public good's benefits.... Knowledge of just the properties of a public good is not always sufficient to provide a prognosis for collective action."

Source: Author's elaboration based on Sandler (2004)

[65] To illustrate these results with numbers, assume that the costs and benefits are the same as in the two-country example (c_i = 12 and b_i = 10) and assume further that the world is composed of the 194 United Nations member countries (*n* = 194). Then, the planetary payoff in the social optimum would equal 194²*10-194*12=374,032, with each individual country obtaining a payoff of 194*10-12=1,928. But the socially optimal outcome is not an equilibrium, because nation *i* (and thus also all other nations) would have an incentive to free-ride (the country's payoff would be greater if it free-rides and all the other *n-1* countries contribute: (194-1)*10=1,930>1,928). Thus the world ends up in the unique Nash equilibrium with a planetary payoff of 0, which is clearly less than the social optimum.

[66] More complicated game structures can incorporate some of these additional factors. See Annex 1 for additional reading material on this issue.

4.3.3 Climate change mitigation: Lessons from game theory models

Section 4 started by asking how economic theory explains the fact that the international community has been struggling for decades to solve the climate change problem, even though the apparently simple solution has been known for a long time. Sections 4.1, 4.3.1 and 4.3.2 provided the theoretical answer to this question. The two games modelling the strategic interaction between countries showed that, due to the global public good nature of mitigating climate change, the payoff countries obtain from free-riding is higher than the payoff they would obtain from reducing their emissions. Rationally behaving countries thus have strong incentives to free-ride and not reduce their emissions. This results in a massive collective action failure.

In addition to explaining this outcome, game theory also provides certain insights on how this outcome might be changed. Clearly, payoffs from acting alone matter. If they were positive, each country would have an incentive to act alone and reduce emissions. This would lead to a situation where the Nash equilibrium corresponds to the social optimum. Stated differently, if the payoffs from acting alone were positive, the social optimum would be incentive-compatible: individual countries would have incentives to reduce emissions single-handedly because of the positive payoff, leading automatically to a socially optimal situation.

Such an outcome could be reached through a binding international agreement between countries (Common and Stagl, 2004; Perman *et al.*, 2011; Sandler, 2004; Tietenberg and Lewis, 2012). The countries would have to agree that they all reduce their emissions. However, as each country has a strong incentive to sign on to such a treaty and subsequently free-ride to maximize its payoff, the agreement would need to contain penalties. In theory, any penalty larger than c_i-b_i would do the job. With this penalty, the payoff of acting alone (b_i-c_i) would be larger than the payoff of not acting (0-p, whereas $p>c_i$-b_i is the penalty) and the Nash equilibrium would correspond to the social optimum. However, putting in place such a penalty system is not straightforward, as the history of climate change negotiations has shown (see Module 4).[67] At least equally difficult would be enforcement of such a penalty system. Countries could only be forced to pay penalties if there were a third party with the power to force countries to pay (Perman *et al.*, 2011). As today's world consists of sovereign states, no such enforcer exists on the global level. International environmental agreements therefore rely on voluntary actions of countries and should thus be designed in a self-enforcing way. The theoretical literature (see Perman *et al.*, 2011, for a short review) on international environmental agreements consequently offers rather pessimistic views regarding their efficiency: treaties seem to largely codify actions countries intended to take anyway, and achieve little when the number of affected countries is large. Moreover, as climate change mitigation illustrates, effective cooperation seems hardest to achieve when the stakes are high and when the cooperation is most needed (Barret, 1994). Reviews of international environmental agreements show that effective cooperation requires that (a) the treaty yield positive net benefits for all participating countries, (b) the parties reach a consensus on the design of the treaty, and, most importantly, (c) the treaty can be enforced by the participating countries (Finus, 2003).

Besides self-enforcing international agreements, game theory suggests a number of alternative mechanisms to enforce cooperation.[68] Cooperation can be fostered if countries are able to make credible commitments to reduce emissions regardless of what other countries are doing. Transfers and other side payments could increase the number of cooperating countries. Furthermore, the co-benefits of emission reductions, such as those achieved by linking development and climate change policy issues, might alter the payoffs for countries and thus change the nature of the game. Moreover, theory indicates that the prospects for cooperation are less pessimistic when games are repeated. The two games we introduced above are "one-shot games" played only once. If the same game is played repeatedly over an undefined time horizon, and if countries communicate, a variety of different options emerge. As will be seen in Module 4, the Paris Agreement has been partially built on these mechanisms.

67 Putting in place a penalty system is itself a pure public good problem (Sandler, 2004).

68 See Chapter 9.3 in Perman *et al.* (2011) for an overview.

Short summary

How does economic theory explain why the international community has been struggling for decades to solve the climate change problem, even though the apparently simple solution has been known for a long time? To answer this question, Section 4 showed that climate change mitigation is a global public good with non-rival and non-excludable benefits. As no country is able to change the composition of the atmosphere single-handedly, international cooperation is needed. The section introduced game theory concepts that were subsequently used to analyse the strategic interaction between countries. Two games illustrated the main cause of the collective action failure: that countries have strong incentives to free-ride and not contribute to emission reductions because the benefits of mitigating climate change are non-rival and non-excludable. This leads to an outcome that is not socially optimal. The section concluded by drawing several lessons from game theory models that would allow for fostering cooperation between countries.

5 Exercises and questions for discussion

1 Define Pareto efficiency and discuss the advantages and disadvantages of the concept.

2 Describe the first welfare theorem. Why is this theorem a fundamental result in economics? What assumptions underlying the first welfare theorem are violated in the case of climate change?

3 What criteria are used to classify goods as private and public goods? List two examples of a private and a public good and discuss why these goods are considered private/public by using the criteria you defined above.

4 What are open-access goods? Why is the atmosphere considered to be an open-access good? What happens if markets deal with open-access goods such as the atmosphere?

5 Define externalities and provide an example of a positive and a negative externality. How could governments solve a negative externality problem? Illustrate your reasoning using the example of GHG emissions.

6 Consider a coal plant that releases CO_2 emissions into the atmosphere while producing units of energy. Suppose that the private marginal cost of the plant is given by *PMC* = 50+0.25**Q*, where *PMC* is the private marginal cost in US dollars per unit produced and *Q* is units of energy produced. Because the firm releases CO_2 emissions into the atmosphere, it imposes an external cost on society that equals US$2 per unit of energy produced. Suppose further that the private marginal benefit (*PMC*) – which equals the social marginal benefit (*SMC*) – per unit of energy produced is given by *PMB* = *SMB* = 100-0.25**Q*.

(a) Derive the social marginal cost (SMC) function in US dollars per unit produced.
(b) Draw a diagram illustrating the private marginal cost function, the social marginal cost function, and the private marginal benefit function.
(c) Find the profit-maximizing energy output of the coal plant and the corresponding price per unit of energy produced.
(d) Find the socially optimal energy output and the corresponding price.
(e) Compare the private equilibrium with the socially optimal outcome and discuss underlying externality issues.

7 Suppose player A and player B play a game with the following payoff matrix:

		Player B	
		Left	Right
Player A	Top	1,1	-1,-1
	Bottom	-1,-1	1,1

(a) Define dominant strategies. Does player A have a dominant strategy? Does player B have a dominant strategy?
(b) How many pure-strategy Nash equilibria can you find in the game?
(c) Can you find a real-world example that could be described by such a payoff matrix?

8 How does economic theory explain why the international community has been struggling for decades to solve the climate change problem? To analyse this question, suppose that the world is composed of two countries and discuss the payoff matrix of the mitigation game. What is the likely outcome of this game? Explain the lessons that can be learned from this simple game.

ANNEX 1

Selected additional reading material	
Topic	
Microeconomic foundations of the competitive market model	Chapters 1–9, 14–16, 18–23, and 31–33 of Varian HR (2010). *Intermediate Microeconomics a Modern Approach*, Ninth Edition. W. W. Norton & Company. New York.
	Chapters 1–5, 10, and 15–20 of Mas-Colell et al. (1995). *Microeconomic Theory. Oxford University Press*. New York.
	Chapters 1–9 and 16 of Pindyck R, and Rubinfeld D (2012). *Microeconomics*, Eighth Edition. Pearson Series in Economics. Prentice Hall. Upper Saddle River, NJ.
Public goods and externalities	Chapters 2–4 of Sandler T (2004). *Global Collective Action*. Cambridge University Press. New York.
	Chapters 34 and 36 of Varian HR (2010). *Intermediate Microeconomics: A Modern Approach*, Ninth Edition. W.W. Norton & Company. New York.
	Chapter 11 of Mas-Colell et al. (1995). *Microeconomic Theory*. Oxford University Press. New York.
	Chapter 18 of Pindyck R, and Rubinfeld D (2012). *Microeconomics*, Eighth Edition. Pearson Series in Economics. Prentice Hall. Upper Saddle River, NJ.
	Chapter 4 of Perman R et al. (2011). *Natural Resource and Environmental Economics*, Fourth Edition. Pearson Education Limited. Essex, UK.
Game theory	Chapters 7–9 of Mas-Colell et al. (1995). *Microeconomic Theory*. Oxford University Press. New York.
	Chapter 28 of Varian HR (2010). *Intermediate Microeconomics: A Modern Approach*, Ninth Edition. W.W. Norton & Company. New York.
	Chapter 13 of Pindyck R, and Rubinfeld D (2012). *Microeconomics*, Eighth Edition. Pearson Series in Economics. Prentice Hall. Upper Saddle River, NJ.
	Straffin P (2004). *Game Theory and Strategy*, Fifth Edition. The Mathematical Association of America. Washington, DC.
Environmental economics	Tietenberg T, and Lewis L (2012). *Environmental and Natural Resource Economics*, Ninth Edition. Pearson International Edition. Addison Wesley. Boston.
	Perman et al. (2011). *Natural Resource and Environmental Economics*. Fourth Edition. Pearson Education Limited. Essex, UK.
	Kolstad CD (2000). *Environmental Economics*. Oxford University Press. New York.
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