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2016 NOV 14

For example, two options can help apply prioritarianism to the distribution of freely allocated and globally tradeable emission permits. The first is to ignore the distribution of other goods. Then strict egalitarianism or prioritarianism will require emission permits to be distributed equally, since they will have one price and are thus equivalent to income. The second is to take into account the unequal distribution of other assets. Since people in the developing world are less well off than in the developed world, strict egalitarianism or prioritarianism would require most or all permits to go to the developing world. However, it is questionable whether it is appropriate to bring the overall distribution of goods closer to the prioritarian ideal through the distribution of just one good (Wolff and de-Shalit, 2007; Caney, 2009, 2012).

3.3.4 Historical responsibility and distributive justice

Historical responsibility for climate change depends on countries' contributions to the stock of GHGs. The UNFCCC refers to "common but differentiated responsibilities" among countries of the world.[6] This is sometimes taken to imply that current and historical causal responsibility for climate change should play a role in determining the obligations of different countries in reducing emissions and paying for adaptation measures globally (Rajamani, 2000; Rive et al., 2006; Friman, 2007).

A number of objections have been raised against the view that historical emissions should play a role (see, e.g., Gosseries, 2004; Caney, 2005; Meyer and Roser, 2006; Posner and Weisbach, 2010). First, as currently living people had no influence over the actions of their ancestors, they cannot be held responsible for them. Second, previously living people may be excused from responsibility on the grounds that they could not be expected to know that their emissions would have harmful consequences. Thirdly, present individuals with their particular identities are not worse or better off as a result of the emission-generating activities of earlier generations because, owing to the non-identity problem, they would not exist as the individuals they are had earlier generations not acted as they did.

From the perspective of distributive justice, however, these objections need not prevent past emissions and their consequences being taken into account (Meyer and Roser, 2010; Meyer, 2013). If we are only concerned with the distribution of benefits from emission-generating activities during an individual's lifespan, we should include the benefits present people have received from their own emission-generating activities. Furthermore, present people have benefited since birth or conception from past people's emission-producing actions. They are therefore better off as a result of past emissions, and any principle of distributive justice should take that into account. Some suggest that taking account of the consequences of some past emissions in this way should not be subject to the objections mentioned in the previous paragraph (see Shue, 2010). Other concepts associated with historical responsibility are discussed in Chapter 4.

3.3.5 Intra-generational justice: compensatory justice and historical responsibility

Do those who suffer disproportionately from the consequences of climate change have just claims to compensation against the main perpetrators or beneficiaries of climate change (see, e.g., Neumayer, 2000; Gosseries, 2004; Caney, 2006b)?

One way of distinguishing compensatory from distributive claims is to rely on the idea of a just baseline distribution that is determined by a criterion of distributive justice. Under this approach, compensation for climate damage and adaptation costs is owed only by people who have acted wrongfully according to normative theory (Feinberg, 1984; Coleman, 1992; McKinnon, 2011). Other deviations from the baseline may warrant redistributive measures to redress undeserved benefits or harms, but not as compensation. Some deviations, such as those that result from free choice, may not call for any redistribution at all.

The duty to make compensatory payments (Gosseries, 2004; Caney, 2006b) may fall on those who emit or benefit from wrongful emissions or who belong to a community that produced such emissions. Accordingly, three principles of compensatory justice have been suggested: the polluter pays principle (PPP), the beneficiary pays principle (BPP), and the community pays principle (CPP) (Meyer and Roser, 2010; Meyer, 2013). None of the three measures is generally accepted, though the PPP is more widely accepted than the others. The PPP requires the emitter to pay compensation if the agent emitted more than its fair share (determined as outlined in Section 3.3.2) and it either knew, or could reasonably be expected to know, that its emissions were harmful. The victim should be able to show that the emissions either made the victim worse off than before or pushed below a specified threshold of harm, or both.

The right to compensatory payments for wrongful emissions under PPP has at least three basic limitations. Two have already been mentioned in Section 3.3.4. Emissions that took place while it was permissible to be ignorant of climate change (when people neither did know nor could be reasonably be expected to know about the harmful consequences of emissions) may be excused (Gosseries, 2004, pp. 39–41). See also Section 3.3.6. The non-identity problem (see Section 3.3.2) implies that earlier emissions do not harm many of the people who come into existence later. Potential duty bearers may be dead and cannot therefore have a duty to supply compensatory measures. It may therefore be difficult to use PPP in ascribing compensatory duties and identifying wronged persons. The first and third limitations restrict the

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[6] Specifically, Article 3 of the UNFCCC includes the sentence: "The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities."

assignment of duties of compensation to currently living people for their most recent emissions, even though many more people are causally responsible for the harmful effects of climate change. For future emissions, the third limitation could be overcome through a climate change compensation fund into which agents pay levies for imposing the risk of harm on future people (McKinnon, 2011).

According to BPP, a person who is wrongfully better off relative to a just baseline is required to compensate those who are worse off. Past emissions benefit some and impose costs on others. If currently living people accept the benefits of wrongful past emissions, it has been argued that they take on some of the past wrongdoer's duty of compensation (Gosseries, 2004). Also, we have a duty to condemn injustice, which may entail a duty not to benefit from an injustice that causes harm to others (Butt, 2007). However, BPP is open to at least two objections. First, duties of compensation arise only from past emissions that have benefited present people; no compensation is owed for other past emissions. Second, if voluntary acceptance of benefits is a condition of their giving rise to compensatory duties, the bearers of the duties must be able to forgo the benefits in question at a reasonable cost.

Under CPP, moral duties can be attributed to people as members of groups whose identity persists over generations (De-Shalit, 1995; Thompson, 2009). The principle claims that members of a community, including a country, can have collective responsibility for the wrongful actions of other past and present members of the community, even though they are not morally or causally responsible for those actions (Thompson, 2001; Miller, 2004; Meyer, 2005). It is a matter of debate under what conditions present people can be said to have inherited compensatory duties. Although CPP purports to overcome the problem that a polluter might be dead, it can justify compensatory measures only for emissions that are made wrongfully. It does not cover emissions caused by agents who were permissibly ignorant of their harmfulness. (The agent in this case may be the community or state).

The practical relevance of principles of compensatory justice is limited. Insofar as the harms and benefits of climate change are undeserved, distributive justice will require them to be evened out, independently of compensatory justice. Duties of distributive justice do not presuppose any wrongdoing (see Section 3.3.4). For example, it has been suggested on grounds of distributive justice that the duty to pay for adaptation should be allocated on the basis of people's ability to pay, which partly reflects the benefit they have received from past emissions (Jamieson, 1997; Shue, 1999; Caney, 2010; Gardiner, 2011). However, present people and governments can be said to know about both the seriously harmful consequences of their emission-generating activities for future people and effective measures to prevent those consequences. If so and if they can implement these measures at a reasonable cost to themselves to protect future people's basic rights (see, e.g., Birnbacher, 2009; Gardiner, 2011), they might be viewed as owing intergenerational duties of justice to future people (see Section 3.3.2).

3.3.6 Legal concepts of historical responsibility

Legal systems have struggled to define the boundaries of responsibility for harmful actions and are only now beginning to do so for climate change. It remains unclear whether national courts will accept lawsuits against GHG emitters, and legal scholars vigorously debate whether liability exists under current law (Mank, 2007; Burns and Osofsky, 2009; Faure and Peeters, 2011; Haritz, 2011; Kosolapova, 2011; Kysar, 2011; Gerrard and Wannier, 2012). This section is concerned with moral responsibility, which is not the same as legal responsibility. But moral thinking can draw useful lessons from legal ideas.

Harmful conduct is generally a basis for liability only if it breaches some legal norm (Tunc, 1983), such as negligence, or if it interferes unreasonably with the rights of either the public or property owners (Mank, 2007; Grossman, 2009; Kysar, 2011; Brunée et al., 2012; Goldberg and Lord, 2012; Koch et al., 2012). Liability for nuisance does not exist if the agent did not know, or have reason to know, the effects of its conduct (Antolini and Rechtschaffen, 2008). The law in connection with liability for environmental damage still has to be settled. The European Union, but not the United States, recognizes exemption from liability for lack of scientific knowledge (United States Congress, 1980; European Union, 2004). Under European law, and in some US states, defendants are not responsible if a product defect had not yet been discovered (European Commission, 1985; Dana, 2009). Some legal scholars suggest that assigning blame for GHG emissions dates back to 1990 when the harmfulness of such emissions was established internationally, but others argue in favour of an earlier date (Faure and Nollkaemper, 2007; Hunter and Salzman, 2007; Haritz, 2011). Legal systems also require a causal link between a defendant's conduct and some identified harm to the plaintiff, in this case from climate change (Tunc, 1983; Faure and Nollkaemper, 2007; Kosolapova, 2011; Kysar, 2011; Brunée et al., 2012; Ewing and Kysar, 2012; Goldberg and Lord, 2012). A causal link might be easier to establish between emissions and adaptation costs (Farber, 2007). Legal systems generally also require causal foreseeability or directness (Mank, 2007; Kosolapova, 2011; van Dijk, 2011; Ewing and Kysar, 2012), although some statutes relax this requirement in specific cases (such as the US Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly known as Superfund. Emitters might argue that their contribution to GHG levels was too small and the harmful effects too indirect and diffuse to satisfy the legal requirements (Sinnot-Armstrong, 2010; Faure and Peeters, 2011; Hiller, 2011; Kysar, 2011; van Dijk, 2011; Gerrard and Wannier, 2012).

Climate change claims could also be classified as unjust enrichment (Kull, 1995; Birks, 2005), but legal systems do not remedy all forms of enrichment that might be regarded as ethically unjust (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). Under some legal systems, liability depends on whether benefits were conferred without legal obligation or through a transaction with no clear change of own-

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2016 NOV 14 PM

ership (Zimmermann, 1995; American Law Institute, 2011; Laycock, 2012). It is not clear that these principles apply to climate change.

As indicated, legal systems do not recognize liability just because a positive or negative externality exists. Their response depends on the behaviour that caused the externality and the nature of the causal link between the agent's behaviour and the resulting gain or loss to another.

3.3.7 Geoengineering, ethics, and justice

Geoengineering (also known as climate engineering [CE]), is large-scale technical intervention in the climate system that aims to cancel some of the effects of GHG emissions (for more details see Working Group I (WGI) 6.5 and WGIII 6.9). Geoengineering represents a third kind of response to climate change, besides mitigation and adaptation. Various options for geoengineering have been proposed, including different types of solar radiation management (SRM) and carbon dioxide removal (CDR). This section reviews the major moral arguments for and against geoengineering technologies (for surveys see Robock, 2008; Corner and Pidgeon, 2010; Gardiner, 2010; Ott, 2010; Betz and Cacean, 2012; Preston, 2013). These moral arguments do not apply equally to all proposed geoengineering methods and have to be assessed on a case-specific basis.[7]

Three lines of argument support the view that geoengineering technologies might be desirable to deploy at some point in the future. First, that humanity could end up in a situation where deploying geoengineering, particularly SRM, appears as a lesser evil than unmitigated climate change (Crutzen, 2006; Gardiner, 2010; Keith et al., 2010; Svoboda, 2012a; Betz, 2012). Second, that geoengineering could be a more cost-effective response to climate change than mitigation or adaptation (Barrett, 2008). Such efficiency arguments have been criticized in the ethical literature for neglecting issues such as side-effects, uncertainties, or fairness (Gardiner, 2010, 2011; Buck, 2012). Third, that some aggressive climate stabilization targets cannot be achieved through mitigation measures alone and thus must be complemented by either CDR or SRM (Greene et al., 2010; Sandler, 2012).

Geoengineering technologies face several distinct sets of objections. Some authors have stressed the substantial uncertainties of large-scale deployment (for overviews of geoengineering risks see also Schneider (2008) and Sardemann and Grunwald (2010)), while others have argued that some intended and unintended effects of both CDR and SRM could be irreversible (Jamieson, 1996) and that some current uncertainties are unresolvable (Bunzl, 2009). Furthermore, it has been pointed out that geoengineering could make the situation worse rather than better (Hegerl and Solomon, 2009; Fleming, 2010; Hamilton, 2013) and that several technologies lack a viable exit option: SRM in particular would have to be maintained as long as GHG concentrations remain elevated (The Royal Society, 2009).

Arguments against geoengineering on the basis of fairness and justice deal with the intra-generational and intergenerational distributional effects. SRM schemes could aggravate some inequalities if, as expected, they modify regional precipitation and temperature patterns with unequal social impacts (Bunzl, 2008; The Royal Society, 2009; Svoboda et al., 2011; Preston, 2012). Furthermore, some CDR methods would require large-scale land transformations, potentially competing with agricultural land-use, with uncertain distributive consequences. Other arguments against geoengineering deal with issues including the geopolitics of SRM, such as international conflicts that may arise from the ability to control the "global thermostat" (e.g., Schelling, 1996; Hulme, 2009), ethics (Hale and Grundy, 2009; Preston, 2011; Hale and Dilling, 2011; Svoboda, 2012b; Hale, 2012b), and a critical assessment of technology and modern civilization in general (Fleming, 2010; Scott, 2012).

One of the most prominent arguments against geoengineering suggests that geoengineering research activities might hamper mitigation efforts (e.g., Jamieson, 1996; Keith, 2000; Gardiner, 2010), which presumes that geoengineering should not be considered an acceptable substitute for mitigation. The central idea is that research increases the prospect of geoengineering being regarded as a serious alternative to emission reduction (for a discussion of different versions of this argument see Hale, 2012a; Hourdequin, 2012). Other authors have argued, based on historical evidence and analogies to other technologies, that geoengineering research might make deployment inevitable (Jamieson, 1996; Bunzl, 2009), or that large-scale field tests could amount to full-fledged deployment (Robock et al., 2010). It has also been argued that geoengineering would constitute an unjust imposition of risks on future generations, because the underlying problem would not be solved but only counteracted with risky technologies (Gardiner, 2010; Ott, 2012; Smith, 2012). The latter argument is particularly relevant to SRM technologies that would not affect greenhouse gas concentrations, but it would also apply to some CDR methods, as there may be issues of long-term safety and capacity of storage.

Arguments in favour of research on geoengineering point out that research does not necessarily prepare for future deployment, but can, on the contrary, uncover major flaws in proposed schemes, avoid premature CE deployment, and eventually foster mitigation efforts (e.g. Keith et al., 2010). Another justification for Research and Development (R&D) is that it is required to help decision-makers take informed decisions (Leisner and Müller-Klieser, 2010).

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[7] While the literature typically associates some arguments with particular types of methods (e.g., the termination problem with SRM), it is not clear that there are two groups of moral arguments: those applicable to all SRM methods on the one side and those applicable to all CDR methods on the other side. In other words, the moral assessment hinges on aspects of geoengineering that are not connected to the distinction between SRM and CDR.

3.4 Values and wellbeing

One branch of ethics is the theory of value. Many different sorts of value can arise, and climate change impinges on many of them. Value affects nature and many aspects of human life. This section surveys some of the values at stake in climate change, and examines how far these values can be measured, combined, or weighed against each other. Each value is subject to debate and disagreement. For example, it is debatable whether nature has value in its own right, apart from the benefit it brings to human beings. Decision-making about climate change is therefore likely to be contentious.

Since values constitute only one part of ethics, if an action will increase value overall it by no means follows that it should be done. Many actions benefit some people at the cost of harming others. This raises a question of justice even if the benefits in total exceed the costs. Whereas a cost to a person can be compensated for by a benefit to that same person, a cost to a person cannot be compensated for by a benefit to someone else. To suppose it can is not to "take seriously the distinction between persons", as John Rawls puts it (1971, p. 27). Harming a person may infringe their rights, or it may be unfair to them. For example, when a nation's economic activities emit GHG, they may benefit the nation itself, but may harm people in other nations. Even if the benefits are greater in value than the harms, these activities may infringe other nations' rights. Other nations may therefore be entitled to object to them on grounds of justice.

Any decision about climate change is likely to promote some values and damage others. These may be values of very different sorts. In decision making, different values must therefore be put together or balanced against each other. Some pairs of values differ so radically from each other that they cannot be determinately weighed together. For example, it may be impossible to weigh the value of preserving a traditional culture against the material income of the people whose culture it is, or to weigh the value of biodiversity against human wellbeing. Some economists claim that one person's wellbeing cannot be weighed against another's (Robbins, 1937; Arrow, 1963). When values cannot be determinately weighed, they are said to be 'incommensurable' or 'incomparable' (Chang, 1997). Multi-Criteria Analysis (MCA) (discussed in Section 3.7.2.1) is a technique that is designed to take account of several incommensurable values (De Montis et al., 2005; Zeleny and Cochrane, 1982).

3.4.1 Non-human values

Nature provides great benefits to human beings in ways that range from absorbing our waste, to beautifying the world we inhabit. An increasing number of philosophers have argued in recent years that nature also has value in its own right, independently of its benefits to human beings (Leopold, 1949; Palmer, 2011). They have argued that we should recognize animal values, the value of life itself, and even the value of natural systems and nature itself.

In moral theory, rational adult humans, who are self-conscious subjects of a life, are often taken (following Kant, 1956) to have a kind of unconditional moral worth—sometimes called 'dignity'—that is not found elsewhere on earth. Others believe that moral worth can be found elsewhere (Dryzek, 1997). Many human beings themselves lack rationality or subjectivity, yet still have moral worth—the very young, the very old and people with various kinds of impairment among them. Given that, why deny moral worth to those animals that are to some extent subjects of a life, who show emotional sophistication (Regan, 2004), and who experience pleasure, pain, suffering, and joy (Singer, 1993)?

An argument for recognizing value in plants as well as animals was proposed by Richard Routley (1973). Routley gives the name 'human chauvinism' to the view that humans are the sole possessors of intrinsic value. He asks us to imagine that the last man on earth sets out to destroy every living thing, animal or plant. Most people believe this would be wrong, but human chauvinists are unable to explain why. Human chauvinism appears to be simply a prejudice in favour of the human species (Routley and Routley, 1980). In contrast, some philosophers argue that value exists in the lives of all organisms, to the extent that they have the capacity to flourish (Taylor, 1986; Agar, 2001).

Going further, other philosophers have argued that biological communities and holistic ecological entities also have value in their own right. Some have argued that a species has more value than all of its individuals have together, and that an ecosystem has still more value (Rolston, 1988, 1999; compare discussion in Brennan and Lo, 2010). It has further been proposed that, just as domination of one human group by another is a moral evil, showing disrespect for the value of others, then so is the domination of nature by humans in general. If nature and its systems have moral worth, then the domination of nature is also a kind of disrespect (Jamieson, 2010).

If animals, plants, species, and ecosystems do have value in their own right, then the moral impact of climate change cannot be gauged by its effects on human beings alone. If climate change leads to the loss of environmental diversity, the extinction of plant and animal species, and the suffering of animal populations, then it will cause great harms beyond those it does to human beings. Its effects on species numbers, biodiversity, and ecosystems may persist for a very long time, perhaps even longer than the lifetime of the human species (Nolt, 2011).

It is very difficult to measure non-human values in a way that makes them commensurate with human values. Economists address this issue by dividing value into use value (associated with actual use of nature—instrumental value) and nonuse or existence value (intrinsic value of nature). As an example, biodiversity might have value because of the medical drugs that might be discovered among the diverse biota (use value). Or biodiversity might be valued by individuals sim-

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2015 NOV 14 PM 1: 03

ply because they believe that biologic diversity is important, over and above any use to people that might occur. The total amount people are willing to pay has sometimes been used as an economic measure of the total value (instrumental and intrinsic) of these features (Aldred, 1994). As the discussion of the past few paragraphs has suggested, nature may have additional value, over and above the values placed by individual humans (Broome, 2009; Spash et al., 2009).

3.4.2 Cultural and social values

The value of human wellbeing is considered in Section 3.4.3, but the human world may also possess other values that do not form part of the wellbeing of individual humans. Living in a flourishing culture and society contributes to a person's wellbeing (Kymlicka, 1995; Appiah, 2010), but some authors claim that cultures and societies also possess values in their own right, over and above the contribution they make to wellbeing (Taylor, 1995). Climate change threatens damage to cultural artefacts and to cultures themselves (Adger et al., 2012). Evidence suggests that it may already be damaging the culture of Arctic indigenous peoples (Ford et al., 2006, 2008; Crate, 2008; Hassol, 2004; see also WGII Chapter 12). Cultural values and indigenous peoples are discussed in Section 3.10.2.

The degree of equality in a society may also be treated as a value that belongs to a society as a whole, rather than to any of the individuals who make up the society. Various measures of this value are available, including the Gini coefficient and the Atkinson measure (Gini, 1912; Atkinson, 1970); for an assessment see (Sen, 1973). Section 3.5 explains that the value of equality can alternatively be treated as a feature of the aggregation of individual people's wellbeings, rather than as social value separate from wellbeing.

3.4.3 Wellbeing

Most policy concerned with climate change aims ultimately at making the world better for people to live in. That is to say, it aims to promote people's wellbeing. A person's wellbeing, as the term is used here, includes everything that is good or bad for the person—everything that contributes to making their life go well or badly. What things are those—what constitutes a person's wellbeing? This question has been the subject of an extensive literature since ancient times.[8] One view is that a person's wellbeing is the satisfaction of their preferences. Another is that it consists in good feelings such as pleasure. A third is that wellbeing consists in possessing the ordinary good things of life, such as health, wealth, a long life, and participating well in a good community. The 'capabilities approach' in economics (Sen, 1999) embodies this last view. It treats the good things of life as 'functionings' and 'capabilities'—things that a person does and things that they have a real opportunity of doing, such as living to old age, having a good job, and having freedom of choice.

A person's wellbeing will be affected by many of the other values that are mentioned above, and by many of the considerations of justice mentioned in Section 3.3. It is bad for a person to have their rights infringed or to be treated unfairly, and it is good for a person to live within a healthy culture and society, surrounded by flourishing nature.

Various concrete measures of wellbeing are in use (Fleurbaey, 2009; Stiglitz et al., 2009). Each reflects a particular view about what wellbeing consists in. For example, many measures of 'subjective wellbeing' (Oswald and Wu, 2010; Kahneman and Deaton, 2010) assume that wellbeing consists in good feelings. Monetary measures of wellbeing, which are considered in Section 3.6, assume that wellbeing consists in the satisfaction of preferences. Other measures assume wellbeing consists in possessing a number of specific good things. The Human Development Index (HDI) is intended to be an approximate measure of wellbeing understood as capabilities and functionings (UNDP, 2010). It is based on three components: life expectancy, education, and income. The capabilities approach has inspired other measures of wellbeing too (Dervis and Klugman, 2011). In the context of climate change, many different metrics of value are intended to measure particular components of wellbeing: among them are the numbers of people at risk from hunger, infectious diseases, coastal flooding, or water scarcity. These metrics may be combined to create a more general measure. Schneider et al. (2000) advocates the use of a suite of five metrics: (1) monetary loss, (2) loss of life, (3) quality of life (taking account of forced migration, conflict over resources, cultural diversity, and loss of cultural heritage sites), (4) species or biodiversity loss, and (5) distribution and equity.

3.4.4 Aggregation of wellbeing

Whatever wellbeing consists of, policy-making must take into account the wellbeing of everyone in the society. So the wellbeings of different people have somehow to be aggregated together. How do they combine to make up an aggregate value of wellbeing for a society as a whole? Social choice theory takes up this problem (Arrow, 1963; Sen, 1970). Section 3.6 will explain that the aim of economic valuation is to measure aggregate wellbeing.

Assume that each person has a level of wellbeing at each time they are alive, and call this their 'temporal wellbeing' at that time. In a society, temporal wellbeing is distributed across times and across the people. When a choice is to be made, each of the options leads to a particular distribution of wellbeing. Our aim is to assess the value of such distributions. Doing so involves aggregating wellbeings across times and across people, to arrive at an overall, social value for the distribution.

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[8] For example: Aristotle, *Nicomachean Ethics*. Recent work includes: Griffin (1986); Sumner (1999); Kraut (2007).

3.4.5 Lifetime wellbeing

Next let us assume that each person's temporal wellbeings can be aggregated to determine a 'lifetime wellbeing' for the person, and that the social value of the distribution of wellbeing depends only on these lifetime wellbeings. This is the assumption that each person's wellbeing is "separable", to use a technical term. It allows us to split aggregation into two steps. First, we aggregate each person's temporal wellbeings across the times in their life in order to determine their lifetime wellbeing. The second step in the next section is to aggregate across individuals using a social welfare function.

On one account, a person's lifetime wellbeing is simply the total of their temporal wellbeings at each time they are alive. If a person's wellbeing depended only on the state of their health, this formula would be equivalent to 'QALYs' or 'DALYs' (quality-adjusted life years or disability-adjusted life years), which are commonly used in the analysis of public health (Murray, 1994; Sassi, 2006). These measures take a person's lifetime wellbeing to be the total number of years they live, adjusted for their health in each year. Since wellbeing actually depends on other things as well as health, QALYs or DALYs provide at best an approximate measure of lifetime wellbeing. If they are aggregated across people by simple addition, it assumes implicitly that a year of healthy life is equally as valuable to one person as it is to another. That may be an acceptable approximation for the broad evaluation of climate change impacts and policies, especially for evaluating their effects on health (Nord et al., 1999; Mathers et al., 2009; but also see Currie et al., 2008).

Other accounts give either increasing, (Velleman, 1991) or alternatively decreasing, (Kaplow et al., 2010) weight to wellbeing that comes in later years of life, in determining a person's lifetime wellbeing.

3.4.6 Social welfare functions

Once we have a lifetime wellbeing for each person, the next step is to aggregate these lifetime wellbeings across people, to determine an overall value for society. This involves comparing one person's wellbeing with another's. Many economists have claimed that interpersonal comparisons of wellbeing are impossible.[9] If they are right, the wellbeings of different people are incommensurable and cannot be aggregated. In this section we set this view aside, and assume that temporal wellbeings are measured in a way that is comparable across people.[10] This allows us to aggregate different people's lifetime wellbeings through a social welfare function (SWF) to arrive at an overall value or 'social welfare'.[11]

We shall first consider SWFs under the simplifying but unrealistic assumption that the decisions that are to be made do not affect how many people exist or which people exist: all the options contain the same people. A theorem of Harsanyi's (1955) gives some grounds for thinking that, given this assumption, the SWF is additively separable between people. This means it has the form:

Equation 3.4.1 $V = v_1(w_1) + v_2(w_2) + \ldots + v_I(w_I)$

Here w_i is person i's lifetime wellbeing. This formula says that each person's wellbeing can be assigned a value $v_i(w_i)$, and all these values—one for each person—are added up to determine the social value of the distribution.

The proof of Harsanyi's Theorem depends on assumptions that can be challenged (Diamond, 1967; Broome, 2004; Fleurbaey, 2010). So, although the additively separable form shown in Equation 3.4.1 is commonly assumed in economic valuations, it is not entirely secure. In particular, this form makes it impossible to give any value to equality except indirectly through prioritarianism, which was introduced in Section 3.3.2 and is defined below. The value of inequality cannot be measured by the Gini coefficient, for example, since this measure is not additively separable (Sen, 1973).

It is often assumed that the functions $v_i(\,)$ all have the same form, which means that each person's wellbeing is valued in the same way:

Equation 3.4.2 $V = v(w_1) + v(w_2) + \ldots + v(w_I)$

Alternatively, the wellbeing of people who live later is sometimes discounted relative to the wellbeing of people who live earlier; this implies that the functional form of $v_i(\,)$ varies according to the date when people live. Discounting of later wellbeing is often called 'pure' discounting. It is discussed in Section 3.6.2.

Even if we accept Equation 3.4.2, different ethical theories imply different SWFs. Utilitarianism values only the total of people's wellbeing. The SWF may be written:

Equation 3.4.3 $V = w_1 + w_2 + \ldots + w_I$

Utilitarianism gives no value to equality in the distribution of wellbeing: a given total of wellbeing has the same value however unequally it is distributed among people.

But the idea of distributive justice mentioned in Section 3.3.3 suggests that equality of wellbeing does have value. Equation 3.4.2 will give value to equality if the function $v()$ is strictly concave. This means the graph of $v()$ curves downwards, as Figure 3.1 illustrates. (Section 3.6.1.1 explains that a person's wellbeing w_i is commonly assumed to be a strictly concave function of her consumption, but this is a different point.) The resulting ethical theory is called prioritarianism. As Figure 3.1 shows, according to prioritarianism, improv-

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[9] Examples are: Robbins (1937), Archibald (1959), Arrow (1963). A survey and discussion of this sceptical view appears in Hammond (1993).

[10] Potential bases of interpersonal comparisons are examined in: Fleurbaey and Hammond (2004); Sen (1982); Elster and Roemer (1993); Mirrlees (1982); Broome, (2004); Arrow (1977); Harsanyi (1977); Adler (2011).

[11] A recent major study is Adler (2011).

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2016 NOV 14

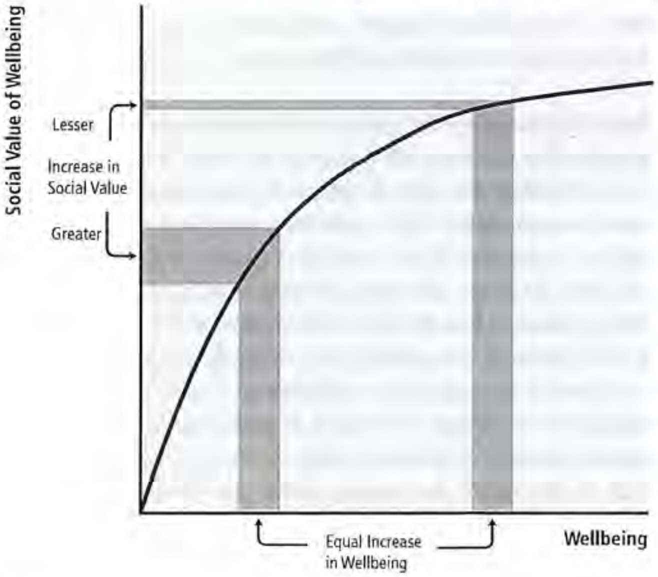

Figure 3.1 | The prioritarian view of social welfare. The figure compares the social values of increases in wellbeing for a better-off and a worse-off person.

ing a *person's* wellbeing contributes more to social welfare if the person is badly off than if they are well off. The prioritarian slogan is "priority to the worse off". Prioritarianism indirectly gives value to equality: it implies that a given total of wellbeing is more valuable the more equally it is distributed (Sen, 1973; Weirich, 1983; Parfit, 1997). In judgements about climate change, a prioritarian function will give relatively more importance to the interests of poorer people and poorer countries.

3.4.7 Valuing population

The next problem in aggregating wellbeing is to take account of changes in population. Climate change can be expected to affect the world's human population. Severe climate change might even lead to a catastrophic collapse of the population (Weitzman, 2009), and even to the extinction of human beings. Any valuation of the impact of climate change and of policies to mitigate climate change should therefore take changes in population into account.

The utilitarian and prioritarian SWFs for a fixed population may be extended in a variety of ways to a variable population. For example, the utilitarian function may be extended to 'average utilitarianism' (Hurka, 1982), whose SWF is the average of people's wellbeing. Average utilitarianism gives no value to increasing numbers of people. The implicit or explicit goal of a great deal of policy-making is to promote per capita wellbeing (Hardin, 1968). This is to adopt average utilitarianism. This goal tends to favour anti-natalist policies, aimed at limiting population. It would strongly favour population control as a means of mitigating climate change, and it would not take a collapse of population to be, in itself, a bad thing.

The utilitarian function may alternatively be extended to 'critical-level utilitarianism', whose SWF is the total of the amount by which each person's wellbeing exceeds some fixed critical level. It is

Equation 3.4.4 $V = (w_1 - c) + (w_2 - c) + \ldots + (w_J - c)$

where c is the critical level (Broome, 2004; Blackorby et al., 2005). Other things being equal, critical-level utilitarianism favours adding people to the population if their wellbeing is above the critical level.

'Total utilitarianism' (Sidgwick, 1907) is critical-level utilitarianism with the critical level set to zero. Its SWF is the total of people's wellbeing. Total utilitarianism is implicit in many Integrated Assessment Models (IAMs) of climate change (e.g., Nordhaus, 2008). Its meaning is indeterminate until it is settled which level of lifetime wellbeing to count as zero. Many total utilitarians set the zero at the level of a life that has no good or bad experiences—that is lived in a coma throughout, for instance (Arrhenius, forthcoming). Since people on average lead better lives than this, total utilitarianism with this zero tends to be less anti-natalist than average utilitarianism. However, it does not necessarily favour increasing population. Each new person damages the wellbeing of existing people, through their emissions of GHG, their other demands on Earth's limited resources, and the emissions of their progeny. If the damage an average person does to others in total exceeds their own wellbeing, total utilitarianism, like average utilitarianism, favours population control as a means of mitigating climate change.[12]

Each of the existing ethical theories about the value of population has intuitively unattractive implications (Parfit, 1986). Average utilitarianism is subject to particularly severe objections. Arrhenius (forthcoming) crystallizes the problems of population ethics in the form of impossibility theorems. So far, no consensus has emerged about the value of population. Yet climate change policies are expected to affect the size of the world's population, and different theories of value imply very different conclusions about the value of these policies. This is a serious difficulty for evaluating policies aimed at mitigating climate change, which has largely been ignored in the literature (Broome, 2012).

3.5 Economics, rights, and duties

Sections 3.2, 3.3 and 3.4 have outlined some of the ethical principles that can guide decision making for climate change. The remainder of this chapter is largely concerned with the concepts and methods of

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[12] Harford (1998) shows that an additional person causes damage from her own emissions and the emissions of her children (and of their children, etc.). Kelly and Kolstad (2001) examine this issue in the specific context of climate change.

economics. They can be used to aggregate values at different times and places, and weigh aggregate value for different policy actions. They can also be used to draw information about value from the data provided by prices and markets. Economics can measure diverse benefits and harms, taking account of uncertainty, to arrive at overall judgements of value. It also has much to contribute to the choice and design of policy mechanisms, as Section 3.8 and later chapters show.

Valuations provided by economics can be used on a large scale: IAMs can be used to simulate the evolution of the world's economy under different climate regimes and determine an economically efficient reduction in GHG emissions. On a smaller scale, economic methods of CBA can be used in choosing between particular policies and technologies for mitigation.

Economics is much more than a method of valuation. For example, it shows how decision making can be decentralized through market mechanisms. This has important applications in policy instruments for mitigation with potential for cost-effectiveness and efficiency (Chapters 6 and 15). Economic analysis can also give guidance on how policy mechanisms for international cooperation on mitigation can be designed to overcome free-rider problems (Chapters 13 and 14). However, the methods of economics are limited in what they can do. They can be based on ethical principles, as Section 3.6 explains. But they cannot take account of every ethical principle. They are suited to measuring and aggregating the wellbeing of humans, but not to taking account of justice and rights (with the exception of distributive justice—see below), or other values apart from human wellbeing. Moreover, even in measuring and aggregating wellbeing, they depend on certain specific ethical assumptions. This section describes the limits of economic methods.

Because of their limitations, economic valuations are often not on their own a good basis for decision making. They frequently need to be supplemented by other ethical considerations. It may then be appropriate to apply techniques of multi-criteria analysis (MCA), discussed in Section 3.7.2.1 (Zeleny and Cochrane, 1982; Keeney and Raiffa, 1993; De Montis et al., 2005).

3.5.1 Limits of economics in guiding decision making

Economics can measure and aggregate human wellbeing, but Sections 3.2, 3.3 and 3.4 explain that wellbeing may be only one of several criteria for choosing among alternative mitigation policies. Other ethical considerations are not reflected in economic valuations, and those considerations may be extremely important for particular decisions that have to be made. For example, some have contended that countries that have emitted a great deal of GHG in the past owe restitution to countries that have been harmed by their emissions. If so, this is an important consideration in determining how much finance rich countries should provide to poorer countries to help with their mitigation efforts. It suggests that economics alone cannot be used to determine who should bear the burden of mitigation (also see Box 3.2).

What ethical considerations can economics cover satisfactorily? Since the methods of economics are concerned with value, they do not take account of justice and rights in general. However, distributive justice can be accommodated within economics, because it can be understood as a value: specifically the value of equality. The theory of fairness within economics (Fleurbaey, 2008) is an account of distributive justice. It assumes that the level of distributive justice within a society is a function of the wellbeings of individuals, which means it can be reflected in the aggregation of wellbeing. In particular, it may be measured by the degree of inequality in wellbeing, using one of the standard measures of inequality such as the Gini coefficient (Gini, 1912), as discussed in the previous section. The Atkinson measure of inequality (Atkinson, 1970) is based on an additively separable SWF, and is therefore particularly appropriate for representing the prioritarian theory described in Section 3.4.6. Furthermore, distributive justice can be reflected in weights incorporated into economic evaluations as Section 3.6 explains.

Economics is not well suited to taking into account many other aspects of justice, including compensatory justice. For example, a CBA might not show the drowning of a Pacific island as a big loss, since the island has few inhabitants and relatively little economic activity. It might conclude that more good would be done in total by allowing the island to drown: the cost of the radical action that would be required to save the island by mitigating climate change globally would be much greater than the benefit of saving the island. This might be the correct conclusion in terms of overall aggregation of costs and benefits. But the island's inhabitants might have a right not to have their homes and livelihoods destroyed as a result of the GHG emissions of richer nations far away. If that is so, their right may override the conclusions of CBA. It may give those nations who emit GHG a duty to protect the people who suffer from it, or at least to make restitution to them for any harms they suffer.

Even in areas where the methods of economics can be applied in principle, they cannot be accepted without question (Jamieson, 1992; Sagoff, 2008). Particular simplifying assumptions are always required, as shown throughout this chapter. These assumptions are not always accurate or appropriate, and decision-makers need to keep in mind the resulting limitations of the economic analyses. For example, climate change will shorten many people's lives. This harm may in principle be included within a CBA, but it remains highly contentious how that should be done. Another problem is that, because economics can provide concrete, quantitative estimates of some but not all values, less quantifiable considerations may receive less attention than they deserve.

The extraordinary scope and scale of climate change raises particular difficulties for economic methods (Stern, forthcoming). First, many of the common methods of valuation in economics are best designed for marginal changes, whereas some of the impacts of climate change and

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2016 NOV 14 PM [illegible]

Box 3.2 | Who mitigates versus who pays?

To mitigate climate change, emissions of GHG will need to be reduced to varying degrees worldwide. Economic analysis tells us that, for the sake of cost-effectiveness, the greatest reductions should be made where they can be made most cheaply. Ideally, emissions should be reduced in each place to just the extent that makes the marginal cost of further reductions the same everywhere. One way of achieving this result is to have a carbon price that is uniform across the world; or it might be approximated by a mix of policy instruments (see Section 3.8).

Since, for efficiency, mitigation should take place where it is cheapest, emissions of GHG should be reduced in many developing countries, as well as in rich ones. However, it does not follow that mitigation must be paid for by those developing countries; rich countries may pay for mitigation that takes place in poor countries. Financial flows between countries make it possible to separate the question of where mitigation should take place from the question of who should pay for it. Because mitigating climate change demands very large-scale action, if put in place these transfers might become a significant factor in the international distribution of wealth. Provided appropriate financial transfers are made, the question of where mitigation should take place is largely a matter for the economic theory of efficiency, tempered by ethical considerations. But the distribution of wealth is a matter of justice among countries, and a major issue in the politics of climate change (Stanton, 2011). It is partly a matter of distributive justice, which economics can take into account, but compensatory justice may also be involved, which is an issue for ethics (Section 3.3).

efforts at mitigation are not marginal (Howarth and Norgaard, 1992). Second, the very long time scale of climate change makes the discount rate crucial at the same time as it makes it highly controversial (see Section 3.6.2). Third, the scope of the problem means it encompasses the world's extremes of wealth and poverty, so questions of distribution become especially important and especially difficult. Fourth, measuring non-market values—such as the existence of species, natural environments, or traditional ways of life of local societies—is fraught with difficulty. Fifth, the uncertainty that surrounds climate change is very great. It includes the likelihood of irreversible changes to societies and to nature, and even a small chance of catastrophe. This degree of uncertainty sets special problems for economics (Nelson, 2013).

3.6 Aggregation of costs and benefits

3.6.1 Aggregating individual wellbeing

Policies that respond to climate change almost always have some good and some bad effects; we say they have 'benefits' and 'costs'. In choosing a policy, we may treat one of the available options as a standard of comparison—for instance, the status quo. Other options will have costs and benefits relative to this standard. Most mitigation strategies have costs in the present and yield benefits in the future. Policy-making involves assessing the values of these benefits and costs and weighing them against each other. Chapter 6 contains an example in which different mitigation strategies yielding different temporal allocations of climate impacts are compared. The weighing of costs and benefits need not be a precise process. Sections 3.2 and 3.4 explain that costs and benefits may be values of very different sorts, which cannot be precisely weighed against each other. They may also be very uncertain.

Nevertheless, the discipline of economics has developed methods for measuring numerically values of one particular sort: human wellbeing. In this section, we describe these methods; Section 3.5 explains their serious limitations. Economists often use money as their unit of measurement for values, but not always. In health economics, for example, the unit of benefit for health care is often the 'quality-adjusted life year' (QALY) (see Box 3.3). In economics, monetary measures of value are used in cost-effectiveness analysis (see Weimer and Vining, 2010), in estimating the social cost of carbon (see Section 3.9.4), in inter-temporal optimization within IAMs (e.g., Stern, 2007; Nordhaus, 2008), in CBA and elsewhere.

Generally the overall value of aggregate wellbeing needs to be measured, and not merely the wellbeing of each individual. A numerical measure of overall wellbeing may be based on ethical analysis, through a SWF of the sort introduced in Section 3.4. This basis of valuation is described here. The literature contains a putative alternative basis built on the 'potential Pareto criterion' (see Box 3.4), but this is subject to severe objections (De Scitovszky, 1941; Gorman, 1955; Arrow, 1963, Chapter 4; Boadway and Bruce, 1984; Blackorby and Donaldson, 1990).

We take as our point of departure the formulation of the SWF in Equation 3.4.2, which is based on assumptions described in Section 3.4.6. To these we now add a further assumption that times are separable, meaning that the distribution of wellbeing can be evaluated at each time separately and its overall value is an aggregate of these separate 'snap-shot' values. A theorem of Gorman's (1968) ensures that social welfare then takes the fully additively separable form:

Equation 3.6.1 $V = \delta_1 V_1 + \delta_2 V_2 + \ldots + \delta_T V_T$

where each V_t is the value of wellbeing at time t and is the total of the values of individual wellbeings at that time. That is:

Equation 3.6.2 $V_t = v(w_{1t}) + v(w_{2t}) + \ldots + v(w_{It})$

Each w_{it} is the temporal wellbeing of person i at time t. Each δ_t is a 'discount factor', which shows how wellbeing at time t is valued relative to wellbeing at other times.

The assumption that times are separable has some unsatisfactory consequences. First, it cannot give value to equality between people's lives taken as a whole, but only to equality at each particular time. Second, Equation 3.6.1 is inconsistent with average utilitarianism, or with valuing per capita temporal wellbeing at any time, whereas per capita wellbeing is a common object of climate-change policy. Third, Equation 3.6.1 makes no distinction between discounting within a single person's life and intergenerational discounting. Yet a case can be made for treating these two sorts of discounting differently (Kaplow et al., 2010). Nevertheless, this assumption and the resulting equation Equation 3.6.1 underlies the usual practice of economists when making valuations. First they aggregate temporal wellbeing across people at each time to determine a snapshot social value for each time. Then all these values are aggregated across times. This section and the next describe the usual practice based on these equations.[13] The second step—aggregation across time—is considered in Section 3.6.1. The rest of this section considers the first step—aggregation at time.

Box 3.3 | The value of life

Climate change may shorten many people's lives, and mitigating climate change may extend many people's lives. Lives must therefore be included in any CBA that is concerned with climate change. The literature contains two different approaches to valuing a person's life. One is based on the length of time the person gains if their life is saved, adjusted according to the quality of their life during that time (QALY), an approach widely used to value lives in health economics and public health. For assessing the impact of climate on human health and longevity, the World Health Organization uses the 'disability-adjusted life year' (DALY), which is similar (Mathers et al., 2009; for DALYs see, Murray, 1994).

The other approach values the extension of a person's life on the basis of what they would be willing to pay for it. In practice, this figure is usually derived from what the person would be willing to pay for an increased chance of having an extended life. If, say, a person is willing to pay $100 to reduce her chance of dying in a road accident from 2 in 10,000 to 1 in 10,000, then her willingness to pay (WTP) for extending her life is $100 x 10,000 = $1 million. A WTP measure of the value of life is widely used in environmental economics (e.g., U.S. Environmental Protection Agency, 2010 Appendix B); it is often known as a 'value of statistical life' (Viscusi and Aldy, 2003).

The main differences between these approaches are:

1. Since WTP is measured in money, it is immediately comparable with other values measured in money. QALYs need to be assigned a monetary value to make them comparable (Mason et al., 2009).
2. The use of QALYs implies a theoretical assumption about the value of extending a life—that it is proportional to the length of the extension, adjusted for quality—whereas WTP methods generally leave it entirely to the individual to set a value on extending their own life (Broome, 1994).
3. Each measure implies a different basis for interpersonal comparisons of value. When QALYs are aggregated across people by addition, the implicit assumption is that a year of healthy life has the same value for each person. When WTP is aggregated across people by addition (without distributional weights), the implicit assumption is that a dollar has the same value for each person. Neither assumption is accurate, but for comparisons involving very rich countries and very poor ones, the former assumption seems nearer the truth (Broome, 2012, Chapter 9).

The two approaches can converge. The text explains that distributional weights should be applied to monetary values before they are aggregated, and this is true of WTP for extending life. If appropriate weights are applied, WTP becomes more nearly proportional to QALYs. Indeed, if we adopt the assumption that a QALY has the same value for each person, we may use it to give us a basis for calculating distributional weights to apply to money values (Somanathan, 2006). For example, suppose WTP for a 30-year extension to healthy life in the United States is USD 5 million, and in India it is USD 250,000; then, on this assumption, USD 1 to an Indian has the same social value as USD 20 to an American.

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[13] An alternative approach does not assume separability of times. First it determines a lifetime wellbeing for each person in the way described in Section 3.4.5. For instance, *i*'s lifetime wellbeing might be a discounted total of her temporal wellbeings. Then this approach aggregates across people using Equation 3.4.2. See Fullerton and Rogers (1993), Murphy and Topel (2006) and Kaplow et al. (2010).

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3.6.1.1 Monetary values

Climate policies affect the wellbeing of individuals by changing their environment and their individual consumption. The first step in a practical economic valuation is to assign a monetary value to the costs and benefits that come to each person at each time from the change. This value may be either the amount of money the person is willing to pay for the change, or the amount they are willing to accept as compensation for it. If the change is a marginal increase or decrease in the person's consumption of a marketed commodity, it will be equal to the price of the commodity.

The effect of a change on the person's wellbeing is the monetary value of the change multiplied by the rate at which money contributes to the person's wellbeing. This rate is the marginal benefit of money or marginal utility of money to the person. It is generally assumed to diminish with increasing income (Marshall, 1890; Dalton, 1920; Pigou, 1932, p. 89; Atkinson, 1970).

The effects of the change on each person's wellbeing at each time must next be aggregated across people to determine the effect on social value. Equation 3.6.2 shows how each person's wellbeing contributes to social value through the value function v(). The change in wellbeing must therefore be multiplied by the marginal social value of wellbeing, which is the first derivative of this function. It is an ethical parameter. According to utilitarianism, that marginal social value is constant and the same for everyone; according to prioritarianism, it diminishes with increasing wellbeing.

Box 3.4 | Optimality versus Pareto improvement in climate change

The assessment of a change normally requires benefits to be weighed against costs. An exception is a change – known as a 'Pareto improvement' – that benefits some people without harming anyone. Climate change provides one possible example. GHG is an externality: a person whose activities emit GHG does not bear the full cost of their activities; some of the costs are borne by those who are harmed by the emissions. Consequently, climate change causes Pareto inefficiency, which means that a Pareto improvement would in principle be possible. Indeed it would be possible to remove the inefficiency in a way that requires no sacrifice by anyone in any generation, compared to business-as-usual (BAU). To achieve this result, the present generation must reallocate investment towards projects that reduce emissions of GHG, while maintaining its own consumption. Because it maintains its own consumption, the present generation makes no sacrifice. Because it reduces its conventional investment, this generation bequeaths less conventional capital to future generations. Other things being equal, this reallocation would make future generations less well off, but the reduction in emissions will more than compensate them for that loss (Stern, forthcoming; Foley, 2009; Rezai et al., 2011).

It is commonly assumed that climate change calls for sacrifices by the present generation for the sake of future generations. Figure 3.2 illustrates why. The possibility frontier shows what combinations of consumption are possible for present and future generations. Because of the externality, Business-as-usual lies below this frontier. The frontier can be reached by a Pareto improvement. Contours of two different SWFs are shown: one SWF places more value than the other on future consumption relative to present consumption. The two contours reflect in a purely illustrative way SWFs that are implicit in Stern (2007) and Nordhaus (2008) respectively. The point where a contour touches the possibility frontier is the social optimum according to that function. Neither optimum is a Pareto improvement on business-as-usual. Although the inefficiency could be removed without any sacrifices, the best outcomes described by both Stern and Nordhaus do require a sacrifice by the present generation.

From an international rather than an intergenerational perspective, it is also true on the same grounds that the inefficiency of climate change can be removed without any nation making a sacrifice (Posner and Weisbach, 2010). But it does not follow that this would be the best outcome.

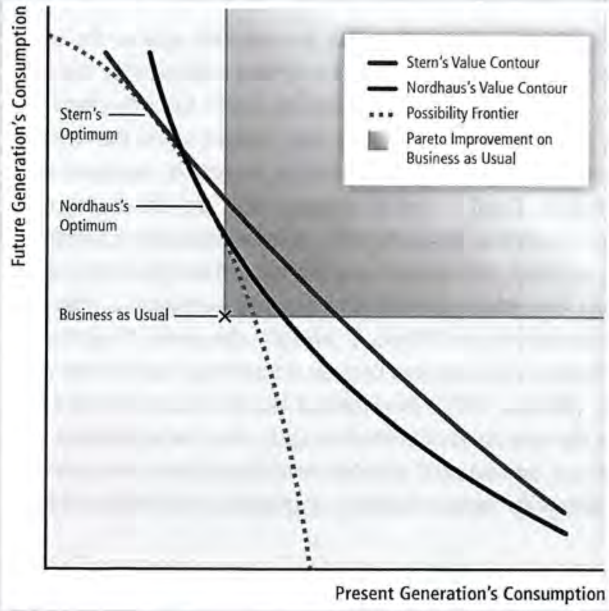

Figure 3.2 | Illustrating optimality versus Pareto improvement in climate change.

In sum, the effect of a change in social value at a particular time is calculated by aggregating the monetary value of the change to each person, weighted by the social marginal value of money to the person, which is the product of the marginal benefit of money to that person and the marginal social value of their wellbeing (Fleurbaey, 2009). Since the marginal benefit of money is generally assumed to diminish with increasing income, the marginal social value of money can be assumed to do the same.

Many practical CBAs value costs and benefits according to aggregated monetary values without any weighting. The implicit assumption is that the marginal social value of money is the same for each person. The consequence of omitting weights is particularly marked when applying CBA to climate change, where extreme differences in wealth between rich and poor countries need to be taken into account. An example appeared in the Second Assessment Report of the IPCC (1995), where it considered the value of human life. The report showed that the effect of ignoring weighting factors would be to assign perhaps twenty times more value to an American life than to an Indian life. (See also Box 3.3). Even within a single country, weighting makes a big difference. Drèze (1998) examined the benefits of reducing pollution in Delhi and contrasts New Delhi, which is relatively rich, with Delhi, which is relatively poorer. If the criterion is reducing pollution for the greatest number of people, then projects in Delhi will be favoured; whereas projects in New Delhi will be favoured if the criterion is unweighted net benefits.

Another example of a monetary measure of value that does not incorporate distributional weights is Gross Domestic Product (GDP). To evaluate changes by their effect on GDP is, once again, to assume that the value of a dollar to a rich person is the same as its value to a poor person (Schneider et al., 2000).

It is sometimes assumed that CBA is conducted against the background of efficient markets and an optimal redistributive taxation system, so that the distribution of income can be taken as ideal from society's point of view. If that were true, it might reduce the need for distributional weights. But this is not an acceptable assumption for most projects aimed at climate change. Credit and risk-sharing markets are imperfect at the world level, global coordination is limited by agency problems, information is asymmetric, and no supra-national tax authority can reduce worldwide inequalities. Furthermore, intergenerational transfers are difficult. In any case, the power of taxation to redistribute income is limited because redistributive taxes create inefficiency (Mirrlees, 1971). Even optimal taxation would therefore not remove the need for distributional weights. Thus, the assumption that incomes are (second-best) optimally redistributed does not neutralize the argument for welfare weights in aggregating costs and benefits.

The need for weights makes valuation more complicated in practice. The data available for costs and benefits is generally aggregated across people, rather than separated for particular individuals. This means that weights cannot be applied directly to individuals' costs and benefits, as they ideally should be. This difficulty can be overcome by applying suitably calculated weights to the prices of commodities, calculated on the basis of income distribution of each commodity's consumers.[14]

3.6.2 Aggregating costs and benefits across time

In climate change decisions, aggregating the pros and cons of alternative actions is particularly difficult because most benefits of mitigation will materialize only in the distant future. On the other hand, the costs of mitigation are borne today. Using a discount rate can therefore make a big difference in evaluating long-term projects or investments for climate change mitigation. For example, a benefit of $1 million occurring in 100 years has a present value of $369,000 if the discount rate is 1 %, $52,000 if it is 3 %, and $ 1,152 if it is 7 %. An important debate in economics since AR4, spawned in part by the Stern (2007) Review, has centred on the discount rate that should be applied in evaluating climate change impacts and mitigation costs (Nordhaus, 2007; Stern, 2008; Dasgupta, 2008; Smith, 2010; see also Quiggin, 2008).

A descriptive approach to discounting examines how human beings trade-off the present against their own futures. It focuses on how individuals and markets make inter-temporal financial decisions, as revealed by the market interest rate. A simple arbitrage argument favours using the interest rate as the discount rate for climate policy decisions: if one reallocates capital from a safe but marginal project (whose return must be equal to the interest rate) to a safe project with the same maturity whose return is smaller than the interest rate, the net impact is null for the current generation, and is negative for future generations. Thus, when projects are financed by a reallocation of capital rather than an increase in aggregate saving (reducing consumption), the discount rate should be equal to the shadow cost of capital.

Table 3.1 documents real returns on different classes of assets in western countries, including government bonds, which are usually considered to be the safest, most risk-free assets. As can be seen, these rates are close to zero.

The same arbitrage argument could be used to discount risky projects. In that case, the discount rate should be equal to the expected rate of return of traded assets with the same risk profile. For example, if the project has the same risk profile as a diversified portfolio of equity, one should use the expected rate of return of equity, as documented in Table 3.1. It contains a relatively large equity premium.

This descriptive approach to the discount rate has many drawbacks. First, we should not expect markets to aggregate preferences efficiently when some agents are not able to trade, as is the case for future generations (Diamond, 1977). Second, current interest rates

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[14] The method is presented in Drèze and Stern (1989, pp. 909–989). Applications of distributional weights to climate change appear in Azar and Sterner (1996); and Fankhauser et al. (1997).

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2014 NOV 14

Table 3.1 | Real returns of financial assets. Source: Updated data from (Dimson, 2002), in Gollier (2012).

	Government Bills (maturity < 1 year)		Government Bonds (maturity =10 years)		Equity	
	1900–2006	1971–2006	1900–2006	1971–2006	1900–2006	1971–2006
Australia	0.6 %	2.5 %	1.3 %	2.8 %	7.8 %	6.3 %
France	−2.9 %	1.2 %	−0.3 %	6.6 %	3.7 %	7.8 %
Japan	−2.0 %	0.4 %	−1.3 %	3.9 %	4.5 %	5.0 %
United Kingdom	1.0 %	1.9 %	1.3 %	3.9 %	5.6 %	7.1 %
USA	1.0 %	1.3 %	1.9 %	4.0 %	6.6 %	6.6 %

are driven by the potentially impatient attitude of current consumers towards transferring their *own* consumption to the future. But climate change is about transferring consumption across different people and generations, so that determining the appropriate social discount rate is mostly a normative problem. Thirdly, we do not observe safe assets with maturities similar to those of climate impacts, so the arbitrage argument cannot be applied.

We now examine the problem of a social policy-maker who must make climate policy choices using a SWF discussed earlier. In aggregating damages and costs over time, in order to make things comparable across long periods we value consumption changes in the future by equivalent changes in consumption today. These changes in the structure of consumption should be evaluated in monetary terms using values described in Section 3.6.1.1. The incorporation of the intergenerational equity objective has challenged the traditional CBA approach for the evaluation of climate change policies. Practitioners of CBA and evaluators are expected to use discount rates that are consistent with the pre-specified SWF that represents the society's intergenerational values, as in AR2 (1995). We simplify the model used in Section 3.6.1.1 by assuming only one generation per period and only one consumer good. In an uncertain context, an action is socially desirable if it raises the SWF given by 3.6.1:

Equation 3.6.3 $$V = \sum_{t=0}^{\infty} e^{-\delta t} Eu(c_t)$$

where $u(c_t) = v(w(c_t)) = V_t$ is the contribution to the SWF of generation t consuming c_t. Because c_t is uncertain, one should take the expectation $Eu(c_t)$ of this uncertain contribution. The concavity of function u combines prioritarism (inequality aversion) and risk aversion. Parameter δ measures our collective pure preference for the present, so that the discount factor $d(t) = e^{-\delta t}$ decreases exponentially. δ is an ethical parameter that is not related to the level of impatience shown by individuals in weighting their own future wellbeing (Frederick et al., 2002). Many authors have argued for a rate of zero or near-zero (Ramsey, 1928; Pigou, 1932; Harrod, 1949; Parfit, 1986; Cowen, 1992; Schelling, 1995; Broome, 2004; Stern, 2008). Assuming $\delta > 0$ would penalize future generations just because they are born later. Many regard such 'datism' to be as ethically unacceptable as sexism or racism. Cowen (1992) points out that discounting violates the Pareto principle for a person who might live either at one time or at a later time. Some have argued for a positive rate (Dasgupta and Heal, 1980; Arrow, 1999). A traditional argument against a zero rate is that it places an extremely heavy moral burden on the current generation (see, e.g., Dasgupta, 2007). But even when $\delta = 0$, as we see below, we still end up with a discount rate of about 4 %, which is higher than it was during the last century. Stern (2008) used $\delta = 0.1$ % to account for risk of extinction. We conclude that a broad consensus is for a zero or near-zero pure rate of time preference for the present.

In a growing economy ($c_t > c_0$), investing for the future in a safe project has the undesirable effect of transferring consumption from the poor (current generations) to the wealthy (future generations). Thus, investing in safe projects raises intergenerational inequalities. The discount rate can then be interpreted as the minimum rate of return that is necessary to compensate for this adverse effect on the SWF of investing for the future. This is summarized by the Ramsey rule (i.e., the consumption approach to discounting) (Ramsey, 1928). Assuming a standard constant elasticity in the consumption utility function (e.g., $u(c) = c^{1-\eta}/(1-\eta)$), and no uncertainty,[15] the minimum rate of return ρ_t of a project that marginally transfers consumption from 0 to t and that guarantees an increase of intergenerational welfare V is defined as follows:

Equation 3.6.4 $$\rho_t = \delta + \eta g_t$$

where δ represents the pure rate at which society discounts the utility of future generations, and g_t is the annualized growth rate of monetized consumption anticipated at date *t*, and $\eta > 0$ measures inequality aversion. The greater the anticipated economic growth rate g_t, the higher the social discount rate ρ_t. The growth rate g_t is an empirical variable that represents our collective beliefs about prospective economic growth. In Box 3.5, we discuss plausible values for the inequality aversion parameter η.

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[15] For alternative assumptions, see Gollier (2002).

Box 3.5 | Plausible values for collective inequality aversion (η)

Consider the following thought experiment. A country has two equally populated social groups. The wealthy group consumes twice as many goods and services as the poor group. Consider also an economic policy whose aim is to increase consumption by 1 unit for every person in the poor group. This implies a reduction of consumption for every wealthy person by x units, which may not be equal to 1 owing to inherent inefficiencies in the tax system. If one is neutral about inequalities, one would not accept this policy if x is larger than 1. Inequality aversion justifies accepting some productive inefficiency, so that an x larger than 1 may be allowed. What is the maximum value of x that one would accept to implement the policy? Answering this question tells us something about inequality aversion, with a large x being associated with a larger η. If one is collectively ready to sacrifice as much as $x = 2$ units of consumption from the rich to provide one unit of consumption to the poor, this is compatible with an inequality aversion index $\eta = 1$. An x of 4 or 8 would correspond to an index of inequality aversion of 2 and 3, respectively.

Behind the veil of ignorance (Rawls, 1971), our collective preferences towards inequality should be identified as our individual risk aversion. The economic literature in finance and macroeconomics usually assumes a η between 1 and 5 to explain observed behaviours towards risk, as well as asset prices (Kocherlakota, 1996).

By using a near-zero time discount rate, Stern (2007, see also 2008) advanced the debate in the literature. Despite disagreement on the empirical approach to estimating the discount rate, the literature suggests consensus for using declining discount rates over time. Different prominent authors and committees have taken different positions on the values of δ, η and *g*, making different recommendations for the social discount rate ρ. We summarize them in Table 3.2.

In Table 3.2, the Ramsey formula can be seen to yield a wide range of discount rates, although most or all of the estimates reflect developed country experience. From this table and Box 3.5, a relative consensus emerges in favour of $\delta = 0$ and η between 1 and 3, although they are prescriptive parameters. This means that the normative Ramsey rule leads to a recommendation for a social discount rate of between one and three times the estimated growth rate in consumption between today and the relevant safe benefit or cost to be discounted. The social discount rate is normative because it relies on the intensity of our collective inequality aversion. However, the practical coherence of our ethical principles requires that if one has high inequality aversion, one should also redistribute wealth more assiduously from the currently rich to the currently poor. Furthermore, it is ultimately a judgement by the policymaker on the appropriate value of the parameters of the Ramsey rule, and thus the social discount rate.

The discount rate described here should be used to discount risk-free costs and benefits (Anthoff et al., 2009). The rates that appear in Table 3.2 are higher than real interest rates observed on financial markets, as documented in Table 3.1. This discrepancy defines the risk-free rate puzzle (Weil, 1989). The recent literature on discounting has tried to solve this puzzle by taking into account the uncertainty surrounding economic

Table 3.2 | Calibration of the discount rate based on the Ramsey rule (Equation 3.6.4).

Author	Rate of pure preference for present	Inequality aversion	Anticipated Growth rate	Implied social discount rate
Cline (1992)	0%	1.5	1%	1.5%
IPCC (1996)	0%	1.5–2	1.6%–8%	2.4%–16%
Arrow (1999)	0%	2	2%	4%
UK: Green Book (HM Treasury, 2003)	1.5%	1	2%	3.5%*
US UMB (2003)**				3%–7%
France: Rapport Lebègue (2005)	0%	2	2%	4%*
Stern (2007)	0.1%	1	1.3%	1.4%
Arrow (2007)		2–3		
Dasgupta (2007)	0.1%	2–4		
Weitzman (2007a)	2%	2	2%	6%
Nordhaus (2008)	1%	2	2%	5%

Notes:

* Decreasing with the time horizon.

** OMB uses a descriptive approach.

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2016 NOV 14

Table 3.3 | Country-specific discount rate computed from the Ramsey rule (Equation 3.6.5) using the historical mean g and standard deviation σ of growth rates of real GDP/cap 1969–2010, together with $\delta = 0$, and $\eta = 2$. Source: Gollier (2012).

	Country	g	σ	Discount rate	
				Ramsey rule Equation 3.6.4	Extended Ramsey rule
OECD countries	United States	1.74 %	2.11 %	3.48 %	3.35 %
	United Kingdom	1.86 %	2.18 %	3.72 %	3.58 %
	Japan	2.34 %	2.61 %	4.68 %	4.48 %
Economies in transition	China	7.60 %	3.53 %	15.20 %	14.83 %
	India	3.34 %	3.03 %	6.68 %	6.40 %
	Russia	1.54 %	5.59 %	3.08 %	2.14 %
Africa	Gabon	1.29 %	9.63 %	2.58 %	−0.20 %
	Zaire (RDC)	−2.76 %	5.31 %	−5.52 %	−6.37 %
	Zambia	−0.69 %	4.01 %	−1.38 %	−1.86 %
	Zimbabwe	−0.26 %	6.50 %	−0.52 %	−1.79 %

growth. Prudent agents should care more about the future if the future is more uncertain, in line with the concept of sustainable development. Assuming a random walk for the growth rate of consumption per capita, this argument applied to Equation 3.6.4 leads to an extended Ramsey rule in which a negative precautionary effect is added:

Equation 3.6.5 $\rho_t = \delta + \eta g_t - 0.5\,\eta(\eta + 1)\sigma_t^2$

where σ_t is the annualized volatility of the growth rate of GDP/cap, and g_t is now the expected annualized growth rate until time horizon t. In Table 3.3, we calibrate this formula for different countries by using the estimation of the trend and volatility parameters of observed growth rates of consumption per capita over the period 1969–2010, using $\eta = 2$. We learn from this Table that the Ramsey rule (Equation 3.4.1) often provides a good approximation of the social discount rate to be applied to consumption. It also shows that because of differences in growth expectations, nations may have different attitudes towards reducing present consumption for the benefit of future generations. This is also a further source of international disagreement on the strength of GHG mitigation efforts. The global discount rate for evaluating global actions will therefore depend on how costs and benefits are allocated across countries.[16]

A prudent society should favour actions that generate more benefits for the generations that face greater uncertainty, which justifies a decreasing term structure for risk-free discount rates (Gollier, 2012; Arrow et al., 2013; Weitzman, 2013). These results are related to the literature on Gamma discounting (Weitzman, 1998, 2001, 2010b; Newell and Pizer, 2003; Gollier and Weitzman, 2010). A simple guideline emerging from this literature is that the long-maturity discount rate is equal to the smallest discount rate computed from Equation 3.6.5 with the different plausible levels of its parameters. For example, assuming $\eta = 2$, if the trend of growth g_t is unknown but somewhere between 1 % and 3 %, a discount rate around 2 x mean (1 %, 3 %) = 4 % is socially desirable in the short term, although a discount rate of only 2 x min (1 %, 3 %) = 2 % is desirable for very long maturities.

Assuming a constant rate of pure preference for the present (actually $\delta = 0$), these recommendations yield a perfectly time-consistent valuation strategy, although the resulting discount rates decrease with maturity. A time inconsistency problem arises only if we assume that the rate of pure preference for the present varies according to the time horizon. Economists have tended to focus on hyperbolic discounting and time inconsistency (Laibson, 1997) and the separation between risk aversion and consumption aversion fluctuations over time (Epstein and Zin, 1991). See Section 3.10.1 and Chapter 2.

The literature deals mainly with the rate at which safe projects should be discounted. In most cases, however, actions with long-lasting impacts are highly uncertain, something that must be taken into account in their evaluation. Actions that reduce the aggregated risk borne by individuals should be rewarded and those that increase risk should be penalized. This has traditionally been done by raising the discount rate of a project by a risk premium $\pi = \beta\pi_g$ that is equal to the project-specific risk measure β times a global risk premium π_g. The project-specific beta is defined as the expected increase in the benefit of the project when the consumption per capita increases by 1 %. It measures the additional risk that the action imposes on the community. On average, it should be around 1. As we see from Table 3.3,

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[16] Table 3.3 is based on the assumption that the growth process is a random walk, so that the average growth rate converges to its mean in the very long run. It would be more realistic to recognize that economic growth has a much more uncertain nature in the long run: shocks on growth rates are often persistent, economies faces long-term cycles of uncertain length, and some parameters of the growth process are uncertain. Because these phenomena generate a positive correlation in future annual growth rates, they tend to magnify the uncertainty affecting the wellbeing of distant generations, compared to the random walk hypothesis of the extended Ramsey rule (Equation 3.6.5).

the risk premium as measured by the difference between the rate of return on bonds and the rate of return on equity is between 3 % and 6 %. A more normative approach described by the consumption-based capital asset pricing model (Cochrane, 2001) would lead to a much smaller risk premium equalling $\pi_{gt} = \eta\sigma_t^2$ if calibrated on the volatility of growth in western economies.[17] However, Barro (2006, 2009) and Martin (2013) recently showed that the introduction of rare catastrophic events—similar to those observed in some developing countries during the last century—can justify using a low safe discount rate of around 1 % and a large aggregate risk premium of around 4 % at the same time. The true discount rate to be used in the context of climate change will then rely heavily on the climate beta. So far, almost no research has been conducted on the value of the climate beta, that is, the statistical relationship between the level of climate damage and the level of consumption per capita in the future. The exception is Sandsmark and Vennemo (2006), who suggest that it is almost zero. But existing Integrated Assessment Models (IAMs) show that more climate damage is incurred in scenarios with higher economic growth, suggesting that combating climate change does not provide a hedge against the global risk borne by future generations. Nordhaus (2011b) assumes that the actual damages borne by future generations are increasing, so that the climate beta is positive, and the discount rate for climate change should be larger than just applying the extended Ramsey rule.

Several authors (Malinvaud, 1953; Guesnerie, 2004; Weikard and Zhu, 2005; Hoel and Sterner, 2007; Sterner and Persson, 2008; Gollier, 2010; Traeger, 2011; Guéant et al., 2012) emphasize the need to take into account the evolution of relative prices in CBAs involving the distant future. In a growing economy, non-reproducible goods like environmental assets will become relatively scarcer in the future, thereby implying an increasing social value.

3.6.3 Co-benefits and adverse side-effects

This section defines the concept of co-benefits and provides a general framework for analysis in other chapters (a negative co-benefit is labelled an 'adverse side effect'). A good example of a co-benefit in the literature is the reduction of local pollutants resulting from a carbon policy that reduces the use of fossil fuels and fossil-fuel-related local pollutants (see Sections 5.7 and 6.6.2.1). It is also important to distinguish between co-benefits and the societal welfare consequences of generated co-benefits. To use the same example, if local pollutants are already heavily regulated, then the net welfare benefits of further reductions in local pollutants may be small or even negative.

3.6.3.1 A general framework for evaluation of co-benefits and adverse side-effects

As a simple example, suppose social welfare V is a function of different goods or objectives z_i ($i = 1, \ldots, m$), and that each of those objectives might be influenced by some policy instrument, p_1.[18] The policy may have an impact on several objectives at the same time. Now consider a marginal change dp_1 in the policy. The welfare effect is given by:

Equation 3.6.6 $$dV = \sum_{i=1}^{m} \frac{\partial V}{\partial z_i} \frac{\partial z_i}{\partial p_1} dp_1$$

For example, suppose $dp_1 > 0$ is additional GHG abatement (tightening the cap on carbon dioxide (CO_2) emissions). Then the 'direct' benefits of that climate policy might include effects on climate objectives, such as mean global temperature (z_1), sea level rise (z_2), agricultural productivity (z_3), biodiversity (z_4), and health effects of global warming (z_5). The 'co-benefits' of that climate policy might include changes in a set of objectives such as SO_2 emissions (z_6), energy security (z_7), labour supply and employment (z_8), the distribution of income (z_9), the degree of urban sprawl (z_{10}), and the sustainability of the growth of developing countries (z_{11}). See Table 15.1 for an overview of objectives discussed in the sector chapters in the context of co-benefits and adverse side effects. The few studies that attempt a full evaluation of the global welfare effects of mitigation co-benefits focus only on a few objectives because of methodological challenges (as assessed in Section 6.6). For discussion of income distribution objectives, see the 'social welfare functions' in Section 3.4.6.

Because this problem inherently involves multiple objectives, it can be analysed using Multi-Criteria Analysis (MCA) that "requires policymakers to state explicit reasons for choosing policies, with reference to the multiple objectives that each policy seeks to achieve" (Dubash et al., 2013, p. 47). See also Section 3.7.2.1, Section 6.6 and McCollum et al. (2012).

Even external effects on public health could turn out to be either direct benefits of climate policy or co-benefits. The social cost of carbon includes the increased future incidence of heat stroke, heart attacks, malaria, and other warm climate diseases. Any reduction in such health-related costs of climate change is therefore a direct benefit of climate policy. The definition of a co-benefit is limited to the effect of reductions in health effects caused by non-climate impacts of mitigation efforts.

Use of the terminology should be clear and consistent. CBAs need to include *all* gains and losses from the climate policy being analysed—as shown in Equation 3.6.6—the sum of welfare effects from direct benefits net of costs, plus the welfare effects of co-benefits and adverse side effects.

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[17] With a volatility in the growth rate of consumption per capita around $\sigma_t = 4\,\%$ (see Table 3.3), and a degree of inequality aversion of, $\eta = 2$, we obtain a risk premium of only $\pi_{gt} = 0.32\,\%$.

[18] This V is a loose interpretation of a social welfare function, such as defined in Equation 3.6.2, insofar as welfare is not usually represented a function of policy objectives or aggregate quantities of goods.

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Here, the co-benefit is defined as the effect on a non-climate objective ($\partial z_i/\partial p_1$), leaving aside social welfare (not multiplied by $\partial V/\partial z_i$). In contrast, the 'value' of the co-benefit is the effect on social welfare ($\partial V/\partial z_i$), which could be evaluated by economists using valuation methods discussed elsewhere in this chapter.[19] It may require use of a 'second-best' analysis that accounts for multiple market distortions (Lipsey and Lancaster, 1956). This is not a minor issue. In particular, $\partial V/\partial z_i$ may be positive or negative.

The full evaluation of dV in the equation above involves four steps: first, identify the various multiple objectives z_i ($i = 1, \ldots, m$) (see, e.g., Table 4.8.1 for a particular climate policy such as a CO_2 emissions cap); second, identify all significant effects on all those objectives (direct effects and co-effects $\partial z_i/\partial p_1$, for $i = 1, \ldots, m$) (see Chapters 7–12); third, evaluate each effect on social welfare (multiply each $\partial z_i/\partial p_1$ by $\partial V/\partial z_i$); and fourth, aggregate them as in Equation 3.6.6. Of course, computing social welfare also has normative dimensions (see Section 3.4.6).

3.6.3.2 The valuation of co-benefits and adverse side-effects

The list of goods or objectives z_i ($i = 1, \ldots, m$) could include any commodity, but some formulations allow the omission of goods sold in markets with no market failure or distortion, where the social marginal benefit (all to the consumer) is equal to the social marginal cost (all on the producer). With no distortion in a market for good i, a small change in quantity has no net effect on welfare ($\partial V/\partial z_i = 0$). The effect on welfare is *not* zero, however, if climate policy affects the quantity of a good sold in a market with a 'market failure', such as non-competitive market power, an externality, or any pre-existing tax. In general, either monopoly power or a tax would raise the price paid by consumers relative to the marginal cost faced by producers. In such cases, any increase in the commodity would have a social marginal benefit higher than social marginal cost (a net gain in welfare).

We now describe a set of studies that have evaluated some co-benefits and adverse side-effects (many more studies are reviewed in Sections 5.7, 7.9, 8.7, 9.7, 10.8, 11.7, 12.8 and synthesized in Section 6.6). First, oligopolies may exert market power and raise prices above marginal cost in large industries such as natural resource extraction, iron and steel, or cement. And climate policy may affect that market power. Ryan (2012) finds that a prominent environmental policy in the United States actually increased the market power of incumbent cement manufactures, because it decreased competition from potential entrants that faced higher sunk costs. That is, it created barriers to entry. That effect led to a significant loss in consumer surplus that was not incorporated in the policy's initial benefit-cost analysis.

Second, Ren et al. (2011) point out that a climate policy to reduce CO_2 emissions may increase the use of biofuels, but that "corn-based ethanol production discharges nitrogen into the water environment … [which] … can cause respiratory problems in infants and exacerbate algae growth and hypoxia in water bodies" (p. 498). In other words, a change in climate policy (dp_1) affects the use of nitrogen fertilizer and its runoff ($\partial z/\partial p_1$). The effect is an 'adverse side effect.' If nitrogen runoff regulation is less than optimal, the effect on social welfare is negative ($\partial V/\partial z_i < 0$).

Third, arguably the most studied co-benefits of climate policy are the effects on local air pollutant emissions, air quality, and health effects of ground-level ozone (see Section 6.6 for a synthesis of findings from scenario literature and sector-specific measures). Burtraw et al. (2003) conclude that a USD 25 per tonne carbon tax in the United States would reduce NO_X emissions and thereby provide health improvements. Further, the researchers valued these health co-benefits at USD_{1997} 8 (USD_{2010} 10,50) per tonne of carbon reduction in the year 2010. More recently, Groosman et al. (2011) model a specific U.S. climate policy proposal (Warner-Lieberman, S.2191). They calculate effects on health from changes in local flow pollutants (a co-benefit). These health co-benefits mainly come from reductions in particulates and ozone, attributable to reductions in use of coal-fired power plants (Burtraw et al., 2003; Groosman et al., 2011).[20] The authors also value that co-benefit at USD_{2006} 103 billion to USD_{2006} 1.2 trillion (USD_{2010} 111 billion to USD_{2010} 1,3 billion) for the years 2010–2030. That total amount corresponds to USD 1 to USD 77 per tonne of CO_2 (depending on model assumptions and year; see Section 5.7 for a review of a broader set of studies with higher values particularly for developing countries).

Researchers have calculated climate policy co-benefits in many other countries; for instance, Sweden (Riekkola et al., 2011), China (Aunan et al., 2004), and Chile (Dessus and O'Connor, 2003).

A complete analysis of climate policy would measure all such direct or side-effects ($\partial z_i/\partial p_1$) while recognizing that other markets may be functioning properly or be partially regulated (for optimal regulation, $\partial V/\partial z_i = 0$). If the externality from SO_2 is already partly corrected by a tax or permit price that is less than the marginal environmental damage (MED) of SO_2, for example, then the welfare gain from a small reduction in SO_2 may be less than its MED. Or, if the price per tonne of SO_2 is equal to its MED, and climate policy causes a small reduction in SO_2, then the social value of that co-benefit is zero.[21] Similarly, if the labour market is functioning properly with no involuntary unemploy-

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[19] We distinguish here between the welfare effect of the co-benefit ($\partial V/\partial z_i$) and the welfare effect of the policy operating through a particular co-benefit ($\frac{\partial V}{\partial z_i}\frac{\partial z_i}{\partial p_1}dp_1$).

[20] Both of the cited studies estimate the dollar value of health improvements, but these are 'gross' benefits that may or may not correctly account for the offsetting effects of existing controls on these local pollution emissions, which is necessary to determine the net welfare effects.

[21] This 'marginal' analysis contemplates a small change in either CO_2 or SO_2. If either of those changes is large, however, then the analysis is somewhat different.

ment, then climate policy may have direct costs from use of that labour but no welfare gain from changes in employment. In other words, in measuring the welfare effects of co-benefits, it is not generally appropriate simply to use the gross marginal value associated with a co-benefit.

In the context of externalities and taxes, this point can be formalized by the following extension of Fullerton and Metcalf (2001):

Equation 3.6.7 $$dV = \sum_{i=1}^{m} (t_i - \mu_i) \frac{\partial z_i}{\partial p_1} dp_1$$

On the right side of the equation, μ_i is the MED from the ith commodity; and t_i is its tax rate (or permit price, or the effect of a mandate that makes an input such as emissions more costly). The effect of each good on welfare ($\partial V/\partial z_i$ in Equation 3.6.6 above) is reduced in this model to just $(t_i - \mu_i)$. The intuition is simple: t_i is the buyer's social marginal benefit minus the seller's cost; the externality μ_i is the social marginal cost minus the seller's cost. Therefore, $(t_i - \mu_i)$ is the social marginal benefit minus social marginal cost. It is the net effect on welfare from a change in that commodity. If every externality μ_i is corrected by a tax rate or price exactly equal to μ_i, then the outcome is 'first best'. In that case, dV in Equation 3.6.7 is equal to zero, which means welfare cannot be improved by any change in any policy. If any t_i is not equal to μ_i, however, then the outcome is not optimal, and a 'second best' policy might improve welfare if it has any direct or indirect effect on the amount of that good.

Although the model underlying Equation 3.6.7 is static and climate change is inherently dynamic, the concepts represented in the static model can be used to understand the application to climate. Climate policy reduces carbon emissions, but Equation 3.6.7 shows that this 'direct' effect does not add to social welfare unless the damage per tonne of carbon (μ_C) exceeds the tax on carbon (t_C). The social cost of carbon is discussed in Section 3.9.4. To see a co-benefit in this equation, suppose z_S is the quantity of SO_2 emissions, t_S is the tax per tonne, and μ_S is the MED of additional SO_2. If the tax on SO_2 is too small to correct for the externality ($t_S - \mu_S < 0$), then the market provides 'too much' of it, and any policy such as a carbon tax that reduces the amount of SO_2 ($\partial z_S/\partial p_1 < 0$) would increase economic welfare. The equation sums over all such effects in all markets for all other inputs, outputs, and pollutants.

If those local pollution externalities are already completely corrected by a tax or other policy ($t_S = \mu_S$), however, then a reduction in SO_2 adds nothing to welfare. The existing policy raises the firm's cost of SO_2 emissions by exactly the MED. That firm's consumers reap the full social marginal benefit per tonne of SO_2 through consumption of the output, but those consumers also pay the full social marginal cost per tonne of SO_2. In that case, one additional tonne of SO_2 has social costs exactly equal to social benefits, so any small increase or decrease in SO_2 emissions caused by climate policy provides no net social gain. In fact, if $t_S > \mu_S$, then those emissions are already over-corrected, and any decrease in SO_2 would reduce welfare.

3.6.3.3 The double dividend hypothesis

Another good example of a co-benefit arises from the interaction between carbon policies and other policies (Parry, 1997; Parry and Williams, 1999). Though enacted to reduce GHG emissions, a climate policy may also raise product prices and thus interact with other taxes that also raise product prices. Since the excess burden of taxation rises more than proportionately with the size of the overall effective marginal tax rate, the carbon policy's addition to excess burden may be much larger if it is added into a system with high taxes on output or inputs.

This logic has given rise to the 'double dividend hypothesis' that an emissions tax can both improve the environment and provide revenue to reduce other distorting taxes and thus improve efficiency of the tax system (e.g., Oates and Schwab, 1988; Pearce, 1991; Parry, 1995; Stern, 2009).[22] Parry (1997) and Goulder et al. (1997) conclude that the implementation of a carbon tax or emissions trading can increase the deadweight loss of pre-existing labour tax distortions (the 'tax interaction effect'), but revenue can be used to offset distortionary taxes (the 'revenue recycling effect'). Parry and Williams (1999) investigate the impacts of existing tax distortions in the labour market for eight climate policy instruments (including energy taxes and performance standards) for the United States in 1995. They conclude that pre-existing tax distortions raise the costs of all abatement policies, so the co-benefits of carbon taxes or emissions trading depend on whether generated revenues can be directed to reduce other distortionary taxes. A lesson is that forgoing revenue-raising opportunities from a GHG regulation can significantly increase inefficiencies. The European Union is auctioning an increasing share of permits with revenue going to Member States (see 14.4.2). Australia is using a large share of carbon pricing revenue to reduce income tax (Jotzo, 2012).

To put this discussion into the context of co-benefits, note that Fullerton and Metcalf (2001) use their version of Equation 3.6.7 to consider labour (z_L), taxed at a pre-existing rate t_L (with marginal external damages of zero, so $\mu_L = 0$). Suppose the only other distortion is from carbon emissions (z_C), with MED of μ_C. Thus the economy has 'too little' labour supply, and 'too much' pollution. The combination 'policy change' is a small carbon tax with revenue used to cut the tax rate t_L. Other taxes and damages are zero ($t_i = \mu_i = 0$) for all goods other than z_L and z_C. Thus, Equation 3.6.7 above simplifies further, to show that the two key outcomes are just the net effect on pollution (dz_C) and the net effect on labour (dz_L):

Equation 3.6.8 $$dV = t_L dz_L + (t_C - \mu_C) dz_C$$

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[22] The literature contains two versions of the double dividend hypothesis. A 'strong' version says that efficiency gains from diminishing distortionary taxes can more than compensate the costs of pollution taxes. Another 'weak' version says that those gains compensate only part of the costs of pollution taxes (Goulder, 1995).

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Therefore, an increase in the carbon tax that reduces emissions ($dz_C < 0$) has a direct benefit of increased economic welfare through the second term, but only to the extent that emissions damages exceed the tax rate ($\mu_C > t_C$). If the labour tax cut increases labour supply, then the first term also increases welfare (a double dividend). But the carbon tax also raises the cost of production and the equilibrium output price, which itself *reduces* the *real* net wage (the tax interaction effect). If that effect dominates the reduction in the labour tax rate (from the revenue recycling effect), then labour supply may fall ($dz_L < 0$). In that case, the first term has a negative effect on wellbeing. In other words, the double-dividend is possible under some circumstances and not others. If the revenue is *not* used to cut the labour tax rate, then the real net wage does fall, and the labour supply may fall.

3.7 Assessing methods of policy choice

Specific climate policies are discussed in Section 3.8; in this section, we discuss methods for evaluating the relative merits of different policies. See also Alkin (2004), Pawson and Tilley (1997), Bardach (2005), Majchrzak (1984), Scriven (1991) Rossi et al. (2005), and Chen (1990). The design and choice of a specific climate policy instrument (or mix of instruments) depends on many economic, social, cultural, ethical, institutional, and political contexts. Different methods for ex-ante and ex-post analysis are available and different types of analytical approaches may be used in tandem to provide perspectives to policymakers.

3.7.1 Policy objectives and evaluation criteria

In addition to reducing GHG emissions, climate policy may have other objectives. Following WGIII AR4 (Gupta et al., 2007), these objectives are organized below in four broad categories: economic, distributional/fairness, environmental, and institutional/political feasibility.[23] The relative importance of these policy objectives differs among countries, especially between developed and developing countries.

In this section we discuss elements of these four categories and expand on recent policy evaluation studies (e.g., Opschoor and Turner, 1994; Ostrom, 1999; Faure and Skogh, 2003; Sterner, 2003; Mickwitz, 2003; Blok, 2007), leaving details of applications and evidence to Chapters 8–11 and 13–15.

The basic economic framework for policy analysis is depicted in Figure 3.3. This diagram illustrates both the impacts of policies and the criteria for evaluating them in the context of the production of a polluting good (i.e., emissions associated with producing a good). The focus is stylized, but we note that many 'non-economic' values can still be incorporated, to the extent that values can be placed on other considerations, such as effects on nature, culture, biodiversity and 'dignity' (see Sections 3.4.1 and 3.4.2).

As shown in Figure 3.3, the quantity of GHG emissions from producing a good, such as electricity, is shown on the horizontal axis, and the price or cost per unit of that good is shown on the vertical axis. The demand for the emissions is derived from the demand for electricity, as shown by the curve called Private Marginal Benefit (PMB). The private market supply curve is the Private Marginal Cost (PMC) of production, and so the unfettered equilibrium quantity would be Q^0 at equilibrium price P^0. This polluting activity generates external costs, however, and so each unit of output has a Social Marginal Cost (SMC) measured by the vertical sum of PMC plus Marginal External Cost (MEC). With no externalities on the demand side, PMB = SMB.

Under the stated simplifying assumptions, the social optimum is where SMC = PMB, at Q'. The first point here, then, is that the optimal quantity can be achieved by several different policies under these simple conditions. A simple regulatory quota could restrict output from Q^0 to Q', or a fixed number of tradeable permits could restrict pollution to the quantity Q'. In that case, P^n is the equilibrium price net of permit cost (the price received by the firm), while P^g is the price gross of permit cost (paid by the consumer). The permit price is the difference,

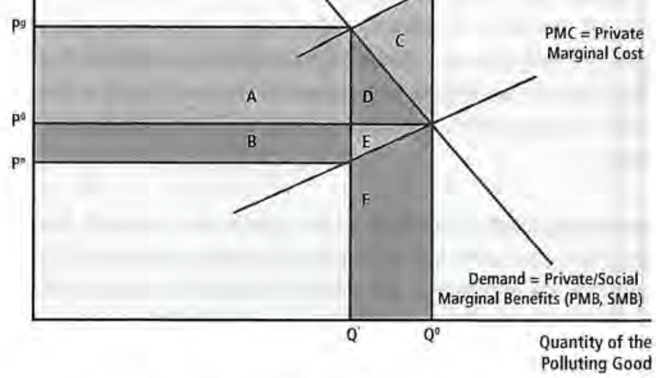

Figure 3.3 | A partial equilibrium model of the costs and benefits of a market output, assuming perfect competition, perfect information, perfect mobility, full employment, and many identical consumers (so all individuals equally benefit from production and they equally bear the external cost of pollution).

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[23] Political factors have often been more important than economic factors in explaining instrument choice (Hepburn, 2006). Redistribution to low-income households is an important feature in Australia's emissions pricing policy (Jotzo and Hatfield-Dodds, 2011).

$P^g - P^n$. Alternatively, a tax of ($P^g - P^n$) per unit of pollution would raise the firm's cost to SMC and result in equilibrium quantity Q'.

The diagram in Figure 3.3 will be used below to show how the equivalence of these instruments breaks down under more general circumstances, as well as gains and losses to various groups. In other words, we use this diagram to discuss economic as well as distributional, other environmental and cultural objectives, and institutional/political feasibility.

3.7.1.1 Economic objectives

Economic efficiency. Consider an economy's allocation of resources (goods, services, inputs, and productive activities). An allocation is efficient if it is not possible to reallocate resources so as to make at least one person better off without making someone else worse off. This is also known as the Pareto criterion for efficiency (discussed in Section 3.6.1) (see e.g., Sterner, 2003; Harrington et al., 2004; Tietenberg, 2006). In Figure 3.3, any reduction in output from Q^0 improves efficiency because it saves costs (height of SMC) that exceed the benefits of that output (height of PMB).[24] This reduction can be achieved by a tax levied on the externality (a carbon tax), or by tradeable emission permits. Further reductions in output generate further net gains, by the extent to which SMC exceeds SMB, until output is reduced to Q' (where SMC = SMB). Hence, the gain in economic efficiency is area C. Perfect efficiency is difficult to achieve, for practical reasons, but initial steps from Q^0 achieve a larger gain (SMC > SMB) than the last step to Q' (because SMC ≈ SMB near the left point of triangle C).

An aspect of economic efficiency over time is the extent to which a carbon policy encourages the right amount of investment in research, innovation, and technological change, in order to reduce GHG emissions more cheaply (Jung et al., 1996; Mundaca and Neij, 2009). See Section 3.11.

Cost-effectiveness. Pollution per unit of output in Figure 3.3 is fixed, but actual technologies provide different ways of reducing pollution per unit of output. A policy is cost-effective if it reduces pollution (given a climate target) at lowest cost. An important condition of cost-effectiveness is that marginal compliance costs should be equal among parties (ignoring other distortions such as regulations) (Babiker et al., 2004).

Transaction costs. In addition to the price paid or received, market actors face other costs in initiating and completing transactions. These costs alter the performance and relative effectiveness of different policies and need to be considered in their design, implementation, and assessment (Mundaca et al., 2013; see also Matthews, 1986, p. 906).

3.7.1.2 Distributional objectives

Six distributional effects. A policy may generate gains to some and losses to others. The fairness or overall welfare consequences of these distributional effects is important to many people and can be evaluated using a SWF, as discussed in Section 3.4.6. These effects fall into six categories (Fullerton, 2011), and are illustrated in Box 3.6 below. In Figure 3.3, any policy instrument might reduce the quantity of polluting output, such as from Q^0 to Q', which reduces emissions, raises the equilibrium price paid by consumers (from P^0 to P^g), and reduces the price received by firms (from P^0 to P^n). The six effects are illustrated in Box 3.6. The framework can be applied to any environmental problem and any policy to correct it.

With reference to Box 3.6, the first effect of a carbon policy on consumers is generally regressive (though most analyses are for developed countries), because the higher price of electricity imposes a heavier burden on lower income groups who spend more of their income on electricity (Metcalf, 1999; Grainger and Kolstad, 2010). However, fuel taxes tend to be progressive in developing countries (Sterner, 2011). The sign of the second effect, on factors of production, is generally ambiguous. The third effect is regressive if permits are given to firms, because then profits accrue to shareholders who tend to be in high-income brackets (Parry, 2004). But if government captures the scarcity rents by selling permits or through a carbon tax, the funds can be used to offset burdens on low-income consumers and make the overall effect progressive instead of regressive. Other effects are quite difficult to measure.

Much of the literature on 'environmental justice' discusses the potential effects of a pollution policy on neighbourhoods with residents from different income or ethnic groups (Sieg et al., 2004). Climate policies affect both GHG emissions and other local pollutants such as SO_2 or NO_X, whose concentrations vary widely. Furthermore, the cost of mitigation may not be shared equally among all income or ethnic groups. And even 'global' climate change can have different temperature impacts on different areas, or other differential effects (e.g., on coastal areas via rise in sea level).

The distributional impacts of policies include aspects such as fairness/equity (Gupta et al., 2007). A perceived unfair distribution of costs and benefits could prove politically challenging (see below), since efficiency may be gained at the expense of equity objectives.

3.7.1.3 Environmental objectives

Environmental effectiveness. A policy is environmentally effective if it achieves its expected environmental target (e.g., GHG emission reduction). The simple policies mentioned above might be equally effective in reducing pollution (from Q^0 to Q' in Figure 3.3), but actual policies differ in terms of ambition levels, enforcement and compliance.

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[24] Other approaches are discussed in Section 3.6.

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BUREAU OF LAND MGMT
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2016 NOV 14

Box 3.6 | Six distributional effects of climate policy, illustrated for a permit obligation or emissions tax on coal-fired electricity, under the assumption of perfectly competitive electricity markets

First, the policy raises the cost of generating electricity and if cost increases are passed through to consumers, for example through competitive markets or changes in regulated prices, the consumer's price increases (from P^0 to P^g), so it reduces consumer surplus. In Figure 3.3, the loss to consumers is the sum of areas A + D. Losses are greater for those who spend more on electricity.

Second, the policy reduces the net price received by the firm (from P^0 to P^n), so it reduces producer surplus by the sum of areas B + E. The effect is reduced payments to factors of production, such as labour and capital. Losses are greater for those who receive more income from the displaced factor.

Third, pollution and output are restricted, so the policy generates 'scarcity rents' such as the value of a restricted number of permits (areas A + B). If the permits are given to firms, these rents accrue to shareholders. The government could partly or fully capture the rents by selling the permits or by a tax per unit of emissions (Fullerton and Metcalf, 2001).

Fourth, because the policy restricts GHG emissions, it confers benefits on those who would otherwise suffer from climate change. The value of those benefits is areas C + D + E.

Fifth, the electricity sector uses less labour, capital and other resources. It no longer pays them (areas E + F). With perfect mobility, these factors are immediately redeployed elsewhere, with no loss. In practice however, social costs may be substantial, including transaction costs of shifting to other industries or regions, transitional or permanent unemployment, and social and psychological displacement.

Sixth, any gain or loss described above can be capitalized into asset prices, with substantial immediate effects for current owners. For example, the value of a corporation that owns coal-fired generation assets may fall, in line with the expected present value of the policy change, while the value of corporations that own low-emissions generation technologies may rise.

The connection between these distributional effects and 'economic efficiency' is revealed by adding up all the gains and losses just described: the consumer surplus loss is A + D; producer surplus loss is B + E; the gain in scarcity rents is A + B; and the environmental gain is C + D + E, assuming the gainers and losers receive equal weights. The net sum of the gains and losses is area C, described above as the net gain in economic efficiency.

In many cases, a distributional implication of imposing efficient externality pricing (e.g., area A + B) is much larger than the efficiency gains (area C). This illustrates the importance of distributional considerations in discussions on emissions-reducing policies, and it indicates why distributional considerations often loom large in debates about climate policy.

Co-benefits. Climate policy may reduce both GHG emissions and local pollutants, such as SO_2 emissions that cause acid rain, or NO_X emissions that contribute to ground level ozone. As described in Section 3.6.3, reductions in other pollutants may not yield any net gain to society if they are already optimally regulated (where their marginal abatement costs and their marginal damages are equal). If pollutants are inefficiently regulated, however, climate regulations can yield positive or negative net social gains by reducing them.

Climate policy is also likely to affect other national objectives, such as energy security. For countries that want to reduce their dependence on imported fossil fuels, climate policy can bolster energy efficiency and the domestic renewable energy supply, while cutting GHG emissions. See Section 3.6.3 on co-benefits.

Carbon leakage. The effectiveness of a national policy to reduce emissions can be undermined if it results in increased emissions in other countries, for example, because of trading advantages in countries with more relaxed policies (see Section 3.9.5). Another type of leakage occurs within emission trading systems. Unilateral emission reductions by one party will release emission permits and be outweighed by new emissions within the trading regime.

3.7.1.4 Institutional and political feasibility

Administrative burden. This depends on how a policy is implemented, monitored, and enforced (Nordhaus and Danish, 2003). The size of the burden reflects, inter alia, the institutional framework, human and financial costs and policy objectives (Nordhaus and Danish, 2003; Mundaca et al., 2010). Administrative costs in public policy are often overlooked (Tietenberg, 2006)

Political feasibility is the likelihood of a policy gaining acceptance and being adopted and implemented (Gupta et al., 2007, p. 785). It covers the obstacles faced and key design features that can generate or reduce resistance among political parties (Nordhaus and Danish, 2003). Political feasibility may also depend on environmental effectiveness and whether regulatory and other costs are equitably distributed across society (Rist, 1998). The ability of governments to implement political decisions may be hampered by interest groups; policies will be more feasible if the benefits can be used to buy the support of a winning coalition (Compston, 2010). *Ex ante*, these criteria can be used in assessing and improving policies. *Ex post*, they can be used to verify results, withdraw inefficient policies and correct policy performance. For specific applications, see Chapters 7–15.

3.7.2 Analytical methods for decision support

Previous IPCC Assessment Reports have addressed analytical methods to support decision making, including both numerical and case-based methods. Bruce et al. (1996, chap. 2 and 10) focus heavily on quantitative methods and IAMs. Metz et al. (2001) provide a wider review of approaches, including emerging participatory forms of decision making. Metz et al. (2007) briefly elaborate on quantitative methods and list sociological analytical frameworks. In this section, we summarize the core information on methodologies separated into quantitative- and qualitative-oriented approaches.

3.7.2.1 Quantitative-oriented approaches

In decision making, quantitative methods can be used to organize and manage numerical information, provide structured analytical frameworks, and generate alternative scenarios—with different levels of uncertainty (Majchrzak, 1984). An approach that attempts to estimate and aggregate monetized values of all costs and benefits that could result from a policy is CBA. It may require estimating non-market values, and choosing a discount rate to express all costs and benefits in present value. When benefits are difficult to estimate in monetary terms, a Cost-Effectiveness Analysis (CEA) may be preferable. A CEA can be used to compare the costs of different policy options (Tietenberg, 2006) for achieving a well-defined goal. It can also estimate and identify the lowest possible compliance costs, thereby generating a ranking of policy alternatives (Levin and McEwan, 2001). Both CEA and CBA are similarly limited in their ability to generate data, measure and value future intangible costs.

Various types of model can provide information for CBA, including energy-economy-environment models that study energy systems and transitions towards more sustainable technology. A common classification of model methodologies includes 'bottom-up' and 'top-down' approaches. Hybrids of the two can compensate for some known limitations and inherent uncertainties (Rivers and Jaccard, 2006):[25]

- Given exogenously defined macroeconomic and demographic scenarios, bottom-up models can provide detailed representations of supply- and demand-side technology paths that combine both cost and performance data. Conventional bottom-up models may lack a realistic representation of behaviour (e.g., heterogeneity) and may overlook critical market imperfections, such as transaction costs and information asymmetries (e.g., Craig et al., 2002; DeCanio, 2003; Greening and Bernow, 2004).

- By contrast, top-down models, such as computable general equilibrium (CGE), represent technology and behaviour using an aggregate production function for each sector to analyze effects of policies on economic growth, trade, employment, and public revenues (see, e.g., DeCanio, 2003). They are often calibrated on real data from the economy. However, such models may not represent all markets, all separate policies, all technological flexibility, and all market imperfections (Laitner et al., 2003). Parameters are estimated from historical data, so forecasts may not predict a future that is fundamentally different from past experience (i.e., path dependency) (Scheraga, 1994; Hourcade et al., 2006). For potential technology change, many models use sub-models of specific supply or end-use devices based on engineering data (Jacoby et al., 2006; Richels and Blanford, 2008; Lüken et al., 2011; Karplus et al., 2013).

With CBA, it is difficult to reduce all social objectives to a single metric. One approach to dealing with the multiple evaluation criteria is Multi-Criteria Analysis, or MCA (Keeney and Raiffa, 1993; Greening and Bernow, 2004). Some argue that analyzing environmental and energy policies is a multi-criteria problem, involving numerous decision makers with diverse objectives and levels of understanding of the science and complexity of analytical tools (Sterner, 2003; Greening and Bernow, 2004). The advantage of MCA is that the analyst does not have to determine how outcomes are traded-off by the policymaker. For instance, costs can be separated from ecosystem losses. But even with MCA, one must ultimately determine the appropriate trade-off rates among the different objectives. Nevertheless, it can be a useful way of analyzing problems where being restricted to one metric is problematic, either politically or practically. CGE models can specify consumer and producer behaviour and 'simulate' effects of climate policy on various outcomes, including real gains and losses to different groups (e.g., households that differ in income, region or demographic characteristics). With behavioural reactions, direct burdens are shifted from one taxpayer to another through changes in prices paid for various outputs and received for various inputs. A significant challenge is the definition of a 'welfare baseline' (i.e., identifying each welfare level without a specific policy).

Integrated Assessment Models (IAMs) or simply Integrated Models (IAs) combine some or all of the relevant components necessary to evaluate the consequences of mitigation policies on economic activity, the global climate, the impacts of associated climate change, and the relevance of that change to people, societies, and economies. Some

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[25] The literature acknowledges that it is difficult to make a clear classification among modelling approaches, as variations among categories and also alternative simulation methodologies do exist (e.g., macroeconometric Keynesian models, agent-based approaches) (Hourcade et al., 2006; Mundaca et al., 2010; Scrieciu et al., 2013).

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2016 NOV 14 PM

models may only be able to represent how the economy responds to mitigation policy and no more; some models may include a physical model of the climate and be able to translate changes in emissions into changes in global temperature; some models may also include a representation of the impacts of climate change; and some models may translate those impacts into damage to society and economies. Models can be highly aggregate (top-down) or detailed process analysis models (bottom-up), or a combination of both (see also Chapter 6). Some IAMs relate climate change variables with other physical and biological variables like crop yield, food prices, premature death, flooding or drought events, or land use change (Reilly et al., 2013). Computational limits may preclude the scales required for some climate processes (Donner and Large, 2008),[26] but recent attempts are directed towards integrating human activities with full Earth System models (Jones et al., 2013). All of the models used in WGIII (primarily Chapter 6) focus on how mitigation policies translate into emissions; none of those models have a representation of climate damages. IAMs have been criticized in recent years (e.g., Ackerman et al., 2009; Pindyck, 2013). Much of the most recent criticism is directed at models that include a representation of climate damage; none of the models used in Chapter 6 fall into this category. Refer to Chapter 6 for more detail in this regard.

Other quantitative-oriented approaches to support policy evaluation include tolerable windows (Bruckner et al., 1999), safe-landing/guard rail (Alcamo and Kreileman, 1996), and portfolio theory (Howarth, 1996). Outside economics, those who study decision sciences emphasize the importance of facing difficult value-based trade-offs across objectives, and the relevance of various techniques to help stakeholders address trade-offs (see, e.g., Keeney and Raiffa, 1993).

3.7.2.2 Qualitative approaches

Various qualitative policy evaluation approaches focus on the social, ethical, and cultural dimensions of climate policy. They sometimes complement quantitative approaches by considering contextual differences, multiple decision makers, bounded rationality, information asymmetries, and political and negotiation processes (Toth et al., 2001; Halsnæs et al., 2007). Sociological analytical approaches examine human behaviour and climate change (Blumer, 1956), including beliefs, attitudes, values, norms, and social structures (Rosa and Dietz, 1998). Focus groups can capture the fact that "people often need to listen to others' opinions and understandings to form their own" (Marshall and Rossman, 2006, p. 114). Participatory approaches focus on process, involving the active participation of various actors in a given decision-making process (van den Hove, 2000). Participatory approaches in support of decision making include appreciation-influence-control, goal oriented project planning, participatory rural appraisal, and beneficiary assessment. MCA can also take a purely qualitative form. For the pros and cons of participatory approaches, see Toth et al. (2001, p. 652). Other qualitative-oriented approaches include systematic client consultation, social assessment and team up (Toth et al., 2001; Halsnæs et al., 2007).

3.8 Policy instruments and regulations

A broad range of policy instruments for climate change mitigation is available to policymakers. These include economic incentives, such as taxes, tradeable allowances, and subsidies; direct regulatory approaches, such as technology or performance standards; information programs; government provision, of technologies or products; and voluntary actions.

Chapter 13 of WGIII AR4 provided a typology and definition of mitigation policy instruments. Here we present an update on the basis of new research on the design, applicability, interaction, and political economy of policy instruments, as well as on applicability of policy instruments in developed and developing countries (see Box 3.8). For details about applications and empirical assessments of mitigation policy instruments, see Chapters 7–12 (sectoral level), Chapter 13 (international cooperation), Chapter 14 (regional cooperation), and Chapter 15 (national and sub-national policies).

3.8.1 Economic incentives

Economic (or market) instruments include incentives that alter the conditions or behaviour of target participants and lead to a reduction in aggregate emissions. In economic policy instruments, a distinction is made between 'price' and 'quantity'. A tradeable allowance or permit system represents a quantity policy whereby the total quantity of pollution (a cap) is defined, and trading in emission rights under that cap is allowed. A price instrument requires polluters to pay a fixed price per unit of emissions (tax or charge), regardless of the quantity of emissions.

3.8.1.1 Emissions taxes and permit trading

Both the approaches described above create a price signal as an incentive to reducing emissions (see Box 3.7), which can extend throughout the economy. Economic instruments will tend to be more cost-effective than regulatory interventions and may be less susceptible to rent-seeking by interest groups. The empirical evidence is that economic instruments have, on the whole, performed better than regulatory instru-

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[26] Stanton et al. (2009) also place climate change models into categories (welfare maximization, general equilibrium, partial equilibrium, cost minimization, and simulation models).

ments, but that in many cases improvements could have been made through better policy design (Hahn, 1989; Anthoff and Hahn, 2010).

3.8.1.2 Subsidies

Subsidies can be used as an instrument of mitigation policy by correcting market failures in the provision of low-carbon technologies and products. They have a particular role in supporting new technologies. Empirical research has shown that social rates of return on R&D can be higher than private rates of return, since spillovers are not fully internalized by the firms (see 3.11).

Subsidies are also used to stimulate energy efficiency and renewable energy production. Such subsidies do generally not fully correct negative externalities but rather support the alternatives, and are less efficient alternatives to carbon taxes and emission trading for inducing mitigation. Energy subsidies are often provided for fossil fuel production or consumption, and prove to increase emissions and put heavy burdens on public budgets (Lin and Jiang, 2011; Arze del Granado et al., 2012; Gunningham, 2013). Lowering or removing such subsidies would contribute to global mitigation, but this has proved difficult (IEA et al., 2011).

Subsidies to renewable energy and other forms of government expenditure on mitigation also have other drawbacks. First, public funds need to be raised to finance the expenditures, with well-known economic inefficiencies arising from taxation (Ballard and Fullerton, 1992). Second, subsidies, if not correcting market failures, can lead to excessive entry into, or insufficient exit from, an industry (Stigler, 1971). Third, subsidies can become politically entrenched, with the beneficiaries lobbying governments for their retention at the expense of society overall (Tullock, 1975).

Hybrids of fees and subsidies are also in use. A renewable energy certificate system can be viewed as a hybrid with a fee on energy consumption and a subsidy to renewable production (e.g., Amundsen and Mortensen, 2001). Feebates (Greene et al., 2005) involve setting an objective, such as average vehicle fuel economy; then firms or individuals that under-perform pay a fee per unit of under-performance and over-performers receive a subsidy. The incentives may be structured to generate no net revenue—the fees collected finance the subsidy.

3.8.2 Direct regulatory approaches

Prescriptive regulation involves rules that must be fulfilled by polluters who face a penalty in case of non-compliance. Examples are performance standards that specify the maximum allowable GHG emissions from particular processes or activities; technology standards that mandate specific pollution abatement technologies or production methods; and product standards that define the characteristics of potentially polluting products, including labelling of appliances in buildings, industry, and the transport sector (Freeman and Kolstad, 2006).

These regulatory approaches will tend to be more suitable in circumstances where the reach or effectiveness of market-based instruments is constrained because of institutional factors, including lack of markets in emissions intensive sectors such as energy. In 'mixed economies', where parts of the economy are based on command-and-control

Box 3.7 | Equivalence of emissions taxes and permit trading schemes

Price-based and quantity-based instruments are equivalent under certainty, but differ in the extent of mitigation and costs if emissions and abatement costs are uncertain to the regulator (Weitzman, 1974). Hybrid instruments, where a quantity constraint can be overridden if the price is higher or lower than a threshold, have been shown to be more efficient under uncertainty (Roberts and Spence, 1976; McKibbin and Wilcoxen, 2002; Pizer, 2002). Variants of hybrid approaches featuring price ceilings and price floors have been implemented in recent emissions trading schemes (Chapters 14 and 15). The possibility of periodic adjustments to tax rates and caps and their implementation under permit schemes further breaks down the distinction between price-based and quantity-based market-based instruments.

Equivalence also exists for fiscal effects and the costs imposed on emitters. Until recently, most of the literature has assumed that emissions taxes and permit trading differ in the revenue they yield for governments and the costs imposed on emitters, assuming that emissions tax revenue fully accrues to governments while under emissions trading schemes permits are given freely to emitters. This was also the case in early policy practice (Chapters 14 and 15). It has been widely assumed that permit schemes are easier to implement politically because permits are allocated free to emitters. However, recognition has grown that permits can be wholly or partly auctioned, and that an emissions tax need not apply to the total amount of emissions covered (e.g., Aldy J. E. et al., 2010; Goulder, 2013). Tax thresholds could exempt part of the overall amount of an emitter's liabilities, while charging the full tax rate on any extra emissions, analogous to free permits (Pezzey, 2003; Pezzey and Jotzo, 2012). Conversely, governments could auction some or all permits in an emissions trading scheme, and use the revenue to reduce other more distorting taxes and charges (Section 3.6.3.3), assist consumers, or pay for complementary policies.

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER
2016 NOV 14

approaches while others rely on markets, effective climate change mitigation policy will generally require a mix of market and non-market instruments.

3.8.3 Information programmes

Reductions in GHG emissions can also be achieved by providing accurate and comprehensive information to producers and consumers on the costs and benefits of alternative options. Information instruments include governmental financing of research and public statistics, and awareness-raising campaigns on consumption and production choices (Mont and Dalhammar, 2005).

3.8.4 Government provision of public goods and services, and procurement

Government funding of public goods and services may be aimed directly at reducing GHG emissions, for example, by providing infrastructures and public transport services that use energy more efficiently; promoting R&D on innovative approaches to mitigation; and removing legal barriers (Creutzig et al., 2011).

3.8.5 Voluntary actions

Voluntary agreements can be made between governments and private parties in order to achieve environmental objectives or improve environmental performance beyond compliance with regulatory obligations. They include industry agreements, self-certification, environmental management systems, and self-imposed targets. The literature is ambiguous about whether any additional environmental gains are obtained through voluntary agreements (Koehler, 2007; Lyon and Maxwell, 2007; Borck and Coglianese, 2009).

3.8.6 Policy interactions and complementarity

Most of the literature deals with the use and assessment of one instrument, or compares alternative options, whereas, in reality, numerous, often overlapping instruments are in operation (see Chapters 7–16). Multiple objectives in addition to climate change mitigation, such as energy security and affordability and technological and industrial development, may call for multiple policy instruments. Another question is whether and to what extent emissions pricing policies need to be complemented by regulatory and other instruments to achieve cost-effective mitigation, for example, because of additional market failures, as in the case of energy efficiency (Box 3.10) and technological development (3.11.1).

However, the coexistence of different instruments creates synergies, overlaps and interactions that may influence the effectiveness and costs of policies relative to a theoretical optimum (Kolstad et al., 1990; see also Section 3.6 above). Recent studies have analyzed interactions between tradeable quotas or certificates for renewable energy and emission trading (e.g., Möst and Fichtner, 2010; Böhringer and Rosendahl, 2010) and emissions trading and tradeable certificates for energy efficiency improvements (e.g., Mundaca, 2008; Sorrell et al., 2009) (see also Chapters 9 and 15). Similar effects occur in the overlay of other selective policy instruments with comprehensive pricing instruments. Policy interactions can also create implementation and enforcement challenges when policies are concurrently pursued by different legal or administrative jurisdictions (Goulder and Parry, 2008; Goulder and Stavins, 2011).

3.8.7 Government failure and policy failure

To achieve large emissions reductions, policy interventions will be needed. But failure is always a possibility, as shown by recent experiences involving mitigation policies (Chapters 13–16). The literature is beginning to reflect this. The failure of such policies tends to be associated with the translation of individual preferences into government action.

3.8.7.1 Rent-seeking

Policy interventions create rents, including subsidies, price changes arising from taxation or regulation, and emissions permits. Private interests lobby governments for policies that maximize the value of their assets and profits. The sums involved in mitigating climate change provide incentives to the owners of assets in GHG intensive industries or technologies for low-carbon production to engage in rent-seeking.[27]

The political economy of interest group lobbying (Olson, 1971) is apparent in the implementation of climate change mitigation policies. Examples include lobbying for allocations of free permits under the emissions trading schemes in Europe (Hepburn et al., 2006; Sijm et al., 2006; Ellerman, 2010) and Australia (Pezzey et al., 2010) as well as renewable energy support policies in several countries (Helm, 2010).

To minimize the influence of rent-seeking and the risk of regulatory capture, two basic approaches have been identified (Helm, 2010). One is to give independent institutions a strong role, for example, the United Kingdom's Committee on Climate Change (McGregor et al., 2012) and Australia's Climate Change Authority (Keenan R.J et al., 2012) (see also Chapter 15).

Another approach to reducing rent-seeking is to rely less on regulatory approaches and more on market mechanisms, which are less prone to capture by special interests because the value and distribution of rents

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[27] CBA takes into account that governments are social-profit maximizers, which may not necessarily be the case.

Box 3.8 | Different conditions in developed and developing countries and implications for suitability of policy instruments

Differences in economic structure, institutions, and policy objectives between low-income and high-income countries can mean differences in the suitability and performance of policy instruments. Overriding policy objectives in most developing countries tend to be strongly oriented towards facilitating development (Kok et al., 2008), increasing access to energy and alleviating poverty (see Chapters 4 and 14). In general, they have fewer human and financial resources, less advanced technology, and poorer institutional and administrative capacity than developed countries. This may constrain their ability to evaluate, implement, and enforce policies. Further, the prerequisites for effectiveness, such as liberalized energy markets to underpin price-based emissions reduction instruments, are often lacking. Thus, the use of some policy instruments, including carbon trading schemes, can pose greater institutional hurdles and implementation costs, or not be feasible. Capacity building is therefore critical in creating mechanisms to support policy choices and implementation. Economic reform may also be needed in order to remove distortions in regulatory and pricing mechanisms and enable effective mitigation policies to be devised and implemented.

The opportunity cost of capital, and of government resources in particular, may be higher in developing countries than in developed countries. Consequently, the payoff from mitigation policies needs to be higher than in developed countries in order for mitigation investment to be judged worthwhile. Thus, developing countries may require international financial assistance in order to support their mitigation activities or make them economically viable.

is more transparent. This may of course lead to other problems associated with regulatory design.

3.8.7.2 Policy uncertainty

One aim of climate change mitigation policy is to promote emissions-reducing investments in sectors where assets have a long economic lifespan, such as energy (Chapter 7), buildings (Chapter 9) and transport (Chapter 8). Investment decisions are mainly based on expectations about future costs and revenues. Therefore, expectations about future policy settings can be more important than current policies in determining the nature and extent of investment for mitigation (Ulph, 2013).

Uncertainty over future policy directions, including changes in existing policies arising from, say, political change, can affect investment decisions and inhibit mitigation, as well as create economic costs (Weitzman, 1980; see also Chapter 2). To achieve cost-effective mitigation actions, a stable and predictable policy framework is required.

3.9 Metrics of costs and benefits

This section focuses on conceptual issues that arise in the quantification and measurement, using a common metric, of the pros and cons associated with mitigation and adaptation (i.e., benefits and costs). How costs are balanced against benefits in evaluating a climate policy is a matter for ethics, as has repeatedly been emphasized in this chapter. The discussion is largely based on the economic paradigm of balancing costs against benefits, with both measured in monetary units. But leaving aside how benefits and costs are monetized or balanced to develop policy, the underlying information can be helpful for policy makers who adopt other ethical perspectives. This section is also relevant for methods that reduce performance to a small number of metrics rather than a single one (such as MCA).

We begin with the chain of cause and effect. The chain starts with human activity that generates emissions that may be reduced with mitigation (recognizing that nature also contributes to emissions of GHGs). The global emissions of GHGs lead to changes in atmospheric concentrations, then to changes in radiative forcing, and finally to changes in climate. The latter affect biological and physical systems in good as well as bad ways (including through impacts on agriculture, forests, ecosystems, energy generation, fire, and floods). These changes in turn affect human wellbeing, negatively or positively, with both monetary and other consequences.[28] Each link in the chain has a time dimension, since emissions at a particular point in time lead to radiative forcing at future points in time, which later lead to more impacts and damages. The links also have spatial dimensions. Models play a key role in defining the relationships between the links in the chain. Global Climate Models (GCMs) translate emissions through atmospheric concentrations and radiative forcing into changes in climate. Other models—including crop, forest growth and hydrology models—translate

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[28] We refer to effects on biological and physical systems as 'impacts', and effects of those impacts on human wellbeing as 'damages', whether positive or negative. These effects may include non-human impacts that are of concern to humans (see also Sections 3.4.1 and 3.4.3).

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
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changes in climate into physical impacts. Economic models translate those impacts into measures that reflect a human perspective, typically monetary measures of welfare loss or gain. GCMs aggregate emissions of various gases into an overall level of radiative forcing; hydrology models aggregate precipitation at multiple locations within a watershed into stream flow at a given location; economic models aggregate impacts into an overall measure of welfare loss.

Much of the literature on impacts focuses on particular types of impacts at particular locations. Another aspect involves metrics that allow differential regulation of different GHGs, for instance, the relative weight that regulators should place on CH_4 and CO_2 in mitigation strategies. Because impacts and damages are so poorly known it has proved surprisingly difficult to provide a rigorous answer to that question.

3.9.1 The damages from climate change

The impacts of climate change may benefit some people and harm others. It can affect their livelihood, health, access to food, water and other amenities, and natural environment. While many non-monetary metrics can be used to characterize components of impacts, they provide no unambiguous aggregation methods for characterizing overall changes in welfare. In principle, the economic theory of monetary valuation provides a way, albeit an imperfect one, of performing this aggregation and supporting associated policy-making processes.

Changes that affect human wellbeing can be 'market' or 'non-market' changes. Market effects involve changes in prices, revenue and net income, as well as in the quantity, quality, or availability of market commodities. Key is the ability to observe both prices and how people respond to them when choosing quantities to consume. Non-market changes involve the quantity, quality, or availability of things that matter to people and which are not obtained through the market (e.g., quality of life, culture, and environmental quality). A change in a physical or biological system can generate both market and non-market damage to human wellbeing. For example, an episode of extreme heat in a rural area may generate heat stress in farm labourers and may dry up a wetland that serves as a refuge for migratory birds, while killing some crops and impairing the quality of others. From an economic perspective, damages would be conceptualized as a loss of income for farmers and farm workers, an increase in crop prices for consumers and a reduction in their quality; and non-market impacts might include the impairment of the ecosystem and human health (though some health effects may be captured in the wages of farm workers).

Economists define value in terms of a 'trade-off'. As discussed in Section 3.6.1, the economic value of an item, measured in money terms, is defined as the amount of income that would make a person whole, either in lieu of the environmental change or in conjunction with the environmental change; that is, its 'income equivalent'. This equivalence is evaluated through the Willingness To Pay (WTP) and Willingness To Accept (WTA) compensation measures (see also Willig, 1976; Hanemann, 1991). The item in question may or may not be a marketed commodity: it can be *anything* that the person values. Thus, the economic value of an item is *not* in general the same as its price or the total expenditure on it. The economic concept of value based on a trade-off has some critics. The item being valued may be seen as incommensurable with money, such that no trade-off is possible. Or, the trade-off may be deemed inappropriate or unethical (e.g., Kelman, 1981; see also Jamieson, 1992; Sagoff, 2008). In addition, while the economic concept of value is defined for an individual, it is typically measured for aggregates of individuals, and the issue of equity-weighting is often disregarded (Nyborg, 2012; see also Subsection 3.5.1.3).[29]

The methods used to measure WTP and WTA fall into two categories, known as 'revealed preference' and 'stated preference' methods. For a marketed item, an individual's purchase behaviour reveals information about their value of it. Observation of purchase behaviour in the marketplace is the basis of the revealed preference approaches. One can estimate a demand function from data on observed choice behaviour. Then, from the estimated demand function, one can infer the purchaser's WTP or WTA values for changes in the price, quantity, quality, or availability of the commodity. Another revealed preference approach, known as the hedonic pricing method, is based on finding an observed relationship between the quality characteristics of marketed items and the price at which they are sold (e.g., between the price of farmland and the condition and location of the farmland). From this approach, one can infer the 'marginal' value of a change in characteristics.[30] For instance, some have attempted to measure climate damages using an hedonic approach based on the correlation of residential house prices and climate in different areas (Cragg and Kahn, 1997; Maddison, 2001, 2003; Maddison and Bigano, 2003; Rehdanz and Maddison, 2009). The primary limitation of revealed preference methods is the frequent lack of a market associated with the environmental good being valued.

With stated preference, the analyst employs a survey or experiment through which subjects are confronted with a trade-off. With contingent valuation, for example, they are asked to choose whether or not to make a payment, such as a tax increase that allows the government to undertake an action that accomplishes a specific outcome (e.g., protecting a particular ecosystem). By varying the cost across subjects and then correlating the cost offered with the percentage of 'yes' responses, the analyst traces out a form of demand function from which the WTP (or WTA) measure can be derived. With choice experiments, subjects are asked to make repeated choices among alternative

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[29] The use of the term 'willingness' in WTP and WTA should not be taken literally. For instance, individuals may have a willingness to pay for cleaner air (the reduction in income that would be equivalent in welfare terms to an increase in air quality) but they may be very unwilling to make that payment, believing that clean air is a right that should not have to be purchased.

[30] Details of these methods can be found in Becht (1995), chapters by McConnell and Bockstael (2006), Palmquist (2006), Phaneuf and Smith (2006), Mäler and Vincent (2005), or in textbooks such as Kolstad (2010), Champ, Boyle and Brown (2003), Haab and McConnell (2002) or Bockstael and McConnell (2007).

options that combine different outcomes with different levels of cost.[31] Although a growing number of researchers use stated preference studies to measure the public's WTP for climate change mitigation, one prominent criticism is the hypothetical nature of the choices involved.[32]

All these methods have been applied to valuing the damages from climate change.[33] AR2 contained a review of the literature on the economic valuation of climate change impacts. Since then, the literature has grown exponentially. The economic methodology has changed little (except for more coverage of non-market impacts and more use of stated preference). The main change is in the spatial representation of climate change impacts; whereas the older literature tended to measure the economic consequences of a uniform increase of, say 2.5 °C across the United States, the recent literature uses downscaling to measure impacts on a fine spatial scale. Most of the recent literature on the economic valuations of climate change has focused on market impacts, especially impacts on agriculture, forestry, sea level, energy, water, and tourism.[34]

The most extensive economic literature pertains to agriculture. The demand for many such commodities is often inelastic, so the short-run consequence of a negative supply shock is a price increase; while a benefit to producers, it is harmful for consumers (Roberts and Schlenker, 2010; Lobell et al., 2011). Some studies measure the effect of weather on current profits, rather than that of climate on long-term profitability (e.g., Deschênes and Greenstone, 2007), and some explore the effect of both weather and climate on current profits (Kelly et al., 2005). Examining weather and climate simultaneously leads to difficulties in identifying the separate effects of weather and climate (Deschênes and Kolstad, 2011), as well as in dealing with the confounding effects of price changes (Fisher et al., 2012). While some recent studies have found that extreme climate events have a disproportionate impact on agricultural systems (Schlenker and Roberts, 2009; Lobell et al., 2011; Deschênes and Kolstad, 2011; see also WGII, Section 7.3.2.1), the relatively high degree of spatial or temporal aggregation means that those events are not well captured in many existing economic analyses. Another difficulty is the welfare significance of shifts in location of agricultural production caused by climate. Markets for agricultural commodities are national or international in scope, so some economic analyses focus on aggregate international producer and consumer welfare. Under the potential Pareto criterion, transfers of income from one region to another are of no welfare significance, though of real policy significance.[35]

With other market sectors, the literature is both sparse and highly fragmented, but includes some estimates of economic impacts of climate change on energy, water, sea level rise, tourism, and health in particular locations. With regard to energy, climate change is expected to reduce demand for heating and increase demand for cooling (see WGII AR5, Chapter 10). Even if those two effects offset one another, the economic cost need not be negligible. With water supply, what matters in many cases is not total annual precipitation but the match between the timing of precipitation and the timing of water use (Strzepek and Boehlert, 2010). Those questions require analysis on a finer temporal or spatial scale than has typically been employed in the economic damage literature.

Estimates of the economic costs of a rise in sea level generally focus on either the property damage from flooding or on the economic costs of prevention, for example, sea wall construction (Hallegatte et al., 2007; Hallegatte, 2008; 2012). They sometimes include costs associated with the temporary disruption of economic activity. Estimates typically do not measure the loss of wellbeing for people harmed or displaced by flooding.[36] Similarly, the economic analyses of climate change impacts on tourism have focused on changes, for example, in the choice of destination and the income from tourism activities attributable to an increase in temperature, but not on the impacts on participants' wellbeing.[37]

The economic metrics conventionally used in the assessment of non-climate health outcomes have also been used to measure the impact of climate on health (e.g., Deschênes and Greenstone, 2011; Watkiss and Hunt, 2012). Measures to reduce GHGs may also reduce other pollutants associated with fossil fuel combustion, such as NO_x and particulates, which lead to time lost from work and reduced productivity (Östblom and Samakovlis, 2007). Exposure to high ambient tempera-

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[31] Details can be found in Carson and Hanemann (2005), or in textbooks such as Champ, Boyle and Brown (2003), Haab and McConnell (2002), and Bennett and Blamey (2001).

[32] Examples include Berrens et al. (2004), Lee and Cameron (2008), Solomon and Johnson (2009), and Aldy et al. (2012) for the U.S.; Akter and Bennett (2011) for Australia; Longo et al. (2012) for Spain; Lee et al. (2010) for Korea; Adaman et al. (2011) for Turkey; and Carlsson et al. (2012) for a comparative study of WTP in China, Sweden and the US.

[33] Other economic measures of damage are sometimes used that may not be appropriate. The economic damage is, in principle, the lesser of the value of what was lost or the cost of replacing it (assuming a suitable and appropriate replacement exists). Therefore, the replacement cost itself may or may not be a relevant measure. Similarly, if the cost of mitigation is actually incurred, it is a lower bound on the value placed on the damage avoided. Otherwise, the mitigation cost is irrelevant if nobody is willing to incur it.

[34] While there is a large literature covering physical and biological impacts, except for agriculture and forestry only a tiny portion of the literature carries the analysis to the point of measuring an economic value. However, the literature is expanding. A *Web of Knowledge* search on the terms ("climate change" or "global warming") and "damage" and "economic impacts" returns 39 papers for pre-2000, 136 papers for 2000–2009 and 209 papers for 2010 through September 2013.

[35] The same issue arises with the effects on timber production in a global timber market; see for example, Sohngen et al. (2001).

[36] Exceptions include Daniel et al. (2009) and Botzen and van den Bergh (2012). Cardoso and Benhin (2011) provide a stated preference valuation of protecting the Columbian Caribbean coast from sea level rise.

[37] Exceptions include Pendleton and Mendelsohn (1998); Loomis and Richardson (2006); Richardson and Loomis (2004); Pendleton et al. (2011); Tseng and Chen (2008); and for commercial fishing, Narita et al. (2012).

U.S. DEPT OF INTERIOR
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2015 NOV 15 [illegible]

tures is known to diminish work capacity and reduce labour productivity.[38]

3.9.2 Aggregate climate damages

This section focuses on the aggregate regional and global economic damages from climate change as used in IAMs to balance the benefits and costs of mitigation on a global scale.

The first estimates of the economic damage associated with a specific degree of climate change were made for the United States (Smith and Tirpak, 1989; Nordhaus, 1991; Cline, 1992; Titus, 1992; Fankhauser, 1994). These studies involved static analyses estimating the damage associated with a particular climate end-point, variously taken to be a 1 °C, 2.5 °C, or 3 °C increase in global average annual temperature. This approach gave way to dynamic analyses in IAMs that track economic output, emissions, atmospheric CO_2 concentration, and damages. Because some IAMs examine costs and benefits for different levels of emissions, they need damage 'functions' rather than point estimates.

Three IAMs have received most attention in the literature, all initially developed in the 1990s. The DICE model was first published in Nordhaus (1993a; b) but had its genesis in Nordhaus (1977); its regionally disaggregated sibling RICE was first published by Nordhaus and Yang (1996).[39] The FUND model was first published in Tol (1995). And the PAGE model, developed for European decision makers, was first published in Hope et al. (1993) and was used in the Stern (2007) review.[40] The models have undergone various refinements and updates.[41] While details have changed, their general structure has stayed the same, and questions remain about the validity of their damage functions (see Pindyck, 2013).

The IAMs use a highly aggregated representation of damages. The spatial unit of analysis in DICE is the entire world, whereas the worldis divided into 12 broad regions in RICE, 16 regions in FUND, and eight in PAGE. DICE and RICE have a single aggregate damage function for the change in global or regional GDP as a function of the increase in global average temperature, here denoted ΔT_t, and sea-level rise (which in turn is modelled as a function of ΔT_t). PAGE has four separate damage functions for different types of damages in each region: economic, non-economic, sea-level rise, and climate discontinuity (as a function of ΔT_t and the derivative rise in sea level). FUND has eight sectoral damage functions for each region, with each damage dependent on the regional ΔT_t and, in some cases, the rate of change in ΔT_t. Adaptation and catastrophic damage are included in a very simple way in some models (Greenstone et al., 2013).

Let D_{jkt} denote damages of type j in year t and region k, expressed as a proportion of per capita GDP in that year and region, Y_{kt}. The damage functions, say $D_{jkt} = D_{jkt}(\Delta T_t)$ are calibrated based on: (1) the modeller's choice of a particular algebraic formula for $D_{jkt}(\Delta T_t)$: (2) the common assumption of zero damage at the origin $[D_{jkt}(0) = 0]$; and (3) the modeller's estimate of damages at a benchmark change in global average temperature, ΔT^* (typically associated with a doubling of atmospheric CO_2). For example, in the original versions of PAGE and DICE the damage function resolves into a power function:

Equation 3.9.1 $\quad D_{jt} = a_j[\Delta T_t/\Delta T^*]^b Y_t$

where b is a coefficient estimated or specified by the modeller, and a_j is the modeller's estimate of the economic damage for the benchmark temperature change.[42] In DICE, $b = 2$ is chosen.[43] In PAGE, b is a random variable between 1.5 and 3. In FUND, the damage functions are deterministic but have a slightly more complicated structure and calibration than in Equation 3.9.1.

Because each damage function is convex (with increasing marginal damage), the high degree of spatial and temporal aggregation causes the model to understate aggregate damages. This can be seen by representing the spatial or temporal distribution of warming by a mean and variance, and writing expected damages in a second order expansion around the mean.

A concern may be whether the curvature reflected in Equation 3.9.1 is adequate. The functions are calibrated to the typical warming associated with a doubling of CO_2 concentration, along with associated damage. The aggregate damage is based on heroic extrapolations to a regional or global scale from a sparse set of studies (some from the 1990s) done at particular geographic locations. The impacts literature is now paying somewhat more attention to higher levels of warming (New et al. (2011), World Bank (2012), and WGII Section 19.5.1), though estimates of monetary damage remain scarce (however, the literature is expanding rapidly). Another concern is the possibility of tipping points and extreme events (Lenton et al., 2008) (see also Box 3.9), possibly including increases in global temperature as large as 10–12 °C that are not always reflected in the calibration (Sherwood and Huber, 2010).

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[38] See Kjellstrom et al. (2009), Zivin and Neidell (2010), or Dunne et al. (2013). Some recent studies have focused on the correlation between high temperatures and poverty (Nordhaus, 2006), the link between fluctuations in temperature, cyclones and fluctuations in economic activity (Dell et al., 2009, 2012; Hsiang, 2010), and the connection between climate change and human conflict (Hsiang et al., 2013).

[39] There are many extensions of DICE, including AD-DICE (de Bruin et al., 2009), with a more explicit treatment of adaptation.

[40] Some other IAMs have damage functions, including the MERGE Model (Manne and Richels, 1992, 1995, 2004a); the CETA model (Peck and Teisberg, 1992, 1994); and, more recently, several IAMs developed by European researchers including the WITCH model (Bosetti et al., 2006), its extension the AD-WITCH model (Bosello et al., 2010), the ENVISAGE model (Roson and Mensbrugghe, 2012), and a model developed by Eboli et al. (2010) and Bosello et al. (2012).

[41] The most recent versions are: DICE2013 (Nordhaus and Sztorc, 2013); RICE2010 (Nordhaus, 2010); PAGE 2009 (Hope, 2011, 2013); FUND 3.7 (Anthoff and Tol, 2013).

[42] Typically, ΔT^* is 2.5 or 3 °C. When $\Delta T_t = \Delta T^*$ in this equation, then $D_{jt} = a_j Y_t$.

[43] This formulation is also used by Kandlikar (1996) and Hammitt et al. (1996a) with $b = 1$, 2 or 3.

Box 3.9 | Uncertainty and damages: the fat tails problem

Weitzman (2009, 2011) has drawn attention to what has become known as the fat-tails problem. He emphasized the existence of a chain of structural uncertainties affecting both the climate system response to radiative forcing and the possibility of some resulting impacts on human wellbeing that could be catastrophic. Uncertainties relate to both means of distributions and higher moments. The resulting compounded probability distribution of possible economic damage could have a fat bad tail: i.e., the likelihood of an extremely large reduction in wellbeing does not go quickly to zero.[1] With or without risk aversion, the expected marginal reduction in wellbeing associated with an increment in emissions today could be very large, even infinite[2] See also Section 2.5.3.3.

A policy implication of the conditions described in the previous paragraph is that tail events can become much more important in determining expected damage than would be the case with probability distributions with thinner tails. Weitzman (2011) illustrates this for the distribution of temperature consequences of a doubling of atmospheric CO_2 (climate sensitivity), using WGI AR4 estimates to calibrate two distributions, one fat-tailed and one thin-tailed, to have a median temperature change of 3 °C and a 15 % probability of a temperature change in excess of 4.5 °C. With this calibration, the probability of temperatures in excess of 8 °C is nearly ten times greater with the fat-tailed distribution than the thin-tailed distribution. If high consequence, low probability events become more likely at higher temperatures, then tail events can dominate the computation of expected damages from climate change, depending on the nature of the probability distribution and other features of the problem (including timing and discounting).

At a more technical level, with some fat-tailed distributions and certain types of utility functions (constant relative risk aversion), the expectation of a marginal reduction in wellbeing associated with an increment in emissions is infinite. This is because in these cases, marginal utility becomes infinite as consumption goes to zero. This is a troubling result since infinite marginal damage implies all available resources should be dedicated to reducing the effects of climate change. But as Weitzman himself and other authors have pointed out, this extreme result is primarily a technical problem that can be solved by bounding the utility function or using a different functional form.

The primary conclusion from this debate is the importance of understanding the impacts associated with low probability, high climate change scenarios. These may in fact dominate the expected benefits of mitigation.

The policy implication of this conclusion is that the nature of uncertainty can profoundly change how climate policy is framed and analyzed with respect to the benefits of mitigation. Specifically, fatter tails on probability distributions of climate outcomes increase the importance in understanding and quantifying the impacts and economic value associated with tail events (such as 8 °C warming). It is natural to focus research attention on most likely outcomes (such as a 3 °C warming from a CO_2 doubling), but it may be that less likely outcomes will dominate the expected value of mitigation.

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[1] Weitzman (2009) defines a fat-tailed distribution as one with an infinite moment generating function (a thin-tailed distribution has a finite moment generating function); more intuitively, for a fat-tailed distribution, the tail probability approaches zero more slowly than exponentially. For example, the normal (and any distribution with finite support) would be thin-tailed whereas the Pareto distribution (a power law distribution) would be fat-tailed.

[2] Weitzman (2007b, 2009) argued that the expected marginal reduction in wellbeing could be infinite. His results have been challenged by some as too pessimistic, e.g., Nordhaus (2011a), Pindyck (2011) and Costello et al. (2010).

The economic loss or gain from warming in a given year typically depends on the level of warming in that same year, with no lagged effects (at least for damages other than sea-level rise in DICE, the non-catastrophe component of damages in PAGE, and some sectors of FUND). Thus, impacts are (a) reversible, and (b) independent of the prior trajectory of temperatures. This assumption simplifies the computations, but some impacts and damages may actually depend on the rate of increase in temperature.[44] The optimal trajectory of mitigation and the level of damages could also depend on the cumulative amount of warming in previous years (measured, say, in degree years).

DICE, FUND and PAGE represent damage as equivalent to a change in production of market commodities that is proportional to output (a 'multiplicative' formulation). Weitzman (2010a) finds that this specification matters with high levels of warming because an additive formulation leads to more drastic emission reduction. Besides affecting current market production, climate change could damage natural, human, or physical capital (e.g., through wildfires or floods). Damage to capital stocks may last beyond a year and have lingering impacts that are not captured in current formulations (Wu et al., 2011). Economic consequences

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[44] This rate of change was considered by Manne and Richels (2004a) in MERGE and by Peck and Teisberg (1994) in CETA. The latter found that it can have quite a large effect on the size of the optimal carbon tax.

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM

depend on what is assumed about the elasticity of substitution in the utility function between market commodities and non-market climate impacts. An elasticity of substitution of unity is equivalent to the conventional multiplicative formulation, but a value less than unity, generates a more drastic trajectory of emission reductions (Krutilla, 1967; Sterner and Persson, 2008).

The utility function in these three IAMs does not distinguish between the welfare gains deriving from risk reduction when people are risk averse versus the gains from smoothing consumption over time when people have declining marginal utility of income: both preferences are captured by the curvature of the utility function as measured by η, in Equation 3.6.4. However, Kreps and Porteus (1978) and Epstein and Zin (1991) show that two separate functions can have separate parameters for risk aversion and inter-temporal substitution. This formulation is used successfully in the finance literature to explain anomalies in the market pricing of financial assets, including the equity premium (Campbell, 1996; Bansal and Yaron, 2004). The insight from this literature is that the standard model of discounted expected utility, used in DICE, FUND and PAGE, sets the risk premium too low and the discount rate too high, a result confirmed by Ackerman et al. (2013) and Crost and Traeger (2013).

Our general conclusion is that the reliability of damage functions in current IAMs is low. Users should be cautious in relying on them for policy analysis: some damages are omitted, and some estimates may not reflect the most recent information on physical impacts; the empirical basis of estimates is sparse and not necessarily up-to-date; and adaptation is difficult to properly represent. Furthermore, the literature on economic impacts has been growing rapidly and is often not fullyrepresented in damage functions used in IAMs. Some authors (e.g., WGII Chapter 19) conclude these damage functions are biased downwards. It should be underscored that most IAMs used in Chapter 6 of this volume do not consider damage functions so this particular criticism does not apply to Chapter 6 analyses.

3.9.3 The aggregate costs of mitigation

Reductions in GHG emission often impose costs on firms, households (see also Box 3.10), and governments as a result of changes in prices, revenues and net income, and in the availability or quality of commodities. GHG reduction requires not only technological but also behavioural and institutional changes, which may affect wellbeing. The changes in wellbeing are measured in monetary terms through a change in income that is equivalent to the impact on wellbeing. Changes in prices and incomes are often projected through economic models (see Chapter 6). In many cases, mitigation primarily involves improvements in energy efficiency or changes in the generation and use of energy from fossil fuels in order to reduce GHG emissions.

The models assessed in Chapter 6 are called IAMs (or Integrated Models—IMs) because they couple several systems together (such as the economy and the climate) in an integrated fashion, tracking the impact of changes in economic production on GHG emissions, as well as of emissions on global temperatures and the effect of mitigation policies on emissions. As discussed in Section 6.2, the IAMs used in Chapter 6 are heterogeneous. However, for most of the Chapter 6 IAMs, climate change has no feedback effects on market supply and demand, and most do not include damage functions.[45]

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[45] Climate is assumed to be *separable* from market goods in the models' utility functions. If that assumption is incorrect, Carbone and Smith (2013) show that the welfare calculation may have significant error.

Box 3.10 | Could mitigation have a negative private cost?

A persistent issue in the analysis of mitigation options and costs is whether available mitigation opportunities can be privately profitable—that is, generate benefits to the consumer or firm that are in excess of their own cost of implementation—but which are not voluntarily undertaken. Absent another explanation, a negative private cost implies that a person is not fully pursuing his own interest. (By contrast, a negative social cost arises when the total of everybody's benefits exceeds costs, suggesting that some private decision-maker is not maximizing the interests of others.) The notion that available mitigation opportunities may have negative costs recently received attention because of analyses by McKinsey & Company (2009), Enkvist et al. (2007) and others that focused especially on energy use for lighting and heating in residential and commercial buildings, and on some agricultural and industrial processes. Much of this literature is in the context of the "energy efficiency gap,"[1] which dates to the 1970s, and the "Porter hypothesis".[2]

The literature suggesting that available opportunities may have negative cost often points to institutional, political, or social barriers as the cause. But other literature suggests economic

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[1] The efficiency gap is defined as the difference between the socially desirable amount of energy efficiency (however defined) and what firms and consumers are willing to undertake voluntarily (see Meier and Whittier, 1983; Joskow and Marron, 1992, 1993; Jaffe and Stavins, 1994).

[2] Porter (1991) and Porter and van der Linde (1995) argued that unilateral reductions in pollution could stimulate innovation and improve firms' competitiveness as a by-product; see also Lanoie et al. (2008); Jaffe and Palmer (1997). The subsequent literature has obtained mixed finding (Ambec and Barla, 2006; Ambec et al., 2013).

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explanations. In addition, however, evidence indicates that the extent of such negative cost opportunities can be overstated, particularly in purely engineering studies.

Engineering studies may overestimate the energy savings, for example because they assume perfect installation and maintenance of the equipment (Dubin et al., 1986; Nadel and Keating, 1991) or they fail to account for interactions among different investments such as efficient lighting and cooling (Huntington, 2011). Engineering studies also may fail to account for all costs actually incurred, including time costs, scarce managerial attention and the opportunity cost of the money, time, or attention devoted to energy efficiency.[3] In some cases, the engineering analysis may not account for reductions in quality (e.g., CFL lighting is perceived as providing less attractive lighting services). Choices may also be influenced by uncertainty (e.g., this is an unfamiliar product, one doesn't know how well it will work, or what future energy prices will be). Another consideration sometimes overlooked in engineering analyses is the rebound effect—the cost saving induces a higher rate of equipment usage (see Section 3.9.5). The analyses may overlook heterogeneity among consumers: what appears attractive for the average consumer may not be attractive for all (or many) consumers, based on differences in their circumstances and preferences. One approach to validation is to examine energy efficiency programs and compare ex ante estimates of efficiency opportunities with ex post accomplishment; the evidence from such comparisons appears to be inconclusive, though more analysis may be fruitful.[4]

Economic explanations for the apparent failure to pursue profitable mitigation/energy saving opportunities include the following.[5] Given uncertainty and risk aversion, consumers may rationally desire a higher return as compensation. Price uncertainty and the irreversibility of investment may also pose additional economic barriers to the timing of adoption—it may pay to wait before making the investment (Hassett and Metcalf, 1993; Metcalf, 1994). Mitigation investments take time to pay off, and consumers act as if they are employing high discount rates when evaluating such investments (Hausman, 1979). These consumer discount rates might be much higher than those of commercial businesses, reflecting liquidity and credit constraints. The durability of the existing capital stock can be a barrier to rapid deployment of otherwise profitable new technologies. Also, a principal-agent problem arises when the party that pays for an energy-efficiency investment doesn't capture all the benefits, or vice versa. For example a tenant installs an efficient refrigerator, but the landlord retains ownership when the tenant leaves (split incentives). Or the landlord buys a refrigerator but doesn't care about its energy efficiency. Such problems can also arise in organizations where different actors are responsible, say, for energy bills and investment accounts.[6] Finally, energy users, especially residential users, may be uninformed, or poorly informed, about the energy savings they are forgoing. In some cases, the seller of the product has better information than the potential buyer (asymmetric information) and may fail to convey that information credibly (Bardhan et al., 2013).

Recently, some economists have suggested that systematic behavioral biases in decision-making can cause a failure to make otherwise profitable investment. These have been classified as non-standard beliefs (e.g., incorrect assessments of fuel savings—Allcott, 2013), non-standard preferences (e.g., loss aversion—Greene et al., 2009), and non-standard decision making (e.g., tax salience—Chetty et al., 2009). Such phenomena can give rise to what might be considered 'misoptimization' by decision makers, which in turn could create a role for efficiency-improving policy not motivated by conventional market failures (Allcott et al., forthcoming); see Section 3.10.1 for a fuller account.

In summary, whether opportunities for mitigation at negative private cost exist is ultimately an empirical question. Both economic and non-economic reasons can explain why they might exist, as noted in recent reviews (Huntington, 2011; Murphy and Jaccard, 2011; Allcott and Greenstone, 2012; Gillingham and Palmer, 2014). But, evidence also suggests that the occurrence of negative private costs is sometimes overstated, for reasons identified above. This remains an active area of research and debate.

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[3] For example, Anderson and Newell (2004) examined energy audits for manufacturing plants and found that roughly half of the projects recommended by auditors were not adopted despite extremely short payback periods. When asked, plant managers responded that as much as 93 % of the projects were rejected for economic reasons, many of which related to high opportunity costs. Joskow and Marron (1992, 1993) show some engineering estimates understated actual costs.

[4] Arimura et al. (2012) review US electricity industry conservation programmes (demand side management—DSM) and conclude that programmes saved energy at a mean cost of USD 0.05 per kWh, with a 90 % confidence interval of USD 0.003 to USD 0.010. Allcott and Greenstone (2012) conclude that this average cost is barely profitable. Although this may be true, one cannot conclude that on this evidence alone that ex ante engineering estimates of costs were too optimistic.

[5] Allcott and Greenstone (2012) and Gillingham and Palmer (2014) provide excellent reviews.

[6] Davis (2011) and Gillingham et al. (2012) provide evidence of principal-agent problems in residential energy, although amount of energy lost as a result was not large in the cases examined.

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The calculation of cost depends on assumptions made (1) in specifying the model's structure and (2) in calibrating its parameters. The models are calibrated to actual economic data. While more validation is required, some models are validated by making and testing predictions of the response to observed changes (Valenzuela et al., 2007; Beckman et al., 2011; Baldos and Hertel, 2013). While some models do not address either the speed or cost of adjustment, many models incorporate adjustment costs and additional constraints to reflect deviations from full optimization (see Jacoby et al., 2006; Babiker et al., 2009; van Vuuren et al., 2009). Most models allow little scope for endogenous (price-induced) technical change (3.11.4) or endogenous non-price behavioural factors (3.10.1). It is a matter of debate how well the models accurately represent underlying economic processes (see Burtraw, 1996; Burtraw et al., 2005; Hanemann, 2010).

Besides estimating total cost, the models can be used to estimate Marginal Abatement Cost (MAC), the private cost of abating one additional unit of emissions. With a cap-and-trade system, emissions would theoretically be abated up to the point where MAC equals the permit price; with an emissions tax, they would be abated to the point where MAC equals the tax rate. It is common to graph the MAC associated with different levels of abatement. Under simplified conditions, the area under the MAC curve measures the total economic cost of emissions reduction, but not if it fails to capture some of the economy-wide effects associated with large existing distortions (Klepper and Peterson, 2006; Paltsev et al., 2007; Kesicki and Ekins, 2012; Morris et al., 2012). However, a MAC is a static approximation to the dynamic process involved in pollution abatement; it thus has its limitations.

3.9.4 Social cost of carbon

Although estimates of aggregate damages from climate change are useful in formulating GHG mitigation policies (despite the caveats listed in Section 3.9.2), they are often needed for more mundane policy reasons. Governments have to make decisions about regulation when implementing energy policies, such as on fuel or EE standards for vehicles and appliances. The social cost of carbon emissions can be factored into such decisions.

To calculate the social cost, consider a baseline trajectory of emissions $(E_0,\ldots,E_t)$ that results in a trajectory of temperature changes, ΔT_t. Suppose a damage function for year *t* is discounted to the present and called $D(\Delta T_t)$, as discussed in Equation 3.9.2. These trajectories result in a discounted present value of damages:

Equation 3.9.2 $$PVD \equiv \int_0^{\infty} D(\Delta T_t)dt$$

Then take the derivative with respect to a small change in emissions at $t = 0$, E_0, to measure the extra cost associated with a one tonne increase in emissions at time 0 (that is, the increment in *PVD*):

Equation 3.9.3 $$MDCC = \frac{\partial PVD}{\partial E_0}$$

When applied to CO_2 this equation gives the marginal damage from the change in climate that results from an extra tonne of carbon. It is also called the social cost of carbon (SCC). It should be emphasized that the calculation of SCC is highly sensitive to the projected future trajectory of emissions and also any current or future regulatory regime.[46]

Because of its potential use in formulating climate or energy regulatory policy, governments have commissioned estimates of SCC. Since 2002, an SCC value has been used in policy analysis and regulatory impact assessment in the United Kingdom (Clarkson and Deyes, 2002). It was revised in 2007 and 2010. In 2010, a standardized range of SCC values based on simulations with DICE, FUND, and PAGE using alternative projections of emissions and alternative discount rates, was made available to all U.S. Government agencies.[47] It was updated in 2013 (US Interagency Working Group, 2013).

3.9.5 The rebound effect

Technological improvements in energy efficiency (EE) have direct effects on energy consumption and thus GHG emissions, but can cause other changes in consumption, production, and prices that will, in turn, affect GHG emissions. These changes are generally called 'rebound' or 'takeback' because in most cases they reduce the net energy or emissions reduction associated with the efficiency improvement. The size of rebound is controversial, with some research papers suggesting little or no rebound and others concluding that it offsets most or all reductions from EE policies (Greening et al., 2000; Binswanger, 2001; Gillingham et al., 2013, summarize the empirical research). Total EE rebound can be broken down into three distinct parts: substitution-effect, income-effect, and economy-wide.

In end-use consumption, substitution-effect rebound, or 'direct rebound' assumes that a consumer will make more use of a device if it becomes more energy efficient because it will be cheaper to use. Substitution-effect rebound extends to innovations triggered by the improved EE that results in new ways of using the device. To pay for that extra use, the individual must still consume less of something else, so net substitution-effect rebound is the difference between the energy expended in using more of the device and the energy saved from using whatever was previously used less (see Thomas and Azevedo, 2013).

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[46] Some ambiguity regards the definition of the SCC and the correct way to calculate it in the context of an equilibrium IAM (in terms of distinguishing between a marginal change in welfare vs. a marginal change in damage only). See, for instance, an account of the initial U.S. Government effort (Greenstone et al., 2013).

[47] Obviously, estimates of the SCC are sensitive to the structural and data assumptions in the models used to compute the SCC. Weitzman (2013), for instance, demonstrates the significance of the discount rate in the calculation.

Income-effect rebound or 'indirect rebound', arises if the improvement in EE makes the consumer wealthier and leads them to consume additional products that require energy. Even if energy efficient light bulbs lead to no substitution-effect rebound (more lighting), income-effect rebound would result if the consumer spends the net savings from installing the bulbs on new consumption that uses energy. The income-effect rebound will reflect the size of the income savings from the EE improvement and the energy intensity of marginal income expenditures.

Analogous rebound effects for EE improvements in production are substitution towards an input with improved energy efficiency, and substitution among products by consumers when an EE improvement changes the relative prices of goods, as well as an income effect when an EE improvement lowers production costs and creates greater wealth.

Economy-wide rebound refers to impacts beyond the behaviour of the entity benefiting directly from the EE improvement, such as the impact of EE on the price of energy. For example, improved fuel economy lowers vehicle oil demand and prices leading some consumers to raise their consumption of oil products. The size of this energy price effect will be greater with less elastic supply and more elastic demand. Some argue that the macroeconomic multiplier effects of a wealth shock from EE improvement also create economy-wide rebound.

Rebound is sometimes confused with the concept of economic leakage, which describes the incentive for emissions-intensive economic activity to migrate away from a region that restricts GHGs (or other pollutants) towards areas with fewer or no restrictions on such emissions. Energy efficiency rebound will occur regardless of how broadly or narrowly the policy change is adopted. As with leakage, however, the potential for significant rebound illustrates the importance of considering the full equilibrium effects of a policy designed to address climate change.

3.9.6 Greenhouse gas emissions metrics

The purpose of emissions metrics is to establish an exchange rate, that is, to assign relative values between physically and chemically different GHGs and radiative forcing agents (Fuglestvedt et al., 2003; Plattner et al., 2009). For instance, per unit mass, CH_4 is a more potent GHG than CO_2 in terms of instantaneous radiative forcing, yet it operates on a shorter time scale. In a purely temporal sense, the impacts are different. Therefore, how should mitigation efforts be apportioned for emissions of different GHGs?[48]

GHG emissions metrics are required for generating aggregate GHG emissions inventories; to determine the relative prices of different GHGs in a multi-gas emissions trading system; for designing multi-gas mitigation strategies; or for undertaking life-cycle assessment (e.g., Peters et al., 2011b). Since metrics quantify the trade-offs between different GHGs, any metric used for mitigation strategies explicitly or implicitly evaluates the climate impact of different gases relative to each other.

The most prominent GHG emissions metric is the Global Warming Potential (GWP), which calculates the integrated radiative forcing from the emission of one kilogram of a component *j* out to a time horizon *T*:

Equation 3.9.4 $$AGWP_j(T) = \int_0^T RF_j(t)\,dt$$

The AGWP is an absolute metric. The corresponding relative metric is then defined as $GWP_j = AGWP_j / AGWP_{CO2}$.

The GWP with a finite time horizon *T* was introduced by the IPCC (1990). With a 100-year time horizon, the GWP is used in the Kyoto Protocol and many other scientific and policy applications for converting emissions of various GHGs into 'CO_2 equivalents'. As pointed out in WGI, no scientific argument favours selecting 100 years compared with other choices. Conceptual shortcomings of the GWP include: (a) the choice of a finite time horizon is arbitrary, yet has strong effects on metric value (IPCC, 1990); (b) the same CO_2-equivalent amount of different gases may have different physical climate implications (Fuglestvedt et al., 2000; O'Neill, 2000; Smith and Wigley, 2000); (c) physical impacts and impacts to humans (well-being) are missing; and (d) temporal aggregation of forcing does not capture important differences in temporal behaviour. Limitations and inconsistencies also relate to the treatment of indirect effects and feedbacks (see WGI, Chapter 8).

Many alternative metrics have been proposed in the scientific literature. It can be argued that the net impacts from different gases should be compared (when measured in the same units) and the relative impact used for the exchange rate. The Global Damage Potential (GDamP) follows this approach by using climate damages as an impact proxy, and exponential discounting for inter-temporal aggregation of impacts (Hammitt et al., 1996b; Kandlikar, 1996). Since marginal damages depend on the time at which GHGs are emitted, the GDamP is a time-variant metric. The GDamP accounts for the full causal chain from emissions to impacts. One advantage of the framework is that relevant normative judgements, such as the choice of inter-temporal discounting and the valuation of impacts, are explicit (Deuber et al., 2013). In practice, however, the GDamP is difficult to operationalize. The difficulties in calculating the GDamP and SCC are closely related (see Section 3.9.4).

The Global Cost Potential (GCP) calculates the time-varying ratio of marginal abatement costs of alternative gases arising in a cost-effective multi-gas mitigation strategy given a prescribed climate target (Manne and Richels, 2001), such as a cap on temperature change or

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[48] This issue is discussed in Chapter 8 of WGI.

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2016 NOV 14

Table 3.4 | Overview and classification of different metrics from the scientific literature.

Name of metric		Impact function	Atmospheric background	Time dimension	Reference
GWP	Global Warming Potential	*RF*	Constant	Constant temporal weighting over fixed time horizon	IPCC (1990)
GWP-LA	Global Warming Potential (discounting)	*RF*	Constant, average of future conditions	Exponential discounting	Lashof and Ahuja (1990)
GTP-H	Global Temperature Change Potential (fixed time horizon)	ΔT	Constant	Evaluation at a fixed time T after emission	Fuglestvedt et al., (2010), Shine et al. (2005)
GTP(t)	Time-dependent global temperature change potential	ΔT	Time-varying	Evaluation at a fixed end point time in the future	Shine et al. (2007)
CETP	Cost Effective Temperature Potential	ΔT	Exogenous scenario	Complex function of time when climate threshold is reached	Johannson (2012)
MGTP	Mean Global Temperature Change Potential	ΔT	Time-varying	Constant temporal weighting over fixed time horizon	Gillet and Mathews (2010), Peters et al. (2011a)
GCP	Global Cost Potential	Infinite damage above climate target	Time-varying	Exponential discounting	Manne and Richels (2001)
GDamP	Global Damage Potential	$D(\Delta T)$	Time-varying	Exponential discounting	Kandlikar (1996), Hammit et al. (1996a)

on GHG concentrations. While the GCP avoids the problems associated with damage functions, it still requires complex integrated energy-economy-climate models to calculate GHG price ratios, and is therefore less transparent to stakeholders than physical metrics.[49]

The time-dependant Global Temperature Change Potential (GTP) is a physical metric that does not involve integration of the chosen impact parameter over time (Shine et al., 2007). It is defined as the relative effect of different gases on temperature at a predefined future date from a unit impulse of those gases. Typically these are normalized to a base, such as same mass of CO_2 emitted. While the GWP and GTP were not constructed with a specific policy target in mind, the GCP is conceptually more consistent with a policy approach aiming at achieving climate objectives in a cost-effective way (Fuglestvedt et al., 2003; Manning and Reisinger, 2011; Tol et al., 2012).

Virtually all absolute metrics (AM_j) can be expressed in terms of a generalization of Equation 3.9.4 (Kandlikar, 1996; Forster et al., 2007):

Equation 3.9.5 $$AM_j = \int_0^\infty I_j(\Delta T(t), RF(t), \ldots) W(t)\, dt$$

where the *impact function* I_j links the metric to the change in a physical climate parameter, typically the global mean radiative forcing *RF* (e.g., in the case of the GWP) or the change in global mean temperature ΔT (e.g., GTP and most formulations of the GDamP). In some cases, the impact function also considers the rate of change of a physical climate parameter (Manne and Richels, 2001; Johansson et al., 2006).

The temporal 'weighting function, W(t)', determines how the metric aggregates impacts over time. It can prescribe a finite time horizon (GWP), evaluation at a discrete point in time (GTP), or exponential discounting over an infinite time horizon (GDamP), which is consistent with the standard approach to inter-temporal aggregation used in economics (see Section 3.6.2). The weighting used in the GWP is a weight equal to one up to the time horizon and zero thereafter.

The categorization according to their choice of impact and temporal weighting function (Table 3.4) serves to expose underlying explicit and implicit assumptions, which, in turn, may reflect normative judgements. It also helps to identify relationships between different metric concepts (Tol et al., 2012; Deuber et al., 2013). In essence, the choice of an appropriate metric for policy applications involves a trade-off between completeness, simplicity, measurability, and transparency (Fuglestvedt et al., 2003; Plattner et al., 2009; Deuber et al., 2013). The GDP and GCP are cost effective in implementing multi-gas mitigation policies, but are subject to large measurability, value-based, and scientific uncertainties. Simple physical metrics, such as the GWP, are easier to calculate and produce a more transparent result, but are inaccurate in representing the relevant impact trade-offs between different GHGs (Fuglestvedt et al., 2003; Deuber et al., 2013).

The choice of metric can have a strong effect on the numerical value of GHG exchange rates. This is particularly relevant for CH_4, which operates on a much shorter timescale than CO_2. In WGI, Section 8.7, an exchange ratio of CH_4 to CO_2 of 28 is given for GWP and of 4 for a time horizon of 100 years for GTP.[50] For a quadratic damage function and a

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[49] In the context of a multi-gas integrated assessment model which seeks to minimize the cost of meeting a climate target.

[50] See WGI Chapter 8, Appendix 8A for GWP and GTP values for an extensive list of components.

discount rate of 2 %, Boucher (2012) obtained a median estimate of the GDamP exchange ratios of 24.3. This exchange rate obviously has very significant implications for relative emphasis a country may place on methane mitigation vs. carbon dioxide mitigation.

A small but increasing body of literature relates to the economic implications of metric choice. A limited number of model-based examinations find that, despite its conceptual short-comings, the GWP-100 performs roughly similarly to GTP or a cost-optimizing metric (such as the GCP) in terms of aggregate costs of reaching a prescribed climate target, although regional and sectoral differences may be significant (Godal and Fuglestvedt, 2002; Johansson et al., 2006; Reisinger et al., 2013; Smith et al., 2013; Ekholm et al., 2013). In other words, based on these few studies, the scope for reducing aggregate mitigation costs of reaching a particular climate target by switching to a metric other than the currently used GWP-100 may be limited, although there may be significant differences in terms of regional costs.

In the Kyoto Protocol, emission reductions of one GHG can be traded with reductions in all other GHGs. Such 'single-basket' approaches implicitly assume that the GHGs can linearly substitute each other in the mitigation effort. However, the same CO_2-equivalent amount of different GHGs can result in climate responses that are very different for transitional and long-term temperature change, chiefly due to different life-times of the substances (Fuglestvedt et al., 2000; Smith and Wigley, 2000). As an alternative, multi-basket approaches have been proposed, which only allow trading within groups of forcing agents with similar physical and chemical properties (Rypdal et al., 2005; Jackson, 2009; Daniel et al., 2012; Smith et al., 2013). Smith et al. (2013) propose a methodology for categorizing GHGs into two baskets of (a) long-lived species, for which the cumulative emissions determine the long-term temperature response, and (b) shorter-lived species for which sustained emissions matter. Applying separate emission equivalence metrics and regulations to each of the two baskets can effectively control the maximum peak temperature reached under a global climate policy regime. However, further research on the institutional requirements and economic implications of such an approach is needed, as it requires regulators to agree on separate caps for each basket and reduces the flexibility of emission trading systems to harvest the cheapest mitigation options.

3.10 Behavioural economics and culture

This section summarizes behavioural economics related to climate change mitigation. We focus on systematic deviations from the traditional neoclassical economic model, which assumes that preferences are complete, consistent, transitive, and non-altruistic, and that humans have unbounded computational capacity and rational expectations. In this context, social and cultural issues and conditions that frame our attitudes, as well as living conditions, are also addressed. Chapter 2 also considers behavioural questions, though primarily in the context of risk and uncertainty.

Although the focus is on the behaviour of individuals, some firms and organizations also take actions that appear to be inconsistent with the standard neoclassical model of the profit-maximizing firm (Lyon and Maxwell, 2007).

3.10.1 Behavioural economics and the cost of emissions reduction

Behavioural economics deals with cognitive limitations (and abilities) that affect people's economic decision-making processes. Choices can be affected and/or framed by perceived fairness, social norms, cooperation, selfishness, and so on.[51] Behavioural economics emphasizes the cognitive, social, and emotional factors that lead to apparently irrational choices. A growing number of documented systematic deviations from the neoclassical model help explain people's behaviour, but here we focus on several that we see as most relevant to climate change mitigation.[52]

3.10.1.1 Consumer undervaluation of energy costs

Consumers may undervalue energy costs when they purchase energy-using durables, such as vehicles, or make other investment decisions related to energy use.[53] By 'undervalue', we mean that consumers' choices systematically fail to maximize the utility they experience when the choices are implemented ('experienced' utility) (Kahneman and Sugden, 2005; see also, e.g., Fleurbaey, 2009). This misoptimization reduces demand for EE. Three potential mechanisms of undervaluation may be most influential (see also Box 3.10). First, when considering a choice with multiple attributes, evidence suggests that consumers are inattentive to add-on costs and ancillary attributes, such as shipping and handling charges or sales taxes (Hossain and Morgan, 2006; Chetty et al., 2009). It could be that EE is a similar type of ancillary product attribute and is thus less salient at the time of purchase. Second, significant evidence across many contexts also suggests that humans are 'present biased' (DellaVigna, 2009). If energy costs affect consumption in the future while purchase prices affect consumption in the present, this would lead consumers to be less energy efficient. Third, people's beliefs about the implications of different choices may

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[51] See, e.g., Babcock and Loewenstein (1997), Shiv and Fedorikhin (1999), Asheim et al. (2006), Barrett (2007), Levati et al. (2007), Potters et al. (2007), Shogren and Taylor (2008) and Dannenberg et al. (2010).

[52] See Rachlinksi (2000), Brekke and Johansson-Stenmann (2008), Gowdy (2008) and the American Psychological Association (2010).

[53] This can even apply to cases that use sophisticated methods to support decisions (e.g., Korpi and Ala-Risku, 2008).

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER
2016 NOV 14

be systematically biased (Jensen, 2010; Bollinger et al., 2011; Kling et al., 2012; McKenzie et al., 2013). Attari et al. (2010) show that people systematically underestimate the energy savings from a set of household energy conserving activities, and Allcott (2013) shows that the average consumer either correctly estimates or systematically slightly underestimates the financial savings from more fuel-efficient vehicles. Each of these three mechanisms of undervaluation appears plausible based on results from other contexts. However, rigorous evidence of misoptimization is limited in the specific context of energy demand (Allcott and Greenstone, 2012).

Three implications arise for climate and energy policy if the average consumer who is marginal to a policy does, in fact, undervalue energy costs. The first is an 'internality dividend' from carbon taxes (or other policies that internalize the carbon externality into energy prices): a carbon tax can actually increase consumer welfare when consumers undervalue energy costs (Allcott et al., forthcoming). This occurs because undervaluation would be a pre-existing distortion that reduces demand for EE below consumers' private optima, and one that increasing carbon taxes helps to correct. Second, in addition to carbon taxes, other tax or subsidy policies that raise the relative purchase price of energy-inefficient durable goods can improve welfare (Cropper and Laibson, 1999; O'Donoghue and Rabin, 2008; Fullerton et al., 2011). Third, welfare gains are largest from policies that preferentially target consumers who undervalue energy costs the most. This effect is related to the broader philosophies of libertarian paternalism (Sunstein and Thaler, 2003) and asymmetric paternalism (Camerer et al., 2003), which advocate policies that do not infringe on freedom of choice but could improve choices by the subset of people who misoptimize. In the context of energy demand, such policies might include labels or programmes that provide information about, and attract attention to, energy use by durable goods.

3.10.1.2 Firm behaviour

Some of the phenomena described above may also apply to firms. Lyon and Maxwell (2004, 2008) examine in detail the tendency of firms to undertake pro-environment actions, such as mitigation, without being prompted by regulation. Taking a neoclassical approach to the problem, they find that firms view a variety of pro-environment actions as being to their advantage. However, evidence of a compliance norm has been found in other contexts where firms' responses to regulation have been studied (Ayres and Braithwaite, 1992; Gunningham et al., 2003).

The conventional economic model represents the firm as a single, unitary decision-maker, with a single objective, namely, profit maximization. As an alternative to this 'black-box' model of the firm (Malloy, 2002), the firm may be seen as an organization with a multiplicity of actors, perhaps with different goals, and with certain distinctive internal features (Coase, 1937; Cyert and March, 1963; Williamson, 1975).

3.10.1.3 Non-price interventions to induce behavioural change

Besides carbon taxes and other policies that affect relative prices, other non-price policy instruments can reduce energy demand, and, therefore, carbon emissions. Such interventions include supplying information on potential savings from energy-efficient investment, drawing attention to energy use, and providing concrete examples of energy-saving measures and activities (e.g., Stern, 1992; Abrahamse et al., 2005). They also include providing feedback on historical energy consumption (Fischer, 2008) and information on how personal energy use compares to a social norm (Allcott, 2011).[54]

In some cases, non-price energy conservation and efficiency programmes may have low costs to the programme operator, and it is therefore argued that they are potential substitutes if carbon taxes are not politically feasible (Gupta et al., 2007). However, it is questionable whether such interventions are appropriate substitutes for carbon taxes, for example, in terms of environmental and cost effectiveness, because their impact may be small (Gillingham et al., 2006) and unaccounted costs may reduce the true welfare gains. For example, consumers' expenditures on energy-efficient technologies and time spent turning lights off may not be observed.

Research in other domains (e.g., Bertrand et al., 2010) has shown that a person's choices are sometimes not consistent. They may be malleable by 'ancillary conditions'—non-informational factors that do not affect experienced utility. In the context of EE, this could imply that energy demand may be reduced with relatively low welfare costs through publicity aimed at changing consumer preferences. However, publicly-funded persuasion campaigns bring up important ethical and political concerns, and the effectiveness of awareness-raising programmes on energy and carbon will depend on how consumers actually use the information and the mix of policy instruments (Gillingham et al., 2006; Gupta et al., 2007; also Worrell et al., 2004; Mundaca et al., 2010).

3.10.1.4 Altruistic reductions of carbon emissions

In many contexts, people are altruistic, being willing to reduce their own welfare to increase that of others. For example, in laboratory 'dictator games', people voluntarily give money to others (Forsythe et al., 1994), and participants in public goods games regularly contribute more than the privately-optimal amount (Dawes and Thaler, 1988; Ledyard, 1993). Charitable donations in the United States amount to more than 2% of GDP (List, 2011). Similarly, many individuals voluntarily contribute to environmental public goods, such as reduced carbon

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[54] The efficacy of these interventions can often be explained within neoclassical economic models. From an expositional perspective, it is still relevant to cover them in this section.

emissions. For example, USD 387 million were spent in the U.S. on voluntary carbon offset purchases in 2009 (Bloomberg, 2010).

Pre-existing altruistic voluntary carbon emission reductions could moderate the effects of a new carbon tax on energy demand because the introduction of monetary incentives can 'crowd out' altruistic motivations (Titmuss, 1970; Frey and Oberholzer-Gee, 1997; Gneezy and Rustichini, 2000). Thus, a carbon tax could reduce voluntary carbon emission reductions even as it increases financially-motivated reductions. While this effect might not weaken the welfare argument for a carbon tax, it does reduce the elasticity of carbon emissions with respect to a carbon tax.

Reciprocity, understood as the practice of people rewarding generosity and castigating cruelty towards them, has been found to be a key driver of voluntary contributions to public goods. Positive reciprocity comes in the form of conditional cooperation, which is a tendency to cooperate when others do so too (Axelrod, 1984; Fischbacher et al., 2001; Frey and Meier, 2004). However, cooperation based on positive reciprocity is often fragile and is declining over time (Bolton et al., 2004; Fischbacher and Gächter, 2010). Incentives and penalties are fundamental to maintaining cooperation in environmental treaties (Barrett, 2003). Adding a strategic option to punish defectors often stabilizes cooperation, even when punishment comes at a cost to punishers (Ostrom et al., 1992; Fehr and Gächter, 2002). Yet, if agents are allowed to counter-punish, the effectiveness of reciprocity to promote cooperation might be mitigated (Nikiforakis, 2008). However, most laboratory studies have been conducted under symmetric conditions and little is known about human cooperation in asymmetric settings, which tend to impose more serious normative conflicts (Nikiforakis et al., 2012).

Experiments also reveal a paradox: actors can agree to a combined negotiated climate goal for reducing the risk of catastrophe, but behave as if they were blind to the risks (Barrett and Dannenberg, 2012). People are also often motivated by concerns about the fairness of outcomes and procedures; in particular, many do not like falling behind others (Fehr and Schmidt, 1999; Bolton and Ockenfels, 2000; Charness and Rabin, 2002; Bolton et al., 2005). Such concerns can both promote and hamper the effectiveness of negotiations, including climate negotiations, in overcoming cooperation and distributional problems (Güth et al., 1982; Lange and Vogt, 2003; Lange et al., 2007; Dannenberg et al., 2010).

Uncertainty about outcomes and behaviours also tends to hamper cooperation (Gangadharan and Nemes, 2009; Ambrus and Greiner, 2012). As a result, the information given to, and exchanged by, decision makers may affect social comparison processes and reciprocal interaction, and thus the effectiveness of mechanisms to resolve conflicts (Goldstein et al., 2008; Chen et al., 2010; Bolton et al., 2013). In particular, face-to-face communication has been proved to significantly promote cooperation (Ostrom, 1990; Brosig et al., 2003). Concerns about free-riding are perceived as a barrier to engaging in mitigation actions (Lorenzoni et al., 2007). The importance of fairness in promoting international cooperation (see also Chapter 4) is one of the few non-normative justifications for fairness in climate policy.

3.10.1.5 Human ability to understand climate change

So far, we have covered deviations from the neoclassical model that affect energy demand. Such deviations can also affect the policy-making process. The understanding of climate change as a physical phenomenon with links to societal causes and impacts is highly complex (Weber and Stern, 2011). Some deviations are behavioural and affect perceptions and decision making in various settings besides climate change. (See Section 2.4 for a fuller discussion). For example, perceptions of, and reactions to, uncertainty and risk can depend not only on external reality, as assumed in the neoclassical model, but also on cognitive and emotional processes (Section 2.4.2). When making decisions, people tend to overweight outcomes that are especially 'available' or salient (Kahneman and Tversky, 1974, 1979). They are more averse to losses than they are interested in gains relative to a reference point (Kahneman and Tversky, 1979). Because climate change involves a loss of existing environmental amenities, this can increase its perceived costs. However, if the costs of abatement are seen as a reduction relative to a reference rate of future economic growth, this can increase the perceived costs of climate change mitigation.

Some factors make it hard for people to think about climate change and lead them to underweight it: change happens gradually; the major effects are likely to occur in the distant future; the effects will be felt elsewhere; and their nature is uncertain. Furthermore, weather is naturally variable, and the distinction between weather and climate is often misunderstood (Reynolds et al., 2010). People's perceptions and understanding of climate change do not necessarily correspond to scientific knowledge (Section 2.4.3) because they are more vulnerable to emotions, values, views, and (unreliable) sources (Weber and Stern, 2011). People are likely to be misled if they apply their conventional modes of understanding to climate change (Bostrom et al., 1994).

3.10.2 Social and cultural issues

In recent years, the orientation of social processes and norms towards mitigation efforts has been seen as an alternative or complement to traditional mitigation actions, such as incentives and regulation. We address some of the concepts discussed in the literature, which, from a social and cultural perspective, contribute to strengthening climate change actions and policies.

3.10.2.1 Customs

In both developed and developing countries, governments, social organizations, and individuals have tried to change cultural attitudes

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER
2015 NOV 14

Box 3.11 | Gross National Happiness (GNH)

The Kingdom of Bhutan has adopted an index of GNH as a tool for assessing national welfare and planning development (Kingdom of Bhutan, 2008). According to this concept, happiness does not derive from consumption, but rather from factors such as the ability to live in harmony with nature (Taplin et al., 2013). Thus, GNH is both a critique of, and an alternative to, the conventional global development model (Taplin et al., 2013). The GNH Index measures wellbeing and progress according to nine key domains (and 72 core indicators) (Uddin et al., 2007). The intention is to increase access to health, education, clean water, and electrical power (Pennock and Ura, 2011) while maintaining a balance between economic growth, environmental protection, and the preservation of local culture and traditions. This is seen as a 'Middle Way' aimed at tempering the environmental and social costs of unchecked economic development (Frame, 2005; Taplin et al., 2013).

towards emissions, energy use, and lifestyles (European Commission, 2009). For example, household energy-use patterns for space and water heating differ significantly between Japan and Norway because of lifestyle differences (Wilhite et al., 1996; Gram-Hanssen, 2010). Some have argued that the bio-cultural heritage of indigenous peoples is a resource that should be valued and preserved as it constitutes an irreplaceable bundle of teachings on the practices of mitigation and sustainability (Sheridan and Longboat, 2006; Russell-Smith et al., 2009; Kronik and Verner, 2010). Sometimes local strategies and indices have metamorphosed into national policies, as in the case of '*Buen Vivir*' in Ecuador (Choquehuanca, 2010; Gudynas, 2011) and 'Gross National Happiness' (GNH), described in Box 3.11. In rich countries, and among social groups with high levels of environmental awareness, interest in sustainability has given rise to cultural movements promoting change in modes of thought, production, and consumption. Including the cultural dimension in mitigation policies facilitates social acceptability.

3.10.2.2 Indigenous peoples

Indigenous peoples number millions across the globe (Daes, 1996). Land and the natural environment are integral to their sense of identity and belonging and to their culture, and are essential for their survival (Gilbert, 2006; Xanthaki, 2007). The ancestral lands of indigenous peoples contain 80 % of the earth's remaining healthy ecosystems and global biodiversity priority areas, including the largest tropical forests (Sobrevila, 2008). Because they depend on natural resources and inhabit biodiversity-rich but fragile ecosystems, indigenous peoples are particularly vulnerable to climate change and have only limited means of coping with such change (Henriksen, 2007; Permanent Forum on Indigenous Issues, 2008). They are often marginalized in decision making and unable to participate adequately in local, national, regional, and international climate-change mechanisms. Yet, it is increasingly being recognized that indigenous peoples can impart valuable insights into ways of managing mitigation and adaptation (Nakashima et al., 2012), including forest governance and conserving ecosystems (Nepstad et al., 2006; Hayes and Murtinho, 2008; Persha et al., 2011).

3.10.2.3 Women and climate change

Women often have more restricted access to, and control of, the resources on which they depend than men. In many developing countries, most small-scale food producers are women. They are usually the ones responsible for collecting water and fuel and for looking after the sick. If climate change adversely affects crop production and the availability of fuel and water, or increases ill health, women may bear a disproportionate burden of those consequences (Dankelman, 2002; UNEP, 2011).[55] On the other hand, they may be better at adapting to climate change, both at home and in the community. But given their traditional vulnerability, the role of women across society will need to be re-examined in a gender-sensitive manner to ensure they have equal access to all types of resources (Agostino and Lizarde, 2012).

3.10.2.4 Social institutions for collective action

Social institutions shape individual actions in ways that can help in both mitigation and adaptation. They promote trust and reciprocity, establish networks, and contribute to the evolution of common rules. They also provide structures through which individuals can share information and knowledge, motivate and coordinate behaviour, and act collectively to deal with common challenges. Collective action is reinforced when social actors understand they can participate in local solutions to a global problem that directly concerns them.

As noted in Sections 3.10.1.5 and 2.4, public perceptions of the cause and effect of climate change vary, in both developed and developing countries, with some erroneous ideas persisting even among well-educated people. Studies of perceptions (O'Connor et al., 1999; Corner et al., 2012) demonstrate that the public is often unaware of the roles that individuals and society can play in both mitigation and adaptation. The concepts of social and policy learning can be used in stimu-

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[55] Natural disasters over the period 1981–2002 revealed evidence of a gender gap: natural disasters lowered women's life expectancy more than men's: the worse the disaster and the lower the woman's socio-economic status the bigger the disparity (Neumayer and Plümper, 2007).

lating and organizing collective action. Social learning involves participation by members of a group in discourse, imitation, and shared collective or individual actions. The concept of policy learning describes the process of adaptation by organizations to external change while retaining or strengthening their own objectives and domination over existing socio-economic structures (Adger and Kelly, 1999). The task of an educational programme in mitigating and adapting to climate change is to represent a collective global problem in individual and social terms. This will require the strategies for disseminating scientific information to be reinforced and the practical implications advertised in ways that are understandable to diverse populations (González Gaudiano and Meira Cartea, 2009).

3.11 Technological change

Mitigation scenarios aim at significant reductions in current emission levels that will be both difficult and costly to achieve with existing technological options. However, cost-reducing technological innovations are plausible. The global externality caused by climate change compounds market failures common to private sector innovations. Appropriate policy interventions are accordingly needed to encourage the type and amount of climate-friendly technological change (TC) that would lead to sizable reductions in the costs of reducing carbon emissions. This section reviews theories, concepts, and principles used in the study of environmentally oriented TC, and highlights key lessons from the literature, in particular, the potential of policy to encourage TC. Examples of success and failure in promoting low carbon energy production and consumption technologies are further evaluated in Chapters 6–16.

3.11.1 Market provision of TC

As pollution is not fully priced by the market, private individuals lack incentives to invest in the development and use of emissions-reducing technologies in the absence of appropriate policy interventions. Market failures other than environmental pollution include what is known as the 'appropriability problem'. This occurs when inventors copy and build on existing innovations, and reap part of the social returns on them. While the negative climate change externality leads to over use of the environment, the positive 'appropriability' externality leads to an under-supply of technological innovation.[56] Indeed, empirical research provides ample evidence that social rates of return on R&D are higher than private rates of return (Griliches, 1992). Thus, the benefits of new knowledge may be considered as a public good (see, e.g., Geroski, 1995).

Imperfections in capital markets often distort the structure of incentives for financing technological development. Information about the potential of a new technology may be asymmetrically held, creating adverse selection (Hall and Lerner, 2010). This may be particularly acute in developing countries. The issue of path dependence, acknowledged in evolutionary models of TC, points to the importance of transformative events in generating or diverting technological trajectories (see Chapters 4 and 5). Even endogenously induced transformative events may not follow a smooth or predictable path in responding to changing economic incentives, suggesting that carbon-price policy alone may not promote the desired transformative events.

3.11.2 Induced innovation

The concept of 'induced innovation' postulates that investment in R&D is profit-motivated and responds positively to changes in relative prices[57] (Hicks, 1932; Binswanger and Ruttan, 1978; Acemoglu, 2002).[58] Initial evidence of induced TC focused on the links between energy prices and innovation and revealed the lag between induced responses and the time when price changes came into effect, which is estimated at five years by Newell et al. (1999) and Popp (2002) (see Chapter 5). Policy also plays an important role in inducing innovation, as demonstrated by the increase in applications for renewable energy patents within the European Union in response to incentives for innovation provided by both national policies and international efforts to combat climate change (Johnstone et al., 2010). Recent evidence also suggests that international environmental agreements provide policy signals that encourage both innovation (Dekker et al., 2012) and diffusion (Popp et al., 2011). With the exception of China, most climate-friendly innovation occurred in developed countries (Dechezlepretre et al., 2011).[59]

3.11.3 Learning-by-doing and other structural models of TC

An extensive literature relates to rates of energy cost reduction based on the concept of 'experience' curves (see Chapter 6). In economics, this concept is often described as learning-by-doing (LBD)—to describe the decrease in costs to manufacturers as a function of cumulative output—or 'learning-by-using', reflecting the reduction in costs

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[56] For incremental innovations, the net technology externality can be negative. Depending on market structure and intellectual property rules, the inventor of an incremental improvement on an existing technology may be able to appropriate the entire market, thereby earning profits that exceed the incremental value of the improvement.

[57] It should be pointed out that in economics, 'induced innovation' typically means innovation induced by relative price differences. The IPCC uses a different definition: innovation induced by policy.

[58] In economics, 'induced innovation' typically means innovation induced by relative price differences. The IPCC uses a different definition: innovation induced by policy.

[59] Global R&D expenditures amounted to USD 1.107 trillion in 2007, with OECD nations accounting for 80 %, and the U.S. and Japan together accounting for 46 % (National Science Board, 2010).

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER
2015 NOV 19

(and/or increase in benefits) to consumers as a function using a technology. While learning curves are relatively easy to incorporate into most climate integrated assessment models (IAMs), the application of LBD has limitations as a model of TC (Ferioli et al., 2009). Learning curves ignore potential physical constraints. For example, while costs may initially fall as cumulative output expands, if renewable energy is scaled up, the use of suboptimal locations for production would increase costs. Ferioli et al. (2009) also provide evidence that learning can be specific to individual components, so that the savings from learning may not fully transfer from one generation of equipment to the next. They therefore suggest caution when extrapolating cost savings from learning curves to long-term frames or large-scale expansions. Similarly, in a study on cost reductions associated with photovoltaic cells, Nemet (2006) finds that most efficiency gains come from universities, which have little traditional LBD through production experience. Hendry and Harborne (2011) provide examples of the interaction of experience and R&D in the development of wind technology.

3.11.4 Endogenous and exogenous TC and growth

Within climate policy models, TC is either treated as exogenous or endogenous. Köhler et al. (2006), Gillingham et al. (2008) and Popp et al. (2010) provide reviews of the literature on TC in climate models.

Exogenous TC (most common in models) progresses at a steady rate over time, independently of changes in market incentives. One drawback of exogenous TC is that it ignores potential feedback between climate policy and the development of new technologies. Models with endogenous TC address this limitation by relating technological improvements in the energy sector to changes in energy prices and policy. These models demonstrate that ignoring induced innovation overstates the costs of climate control.

The Nordhaus (1977, 1994) DICE model is the pioneering example of a climate policy model incorporating TC into IAMs. In most implementations of DICE, TC is exogenous. Efforts to endogenize TC have been difficult, mainly because market-based spillovers from R&D are not taken into account when deciding how much R&D to undertake. Recent attempts to endogenize TC include WITCH model (Bosetti et al., 2006) and Popp's (2004) ENTICE model. Popp (2004) shows that models that ignore directed TC do indeed significantly overstate the costs of environmental regulation (more detailed discussion on TC in these and more recent models is provided in Chapter 6).

An alternative approach builds on new growth theories, where TC is by its nature endogenous, in order to look at the interactions between growth and the environment. Policies like R&D subsidies or carbon taxes affect aggregate growth by affecting entrepreneurs' incentives to innovate. Factoring in firms' innovations dramatically changes our view of the relationship between growth and the environment. More recent work by Acemoglu et al. (2012) extends the endogenous growth literature to the case where firms can choose the direction of innovation (i.e., they can decide whether to innovate in more or less carbon-intensive technologies or sectors).[60]

In contrast, LBD models use learning curve estimates to simulate falling costs for alternative energy technologies as cumulative experience with the technology increases. One criticism of these models is that learning curve estimates provide evidence of correlation, but not causation. While LBD is easy to implement, it is difficult to identify the mechanisms through which learning occurs. Goulder and Mathai (2000) provide a theoretical model that explores the implications of modelling technological change through R&D or LBD (several empirical studies on this are reviewed in more detail in Chapter 6).

3.11.5 Policy measures for inducing R&D

Correcting the environmental externality or correcting knowledge market failures present two key options for policy intervention to encourage development of climate-friendly technologies. Patent protection, R&D tax credits, and rewarding innovation are good examples of correcting failures in knowledge markets and promoting higher rates of innovation. On the other hand, policies regulating environmental externalities, such as a carbon tax or a cap-and-trade system, influence the direction of innovation.

Chapter 15 discusses in more detail how environmental and technology policies work best in tandem (e.g., Popp, 2006; Fischer, 2008; Acemoglu et al., 2012). For instance, in evaluating a broad set of policies to reduce CO_2 emissions and promote innovation and diffusion of renewable energy in the United States electricity sector, Fischer & Newell (2008) find that a portfolio of policies (including emission pricing and R&D) achieves emission reductions at significantly lower cost than any single policy (see Chapters 7 to 13). However, Gerlagh and van der Zwaan (2006) note the importance of evaluating the trade-off between cost savings from innovation and Fischer and Newell (2008) assumptions of decreasing returns to scale due to space limitations for new solar and wind installations.

3.11.6 Technology transfer (TT)

Technology transfer (TT) has been at the centre of the scholarly debate on climate change and equity in economic development as a way for developed countries to assist developing countries access new low carbon technologies. Modes of TT include, trade in products, knowledge and technology, direct foreign investment, and international move-

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[60] Other works investigating the response of technology to environment regulations include Grübler and Messner (1998), Manne and Richels (2004b), Messner (1997), Buonanno et al. (2003), Nordhaus (2002), Di Maria and Valente (2008), Bosetti et al. (2008), Massetti et al. (2009), Grimaud and Rouge (2008), and Aghion et al. (2009).

ment of people (Hoekman et al., 2005). Phases and steps for TT involve absorption and learning, adaptation to the local environment and needs, assimilation of subsequent improvements, and generalization. Technological learning or catch-up thus proceeds in stages: importing foreign technologies; local diffusion and incremental improvements in process and product design; and marketing, with different policy measures suited to different stages of the catch-up process.

'Leapfrogging', or the skipping of some generations of technology or stages of development, is a useful concept in the climate change mitigation literature for enabling developing countries to avoid the more emissions-intensive stages of development (Watson and Sauter, 2011). Examples of successful low-carbon leapfrogging are discussed in more detail in Chapter 14.

Whether proprietary rights affect transfers of climate technologies has become a subject of significant debate. Some technologies are in the public domain; they are not patented or their patents have expired. Much of the debate on patented technologies centres on whether the temporary monopoly conferred by patents has hampered access to technology. Proponents of strong intellectual property (IP) rights believe that patents enhance TT as applicants have to disclose information on their inventions. Some climate technology sectors, for example, those producing renewable energy, have easily available substitutes and sufficient competition, so that patents on these technologies do not make them costly or prevent their spread (Barton, 2007). In other climate-related technology sectors, IP protection could be a barrier to TT (Lewis, 2007). (The subject is further discussed in Chapters 13 and 15.)

Various international agreements on climate change, trade, and intellectual property include provisions for facilitating the transfer of technology to developing countries. Climate change agreements encourage participation by developing countries and address barriers to the adoption of technologies, including financing. However, some scholars have found these agreements to be ineffective because they do not incorporate mechanisms for ensuring technology transfers to developing countries (Moon, 2008). (The literature on international cooperation on TT is further discussed in Chapters 13, 14 and 16.)

3.12 Gaps in knowledge and data

As this chapter makes clear, many questions are not completely answered by the literature. So it is prudent to end our assessment with our findings on where research might be directed over the coming decade so that the AR6 (should there be one) may be able to say more about the ethics and economics of climate change.

- To plan an appropriate response to climate change, it is important to evaluate each of the alternative responses that are available. How can we take into account changes in the world's population? Should society aim to promote the total of people's wellbeing in the world, or their average wellbeing, or something else? The answer to this question will make a great difference to the conclusions we reach.
- The economics and ethics of geoengineering is an emerging field that could become of the utmost importance to policymakers. Deeper analysis of the ethics of this topic is needed, as well as more research on the economic aspects of different possible geoengineering approaches and their potential effects and side-effects.
- To develop better estimates of the social cost of carbon and to better evaluate mitigation options, it would be helpful to have more realistic estimates of the components of the damage function, more closely connected to WGII assessments of physical impacts. Quantifying non-market values, that is, measuring valuations placed by humans on nature and culture, is highly uncertain and could be improved through more and better methods and empirical studies. As discussed in Section 3.9, the aggregate damage functions used in many IAMs are generated from a remarkable paucity of data and are thus of low reliability.
- The development of regulatory mechanisms for mitigation would be helped by more ex-post evaluation of existing regulations, addressing the effectiveness of different regulatory approaches, both singly and jointly. For instance, understanding, retrospectively, the effectiveness of the European Union Emissions Trading Scheme (EU ETS), the California cap-and-trade system, or the interplay between renewable standards and carbon regulations in a variety of countries.
- Energy models need to provide a more realistic portrait of micro-economic decision-making frameworks for technology-choice (energy-economy models).
- A literature is emerging in economics and ethics on the risk of catastrophic climate change impacts, but much more probing into the ethical dimensions is needed to inform future economic analysis.
- More research that incorporates behavioural economics into climate change mitigation is needed. For instance, more work on understanding how individuals and their social preferences respond to (ambitious) policy instruments and make decisions relevant to climate change is critical.
- Despite the importance of the cost of mitigation, the aggregate cost of mitigating x tonnes of carbon globally is poorly understood. To put it differently, a global carbon tax of x dollars per tonne

U.S. DEPT OF INTERIOR
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2016 NOV 14 [illegible]

would yield y(t) tonnes of carbon abatement at time, t. We do not understand the relationship between x and y(t).

- The choice of the rate at which future uncertain climate damages are discounted depends on their risk profile in relation to other risks in the economy. By how much does mitigating climate change reduce the aggregate uncertainty faced by future generations?

- As has been recently underscored by several authors (Pindyck, 2013; Stern, 2013) as well as this review, integrated assessment models have very significant shortcomings for CBA, as they do not fully represent climate damages, yet remain important tools for investigating climate policy. They have been widely and successfully applied for CEA analysis (Paltsev et al., 2008; Clarke et al., 2009; Krey and Clarke, 2011; Fawcett et al., 2013). Research into improving the state-of-the-art of such models (beyond just updating) can have high payoff.

3.13 Frequently Asked Questions

FAQ 3.1 The IPCC is charged with providing the world with a clear scientific view of the current state of knowledge on climate change. Why does it need to consider ethics?

The IPCC aims to provide information that can be used by governments and other agents when they are considering what they should do about climate change. The question of what they should do is a normative one and thus has ethical dimensions because it generally involves the conflicting interests of different people. The answer rests implicitly or explicitly on ethical judgements. For instance, an answer may depend on a judgement about the responsibility of the present generation towards people who will live in the future or on a judgement about how this responsibility should be distributed among different groups in the present generation. The methods of ethical theory investigate the basis and logic of judgements such as these.

FAQ 3.2 Do the terms justice, fairness and equity mean the same thing?

The terms 'justice', 'fairness' and 'equity' are used with subtly different meanings in different disciplines and by different authors. 'Justice' and 'equity' commonly have much the same meaning: 'justice' is used more frequently in philosophy; 'equity' in social science. Many authors use 'fairness' as also synonymous with these two. In reporting on the literature, the IPCC assessment does not impose a strictly uniform usage on these terms. All three are often used synonymously. Section 3.3 describes what they refer to, generally using the term 'justice'.

Whereas justice is broadly concerned with a person receiving their due, 'fairness' is sometimes used in the narrower sense of receiving one's due (or 'fair share') in comparison with what others receive. So it is unfair if people do not all accept an appropriate share of the burden of reducing emissions, whereas on this narrow interpretation it is not unfair—though it may be unjust—for one person's emissions to harm another person. Fairness is concerned with the distribution of goods and harms among people. 'Distributive justice'—described in Section 3.3—falls under fairness on the narrow interpretation.

FAQ 3.3 What factors are relevant in considering responsibility for future measures that would mitigate climate change?

It is difficult to indicate unambiguously how much responsibility different parties should take for mitigating future emissions. Income and capacity are relevant, as are ethical perceptions of rights and justice. One might also investigate how similar issues have been dealt with in the past in non-climate contexts. Under both common law and civil law systems, those responsible for harmful actions can only be held liable if their actions infringe a legal standard, such as negligence or nuisance. Negligence is based on the standard of the reasonable person. On the other hand, liability for causing a nuisance does not exist if the actor did not know or have reason to know the effects of its conduct. If it were established that the emission of GHGs constituted wrongful conduct within the terms of the law, the nature of the causal link to the resulting harm would then have to be demonstrated.

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U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 1:07

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Sustainable Development and Equity

Coordinating Lead Authors:
Marc Fleurbaey (France/USA), Sivan Kartha (USA)

Lead Authors:
Simon Bolwig (Denmark), Yoke Ling Chee (Malaysia), Ying Chen (China), Esteve Corbera (Spain), Franck Lecocq (France), Wolfgang Lutz (IIASA/Austria), Maria Silvia Muylaert (Brazil), Richard B. Norgaard (USA), Chukwumerije Okereke (Nigeria/UK), Ambuj Sagar (USA/India)

Contributing Authors:
Paul Baer (USA), Donald A. Brown (USA), Josefa Francisco (Philippines), Michael Zwicky Hauschild (Denmark), Michael Jakob (Germany), Heike Schroeder (Germany/UK), John Thøgersen (Denmark), Kevin Urama (Nigeria/UK/Kenya)

Review Editors:
Luiz Pinguelli Rosa (Brazil), Matthias Ruth (Germany/USA), Jayant Sathaye (USA)

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Contents

BUREAU OF LAND MGMT
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2016 NOV 14 PM

U.S. DEPT OF INTERIOR
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COLO STATE OFFICE DENVER

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Executive Summary

Since the first assessment report, the Intergovernmental Panel on Climate Change (IPCC) has considered issues of sustainable development (SD) and equity: acknowledging the importance to climate decision making, and progressively expanding the scope to include: the co-benefits of climate actions for SD and equity, the relevance of lifestyle and behaviour, the relevance of technological choices, the relevance of procedural equity to effective decision making, and the relevance of ethical frameworks and equitable burden sharing in assessing climate responses. This Assessment Report further explores key dimensions of SD and equity, highlighting the significance of disparities across different regions and groups, and the ways in which designing a climate policy is a component of a wide-ranging societal choice of a development path. [Section 4.1, 4.2]

Sustainable development, a central framing issue in this Assessment Report, is intimately connected to climate change (*high confidence*). SD is variably conceived as development that preserves the interests of future generations, that preserves the ecosystem services on which continued human flourishing depends, or that harmonizes the co-evolution of three pillars (economic, social, environmental) [4.2]. First, the climate threat constrains possible development paths, and sufficiently disruptive climate change could preclude any prospect for a sustainable future (*medium evidence, high agreement*). Thus, a stable climate is one component of SD. Second, there are synergies and tradeoffs between climate responses and broader SD goals, because some climate responses generate co-benefits for human and economic development, while others can have adverse side-effects and generate risks (*robust evidence, high agreement*). These co-benefits and risks are studied in the sector chapters of this report, along with measures and strategies to optimize them. Options for equitable burden sharing can reduce the potential for the costs of climate action to constrain development (*medium evidence, high agreement*). Third, at a more fundamental level, the capacities underlying an effective climate response overlap strongly with capacities for SD (*medium evidence, high agreement*) and designing an effective climate policy involves 'mainstreaming' climate in the design of comprehensive SD strategies and thinking through the general orientation of development (*medium evidence, medium agreement*). [4.2, 4.5]

Equity is an integral dimension of SD (*high confidence*). First, intergenerational equity underlies the concept of sustainability. Intragenerational equity is also often considered an intrinsic component of SD. In the particular context of international climate policy discussions, several arguments support giving equity an important role: a moral justification that draws upon ethical principles; a legal justification that appeals to existing treaty commitments and soft law agreements to cooperate on the basis of stated equity principles; and an effectiveness justification that argues that a fair arrangement is more likely to be agreed internationally and successfully implemented domestically (*medium evidence, medium agreement*). A relatively small set of core equity principles serve as the basis for most discussions of equitable burden sharing in a climate regime: responsibility (for GHG emissions), capacity (ability to pay for mitigation, but sometimes other dimensions of mitigative capacity), the right to development, and equality (often interpreted as an equal entitlement to emit). [4.2, 4.6]

While it is possible to envision an evolution toward equitable and sustainable development, its underlying determinants are also deeply embedded in existing societal patterns that are unsustainable and highly inertial (*high confidence*). A useful set of determinants from which to examine the prospects for and impediments to SD and equity are: the legacy of development relations; governance and political economy; population and demography; values and behaviour; human and social capital; technology; natural resource endowments; and finance and investment. The evolution of each of these determinants as a driver (rather than barrier) to a SD transition is conceivable, but also poses profound challenges (*medium evidence, medium agreement*). [4.3]

Governing a transition toward an effective climate response and SD pathway is a challenge involving rethinking our relation to nature, accounting for multiple generations and interests (including those based on endowments in natural resources), overlapping environmental issues, among actors with widely unequal capacities, resources, and political power, and divergent conceptions of justice (*high confidence*). Key debated issues include articulating top-down and bottom-up approaches, engaging participation of diverse countries and actors, creating procedurally equitable forms of decentralization and combining market mechanisms with government action, all in a particular political economic context (*robust evidence, high agreement*). [4.3]

Technology and finance both are strong determinants of future societal paths, and while society's current systems of allocating resources and prioritizing efforts toward investment and innovation are in many ways robust and dynamic, there are also some fundamental tensions with the underlying objectives of SD (*high confidence*). First, the technological innovation and financial systems are highly responsive to short-term motivations, and are sensitive to broader social and environmental costs and benefits only to the—often limited—extent that these costs and benefits are internalized by regulation, taxation, laws and social norms. Second, while these systems are quite responsive to market demand that is supported by purchasing power, they are only indirectly responsive to needs, particularly of those of the world's poor, and they operate with a time horizon that disregards potential needs of future generations (*medium evidence, medium agreement*). [4.3]

Enhancing human capital based on individual knowledge and skills, and social capital based on mutually beneficial formal and informal relationships is important for facilitating a transition toward sustainable development (*medium evidence, high agreement*). 'Social dilemmas' arise in which short-term individual interests conflict with long-term social interests, with altruistic values being favourable to SD. However, the formation of values and their translation into behaviours is mediated by many factors, including the available set of market choices and lifestyles, the tenor of dominant information sources (including advertisements and popular culture), the culture and priorities of formal and civil institutions, and prevailing governance mode (*medium evidence, medium agreement*). The demographic transition toward low fertility rates is usually viewed favorably, though an ageing population creates economic and social challenges, and migrations due to climate impacts may exacerbate tensions (*medium evidence, medium agreement*). [4.3, 4.4]

The global consumption of goods and services has increased dramatically over the last decades, in both absolute and per capita terms, and is a key driver of environmental degradation, including global warming (*high confidence*). This trend involves the spread of high-consumption lifestyles in some countries and subregions, while in other parts of the world large populations continue to live in poverty. There are high disparities in consumption both between and within countries (*robust evidence, high agreement*). [4.4]

Two basic types of decoupling are often invoked in the context of a transition toward sustainable development: the decoupling of material resource consumption (including fossil fuels) and environmental impact (including climate change) from economic growth, and the decoupling of economic growth from human well-being (*high confidence*). The first type—the dematerialization of the economy, i.e., of consumption and production—is generally considered crucial for meeting SD and equity goals, including mitigation of climate change. Production-based (territorial) accounting suggests that some decoupling of impacts from economic growth has occurred, especially in industrialized countries, but its extent is significantly diminished based on a consumption-based accounting (*robust evidence, medium agreement*). Consumption-based emissions are more strongly associated with Gross Domestic Product (GDP) than production-based emissions, because wealthier countries generally satisfy a higher share of their final consumption of products through net imports compared to poorer countries. Ultimately, absolute levels of resource use and environmental impact—including GHG emissions—generally continue to rise with GDP (*robust evidence, high agreement*), though great variations between countries highlight the importance of other factors such as geography, energy system, production methods, waste management, household size, diet and lifestyle. The second type of decoupling—of human well-being from economic growth—is a more controversial goal than the first. There are ethical controversies about the measure of well-being and the use of subjective data for this purpose (*robust evidence, medium agreement*). There are also empirical controversies about the relationship between subjective well-being and income, with some recent studies across countries finding a clear relationship between average levels of life satisfaction and per capita income, while the evidence about the long-term relationship between satisfaction and income is less conclusive and quite diverse among countries (*medium evidence, medium agreement*). Studies of emotional well-being do identify clear satiation points beyond which further increases in income no longer enhance emotional well-being (*medium evidence, medium agreement*). Furthermore, income inequality has been found to have a marked negative effect on average subjective well-being, due to perceived unfairness and undermined trust of institutions among low income groups (*medium evidence, medium agreement*). [4.4]

Understanding the impact of development paths on emissions and mitigative capacity, and, more generally, how development paths can be made more sustainable and more equitable in the future requires in-depth analysis of the mechanisms that underpin these paths (*high confidence*). Of particular importance are the processes that may generate path dependence and lock-ins, notably 'increasing returns' but also use of scarce resources, switching costs, negative externalities or complementarities between outcomes (*robust evidence, high agreement*). [4.5, 4.6] The study of transitions between pathways is an emerging field, notably in the context of technology transitions. Yet analyzing how to transition to a sustainable, low-emission pathway remains a major scientific challenge. It would be aided by models with a holistic framework encompassing the economy, society (in particular the distribution of resources and well-being), and the environment, that take account of relevant technical constraints and trends, and explore a long-term horizon while simultaneously capturing processes relevant for the short-term and the key uncertainties (*medium evidence, medium agreement*). [4.5, 4.7]

Mitigation and adaptation measures can strongly affect broader SD and equity objectives, and it is thus useful to understand their broader implications (*high confidence*). Building both mitigative capacity and adaptive capacity relies to a profound extent on the same factors as those that are integral to equitable and sustainable development (*medium evidence, high agreement*), and equitable burden sharing can enhance these capacities where they are most fragile [4.6]. This chapter focuses on examining ways in which the broader objectives of equitable and sustainable development provide a policy frame for an effective, robust, and long-term response to the climate problem. [4.8]

U.S. DEPT OF INTERIOR
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4.1 Introduction

4.1.1 Key messages of previous IPCC reports

This chapter seeks to place climate change, and climate change mitigation in particular, in the context of equity and SD. Prior IPCC assessments have sought to do this as well, progressively expanding the scope of assessment to include broader and more insightful reflections on the policy-relevant contributions of academic literature.

The IPCC First Assessment Report (FAR) (IPCC, 1990) underscored the relevance of equity and SD to climate policy. Mandated to identify "possible elements for inclusion in a framework convention on climate change", the IPCC prominently put forward the "endorsement and elaboration of the concept of sustainable development" for negotiators to consider as part of the Convention's Preamble. It noted as key issues "how to address equitably the consequences for all" and "whether obligations should be equitably differentiated according to countries' respective responsibilities for causing and combating climate change and their level of development". This set the stage for the ensuing United Nations Framework Convention on Climate Change (UNFCCC) negotiations, which ultimately included explicit appeals to equity and SD, including in its Preamble, its Principles (Article 2), its Objective (Article 3), and its Commitments (Article 4).

The IPCC Second Assessment Report (SAR) (IPCC, 1995), published after the UNFCCC was signed, maintained this focus on equity and SD. It reflected a growing appreciation for the prospects for SD co-benefits and reiterated the policy relevance of equity and SD. It did this most visibly in a special section of the Summary for Policymakers presenting "Information Relevant to Interpreting Article 2 of the UNFCCC", including "Equity and social considerations" and "Economic development to proceed in a sustainable manner". Notably, the SAR added an emphasis on procedural equity through a legitimate process that empowers all actors to effectively participate, and on the need to build capacities and strengthen institutions, particularly in developing countries.

The IPCC Special Report on Emission Scenarios (SRES) (IPCC, 2000) demonstrated that broader SD goals can contribute indirectly, yet substantially, to reducing emissions. This IPCC contribution reflected a change in the scientific literature, which had in recent years expanded its discussion of SD to encompass analyses of lifestyles, culture, and behaviour, complementing its traditional techno-economic analyses. It also reflected a recognition that economic growth (especially as currently measured) is not the sole goal of societies. The SRES thus provided insights into how policy intervention can decouple economic growth from emissions and well-being from economic growth, showing that both forms of decoupling are important elements of a transition to a world with low greenhouse gas (GHG) emissions.

The IPCC Third Assessment Report (TAR) (IPCC, 2001) deepened the consideration of broader SD objectives in assessing response strategies. Perhaps owing to a growing appreciation for the severity of the climate challenge, the TAR stressed the need for an ambitious and encompassing response, and was thus more attentive to the risk of climate-focused measures conflicting with basic development aspirations. It thus articulated the fundamental equity challenge of climate change as ensuring "that neither the impact of climate change nor that of mitigation policies exacerbates existing inequities both within and across nations", specifically because "restrictions on emissions will continue to be viewed by many people in developing countries as yet another constraint on the development process" (See Box 4.1 for further discussion of the relationship between climate change and development challenges in developing countries.). The TAR recognized the need to deepen the analysis of equitable burden sharing in order to avoid undermining prospects for SD in developing countries. More generally, the TAR observed that equitable burden sharing is not solely an ethical matter. Even from a rational-actor game-theoretic perspective, an agreement in which the burden is equitably shared is more likely to be signed by a large number of countries, and thus to be more effective and efficient.

The IPCC Fourth Assessment Report (AR4) (IPCC, 2007) further expanded the consideration of broader SD objectives. It stressed the importance of civil society and other non-government actors in designing climate policy and equitable SD strategies generally. The AR4 focused more strongly on the distributional implications of climate policies, noting that conventional climate policy analysis that is based too narrowly on traditional utilitarian or cost-benefit frameworks will neglect critical equity issues. These oversights include human rights implications and moral imperatives; the distribution of costs and benefits of a given set of policies, and the further distributional inequities that arise when the poor have limited scope to influence policy. This is particularly problematic, the AR4 notes, in integrated assessment model (IAM) analyses of 'optimal' mitigation pathways, because climate impacts do not affect the poor exclusively through changes in incomes. Nor do they satisfactorily account for uncertainty and risk, which the poor treat differently than the rich. The poor have higher risk aversion and lower access to assets and financial mechanisms that buffer against shocks. The AR4 went on to outline alternative ethical frameworks including rights-based and capabilities-based approaches, suggesting how they can inform climate policy decisions. In particular, the AR4 discussed the implications of these different frameworks for equitable international burden sharing.

The IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) (IPCC, 2011) deepened the consideration of broader SD objectives in assessing renewable energy options, noting particularly that while synergies can arise (for example, helping to expand access to energy services, increase energy security, and reduce some environmental pressures), there can also be tradeoffs (such as increased pressure on land resources, and affordability) and these must be negotiated in a manner sensitive to equity considerations.

The IPCC Special Report on Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (SREX) (IPCC 2012a) highlighted key further dimensions of SD and equity, including the distinction and interplay between incremental and transformative changes—both of which are necessary for an effective climate policy response, and emphasized the diversity of values that underlie decision making, e.g., a human rights framework vs. utilitarian cost-benefit analysis.

4.1.2 Narrative focus and key messages

In keeping with the previous IPCC assessments, this chapter considers SD and equity as matters of policy relevance for climate change decision makers. The chapter examines the ways in which climate change is in fact inextricably linked with SD and equity, and it does so with the aim of drawing policy-relevant conclusions regarding equitable and sustainable responses to climate change.

In one direction, the link is self-evident: an effective climate response is necessary for equitable and sustainable development to occur. The disruptions that climate change would cause in the absence of an effective societal response are sufficiently severe (see Working Group (WG) I and II contributions to the IPCC Fifth Assessment Report (AR5)) to severely compromise development, even taking into account future societies' ability to adapt (Shalizi and Lecocq, 2010). Nor is this development likely to be equitable, as an increasingly inhospitable climate will most seriously undermine the future prospects of those nations, communities, and individuals that are in greatest need of development. Without an effective response to climate change, including both timely mitigation and proactive adaptation, development can be neither sustainable nor equitable.

In recent years, the academic community has come increasingly to appreciate the extent to which SD and equity are also needed as frameworks for assessing and prioritizing climate responses: given the strong tradeoffs and synergies between the options for a climate response and SD, the design of an effective climate response must accord with the objectives for development and equity and exploit the synergies. A climate strategy that does not do so runs the risk either of being ineffective for lack of consensus and earnest implementation or of jeopardizing SD just as would unabated climate change. Therefore, a shift toward more equitable and sustainable modes of development may provide the only context in which an effective climate response can be realized.

The scientific community is coming to understand that climate change is but one example of how humankind is pressing up against its planetary limits (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009a). Technical measures can certainly help in the near-term to alleviate climate change. However, the comprehensive and durable strategies society needs are those that recognize that climate change shares its root causes with other dimensions of the global sustainability crisis, and that without addressing these root causes, robust solutions may not be accessible.

This chapter, and many parts of this report, uncovers ways in which a broader agenda of SD and equity may support and enable an effective societal response to the climate challenge, by establishing the basis by which mitigative and adaptive capacity can be built and sustained. In examining this perspective, this chapter focuses on several broad themes.

4.1.2.1 Consumption, disparities, and well-being

The first theme relates to well-being and consumption. The relationship between consumption levels and environmental pressures, including GHG emissions, has long been a key concern for SD, with a growing focus on high-consumption lifestyles in particular and consumption disparities. A significant part of the literature develops methodologies for assessing the environmental impacts across national boundaries of consumption, through consumption-based accounting and GHG footprint analysis. Important research is now also emerging on the relationship between well-being and consumption, and how to moderate consumption and its impacts without hindering well-being—and indeed, while enhancing it. More research is now available on the importance of behaviour, lifestyles, and culture, and their relationship to over-consumption (Sections 4.3, 4.4).

Research is emerging to help understand 'under-consumption', i.e., poverty and deprivation, and its impacts on well-being more broadly, and specifically on the means by which it undermines mitigative and adaptive capacity (WGII Chapter 20). Energy poverty is one critical example, linked directly to climate change, of under-consumption that is well-correlated with weakened livelihoods, lack of resilience, and limited mitigative and adaptive capacity. Overcoming under-consumption and reversing over-consumption, while maintaining and advancing human well-being, are fundamental dimensions of SD, and are equally critical to resolving the climate problem (Sections 4.5, 4.6).

4.1.2.2 Equity at the national and international scales

Given the disparities evident in consumption patterns, the distributional implications of climate response strategies are critically important. As recent history shows, understanding how policies affect different segments of the population is essential to designing and implementing politically acceptable and effective national climate response strategies. A transition perceived as just would attract a greater level of public support for the substantial techno-economic, institutional, and lifestyle shifts needed to reduce emissions substantially and enable adaptive responses.

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2016 NOV 14 PM 1:17

At the international level, an equitable regime with fair burden sharing is likely to be a key condition for an effective global response (Sections 4.2, 4.6). Given the urgency of the climate challenge, a rather rapid transition will be required if the global temperature rise is to remain below the politically discussed targets, such as 1.5 °C or 2 °C over pre-industrial levels, with global emissions possibly peaking as soon as 2020 (see WGI, Figure 6.25). Particularly in a situation calling for a concerted global effort, the most promising response is a cooperative approach "that would quickly require humanity to think like a society of people, not like a collection of individual states" (Victor, 1998).

While scientific assessments cannot define what equity is and how equitable burden sharing should be implementing the Convention and climate policies in general, they can help illuminate the implications of alternative choices and their ethical basis (Section 4.6, also Sections 3.2, 3.3, 6.3.6, 13.4.3).

Box 4.1 | Sustainable development and climate change mitigation in developing countries

The interconnectedness of climate change, sustainable development, and equity poses serious challenges for developing countries but it also presents opportunities.

Developing countries are confronted by a daunting mitigation challenge in the midst of pressing development needs. Developing country emissions comprised more than half of global emissions in 2010, and grew during the preceding decade by an amount that accounted for the total global emissions rise (JRC/PBL (2013), IEA (2012a), see Annex II.9; see Section 5.2). In the absence of concerted mitigation actions, the coming decades would see this trend prolonged, with a continued growth in global emissions driven predominantly by developing countries' rising emissions (see Section 6.3). This trend is the unsurprising outcome of the recent economic growth in many developing countries. The increase in emissions coincided with a number of positive developments: over the past decade, the overall poverty rate has declined, maternal and child mortality have fallen, the prevalence of several preventable diseases has decreased, and access to safe drinking water and sanitation has expanded, while the Human Development Index (HDI) across nations has risen and its convergence has become more pronounced. This "rise of the South" has been termed "unprecedented in its speed and scale [...] affecting a hundred times as many people as the Industrial Revolution" and setting in motion a "dramatic rebalancing" of economic and geopolitical forces (United Nations, 2011a; United Nations Development Programme, 2013).

Notwithstanding these gains, further developmental progress is urgently needed throughout the developing world. More than 1.5 billion people remain in multi-dimensional poverty, energy insecurity is still widespread, inequality of income and access to social services is persistently high, and the environmental resource base on which humans rely is deteriorating in multiple ways (Millennium Ecosystem Assessment, 2005; Bazilian et al., 2010; United Nations Development Programme, 2013). Moreover, unavoidable climate change will amplify the challenges of development: climate impacts are expected to slow economic growth and exacerbate poverty, and current failures to address emerging impacts are already eroding the basis for sustainable development (WGII SPM).

Thus, the challenge confronting developing countries is to preserve and build on the developmental achievements to date, sharing them broadly and equitably across their populations, but to do so via a sustainable development pathway that does not reproduce the fossil-fuel based and emissions-intensive conventional pathway by which the developed world moved from poverty to prosperity. Faced with this dilemma, developing countries have sought evidence that such alternative development pathways exist, looking in particular to developed countries to take the lead during the two decades since the UNFCCC was negotiated. Some such evidence has emerged, in the form of a variety of incipient climate policy experiments (see Section 15.6, 15.7) that appear to have generated some innovation in low-carbon technologies (see Section 4.4) and modestly curbed emissions in some countries (see Section 5.3).

Developing countries have stepped forward with significant actions to address climate change, but will need to build mitigative and adaptive capacity if they are to respond yet more effectively (see Section 4.6). More broadly, the underlying determinants of development pathways in developing countries are often not aligned toward a sustainable pathway (see Sections 4.3, 4.5). At the same time, developing countries are in some ways well-positioned to shift toward sustainable pathways: most developing countries are still in the process of building their urban and industrial infrastructure and can avoid lock-in (see Sections 4.5, 5.6). Many are also in the process of establishing the cultural norms and lifestyles of an emerging middle class, and can do so without reproducing the consumerist values of many developed countries (4.3, 4.4). Some barriers, such as lack of access to financial and technological resources, can be overcome through international cooperation based on principles of equity and fair burden sharing (see Sections 4.6, 6.3).

4.1.2.3 Building institutions and capacity for effective governance

While there is strong evidence that a transition to a sustainable and equitable path is technically feasible (see Sections 6.1.2, 6.3), charting an effective and viable course through the climate challenge is not merely a technical exercise. It will involve myriad and sequential decisions, among states and civil society actors, supported by the broadest possible constituencies (Section 4.3). Such a process benefits from the education and empowerment of diverse actors to participate in systems of decision making that are designed and implemented with procedural equity as a deliberate objective. This applies at the national as well as international levels, where effective governance relating to global common resources, in particular, is not yet mature.

Any given approach to addressing the climate challenge has potential winners and losers. The political feasibility of that approach will depend strongly on the distribution of power, resources, and decision-making authority among the potential winners and losers. In a world characterized by profound disparities, procedurally equitable systems of engagement, decision making, and governance appear needed to enable a polity to come to equitable and sustainable solutions to the sustainable development challenge.

4.2 Approaches and indicators

This section maps out the various conceptual approaches to the issues of SD (4.2.1), equity (4.2.2), and their linkages to climate change and climate policy.

4.2.1 Sustainability and sustainable development (SD)

4.2.1.1 Defining and measuring sustainability

The most frequently quoted definition of SD is "development that meets the needs of the present without compromising the ability of future generations to meet their own needs", from the Brundtland Report (World Commission on Environment and Development, 1987). This definition acknowledges a tension between sustainability and development (Jabareen, 2006), and that development objectives aim at meeting basic needs for all citizens and securing them in a sustainable manner (Murdiyarso, 2010). One of the first definitions of SD (Prescott-Allen, 1980) refers to a development process that is compatible with the preservation of ecosystems and species.

A popular conceptualization of SD goes beyond securing needs and preserving the environment and involves three 'pillars' or three 'bottom-lines' of sustainability: environmental, economic, and social aspects (Dobson, 1991; Elkington, 1998; Flint and Danner, 2001; Pope et al., 2004; Sneddon et al., 2006; Murdiyarso, 2010; Okereke, 2011). There is some variation in the articulation of the three spheres, with some scholars arguing for an equal appraisal of their co-evolution and mutual interactions, and others positing a hierarchy with economic activities embedded in the social matrix, which is itself grounded in the ecosphere (Levin, 2000; Fischer et al., 2007). This broad SD framework is equally relevant for rich countries concerned with growth, well-being, human development, and lifestyles.

A well-known distinction opposes weak sustainability to strong sustainability approaches (Neumayer, 2010). The former relies on the assumption that human-made capital can replace natural resources and ecosystem services with a high degree of substitutability. Strong sustainability, in contrast, takes the view that certain critical natural stocks—such as the climate system and biodiversity—cannot be replaced by human-made capital and must be maintained. Weak sustainability is often believed to be inherent to economic modelling that aggregates all forms of capital together (Dietz and Neumayer, 2007), but economic models and indicators can accommodate any degree of substitutability between different forms of capital (Fleurbaey and Blanchet, 2013). The linkage between strong sustainability and IAMs is discussed in Sathaye et al. (2011). A different but related issue is whether one should evaluate development paths only in terms of human well-being, which depends on the environment services (Millennium Ecosystem Assessment, 2005), or also account for natural systems as intrinsically valuable (McShane, 2007; Attfield, 2008).

Sustainability is closely related to resilience (WII AR5 2.5 and 20.2–20.6; Folke et al., 2010; Gallopin, 2006; Goerner et al., 2009) and vulnerability (Kates, 2001; Clark and Dickson, 2003; IPCC, 2012a). A key premise of this direction of research is that social and biophysical processes are interdependent and co-evolving (Polsky and Eakin, 2011). The biosphere itself is a complex adaptive system, the monitoring of which is still perfectible (Levin, 2000; Thuiller, 2007). Critical perspectives on these concepts, when applied to SD analysis, can be found in Turner (2010) and Cannon and Müller-Mahn (2010).

Although there are various conceptions of sustainability in the literature, there are internationally agreed principles of SD adopted by heads of states and governments at the 1992 UN Conference on Environment and Development (UNCED) and reaffirmed at subsequent review and implementation conferences (United Nations, 1992a, 1997, 2002, 2012a). A key guiding principle is: "The right to development must be fulfilled so as to equitably meet developmental and environmental needs of present and future generations" (1992 Rio Declaration Principle 3). The Rio principles were reaffirmed at the June 2012 summit level UN Conference on SD.

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2016 NOV 14 PM 12:07

Box 4.2 | Sustainable development indicators (SDI)

When SD became a prominent consideration in policymaking in the early 1990s, SDI initiatives flourished. Pressure-state-response (PSR) and capital accounting-based (CAB) frameworks, in particular, were widely used to assess sustainability. The PSR approach was further modified as driving force-state-response (DSR) by the United Nations Conference on Sustainable Development (UNCSD) (2001) and driving force-pressure-state-impact-response (DPSIR) by the United Nations Environment Programme (UNEP) (UNEP, 1997, 2000, 2002). The System of Integrated Environmental-Economic Accounting (SEEA) of the United Nations offers a wealth of information about the state of ecosystems and is currently under revision and expansion.[1] The CAB approach is embodied in the Adjusted Net Savings indicator of the World Bank (2003, 2011), which is mentioned in Section 4.3 and 14.1 of this report. It is based on the economic theory of 'genuine savings' (understood as the variation of all natural and man-made capital stocks, evaluated at certain specific accounting prices), which shows that on a path that maximizes the discounted utilitarian sum, a negative value for genuine savings implies that the current level of well-being is not sustainable (Hamilton and Clemens, 1999; Pezzey, 2004).

General presentations and critical assessments of SDIs can be found in a large literature (Daly, 1996; Aronsson et al., 1997; Pezzey and Toman, 2002; Lawn, 2003; Hamilton and Atkinson, 2006; Asheim, 2007; Dietz and Neumayer, 2007; Neumayer, 2010; Martinet, 2012; Mori and Christodoulou, 2012; Fleurbaey and Blanchet, 2013). This literature is pervaded by a concern for comprehensiveness—i.e., recording all important aspects of well-being, equity, and nature preservation for current and future generations—and accuracy—i.e., avoiding arbitrary or unreliable weighting of the relevant dimensions when synthesizing multidimensional information. The general conclusion of this literature is that there is currently no satisfactory empirical indicator of sustainability.

A limitation of the PSR model is that it fails to identify causal relations, and it oversimplifies the links between dimensions. It is moreover based upon aggregate indices, which lose much information contained in the underlying indicators. An important limitation of the SEEA is that social and institutional issues are essentially left out, and its stock-and-flow approach is problematic with respect to environmental and social aspects that do not have a market price. Similarly, computing CAB indicators compounds the difficulty of comprehensively estimating the evolution of capital stocks with the difficulty of computing the accounting prices. Market prices do provide relevant information for valuing capital stocks in a perfectly managed economy (as shown by Weitzman, 1976), but may be very misleading in actual conditions (Dasgupta and Mäler, 2000; Arrow et al., 2012).

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[1] Documentation is available at http://unstats.un.org/unsd/envaccounting/seea.asp.

4.2.1.2 Links with climate change and climate policy

The literature on the complex relations between climate change, climate policies, and SD is large (Swart et al., 2003; Robinson et al., 2006; Bizikova et al., 2007; Sathaye et al., 2007; Thuiller, 2007; Akimoto et al., 2012; Janetos et al., 2012). The links between SD and climate issues are examined in detail in WGII Chapter 20. Mapping out these links is also important in this WGIII report, and is done in this section.

Three main linkages can be identified, each of which contains many elements. First, the climate threat constrains possible development paths, and sufficiently disruptive climate change could preclude any prospect for sustainable future (WGII Chapter 19). In this perspective, an effective climate response is necessarily an integral objective of an SD strategy.

Second, there are tradeoffs between climate responses and broader SD goals, because some climate responses can impose other environmental pressures, have adverse distributional effects, draw resources away from other developmental priorities, or otherwise impose limitations on growth and development (Sections 4.6, 7.11, 8.9, 9.9, 10.10, 11.9, 12.8). Section 4.4 examines how to avoid such tradeoffs by changing behavioural patterns and decoupling emissions and growth, and/or decoupling growth and well-being.

Third, there are multiple potential synergies between climate responses and broader SD objectives. Climate responses may generate co-benefits for human and economic development (Sections 3.6, 4.8, 6.6, 7.9, 8.7, 9.7, 10.8, 11.7). At a more fundamental level, capacities underlying an effective climate response overlap strongly with capacities for SD (Sections 4.6, 5.3).

A key message of this report is that designing a successful climate policy may require going beyond a narrow focus on mitigation and adaptation, beyond the analysis of a few co-benefits of climate policy, and may instead require 'mainstreaming' climate issues into the design of comprehensive SD strategies, including at local and regional levels. Figure 4.1 illustrates the different perspectives from which climate policy can be envisioned. In the broadest, boldest perspective, the choice of the development path (see Sections 4.5, 6.1) is at stake.

4.2.2 Equity and its relation to sustainable development and climate change

Equity is prominent in research and policy debates about SD and climate, both as distributive equity (distribution of resources in contexts such as burden sharing, distribution of well-being in the broader context of social justice, see Sections 3.3, 4.4, 4.6) and procedural equity (participation in decision making, see Section 4.3). Various aspects of the general concept, as developed in social ethics, are introduced in Section 3.2 under the name of fairness and justice. (In this chapter the terms equity, fairness, and justice are not distinguished but are used according to common usage depending on context). The aim of this subsection is to analyze the links between equity, SD, and climate issues.

Equity *between* generations underlies the very notion of SD. Figure 4.2, a variant of a figure from Howarth and Norgaard (1992), illustrates sustainability as the possibility for future generations to reach at least the same level of well-being as the current generation. It shows in particular that sustainability is a matter of distributive equity, not of efficiency, even if eliminating inefficiencies affecting future sustainable well-being may improve sustainability, as stressed in Grubb et al. (2013).

There has been a recent surge of research on intergenerational equity, motivated by dissatisfaction with the tradition of discounting the utility of future generations in the analysis of growth paths (see, e.g., Asheim (2007), Roemer and Suzumura (2002) for recent syntheses). The debate on discounting is reviewed in Section 3.6.2. Recent literature presents new arguments deriving the imperative of sustaining well-being across generations from more basic equity principles (Asheim et al., 2001, 2012).

Equity *within* every generation is often considered an intrinsic component of SD linked to the social pillar. The Millennium Development Goals (MDGs) may be seen as one indication of a more explicit global commitment to the social pillar (United Nations, 2000). Yet, the relation between equity within generations and SD is complex. Attempting to meet the needs of the world's poor by proliferating the consumption patterns and production processes of the world's richest populations would be unsustainable (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009b; Steffen et al., 2011; IPCC, 2014). Such a scenario would not likely play out well for the world's poor. Environmental issues are interwoven with the fabric of racial, social, and economic injustice. Environmental costs and benefits are often distributed so that those who already suffer other socio-economic disadvantages tend to bear the greatest burden (Okereke, 2011).

Figure 4.3 illustrates the normative framework in which a SD path can be grounded on certain values (well-being, equity) and interrelated goals (development and conservation), and the synergies and tradeoffs between SD and climate policy, with procedural equity and iterative learning nurturing each step, from conceptualization to implementation.

In the rest of this section, we focus on one key dimension of equity that is of central importance to international negotiations toward an effective global response to climate change. As in many other contexts, fundamental questions of resource allocation and burden sharing arise in climate change, and therefore equity principles are invoked and debated. Three lines of argument have been put forward to justify a reference to equity in this context (Section 4.6 examines the details of burden sharing principles and frameworks in a climate regime.)

The first justification is the normative claim that it is morally proper to allocate burdens associated with our common global climate challenge according to ethical principles. The broad set of ethical arguments for ascribing moral obligations to individual nations has been reviewed in Section 3.3, drawing implicitly upon a cosmopolitan view of justice, which posits that some of the basic rights and duties that arise between people within nations also hold between people of different nations.

The second justification is the legal claim that countries have accepted treaty commitments to act against climate change that include the commitment to share the burden of action equitably. This claim derives from the fact that signatories to the UNFCCC have agreed that: "Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities" (UNFCCC, 2002). These commitments are consistent with a body of soft law and norms such as the no-harm rule according to which a state must prevent, reduce or control the risk of serious environmental harm to other states (Stockholm Convention (UNEP, 1972), Rio declaration (United Nations, 1992b), Stone, 2004). In addition, it has been noted that climate change adversely affects a range of human rights that are incorporated in widely ratified treaties (Aminzadeh, 2006; Humphreys, 2009; Knox, 2009; Wewerinke and Yu III, 2010; Bodansky, 2010).

Figure 4.1 | Three frameworks for thinking about mitigation.

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2016 NOV 14 PM 4:07

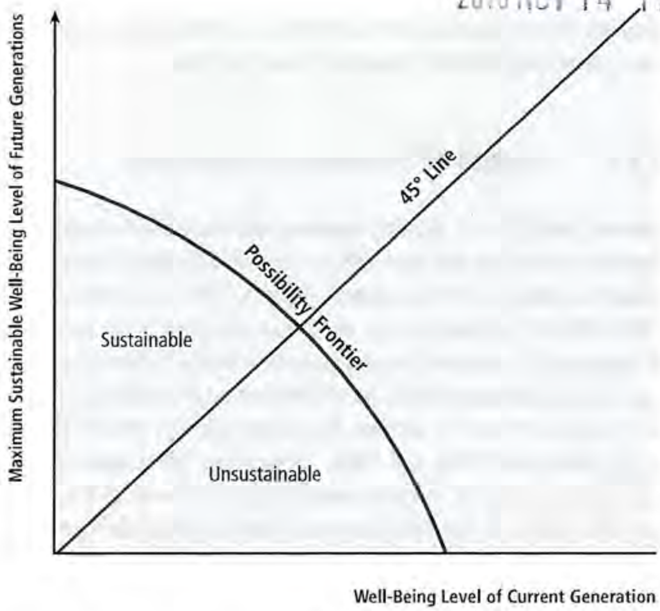

Figure 4.2 | The well-being level of the current generation is sustainable if it does not exceed the maximum sustainable well-being level of the future generations—independently of whether one is or is not on the possibility frontier. Modified from Howarth and Norgaard (1992).

The third justification is the positive claim that equitable burden sharing will be necessary if the climate challenge is to be effectively met. This claim derives from the fact that climate change is a classic commons problem (Hardin, 1968; Soroos, 1997; Buck, 1998; Folke, 2007) (also see Section 13.2.1.1). As with any commons problem, the solution lies in collective action (Ostrom, 1990). This is true at the global scale as well as the local, only more challenging to achieve (Ostrom et al., 1999). Inducing cooperation relies, to an important degree, on convincing others that one is doing one's fair share. This is why notions of equitable burden-sharing are considered important in motivating actors to effectively respond to climate change. They are even more important given that actors are not as equal as the proverbial 'commoners', where the very name asserts homogeneity (Milanović et al., 2007). To the contrary, there are important asymmetries or inequalities between stakeholders (Okereke et al., 2009; Okereke, 2010): asymmetry in contribution to climate change (past and present), in vulnerability to the impacts of climate change, in capacity to mitigate the problem, and in power to decide on solutions. Other aspects of the relation between intragenerational equity and climate response include the gender issues noted in 4.3, and the role of virtue ethics and citizen attitudes in changing lifestyles and behaviours (Dobson, 2007; Lane, 2012), a topic analyzed in Section 4.4.

Young (2013) has identified three general conditions—which apply to the climate context—under which the successful formation and eventual effectiveness of a collective action regime may hinge on equitable burden sharing: the absence of actors who are powerful enough to coercively impose their preferred burden sharing arrangements; the inapplicability of standard utilitarian methods of calculating costs and benefits; and the fact that regime effectiveness depends on a long-term commitment of members to implement its terms. With respect to climate change, it has long been noted that a regime that many members find unfair will face severe challenges to its adoption or be vulnerable to festering tensions that jeopardize its effectiveness (Harris, 1996; Müller, 1999; Young, 2012). Specifically, any attempt to protect the climate by keeping living standards low for a large part of the world population will face strong political resistance, and will almost certainly fail (Roberts and Parks, 2007; Baer et al., 2009). While costs of participation may provide incentives for non-cooperation or defection in the short-term, the climate negotiations are not a one-shot game, and they are embedded in a much broader global context; climate change is only one of many global problems—environmental, economic, and social—that will require effective cooperative global governance if development—and indeed human welfare—is to be sustained in the long term (Singer, 2004; Jasanoff, 2004; Speth and Haas, 2006; Kjellen, 2008).

Despite these three lines of justification, the question of the role that equity does or should play in the establishment of global climate policy and burden sharing in particular is nonetheless controversial (Victor, 1998). The fact that there is no universally accepted global authority to enforce participation is taken by some to mean that sovereignty, not equity is the prevailing principle. Such a conception implies that the bottom-line criterion for a self-enforcing (Barrett, 2005) cooperative agreement would be simply that everyone is no worse off than at the status quo. This has been termed "International Paretianism" (Posner and Weisbach, 2010), and its ironic, even perverse results have been pointed out: "an optimal climate treaty could well require side payments to rich countries like the United States and rising countries like China, and indeed possibly from very poor countries which are extremely vulnerable to climate change—such as Bangladesh." (Posner and Weisbach, 2010).

Figure 4.3 | Links between SD, equity, and climate policy.

However, both critics and advocates of the importance of equity in the climate negotiations acknowledge that governments can choose to act on moral rather than purely self-interested principles (DeCanio and Fremstad, 2010; Posner and Weisbach, 2010, 2012; Baer, 2013; Jamieson, 2013) (see also Section 3.10). Whether or not states behave as rational actors, given the significant global gains to be had from cooperation, this leaves ample room for discussion of the role of equity in the distribution of those global gains, while still leaving all parties better off (Stone, 2004).

While the above discussion focuses on equity among nations, equally relevant concerns regarding equity within nations also arise, and indeed can be overriding determinants of the prospects for climate policy to be adopted. Demands for equity have been articulated by labour communities primarily in terms of a just transition (International Labour Office, 2010; Newell and Mulvaney, 2013), and often by marginalized populations and racial minorities in terms of environmental justice and just sustainability (Agyeman and Evans, 2004; Walker and Bulkeley, 2006; Shiva, 2008). While the particular demands are highly location- and context-specific, the broad concerns are procedural and about distributive justice with reduced power asymmetries, as underscored throughout this chapter.

4.3 Determinants, drivers and barriers

This section explores the determinants of SD, emphasizing how each influences the extent to which societies can balance the economic, social, and environmental pillars of SD, while highlighting potential synergies and tradeoffs for the building of mitigative and adaptive capacity and the realization of effective and equitable mitigation and adaptation strategies. Determinants refer to social processes, properties, and artefacts, as well as natural resources, which together condition and mediate the course of societal development, and thus the prospects for SD. When determinants facilitate SD they act as drivers and when they constrain it they act as barriers.

The determinants discussed include: the legacy of development relations; governance and political economy; population and demography; human and social capital; behaviour, culture, and values; technology and innovation processes; natural resources; and finance and investment. These determinants are interdependent, characterized by feedbacks that blur the distinction between cause and effect, and their relative importance depends on context—see analogous discussion in the context of GHG emission drivers in Section 5.3. They are not unique, and other determinants such as leadership (Jones and Olken, 2005), randomness (Holling, 1973; Arthur, 1989), or human nature (Wilson, 1978) could be added to the list, but they are less amenable to deliberate intervention by policy-makers and other decision makers and have therefore been excluded. What follows lays the foundations for understanding concepts that recur throughout this chapter and those that follow.

4.3.1 Legacy of development relations

Following World War II, security, economic, and humanitarian relations between rich nations and poor nations were comingled and addressed under the umbrella of 'development' (Truman, 1949; Sachs, Wolfgang, 1999). Differing perspectives on the mixed outcomes of six decades of development, and what the outcomes may indicate about underlying intentions and capabilities, inform different actors in different ways as to what will work to address climate change and the transition to SD. During the 1950s and 1960s, for example, expectations were that poverty would be reduced dramatically by the end of the century (Rist, 2003). It was widely believed that economic development could be instigated through aid from richer nations, both financial and in kind. Development was seen as a process of going through stages starting with transforming traditional agriculture through education, the introduction of new agricultural technologies, improved access to capital for farm improvements, and the construction of transportation infrastructure to facilitate markets. Improved agriculture would release workers for an industrial stage and thereby increase opportunities for education and commercial development in cities. As development proceeded, nations would increasingly acquire their own scientific capabilities and, later, sophisticated governance structures to regulate finance and industry in the public good, becoming well-rounded, well-governed economies comparable to those of rich nations.

By the 1970s, however, it was clear that development was not on a path to fulfilling these linear expectations because: 1) contributions of aid from the rich nations were not at levels anticipated; 2) technological and institutional changes were only partially successful, proved inappropriate, or had unpredicted, unfortunate consequences; 3) requests for military aid and the security and economic objectives of richer nations in the context of the Cold War were frequently given priority over poverty reduction; and 4) graft, patronage, and the favouring of special interests diverted funds from poverty reduction. The general belief that nations naturally went through stages of development to become well-rounded economies faded by the early 1980s. Greater participation in global trade, with its implied specialization, was invoked as the path to economic growth. Diverse other efforts were made to improve how development worked, but with only modest success, leaving many in rich and poor nations concerned about development process and prospects (United Nations, 2011a).

Layering the goal of environmental sustainability onto the goal of poverty reduction further compounded the legacy of unmet expectations (World Commission on Environment and Development, 1987). There have been difficulties determining, shifting to, and governing for sustainable pathways (Sanwal, 2010)—see Section 4.3.2 below. The negotiation of new rules for the mobility of private capital and the drive for globalization of the economy also came with new expec-

U.S. DEPT OF INTERIOR
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2015 NOV 16

tations for development (Stiglitz, 2002). The Millennium Development Goals (MDG) established in 2000 to be met by 2015 are an example of how such expectations were thought to be realizable in the rapidly evolving times of the global financial economy. In retrospect and after the 2008 financial sector induced recession, significant improvements are largely in China and India where economic growth accelerated through private capital flows independent of the MDG process. Excluding these countries, the record is mixed at best and still poor in most of Africa (Keyzer and Wesenbeeck, 2007; Easterly, 2009; United Nations, 2011a). Additionally, since the 1990s, greenhouse gas emissions became another focus of contention (Roberts and Parks, 2007; Penetrante, 2011; Dryzek et al., 2011). The developed nations became rich through the early use of fossil fuels and land transformations that put GHGs in the atmosphere, imposing costs on all people, rich and poor, through climate impacts that will persist over centuries (Srinivasan et al., 2008). Connections between causal and moral responsibility arose, complicating the legacy of development.

Such legacy of unmet development and sustainability expectations is open to multiple interpretations. In richer nations, the evidence can be interpreted to support the views of fiscal conservatives who oppose aid, libertarians who oppose humanitarian and environmental interventions, progressives who urge that more needs to be done to reach social and environmental goals, and some environmentalists who urge dematerialization and degrowth among the rich as necessary to meet the needs of the poor. In poorer nations, the legacy similarly supports various views including a distrust of rich nations for not delivering development and environmental assistance as promised, cynicism toward the intentions and conceptual rationales when it is provided, and also a wariness of development's unpredicted outcomes.

In both developed and developing nations these diverse sentiments among the public, policy makers, and climate negotiators contribute to what philosopher Gardiner (2011b) refers to as the "perfect moral storm" of climate policy. Some analysts argue that the legacy of development and interrelated issues of equity so cloud global climate negotiations that *ad hoc* agreements and voluntary pledges are the most that can be achieved (Victor, 2004) and considerations of development and equity are better left aside (Posner and Weisbach, 2010), although this leaves open whether such arrangements could provide an adequately ambitious climate response consistent with the UNFCCC's objectives. (See Section 4.6.2 for further discussion of perspectives on equity in a climate regime, and Section 13.4.3 for further discussion of regime architectures).

4.3.2 Governance and political economy

Governance and political economy are critical determinants for SD, equity, and climate change mitigation because they circumscribe the process through which these goals and how to attain them are articulated and contested. The quest for equity and climate change mitigation in the context of SD thus necessitates an improved understanding and practice of governance (Biermann et al., 2009; Okereke et al., 2009). Governance in the broadest sense refers to the processes of interaction and decision making among actors involved in a common problem (Kooiman, 2003; Hufty, 2011). It goes beyond notions of formal government or political authority and integrates other actors, networks, informal institutions, and incentive structures operating at various levels of social organization (Rosenau, 1990; Chotray and Stoker, 2009). In turn, climate governance has been defined as the mechanisms and measures "aimed at steering social systems towards preventing, mitigating or adapting to the risks posed by climate change" (Jagers and Stripple, 2003). From this definition, it can be seen as a broad phenomenon encompassing not only formal policymaking by states, but all the processes through which authority is generated and exerted to affect climate change and sustainability. This includes policymaking by states but also by many other actors -NGOs, TNCs, municipalities, for example—operating across various scales (Okereke et al., 2009).

Many scholars have highlighted the challenges associated with governing for SD and climate change (Adger and Jordan, 2009; Levin et al., 2012). First, it involves rethinking the ways society relates to nature and the underlying biophysical systems. This is relevant in the context of the growing evidence of the impact of human activity on the planet and the understanding that extraordinary degrees of irreversible damage and harm are distinct possibilities if the right measures are not taken within an adequate timescale (Millennium Ecosystem Assessment, 2005; Rockström et al., 2009a). Second, governing climate change involves complex intergenerational considerations. On the one hand, cause and effect of some environmental impacts and climate change are separated by decades, often generations, and on the other hand, those who bear the costs of remediation and mitigation may not be the ones to reap the benefits of avoided harm (Biermann, 2007).

Third, effective response to climate change may require a fundamental restructuring of the global economic and social systems, which in turn would involve overcoming multiple vested interests and the inertia associated with behavioural patterns and crafting new institutions that promote sustainability (Meadows et al., 2004; Millennium Ecosystem Assessment, 2005). This challenge is exacerbated by the huge mismatch between the planning horizon needed to address global environmental problems and climate change and the tenure of decision makers (Hovi et al., 2009).

Fourth, and finally, SD governance cuts across several realms of policy and organization. Particularly, the governance of mitigation and adaptation is an element of a complex and evolving arena of global environmental governance, which deals with other, and often overlapping, issues such as biodiversity loss, desertification, water management, trade, energy security, and health, among others (Adger and Jordan, 2009; Brown, 2009; Bell et al., 2010; Balsiger and Debarbieux, 2011; da Fonseca et al., 2012; Bark et al., 2012). Sites of climate change governance and policymaking are thus multiple and are not confined to the UNFCCC and national rule-making processes, a situation which raises challenges in relation to coordination, linkages, and synergies (Ostrom, 2010; Zelli, 2011; Jinnah, 2011)—see Sections 13.4, 13.13, 14.1, 15.2, notably Figure 13.1 for a visual summary.

These considerations explain why climate governance has attracted more political controversy than other issues in relation to global sustainability and its equity considerations. Some of the main aspects of this controversy include: who should participate in decision making; how to modulate power asymmetry among stakeholders; how to share responsibility among actors; what ideas and institutions should govern response measures; and where should interventions focus? Questions of justice are embedded throughout, aggravated by the high stakes involved and the stark asymmetry among states and others actors in terms of cause, effect, and capability to respond to the problem (Okereke and Dooley, 2010; Okereke, 2010; Schroeder et al., 2012).

Scholars have long analyzed the above issues within climate governance, offering a multitude of possible solutions. Concerning participation, a departure from the top-down approach implied in the Kyoto Protocol towards a more voluntary and bottom-up approach has been suggested (Rayner, 2010). Some argue that limiting participation to the "most capable, responsible and vulnerable" countries can foster progress toward more stringent mitigation policy (Eckersley, 2012). However, the latter has been opposed on the basis that it would further exacerbate issues of inequity (Aitken, 2012; Stevenson and Dryzek, 2012). Others have discussed the need to create spaces for collaborative learning to debate, legitimize, and potentially overcome knowledge divides between experts and lay people in sectoral climate policy development (Swanson et al., 2010; Armitage et al., 2011; Colfer, 2011; Larsen et al., 2012)—see Sections 13.3.1 and 13.5 for further detail. On allocation of responsibility, a global agreement has been elusive not merely because parties and other key actors have differing conceptions of a fair allocation (Okereke, 2008), but because the pertinent policies are highly contentious given the combination of factors at play, prominent among which are finance, politics, ineffective institutions, and vested interests.

A defining image of the climate governance landscape is that key actors have vastly disproportionate capacities and resources, including the political, financial, and cognitive resources that are necessary to steer the behaviour of the collective within and across territorial boundaries (Dingwerth and Pattberg, 2009). A central element of governance therefore relates to huge asymmetry in such resources and the ability to exercise power or influence outcomes. Some actors, including governments, make use of negotiation power and/or lobbying activities to influence policy decisions at multiple scales and, by doing so, affect the design and the subsequent allocation and distribution of benefits and costs resulting from such decisions (Markussen and Svendsen, 2005; Benvenisti and Downs, 2007; Schäfer, 2009; Sandler, 2010)—see e.g., Section 15.5.2. The problem, however, also resides in the fact that those that wield the greatest power either consider it against their interest to facilitate rapid progress towards a global low carbon economy or insist that the accepted solutions must be aligned to increase their power and material gains (Sæverud and Skjærseth, 2007; Giddens, 2009; Hulme, 2009; Lohmann, 2009, 2010; Okereke and McDaniels, 2012; Wittneben et al., 2012). The most notable effect of this is that despite some exceptions, the prevailing organization of the global economy, which confers significant power on actors associated with fossil fuel interests and with the financial sector, has provided the context for the sorts of governance practices of climate change that have dominated to date (Newell and Paterson, 2010).

Many specific governance initiatives, described in Sections 13.13 and 15.3, whether organized by states or among novel configurations of actors, have focused on creating new markets or investment opportunities. This applies, for example, to carbon markets (Paterson, 2009), carbon offsetting (Bumpus and Liverman, 2008; Lovell et al., 2009; Corbera and Schroeder, 2011; Corbera, 2012), investor-led governance initiatives such as the Carbon Disclosure Project (CDP) (Kolk et al., 2008) or partnerships such as the Renewable Energy and Energy Efficiency Partnership (REEEP) (Parthan et al., 2010). Some scholars find that carbon markets can contribute to achieving a low fossil carbon transition, but require careful designs to achieve environmental and welfare gains (Wood and Jotzo, 2011; Pezzey and Jotzo, 2012; Springmann, 2012; Bakam et al., 2012). Others note that such mechanisms are vulnerable to 'capture' by special interests and against the original purposes for which they are conceived. Several authors have discussed this problem in the context of the Clean Development Mechanism (CDM) and the European Union Emissions Trading Scheme (EU-ETS) (Lohmann, 2008; Clò, 2010; Okereke and McDaniels, 2012; Böhm et al., 2012).

Governing for SD and climate change requires close attention to three key issues. First, there is a need to understand current governance as encompassing more than the actors within formal government structures, and to understand how choices are driven by more than optimal decision making theory. Second effective governance requires understanding the dynamics that determine whether and how policy options are legitimized, and then formally deliberated and adopted (or not). Consequently, it is necessary to examine how these modes of governance are defined and established in the first place, by whom and for whose benefit, thus illuminating the relationship and tensions between effective governance and existing trends in political economy. Third, there is a need to explore how different modes of governance translate into outcomes, affecting the decisions and actions of actors at multiple scales, and to draw lessons about their environmental effectiveness and distributional implications. While some argue that states should still be regarded as key agents in steering such transitions (Eckersley, 2004; Weale, 2009), most decision making relevant to SD and climate remains fundamentally decentralized. A key challenge of governance is thus to recognize the political economy context of these decision makers, to ensure procedurally equitable processes that address the allocation of responsibilities and ensure transparency and accountability in any transition towards SD.

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2016 NOV 14 PM 4:07

4.3.3 Population and demography

Population variables, including size, density, and growth rate, as well as age, sex, education, and settlement structures, play a determinant role in countries' SD trajectories. Their drivers, in particular fertility, mortality, and migration, are reciprocally influenced by development pathways, including evolving policies, socio-cultural trends, as well as by changes in the economy (Bloom, 2011). In the climate change context, population trends have been shown to matter both for mitigation efforts as well as for societies' adaptive capacities to climate change (O'Neill et al., 2001).

Current demographic trends show distinct patterns in different parts of the world. While population sizes are on a declining trajectory in Eastern Europe and Japan, they are set for significant further increase in many developing countries (particularly in Africa and south-western Asia) due to a very young population age structure and continued high levels of fertility. As most recent projections show, the world's population is almost certain to increase to between 8 and 10 billion by mid-century. After that period, uncertainty increases significantly, with the future trend in birth rates being the key determinant, but it is also amplified by the uncertainty about future infectious disease mortality and the still uncertain consequences of climate change on future mortality trajectories (O'Neill et al., 2001; Lutz and KC, 2010; United Nations, 2011b; Lee, 2011; Scherbov et al., 2011). The population of Sub-Saharan Africa will almost certainly double and could still increase by a factor of three or more depending on the course of fertility over the coming decades, which depends primarily on progress in female education and the availability of reproductive health services (Bongaarts, 2009; Bloom, 2011; Bongaarts and Sinding, 2011).

Declining fertility rates, together with continued increases in life-expectancy, result in significant population ageing around the world, with the current low fertility countries being most advanced in this process. Population ageing is considered a major challenge for the solvency of social security systems. For populations still in the process of fertility decline, the expected burden of ageing is a more distant prospect, and the declining birth rates are expected to bring some near term benefits. This phase in the universal process of any demographic transition, when the ratio of children to adults is already declining and the proportion of elderly has not yet increased, is considered a window of opportunity for economic development, which may also result in an economic rebound effect leading to higher per capita consumption and emissions (Bloom and Canning, 2000).

Low development is widely understood to contribute to high population growth, which declines only after the appearance of widespread access to key developmental needs such as perinatal and maternal healthcare, and female education and empowerment. Conversely, high population growth is widely regarded as an obstacle to SD because it tends to make efforts such as the provision of clean drinking water and agricultural goods and the expansion of health services and school enrollment rates difficult (Dyson, 2006; Potts, 2007; Pimentel and Paoletti, 2009).

This has given rise to the fear of a vicious circle of underdevelopment and gender inequity yielding high population growth and environmental degradation, in turn inhibiting the development necessary to bring down fertility (Caole and Hoover, 1958; Ehrlich and Holdren, 1971; Dasgupta, 1993). However, history shows that countries can break this vicious circle with the right social policies, with an early emphasis on education and family planning; prominent examples include South Korea and Mauritius, which were used in the 1950s as textbook examples of countries trapped in such a vicious circle (Meade, 1967).

With respect to adaptation to climate change, the literature on population and environment has begun to explore more closely people's vulnerability to climate stressors, including variability and extreme events, and to analyze their adaptive capacity and reliance on environmental resources to cope with adversities and adapt to gradual changes and shocks (Bankoff et al., 2004; Adger et al., 2009)—see also Section 4.6.1 and WGII AR5. Generally speaking, not only does the number of people matter, but so does their composition by age, gender, place of residence, and level of education, as well as the institutional context that influences people's decision making and development opportunities (Dyson, 2006). One widely and controversially discussed form of adaptation can be international migration induced by climate change. There is often public concern that massive migration of this sort could contribute to political instability and possibly conflict. However, a major recent review of our knowledge in this field has concluded that much environmentally induced migration is likely to be internal migration and there is very little science-based evidence for assessing possible consequences of environmental change on large international migration streams (UK Government Office for Science, 2011).

4.3.4 Values and behaviours

Research has identified a range of individual and contextual predictors of behaviours in favour or against climate change mitigation, ranging from individuals' psychological needs to cultural and social orientations towards time and nature (Swim et al., 2009)—see Sections 2.4, 3.10, and 5.5. Below we discuss some of these factors, focusing on human values that influence individual and collective behaviours and affect our priorities and actions concerning the pursuit of SD, equity goals, and climate mitigation. Values have been defined as "enduring beliefs that pertain to desirable end states or behaviours, transcend specific situations, guide selection or evaluation of behaviour and events and are ordered by importance" (Pepper et al., 2009; citing Schwartz and Bilsky, 1987). Values provide "guides for living the best way possible for individuals, social groups and cultures" (Pepper et al., 2009; citing Rohan, 2000) and so influence actions at all levels of society—including the individual, the household, the firm, civil society, and government. Individuals acquire values through socialization and learning experience (Pepper et al., 2009) and values thus relate to many of the other determinants discussed in this section. Values may be rooted in cultural, religious, and other belief systems, which may sometimes conflict with scientific understandings of environmental risks. In particular, distinct values may influence perceptions and interpretations of climate impacts and hence climate responses (Wolf et al., 2013).

The relevance of values to SD and, particularly, to ecologically conscious (consumer) behaviour, is related to the nature of environmental issues as 'social dilemmas', where short-term narrow individual interests conflict with the longer term social interest (Pepper et al., 2009). Researchers have highlighted the role of non-selfish values that promote the welfare of others (including nature), noting that some but not all indigenous societies are known to focus on 'collective' as opposed to 'individual' interests and values, which often result in positive resource conservation strategies and wellbeing (Gadgil et al., 1993; Sobrevila, 2008; Watson et al., 2011). However, it is well known that a range of factors also mediate the impact of values on behaviour so that the link from values to ecologically conscious behaviour is often loose (Pepper et al., 2009).

In fact, this 'value-action' gap suggests that pursuing climate change mitigation and SD globally may require substantial changes in behaviour in the short term along with a transformation of human values in the long term, e.g., progressively changing conceptions and attitudes toward biophysical systems and human interaction (Gladwin et al., 1995; Leiserowitz et al., 2005; Vlek and Steg, 2007; Folke et al., 2011a). Changing human values would require a better understanding of cross-cultural behavioural differences that in turn relate to environmental, economic, and political histories (Norenzayan, 2011).

Behavioural change can be induced by changes in formal and civil institutions and governance, human values (Jackson, 2005a; Folke et al., 2011a; Fischer et al., 2012), perceptions of risk and causality, and economic incentives. Removing perverse subsidies for environmentally harmful products, favouring greener consumption and technologies, adopting more comprehensive forms of biophysical and economic accounting, and providing safer working conditions are considered central for achieving pro-SD behavioural change (Lebel and Lorek, 2008; Le Blanc, 2010; Thøgersen, 2010). Yet behaviour experiments (Osbaldiston and Schott, 2012) suggest there is no 'silver bullet' for fostering ecologically conscious behaviour, as favourable actions (e.g., to conserve energy) are triggered by different stimuli, including information, regulation or economic rewards, and influenced by the nature of the issue itself. Furthermore, people are able to "express both relatively high levels of environmental concern and relatively high levels of materialism simultaneously" (Gatersleben et al., 2010). This suggests the need to be issue, context, and culturally aware when designing specific actions to foster pro-SD behaviour, as both environmental and materialistic concerns must be addressed. These complexities underscore the challenges in changing beliefs, preferences, habits, and routines (Southerton, 2012)—see Sections 4.4 and 5.5.2.

4.3.5 Human and social capital

Levels of human and social capital also critically influence a transition toward SD and the design and implementation of mitigation and adaptation strategies. Human capital results from individual and collective investments in acquiring knowledge and skills that become useful for improving wellbeing (Iyer, 2006). Such knowledge and skills can be acquired through formal schooling and training, as well as informally through customary practices and institutions, including communities and families. Human capital can thus be viewed as a critical component of a broader-encompassing human capability, i.e., a person's ability to achieve a given list of 'functionings' or achievements, which depend on a range of personal and social factors, including education, age, gender, health, income, nutritional knowledge, and environmental conditions, among others (Sen, 1997, 2001). See Clark (2009) and Schokkaert (2009) for a review of Sen's capability approach and its critiques.

Economists have long considered improvements in human capital a key explanatory reason behind the evolution of economic systems, in terms of growth and constant innovation (Schultz, 1961; Healy and Cote, 2001). Macro-economic research shows a strong correlation between levels of economic development and levels of human capital and vice versa (Schultz, 2003; Iyer, 2006), while micro-economic studies reveal a positive relationship between increases in the quantity and quality of formal education and future earnings (Duflo, 2001). Gains in human capital can be positively correlated to economic growth and efficiency, but also to nutritional, health, and education standards (Schultz, 1995). As such, improvements in human capital provide a basis for SD, as they shape countries' socio-economic systems and influence people's ability to make informed choices. Seemingly, human capital often also explains the development and survival of business ventures (Colombo and Grilli, 2005; Patzelt, 2010; Gimmon and Levie, 2010), which are an important source of innovation and diffusion of principles and technologies that can contribute to SD and to ambitious mitigation and adaptation goals (Marvel and Lumpkin, 2007; Terjesen, 2007).

Additionally, a growing body of literature in economics, geography, and psychology (reviewed in Sections 2.4, 2.6.6 and 3.10 as well as in WGII Chapter 2) has shown that the diversity of environmental, socio-economic, educational and cultural contexts in which individuals make decisions shape their willingness and/or ability to engage in mitigation and adaptation action (Lorenzoni et al., 2007). It is important to distinguish between formally acquired knowledge on climate change—often based on scientific developments—and traditional knowledge on climate-related issues (Smith and Sharp, 2012), as well as to recognize that the relative validity of both types of knowledge to different audiences, and the meaning and relevance of personal engagement, will be influenced by individual perceptions, preferences, values, and beliefs. Therefore, knowledge on climate issues does not alone explain individual and collective responses to the climate challenge (Whitmarsh, 2009; Sarewitz, 2011; Wolf and Moser, 2011; Berkhout, 2012). There is evidence of cognitive dissonance and strategic behaviour in both mitigation and adaptation. Denial mechanisms that overrate the costs of changing lifestyles, blame others, and that cast doubt on the effectiveness of individual action or the soundness

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
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2015 NOV 14 PM [illegible]

of scientific knowledge are well documented (Stoll-Kleemann et al., 2001; Norgaard, 2011; McCright and Dunlap, 2011), as is the concerted effort by opponents of climate action to seed and amplify those doubts (Jacques et al., 2008; Kolmes, 2011; Conway and Oreskes, 2011).

Among the different definitions of social capital, one of the most influential was proposed by Fukuyama (2002): the shared norms or values that promote social cooperation, which are founded in turn on actual social relationships, including trust and reciprocity. Social capital appears in the form of family bonds, friendship and collective networks, associations, and other more or less institutionalized forms of collective action. Social capital is thus generally perceived as an asset for both the individuals that recognize and participate in such norms and networks and for the respective group/society, insofar as they derive benefits from information, participating in decision making and belonging to the group. Social capital can be linked to successful outcomes in education, employment, family relationships, and health (Gamarnikow and Green, 1999), as well as to economic development and participatory, democratic governance (Woolcock, 1998; Fukuyama, 2002; Doh and McNeely, 2012). Indeed, social capital can also be sustained on unfair social norms and institutions that perpetuate an inequitable access to the benefits provided by social organization (Woolcock and Narayan, 2000), through social networks of corruption or criminal organizations, for example, that perpetuate the uneven distribution of public resources, and undermine societies' cohesion and physical security.

Scholarship suggests that social capital is supportive for SD (Rudd, 2000; Bridger and Luloff, 2001; Tsai, 2008; Ostrom, 2008; Jones et al., 2011), having shown that it can be instrumental to address collective action problems (Ostrom, 1998; Rothstein, 2005), combat injustices and conditions of poverty and vulnerability (Woolcock and Narayan, 2000), and benefit from resources (Bebbington, 1999; Diaz et al., 2002), and to foster mitigation and adaptation (Adger, 2003; Wolf et al., 2010).

4.3.6 Technology

Technology has been a central element of human, social, and economic development since ancient times (Jonas, 1985; Mokyr, 1992). It can be a means to achieving equitable SD, by enabling economic and social development while using environmental resources more efficiently. The development and deployment of the overwhelming majority of technologies is mediated by markets, responding to effective demand of purchasers (Baumol, 2002), and carried out by private firms, where the pre-requisites of technological capacity and investment resources tend to be found. However, this process does not necessarily address the basic needs of those members of society with insufficient market demand to influence the decisions of innovators and investors, nor does it provide an incentive to reduce externalized costs, such as the costs of GHG pollution (Jaffe et al., 2005).

Fundamental objectives of equity and SD are still unmet. For example, the basic energy and nutritional needs of large parts of the world's population remain unfulfilled. An estimated 1.3 billion people lacked access to electricity in 2010 and about 3 billion people worldwide relied on highly polluting and unhealthy traditional solid fuels for household cooking and heating (Pachauri et al., 2012; IEA, 2012b) (see Section 14.3.2.1). Similarly, the Food and Agricultural Organization (FAO) indicates that almost 870 million people (mostly in developing countries) were chronically undernourished in 2010–12 (FAO, 2012). Achieving the objectives of equitable SD demands the fulfilment of such basic and other developmental needs. The challenge is therefore to design, implement, and provide support for technology innovation and diffusion processes that respond to social and environmental goals, which at present do not receive adequate incentives through conventional markets.

Scholars of technological change have, in recent years, begun to highlight the 'systemic' nature of innovation processes as well as the fundamental importance of social and technical interactions in shaping technological change (see Section 4.5.2.2). Accordingly, as a first step toward understanding how innovation could help meet social and environmental goals, a systematic assessment of the adequacy and performance of the relevant innovation systems would be helpful, including an examination of the scale of innovation investments, the allocation among various objectives and options, the efficiency by which investments yield outputs, and how effectively the outputs are utilized for meeting the diffusion objectives (Sagar and Holdren, 2002; Sanwal, 2011; Aitken, 2012). For example, many reports and analyses have suggested that investments in innovation for public goods such as clean energy and energy access are not commensurate with the nature and scale of these challenges (Nemet and Kammen, 2007; AEIC, 2010; Bazilian et al., 2010). Innovation in and diffusion of new technologies also require skills and knowledge from both developers and users, as well as different combinations of enabling policies, institutions, markets, social capital, and financial means depending on the type of technology and the application being considered (Bretschger, 2005; Dinica, 2009; Blalock and Gertler, 2009; Rao and Kishore, 2010; Weyant, 2011; Jänicke, 2012). Appropriately harnessing these kinds of capabilities and processes themselves may require novel mechanisms and institutional forms (Bonvillian and Weiss, 2009; Sagar et al., 2009).

At the same time, the role of public policy in creating demand for technologies that have a public goods nature cannot be overstated (see also Section 3.11), although these policies need to be designed carefully to be effective. In the case of renewables, for example, it has been shown that intermittent policy subsidies, governments' changing R&D support, misalignments between policy levels, sectors, and institutions can greatly impede the diffusion of these technologies (Negro et al., 2012). Similarly, in agriculture, while there are many intersections between mitigation and SD through options such as 'sustainable agriculture', the potential for leveraging these synergies is contingent on appropriate and effective policies (Smith et al., 2007)—see also Sections 4.6.1 and 11.10.

Sometimes there may be a clear alignment between achieving equitable SD benefits and meeting climate goals such as the provision of clean energy to the rural poor. But in meeting multiple objectives, potential for conflicts and tradeoffs can also arise. For example, our likely continued reliance on fossil fuels (IEA 2012b) underlies the current exploration of new or well-established GHG mitigation options, such as biofuels or nuclear power, and other approaches like carbon dioxide capture and storage (CCS) and geo-engineering, including solar radiation management techniques, to avoid a dangerous increase of the Earth's temperature (Crutzen, 2006; Rasch et al., 2008; IPCC, 2012b). While such technological options may help mitigate global warming, they also pose potential adverse environmental and social risks, and thus give rise to concerns about their regulation and governance (Mitchell, 2008; Pimentel et al., 2009; de Paula Gomes and Muylaert de Araujo, 2011; Shrader-Frechette, 2011; Jackson, 2011b; Scheidel and Sorman, 2012; Scott, 2013; Diaz-Maurin and Giampietro, 2013)—see Sections 7.9 and 11.7.

The public perception and acceptability of technologies is country and context-specific, mediated by age, gender, knowledge, attitudes towards environmental risks and climate change, and policy procedures (Shackley et al., 2005; Pidgeon et al., 2008; Wallquist et al., 2010; Corner et al., 2011; Poumadere et al., 2011; Visschers and Siegrist, 2012) and therefore resolution of these kinds of tradeoffs and conflicts may not be easy. Yet the tradeoffs and synergies between the three dimensions of SD, as well as the impacts on socio-ecological systems across geographical scales will need to be systematically considered, which in turn will require the acknowledgement of multiple stakeholder perspectives. Assessment of energy technology options, for example, will need to include impact on landscapes' ecological and social dimensions—accounting for multiple values—and on energy distribution and access (Wolsink, 2007; Zografos and Martinez-Alier, 2009).

There are also some crosscutting issues, such as regimes for technology transfer (TT) and intellectual property (IP) that are particularly relevant to international cooperation in meeting the global challenge of pursuing equitable SD and mitigation, although progress under the UNFCCC has been incomplete. For example, TT under the CDM has been limited to selective conditions and mainly to a few countries (Dechezleprêtre et al., 2009; Seres et al., 2009; Wang, 2010). IP rights and patent laws have been shown as promoting innovation in some countries (Khan, 2005), although recent work suggests a more nuanced picture (Moser, 2013; Hudson and Minea, 2013). In fact, IP protection has also been regarded as a precondition for technology transfer but, again, reality has proven more complex (United Nations Environment Programme et al., 2010). A recent study shows that in the wind sector, there are 'patent thickets', which might restrain the extent and scope of dissemination of wind power technologies (Wang et al., 2013). In part, there are such divergent views on this issue since IP and TT also touch upon economic competitiveness (Ockwell et al., 2010). As noted earlier, perspectives are shaped by perceived national circumstances, capabilities, and needs, yet these issues do need to be resolved—in fact, there may be no single approach that will meet all needs. Different IP regimes, for example, are required to meet development objectives at different stages of development (Correa, 2011). The importance of this issue and the lack of consensus provide impetus for further analysis of the evidence and for exploration to develop IP and TT regimes that further international cooperation to meet climate, SD, and equity objectives.

4.3.7 Natural resources

Countries' level of endowment with renewable and/or non-renewable resources influences but does not determine their development paths. The location, types, quantities, long-term availability and the rates of exploitation of non-renewable resources, including fossil fuels and minerals, and renewable resources such as fertile land, forests, or freshwater affect national economies (e.g., in terms of GDP, trade balance, and rent potential), agricultural and industrial production systems, the potential for civil conflict, and countries' role in global geo-political and trade systems (Krausmann et al., 2009; Muradian et al., 2012; Collier and Goderis, 2012). Economies can evolve to reflect changes in economic trends, in policies or in consumption patterns, both nationally and internationally. In the context of climate change, natural resource endowments affect the level and profile of GHG emissions, the relative cost of mitigation, and the level of political commitment to climate action.

Resource-rich countries characterized by governance problems, including rent-seeking behaviour and weak judiciary and political institutions, have more limited capacity to distribute resource extraction rents and increase incomes (Mehlum et al., 2006; Pendergast et al., 2011; Bjorvatn et al., 2012). Some have negative genuine savings, i.e., they do not fully reinvest their resource rents in foreign assets or productive capital, which in turn impoverishes present and future generations and undermines both natural capital and human development prospects (Mehlum et al., 2006; van der Ploeg, 2011). Furthermore, these countries also face risks associated with an over-specialization on agriculture and resource-based exports that can undermine other productive sectors, e.g., through increases in exchange rates and a reliance on importing countries economic growth trajectories (Muradian et al., 2012). In some countries, an increase in primary commodity exports can lead to the rise of socio-environmental conflicts due to the increasing exploitation of land, mineral, and other resources (Martinez-Alier et al., 2010; Mitchell and Thies, 2012; Muradian et al., 2012).

Scholars have not reached definitive conclusions on the inter-relationships between resource endowment and development paths, including impacts on social welfare and conflict, and prospects for SD. Recent reviews, for example, note the need to continue investigating current resource booms and busts and documenting the latter's effect on national economies, policies, and social well-being, and to draw historical comparisons across countries and different institutional contexts (Wick and Bulte, 2009; Deacon, 2011; van der Ploeg, 2011). It is clear though that the state and those actors involved in natural resources use play a determining role in ensuring a fair distribution of any bene-

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 4:07

fits and costs (Banai et al., 2011). Further, economic valuation studies have noted that systematic valuations of both positive and negative externalities can inform policymaking relating to resource exploitation, in some cases showing that the exploitation of land and mineral resources may not always be socially optimal, i.e., the social and environmental costs of action may be higher than the economic benefits of exploitation (de Groot, 2006; Thampapillai, 2011).

These considerations are relevant for mitigation policy for at least three reasons. First, they raise questions about if and how countries invest resource rents across economic, social, and environmental sectors for SD (see Section 4.3.8). Second, they suggest that nations or sub-national actors with abundant fossil fuel reserves have, in principle, strong economic interest in exploiting them, and thus in opposing the adoption of policies that constrain such exploitation. The timeliness of this issue is underscored by the growing financial sector attention (although not yet academic attention) to the potential impact of a global carbon constraint on the fossil sector (Grantham Institute and CTI 2013; HSBC Global Research, 2013; Standard & Poor's, 2013). This raises the issue of how to compensate resource-rich countries for forgone benefits if necessary to win their participation in international mitigation efforts (Rival, 2010; Waisman et al., 2013). It similarly raises the issue of compensating (or circumventing) sub-national actors who are politically powerful enough to impede domestic climate efforts. And third, they suggest that, if any given resource-rich country faces increased exposure to climate variability and extreme events, the forgone benefits of resource rents may undermine its ability to absorb increasing adaptation costs. In this regard, a recent analysis of the relationship between countries' adoption of mitigation policies and their vulnerability to climate change confirms that countries that may suffer considerable impacts of climate change in the future, which include many resource-rich developing countries, do not show a strong commitment to either mitigation or adaptation, while countries exhibiting strong political commitment and action towards mitigation are also active in promoting adaptation policies (Tubi et al., 2012).

4.3.8 Finance and investment

The financial system, comprising a large set of private and public institutions and actors, is the medium by which households, firms, and collectivities manage insurable risks and fund investments to secure future returns, thereby laying the foundations for future well-being. As such, it is a key determinant of society's development pathway and thus its prospects for an SD transition.

The financial system is characterized by four structural tensions with the ideals of SD. First, its dominant private component (banks and financial markets) is focused on commercial returns and cannot spontaneously internalize environmental and social spillovers, even if some investors' interest in 'sustainable investment' is growing (UNPRI, 2012). Climate change, identified as the "greatest and widest-ranging market failure ever seen" (Stern and Treasury, 2007), is but one obvious example of a large societally important cost that is neglected by capital markets. Second, the private component of the financial system is also largely unattuned to distributive issues and particularly insensitive to "the essential needs of the world's poor, to which overriding priority should be given" (World Commission on Environment and Development, 1987), even if foreign direct investments have contributed to overall growth in emerging economies. Third, the interests of future generations may be neglected (although over-investment is also possible—see Gollier, 2013) and within a generation, there are various governance, organizational and sociological mechanisms contributing to short-termism (Tonello, 2006; Marginson and McAulay, 2008). Fourth, the recent crisis has led some to conclude that the financial system itself is a source of economic instability (Farmer et al., 2012), an issue reinforced by the recent financialization of the global economy, with accelerated growth of the financial sector relative to the 'real' economy, and an increasing role of the financial system in mediating short-term speculation as distinct from long-term investment (Epstein, 2005; Krippner, 2005; Palley, 2007; Dore, 2008).

These inherent problems in the financial system are sometimes compounded by hurdles in the economic and institutional environment. The challenges are felt especially in many developing countries, which face several investment barriers that affect their capacity to mobilize private sector capital toward SD objectives and climate change mitigation and adaptation. These barriers include the comparatively high overall cost of doing business; market distortionary policies such as subsidies for conventional fuels; absence of credit-worthy off-takers; low access to early-stage financing; lower public R&D spending; too few wealthy consumers willing to pay a premium for 'green products'; social and political instability; poor market infrastructure; and weak enforcement of the regulatory frameworks. Establishing better mechanisms for leveraging private sector finance through innovative financing can help (EGTT, 2008), but there are also risks in relying on the private sector as market-based finance focuses on short term lending, and private financing during episodes of abundant liquidity may not constitute a source of stable long-term climate finance (Akyüz, 2012) –see Section 16.4 for further discussion and references on barriers, risks, and innovative mechanisms.

While some developing countries are able to mobilize domestic resources to finance efforts toward SD, the needs for many developing countries exceed their financial capacity. Consequently, their ability to pursue SD, and climate change mitigation and adaptation actions in particular, can be severely constrained by lack of finance. The international provision of finance, alongside technology transfer, can help to alleviate this problem, as well as accord with principles of equity, international commitments, and arguments of effectiveness—see Sections 4.2.2 and 4.6.2. Under international agreements, in particular Agenda 21 and the Rio Conventions of 1992, and reaffirmed in subsequent UN resolutions and programs including the 2012 UN Conference on Sustainable Development (United Nations, 2012a), developed countries have committed to provide financial resources to developing countries that are new and additional to conventional development assistance.

4.4 Production, trade, consumption and waste patterns

The previous section has highlighted the role of behaviours and lifestyles and the complex interaction of the values, goals, and interests of many actors in the political economy of SD and equity. In order to better understand the possibilities and difficulties to equitably sustain well-being in the future, this section examines the consumption of goods and services by households, consumption trends and disparities, and the relationship between consumption and GHG emissions. It also discusses the components and drivers of consumption, efforts to make consumption (and production) more sustainable, and how consumption affects well-being. In order to shed light on important debates about equity in mitigation, this chapter also reviews approaches to consumption-based accounting of GHG emissions (carbon footprinting) and their relationship to territorial approaches. So while subsequent chapters analyze GHG emissions associated with specific sectors and transformation pathways, this chapter focuses on a particular group (consumers) and examines their emissions in an integrated way.

The possibility of a SD pathway for the world hinges on 'decoupling' (von Weizsäcker et al., 1997, 2009; Jackson, 2005b, 2009). We consider two types of decoupling at the global scale and in the long term: the decoupling of material resource consumption (including fossil carbon) and environmental impact (including climate change) from economic growth ('dematerialization'); and the decoupling of human well-being from economic growth and consumption. The first type (see Sections 4.4.1 and 4.4.3) involves an increased material efficiency and environmental efficiency of production and is generally considered crucial for meeting SD and equity goals (UNEP, 2011); yet while some dematerialization has occurred, absolute levels of resource use and environmental impact have continued to rise, highlighting the important distinction between relative and absolute decoupling (Krausmann et al., 2009). This has inspired examination of the second type of decoupling (Jackson, 2005b, 2009; Assadourian, 2010), including the reduction of consumption levels in wealthier countries. We address this topic (in Section 4.4.4) by examining how income and income inequality affect dimensions of well-being. While the second type of decoupling represents a 'stronger' form than the first, it is also a more controversial goal, even though the unsustainability of excessive consumption was highlighted by Chapter 4 of Agenda 21 (United Nations, 1992c).

4.4.1 Consumption patterns, inequality and environmental impact

4.4.1.1 Trends in resource consumption

Global levels of resource consumption and GHG emissions show strong historical trends, driven primarily by developments in industrialized countries and emerging economies (see Sections 5.2 and 14.3). The global annual use (extraction) of material resources—i.e., ores and industrial minerals, construction materials, biomass, and fossil energy carriers—increased eightfold during the 20th century, reaching about 55 Gt in 2000, while the average resource use per capita (the metabolic rate) doubled, reaching 8.5–9.2 tonnes per capita per year in 2005 (Krausmann et al., 2009; UNEP, 2011). The value of the global consumption of goods and services (the global GDP) has increased sixfold since 1960 while consumption expenditures per capita have almost tripled (Assadourian, 2010). Consumption-based GHG emissions ('carbon footprints'—see Section 4.4.2.2) increased between 1990 and 2009 in the world's major economies, except the Russian Federation, ranging from 0.1–0.2 % per year in the EU27, to 4.8–6.0 % per year in China (Peters et al., 2012) (see Section 5.2.1).

Global resource consumption has risen slower than GDP, especially after around 1970, indicating some decoupling of economic development and resource use, and signifying an aggregate increase in resource productivity of about 1–2 % annually (Krausmann et al., 2009; UNEP, 2011). While dematerialization of economic activity has been most noticeable in the industrialized countries, metabolic rates across countries remain highly unequal, varying by a factor of 10 or more due largely to differences in level of development, although there is also significant cross-country variation in the relation between GDP and resource use (Krausmann et al., 2009; UNEP, 2011).

4.4.1.2 Consumerism and unequal consumption levels

The spread of material consumption with rising incomes is one of the 'mega-drivers' of global resource use and environmental degradation (Assadourian, 2010). While for the world's many poor people, consumption is driven mainly by the need to satisfy basic human needs, it is increasingly common across cultures that people seek meaning, contentment and acceptance in consumption. This pattern is often referred to as 'consumerism', defined as a cultural paradigm where "the possession and use of an increasing number and variety of goods and services is the principal cultural aspiration and the surest perceived route to personal happiness, social status and national success" (Assadourian, 2010, p. 187).

Consumerist lifestyles in industrialized countries seem to be imitated by the growing elites (Pow, 2011) and middle-class populations in developing countries (Cleveland and Laroche, 2007; Gupta, 2011), exemplified by the increased demand for space cooling in emerging economies (Isaac and van Vuuren, 2009). Together with the unequal distribution of income in the world, the spread of consumerism means that a large share of goods and services produced are 'luxuries' that only the wealthy can afford, while the poor are unable to afford even basic goods and services (Khor, 2011).

A disproportionate part of the GHG emissions arising from production are linked to the consumption of products by a relatively small

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 4:07

portion of the world's population, illustrated by the great variation in the per capita carbon footprint between countries and regions at different income levels (Hertwich and Peters, 2009; Davis and Caldeira, 2010; Peters et al., 2011) (see Section 14.3.1). The carbon footprint is strongly correlated with consumption expenditure. Across countries, Hertwich and Peters (2009) found an expenditure elasticity of 0.57 for all GHGs: as nations become wealthier, the per capita carbon footprint increases by 57 % for each doubling of consumption. Within countries, similar relationships have been found between household expenditure and carbon footprint (Druckman and Jackson, 2009; Hertwich, 2011). Because wealthier countries meet a higher share of their final demand from (net) imports than do less wealthy countries, consumption-based emissions are more closely associated with GDP than are territorial emissions, the difference being the emissions embodied in trade (see Section 4.4.2 as well as 5.2 and 14.3).

4.4.1.3 Effect of non-income factors on per capita carbon footprint

Non-income factors such as geography, energy system, production methods, waste management (GAIA, 2012; Corsten et al., 2013), household size, diet, and lifestyle also affect per capita carbon footprints and other environmental impacts (Tukker et al., 2010a) so that the effects of increasing income varies considerably between regions and countries (Lenzen et al., 2006; Hertwich, 2011; Homma et al., 2012), cities (Jones and Kammen, 2011) and between rural and urban areas (Lenzen and Peters, 2010). In this regard, the environmental impact of specific consumption patterns has been studied intensely in recent years (Druckman and Jackson, 2009; Davis and Caldeira, 2010; Tukker et al., 2010a; Hertwich, 2011). At the global level, Hertwich and Peters (2009) found that food is the consumption category with the greatest climate impact, accounting for nearly 20 % of GHG emissions, followed by housing/shelter, mobility, services, manufactured products, and construction (see Sections 8.2, 9.2, 10.3, 11.2, 12.2). Food and services were a larger share in poor countries, while at high expenditure levels, mobility and the consumption of manufactured goods caused the largest GHG emissions (Hertwich and Peters, 2009). The factors responsible for variations in carbon footprints across households at different scales are further discussed in Sections 5.3, 5.5, 12.2 and 14.3.4.

4.4.2 Consumption patterns and carbon accounting

4.4.2.1 Choice of GHG accounting method

New GHG accounting methods have emerged and proliferated in the last decade, in response to interest in 1) determining whether nations are reducing emissions (Bows and Barrett, 2010; Peters et al., 2011, 2012), 2) allocating GHG responsibility (Peters and Hertwich, 2008a; b; Bows and Barrett, 2010), 3) assuring the accountability of carbon markets (Stechemesser and Guenther, 2012), 4) determining the full implications of alternative energy technologies (von Blottnitz and Curran, 2007; Martinez et al., 2009; Cherubini et al., 2009; Soimakallio et al., 2011) and of outsourcing of industrial production (see Section 4.4.3.3) helping corporations become greener (Wiedmann et al., 2009), and 6) encouraging consumers to reduce their carbon footprints (Bolwig and Gibbon, 2010; Jones and Kammen, 2011). Methods differ on whether consumers or producers of products are responsible; whether emissions embedded in past or potential replacement of capital investments are included; and whether indirect emissions, for example, through global land-use change resulting from changing product prices, are included (Finkbeiner, 2009; Plevin et al., 2010; Plassmann et al., 2010). These methodological differences have normative implications.

Systems of GHG emissions accounting are constructed according to certain conventions and purposes (Davis and Caldeira, 2010). Better ways may be excessively expensive given the plausible importance of the value of better information in the decision process. Some interests will plead for standardized techniques based on past data because it favours them. Others will argue for tailored approaches that make their technologies or products look good. Producers favour responsibility being assigned to consumers, as do nations that are net exporters of industrial goods. Controversies over GHG emissions accounting approaches play into the broader issue of mitigation governance (see Section 4.4.2.4). And whether carbon markets are effective or not depends on good accounting and enforcement—but what will be enforced will depend on the accounting measures agreed upon. The next section discusses consumption-based GHG emissions accounting.

4.4.2.2 Carbon footprinting (consumption-based GHG emissions accounting)

Carbon (or GHG) accounting refers to the calculation of the GHG emissions associated with economic activities at a given scale or with respect to a given functional unit—including products, households, firms, cities, and nations (Peters, 2010; Pandey et al., 2011). GHG accounting has traditionally focused on emission sources, but recent years have seen a growing interest in analyzing the drivers of emissions by calculating the GHG emissions that occur along the supply chain of different functional units such as those just mentioned (Peters, 2010). The result of this consumption-based emissions accounting is often referred to as 'carbon footprint' even if it involves other GHGs along with CO_2. Carbon footprinting starts from the premise that the GHG emissions associated with economic activity are generated at least partly as a result of people's attempts to satisfy certain functional needs and desires (Lenzen et al., 2007; Druckman and Jackson, 2009; Bows and Barrett, 2010). These needs and desires carry the consumer demand for goods and services, and thereby the production processes that consume resources and energy and release pollutants. Emission drivers are not limited to individuals' consumption behaviour, however, but include also the wider contexts of consumption such as transport infrastructure, production and waste systems, and energy systems (see below and Sections 7.3, 8.2, 9.2, 10.3, 11.2, 12.2).

There is no single accepted carbon footprinting methodology (Pandey et al., 2011), nor is there one widely accepted definition of carbon footprint. Peters (2010) proposes this definition, which allows for all possible applications across scales: "[t]he 'carbon footprint' of a functional unit is the climate impact under a specific metric that considers all relevant emission sources, sinks and storage in both consumption and production within the specified spatial and temporal system boundary" (pp. 245). The emissions associated with the functional unit (but physically not part of the unit) are referred to as 'embodied carbon', 'carbon flows' or similar terms. (Annex II of this report discusses different carbon footprint methodologies, including Life Cycle Assessment (LCA) and environmentally-extended input-output (EIO) models.) Carbon footprints have been estimated with respect to different functional units at different scales. Most relevant to the analysis of consumption patterns and mitigation linkages are the carbon footprints of products and nations, discussed in turn.

4.4.2.3 Product carbon footprinting

A product carbon footprint includes all emissions generated during the lifecycle of a good or service—from production and distribution to end-use and disposal or recycling. Carbon footprinting of products (and firms) can enable a range of mitigation actions and can have co-benefits (Sinden, 2009; Bolwig and Gibbon, 2010). Informing consumers about the climate impact of products through labelling or other means can influence purchasing decisions in a more climate-friendly direction and at the same time enable product differentiation (Edwards-Jones et al., 2009; Weber and Johnson, 2012). Carbon footprinting can also help companies reduce GHG emissions cost-effectively by identifying the various emission sources within the company and along the supply chain (Sinden, 2009; Sundarakani et al., 2010; Lee, 2012). Those emissions can be reduced directly, or by purchasing offsets in carbon markets. There is both theoretical and empirical evidence of a positive relationship between a company's environmental and financial performance (Delmas and Nairn-Birch, 2011; Griffin et al., 2012). The specific effect of carbon footprinting on company financial performance and investor valuation is not well researched, however, and the results are ambiguous: in the United Kingdom, Sullivan and Gouldson (2012) found limited investor interest in the climate change-related data provided by retailers, while a study from North America concludes that investors do care about companies' GHG emission disclosures, whether these occur through a voluntary scheme or informal estimates (Griffin et al., 2012).[1] (See also Section 15.3.3)

There are also risks associated with product carbon footprinting. It can affect competitiveness and trade by increasing costs and reduce demand for products made abroad, including in developing countries, and it may violate World Trade Organization (WTO) trade rules (Brenton et al., 2009; Edwards-Jones et al., 2009; Erickson et al., 2012). A one-sided focus on GHG emissions in product development and consumer choice could also involve tradeoffs with other sustainability dimensions (Finkbeiner, 2009; Laurent et al., 2012). So there are reasons to adopt more broadly encompassing concepts and tools to assess and manage sustainability in relation to the consumption of goods and services.

4.4.2.4 Consumption-based and territorial approaches to GHG accounting

Consumption-based accounting of GHG emissions (carbon footprinting) at national level differs from the production-based or territorial framework because of imports and exports of goods and services that, directly or indirectly, involve GHG emissions (Davis and Caldeira, 2010; Peters et al., 2011, 2012). The territorial framework allocates to a nation (or other jurisdiction) those emissions that are physically produced within its territorial boundaries. The consumption-based framework assigns the emissions released through the supply chain of goods and services consumed within a nation irrespective of their territorial origin. The difference in inventories calculated based on the two frameworks are the emissions embodied in trade (Peters and Hertwich, 2008b; Bows and Barrett, 2010). We emphasize that territorial and consumption-based accounting of emissions as such represent pure accounting identities measuring the emissions embodied in goods and services that are produced or consumed, respectively, by an individual, firm, country, region, etc. Responsibility for these emissions only arises once it is assigned within a normative or legal framework, such as a climate agreement, specifying rights to emit or obligations to reduce emission based on one of these metrics. As detailed below, the two approaches function differently in a global versus a fragmented climate policy regime.

Steckel et al. (2010) show that within a global regime that internalizes a cost of GHG emissions, the two approaches are theoretically equivalent in terms of their efficiency in inducing mitigation. For example, with a global cap-and-trade system with full coverage (i.e., an efficient global carbon market) and given initial emission allocations, countries exporting goods benefit from export revenues, with costs related to GHG emissions and any other negative impacts of production of those goods priced in, such that the choice of accounting system has no influence on the efficiency of production. Nor will it influence the welfare of countries, irrespective of being net exporters or importers of emissions, since costs associated with these emissions are fully internalized in product prices and will ultimately be borne by consumers. In practice, considerations such as transaction costs and information asymmetries would influence the relative effectiveness and choice of accounting system.

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[1] In the United States, increasing carbon emissions was found to positively impact the financial performance of firms when using accounting-based measures, while the impact was negative when using market-based performance measures (Delmas and Nairn-Birch, 2011).

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 4:23

In the case of a fragmented climate policy regime, one argument put in favour of a consumption-based framework is that, unlike the territorial approach, it does not allow current emission inventories to be reduced by outsourcing production or relying more on imports to meet final demand. Hence, some authors (e.g., Peters and Hertwich, 2008b; Bows and Barrett, 2010) argue that this approach gives a fairer illustration of responsibility for current emissions. Carbon footprinting also increases the range of mitigation options by identifying the distribution of GHG emissions among different activities, final uses, locations, household types, etc. This enables a better targeting of policies and voluntary actions (Bows and Barrett, 2010; Jones and Kammen, 2011).

On the other hand, reducing emissions at the 'consumption end' of supply chains requires changing deeply entrenched lifestyle patterns and specific behaviours among many actors with diverse characteristics and preferences, as opposed to among the much fewer actors emitting GHGs at the source. It has also been pointed out that—identical to the accounting of production-based emissions—there is no direct one-to-one relationship between changes in consumption-based and global emissions (Jakob and Marschinski, 2012). That is, if some goods or services were not consumed in a given country, global emissions would not necessarily decrease by the same amount of emissions generated for their production, as this country's trade partners would adjust their consumption—as well as production—patterns in response to price changes resulting from its changed demand profile. This has been shown for China (Peters et al., 2007) and India (Dietzenbacher and Mukhopadhyay, 2007): while these countries are large net exporters of embodied carbon, territorial emissions would remain roughly constant or even increase if they were to withdraw from international trade (and produce their entire current consumption domestically instead). Hence, without international trade, consumption-based emissions of these countries' trade partners would likely be reduced, but not global emissions.

It is for this reason that Jakob and Marschinski (2012) argue that a more detailed understanding of the underlying determinants of emissions is needed than what is currently provided by either territorial or consumption-based accounts, in order to guide policies that will effectively reduce global emissions in a fragmented climate policy regime. In particular, a better understanding of system interrelationships in a global economy is required in order to be able to attribute how, e.g., policy choices in one region affect global emissions by transmission via world market prices and associated changes in production and consumption patterns in other regions. Furthermore, as market dynamics and resource use are driven by both demand and supply, it is conceivable to rely on climate policies that target the consumption as well as the production side of emissions, as is done in some other policy areas

4.4.3 Sustainable consumption and production—SCP

The concepts of 'sustainable consumption' and 'sustainable production' represent, respectively, demand- and supply-side perspectives on sustainability. The efforts by producers to improve the environmental or social impact of a product are futile if consumers do not buy the good or service (Moisander et al., 2010). Conversely, sustainable consumption behaviour depends on the availability and affordability of such products in the marketplace. The idea of sustainable consumption and production (SCP) was first placed high on the international policy agenda at the 1992 UN Conference on Environment and Development and was made part of Agenda 21. In 2003, a 10-year Framework of Programmes on SCP was initiated, which was formalized in a document adopted by the 2012 UN Conference on Sustainable Development (United Nations, 2012b, p. 2). A great variety of public and private SCP policies and initiatives have developed alongside the UN-led initiatives (see Section 10.11.3), as has a large body of research that we report on below.

4.4.3.1 Sustainable consumption and lifestyle

A rich research literature on sustainable consumption has developed over the past decade, including several special issues of international journals (Tukker et al., 2010b; Le Blanc, 2010; Kilbourne, 2010; Black, 2010; Schrader and Thøgersen, 2011). Several books, such as *Prosperity without Growth* (Jackson, 2009), discuss the unsustainable nature of current lifestyles, development trajectories, and economic systems, and how these could be changed in more sustainable directions. Several definitions of sustainable consumption have been proposed within policy, business, and academia (Pogutz and Micale, 2011). At a meeting in Oslo in 2005, a group of scientists agreed on the following broad and integrating conceptualization of sustainable consumption:

> *The future course of the world depends on humanity's ability to provide a high quality of life for a prospective nine billion people without exhausting the Earth's resources or irreparably damaging its natural systems … In this context, sustainable consumption focuses on formulating strategies that foster the highest quality of life, the efficient use of natural resources, and the effective satisfaction of human needs while simultaneously promoting equitable social development, economic competitiveness, and technological innovation.*
> *(Tukker et al., 2006)*

This perspective encompasses both demand-side and production issues, and addresses all three pillars of SD (social, economic, and environmental) as well as equity and well-being, illustrating the complexity of sustainable consumption and its connections to other issues.

Research has demonstrated that consumption practices and patterns are influenced by a range of economic, informational, psychological, sociological, and cultural factors, operating at different levels or spheres in society—including the individual, the family, the locality, the market, and the work place (Thøgersen, 2010). Furthermore, consumers' preferences are often constructed in the situation (rather than pre-existing) and their decisions are highly contextual (Weber and Johnson, 2009) and often inconsistent with values, attitudes, and perceptions of themselves as responsible and green consumers and citizens (Barr, 2006; de Barcellos et al., 2011) (see below, as well as Sections 2.6.6 and 3.10).

The sustainable consumption of goods and services can be viewed in the broader context of lifestyle and everyday life. Conversely, sustainable consumption practices are bound up with perceptions of identity, ideas of good life, and so on, and considered alongside other concerns such as affordability and health. Ethical consumption choices are also negotiated among family members with divergent priorities and interpretations of sustainability. Choosing a simpler lifestyle ('voluntary simplifying') seems to be related to environmental concern (Shaw and Newholm, 2002; Huneke, 2005), but frugality, as a more general trait or disposition, is not (Lastovicka et al., 1999; Pepper et al., 2009).

Other research draws attention to the constraints placed on consumption and lifestyle choices by factors beyond the influence of the individual, family or community, which tends to lock consumption into unsustainable patterns by reducing 'green agency' at the micro level (Thøgersen, 2005; Pogutz and Micale, 2011). These structural issues include product availability, cultural norms and beliefs, and working conditions that favour a 'work-and-spend' lifestyle (Sanne, 2002). Brulle and Young (2007) found that the growth in personal consumption in the United States during the 20th century is partly explained by the increase in advertising. According to this study, the effect of advertising on spending is concentrated on luxury goods (household appliances and supplies and automobiles) while it is nonexistent in the field of basic necessities (food and clothes), while Druckman and Jackson (2010) found that in the UK, expenditures on food and clothes clearly exceeded 'necessary' levels.

The strength and pervasiveness of political economy factors such as those just mentioned, and the inadequate attention to them by policy, is an important cause of the lack of real progress towards more sustainable consumption patterns (Thøgersen, 2005; Tukker et al., 2006; Le Blanc, 2010). Furthermore, the unsustainable lifestyles in industrialized countries are being replicated by the growing elites (Pow, 2011) and middle-class populations in developing countries (Cleveland and Laroche, 2007; Gupta, 2011). Finally, most Sustainable Consumption (SC) studies are done in a consumer culture context, which limits discussion of instances where sustainable consumption has pre-empted consumerism.

4.4.3.2 Consumer sustainability attitudes and the relation to behaviour

Despite the overwhelming impact of structural factors on consumer practices, choices and behaviour, it is widely agreed that the achievement of more sustainable consumption patterns also depends on how consumers value environmental quality and other dimensions of sustainability (Jackson, 2005a; Thøgersen, 2005; Bamberg and Möser, 2007). It also depends on whether people believe that their consumption practices make a difference to sustainability (Frantz and Mayer, 2009; Hanss and Böhm, 2010), which in turn is influenced by their value priorities and how much they trust the environmental information provided to them by scientists, companies, and public authorities (Kellstedt et al., 2008). The motivational roots of sustainable consumer choices seem to be substantially the same, although not equally salient in different national and cultural contexts (Thøgersen, 2009; Thøgersen and Zhou, 2012).

In a survey of European attitudes towards sustainable consumption and production (Gallup Organisation, 2008a), 84 % of EU citizens said that the product's impact on the environment is "very important" or "rather important" when making purchasing decisions. This attitude is rarely reflected in behaviour, however. There is plenty of evidence demonstrating the presence of an 'attitude-behaviour' or 'values-action' gap whereby consumers expressing 'green' attitudes fail to adopt sustainable consumption patterns and lifestyles (Barr, 2006; Young et al., 2010; de Barcellos et al., 2011). To a large measure, this gap can be attributed to many other goals and concerns competing for the person's limited attention (Weber and Johnson, 2009). This observation is reflected in the substantial difference in the level of environmental concern that Europeans express in opinion polls when the issue is treated in isolation, and when the environment is assessed in the context of other important societal issues. For example, in 2008, 64 % of Europeans said protecting the environment was "very important" to them personally when the issue was presented in isolation (Gallup Organisation, 2008b) while only 4 % pointed at environmental pollution as one of the two most important issues facing their country at the moment (Gallup Organisation, 2008a). When there are many important issues competing for the person's limited attention and resources, those that appear most pressing in everyday life are likely to prevail.

The likelihood that a person will act on his or her environmental concern is further diminished by factors affecting everyday decisions and behaviour, including the structural factors mentioned above, but also more specific factors such as habit, high transactions costs (i.e., time for information search and processing and product search), availability, affordability, and the influence of non-green criteria such as quality, size, brand, and discounts (Young et al., 2010). Some of these factors vary across different product categories and within sectors (McDonald et al., 2009). The impact of all of these impeding factors is substantial, calling into question the capacity of 'the green consumer' to effectively advance sustainable consumption and production (Csutora, 2012) and, more generally, the individualistic view of the consumer as a powerful market actor (Moisander et al., 2010).

Third-party eco-labels and declarations have proven to be an effective tool to transform consumer sustainability attitudes into behaviour in many cases (Thøgersen, 2002). One of the reasons is that a trusted label can function as a choice heuristic in the decision situation, allowing the experienced consumer to make sustainable choices in a fast and frugal way (see Section 2.6.5 and Thøgersen et al., 2012). Labeling products with their carbon footprint may help to create new goals

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER
2015 NOV 11 PM

(e.g., to reduce CO_2 emissions) and to attract and keep attention on those goals, in the competition between goals (Weber and Johnson, 2012). In Europe, 72 % of EU citizens thought that carbon labelling should be mandatory (Gallup Organisation, 2008a). In Australia, Vanclay et al. (2010) found a strong purchasing response of 20 % when a green-labelled product (indicating relatively low lifecycle CO_2 emissions) was also the cheapest, and a much weaker response when green-labelled products were not the cheapest. Hence, consumers, at least in developed countries, show interest in product carbon footprint information and many consumers would prefer carbon-labelled products and firms over others, other things being equal (Bolwig and Gibbon, 2010). Yet the impeding factors and the related 'attitude-behaviour' gap limit how far one can get towards sustainable consumption with labelling and other information-based means alone.

Research on these topics in the developing world is lacking. Considering the notion of a hierarchy of needs (Maslow, 1970; Chai and Moneta, 2012) and the challenges facing consumers in developing countries, carbon footprints and other environmental declarations might be seen as a luxury concern that only developed countries can afford. Countering this view, Kvaløy et al. (2012) find environmental concern in developing countries at the same level as in developed countries. Furthermore, eco-labelled products increasingly appear at retail level in developing countries (Roitner-Schobesberger et al., 2008; Thøgersen and Zhou, 2012).

4.4.3.3 Sustainable production

Research and initiatives on sustainable production have been concerned with increasing the resource efficiency of, and reducing the pollution and waste from, the production of goods and services through technological innovations in process and product design at the plant and product levels, and, more lately, through system-wide innovations across value chains or production networks (Pogutz and Micale, 2011). Policies that incentivize certain product choices have also been developed (see Section 10.11.3). Eco-efficiency (Schmidheiny and WBSCD, 1992) is the main management philosophy guiding sustainable production initiatives among companies (Pogutz and Micale, 2011) and is expressed as created value or provided functionality per caused environmental impact. Moving towards a more eco-efficient production thus means creating the same or higher value or functionality while causing a lower environmental impact (relative or even absolute decoupling). This involves consideration of multiple impacts across scales, ranging from global impacts like climate change over regional impacts associated with air and water pollution, to local impacts caused by use of land or water.

A strong increase in the eco-efficiency of production is a pre-requisite for developing a sustainable society (Pogutz and Micale, 2011). The I=PAT equation expresses the environmental impact I as a product of the population number P, the affluence A (value created or consumed per capita), and a technology factor T perceived as the reciprocal of eco-efficiency. Considering the foreseeable growth in P and A, and the current unsustainable level of I for many environmental impacts it is clear that the eco-efficiency (1/T) must increase many times (a factor 4 to 20)[2] to ensure a sustainable production. While a prerequisite, even this kind of increases in eco-efficiency may not be sufficient since A and T are not mutually independent due to the presence of rebound—including market effects; indeed, sometimes a reduction in T (increased eco-efficiency) is accompanied by an even greater growth in A, thereby increasing the overall environmental impact I (Pogutz and Micale, 2011). (A related concept to I=PAT is the Kaya identity, see Section 5.3)

With its focus on the provided function and its broad coverage of environmental impacts, LCA is frequently used for evaluation of the eco-efficiency of products or production activities (Hauschild, 2005; Finnveden et al., 2009) (see Annex II.4.2). LCA has been standardized by the International Organization for Standardization (ISO 14040 and ISO 14044) and is a key methodology underlying standards for eco-labelling and environmental product declarations. LCA is also the analytical tool underlying DFE (design for environment) methods (Bhander et al., 2003; Hauschild et al., 2004).

With the globalization and outsourcing of industrial production, analyzing the entire product lifecycle (or product chain)—from resource extraction to end-of-life—gains increased relevance when optimizing the energy and material efficiency of production. A lifecycle approach will reveal the potential problem shifting that is inherent in outsourcing and that may lead to increased overall resource consumption and GHG emissions of the product over its lifecycle in spite of reduced impacts of the mother company (Shui and Harriss, 2006; Li and Hewitt, 2008; Herrmann and Hauschild, 2009). This is why a lifecycle perspective is applied when calculating the carbon footprint. Indeed, a lifecycle-based assessment is generally needed to achieve resource and emissions optimization across the product chain. The use stage can be especially important for products that use electricity or fuels to function (Wenzel et al., 1997; Samaras and Meisterling, 2008; Yung et al., 2011; Sharma et al., 2011). Improvement potentials along product chains can be large, in particular when companies shift from selling only products to delivering product-service systems, often increasing the number of uses of the individual product (Manzini and Vezzoli, 2003). Exchange of flows of waste materials or energy can also contribute to increasing eco-efficiency. Under the heading of 'industrial symbiosis', such mutually beneficial relationships between independent industries have emerged at multiple locations, generally leading to savings of energy and sometimes also materials and resources (Chertow and Lombardi, 2005; Chertow, 2007; Sokka et al., 2011) (See Section 10.5).

While the broad coverage of environmental impacts supported by LCA is required to avoid unnoticed problem shifting between impacts, a narrower focus on climate change mitigation in relation to produc-

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[2] Factor 4 to factor 20 increases can be calculated depending on the expected increases in P and A and the needed reduction in I (von Weizsäcker et al., 1997; Schmidt-Bleek, 2008).

tion would be supported by considering energy efficiency, which can be addressed at different levels: the individual process, the production facility, the product chain, and the industrial system (industrial symbiosis). At the process level, the operation of the individual process and consideration of the use-stage energy efficiency in the design of the machine tools and production equipment can be addressed (see Section 10.4). Improvements in energy efficiency in manufacturing have focused on both the design and operation of a variety of processes (Gutowski et al., 2009; Duflou et al., 2010; Herrmann et al., 2011; Kara and Li, 2011), finding improvement potentials at the individual process level of up to 70 % (Duflou et al., 2012), and at the plant level by re-using e. g., waste heat from one process for heating in another (Hayakawa et al., 1999). Exergy analysis and energy pinch analysis can be used to identify potentials for reutilization of energy flows in other processes (Creyts and Carey, 1999; Bejan, 2002).

Research on the social dimensions of production systems have addressed such issues as worker conditions (Riisgaard, 2009), farm income (Bolwig et al., 2009), small producer inclusion into markets and value chains (Bolwig et al., 2010; Mitchell and Coles, 2011) and the role of standards in fostering sustainability (Gibbon et al., 2010; Bolwig et al., 2013). Recently, the LCA methodology has been elaborated to include assessment of social impacts such as labour rights (Dreyer et al., 2010), in order to support the assessment of problem shifting and tradeoffs between environmental and social dimensions (Hauschild et al., 2008).

4.4.4 Relationship between consumption and well-being

As noted earlier, global material resource consumption continues to increase despite substantial gains in resource productivity or eco-efficiency, causing further increases in GHG emissions and overall environmental degradation. In this light it is relevant to discuss whether human well-being or happiness can be decoupled from consumption or growth (Ahuvia and Friedman, 1998; Jackson, 2005b; Tukker et al., 2006). We do this here by examining the relationship between different dimensions of well-being and income (and income inequality) across populations and over time.

Happiness is an ambiguous concept that is often used as a catchword for subjective well-being (SWB). SWB is multidimensional and includes both cognitive and affective components (Kahneman et al., 2003). Cognitive well-being refers to the evaluative judgments individuals make when they think about their life and is what is reported in life satisfaction or ladder-of-life data, whereas affective or emotional well-being refers to the emotional quality of an individual's everyday experience as captured by surveys about the intensity and prevalence of feelings along the day (Kahneman and Deaton, 2010). Emotional well-being has been defined as "the frequency and intensity of experiences of joy, fascination, anxiety, sadness, anger, and affection that makes one's life pleasant or unpleasant" (Kahneman and Deaton, 2010, p. 16489). Camfield and Skevington (2008) examine the relationship between SWB and quality of life (QoL) as used in the literature. They find that SWB and QoL are virtually synonymous; that they both contain a substantial element of life satisfaction, and that health and income are key determinants of SWB or QoL, while low income and high inequality are both associated with poor health and high morbidity.

The "Easterlin paradox" refers to an emerging body of literature suggesting that while there is little or no relationship between SWB and the aggregate income of countries or long-term GDP growth, *within* countries people with more income are happier (Easterlin, 1973, 1995). Absolute income is, it is argued, only important for happiness when income is very low, while relative income (or income equality) is important for happiness at a wide range of income levels (Layard, 2005; Clark et al., 2008). These insights have been used to question whether economic growth should be a primary goal of government policy (for rich countries), instead of, for example, focusing on reducing inequality within countries and globally, and on maximizing subjective well-being. For instance, Assadourian (2010) argues against consumerism on the grounds that increased material wealth above a certain threshold does not contribute to subjective well-being.

The Easterlin paradox has been contested in comparisons across countries (Deaton, 2008) and over time (Stevenson and Wolfers, 2008; Sacks et al., 2010), on the basis of the World Gallup survey of well-being. These works establish a clear linear relationship between average levels of ladder-of-life satisfaction and the logarithm of GDP per capita across countries, and find no satiation threshold beyond which affluence no longer enhances subjective well-being. Their time series analysis also suggests that economic growth is on average associated with rising happiness over time. On this basis they picture a strong role for absolute income and less for relative income comparisons in determining happiness.

These results contrast with studies of emotional well-being, which generally find a weak relationship between income and well-being at higher income levels. In the United States, for example, Kahneman and Deaton (2010) find a clear satiation effect: beyond around USD_{2010} 75,000 annual household income (just above the mean United States household income) "further increases in income no longer improve individuals' emotional well-being (including aspects such as spending time with people they like, avoiding pain and disease, and enjoying leisure)" (p. 16492).[3] But even for life satisfaction, there is contrasting evidence. In particular, Deaton (2008) finds much variation of SWB between countries at the same level of development, and Sacks et al. (2010) finds the long term positive relationship between income and life satisfaction to be weakly significant and sensitive to the sample of countries (see also Graham, 2009; Easterlin et al., 2010; Di Tella and MacCulloch, 2010). An important phenomenon is that all components of SWB, in various degrees, adapt to most changes in objective conditions of life, except a

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[3] This result is based on cross-sectional data and do not refer to the effects of a *change* in a person's income.

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 1:08

few things, such as physical pain (Kahneman et al., 2003; Layard, 2005; Clark et al., 2008; Graham, 2009; Di Tella and MacCulloch, 2010).

The great variability of SWB data across individuals and countries and the adaptation phenomenon suggest that these data do not provide indices of well-being that are comparable across individuals and over time. Respondents have different standards when they answer satisfaction questions at different times or in different circumstances. Therefore, the weakness of the observed link between growth and SWB is not only debated, but it is quite compatible with a strong and firm desire in the population for ever-growing material consumption (Fleurbaey, 2009). Decoupling growth and well-being may be more complicated than suggested by raw SWB indicators.

Decoupling individual well-being from consumption may be fraught with controversies, but decoupling social welfare from average consumption might be possible via inequality reduction. It has been found that inequality in society has a marked negative effect on average SWB. For example, Oishi et al. (2011) found that over a 37-year period, Americans were less happy on average during years with greater income inequality. This was explained by the fact that lower-income respondents "trusted other people less and perceived other people to be less fair in the years with more national income inequality" (Oishi et al., 2011, p. 1095). The potential decoupling of social welfare from average consumption is even more obvious if social welfare is defined in a way that gives priority to those who are less well-off (Atkinson, 1970).

4.5 Development pathways

Sustainable development provides a framework for the evaluation of climate policies. This is particularly useful in view of the fact that a given concentration pathway or climate objective can typically be achieved through various policies and development pathways inducing different impacts on the economy, the society, and other aspects of the environment. Integrated models provide valuable tools for the analysis of pathways, though most models suffer from limitations analyzed in this section.

4.5.1 Definition and examples

Though widely used in the literature, the concept of development pathway has rarely been defined.[4] According to AR4, a development path is "an evolution based on an array of technological, economic, social, institutional, cultural, and biophysical characteristics that determine the interactions between human and natural systems, including consumption and production patterns in all countries, over time at a particular scale" (WGIII, AR4, Glossary, p. 813). AR4 also indicates that "alternative development paths refer to different possible trajectories of development, the continuation of current trends being just one of the many paths". Though AR4 defines development pathways as global, the concept has also been used at regional (e.g., Li and Zhang, 2008), national (e.g.,Poteete, 2009) and subnational scales (e.g. Dusyk et al., 2009) at provincial scale and (Yigitcanlar and Velibeyoglu, 2008) at city scale. In the present report, a development pathway characterizes all the interactions between human and natural systems in a particular territory, regardless of scale.

The concept of development pathway is holistic. It is broader than the development trajectory of a particular sector, or of a particular group of people within a society. Thus, a wide range of economic, social, and environmental indicators are necessary to describe a development pathway, not all of which may be amenable to quantitative representation. As defined by AR4, however, a "pathway" is not a random collection of indicators. It has an internal narrative and causal consistency that can be captured by the *determinants* of the interactions between human and natural systems. The underlying assumption is that the observed development trajectory—as recorded by various economic, social, and environmental indicators—can be explained by identifiable drivers. This roots the concept of development pathway in the (dominant) intellectual tradition according to which history has some degree of intelligibility (while another tradition holds that history is a chaotic set of events that is essentially not intelligible (Schopenhauer, 1819).

The literature on development pathways has two main branches. A 'backward-looking' body of work describes past and present development trajectories for given territories and explores their determinants. For example, most of the growth literature as well as a large part of the (macro) development literature fall into this category.[5] This body of work is discussed in Section 4.3 as well as in several other chapters. In particular, Section 5.3.1 reviews the determinants of GHG emissions, Section 12.2 reviews past trajectories of human settlements, and Section 14.3 discusses past trajectories of development at regional scale. In addition, 'forward-looking' studies construct plausible development pathways for the future and examine the ways by which development might be steered towards one pathway or another. Box 4.3 briefly reviews the main forward-looking development pathways published since AR4. Most of Chapter 6 is devoted to forward-looking studies.

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[4] Development path and development pathway are synonymous.

[5] This literature can itself be divided in two main groups: papers aimed at identifying individual mechanisms that drive development trajectories, and papers aimed at identifying broad patterns of development. One example of the former is the literature on the relationships between GDP and emissions, discussed in Chapter 5, and in Section 4.4. One example of the latter is the so-called "investment development path" literature, which, following Dunning (1981), identifies stages of development for countries based on the direction of foreign direct investment flows and the competitiveness of domestic firms on international markets.

Box 4.3 | Forward-Looking Development Pathways: new developments since AR4

Forward-looking development pathways aim at illuminating possible futures, and at providing a sense of how these futures might be reached (or avoided). Forward-looking pathways can be constructed using various techniques, ranging from simulations with numerical models to qualitative scenario construction or group forecasting exercises (van Notten et al., 2003).

New sets of forward-looking development pathways have been proposed since the AR4 review (in Sathaye et al. (2007), Section 12.2.1.2). At the global scale, they include, inter alia, the climate smart pathway (World Bank, 2010), the Tellus Institute scenarios (Raskin et al., 2010), and degrowth strategies (Martínez-Alier et al., 2010) or the scenarios developed under the Integrated Assessment Modelling Consortium (IAMC) umbrella (Moss et al., 2010) to update the 2000 SRES scenarios (IPCC, 2000). Pathways have also been proposed for specific sectors, such as health (Etienne and Asamoa-Baah, 2010), agriculture (Paillard et al., 2010), biodiversity (Leadley et al., 2010; Pereira et al., 2010), and energy (Ayres and Ayres, 2009).

At the national and regional levels, the emergence of the "green growth" agenda (OECD, 2011) has spurred the development of many short- to medium-term exercises (e.g. Republic of Korea, 2009; Jaeger et al., 2011); as well as renewed discussions on SD trajectories (e.g. Jupesta et al., 2011). Similarly, there is growing research on the ways by which societies can transition towards a "low carbon economy", considering not only mitigation and adaptation to climate change, but also the need for social, economic, and technological (Shukla et al., 2008) (see Section 6.6.2 for a broader review). For instance, studies in China show that controlling emissions without proper policies to counteract the negative effects will have an adverse impact on the country's economic development, reducing its per capita income and the living standards of both urban and rural residents (Wang Can et al., 2005; Wang Ke, 2008). China is developing indicators for low-carbon development and low-carbon society (UN (2010), with many citations) with specific indicators tested on selected cities and provinces (Fu, Jiafeng et al., 2010), providing useful data on challenges and gaps as well as the need for clearly defined goals and definitions of "low-carbon" and its SD context.

4.5.2 Transition between pathways

Backward-looking studies reveal that past development pathways have differed in many respects, notably in terms of GHG emissions because of differences in, inter alia, fuel supply mix, location patterns, structure of economic activity, composition of household demand, etc.—even across countries with otherwise very similar economic characteristics. Similarly, forward-looking studies point to very contrasted, yet equally plausible, futures in terms of GHG emissions. Shifting from a high- to a low-emissions development pathway requires modifying the trajectory of the system that generates (among others) GHG emissions. It thus requires time as well as action over multiple dimensions of development (location, technology, lifestyles, etc.). Yet, shifting from a high- to a low-emissions development pathway could potentially be as important for climate change mitigation as implementing 'climate' policies (Halsnaes et al., 2011).

A central theme of the present report is to explore the conditions of a transition towards development pathways with lower emissions, globally (Chapter 6), sectorally (Chapters 7–12), and regionally (Chapters 13–15). To frame these subsequent discussions, the present section does two things. First, it discusses the obstacles to changing course by introducing the key notions of path dependence and lock-ins (4.5.2.1). Second, examples and lessons from the technology transition literature are discussed (4.5.2.2). The policy and institutional aspects of building strategies to transition between pathways are discussed in the subsequent chapters.[6]

4.5.2.1 Path dependence and lock-ins

Path dependence is the tendency for past decisions and events to self-reinforce, thereby diminishing and possibly excluding the prospects for alternatives to emerge. Path dependence is important for analyzing transitions between development pathways. For example, development of inter-city highways may make further extension of the road network more likely (if only for feeder roads) but also make further extension of rail networks less cost-effective by drawing out traffic and investment financing (see Section 12.5), thereby diminishing the prospects for alternative transportation investments.

Chief among the mechanisms that underlie path-dependence are 'increasing returns' mechanisms (Page, 2006)—in which an outcome in one period increases the probability of generating that same outcome in the next period. Increasing returns is a large group that com-

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[6] The key point, as emphasized in AR4, is that a development pathway results from the interactions of decisions by multiple agents, at all levels. Thus in general public policies alone cannot trigger changes in pathways, and cooperation between governments, markets, and civil societies are necessary (Sathaye et al., 2007).

DEPT OF INTERIOR
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2016 NOV 14 PM 1:[illegible]8

prises, inter alia, increasing returns to scale, learning by doing, induced technological change, or agglomeration economies. As Shalizi and Lecocq (2013) note, the concept of increasing returns has a long tradition in economic history, and the implications of increasing returns mechanisms have been systematically explored over the past three decades or so, notably around issues of monopolistic competition (Dixit and Stiglitz, 1977), international trade (Krugman, 1979), economic geography (Fujita et al., 1999), economic growth (Romer, 1990), industrial organizations, or adoption of technologies (Arthur, 1989).

Yet increasing returns are neither sufficient nor necessary to generate path-dependence. They are not sufficient because competing increasing returns can cancel out. And they are not necessary because other mechanisms might generate path-dependence. For example, decisions that involve the use of scarce resources, such as land, labour or exhaustible natural resources constrain future agents' options, either temporarily (for labour) or permanently (for exhaustible resources). Similarly, in the presence of switching costs—e.g., costs attached to premature replacement of long-lived capital stock—decisions made at one point in time can partially or totally lock-in decision makers' subsequent choices (Farrell and Klemperer, 2007). Also, path-dependence can emerge from coordination failures in complex systems that require high degree of articulation between actors (Yarime, 2009). The key message is that it is essential to look broadly for mechanisms that may generate path-dependence when analyzing the determinants of pathways (past or anticipated) (Shalizi and Lecocq, 2013).

Lock-in is the most extreme manifestation of path dependence, when it becomes extremely costly or impossible to shift away from the current pathway. Lock-ins can emerge in many domains, with examples ranging from end-use technology standards (e.g. the competition between the AZERTY and the QWERTY keyboards, or between the VHS and BETAMAX video standards), energy supply networks to expansion pathways of regions once initial choices are made (Fujita et al., 1999). Lock-ins are not 'good' or 'bad' per se (Shalizi and Lecocq, 2013), but identifying risks of 'bad' lock-ins and taking advantage of possible 'good' lock-ins matters for policymaking, so that ex ante decisions are not regretted ex post (Liebowitz and Margolis, 1995). The literature, however, underlines that lock-ins do not stem only from lack of information. There are also many cases in which rational agents might make decisions based only on part of the information available, because of, inter alia, differences between local and global optimum, time and resource constraints on the process or information symmetry (Foray, 1997); which points to the process of decision making (see Section 4.3.2 on Governance and Political Economy).

4.5.2.2 Examples and lessons from the technology transition literature

Part of the literature on innovation (reviewed in Sections 3.11 and 4.3.6; technological change is reviewed in Section 5.6) adopts a broad, systemic perspective to try to explain how new technologies emerge. It thus provides examples of, and insights on how transition between pathways can occur. In fact, changes in technologies, their causes, and their implications for societies have been actively studied in social sciences since the late 18th century by historians, economists, and sociologists. A common starting point is the observation that "technological change is not a haphazard process, but proceeds in certain directions" (Kemp, 1994). For example, processors tend to become faster, planes to become lighter, etc. To characterize these regularities, scholars have developed the concepts of *technological regime* (Nelson and Winter, 2002) and *technological paradigms* (Dosi, 1982; Dosi and Nelson, 1994). Technological regimes refer to shared beliefs among technicians about what is feasible. Technological paradigms refer to the *selected* set of objects engineers are working on, and to the *selected* set of problems they choose to address. How technological regimes may change (such as with the development of information technologies) is a subject of intense research. Radical innovations (e.g., the steam engine) are seen as a necessary condition. But the drivers of radical innovation themselves are not clearly understood. In addition, once an innovation is present, the shift in technological regime is not a straightforward process: the forces that maintain technological regimes (e.g., increasing returns to scale, vested interests, network externalities) are not easy to overcome—all the more so that new technologies are often less efficient, in many respects, than existing ones, and competing technologies may coexist for a while. History thus suggests that the diffusion of new technologies is a slow process (Kemp, 1994; Fouquet, 2010).

More recent research over the past 20 years has yielded two major perspectives on technology transitions (Truffer and Coenen, 2012): the multi-level perspective on socio-technical systems (Geels, 2002) and the concept of technological innovations systems (Bergek et al., 2008). The multi-level perspective distinguishes three levels of analysis: niche innovations, socio-technical regimes, and socio-technical landscape (Geels, 2002). A technological niche is the micro-level where radical innovations emerge. Socio-technical regimes correspond to an extended version of the technological regime discussed above. The socio-technical landscape corresponds to the regulatory, institutional, physical, and behavioural environment within which innovations emerge. There is considerable inertia at this third level. Changes in socio-technical regimes emerge from the interactions between these three levels. According to Geels and Schot's typology (2007), changes in socio-technical regimes can follow four different paths. *Transformation* corresponds to cases in which moderate changes in the landscape occur at a time when niche innovations are not yet developed, thus resulting in a relatively small change of direction of the development pathway. An example of transformation occurred when municipal sewer systems were implemented in Dutch cities (Geels, 2006). *De-alignment* and *realignment* correspond to sudden changes in the landscape that cause actors to lose faith in the regime. If no clear replacement is ready yet, a large range of technologies may compete until one finally dominates and a new equilibrium is reached. One example is the transition from horse-powered vehicles to cars. If new technologies are already available, on the other hand, a *transition substitution* might occur, as in the case of the replacement of sailing ships by steamships between 1850 and 1920. Finally, a *reconfiguration* occurs when innovations initially adopted as part of the current regime progressively subvert it into a new one, an example of which is the transition from traditional factories to mass production in the United States.

The technological innovation systems approach (Bergek et al., 2008) adopts a systemic perspective by considering all relevant actors, their interactions, and the institutions relevant for innovation. Early work in this approach argues that beside market failures, 'system failures' such as, inter alia, actor deficiencies, coordination deficits or conflicts with existing institutional structures (institutional deficits) can explain unsuccessful innovation (Jacobsson and Bergek, 2011). More recent analysis focuses on core processes critical for innovation, such as presence of entrepreneurial activities, learning, knowledge diffusion through networks, etc. The technological innovation systems concept was developed to inform public policy on how to better support technologies deemed sustainable with an increasing focus on 'system innovations' as opposed to innovation in single technologies or products (Truffer and Coenen, 2012).

4.5.2.3 Economic modelling of transitions between pathways

As noted above (4.5.1), economic modelling is a major tool for analyzing future development pathways. Models provide different types of information about transition, depending on their features and on how they are used. The present sub-section reviews the use of models for studying transitions. See Section 6.2 for a review of modelling tools for integrated assessment.

There are four increasingly complex ways of using economic models to analyze transitions between development pathways. The first option—*static modelling*—consists of building plausible images of the future at a given date and comparing them (comparative statics). The focus is on the internal consistency of each image, and on the distance between them. Models without explicit representation of time (e.g., input-output, partial equilibrium, or static general equilibrium models) are sufficient. Static models can provide insights on the sustainable character of the long-term images, to the extent that the model captures critical variables for sustainability such as natural resources use or impact of economic activity on the environment (e.g., GHG emissions). However, national accounts typically add up multiple products with very different material content, very different energy contents, and very different prices. Thus, constructing robust relationships between aggregate monetary indicators and physical flows requires in-depth analysis. Similarly, static models can provide insights on the social components of sustainability to the extent they include some form of representation of the *distribution* of economic activity within the society, notably across income groups (see Section 4.4.1). Again, the associated data challenge is significant. By construction, on the other hand, static models do not provide insights on the pathways from the present on to each possible future, let alone on the transitions between pathways.

Dynamic models are needed to depict the pathway towards desirable (or undesirable) long-term futures. Still, the relevance of dynamic models for discussing transitions depends on their structure, content, and way they are used. A large part of the modelling literature on climate change mitigation relies on neoclassical growth models with exogenous (Swan, 1956; Solow, 1956) or endogenous (Koopmans, 1965; Cass, 1965) savings rate. In those models, long-term growth is ultimately driven by the sum of population growth and exogenous total factor productivity growth (exogenous technical change). In the simplest version of the neoclassical model, there is thus only one 'pathway' to speak of, as determined by human fertility and human ingenuity. Any departure from this pathway resorbs itself endogenously through adjustment of the relative weights of capital and labour in the production function, and through adjustment of the savings rate (when endogenous). Empirically, neoclassical growth models have limited ability to explain observed short-term growth patterns (e.g., Easterly, 2002).

Modelling of *processes* is needed to enrich discussions about transitions by differentiating short-term economic processes from long-term processes. The general point is that the technical, economic, and social processes often exhibit more rigidities in the short- than in the long-run. As Solow (2000) suggests, at short-term scales, "something sort of 'Keynesian' is a good approximation, and surely better than anything straight 'neoclassical'. At very long time scales, the interesting questions are best studied in a neoclassical framework and attention to the Keynesian side of things would be a minor distraction". There is a long tradition of debates in economics on the degree to which production technologies and wages should be considered flexible or rigid in the short- and medium-run, with potentially very different results for the assessment of mitigation policies (Rezai et al., 2013), (Guivarch et al., 2011). Other important rigidities include, inter alia, long-lived physical capital, the premature replacement of which is typically very costly, and the dynamics of which have important implications for the costs, timing, and direction of climate policies (e.g. Lecocq et al., 1998; Wing, 1999); rigidities associated with the location of households and firms, changes of which take time; or rigidities associated with preferences of individuals and with institutions. Presence of rigidities may also lead to bifurcations towards different long-term outcome (i.e., equilibrium-dependence and not just path-dependence as in section 4.5.2) (See e.g. Hallegatte et al., 2007).

Recognizing *uncertainty* is a further key element for enriching the analysis of transitions, relaxing the full information hypothesis under which many models are run. If information increases over time, there is a rationale for a sequential decision making framework (Arrow et al., 1996), in which choices made at one point can be re-considered in light of new information. Thus, the issue is no longer to select a pathway once and for all, but to make the best first-step (or short-term) decision, given the structure of uncertainties and the potential for increa-

U.S. DEPT OF INTERIOR
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2016 NOV 14 PM 1:03

sing information over time—factors which are especially relevant in the context of climate change. Inertia plays an especially important role in this context, as the more choices made at one point constrain future opportunity sets, the more difficult it becomes to make advantage of new information (e.g.,Ha-Duong et al., 1997). Another way by which uncertainty can be captured in models is to abandon the intertemporal optimization objective altogether and use simulation models instead, with decisions made at any time based on imperfect expectations (Scrieciu et al., 2013). Such shift has major implications for the transition pathway (Sassi et al., 2010), but results strongly depend on how expectations and decisions under uncertainty are represented.

Ideally, models that produce development pathways should thus (1) be framed in a consistent macroeconomic framework (since a pathway is holistic), (2) impose relevant technical constraints in each sector, such as assumptions about the process of technical change, (3) capture the key relationships between economic activity and the environment, e.g., energy and natural resources consumption or greenhouse gases emissions, (4) have a horizon long enough to assess 'sustainability'—a long-term horizon which also implies, incidentally, that the model must be able to represent structural and technical change—yet (5) recognize short-term economic processes critical for assessing transition pathways, such as market imbalance and rigidities, all this while (6) providing an explicit representation of how economic activity is distributed within the society, and how this retrofits into the growth pattern, and (7) representing key uncertainties.

No model today meets all these specifications. Current models can be classified along two major fault lines: bottom-up vs. top-down, and long-term vs. short-term. By design, computable general equilibrium (CGE) models provide a comprehensive macroeconomic framework, and they can be harnessed to analyze distributional issues, at least amongst income groups, but they typically fail to incorporate key technical constraints. Conversely, bottom-up engineering models provide a detailed account of technical potentials and limitations, but their macro-engine, if at all, is most often rudimentary. Emerging 'hybrid' models developed in the context of climate policy assessment are steps towards closing this gap (Hourcade et al., 2006). A similar rift occurs with regard to time horizon. Growth models like Solow's are designed to capture key features of long-term development pathways, but they do not include short- or medium-term economic processes such as market rigidities. On the other hand, short-term models (econometric or structural) will meet this requirement but are not designed to look deep in the future. Again, emerging models include short-/medium-term processes into analysis of growth in the long-run (see e.g., Barker and Serban Scrieciu, 2010), but this pretty much remains an open research field.

4.6 Mitigative capacity and mitigation, and links to adaptive capacity and adaptation

4.6.1 Mitigation and adaptation measures, capacities, and development pathways

Even though adaptation and mitigation are generally approached as distinct domains of scientific research and practice (Biesbroek et al., 2009) (as reflected, for example, in the IPCC separate Working Groups II and III), a recognition of the deep linkages between mitigation and adaptation has gradually emerged. Initially, mitigation and adaptation were analyzed primarily in terms of techno-economic considerations. But growing attention has been directed at the underlying capacities, first with respect to adaptation, and later -and less fully- with respect

Box 4.4 | Characterizing the sustainability of development pathways

Constructing and modelling forward-looking development pathways is one thing, evaluating how they fare in terms of sustainability within and beyond the time horizon of the modelling is another. Two questions can actually be distinguished (Asheim, 2007). One is to predict whether the current situation (welfare, environment) will be preserved in the future: are we on a sustained development pathway, i.e., a pathway without downturn in welfare or environmental objectives? This question is answered by looking at the evolution of the target variables within the time horizon of the scenario, and what happens beyond the horizon remains undetermined. Another question is to determine whether the current generation's decisions leave it possible for future generations to achieve a sustained pathway: is a sustained development pathway possible given what the current generation does? Unlike the former question, the latter does not require predicting the future generations' decisions, only their future constraints and opportunities. Showing the existence of a sustained pathway is then an argument in favour of the compatibility of current decisions with future sustainability. Some indicators of sustainability such as genuine savings (see Box 4.2) are meant to provide an answer based on the current evolution of (economic, social, environmental) capital stocks and can also be used for the evaluation of scenarios that depict these stocks. In practice, sustainability analysis (of either type) is not frequent in the scenario-building community, though multi-criteria analysis of scenarios has been gaining ground in recent years (see e.g.,GEA, 2012).

to mitigation, (Grothmann and Patt, 2005; Burch and Robinson, 2007; Winkler et al., 2007; Goklany, 2007; Pelling, 2010).

This attention has necessitated a broadening of the scope of analysis well beyond narrow techno-economic considerations, to the social, political, economic, and cultural domains, as ultimately, this is where the underlying determinants of mitigative and adaptive capacity lie. Following the literature enumerated above, a non-exhaustive list of these underlying determinants include: the level and distribution of wealth, robustness and legitimacy of institutions, availability of credible information, existence and reliability of infrastructure, access to and adequacy of technologies and systems of innovation, effective governance, social cohesion and security, distribution of decision-making power among actors, conditions of equity and empowerment among citizens, and the opportunity costs of action, as well as individual cognitive factors, including relevant skills, knowledge and cultural framings. The fact that mitigative and adaptive capacities share and are similarly affected by these underlying determinants highlights their similarity, blurring the distinction between them and leading some scholars to argue that there is simply 'response capacity' (Tompkins and Adger, 2005; Wilbanks, 2005; Burch and Robinson, 2007). Because response capacity is directly shaped by these underlying technological, economic, institutional, socio-cultural, and political determinants, it is in other words directly shaped by the overall development pathway, which is the combined product of those same inter-related determinants. This dependence of response capacity on development pathway is underscored by the strong parallel between its determinants (outlined above) and the defining dimensions of a development pathway (discussed in Sections 4.3 and 4.5). Indeed, response capacity is determined much more by the overall development pathway than by targeted climate-specific policies. The academic consensus on this point has been clearly reflected in the AR4 (IPCC, 2007), in WGI Chapter 12 in the case of mitigative capacity, and WGII Chapter 18 in the case of adaptive capacity. Of course, more nuanced and site-specific assessments of the determinants of such capacity can provide further useful insight (see e.g., Keskitalo et al, 2011).

Moreover, there is consensus that an effective transition toward a SD pathway in particular can more effectively foster response capacity (IPCC, 2007; Matthew and Hammill, 2009; Parry, 2009; Halsnaes et al., 2011; Harry and Morad, 2013). There are various elements of fostering a transition toward SD that naturally accord with the creation of mitigative and adaptive capacity, including, for example, the establishment of innovation systems that are supportive of environmental and social priorities, the support for adaptive ecosystem management and conservation, the strengthening of institutions and assets to support food and water security and public health, and the support for procedurally equitable systems of governance (Banuri, 2009; Barbier, 2011; Bowen et al., 2011; Bowen and Friel, 2012). Mitigation and adaptation outcomes can of course still be expected to depend on the extent to which explicit efforts are taken to implement and mainstream climate change policies and measures, as well as on the manner in which a particular SD approach may evolve—with more or less emphasis on economic, social, or environmental objectives (Giddings et al., 2002; Beg et al., 2002; Grist, 2008; Halsnæs et al., 2008).

The centrality of mitigative and adaptive capacity to SD is highlighted by the growing attention to the idea that the Earth system has moved from the Holocene into the Anthropocene (Steffen et al., 2011), where societies are the most important drivers of the Earth's dynamics. Mitigative and adaptive capacity can be seen in general terms, i.e., not just with respect to GHG emissions and climate impacts, but all anthropogenic environmental pressures and impacts from ecosystem degradation. In this view, mitigative and adaptive capacity are central to sustainable ecosystem management (Holling, 1978; Walters and Holling, 1990; McFadden et al., 2011; Williams, 2011), and thus fundamental to SD (Chapin et al., 2010; Folke et al., 2011b; Polasky et al., 2011; Biermann et al., 2012). Some scholars interpret this as a fundamental redefinition of development calling for transformational shifts based on re-imagining possibilities for future development pathways (Pelling, 2010; Jackson, 2011a; Kates et al., 2012; Ehrlich et al., 2012).

Scholarship exploring the links between mitigation, adaptation, socio-ecological resilience and SD more generally, has generally pointed toward the existence of (potential) synergies and tradeoffs within and across policy sectors and across implementation measures (Gallopín, 2006; Rosenzweig and Tubiello, 2007; Vogel et al., 2007; Boyd et al., 2009; Thornton and Gerber, 2010; Adger et al., 2011; Warren, 2011; Lal et al., 2011; Vermeulen et al., 2012; Denton and Wilbanks, 2014; Hill, 2013). These studies show that, in spite of mitigative and adaptive *capacities* being so closely intertwined with each other and with SD, the relationship between mitigation and adaptation *measures* is more ambiguous and, in line with the AR4, suggest that outcomes are highly dependent on the measures and the context in which they are undertaken, with some policy sectors being more conducive to synergies than others.

In the agricultural sector, for example, scholars have for many years highlighted the potential of fostering both mitigation and adaptation by supporting traditional and biodiverse agro-ecological systems around the world (Campbell, 2011; Altieri and Nicholls, 2013, and see Section 11.5). A recent modelling exercise suggests that investing substantially in adapting agriculture to climate change in some regions—Asia and North America—can result in substantial mitigation co-benefits, while the latter may be insignificant in Africa (Lobell et al., 2013). There are empirical studies where interventions in agricultural systems have led to positive mitigation and adaptation outcomes—or vice versa—(Kenny, 2011; Wollenberg, 2012; Bryan et al., 2012), or where synergies between adaptation and mitigation have not materialized due to, for example, limited scientific and policy knowledge, as well as institutional and farmers' own financial and cognitive constraints (Haden et al., 2012; Arbuckle Jr. et al., 2013; Bryan et al., 2013). In forestry, the links between fostering mitigation strategies, e.g., through planting trees, developing agro-forestry systems or conserving diverse ecosystems, and the adaptation of both forests and people to climate change have been widely acknowledged

U.S. DEPT OF INTERIOR
BUREAU OF LAND MGMT
COLO STATE OFFICE DENVER

2013 NOV 14 [illegible]

and the possibility of effective linkages in policy and action have also been identified (Locatelli et al., 2011; Schoeneberger et al., 2012; Mori et al., 2013). Methods for identifying tradeoffs between mitigation and adaptation at policy and implementation levels and to foster legitimate decision making have also been recently developed (Laukkonen et al., 2009; Janetos et al., 2012).

This evolving literature highlights the need to examine adaptation and mitigation for their SD implications, and ultimately to mainstream them in broader development policy. It also explains the parallel emergence of environmental governance research about reforming existing or developing institutions in different policy domains to meet this need (Folke et al., 2005; Folke, 2007; Brunner and Lynch, 2010). Recent studies highlight the organizational, institutional, financial, and knowledge barriers to the development of effective governance for mitigation and adaptation in general government policy (Picketts et al., 2012), as well as in particular policy sectors, e.g., in forestry (Johnston and Hesseln, 2012); in health (Bowen et al., 2013); or in urban planning (Barton, 2013). Others identify the multi-scale, inter-connected, and dynamic nature of many climate issues and their associated responses as a key barrier to action, particularly at local level (Romero-Lankao, 2012). Analyses of the effectiveness of public-private partnerships and other forms of multi-actor cooperation to mainstream both mitigation and adaptation measures in a given sector and context also reveal the challenging nature of such endeavour (Pattberg, 2010; Pinkse and Kolk, 2012).

There is ample scope to improve response capacity in nations and communities by putting SD at the core of development priorities, despite the considerable governance challenges to mainstreaming mitigation and adaptation measures across policy sectors, collective and individual behaviour, and to exploit possible synergies and confront tradeoffs. Nonetheless, it remains the case that the variation of mitigative and adaptive capacity between different nations—and communities within them—is a function of the vast disparities in the determinants of such capacity. These differences in capacity are in turn driven to a significant degree by differences in development pathways and, specifically, level of development. This is a primary reason why the issue of burden sharing among nations features so prominently in consideration of international cooperation on climate change generally, and the UNFCCC in particular, as discussed further in the following section.

4.6.2 Equity and burden sharing in the context of international cooperation on climate

Chapter 3 (Sections 3.2 to 3.5) introduced the general equity principles in the philosophical literature and their relevance to climate change including burden sharing. This section briefly reviews the extensive literature regarding burden sharing in a global climate regime. If focuses first on the equity principles as they are invoked in the literature, which emphasises those laid out in the UNFCCC. It then reviews several categories of burden sharing frameworks. While the academic literature uses the term 'burden sharing', it is understood that mitigation action entails not only burdens but also benefits.

4.6.2.1 Equity principles pertinent to burden sharing in an international climate regime

The UNFCCC clearly invokes the vision of equitable burden sharing among Parties toward achieving the Convention's objective. While Parties had not articulated a specific burden sharing arrangement in quantified detail, they had established an initial allocation of obligations among countries with explicit references to the need for equitable contributions. All Parties adopted general commitments to mitigate, adapt, and undertake other climate-related actions, but distinct categories of countries reflecting level of development were identified and assigned specific obligations. Developed countries (listed in Annex I) were distinguished from developing countries and obliged to "take the lead on combating climate change and the adverse effects thereof" (Article 3.1), noting "the need for equitable and appropriate contributions by each of these Parties to the global effort regarding [the UNFCCC] objective" (Article 4.2(a)). A subset of Annex I countries consisting of the wealthier developed countries (listed in Annex II) were further obliged to provide financial and technological support "to developing countries to enable them to effectively implement their UNFCCC commitments" (Article 4.7), noting that they "shall take into account … the importance of appropriate burden sharing among the developed country Parties".

While Parties' equitable contributions are elaborated further in subsequent UNFCCC decisions and under the Durban Platform for Enhanced Action, an explicit arrangement for equitable burden sharing remains unspecified. Because there is no absolute standard of equity, countries (like people) will tend to advocate interpretations which tend to favour their (often short term) interests (Heyward, 2007; Lange et al., 2010; Kals and Maes, 2011). It is thus tempting to say that no reasoned resolution is possible and to advocate a purely procedural resolution (Müller, 1999). However, there is a basic set of shared ethical premises and precedents that apply to the climate problem, and impartial reasoning (as behind a Rawlsian (Rawls, 2000) "veil of ignorance") can help put bounds on the plausible interpretations of equity in the burden sharing context. Even in the absence of a formal, globally agreed burden sharing framework, such principles are important in establishing expectations of what may be reasonably required of different actors. They influence the nature of the public discourse, the concessions individuals are willing to grant, the demands citizens are inclined to impose on their own governments, and the terms in which governments represent their negotiating positions both to other countries and to their own citizens. From the perspective of an international climate regime, many analysts have considered principles for equitable burden sharing, (Rose 1990; Hayes and Smith 1993; Baer et al. 2000; B. Metz et al. 2002; Ringius, Torvanger, and Underdal 2002; Aldy, Barrett, and Stavins 2003;