Chapter 22

Pathways Toward Sustainable Development

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Executive summary

Model-based scenario analysis can help in identifying ways to achieve the environmental targets of the Sustainable Development Goals (SDGs) and related multilateral environmental agreements (MEAs) (*well established*). Target-seeking scenarios provide insight into the required level of effort, promising measures, and possible synergies and trade-offs between these measures and a range of targets. The usefulness of scenarios can be illustrated by the successful use of such scenarios in the literature on climate policy. Scenarios can be used to explore different pathways for achieving long-term targets and provide insights into the costs and benefits of these pathways. There are important interrelations (synergies and trade-offs) between the achievement of the various SDGs and related MEAs.. This means that strategies that aim to achieve sets of targets will have to take account for these interrelations. At the moment, scenarios that explore the fulfilment of a large set of SDG targets simultaneously are mostly lacking. An assessment of possible pathways must therefore rely on more narrowly focused scenarios in the literature. This does lead to a higher level of uncertainty and some clear knowledge gaps. {22.2}

Overall, available scenario literature suggests that different pathways exist for achieving the targets, but that these pathways require transformative changes (*established, but incomplete*). The rate of change in the pathways, required to meet the targets identified in Chapter 20, indicate that incremental environmental policies will not suffice. Significant improvements in resource efficiency with respect to land, water and energy are required. This includes large productivity gains in agriculture, significant improvements in nutrient-use and water-use efficiency, almost a doubling of the energy efficiency improvement rate and a more rapid introduction of 'carbon-free' energy options. Similarly, achieving full access to food, water and energy resources will require a clear break with current trends. {22.3; 22.4.1}

Achieving the sustainability goals will require a broad portfolio of measures based on technological improvements, lifestyle changes and localized solutions (*established, but incomplete*). The pathways emphasize a number of key transitions that are associated with achieving sustainable consumption and production patterns for energy, food and water, in order to provide universal access to these resources, while preventing climate change, air pollution, land degradation, loss of biodiversity, water scarcity, over-exploitation and pollution of the oceans. These transitions include changes in lifestyle, consumption preferences and consumer behaviour on the one hand, and cleaner production processes, resource efficiency and decoupling, and corporate responsibility on the other. {22.3}

Concurrently eliminating hunger, preventing biodiversity loss and halting land degradation is possible by combining measures related to consumption, production and access to food with nature conservation policies (*well established*). Several measures have been identified that together can help minimize the associated trade-offs, including sustainable agricultural intensification (e.g. increased water- and nutrient-use efficiencies), shifts to low-meat diets, reductions in food loss and waste, improved access to food and nutrition management, landscape management and an expansion of protected areas. {22.3.1}

The strong links between biodiversity loss and land use mean that more coordinated international action is needed (*established, but incomplete*). Scenario literature clearly shows that meeting targets to halt biodiversity loss would not be feasible if land use follows projected business-as-usual trajectories. Also, other policies outside the realm of traditional nature conservation policies are urgently needed to protect biodiversity, such as those related to infrastructure development and climate change. Ensuring more coordinated policy action is therefore important at all levels – within national governments, but also internationally - in particular between land-use planning and biodiversity protection. {22.3.1}

There are multiple pathways to reduce greenhouse gas emissions to levels consistent with the Paris Climate Agreement. Each, however, requires transformative changes and needs to be implemented rapidly (*well established*). Measures that reduce greenhouse gas emissions include lifestyle changes (e.g. a shift to low-meat diets and a move to more public modes of transport), a doubling of energy efficiency improvement, a more rapid introduction of low- and zero-carbon technologies (including hydropower, solar and wind, and carbon-capture-and-storage), reduction of non-CO_2 greenhouse gas emissions and the use of land-based mitigation options (e.g. reforestation and bioenergy). Emission reduction measures need to be implemented rapidly, because the carbon budgets for achieving the Paris Agreement are very tight. As a broad guideline, the rate of decoupling CO_2 emissions from gross domestic product (GDP) needs to increase from the historic rate of 1 to 2 per cent per year to between 4 and 6 per cent per year between now and 2050 if the Paris Agreement targets are to be met. {22.3.2}

Air pollution emissions can be reduced significantly, but pathways towards meeting the most stringent air quality guidelines are currently not available (*established, but incomplete*). Introducing air pollution policies alone is often not enough to achieve stringent air quality standards. However, climate change mitigation (e.g. phasing out fossil fuels) also significantly reduces air pollutant emissions. As a result, scenarios that combine climate policies with stringent air pollution policies show strong reductions in emissions of particulate matter with diameter less than 2.5 μm ($PM_{2.5}$), leading to a significant improvement in air quality in all regions. In the best case scenarios, less than 5 per cent of the population is projected to be exposed to $PM_{2.5}$ levels above the World Health Organization's most lenient interim target of 35 μg/m^3, though more than half of the population is still projected to be exposed to levels above the guideline of 10 μg/ m^3. {22.3.2}

Reducing global water stress, including groundwater depletion, requires more efficient water use, increasing water storage and investing in wastewater reuse and desalination capacity (*established, but incomplete*). To maintain or even reduce the global population suffering from water scarcity by 2050 and beyond, water-use efficiency needs to improve by more than 20-50 per cent globally. This includes increasing agricultural water productivity, improving irrigation efficiency and more efficient water use in domestic and industrial sectors. Wastewater reuse and desalination strategies require a large amount of economic investment and modernizing of existing infrastructure, which might not be feasible for many developing countries. Alternatively, nature-based solutions can increase and / or regulate water supply by mitigating water pollution, while limiting economic investments. {22.3.3}

Achieving environmental targets related to oceans requires consistent policies in other sectors *(well established).* Preventing ocean acidification is highly dependent on climate change mitigation (i.e. reduced CO_2 emissions). Reducing marine nutrient pollution, and related hypoxia and harmful algal blooms, requires a significant reduction in nutrient run-off, primarily from fertilizer use and untreated wastewater {22.3.4}

Ending preventable death of children under five years of age requires continued efforts to reduce environmental risk factors, but also increased emphasis on poverty eradication, education of women and girls, and child and maternal health care (*established, but incomplete*). Ending hunger and achieving universal and equitable access to safe drinking water, adequate sanitation and modern energy services would improve health significantly – especially for children under five. However, even if all the environment-related SDG targets were achieved by 2030, the under-five mortality target would not be met. A healthy planet alone is not enough for healthy people. Achieving the SDG target on child mortality also requires addressing non-environmental risk factors, including poverty alleviation, education of women and girls as well as child and maternal health-care. {22.3.5}

Understanding interlinkages between measures and targets is crucial for synergistic implementation and policy coherence (*well established*). Where measures generally aim at achieving specific targets, or clusters of targets, they can also affect other targets. Integrated approaches are needed to grasp the synergies and deal with the potential trade-offs to achieve the environmental targets simultaneously. {22.3; 22.4.2}

Overall, the literature reveals more synergies than trade-offs within and among the SDGs and their targets (*established, but incomplete*). Significant synergies across human well-being and natural resource targets can be harnessed. For example, reducing agricultural demand by changing dietary patterns towards less meat intake and reducing food loss and waste, reduces the pressure on land and water, thereby reducing biodiversity loss and contributing to climate change mitigation. Other examples discussed in the chapter include education and reducing air pollution. Phasing out unabated use of fossil fuels leads to important co-benefits by achieving both climate and air quality targets, the latter having synergies with improving human health, increasing agricultural production and reducing biodiversity loss. {22.4.2}. The chapter also identifies several trade-offs. This could imply that such measures are less attractive or additional policies are needed to mitigate the trade-offs. {22.3}

Yield improvement and bioenergy are important measures to address biodiversity loss and climate change, respectively, but they can conflict with achieving other targets (*well established*). While nearly all scenarios consistent with the Paris agreement rely on land-based mitigation measures, their use increases demand for land, with related biodiversity impacts, and they potentially lead to higher food prices. Increasing agricultural yields can improve overall food availability and reduce pressure on natural land but could also, through higher levels of water, pesticide and fertiliser use and mechanization, lead to land degradation, water scarcity, hypoxia and harmful algal blooms and biodiversity loss. {22.4.2}

Further model development and pathway analysis is needed to cover a wider set of linkages across the SDGs (*well established*). The scenario literature is still patchy with respect to achieving a broad range of targets. Climate change and land-use issues are well covered, while scenarios addressing land degradation and many challenges related to oceans, but also to chemicals and waste, are mostly lacking. Furthermore, many synergies and trade-offs are discussed in the literature, but besides thematic studies, a thorough overview of all relevant interrelations is lacking. More dedicated analyses are required, including systematic reviews of the existing literature and dedicated integrated assessment modelling, with specific attention to interlinkages that are currently underexplored. {22.5.1}

22.1 Introduction

The identified targets associated with the environmental dimension of the Sustainable Development Goals (SDGs) and related Multilateral Environmental Agreements (MEAs) from Chapter 20 will not be achieved under current trends (Chapter 21). This chapter assesses the scenario literature for possible pathways that would achieve those targets, thereby closing the implementation gap **(Table 21.2)**. The focus is on the question of what would be needed to achieve these targets – and what are important synergies and trade-offs between different measures and these targets. This chapter does not discuss the social or political feasibility of the pathways. Moreover, the focus is on measures (e.g. energy efficiency improvement or changes in yield) and not on the policies to implement these measures (e.g. taxes or regulation). The latter will be discussed further in Chapter 24.

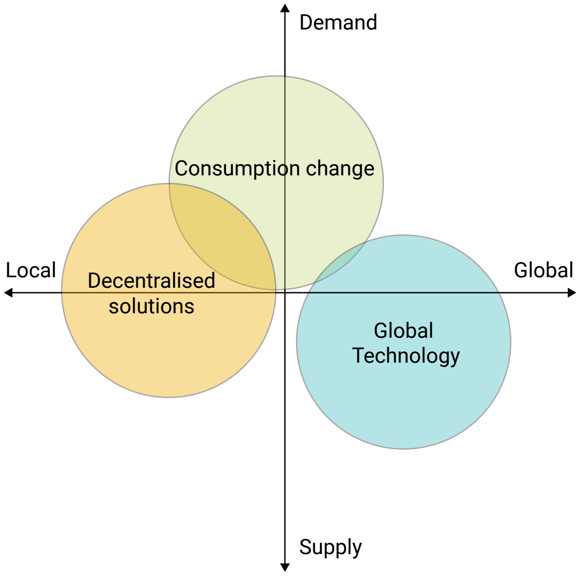
A range of scenarios can be found in the literature that analyse how to implement specific targets such as those related to climate change or land-use change (e.g. Global Energy Assessment [GEA] 2012; Clarke *et al.* 2014; Obersteiner *et al.* 2016). Scenarios that address achieving multiple environmental and/or development targets at the same time are far more scarce, with only a few exceptions (e.g. van Vuuren *et al.* 2015; The World in 2050 Initiative [TWI2050] 2018). Furthermore, there is no comprehensive study that explores all the key interrelations between a broad set of measures and SDG targets. Such studies are important, as the SDG targets and those related to MEAs depend on each other in different ways, leading to both synergies and trade-offs in response strategies (Nilsson, Griggs and Visbeck 2016). This gap in the literature means that, in our assessment, the required measures and the interrelations between different targets need to be based on interpretation of existing work.

22.2 Pathways definition

A range of different scenarios exist that describe a move towards sustainable development (see van Vuuren *et al.* 2012 for an overview of different scenario types). Some scenarios explore the consequences of introducing a set of assumptions about key drivers (e.g. population, economic development and technology) consistent with an emphasis on sustainable development. These subsequently look at the impacts for human development and the environment. Examples include the SSP1 (Sustainable Development) scenario of the Shared Socio-economic Pathways (SSPs) (Riahi *et al.* 2017; van Vuuren *et al.* 2017a; **Box 21.2**), the TechnoGarden scenario of the Millennium Ecosystem Assessment (Millennium Ecosystem Assessment 2005) and the Great Transition Scenarios of the Global Scenarios Group (Raskin *et al.* 2002). These scenarios all lead to relatively positive developments for environmental problems, although they typically do not reach all the targets introduced in Chapter 20. Other scenarios apply a 'back-casting approach' – showing pathways towards reaching a set of sustainable development objectives (e.g. the Road from Rio+20 scenarios; see **Box 22.1**). Two recent scenarios focus specifically on the role of lifestyle change and the possible implications for climate change mitigation (Grubler *et al.* 2018; van Vuuren *et al.* 2018). Sustainable development scenarios differ from current trend scenarios (see Chapter 21) in many ways – including in the nature of economic activities and personal lifestyles, the availability and performance of technologies, and the interventions, regulations and policies that are applied – leading to differences in associated levels of effort, and synergies and trade-offs that will be required to achieve sustainable development (PBL Netherlands Environmental Assessment Agency 2012).

This chapter assesses available scenarios in the literature. No new scenarios were developed. The scenarios cited here should be seen as illustrations of possible pathways towards sustainable development and not as well-defined blueprints. Where possible, SSP-derived scenarios are used **(see Box 21.2)**. Furthermore, the storylines of the Roads from Rio+20 study are used to show that there are different ways to strengthen and direct, or redirect, technologies, preferences and incentives in society towards sustainable development (van Vuuren *et al.* 2015; **Box 22.1**). As such, the underlying dimensions of the Roads from Rio+20 study can also be used to qualify the measures analysed in this chapter. The first dimension then makes the distinction between options that depend on global cooperation and those that specifically focus on the local situation (mostly related to ensuring heterogeneity and local governance). The second dimension distinguishes between options that focus on introducing more sustainable production patterns versus more sustainable consumption patterns. The Roads from Rio+20 scenarios can also be mapped on these dimensions **(Figure 22.1)**. It should be noted that, so far in model-based scenario analysis, strategies based on making production patterns more sustainable have received more attention than strategies focused on changing consumption patterns.

Figure 22.1: The scenarios from the Roads from Rio+20 study



These scenarios are based on a different focus along the dimensions global versus local interventions and production- versus consumption-side orientation. The scenarios are used in this chapter to illustrate that there are different strategies in moving towards sustainable development.

22.3 Pathways towards achieving the targets

A range of measures identified as necessary to achieve the selected targets (see Chapter 20) are listed in **Figure 22.2**. These measures are linked to the five clusters of closely related

Box 22.1: Roads from Rio+20

The Rio+20 study looked into model-based pathways that simultaneously achieve a broad set of long-term environment and development targets (van Vuuren *et al.* 2015). The pathways were developed using the IMAGE integrated assessment model. The targets were based on existing, pre-2012, international agreements (SDGs avant-la-lettre). The study focused on two key sets of related challenges:

1. Eradicating hunger and halting biodiversity loss;
2. Universal access to modern energy and mitigating climate change.

The study further addressed trade-offs with water, nutrients and health. The study introduced three possible pathways towards achieving sustainability targets: (1) global technology, (2) decentralized solutions, and (3) lifestyle change. The different trajectories for the alternative scenarios can be explained by the differences in perceived urgency, economic and institutional effectiveness, and feasible rate of lifestyle changes. The scenarios can be characterized as follows:

- Global technology: In the global technology pathway, international and national decision makers feel an urgency to deal with global sustainability issues and manage to convince most citizens to introduce large-scale, global solutions to resolve these issues. The problems and solutions are primarily perceived and solved as large in scale and global in outreach.
- Decentralized solutions: The belief that a sustainable quality of life can only be realized at the local or regional level gets more priority than the possible impacts of long-term issues. As a result, sustainability problems are primarily seen and resolved in the form of small-scale and decentralized technologies and organizational efforts. Local 'smart' solutions may also fall into this strategy. This is a 'bottom-up' evolving world.
- Consumption change: Partly because there is a growing awareness of sustainability issues, important changes in lifestyle take place that facilitate a transition towards less material- and energy-intensive activities. Targets that still have not been achieved are bridged with additional existing technologies.

Figure 22.2: Selected measures and their related clusters as examined in this chapter

	Agriculture, food, land and biodiversity	Energy, air and climate	Fresh water	Oceans	Human health
Human well-being	• Nutrition management • Improve access to food	• Improve energy access	• Improve access to water, sanitation and hygiene		• Poverty alleviation • Child and maternal healthcare • Education
Sustainable consumption and production	• Reduce food loss and waste • Improve yields • Improve nutrient use efficiency • Dietary change • Land ownership	• Behavioral change • End-use electrification • Low- to zero-emission technologies • Bioenergy • Improve energy efficiency • Air pollution control • Non-CO_2 emission control	• Improve water-use efficiency		
Natural resource base	• Manage soil organic carbon • Protection of terrestrial ecosystems • Forest management • Land use planning • Minimize land damage	• Negative emission technologies	• Wastewater treatment • Water quality standards • Desalination • Integrated water resources management	• Protection of marine ecosystems • Sustainable fisheries • Ocean regulation	

environmental issues and the three groups of SDGs, mirroring the framework of **Figure 22.1**. Note that, in line with Chapter 21, targets associated with production and consumption, such as the rate of yield improvement or energy intensity improvement, are discussed as means to achieve the desired situation. They are discussed within the different clusters and summarized in the synthesis at the end of this chapter.

The following sections review the scenario literature for pathways to achieve the targets within each cluster, discussing the measures required for achieving the targets, and potential synergies and trade-offs between the different measures and targets within each cluster.

In Part A, chemicals and waste, and wastewater were also identified as a major global environmental problem. As explained in **Box 21.1**, there is not a lot of specific scenario literature on these issues. We do discuss reducing food loss and waste in the agriculture, food, land and biodiversity cluster. In the energy, air and climate and freshwater clusters, we pay attention to increasing efficiency – which addresses the issue of wasting energy and water, as well as wastewater treatment.

22.3.1 Agriculture, food, land and biodiversity

The selected targets for the agriculture, food, land and biodiversity cluster can be summarized as ending global hunger, while at the same time halting biodiversity loss and achieving land-degradation neutrality (see Chapter 20). Selected targets that contribute to achieving these endpoint targets include increasing agricultural productivity and increasing nutrient-use efficiency.

Without additional measures, none of these three targets are projected to be met (Chapter 21). While hundreds of millions of people are projected to still be undernourished in 2050, agricultural area is projected to expand by between 150 and 425 million ha between 2010 and 2050, resulting in declines in natural area, including forests. Biodiversity projections suggest a further decline in species richness and abundance, and land degradation is projected to continue. Achieving the targets requires a major transformation of the food production system, the main driver for human-induced land-use change.

With respect to ending hunger, the Food and Agriculture Organization of the United Nations (FAO) definition of food security is used: "Food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life" (FAO 1996). In practice, not all scenarios include enough information to assess all aspects of this definition. Therefore, we have taken qualitative descriptions of the scenarios to assess whether the target is met. For biodiversity, the target is based on the Convention on Biological Diversity (CBD) strategic plan for biodiversity 2011-2020 (CBD 2010), translated to halt biodiversity loss by 2020 for developed countries and from 2030 onward for developing countries (Kok *et al.* 2018). Halting biodiversity loss is therefore taken to mean preventing further declines in the diversity within species, across species and within ecosystems, as well as the abundance and coverage of these organisms. For achieving land degradation neutrality no quantitative analysis is available.

There are important linkages between this cluster and other cluster targets. For instance, combating climate change might require significant amounts of bioenergy and land devoted to its production. Total land area dedicated to bioenergy production is a major uncertainty in future scenarios, especially those with stringent emissions abatement targets (Popp *et al.* 2014). In addition, increased agricultural production could require increasing inputs of freshwater, nitrogen and phosphorus.

In order to simultaneously end hunger and prevent biodiversity loss and further land degradation, enough food needs to be produced to feed a global population of 9-10 billion people by 2050 without expanding agricultural land (at least on a global scale). At the same, there will also be other demands for land such as biomass production for energy and demand to produce timber. Reducing hunger not only requires sufficient production, but also, much more importantly, issues of access (economic and physical) will need to be addressed in order to ensure that all people receive adequate food. Additionally, this needs to occur with minimal pollution (nitrogen, phosphorus or other). Further land protection and land restoration may be required to prevent biodiversity loss and avoid or reverse land degradation.

There are several scenarios in the literature that achieve these targets in an integrated way. These studies show that that there are multiple routes for achieving the targets, such as via more technology-focused routes, changing demand or focusing more on governance structures, land tenure and creating markets (Tilman *et al.* 2011; Bajželj *et al.* 2014; van Vuuren *et al.* 2015; Obersteiner *et al.* 2016). More recent literature based on the SSPs discusses multiple routes that could lead to zero hunger by 2050 (Hasegawa *et al.* 2015), some of which are achieved without expanding agricultural area (Popp *et al.* 2017). However, it is important to note that food security involves not just security of supply but also demand factors such as access to food, including affordability and distributional concerns (Qureshi, Dixon and Wood 2015), and its nutritional value. However, issues of access, distribution and nutritional value are largely excluded from the scenario literature and thus not discussed in depth in this chapter.

Most scenario studies that discuss prevention of biodiversity loss assume a suite of land-, agriculture- and biodiversity-related measures acting together, including increasing agricultural productivity, reducing consumption of meat, dairy and eggs, reducing food loss and waste, avoiding fragmentation and expanding protected areas. Such measures can reduce biodiversity loss (van Vuuren *et al.* 2015) and extinction risks for birds and mammals (Tilman *et al.* 2017).

Overall, a broad range of measures is discussed in the literature, including measures related to agricultural production, agricultural demand-side measures and measures that aim for protection of terrestrial ecosystems.

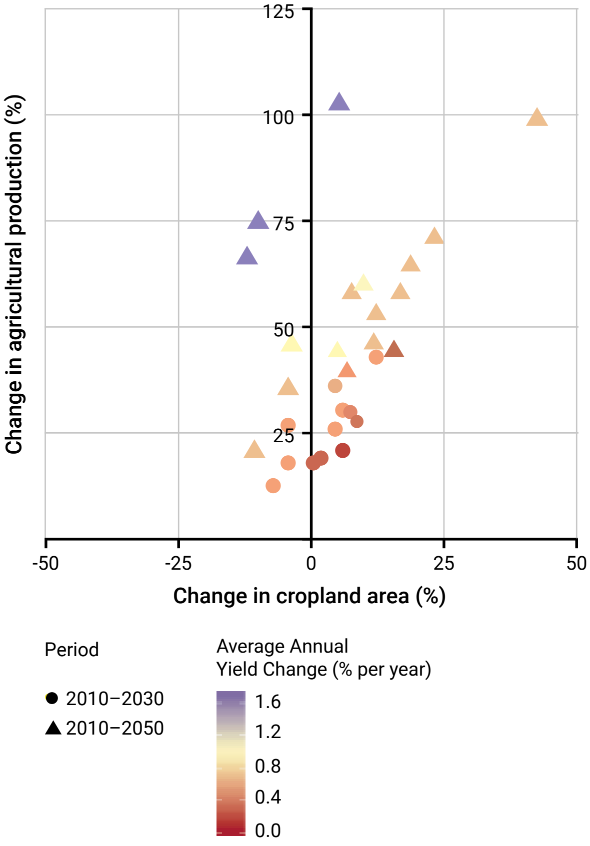
Measures related to agricultural production

One option to achieve the targets in the agriculture, food, land and biodiversity cluster is to change agricultural production patterns. This includes yield improvement (to avoid further expansion of agricultural land), but also other efficiency measures, such as for nutrient and water use, to reduce the environmental pressure of agriculture.

Improving yield

In the SSP2 baseline (Fricko *et al.* 2017), between 2010 and 2050, per capita demand for food, feed and energy crops increases by 60 per cent. In the same period, global average aggregate food, feed and energy crop yields (mean tons of agricultural products per hectare) also increases (by around 1.0 per cent per year). As a result, the net effect in SSP2 is an increase in cropland area of about 15 per cent in 2050 (230 million ha) **(Figure 22.3)**. This is in line with the FAO projection for yield improvements and agricultural area expansion through 2050 (Alexandratos and Bruinsma 2012). To limit cropland expansion, yield growth would need to increase from around 1.0 to 1.4 per cent per year. It is thus useful to look into the evidence on the question whether fast yield improvements are possible in the future. First, similar yield improvement rates have been achieved historically (Alexandratos and Bruinsma 2012). Moreover, several scenarios indeed show high future yield increase **(Figure 22.3)**. There is also a large yield gap between the most- and least-productive regions (Global Yield Gap and Water Productivity Atlas 2018), and transfer of best practices from the leaders to the laggards might raise global average yields (Neumann *et al.* 2010; Foley *et al.* 2011). Finally, new methods to improve yields might also provide further potential (including genetically modified organisms [GMOs]). On the other hand, the easy yield gains may already have been achieved (Slade, Bauen and Gross 2014). Moreover, over the past decades yield increases have coincided with significant increases in environmental pressure such as nitrogen pollution as a result of nitrogen fertilization (Lassaletta *et al.* 2016). Projections of future fertilizer use are uncertain, but it is clear that increasing global production levels would require greater fertilizer use (Alexandratos and Bruinsma 2012). For instance, yield increase could lead to 15-70 per cent increase in nitrogen losses to the environment, leading to further pollution of water and soil (Sutton and Bleeker 2013; Lassaletta *et al.* 2016). Sustained yield improvements may also be reliant on increased irrigation, impacting water resources (Neumann *et al.* 2010). It is also possible that in the future organic farming coupled with reduced food waste and diet change could considerably reduce the environmental footprint of agriculture (Muller *et al.* 2017). However, one might question whether such measures would lead to similar yield levels as through conventional agriculture (Leifeld 2016), or the scalability of existing experiences in both alternative production and food waste reduction methods (Schneider *et al.* 2014). For pasture area, the intensification of livestock production could limit the increase in pasture area, and possibly lead to a decrease.

Figure 22.3: Percentage change in non-energy crop production versus the percentage change in non-energy cropland area from 2010 to 2030 and 2050



Each marker is a model-scenario-year combination. Colour indicates the annual percentage change in yield over the same time period. Yellow is close to historical trends (about 1 per cent per year between 1960 and today from Alexandratos and Bruinsma 2012); blue indicates yield growth faster than historical trends; red indicates yield growth slower than historical trends. For the SSPs, yield is the global average yield for cereal crops. For the Bajželj *et al.* (2014) scenarios, yield is the global average yield for wheat and data are referenced with respect to 2009.

Sources: SSPs (Popp *et al.* 2017) and Bajželj *et al.* (2014).

Reducing environmental pressures associated with agriculture

High-yield agricultural systems are usually associated with high levels of nitrogen loss as reported in the previous section. There is evidence, however, that the negative impact of high-yield agriculture on nitrogen loss could be limited by improving nitrogen-use efficiency (Lassaletta *et al.* 2016; Bouwman *et al.* 2017). This can be shown by the large variation in application rates, with excess application in some regions leading to significant environmental impact, especially in China (Zhang *et al.* 2016; Cui *et al.* 2018). In fact, rapidly increasing global nitrogen-use efficiency from the current 40 per cent to close to 70 per cent may lead to a sharp decline in excess nitrogen to 50 Tg N/year, with the added benefit of potentially leading to stabilization of total nitrogen inputs in global crop production (Zhang *et al.* 2015). Mogollon *et al.* (2018) present similar findings but emphasize that this can only happen in optimistic sustainability scenarios (limited increase in demand and high efficiencies). The relationship of crop yield to nitrogen application means there are diminishing returns to higher nitrogen application in regions with high fertilizer application rates and more potential for increased production in regions with low application rates. This means there is room globally to optimize nitrogen application. The trade-off in this case would be an increase in international trade of agricultural commodities.

It is also important to reduce other environmental pressures – such as high levels of water consumption (see Section 22.3.3), the negative impacts of use of herbicides and pesticides, and eutrophication of inland and coastal waters due to excess nutrient use in food production and sewage water discharge. Scientific evidence shows that it is important to maintain agricultural sustainability to ensure services such as natural pest control, pollination and fertility (Oerke 2006; de Vries *et al.* 2013; Garibaldi *et al.* 2017). For instance, except for cereals (which are not insect-pollinated), many important global food crops depend, at least partly, on animal pollinators (usually insects) for yield and/or quality, and pollinator-dependent crops contribute 35 per cent of the global crop production volume (Klein *et al.* 2007). Reducing negative impacts can to some degree be achieved in high-yield agricultural systems. There is some evidence that organic farming could be an alternative as it may support greater local species richness and higher densities of natural organisms compared with conventional farms (Bengtsson, Ahnström and Weibull 2005; Tuck *et al.* 2014). However, organic farming could also lead to lower yields and thus increased land use (Clark and Tilman 2017). The role of organic farming cannot be really assessed in this chapter as, at present, the issue of organic farming is hardly addressed in scenario studies. In fact, the same goes for strategies to preserve sufficient genetic diversity. While there is some evidence that it is important to maintain diversity as a buffer against all kinds of environmental variability, again this is not really addressed in scenario studies. Such diversity can be encouraged by rotating crops, intercropping and varying crop varieties.

Preventing land degradation

The loss of soil organic carbon and other forms of soil degradation can significantly impact crop yields and the nutritional values of food produced (Godfray *et al.* 2010; Lal 2015; Rojas *et al.* 2016). Therefore, maintaining soil health, through the management of soil organic carbon and preventing land degradation, is important. The recently published Global Land Outlook is one of the few studies that discuss land degradation in the context of different scenarios, but it only discusses trend scenarios and not pathways towards achieving the land degradation neutrality target (United Nations Convention to Combat Desertification [UNCCD] 2017; van der Esch *et al.* 2017). Land restoration and protection targets are projected to increase tree cover by 4 million km^2 in 2050 compared to the area in 2000 and increase forest carbon stocks by 50Gt over the same time period (Wolff *et al.* 2018). However, due to the limited scenarios literature, it is hard to assess the role of avoiding land degradation in achieving the SDGs.

Agricultural demand-side measures

To limit cropland expansion, it is also possible to reduce the food demand that would occur in baseline projections. Reductions in demand could come from reduced food consumption, reduced waste or reduced feed/fuel uses of crops.

Dietary change

Changes in diet are considered an effective measure for reducing land-use impacts of agriculture. Diet changes resulting in less meat consumption would reduce crop use as animal feed, which in turn would reduce demand for land, since direct human consumption of crops requires less land (Stehfest *et al.* 2009). In particular, a reduction in beef consumption would have the most direct positive impact on environmental indicators, as ruminants have the lowest feed and protein conversion rates of all livestock (Béné *et al.* 2015). This implies that reduction of meat consumption to levels consistent with health recommendations in high-income countries could lead to positive impacts in terms of reducing agricultural land-use and increasing human health (Stehfest *et al.* 2009) – as on average current consumption of beef is above this level. Strong reductions in land area for food production as a result of dietary shifts towards more plant-based diets have been reported by Foley *et al.* (2011) and Stehfest *et al.* (2009). Such a shift would also lead to health benefits, according to these studies. Land-efficiency gains can also be gained by eating different meat. Meat from non-ruminant livestock (e.g. pigs) has a lower impact than beef, and the land footprint of their diets can be improved by shifting to more efficient (higher-yielding) fodder crops (Béné *et al.* 2015; van Zanten *et al.* 2018). Thus, diets based on lower shares of ruminants would reduce land demand. In the case of bivalves, aquaculture may even remove nutrient run-off into estuaries through filtration, a potential synergy.

More recent scenarios in the literature have also focused on dietary change, including the SSP1 scenarios (see Popp *et al.* 2017), and the 'consumption change' pathway from Roads from Rio+20 (van Vuuren *et al.* 2015; van Vuuren *et al.* 2018) and others (Bajželj *et al.* 2014; Tilman and Clark 2014). The dietary change ranges from modest shifts towards non-ruminants (the SSP1 scenario) to complete elimination of meat (Tilman and Clark's Vegetarian scenario). Several of these scenarios limit the expansion of cropland area, but these also include enhanced yields, suggesting that dietary change alone is not enough to limit cropland expansion given a growing population. Note that, in addition to changes in yield and diet, these scenarios also have limited expansion of bioenergy cropland (60 and 140 million ha in 2050 in the SSP1 scenario of the IMAGE and GCAM models, respectively). In the end, this means that a combination of yield improvement, diet change and control of bioenergy expansion offers the most likely situation in which expansion of agricultural area can be avoided.

Waste and loss reduction

Global agricultural production in 2010 (about 3,900 kcal of food crops per person per day) was more than enough food to feed the world, yet more than 800 million people were undernourished (Alexandratos and Bruinsma 2012; Kummu *et al.* 2012). One reason is that 25-40 per cent of food produced is wasted, either through supply-chain waste or end-consumption waste (Godfray *et al.* 2010; Kummu *et al.* 2012). Reducing food waste and loss is one way of reducing hunger, while limiting cropland expansion. The amount of food wasted today is enough to feed several hundred million people a year (West *et al.* 2014), with some studies showing that if half of this waste were redistributed to consumers an extra billion people could be fed (Kummu *et al.* 2012). Similarly, Bajželj *et al.* (2014) show that cutting food waste in half would reduce cropland area by 14 per cent. Muller *et al.* (2017) show that, in addition to reducing land demand, dietary change and waste reduction can result in reduced fertilizer and water use. Bijl *et al.* (2017) show that, although significant improvement can be achieved through yield increase, the improvement is less than expected – mostly because meat is, on average, wasted less than other agricultural products. Several of the scenarios that look into waste reduction also report limited cropland expansion (consumption change from van Vuuren *et al.* 2015 and some scenarios of Bajželj *et al.* 2014). Each of these scenarios also assumes enhanced yields leading to the conclusion that waste reduction alone is not enough to limit cropland expansion given an increasing population.

Changes in food distribution

Hunger is to some degree a function of available calories, but more importantly the distribution of these calories. Income distribution plays a key role in food distribution (Wanner *et al.* 2014; Hasegawa *et al.* 2015). In their analysis, Hasegawa *et al.* (2015) conclude that future developments in global hunger are mostly determined by population growth, inequality in food distribution and per capita domestic food production. Improving access to food for the poorest households significantly reduces the required increase in food production to feed the global population in 2050 (van Vuuren *et al.* 2015). Also avoiding food waste reduces demand for cropland and could still allow for meat consumption, albeit at a lower rate than current-trend projections (Röös *et al.* 2017).

In baseline scenarios, childhood stunting and wasting are also projected to decrease, but not enough to achieve the SDG target of elimination by 2030 (Global Burden of Disease [GBD] 2015 SDG Collaborators 2016; GBD 2016 SDG Collaborators (2017). Meanwhile, the prevalence of overweight children has been increasing over the past 15 years (GBD 2015 SDG Collaborators 2016): fewer than 5 per cent of countries are projected to achieve the SDG target for overweight children (GBD 2016 SDG Collaborators 2017). Achieving these targets therefore requires accelerated action on nutrition as well as the more distal drivers of poor health outcomes – poverty, low levels of education and health spending, as well as conflict (GBD 2016 SDG Collaborators 2017; see also Section 22.3.5).

Maintaining terrestrial biodiversity

The baseline scenarios covered in Chapter 21 show a further decline in biodiversity. Some scenarios have been published that specifically look into how to halt biodiversity loss (e.g. van Vuuren *et al.* 2015; Obersteiner *et al.* 2016; Kok *et al.* 2018; Leclere *et al.* 2018). These scenarios show that, in addition to preserving terrestrial biodiversity in protected areas, it will be at least as important to reduce the external drivers that lead to loss of biodiversity such as expansion of land use, climate change and expansion of infrastructure. We briefly discuss some of these elements below. All-in-all, the scenario literature suggests that pathways to halting biodiversity loss exist – but that such scenarios will be difficult to implement.

Protecting terrestrial ecosystems

Protected areas are a key land management conservation tool. Syntheses have demonstrated that, compared with other locations, the diversity of species within protected areas tends to be 10 per cent greater and the abundance of species 15 per cent greater (Coetzee, Gaston and Chown 2014; Gray *et al.* 2016). Also, habitat conversion rates are 7 per cent lower within protected areas (Geldmann *et al.* 2013). While the CBD's Aichi Target 11 suggests a 17 per cent coverage target, in 2016 protected areas occupied 14.6 per cent of the terrestrial land area. As shown in Chapter 21, current trends will lead to a dramatic loss of biodiversity. Therefore, coordinated international action is urgently needed to balance land-use decision-making and biodiversity conservation. Expansion of the protected land area by 5 per cent in a well-designed way could lead to a significant increase in the protection of biodiversity (Pollock, Thuiller and Jetz 2017). Many scenarios in the literature have explicit assumptions on protected area trends. However, protected area expansion should not be the only consideration and should not come at the expense of effective management of current protected areas (Barnes *et al.* 2018). Furthermore, environmental policy outside of the formal protected areas network is of critical importance.

Land ownership

Land ownership has implications for land management and can therefore have implications for biodiversity residing on it. For example, private versus publicly owned lands have different bird species compositions (Maslo, Lockwood and Leu 2015) and private temperate forests contain a greater diversity and density of microhabitats that can support greater biodiversity (Johann and Schaich 2016). Over one-quarter of the whole terrestrial land surface is managed or under the tenure rights of indigenous groups and this land intersects with approximately 40 per cent of protected areas and ecologically intact landscapes (Garnett *et al.* 2018). In addition to public and private land ownership, local committees, and indigenous peoples' land rights and the manner in which they manage that land is therefore likely to be essential to meeting local and global conservation goals. Assessing the role of land ownership in pathways towards sustainability beyond this is difficult, however, because land ownership is seldom incorporated explicitly into scenario exercises.

Land-use planning

Land-use planning involves the systematic assessment of environmental, economic and social impacts of the range of potential uses of land in order to decide on the optimal pattern of land use. Land-use planning and systematic conservation planning has seldom been explored explicitly as a tool in global scenarios. The most noteworthy exceptions are the recent scenarios by Leclere *et al.* (2018) that use the biodiversity value of land areas to determine optimal land use and also can inform GEO assessments in the future. They find that such an approach in land-use planning can indeed contribute to a strategy that aims to halve biodiversity loss.

Forest management

Meta-analysis shows that different categories of forest management types have different implications for biodiversity loss, with selection and retention systems having the least detrimental effect on species diversity, while timber and fuelwood plantations have the worst effect (Chaudhary *et al.* 2016). Although forest management practices are not always explicitly represented in scenario simulations, studies suggest that consistent implementation of any single management regime results in suboptimal biodiversity outcomes compared with an optimal combination of management regimes (Monkkonen *et al.* 2014).

Significant trade-offs across the targets

A number of trade-offs can be identified between specific measures and the various targets within this cluster. Three important ones are as follows.

- Increases in cropland area can help reduce hunger by enabling increased food production. This expansion is included in many of the scenarios in the literature (e.g. Tilman *et al.* 2011; Bajželj *et al.* 2014; Tilman and Clark 2014; Popp *et al.* 2017). However, expansion of cropland area can lead to clearing of natural lands and increased land-use change emissions, which have implications for biodiversity, land degradation and climate change. Note that limiting the expansion of cropland area has implications for crop yields, fertilizer use and energy crop production as well (see Chapter 5 and Sections 22.3.2). Additionally, limiting cropland expansion could have implications for development (Sandker, Ruiz-Perez and Campbell 2012).

- Increasing fertilizer application rates may help increase agricultural yields in regions with persistent yield gaps but can also have severe consequences for freshwater and coastal ocean eutrophication, and climate change, with excess nitrogen and phosphorus run-off potentially impacting water quality (Beusen *et al.* 2016; Bouwman *et al.* 2017). On the other hand, sustainable intensification of agriculture (e.g. through precision agriculture) can help deliver higher yields while preserving ecosystem services and reducing environmental impacts (Foley *et al.* 2011; Garnett *et al.* 2013; Garbach *et al.* 2017). Increasing global nitrogen-use efficiency can reduce nitrogen run-off to the environment (see Chapter 8).
- Monoculture plantations of exotic, fast-growing trees have been used to maximize carbon sequestration (Chazdon 2008; Hunt 2008), negatively impacting local biodiversity. However, plantations of multiple native species can be an effective alternative (Hulvey *et al.* 2013; Cunningham *et al.* 2015), while also providing greater benefits for biodiversity (Bradshaw *et al.* 2013). Furthermore, natural regrowth is an alternative to plantations that has been shown in tropical forests to be more ecologically beneficial, cost-effective and resilient (Crouzeilles *et al.* 2017).

23.3.2 Energy, climate and air

The selected targets for the energy climate and air cluster can be summarized as the challenge to achieve universal access to modern energy services, while at the same time combating climate change and improving air quality (see Chapter 20). Selected targets that contribute to achieving these endpoint targets include improving energy efficiency and increasing the share of renewable energy.

Under current trends, none of these three targets are projected to be met (Chapter 21). By 2030, more than 2 billion people are still projected to cook on traditional biomass stoves or open fires and around 700 million people do not have access to electricity. The global mean temperature is projected to increase further, while a significant share of the global population is still exposed to concentrations of particulate matter with diameter less than 2.5 μm ($PM_{2.5}$) above 35 μg/m^3. Achieving these targets requires a major transformation of the energy system.

Modern energy services include electricity and clean fuels for cooking, heating and lighting, with 'clean' defined by the emission rate targets and specific fuel recommendations (i.e. compared to unprocessed coal and kerosene) of the World Health Organization (WHO) guidelines for indoor air quality (WHO 2014). Combating climate change means keeping the global mean temperature change well below 2°C and if possible below 1.5°C (United Nations Framework Convention on Climate Change [UNFCCC] 2015). Improving air quality means air pollution levels should, in the long term, be consistent with the WHO guidelines – that is, the interim target of annual mean $PM_{2.5}$ concentration should be below 35 μg/m^3 by 2030 (WHO 2006).

There are important linkages between this cluster and other cluster targets. For instance, most low-carbon pathways that limit global mean temperature to 2°C (or 1.5°C) include significant amounts of bioenergy. The role of land-based ecosystems, both natural and managed, is essential for achieving net-zero and net-negative emissions.

There is a rich literature of scenarios that have looked at the challenge of meeting ambitious climate targets (for an overview, see Clarke *et al.* 2014, and more recent studies including Riahi *et al.* 2017; Rogelj *et al.* 2018; van Vuuren *et al.* 2018). Fewer published scenarios have looked at meeting ambitious energy access targets (e.g. Pachauri *et al.* 2013; International Energy Agency [IEA] 2017) or air pollution targets at a global scale (e.g. Rao *et al.* 2017). A broad range of measures is discussed in the literature, including improving energy access (electricity and clean cooking fuels), reducing greenhouse emissions by addressing both energy demand and production, and air pollution control.

Improving access to energy

Universal access to modern energy services will not be achieved by 2030 in a baseline scenario, particularly not in sub-Saharan Africa (for electricity and clean fuels and technologies) and in Asia (mainly clean fuels and technologies) (see Chapter 21). Achieving universal access to electricity requires further expansion of generation capacity and transmission and distribution networks, as well as access to more efficient and affordable appliances, with a specific focus on poor, remote communities (GEA 2012; IEA 2017; Lucas, Dagnachew and Hof 2017). To achieve universal access to clean fuels and technologies, the affordability, availability and safety of fuels and practices for cooking, heating and lightning should be improved (Modi *et al.* 2006). Improved fuels include liquified petroleum gas (LPG), natural gas and electricity in urban areas, and a range of technologies (including biogas and the use of advanced biomass cookstoves) in rural areas (IEA 2017). Modelling studies have shown that there are different pathways to achieve universal access to modern energy services (Pachauri *et al.* 2013; Dagnachew *et al.* 2017).

The choice of the electrification system – grid-based, mini-grid or off-grid – depends on a range of mostly local factors, including the level of household electricity demand, the distance to the existing grid and local resource availability (Dagnachew *et al.* 2017). Grid-based electrification is attractive for densely populated areas with an expected high demand for electricity and/or within a reasonable distance of existing high voltage power lines, while decentralized electrification systems are key to reaching out to semi-urban areas with low consumption density, and remote rural areas (Dagnachew *et al.* 2017; IEA 2017; Lucas, Dagnachew and Hof 2017). Total annual investments to achieve universal access are estimated at US$52 billion globally (IEA 2017) and US$24-49 billion in sub-Saharan Africa alone (Dagnachew *et al.* 2017; Lucas, Dagnachew and Hof 2017), depending primarily on total household electricity demand and the cost of high-voltage transmission and distribution.

Policies that could encourage a transition to clean fuels and technologies for cooking, heating and lightning include fuel subsidies and grants or microlending facilities to make access to credit easier and lower households' cost of borrowing (Riahi *et al.* 2012). The use of improved or advanced biomass stoves may in fact lead to economic gains instead of costs, as the investments would be countered by the reduction in spending on fuelwood (van Ruijven 2008). Total required investments to achieve universal access to clean fuels for cooking, heating and lighting are projected to be less than 10 per cent of what is needed for achieving universal access to electricity (Pachauri *et al.* 2013; IEA 2017). Improving access to clean fuels can significantly improve health (Pachauri *et al.* 2013; Landrigan *et al.* 2018). Climate policy can induce energy savings, reducing the overall investment required for achieving universal access (Dagnachew *et al.* 2018).

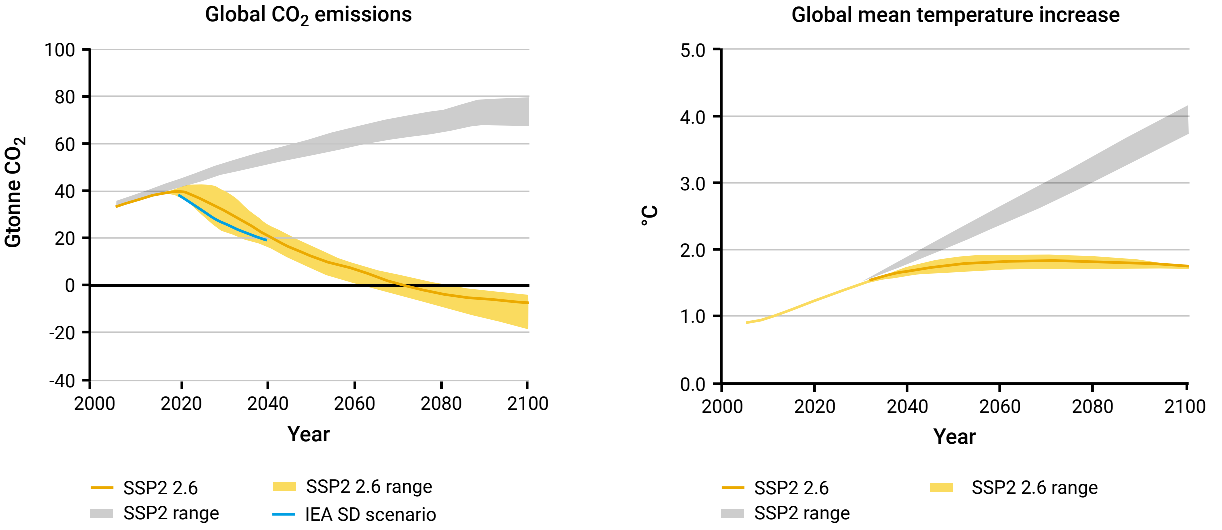
Reducing greenhouse gas emissions

The Paris climate targets set very stringent constraints for the development of future energy systems. Although some recent publications have shown that carbon budgets are subject to considerable uncertainty (Intergovernmental Panel on Climate Change [IPCC] 2018; Rogelj *et al.* 2016; Millar *et al.* 2017), the main message is that they are small compared to current emissions. To meet the Paris climate targets, cumulative CO_2 emissions from now onwards need to be in the order of 1000 -1600 gigatons of CO_2 (2°) or even 300-900 gigatons of CO_2 (1.5°). The current emissions are in the order of 40-42 gigatons CO_2/year (Le Quéré *et al.* 2016; IPCC 2018). Assuming a linear reduction without negative emissions, unabated fossil fuel use thus needs to be phased out somewhere around the middle of the century (van Vuuren *et al.* 2017a). This would require an immediate halt to investments into CO_2-emitting technology, but possibly even a faster retirement of existing fossil fuel infrastructure (Johnson *et al.* 2015; Gambhir *et al.* 2017).

The option, however, also exists to actively remove CO_2 from the atmosphere, for instance by afforestation and bioenergy, combined with carbon-capture-and-storage, direct-air-capture, enhanced weathering and increasing soil carbon (IPCC 2018). However, the amount of CO_2 that can be removed from the atmosphere in this way is not unlimited: both afforestation/reforestation and bioenergy are restricted by the amount of land available, as well as possible impacts on biodiversity and food production (Smith *et al.* 2016). Moreover, the storage potential for CO_2 is limited (Koelbl *et al.* 2013). Among various options for CO_2 removal that have been assessed, under current technologies, only sequestration in geological formations is considered to have the capacity and permanence necessary to store CO_2 at the gigaton level, which is necessary to reduce CO_2 emissions significantly (Benson *et al.* 2012). While the estimated storage capacity is more than enough to meet emissions reduction targets, the estimates do not consider the risks associated with permanent storage (e.g. environmental contamination from leakage, seismic activities) (de Coninck and Benson 2014; Bui *et al.* 2018). Therefore, rapid emissions reduction will be needed in the short term regardless of the availability of negative emissions technologies (van Vuuren *et al.* 2017a). **Figure 22.4** shows the range of scenarios in the SSP database following the SSP2 baseline and those consistent with the Paris targets of well below 2°C (Riahi *et al.* 2017; Rogelj *et al.* 2018). The scenarios depicted here are based on low cost pathways, assuming an immediate response. There are several papers in the literature that show that a delayed response is more expensive and could even make it impossible to reach stringent targets (Riahi *et al.* 2015; Rogelj *et al.* 2018). Such delayed response would, for instance, occur if countries decide to follow the currently formulated climate policies and aim for a rapid implementation of climate policy after 2030.

Globally, energy-related CO_2 emissions would need to be reduced by around 60-70 per cent by the middle of the century in order to meet the Paris target, even when accounting for

Figure 22.4: Global CO_2 emissions and associated global mean temperature increase for the SSP2 baseline and derived scenarios consistent with the Paris target to stay well below 2°C increase

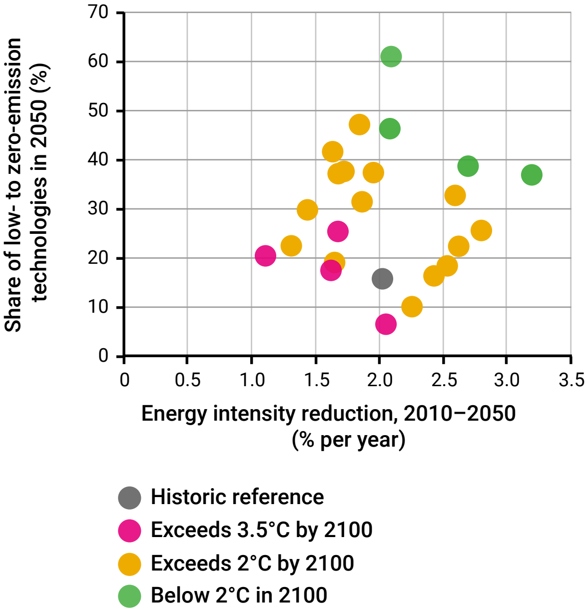


Source: IEA (2017); Riahi *et al.* (2017); Rogelj *et al.* (2018).

negative emissions **(see Figure 22.5)**. There are various ways to reach these targets. While demand-side measures mostly reduce energy intensity, supply-side measures would increase the share of low-carbon options. These two indicators can provide an insight into the challenge that such reductions would pose.

The final energy-intensity (energy divided by GDP) reduction rate in many countries has typically been around 1-2 per cent per year in the period since 1970. This has been driven by both increase in energy efficiency and sectoral changes. Relatively high values for energy intensity reduction occurred during the 1973 and 2005 oil crises in response to prices and government policies in Organisation for Economic Co-operation and Development (OECD) countries that aimed to conserve energy (Schippers and Meyers 1992; Sweeney 2016). The share of low-greenhouse gas emitting technologies is at the moment around 20 per cent, consisting mostly of traditional biomass, hydropower and nuclear power. To reach the 2°C target, the combination of energy intensity reduction and increase in the share of low-greenhouse gas technologies would need to be significantly larger than historical values. As shown in **Figure 22.5**, the large-scale transformation required for this can be achieved by reducing energy demand (by means of energy efficiency and/or different and lower activity levels) and by decarbonizing energy supply (renewables, carbon-capture-and-storage, nuclear, fuel substitution). Energy efficiency increase, however, would need to be at least 2-3.5 per cent per year. Furthermore, the level of non-CO_2 emitting supply options would need to increase from around 15 per cent today to at least 40-60 per cent by 2050 (for the scenarios included in **Figure 22.5**) or even 50 up to 100 per cent for the most stringent scenarios in the wider literature (van Vuuren *et al.* 2016; IPCC 2018). The low-range value of 40 per cent is only sufficient if combined with a rapid decline in energy demand. The amount of renewables would be around 30-40 per cent **(Figure 22.5)** or up to 60 per cent (full range) for 2 degrees (van Vuuren *et al.* 2016) and 70-85 per cent for 1.5 degrees C (IPCC 2018). It should be noted that the range for renewables largely overlaps with the range of total CO_2-free energy production, as the different options can easily be substituted. All-in-all, the reduction in the carbon intensity of the global economy (rate of change of the ratio of CO_2 over GDP) needs to increase from around 1-2 per cent per year historically to around 4-6 per cent per year towards 2050; for the most stringent scenarios, values up to 8 per cent can be found in the literature (van Vuuren *et al.* 2016).

Figure 22.5: 2010-2050 energy intensity reduction rate and the 2050 share of low-greenhouse gas technologies in total energy mix of the scenarios included in the SSP database



The colours of the dots indicate the projected 2100 temperatures.

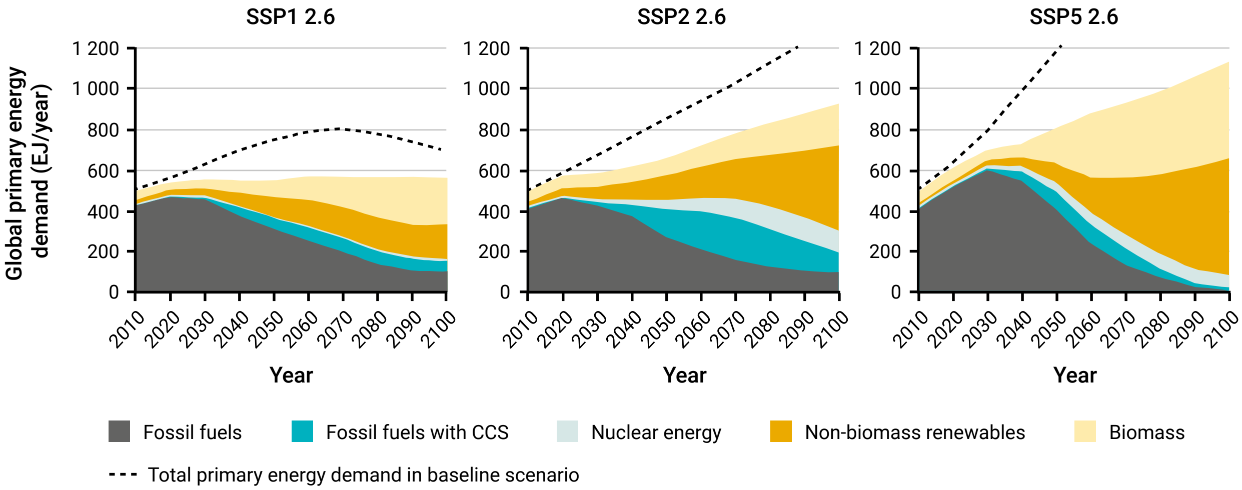
Source: Riahi *et al.* (2017); Rogelj *et al.* (2018).

Emissions of greenhouse gases can be reduced by measures associated with energy demand and decarbonization of energy supply. In addition, it is possible to reduce so-called non-CO_2 emissions from both agricultural and energy systems. In other words, to achieve the Paris targets far-reaching transitions in energy, land, urban infrastructure (including transport and buildings), and industrial systems are needed (IPCC 2018). The contribution of these measures is discussed in more detail in the subsequent paragraphs. **Box 22.2** discusses in more detail the role of land-based mitigation options.

Reducing energy demand

Figure 22.6 presents the aggregated energy use of three different pathways consistent with the 2°C target. The total reduction in energy demand in the pathways is about 25 per cent, compared with the Trend scenario (see also Edelenbosch 2018). Studies focusing on the potential for energy efficiency show even higher possible efficiency improvement rates (Cullen, Allwood and Borgstein 2011; Graus, Blomen and Worrell 2011). Final energy demand is dominated by the industry, transport and residential sectors. Energy consumption in all three sectors would therefore need to be mitigated in order to reach sustainable development targets. Transport is a key sector, as here emissions are increasing most rapidly, driven by increasing emissions from car travel, road freight transport, marine transport and air travel. Different response options exist for decarbonizing the transport sector. For instance, one important option would be an almost complete electrification of most transport modes. This would require a corresponding transition in infrastructure, and its effectiveness in lowering emissions would depend on the carbon intensity of power generation. It should also be noted that, for many parts of the world, such a transition will take a lot of time and, in the meantime, it will be important to minimize emissions, for instance, by promoting car efficiency (Bae and Kim 2017). For modes that cannot be electrified, natural gas (in the short term), fossil fuel with carbon-capture-and-storage (CCS), hydrogen and bioenergy could play a role. Earlier, many studies identified bioenergy use as an effective response strategy for most transport modes. However, because of the possible negative impacts of bioenergy for other targets, the use of bioenergy is assumed to be limited here, restricting bioenergy to those sectors that are hard to abate or that could generate negative emissions. This means that effective measures for transport include electrification, rapid improvement of fuel efficiency and the development of new fuels (hydrogen, synthetic fuels). Alternatively, in a scenario focusing more

Figure 22.6: Different pathways leading to a global mean temperature increase well below 2°C



Source: Bauer *et al.* (2017); Riahi *et al.* (2017).

on lifestyle change (e.g. the 'consumption change' pathway), emission reductions occur primarily through a transition away from the use of airplanes and private cars to local electric public transport and fast trains.

Decarbonizing energy supply

A high proportion of the required emission reductions would need to come from supply-side changes **(see Figure 22.6)**. Fossil fuels currently account for around 80 per cent of total primary energy use. This needs to be reduced to a maximum of 20-30 per cent by 2050, depending on the use of negative emission technologies (after 2050) and the ambition of the climate target (Bauer *et al.* 2017; van Vuuren *et al.* 2017b). The fossil fuels need to be replaced by low- to zero-emission technologies, such as bioenergy, other renewables and nuclear energy, and fossil fuel energy combined with carbon-capture-and-storage.

It will be very important to introduce new policies that stimulate the further penetration of renewables. The literature also shows that there is some degree of freedom in choice of technology. For instance, there can be different roles for renewable energy, nuclear power and carbon-capture-and-storage, depending on societal choices and technology development. It should be noted, however, that the size of the overall transformation is – in absolute terms and the period for which it should be sustained – without historical precedent (van der Zwaan *et al.* 2013; van Sluisveld *et al.* 2015). It is in fact well beyond the rate of transitions in the past, highlighting the considerable challenge of meeting the 2°C target (Napp *et al.* 2017). In relative terms (e.g. per cent of investment in new technologies), there are several examples of similar rapid transitions in the past.

There are many ways to decarbonize energy supply in future scenarios (Clarke *et al.* 2014; Kriegler *et al.* 2018; Rogelj *et al.* 2018). One method is fossil fuel energy combined with carbon-capture-and-storage. Most scenarios rely heavily on this option. While the advantage is that it would require relatively far change in energy supply, this option suffers from a limited storage potential and, above all, relatively little societal support. Renewables such as wind and solar power form an important alternative. The costs of these options have decreased rapidly over the last few years, making these technologies a reasonable alternative for fossil fuels even in the absence of stringent climate policy. However, for higher levels of penetration these options suffer from additional costs related to intermittency. This implies that the expansion of renewable energy will require investment in infrastructure to deal with intermittency (e.g. via expanding grid connections and providing storage options). The transition to renewables would also lead to a change in demand for materials (to create solar and wind power plants). Most assessments find the latter not being restrictive (Arvesen *et al.* 2018). Finally, a transition to renewables will also require different operating regimes for the power system. The option of bioenergy could also be attractive as a supply for fuels and, in combination with carbon storage, a pathway to negative emissions. As bioenergy requires large amounts of land it would, however, compete with the targets

Box 22.2: Contribution of land-use-based mitigation options to climate policies

About 20-30 per cent of total greenhouse gas emissions are associated with agricultural activities (Smith *et al.* 2014). In terms of climate policy, the contribution of the land-use sector is very important. First of all, reaching stringent targets would require reducing land-use-related emissions. In addition, it is also possible to contribute to emission reductions by so-called land-use-related mitigation options. This includes, for instance, reforestation and the use of bioenergy. In fact, more than 80 per cent of the nations that are signatories to the Paris Agreement plan to use land-use-related mitigation options to fulfil their Nationally Determined Contributions (NDCs). Analysis has shown that both afforestation and the use of bioenergy in combination with carbon-capture-and-storage are cost-efficient in nearly all scenarios. As a result, the use of land for mitigation might in 2050 be in the order of 25-30 per cent of total cropland in some scenarios (i.e. 10 per cent of total agricultural area). An important challenge, however, is that the use of land-use-based mitigation options could lead to significant trade-offs with the targets to end hunger and preserve biodiversity, due to competition for land (see Section 22.3.1).

mentioned in the previous cluster. This is discussed further in Section 22.4.2. Alternative pathways that rely less on negative emission technologies could be based on stronger changes in lifestyle (van Vuuren *et al.* 2018). Finally, nuclear power can also provide zero-emission energy. However, this technology poses both safety and waste risks and a lack of societal support in many countries.

Reducing non-CO_2 emissions

Although carbon dioxide forms the lion's share of greenhouse gas emissions, non-CO_2 greenhouse gases such as methane, nitrous oxide and fluorinated greenhouse gases also contribute significantly to climate change. Thus, non-CO_2 emissions in pathways that limit global warming to the Paris targets also show deep reductions (IPCC 2018). Some of the non-CO_2 emissions are relatively easy to abate, such as those associated with losses in the energy system. Moreover, these reductions often have high co-benefits including the reduction of methane (also leading to ozone pollution) and soot (leading to climate change and health impacts). In contrast, other sources are relatively hard to abate. For instance, it is hard to imagine how methane emissions from roaming cattle could be reduced to zero. As a result, in most 2°C scenarios, land-use-related emissions are reduced by around 50 per cent compared with current emission levels. Reducing emissions further would typically require reduced meat consumption (see Section 22.3.1).

Controlling air pollution

Future air pollution emissions stemming from human activities, with the energy sector playing a dominant role, require the application of specific measures to reduce air pollutant emissions. Many of the strategies that decrease greenhouse gas emissions, such as increasing energy efficiency, switching fuel types and changing lifestyles, also lower emissions of other air pollutants, resulting in health co-benefits (Markandya *et al.* 2018). Similarly, air pollution policies have climate implications, for example, by affecting emissions of short-term climate forcers such as black carbon.

To explore the limit on what air pollution emission decreases might be possible by introducing air pollution control measures, Stohl *et al.* (2015) defined a maximum technologically feasible reductions scenario by applying the lowest emission rates from known technology regardless of costs. Other scenarios have taken costs and local circumstances into account, such as the 'new policy' and 'clean air' scenarios of the International Energy Agency (IEA 2016). While the 'new policy' scenario considers policies and measures that had been adopted or announced as intended (as of 2015), the 'clean air' scenario includes additional measures that achieve significant reduction of air pollutant emissions. Relative to the 'new policy scenario', the 'clean air' scenario includes an additional US$2.3 trillion invested in advanced air pollution control technologies and a similar amount (US$2.5 trillion) invested in accelerating the transition to cleaner and renewable energy sources. These measures would result in a 50 per cent decrease in SO_2 and NO_x emissions and an almost 75 per cent decrease in particulate matter emissions and would avoid more than 3 million premature deaths per year, with 1.7 million deaths attributable to reduced ambient air pollution and 1.6 million deaths attributable to reduced household air pollution (IEA 2016).

The importance of climate mitigation for air pollution emissions can also be illustrated using SSP results (Rao *et al.* 2017): increasingly stringent climate policy also reduces emissions of air pollutants. The extent to which coal is used for electricity production and manufacturing has a strong influence on CO_2 emissions and largely determines the path of SO_2 emissions. For transportation sector emissions, the level of electrification is important. Electrification, combined with autonomous vehicles and shared mobility services, could lead to dramatic decreases in emissions and associated pollutant exposures (Fulton, Mason and Meroux 2017). Black carbon emissions, associated with diesel engines and residential combustion of traditional biomass fuels, are much less correlated with fossil fuel use (and thus climate policy), but more with use of traditional energy (and thus with the introduction of access to modern energy services); this is reflected in the different black carbon emission levels for the baselines, but also in a much lower response to climate policies (Rao *et al.* 2017).

Short-lived climate pollutants (SLCPs) contribute to atmospheric warming, and include black carbon, tropospheric ozone, methane and hydrofluorocarbons. Among SLCPs, black carbon, methane and tropospheric ozone contribute to air pollution. Reducing emissions of SLCPs can provide near-term climate benefits (Shindell *et al.* 2017; Xu and Ramanathan 2017; Haines *et al.* 2018). For black carbon, measures are available to decrease emissions from diesel engines, biomass cooking fuel, kerosene lighting, and household and small industry coal use. There are opportunities to decrease methane emissions associated with the extraction of coal, oil and natural gas, disposal of waste, switching management of emissions from livestock and manure and rice paddy production. Compliance with the Kigali Amendment (United Nations 2016) will decrease hydrofluorocarbon emissions by 61 per cent from 2018 to 2050 compared to a reference scenario, but substitutions could be made earlier and a 98 per cent decrease is technically possible (Höglund-Isaksson *et al.* 2017). Implementation of such demonstrated technical measures to address SLCP could decrease average global warming, although estimates on the exact level differ by study (United Nations Environment Programme [UNEP] 2017) (see also **Box 22.3**).

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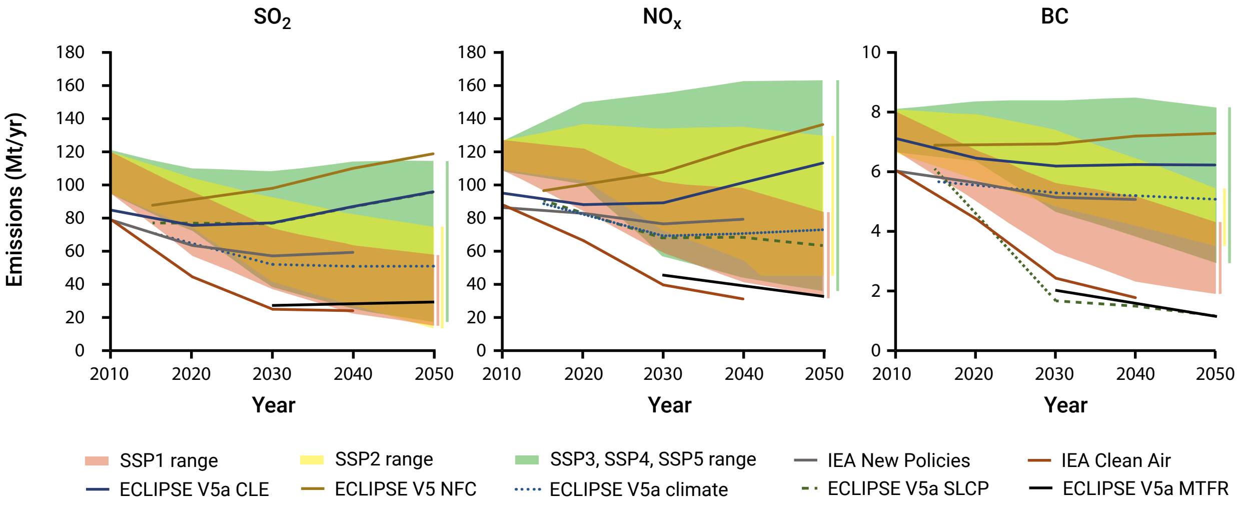
Box 22.3: The Climate and Clean Air Coalition

Efforts to simultaneously address air quality and climate impacts of short-lived climate pollutants (SLCPs) include the Climate and Clean Air Coalition (CCAC; http://www.ccacoalition.org), which was launched in 2012 and is a voluntary partnership of governments, intergovernmental organizations, businesses, scientific institutions and civil society organizations committed to improving air quality and mitigating climate change by reducing SLCPs. Approaches for reducing black carbon include clean and efficient household cooking, lighting and heating technologies; modern brick kiln technology for brick production; and clean fuel for heavy-duty diesel vehicles and engines. The focus for reducing methane emissions includes reducing gas leakage from gas distribution systems, improving manure management, using alternative rice farming practices and strategies to reduce enteric fermentation emissions from livestock. As of July 2017, some 178 countries had included methane, 100 had included hydrofluorocarbons, and four had included black carbon in their Nationally Determined Contributions (NDCs) or Intended NDCs for meeting the climate goals of the Paris Agreement. A number of countries are expected to update their NDC to strengthen the inclusion of SLCPs. It is important to note that reducing emission of SLCPs as a complement to reducing greenhouse gas emissions provides opportunities to limit near-term climate warming but is not a substitute for reducing long-lived greenhouse gases to mitigate long-term climate change.

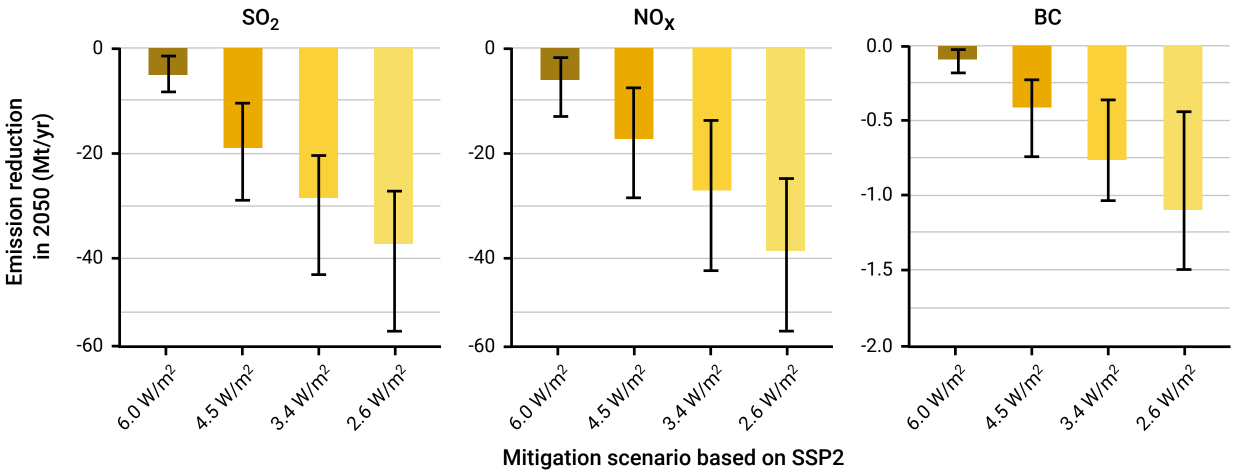
Figure 22.7a: Projected global emissions for SO_2, NO_x and black carbon under different climate and air pollution policies



For the SSP baselines the shading represents the ranges over all Integrated Assessment Models (IAMs) included in Rao *et al.* (2017).

Source: SSPs (Rao *et al.* 2017); ECLIPSE (Stohl *et al.* 2015; Klimont *et al.* 2017); IEA (IEA 2016).

Figure 22.7b: Differences in air pollution emissions between various climate mitigation scenarios, and the SSP2 baseline



Error bars represent the range of all Integrated Assessment Models (IAMs) included in Rao *et al.* (2017).

Source: Rao *et al.* (2017).

Although climate policies lead to significant decreases in air pollution in all SSP marker scenarios, these decreases are not sufficient to achieve the WHO air quality guideline of 10 µg/m^3 for annual mean $PM_{2.5}$ concentrations by 2050 **(Figure 22.8)**. The ECLIPSE maximum technically feasible reduction (MTFR) scenario without climate mitigation, which has the lowest air pollutant emissions among all scenarios **(Figure 22.7)**, is also insufficient to achieve the WHO guideline. Worldwide, about 60 per cent of the population is projected to be exposed to levels above the standard in the best-case air pollution scenarios (SSP1 or SSP5 with 2.6 W/m^2 climate mitigation target, or the ECLIPSE MTFR scenario). The worst exposures are projected for Asia and the Middle East and Africa regions. However, by 2050 less than 5 per cent is expected to be above the most lenient interim target of 35 µg/m^3 annual mean $PM_{2.5}$ concentrations for SSP2 and SSP5 if climate mitigation is included. These results reflect the air quality benefit of strong air pollution control and the co-benefit of climate mitigation, and for the ECLIPSE MTFR scenario, reflecting the maximum air quality benefit achievable with current air pollution control technologies.

Significant synergies and trade-offs between measures and targets

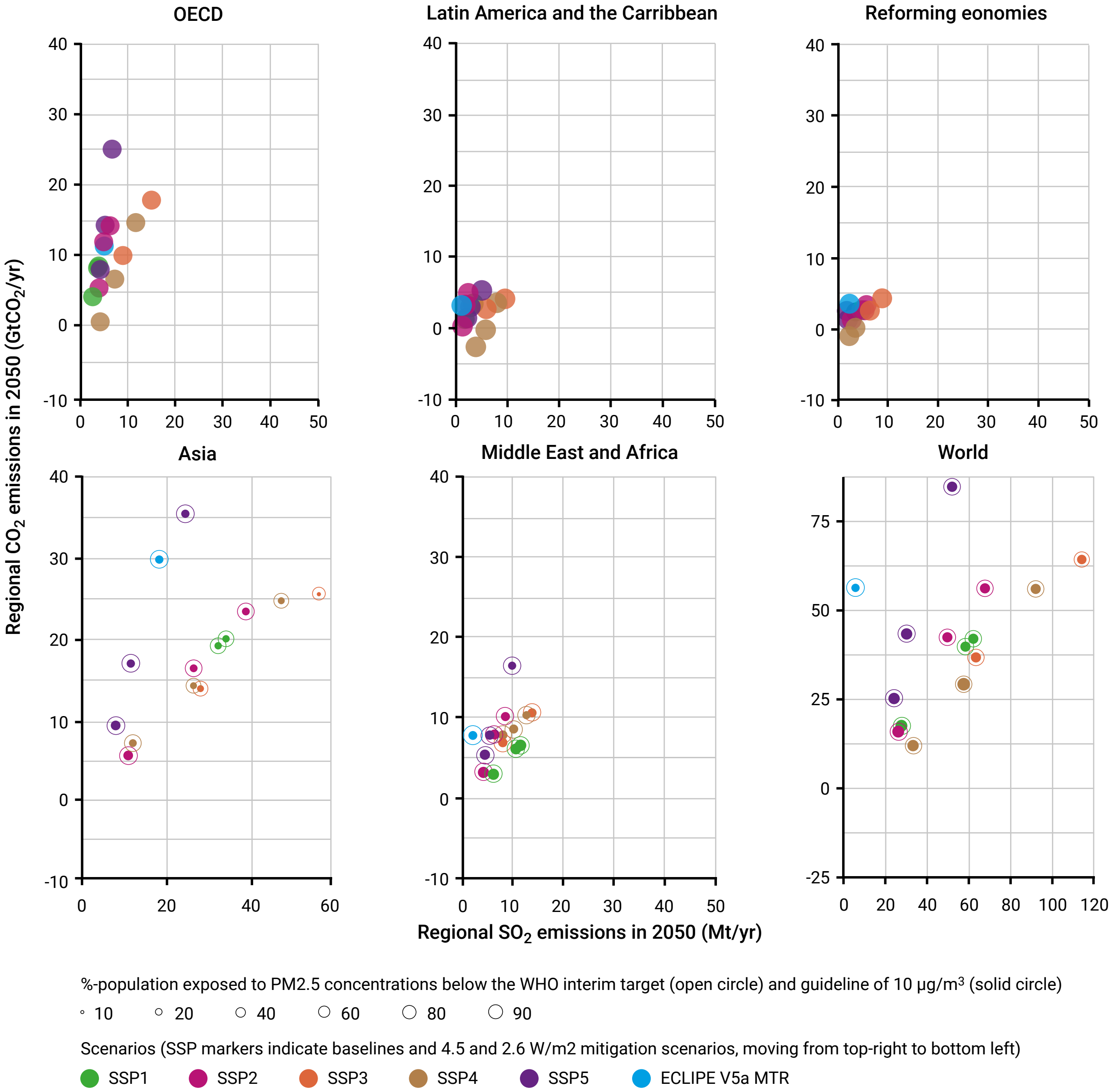
The measures introduced to achieve universal access to modern energy services, combat climate change or improve air quality in cities can have important synergies and trade-offs (e.g. McCollum *et al.* 2018).

- Most of the climate policies lead to an increase in energy system costs, with potentially increasing energy prices as a result. Higher energy prices, especially for clean fuels for cooking (e.g. electricity, liquified petroleum gas, natural gas), make it more difficult to achieve universal energy access, or to provide affordable energy in general (Daioglou, van Ruijven and van Vuuren 2012; Cameron *et al.* 2016). There are, however, various ways to compensate for this, including targeted subsidies or redistribution of carbon taxes (Cameron *et al.* 2016).
- Policies aiming to increase energy access could lead to an increase in energy consumption and thus impact both climate change and air pollution. These impacts, however, are relatively small (van Vuuren *et al.* 2012) and can, if needed, be mitigated by ensuring that energy access is achieved via low-greenhouse gas energy supply systems. Achieving universal electricity access is estimated to have only a very small increasing effect on global greenhouse gas emissions (Pachauri *et al.* 2013; van Vuuren *et al.* 2015; Dagnachew *et al.* 2018). Furthermore, universal access to clean fuels for cooking could reduce total air pollutant and greenhouse gas emissions, resulting from a switch away from traditional biomass, increased biomass-use efficiency and sustainable harvesting of biomass (Pachauri *et al.* 2013; van Vuuren *et al.* 2015). There are also both synergistic effects and trade-offs between air pollution and climate policy. One example of a possible trade-off is that burning biomass as a low-carbon energy source can lead to more air pollution if appropriate air quality management practices are not put in place (Giuntoli *et al.* 2015). Another is that diesel cars emit less CO_2 than petrol (gasoline) cars but emit more PM (Mazzi and Dowlatabadi 2007; Tanaka *et al.* 2012; O'Driscoll *et al.* 2018). Also, the use of end-of-pipe emission controls may reduce PM emissions of passenger vehicles, but at the cost of reducing fuel efficiency. For petrol vehicles, replacing port fuel injection with direct injection engine technology generally increases fuel efficiency, thus reduces CO_2 emissions, but increases PM and black carbon emissions (Zhu *et al.* 2016; Zimmerman *et al.* 2016; Saliba *et al.* 2017).
- However, in most cases, climate policy reduces air pollution by having an impact on emissions of PM, SO_2 and NO_x. If well designed, air pollution control measures can also limit climate change. This implies that especially for countries currently experiencing high air pollution levels, designing strategies that address both air pollution and climate change can be very attractive (see also **Box 22.4**).
- Geo-engineering (e.g. direct air capture) generally requires additional energy use providing a possible trade-off with air pollution or energy access.

Box 22.4: Possible synergy between climate mitigation and reducing air pollution in China

In response to strong public concerns about air pollution, the China State Council announced in 2013 the 'Action Plan of Prevention and Control of Air Pollution'. The action plan sets specific targets for air pollution. Among others, the 2017 concentration of particulate matter with diameter less than 10 µm (PM_{10}) should fall by at least 10 per cent compared to 2012 concentrations. For some regions, however, more stringent targets are formulated. The plan indicates that one way to implement these targets is through promotion of clean energy, including renewable energy, nuclear power, natural gas, combined with a transition of the energy system, energy conservation and control of coal use. This is completely consistent with low-carbon development in China. Since then, the economic and structural changes together with air pollution control measures resulted in a peak in coal production in 2013/2014. This has also led to a reduction of CO_2 emissions. From 2015 to 2017, there was a rapid expansion of wind, solar and hydro power as well as nuclear power. If, in the future, the increase in energy demand is relatively slow, any expansion can be covered by the increase in renewable energy, nuclear and natural gas, so that the decline in coal capacity can continue. Under these circumstances, a further decline of CO_2 emissions is possible. In the meantime, sustainable development is a basic long-term national strategy in China. China has started to enhance its energy efficiency policies in its Eleventh Five-Year plan and is expected to continue to do so in subsequent Five-Year plans. The main focus for these policies will continue to be on improving energy efficiency in the industrial sector, but new policies are also targeting domestic energy consumption. On this basis, the target is to reduce the share of coal in the energy mix from 64 per cent in 2015 to 58 per cent in 2020. According to the announcement of "Interim measures of the replacement of coal consumption in key regions" from China's National Development and Reform Commission (NDRC *et al.* 2014), 8 provinces and municipalities in key areas, including Beijing-Tianjin-Hebei Region, Shandong province, the Yangtze River Delta and the Pearl River Delta will be required to set up the reduction targets for coal consumption. These policies are meant to reduce air pollutants. All-in-all, it means that current Chinese policies to improve air quality could have a huge benefit for public health, but also lead to a reduction of CO_2 emissions.

Figure 22.8: Percentage of the population exposed to particulate matter of less than 2.5 µm in diameter ($PM_{2.5}$) concentrations under the WHO guideline and interim target for 2050



Sources: Rao *et al.* (2017); Population exposure is based $PM_{2.5}$ concentrations determined by applying the TM5-FASST source-receptor model (van Dingenen *et al.* 2018) to marker SSP emission scenarios and the related 4.5 W/m^2 and 2.6 W/m^2 climate mitigation scenarios.

22.3.3 Freshwater

The selected targets for the freshwater cluster may be summarized as reducing water scarcity and ensuring water quality, while at the same time providing universal access to safe drinking water and adequate sanitation (Chapter 20). The world is not on track to achieve these targets (see Chapter 21). More than 400 million people are projected to still lack access to at least basic water facilities in 2030 and about 2 billion people still do not have access to at least basic sanitation. Furthermore, the fraction of the global population that lives in water-stressed areas is projected to increase up to about 50 per cent by the end of the century, mostly driven by population growth.

There are important linkages between this cluster and other clusters, especially the agriculture, food, land and biodiversity cluster and the energy, air and climate cluster. Globally, the largest demand for water comes from the agricultural sector (over 70 per cent). Also, many freshwater and ocean pollutants come from agriculture, and agriculture is the dominant source of nitrogen and phosphorus in global watersheds (see Chapter 21).

There are several scenario studies on water scarcity. However, most of these focus on future projections instead of target-based scenarios. In contrast, Wada, Gleeson and Esnault (2014) propose six strategies, or 'water-stress wedges', that collectively lead to a reduction in the water-stressed population by 2050. Bijl *et al.* (2018) discuss some strategies that could lead to reduced water scarcity, including increased efficiency, other allocation strategies and reducing agricultural water demand via diet change and food waste reduction. Here, we discuss different measures largely linked to the individual targets, addressing increasing access to water, sanitation and hygiene (WASH), decreasing water demand, increasing water supply and reducing water pollution.

Investing in access to water, sanitation and hygiene

Achieving the targets on drinking water and sanitation will require increased investment in infrastructure, especially sanitation (United Nations Conference on Trade and Development 2014; Hutton and Varughese 2016). Due to population growth, an additional 3.4 billion people will require access to sanitation by 2030, or 620,000 per day, 2.5 times the number of people served during the 2001-2015 period (Mara and Evans 2018). The current levels of investment are likely to cover the capital costs of basic service provision for access to WASH by 2030, but not enough for safely managed service provision. To achieve universal access to safely managed WASH services, investment levels will need to increase threefold (Hutton and Varughese 2016). Achieving universal access to safe water and adequate sanitation is as much about changing behaviour as it is about changing infrastructure. This requires better marketing, communication and community-led sanitation (Water and Sanitation Program 2004; Kar and Chambers 2008; Devine and Kullmann 2011).

Increasing water-use efficiency

Water scarcity including groundwater often needs to be managed at the watershed or aquifer level (Scott *et al.* 2014). These can be within one country, but often there are multiple countries involved. In those cases, an international framework is needed to evaluate strategies to reduce water stress and maximize mitigation (Wada, Gleeson and Esnault 2014). Wada, Gleeson and Esnault (2014) conclude that four demand-side measures are required: increasing agricultural water productivity (more crop per drop), improving irrigation efficiency (reducing water losses), more efficient water use in domestic and industrial sectors including reducing water leakage and improving recycling, and limiting the rate of population growth. To maintain or even reduce the global population under water scarcity by 2050 and beyond, water-use efficiency for these demand-side measures needs to improve by more than 20-50 per cent globally (0.5-1.2 per cent improvement per year). Moreover, strategies for water management at the level of watersheds are necessary to deal with competing demands for agricultural production, industrial activities, household water use and ecological services. The precise mix depends on economic, social, legal and political issues such as international or subnational water treaties, rights or disputes (Wada, Gleeson and Esnault 2014). Various scenarios have shown that increased water efficiency in agriculture, households and industry can have a significant impact on reducing water scarcity (e.g. Bijl *et al.* 2017).

Increasing water supply

Increasing water supply can be done using more conventional measures such as building more water storage or dams, by investing more in desalination capacity in coastal regions (Wada, Gleeson and Esnault 2014) or by wastewater reuse. Furthermore, groundwater resources could serve as a buffer during droughts or severe water scarcity because of their ubiquitous presence across the globe.

Increasingly, countries are implementing desalination strategies – for example, in the Middle East, North Africa and the United States of America (e.g. California) (World Water Assessment Programme 2003; Hanasaki *et al.* 2016). The global amount of desalinated water use has been rapidly increasing since the 1990s and it is currently estimated to exceed 10 km^3 annually (Food and Agriculture Organization of the United Nations 2018). Although this amount is important for coastal regions, the global total currently accounts for much less than 1 per cent of water withdrawals worldwide (4,000 km^3). Hanasaki *et al.* (2016) projects that under different SSP scenarios (1-3), the use of seawater desalination will increase 1.4- to 2.1-fold in 2011-2040 compared with the present, and 6.7- to 17.3-fold in 2041-2070. The associated costs are in the order of US$2 billion to US$200 billion. The large spreads in these projections are primarily attributable to substantial socioeconomic variations in the SSP scenarios. To scale up desalination of seawater in coastal water-stressed basins, a 10- to 50-fold increase is projected to be required; however, this would imply significant capital and energy costs, and it would generate wastewater that would need to be disposed of safely (Wada, Gleeson and Esnault 2014; Hanasaki *et al.* 2016).

Wastewater reuse enables upgrading of unsuitable water quality originating from households and industry to sufficient quality for different purposes. The amount of wastewater reuse or recycling has been increasing worldwide especially for agriculture, as small-scale farmers in urban and peri-urban areas of developing countries depend largely on wastewater or wastewater-polluted water sources to irrigate high-value crops for market (Qadir *et al.* 2010). However, higher-quality water is needed for drinking purpose and the establishment of water reuse guidelines is critical (Bixio *et al.* 2006; Bixio *et al.* 2008). Ongoing technological innovations, such as the use of membranes, and dedicated economic instruments are expected to further increase the use of wastewater as a resource in various regions with limited surface- and groundwater resources. In order to reduce water limitations in urban areas or megacities, a similar magnitude of future scaling up is required for wastewater reuse combined with the desalination of seawater (Wada, Gleeson and Esnault 2014).

It should be noted, however, that these two supply-side measures require a large amount of economic investment and modernizing of existing infrastructure, which might not be feasible for many developing countries (Neverre, Dumas and Nassopoulos 2016). Alternatively, nature-based solutions may have high potential to increase and/or regulate water supply by reducing degradation of water quality, while limiting economic investments (Vörösmarty *et al.* 2010). Multiple ecosystem services or sustainable infrastructure can mitigate water pollution and increase water supply for humans and ecosystems (Reddy *et al.* 2015; Liquete *et al.* 2016). These examples highlight an important role for development and deployment of water conservation technologies and practices to achieve water-related SDG targets (Hejazi *et al.* 2014).

Reducing water pollution

Experience in developed countries has shown that it is possible to reduce water pollution. Unfortunately, there is very little scenario literature addressing water pollution problems and ways to achieve future sustainability targets. However, there is some literature discussing reduced nutrient pollution, for example by wastewater treatment. A global decrease in nutrient discharge is possible only when wastewater treatment plants are extended with at least tertiary treatment in developing countries and with advanced treatment in developed countries. Separate collection systems for urine can reduce nutrient pollution to 15TgN/yr and 1.2TgP/yr (van Puijenbroek, Beusen and Bouwman 2019). When all effluent from sewage systems receive tertiary treatment, global nutrient discharge is projected to decrease to 1990 levels (Ligtvoet *et al.* 2018). For phosphorus, a further decrease could be realized when all laundry and dishwasher detergents are phosphorus-free. This is now mandatory in the European Union, United States of America, Japan and some other countries.

Increasing crop yields and fertilizer-use efficiencies will have a direct effect on the nutrient loading of streams and rivers. However, starting from a situation of low crop yields and minimal nutrient inputs, nutrient loading of watersheds may well increase in scenarios with a shift towards food production systems now prevalent in industrialized countries. Since watersheds retain nitrogen and phosphorus, there may be legacies of past management. As a consequence, nitrogen concentrations in many rivers respond only slowly to increased nitrogen-use efficiency in food production. For example, due to these legacies, European water quality is threatened by rapidly increasing nitrogen-phosphorus ratios (e.g. Romero *et al.* 2013). Developing countries can avoid such problems by managing both nitrogen and phosphorus, accounting for residual soil phosphorus, while avoiding legacies associated with the past and continuing mismanagement of high-income countries.

Significant synergies and trade-offs between measures and targets

A number of synergies and trade-offs can be identified between specific measures and the various targets within this cluster. A few important ones are as follows.

- Increased access to and use of improved and safely managed WASH facilities has direct health benefits and can also improve overall quality of life. Women in developing countries often travel long distances to access water and sanitation facilities, even more so than men because of domestic-related tasks that more often fall to women, and because of menstrual hygiene (Pommells *et al.* 2018). Not only does this leave women more susceptible to health risks from more frequent contact with unsafe facilities, but there is a growing body of literature on the prevalence, and lack of documentation, of assault and rape on these trips (Sorenson, Morssink and Campos 2011; Watt and Chamberlain 2011; Sahoo *et al.* 2015; Sommer *et al.* 2015; Freshwater Action Network South Asia and Water Supply and Sanitation Collaborative Council 2016; Pommells *et al.* 2018).
- Increased levels of access to at least basic safe drinking water and adequate sanitation can drive increased domestic water demand, further contributing to water stress (Hanasaki *et al.* 2013a; Hanasaki *et al.* 2013b; Wada *et al.* 2016).
- Water scarcity negatively affects agriculture and biodiversity and also energy supply. In fact, water stress is one of the five global risks of highest concern according to the World Economic Forum (Wada, Gleeson and Esnault 2014).
- Agriculture is the dominant source of nutrients in global watersheds leading to eutrophication, resulting in hypoxia symptoms in many inland and coastal areas. There is a tendency towards increasing nitrogen-phosphorus ratios and declining silica; this distortion of nutrient ratios leads to the proliferation of harmful algal blooms, both in global watersheds and coastal parts of oceans.
- Improved sanitation facilities without, or with only primary, wastewater treatment are major polluters of freshwater, due to nitrogen and phosphorus discharge (van Puijenbroek *et al.* 2015),
- While the only option for some water-scarce communities, desalination is very energy-intensive, potentially counteracting interventions to reduce industrial water demand (Pinto and Marques 2017).

22.3.4 Oceans

The selected targets for the oceans cluster are limiting ocean acidification, reducing nutrient pollution and sustainably managing ocean resources (see Chapter 20). For all three targets, trends are projected to go in the wrong direction (see Chapter 21). There is strong evidence that the current trend towards declining fish populations and reduced species richness impair the ecological functioning of oceans, including their role in providing food (Worm *et al.* 2006). Nutrients from fertilizers used to increase agricultural yields have also found their way into nearly every water body across the globe where they stimulate aquatic plant production. As a consequence, hypoxia, a growing global problem, occurs where organic matter decay consumes oxygen faster than its diffusion from the oxygen-rich surface. Furthermore, the global problem of harmful algae is now on a pathway of more and more frequent blooms, in more places and with increasing severity, with more toxins (Glibert 2017).

Pathways in this cluster are largely linked to developments in other clusters. With respect to ocean acidification, the scenario literature is linked to climate change (i.e. the reduction of CO_2 emissions; Section 22.3.2), marine nutrient pollution with agricultural production measures (Section 22.3.1) and freshwater pollution (Section 22.3.3). Here, we discuss different measures linked to the individual targets, addressing ocean acidification measures and sustainable ocean management. No scenario studies were found that address the reduction of marine nutrient pollution to stop related hypoxia and harmful algal blooms.

Ocean acidification measures

Ocean acidification is a result of the increased absorption of CO_2 in the oceans, which in turn is a result of an increasing global atmospheric CO_2 concentration. Billé *et al.* (2013) identify three means of preventing ocean acidification:

i. reducing CO_2 concentrations, either by lowering emissions or removing CO_2 from the atmosphere, for example through carbon-capture-and-storage under the seabed (see Section 22.3.2);
ii. limiting ocean warming; and
iii. reducing nutrient run-off into the ocean.

Furthermore, they identify means of reversing acidification after it has occurred, including additives (e.g. alkalinization) and ecological restoration.

Reducing emissions of CO_2 thus reduces ocean acidification directly, while other climate policy measures can have an indirect effect via reducing sea surface temperature. For example, Mora *et al.* (2013) find less reduction in ocean pH and ocean productivity in Representative Concentration Pathway (RCP) 4.5 than in RCP 8.5. Similarly, Bopp *et al.* (2013) find a decline in ocean pH of only 0.07 and an increase in sea surface temperature of only 0.71°C in a stringent climate policy scenario, compared with a decline in pH of 0.33 and an increase in sea temperature of 2.73°C in a high-emission scenario. In fact, carbonate ion concentrations do not fall below saturation levels in the stringent climate policy scenario for any ocean (Bopp *et al.* 2013). Concentrations below saturation level can lead to dissolution of shells and skeletons of marine organisms.

Sustainable ocean management

Currently, fisheries worldwide are severely degraded as a result of overfishing. Several scenarios have looked at the impact of strong fisheries management (among others through the reduction of catch) to find that there could be a decrease in the proportion of exploited fish stocks to close to a recovery target biomass. This would, in the long run, also mean an increase in total global fisheries profit, relative to both the trend scenario and even the present day. Costello *et al.* (2016) analysed data excluding small-scale and artisanal fisheries but representing 78 per cent of global catches and found that applying management policies for returning catch to maximum sustainable yield or even maximum profits through rights-based fisheries management was projected to produce improvements in catch profit, and fish stock biomass relative to the business-as-usual management scenario. By 2050, some 98 per cent of stocks could be biologically healthy under strong fisheries management (Costello *et al.* 2016).

Similarly, under a low-greenhouse gas emissions scenario, Lam *et al.* (2016) projected a smaller decline in catch potential (4 per cent versus 7 per cent in the trend scenario), suggesting that climate policy can limit the impacts of climate change on global fisheries. Also, Cheung, Reygondeau and Frölicher (2016) estimated the benefits to global fisheries from meeting the 1.5°C warming target in the Paris Agreement: every degree of warming above this target resulted in a projected 3 million (metric) tons reduction in potential catch.

Another way to promote more sustainable fisheries and protect biodiversity is by introducing protected areas (Agardy 2000). Marine protected areas tend to increase the biomass of fish (Gill *et al.* 2017), but there is debate about the effectiveness of marine protected areas for biodiversity (Worm *et al.* 2006; Edgar *et al.* 2014). The effectiveness of protected areas regimes depends strongly on their management and enforcement (Edgar *et al.* 2014; Gill *et al.* 2017). In addition, by introducing better strategies for selecting protected areas, their impact can be increased significantly (Davis *et al.* 2017). However, similar to protection of terrestrial biodiversity, it is clear that for preventing biodiversity loss, increasing protected areas will not be enough (Mora and Sale 2011).

Significant synergies and trade-offs between measures and targets

A number of synergies and trade-offs can be identified between specific measures and the various targets within this cluster. A few important ones are as follows.

- Reviving current fish stocks will require a period of reduced catches, therefore potentially reducing the contribution of fish resources in reducing hunger. However, as shown, in the long run this will lead to higher sustainable yields.
- Reduced marine nutrient pollution could make coral reefs less vulnerable to ocean acidification and reduce the predicted shift from net accretion to net erosion (Silbiger *et al.* 2018).
- Reducing ocean acidification by means of limiting CO_2 emissions is also important to conserve marine biodiversity and to secure the availability of fish resources to reduce hunger worldwide.

22.3.5 Human development

The selected target for the human development cluster is ending preventable deaths of children under five years of age (see Chapter 20), with the acknowledgement that other environmental health impacts and age groups are also relevant for human health (see also Section 20.3.1). For example, exposure to ambient $PM_{2.5}$ was the fifth-ranking mortality risk factor in 2015 (Cohen *et al.* 2017; Chapter 5) and the deadliest of any environmental risk factor. More than half of the premature deaths attributed to ambient air pollution occur among those older than 50 years of age, while household air pollution, the second highest environmental risk factor, predominantly affects children and women (GBD 2016 Risk Factors Collaborators 2017; see also Section 5.3.1). Future projections show a reduction in the global child mortality rate, but not enough to achieve the target, while air pollution is projected to continue to contribute to millions of premature deaths annually (Chapter 21).

There are strong links between the child mortality target and several other targets discussed in this chapter. Important health risk factors affecting under-five mortality rates include malnutrition (strongly related to hunger), no access to safe drinking water, adequate sanitation and hygiene (WASH), indoor air pollution and (more indirectly) also climate change.

There are very few studies that look at reducing child mortality in relation to a range of environmental risk factors (e.g. Hughes *et al.* 2011; Lucas *et al.* 2018). Most studies focus on individual risks, most prominently malnutrition (i.e. prevalence of undernourishment) and ambient air pollution. Ending preventable death of children under five, especially with respect to environmental health risks, largely depends on achieving specific targets discussed for the other clusters in this chapter. However, pathway studies suggest that a healthy planet alone is not enough for achieving healthy people (Hughes *et al.* 2011; van Vuuren *et al.* 2015; Lucas *et al.* 2018; Moyer and Bohl 2018). The success of the different pathways in reducing child mortality depends on the degree to which they also address non-environmental risk factors, reducing both wealth inequalities and social inequalities. Here, we discuss four broad measures – reducing exposure to environmental risk factors, poverty alleviation, women and girl's education, and child and maternal health care.

Reducing exposure to environmental risk factors

Preventable risks for children under five include malnutrition (e.g. child underweight), exposure to fine particulate emissions causing pneumonia, and micropathogens and vectors that can transmit infectious diseases such as diarrhoea and malaria. Climate change can negatively impact several of these risk factors, including child underweight (Hughes *et al.* 2011) and malaria (Craig, Snow and le Sueur 1999). Measures for reducing exposure to related risk factors are extensively discussed in Sections 22.3.1 to 22.3.3. Here, we repeat some of these measures and discuss overall impacts on child mortality.

For ending malnutrition (SDG target 2.1), interventions include increased food availability through (for example) yield improvement, diet changes and waste reduction, as well as improving access to food and nutrition management for the poor (Section 22.3.1). Reduced consumption in high-income countries does not necessarily increase availability and access for poor communities and therefore has a low impact on reducing malnutrition and related child mortality (Moyer and Bohl 2018). A combination of availability and access measures are thus required. For reducing air pollution (SDG target 11.6), interventions include introducing effective air pollution controls, cleaner vehicles, better public transport and encouragement of active modes of transport via easily accessible walkways and bicycle paths, and finally reduced household air pollution through improved access to cleaner fuels and cookstoves (SDG target 7.1) (Section 22.3.2). For children under five, improving indoor air pollution through a transition away from traditional biomass on open fires or traditional stoves can result in significant health benefits. Finally, interventions to reduce exposure to microbial pathogens include increased levels of access to and knowledge of safe water, safely managed sanitation and hygiene (SDG targets 6.1 and 6.2) (Landrigan *et al.* 2018, p. 40) (Section 22.3.3).

Through interventions on all three risk factors, the environmental risks of under-five mortality are lessened, leading to reduced mortality from malnutrition, diarrhoea, pneumonia and other common infectious diseases (e.g. malaria). However, even if all the related environmental SDG targets were achieved by 2030, the under-five mortality target would not be met (Hughes *et al.* 2011; van Vuuren *et al.* 2015; Lucas *et al.* 2018; Moyer and Bohl 2018). Lucas *et al.* (2018) show that achieving health-related SDG targets on child nutrition, access to improved drinking water and sanitation, and access to modern energy services can avoid globally around 440,000 child deaths in 2030, reducing projected 2030 global under-five mortality by around 8 per cent. Hughes *et al.* (2011) conclude that, between 2005 and 2060, some 131.6 million cumulative child deaths (23 per cent of total deaths related to communicable diseases) could be avoided by gradually reducing childhood underweight, unsafe water, poor sanitation and hygiene, indoor air pollution and global climate change.

Alleviating poverty

There is considerable overlap between poor health and poverty (Aber *et al.* 1997; Yoshikawa, Aber and Beardslee 2012). In fact, while poverty is generally indicated as a measure of income, it can also be defined in terms of relative deprivation in a range of capabilities, including good health, but also higher levels of education (Hulme and Shepherd 2003; Alkire 2007). Poverty as defined by low income negatively impacts both health and education outcomes driving further deprivation (Hulme and Shepherd 2003). Conversely, eradicating extreme poverty (SDG target 1.1), and thereby improving the income situation of poor households, can improve health, especially of children under five.

Women and girl's education

Inclusive and equitable quality education (SDG 4), especially of women, is highly correlated with reduced child mortality. Furthermore, higher levels of education are associated with better overall health, lower fertility rates, increased economic growth, reduced poverty levels and more democracy (Dickson, Hughes and Irfan 2010; Lutz and Samir 2013; Dickson, Irfan and Hughes 2016). Over half the decline in child mortality from 1970 to 2009 can be attributed to increased education of women of reproductive age (Gakidou *et al.* 2010). Lucas *et al.* (2018) show that through a comprehensive strategy that includes universal female education, piped drinking water, a complete phase-out of biomass use for cooking and advanced malaria control, 777,000 child deaths can be avoided in 2030, reducing the projected 2030 global child mortality rate by around 13 per cent. The largest health gains are projected for sub-Saharan Africa.

Child and maternal health care

Reducing child mortality is inseparable from reducing maternal mortality – a healthy life begins with a healthy mother and a healthy birth. Reducing child mortality thus also requires addressing other SDG targets, including reducing maternal mortality itself (SDG target 3.1), increasing access to family planning and reducing the adolescent birth rate (SDG target 3.7), achieving universal health coverage (SDG target 3.8) and registering all births with a civil authority (SDG target 16.9) (United Nations Children's Fund [UNICEF] 2015; WHO and UNICEF 2017). Increased contraceptive use in developing countries has reduced the maternal mortality ratio by 26 per cent over the last decade by reducing unintended pregnancies and could reduce it by another 30 per cent if the unmet need is met (Cleland *et al.* 2012). Further, access to modern contraception directly reduces child mortality because increasing the interval between pregnancies reduces likelihood of prematurity and low birthweight, and infants with siblings less than two years old have a higher likelihood of death (Cleland *et al.* 2012).

Synergies and trade-offs between measures and socioeconomic developments

Apart from the obvious improvements to quality of life for people across the globe, improving health outcomes can also have significant impacts on demographics (Lee 2003; Hughes *et al.* 2011) and economic development (van Zon and Muysken 2003; Bloom, Canning and Sevilla 2004; Ashraf, Lester and Weil 2008; Suri *et al.* 2011).

- Reductions in child mortality are typically followed by fertility rate reduction, with a lag of about ten years (Angeles 2010; Bohl, Hughes and Johnson 2016). This has transformative implications (i.e. a larger working-age population followed by an ageing population) for the demographic structure of regions such as sub-Saharan Africa and South Asia, which currently have relatively high rates of both under-five mortality and fertility (Bohl, Hughes and Johnson 2016). When the working-age population growth rate exceeds that of the youth population, the growing labour force also creates economic opportunities, called the 'demographic dividend' (Bloom *et al.* 2009; Lee and Mason 2011, and see Chapter 2). During this time, fiscal burdens associated with service provision to youth (and elderly) populations are minimized, while aggregate economic productivity tends to increase (Lee and Mason

2011). However, a growing elderly population can create new budgetary constraints and more intense pressures on health and social services (Tabata 2005; Lee and Mason 2011; Bohl, Hughes and Johnson 2016; Burrows, Bohl and Moyer 2017).

- Reductions in mortality often result in reductions in morbidity of working-age populations (Hughes *et al.* 2011), further increasing aggregate economic productivity and attracting foreign investment into an economy via reduced labour-market uncertainty (Jamison *et al.* 2006; Hughes *et al.* 2011). Improved health outcomes can also lead to increased school attendance, improved cognitive skills and better educational outcomes for students (Baldacci *et al.* 2004; Soares 2006; Ashraf, Lester and Weil 2008), which improves human capital, and results in increased productivity and more healthy economies once these children move into working-age cohorts (Hughes *et al.* 2011).
- Decreased child mortality, especially when combined with female education and access to modern contraception, will likely lead to lower fertility rates in the longer term, curbing population growth, one of the major drivers of environmental degradation (Angeles 2010; Gakidou *et al.* 2010).

22.4 An integrated approach

In the previous sections, we discussed how to achieve a set of environment-related SDG targets (see Chapter 20 for target selection) and showed that, for many targets, pathways can be identified that could lead to meeting the targets by 2030 or 2050 – or at least result in a major improvement. Here we discuss some overall results from the analysis and a more in-depth analysis of key synergies and trade-offs between the different clusters.

22.4.1 Transformative change

The analysis showed that, in all areas, marginal improvements will not suffice; large, transformative changes are needed to realize the different targets, including significant improvements in resource efficiency with respect to yields, and water-, energy- and nitrogen-use efficiency **(see Table 22.1)**. For instance, reaching the targets related to energy access, climate change and air pollution, would imply decoupling of CO_2 emissions from economic growth at a rate of 4-6 per cent a year, over the coming three decades. In comparison, the same ratio only declined by 1-2 per cent a year historically, thus requiring a threefold increase of the historical rate. Furthermore, without demand-side measures, an average increase in productivity of around 1.4 per cent per year in agriculture would be needed to end global hunger, while simultaneously limiting biodiversity loss. While here the required efficiency improvements are comparable to historical improvement rates, it is clear that this will be more difficult to achieve in the future given that, in most cases, easy gains have already been implemented and agricultural production also will have to become more sustainable, including reduced water and nutrient use.

Earlier, we indicated that technological changes, lifestyle changes and multi-scale approaches are available. The measures discussed in this chapter are part of such approaches. However, given the scale of the required transition it seems far more likely that these strategies will have to be combined to achieve the level of transformation that is needed. It can also be concluded that the approaches used to unlock the available potential presented by any of these approaches has, thus far, not been very successful. The existing MEAs have not led to any break with the past (Part A and Chapter 21). It is therefore important to ensure that there is sufficient interest among actors to implement a different set of strategies. This interest is, among other influences, related to the different trade-offs and synergies of the different measures.

22.4.2 Synergies and trade-offs

Sections 22.3.1-22.3.5 discussed interrelations between measures and targets within the five clusters. However, there are also many synergies and trade-offs between these clusters. The SDGs and associated targets form a complicated network of interlinkages, not made explicit in their formulation (International Council for Science and International Social Science Council

Table 22.1: Trends in resource-use efficiency: baseline (Chapter 21) versus pathways towards achieving the targets (this chapter)

Target	Indicator	Baseline (Chapter 21)	More sustainable pathways[a] (Chapter 22)
Increase agricultural productivity (Section 22.3.1)	Yield improvement over time (total)	1 per cent/year (2010-2050)	1.4 per cent/year (2010-2050)
Increase nutrient-use efficiency (Section 22.3.1)	Total N inputs to the crop N yields	0.55 in 2050	0.67 in 2050
Increase water-use efficiency (Section 22.3.3)	Change in water-use efficiency over time	0.3-1 per cent (2010-2050)	0.5-1.2 per cent (2010-2050)
Increase the share of renewable energy (Section 22.3.2)	Renewable energy share in total final energy consumption	20-30 per cent in 2050	30-60 per cent[b] in 2050
Increase energy efficiency (Section 22.3.2)	Reduction in energy intensity over time (measured in terms of primary energy and GDP)	1-2.5 per cent (2010-2050)	2.2-3.5 per cent (2010-2050)

N: nitrogen.

[a] Not for all topics, the pathways found in the literature and discussed in this chapter were able to meet the selected target as presented in Chapter 20 (see Section 22.3.1 to 22.3.5).

[b] Renewable energy includes the full range of renewables and non-CO_2 emission reductions in the mitigation scenarios derived from the SSP scenarios (see Section 3.2.2).

2015; Le Blanc 2015). Understanding the interlinkages, beyond the clusters focused on here, is crucial for synergistic implementation and policy coherence (Nilsson, Griggs and Visbeck 2016; TWI2050 2018). Accounting for interlinkages can help enhance the effectiveness of implementation and, to some extent, also reduce the total burden and cost of achieving targets individually (Elder, Bengtsson and Akenji 2016). Furthermore, it can help with identifying coherent clusters of targets to be pursued together (Weitz *et al.* 2018).

Analysing the integrated nature of the SDGs has been a research area since their agreement in 2015. However, only a few broad studies so far have analysed interrelations across all SDGs (e.g. Prahdan *et al.* 2017; Zhou and Moinuddin 2017). Difficulties with such studies are that they generally do not look at specific measures, do not take into account future developments, and can only conclude correlations between targets, not causality. Studies that do take these elements into account in their analysis generally focus on a subset of SDGs (International Council for Science 2017; van Vuuren *et al.* 2015) or specific themes, such as energy (McCollum *et al.* 2018; Nerini *et al.* 2018), climate mitigation (von Stechow *et al.* 2016), air pollution (Elder and Zusman 2016), land use and food security (Obersteiner *et al.* 2016; Conijn *et al.* 2018), oceans (Singh *et al.* 2017) and ecosystem services (Wood *et al.* 2018). These studies are either based on the existing literature – as is also the case in this chapter – or on dedicated modelling.

Overall, these studies identify more synergies than trade-offs within and among the SDGs and their targets. However, many interrelations are highly context-specific (Nilsson, Griggs and Visbeck 2016; Weitz *et al.* 2018). There are multiple links between two targets, with potentially different and sometimes conflicting interrelations. Furthermore, outcomes depend on the governance and geographical context, as well as the time-horizon taken (Nilsson *et al.* 2018), to name a few. Providing a full analysis of all interrelations across the measures and targets discussed in this chapter thus requires a dedicated, place-based analysis, which is beyond the scope of GEO-6. In this section, we therefore further elaborate on some of the interrelations among measures and targets between the different clusters for which the scenario literature concludes significant interrelations.

Table 22.2 provides a broad overview of measures with strong synergistic effects and measures with strong trade-offs across the targets, based on the scenario assessments of Section 22.3.1 to 22.3.5 and a quick-scan presented in **Box 22.5**. From this set, key measures with respect to strong synergies and trade-offs are selected for a more in-depth discussion.

Table 22.2: Measures with significant synergies or trade-offs across the selected targets

	Synergies	**Trade-offs**
Discussed here	(Female) education Reducing agricultural demand via loss and waste reduction, changing diets and nutrition management Reducing air pollution	Land-based mitigation, including large-scale bioenergy deployment Agricultural intensification Environmental policy (potentially conflicting with poverty eradication)
Other examples	Improving resource efficiency of energy, land and water resources (although risk of rebound effects exists) Move towards non-biomass renewable energy (e.g. wind and solar power) Ecosystem restoration Integrated water resources management	Competition for scarce resources Economic development (potentially leading to further demand for resources) Desalination

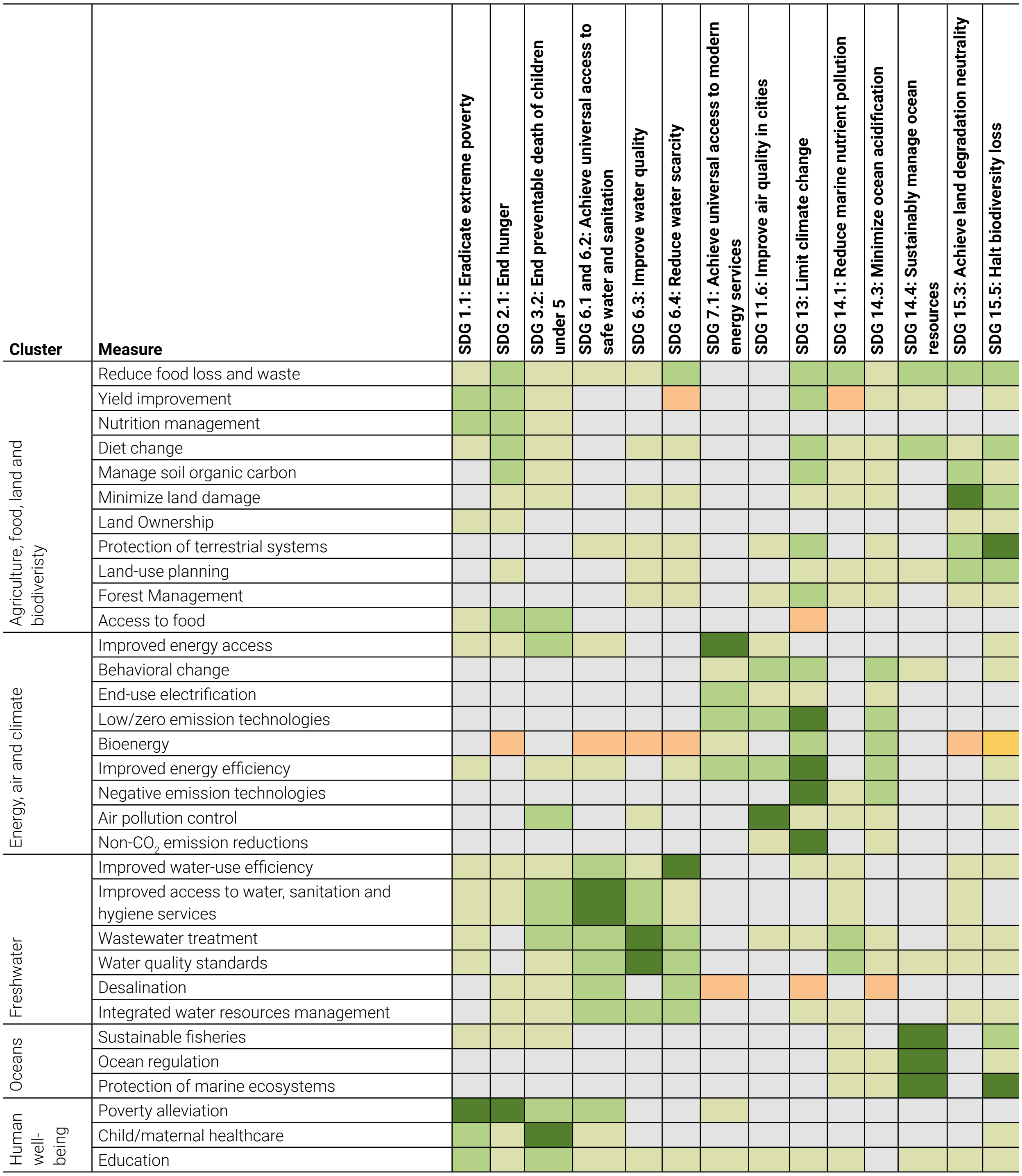
Box 22.5: A snapshot of interrelations between the selected measures and targets

To get an overview of the many interrelations across the selected measures and targets discussed in this chapter, an expert assessment has been conducted under the authors of this chapter. This expert assessment was compared with the literature and the input from authors of Part A of GEO-6. Experts were asked to score the interrelations using the seven-point scale of Nilsson, Griggs and Visbeck (2016). Interrelations were scored from the most positive score (the measure is indivisible to achieve the target) to the most negative score (the measure can cancel achievement of the target). The result (average score over the different expert scores) is presented in **Figure 22.9**.

Some clear patterns emerge from the analysis. Most interlinkages are flagged between the different measures and the targets that address climate change and biodiversity loss. Furthermore, in line with conclusions from earlier interrelation studies, there are more synergies than trade-offs. The strongest synergies are between measures and targets within the same cluster (see the synergies and trade-offs discussion for each of the individual clusters in Section 22.3). Finally, clear trade-offs are identified between the measures for yield improvement, bioenergy use and desalination, and a broad range of targets. However, as the strongest negative score was not given, the experts suggest that these trade-offs could be addressed with extra mitigating measures.

The analysis also concludes that the extent of the interrelations is not always straightforward. For many interrelations, the experts showed some level of disagreement. These stem partly from different assumptions on the overall context in which the measures are taken, but also that several measures can have both synergies and trade-offs requiring some kind of assessment of their strength. From a similar exercise in the literature, focusing on SDGs on health, energy and oceans, it was concluded that interactions depend on key factors such as geographical context, resource endowments, time-horizon and governance (Nilsson *et al.* 2018). **Figure 22.9** thus only presents a first snapshot or quick-scan of key interrelations involved. To draw policy conclusions, a more dedicated analysis is required. This includes systematic reviews, coding existing literature with respect to specific interactions and integrated assessment modelling, with the latter analysing interlinkages within and across a broader range of subsystems than is currently done (see also Nilsson *et al.* 2018).

Figure 22.9: Quick-scan of synergies and trade-offs between selected measures and targets



Cluster	Measure	SDG 1.1: Eradicate extreme poverty	SDG 2.1: End hunger	SDG 3.2: End preventable death of children under 5	SDG 6.1 and 6.2: Achieve universal access to safe water and sanitation	SDG 6.3: Improve water quality	SDG 6.4: Reduce water scarcity	SDG 7.1: Achieve universal access to modern energy services	SDG 11.6: Improve air quality in cities	SDG 13: Limit climate change	SDG 14.1: Reduce marine nutrient pollution	SDG 14.3: Minimize ocean acidification	SDG 14.4: Sustainably manage ocean resources	SDG 15.3: Achieve land degradation neutrality	SDG 15.5: Halt biodiversity loss
Agriculture, food, land and biodiveristy	Reduce food loss and waste	▨	▣	▨	▨	▨	▣	□	□	▣	▣	▨	▣	▣	▣
	Yield improvement	▣	▣	▨	□	□	🟧	□	□	▣	🟧	▨	▨	□	▨
	Nutrition management	▣	▣	▨	□	□	□	□	□	□	□	□	□	□	□
	Diet change	▨	▣	▨	□	▨	▨	□	□	▣	▨	▨	▣	▨	▣
	Manage soil organic carbon	□	▣	▨	□	□	□	□	□	▣	▨	▨	□	▣	▨
	Minimize land damage	□	▨	▨	□	▨	▨	□	□	▨	▨	▨	□	■	▣
	Land Ownership	▨	▨	□	□	□	□	□	□	□	□	□	□	▨	▨
	Protection of terrestrial systems	□	□	□	▨	▨	▨	□	▨	▣	□	▨	□	▣	■
	Land-use planning	□	▨	□	□	▨	▨	□	□	▨	▨	▨	▨	▣	▣
	Forest Management	□	□	□	□	▨	▨	□	▨	▣	▨	▨	□	▨	▨
	Access to food	▨	▣	▣	□	□	□	□	□	🟧	□	□	□	□	□
Energy, air and climate	Improved energy access	▨	▨	▣	▨	□	□	■	▨	□	□	□	□	□	▨
	Behavioral change	□	□	□	□	□	□	▨	▣	▣	□	▣	▨	□	▨
	End-use electrification	□	□	□	□	□	□	▣	▨	▨	□	▨	□	□	□
	Low/zero emission technologies	□	□	□	□	□	□	▣	▣	■	□	▣	□	□	□
	Bioenergy	□	🟧	□	🟧	🟧	🟧	▨	□	▣	□	▣	□	🟧	🟨
	Improved energy efficiency	▨	□	▨	▨	□	▨	▣	▣	■	□	▣	□	□	▨
	Negative emission technologies	□	□	□	□	□	□	□	□	■	▨	▣	□	□	□
	Air pollution control	□	□	▣	□	▨	□	□	■	▨	▨	▨	□	□	▨
	Non-CO$_2$ emission reductions	□	□	□	□	□	□	□	▨	■	□	▨	□	□	□
Freshwater	Improved water-use efficiency	▨	▨	▨	▣	▨	■	□	□	▨	▨	□	□	▨	▨
	Improved access to water, sanitation and hygiene services	▨	▨	▣	■	▣	▨	□	□	□	▨	□	□	▨	□
	Wastewater treatment	▨	□	▣	▣	■	▣	□	▨	▨	▣	▨	□	▨	▨
	Water quality standards	▨	□	▨	▣	■	▣	□	□	□	▣	▨	▨	▨	▨
	Desalination	□	▨	▨	▣	□	▣	🟧	□	🟧	□	🟧	□	□	□
	Integrated water resources management	□	▨	▨	▣	▣	▣	□	□	▨	▨	□	□	▨	▨
Oceans	Sustainable fisheries	▨	▨	▨	□	□	□	□	□	□	▨	□	■	□	▣
	Ocean regulation	□	□	□	□	□	□	□	□	□	▨	▨	■	□	▨
	Protection of marine ecosystems	□	□	□	□	□	□	□	□	□	▨	▨	■	□	■
Human well-being	Poverty alleviation	■	■	▣	▣	□	□	▨	□	□	□	□	□	□	□
	Child/maternal healthcare	▣	▨	■	▨	□	□	□	□	□	□	□	□	□	▨
	Education	▣	▨	▣	▨	▨	▨	▨	▨	▨	▨	□	▨	▨	▨

Nilsson Score

■	Inextricably link to the achievement of target
▣	Aids the achievement of target
▨	Creates conditions that further achievement of target
□	No significant interactions
🟧	Limits options on target
🟨	Clashes with target
🟥	Makes it impossible to reach target

Source: Scores are based on expert elicitation, using the seven-point scale of Nilsson, Griggs and Visbeck (2016).

Selected measures with significant synergies across the selected targets

Education

Education is a basic human right (Universal Declaration of Human Rights, Article 26), an SDG in itself (SDG 4) and, like health, a measure of human development (United Nations Development Programme [UNDP] 2016). Improved education has considerable synergistic effects with both well-being and environment-related targets (United Nations Educational, Scientific and Cultural Organization [UNESCO] 2017). Education, especially for women, has a particularly strong connection with health outcomes. It can significantly affect child health, through reduced malnutrition (Smith and Haddad 2000; Marmot, Allen and Goldblatt 2010) and improved hygiene. Over half the decline in child mortality from 1970 to 2009 can be attributed to increased education in women of reproductive age (Gakidou *et al.* 2010). In addition, higher levels of education are associated with lower fertility rates, increased economic growth, reduced poverty levels and more democracy (Dickson, Hughes and Irfan 2010; Lutz and Samir 2013; Dickson, Irfan and Hughes 2016). The link between improved educational metrics and economic growth and poverty alleviation are well established (Hulme and Shepherd 2003; Verner 2004; Awan *et al.* 2011; Cremin and Nakabugo 2012; UNDP 2016). Improved education also contributes to coping with climate change and coping with the increased occurrence and severity of natural disasters (Cordero, Todd and Abellera 2008; Kagawa and Selby 2012; Chang 2015). Climate change education contributes to capacity-building for decision makers, but also empowers people to implement their own adaptation strategies, among other things, by equipping people to understand complexity and perceive risks (Mochizuki and Bryan 2015). Improving access to safe drinking water, sanitation and hygiene, and sound management of freshwater ecosystems can also benefit from education (Çoban *et al.* 2011; Michelsen and Rieckmann 2015; Karthe *et al.* 2016).

Dietary change

Dietary change, particularly towards reduced ruminant consumption, is synergistic with achieving multiple environmental targets. Furthermore, it can help end hunger and improve human health, with minimal effect on land degradation and biodiversity. In particular, dietary change can reduce cropland expansion (Stehfest *et al.* 2009; Tilman and Clark 2014) and at the same time increase food supply (Foley *et al.* 2011). In addition, dietary change can result in reduced greenhouse gas emissions, reduced pollution, reduced water use and improved health. Dietary change results in reduced emissions of methane from reduced livestock consumption, N_2O and ammonia from reduced fertilizer application, and CO_2 from reduced cropland conversion (Stehfest *et al.* 2009; van Vuuren *et al.* 2017a). The decrease in greenhouse gas emissions associated with dietary change can be significant, with greenhouse gas emission reductions of as much as 70-80 per cent possible (Aleksandrowicz *et al.* 2016). Reducing methane emissions also has positive implications for air quality, as it is a precursor to ozone pollution. Reduction in nitrogen fertilizer use associated with changes in diet has the co-benefit of improving air quality and health by reducing emissions of ammonia and the subsequent formation of fine particulate matter (Zhao *et al.* 2017; Giannadaki *et al.* 2018). Reductions in nitrogen fertilizer use associated with changes in diet also have positive implications for water quality. Reduction in water use can be as much as 50 per cent (Aleksandrowicz *et al.* 2016; Jalava *et al.* 2016; Bijl *et al.* 2017; van Vuuren *et al.* 2017a). Finally, dietary shifts to lower consumption of livestock products yields benefits in all-cause mortality (Milner *et al.* 2015; Aleksandrowicz *et al.* 2016; Springmann *et al.* 2018). It should be noted that some researchers do not find a significant increase of food availability and access for poor communities, resulting from reduced meat consumption in high-income countries (Moyer and Bohl 2018). To be effective, measures to shift diets need to take into account the regional and developmental context (World Economic Forum 2017).

Air pollution control

Reduced air pollution has clear positive impacts on human health. However, there are also synergies with agricultural production, biodiversity and climate change. Ozone is a strong oxidant that can enter plants through the leaves and damage vegetation by affecting photosynthesis and other physiological functions. Several studies have reviewed the links between ozone concentrations, forest productivity and agricultural yields (e.g. Ainsworth *et al.* 2012; Talhelm *et al.* 2014). Averaged over 2010-2012, ozone is estimated to have reduced wheat yield by 9.9 per cent in the Northern Hemisphere and by 6.2 per cent in the Southern Hemisphere (Mills *et al.* 2018). Shindell *et al.* (2012) quantified how measures to reduce black carbon and methane lead to reduced ozone and thus improved agricultural yield, production and value. They found an increase in production of approximately 27 million tons and 24 million tons due to measures to reduce methane and black carbon, respectively. Avnery, Mauzerall and Fiore (2013) report that methane emission controls could increase production of wheat, maize and soybean in North America in 2030 by up to 3.7 million tons. Capps *et al.* (2016) showed that reduction in emissions of nitrogen oxides (NO_x) as a co-benefit of limiting CO_2 emissions from coal power plants in the United States of America could reduce potential productivity loss due to ozone exposure by as much as 16 per cent and 13 per cent for individual crops and tree species, respectively. Reduction in SO_2 and NO_x emissions leads to reductions in acid and nitrogen deposition, and subsequent ecosystem impacts such as eutrophication (Greaver *et al.* 2012).

Selected measures with significant trade-offs across the selected targets

Land-based mitigation

Nearly all climate scenarios consistent with the Paris Agreement rely on significant use of land-use based mitigation (see also **Box 22.2**). This includes the use of bioenergy, avoiding deforestation and afforestation/reforestation. A special case is the role of negative emissions (bioenergy plus carbon-capture-and-storage and afforestation), which seems a requirement for the stringent climate targets – certainly those which allow for higher short-term emissions (Fuss *et al.* 2014; van Vuuren *et al.* 2017a). The use of land-based mitigation options can have important implications for other sustainability targets, in particular food security and protecting terrestrial biodiversity (Wicke 2011; Reilly *et al.* 2012; Calvin *et al.* 2014; Popp *et al.* 2014; Smith *et al.* 2016; Heck *et al.* 2018). For example, pathways with high bioenergy use can negatively impact land degradation and biodiversity, as these pathways would typically lead to higher food prices, reduced forest cover and reduced natural lands. While pathways with significant afforestation could potentially lead to a synergy with reducing biodiversity loss they could still lead to increased competition for land and thus potentially to higher food prices. Bioenergy use could also lead to higher demand for water and more fertilizer use, with the latter increasing the risk of eutrophication from higher nitrogen and phosphorus run-off (e.g. Gerben-Leenes, Hoekstra and van der Meer 2009; Hejazi *et al.* 2015; Mouratiadou *et al.* 2016).

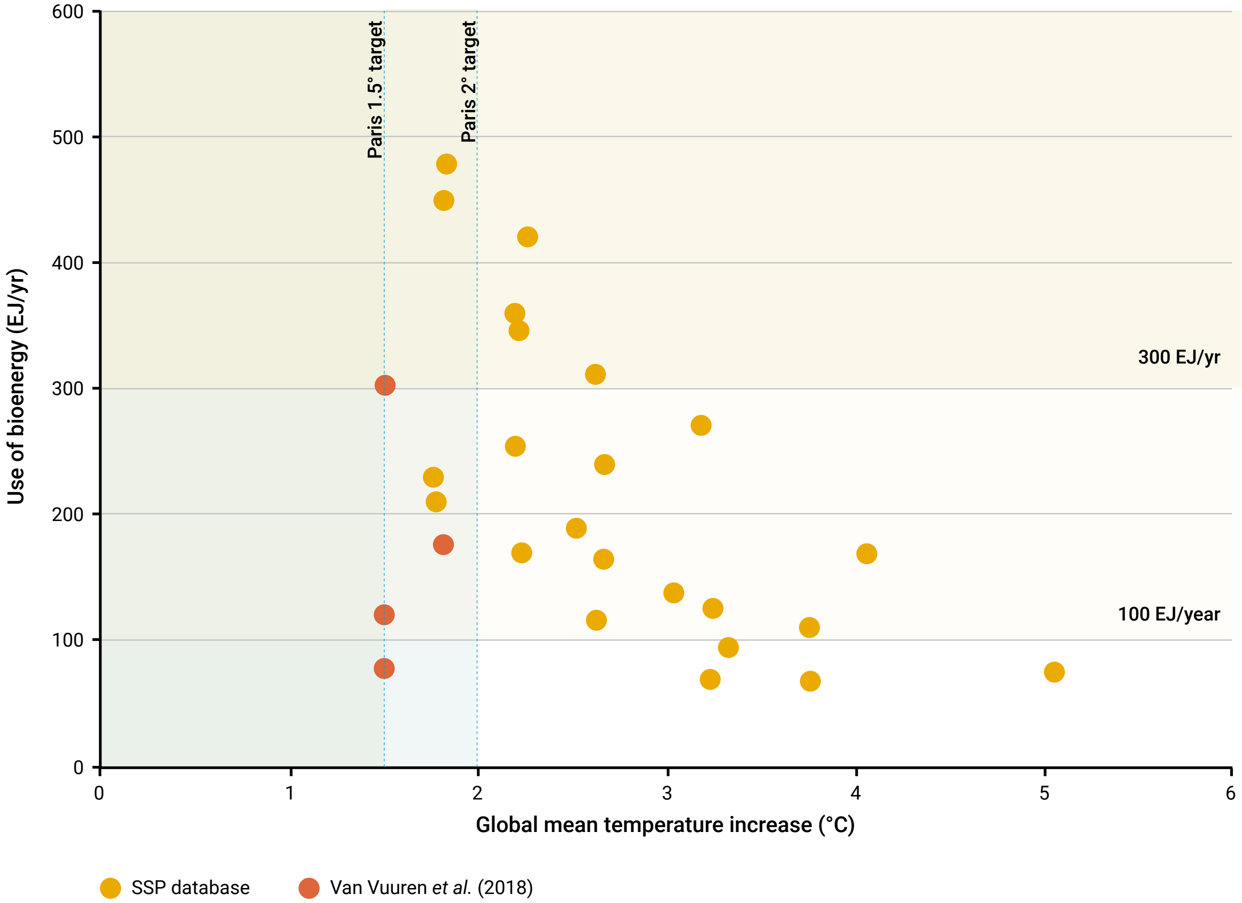
Although bioenergy is one of several important options for future energy systems, increasing global trade and consumption of bioenergy has been accompanied by a growing concern about the environmental, ecological and social impacts of modern bioenergy production (Wicke 2011). For example, trade-offs between bioenergy and food security, and between the impact of biomass on poverty reduction and on the environment have been widely reported (Wicke 2011; Smith *et al.* 2016). Yamagata *et al.* (2018) report water-food-ecosystem trade-offs for global negative CO_2 emission scenarios. They point to three outstanding conflicts:

- vast conversion of food cropland into rain-fed bio-crop cultivations yields a considerable loss of food production;
- when irrigation is applied to bio-crop production, the bioenergy crop productivity is enhanced – this reduces the area necessary for bio-crop production by half, but water consumption is doubled, increasing water scarcity and groundwater depletion; and
- if conversion of forest land for bioenergy crop cultivation is allowed, large areas of tropical forest could be used for bioenergy crop production, which can cause serious extensive decline in carbon stock and related ecosystem services, leading to increasing CO_2 emissions from land-use change.

More attention needs to be paid to the co-benefit of biodiversity conservation and climatic change mitigation activities for optimizing various sustainability benefits.

Figure 22.10 illustrates that in the majority of the scenarios the use of bioenergy increases for more stringent climate targets. In the SSP scenario database in fact all scenarios consistent with the targets of the Paris Agreement lead to a demand for bioenergy of more than 200 exajoules/year in 2050. Earlier, the Intergovernmental Panel on Climate Change (IPCC) did an assessment of the bioenergy supply in 2050 under different sustainability constraints. It concluded that at least 100 exajoules/year would be available under these constraints. It also concluded that possibly 300 exajoules/year

Figure 22.10: Global mean temperature increase in 2100 versus bioenergy use in various SSP reference scenarios and derived mitigation scenarios



The different background colors indicate the Paris Climate Targets (vertical lines, starting at 1.5° and 2°C) and the range for sustainable biodiversity supply indicated by the Intergovernmental Panel on Climate Change (IPCC) (IPCC indicated 100 exajoules/year was most likely available; 300 exajoules/year could be available).

Source: Riahi *et al.*, 2017; Vuuren *et al.* (2018).

would be available (but with a much higher level of uncertainty). A bioenergy potential of about 100 exajoules/year was found to have high agreement of being sustainable, while values above that threshold had lower levels of agreement as to the sustainability of the bioenergy supply (Creutzig *et al.* 2015). This means that no scenarios in the database would actually be consistent with a stringent interpretation of both the Paris target and the sustainability constraints on bioenergy. Van Vuuren *et al.* (2018) explored different alternative pathways to reach ambitious climate targets that could possibly reduce the need for negative emissions (and thus bioenergy). These scenarios, for instance, assumed diet change towards low-meat diets consistent with health recommendations, ambitious implementation of non-CO_2 emission reduction or alternatively the production of cultivated meat. Such assumptions could lead to a much lower demand for negative emission technologies and thereby bioenergy in combination with carbon-capture-and-storage. Recently, a model comparison study looked into stringent climate policy scenarios with limited bioenergy supply (Bauer *et al.* 2018). Here, some models did find low-bioenergy pathways through careful optimization of their use (e.g. the application of bioenergy in combination with carbon-capture-and-storage only for production of transport fuels).

Agricultural intensification
Improving agricultural yields is seen as a prerequisite for producing enough food and bioenergy to meet future demand while at the same minimizing or completely eliminating the need for agricultural land expansion. The use of fertilizers can potentially deliver yield increases but can also have severe consequences for freshwater and ocean quality and related ecosystems, as well as climate change (Bouwman *et al.* 2017). Impacts on biodiversity largely depend on how higher yields are achieved.

Improving yields can increase overall food availability, especially when these yield improvements are achieved in current low-yield countries and areas with high prevalence of undernourishment. At the same time, it can negatively impact nutrition if high-yield crops contain less micronutrients than average dietary requirements (DeFries *et al.* 2015; Rao *et al.* 2018). Furthermore, when yields are increased without specifically addressing distributional aspects, the increased production does not necessarily reach the communities most in need. At the same time, obesity in high- and middle-income countries could rise as a result of overall decreasing food prices (van Vuuren *et al.* 2015). Finally, when yield increases are accompanied by scale increase, smallholders might be forced to move to cities, which does not necessarily improve their income situation.

Improving agricultural yields reduces land demand for growing crops, reducing pressure on existing natural lands, thus potentially reducing deforestation and biodiversity loss. On the other hand, increasing yields usually demands higher levels of fertilizers, pesticides, and water for irrigation, thus negatively impacting water quality and water scarcity. Use of nitrogen fertilizers also causes higher N_2O emissions, meaning trade-offs with climate change mitigation. Mechanization and monocultures associated with yield increases in the past led to erosion, soil compaction and loss of soil organic carbon, increasing the likelihood of land degradation. This can be further exacerbated by leaching and salinization of land from long-term irrigation. All these factors negatively impact biodiversity.

Poverty alleviation and environmental protection
Higher incomes, decreasing hunger and improved access to water and energy are expected to push up demand for food, water and energy, thereby increasing environmental pressures. In reality, however, both synergies and trade-offs exist – and, while some are important to take into account, others are relatively small. Scenario analysis shows that eradicating hunger and providing universal access to modern energy services (beyond production increases that result from population and economic growth) would not necessarily negatively affect global biodiversity or climate change (e.g. Riahi *et al.* 2012; van Vuuren *et al.* 2015; Dagnachew *et al.* 2018). Although most studies addressing access to modern energy services show that a decrease in biomass use is generally accompanied by an increase in the use of fossil-fuel-based products (e.g. liquified petroleum gas, natural gas, electricity), the increase in global CO_2 emissions is usually small (Dagnachew *et al.* 2018). Furthermore, increasing CO_2 emissions are partly compensated by reduced emissions from deforestation and black carbon. Similarly, the additional demand for food, resulting from the eradication of hunger, is estimated to be relatively small, especially when compared to current production levels and the required increase to keep pace with an increasing and more wealthy global population (van Vuuren *et al.* 2015). If hunger eradication would be facilitated by a redistribution of current consumption levels, the required increase in production would be even less (van Vuuren *et al.* 2015). Obviously, however, further development beyond the minimum levels could be associated with further environmental pressure. Therefore, it is important to add sustainability considerations in policies that aim for higher levels of economic development in order to prevent such a trade-off.

Several studies have emphasized another potential trade-off between achieving environmental targets and ensuring access to basic resources and services. This is because, in many cases, policies for achieving environmental targets could lead to a cost increase. While such cost increases might be relatively unimportant for populations with high income levels, they could have a strong impact on the poor. It has been shown that if implemented without additional compensatory measures, climate policy could lead to negative impacts on access to electricity (Dagnachew *et al.* 2017), access to clean fuels for cooking (Cameron *et al.* 2016) and on food security (Hasegawa *et al.* 2018).

22.5 Conclusions and recommendations

We have assessed the scenario literature to analyse a broad range of measures relevant for achieving the selected environmental targets of the SDGs and related MEAs, with a specific focus on synergies and trade-offs. Overall, the scenario literature provides a broad range of options to move towards achieving these targets, but this knowledge is hampered by the lack of concrete pathways.

22.5.1 Knowledge gaps

The discussion in this chapter shows that model-based scenario analysis can be an effective tool to support integration of knowledge in the effort required to reach the environmental targets of the SDGs and related MEAs and to highlight the linkages across time, scales and issues.

However, from the literature assessment, it can be concluded that the scenario literature is still patchy on analysis to show possible pathways to achieving the SDGs. No fully integrated scenario studies exist. Furthermore, the literature is well advanced in some areas, while for other areas literature is mostly lacking. As a result, it is still difficult to estimate the exact size of different strengths and weaknesses of specific measures. There is extensive literature that discusses pathways to achieve the selected targets in the energy, air and climate cluster and, although to a lesser extent, also in the agriculture, food, land and biodiversity cluster. In the latter case, these studies mostly address hunger and biodiversity, with relatively few scenario studies that aim to meet specific targets and virtually no scenario studies that address how to achieve land degradation neutrality. Ocean acidification is well discussed in the literature, mostly linked to scenarios that address climate targets.

For the freshwater, oceans and human well-being (health) clusters, target-seeking scenarios are much less common in the literature. For the freshwater cluster, scenarios look at water scarcity issues, while the literature around WASH and water quality are sparse. For health (e.g. child mortality), very few target-seeking scenarios were found in the literature. Finally, as already concluded in Chapter 21, quantitative scenario studies on chemicals and waste and wastewater are almost non-existent.

While many synergies and trade-offs are discussed in the literature, besides thematic studies (mostly based on existing scenario literature), a thorough overview of all relevant interrelations across the measures and targets discussed in this chapter is still lacking. This is partly because there are still caveats in the scenario literature and because these interrelations are highly context-specific, making it difficult to provide unambiguous scores. Sectoral studies looking at interlinkages often emphasize the key role of that sector in achieving the overall targets, providing very few options for prioritization. As result, large gaps exist in current understanding of linkages with other sectors or themes.

It should be noted that indirect interlinkages often also exist and that, in many cases, interlinkages can lead to both synergies and trade-offs. For example, fertilizer application could lead to higher yields, requiring less land and thus reducing biodiversity loss and potentially land expansion, while it would also increase nitrogen and phosphorus run-off leading to freshwater and marine nutrient pollution, causing hypoxia and harmful algal blooms, and related biodiversity loss. These complex interrelations and the absence of broad interlinkage studies imply that more dedicated analyses are required, including systematic reviews of the existing literature and dedicated integrated assessment modelling, with specific attention to interlinkages that are currently underexplored.

22.5.2 Policy recommendations

From the scenario analysis, it can be concluded that pathways exist towards achieving a broad range of environmental targets of the SDGs and related MEAs, but they require a clear break with current trends (transformational change). Marginal improvements will not suffice. Large, transformative changes are needed to realize the different targets. Significant improvements in resource efficiency with respect to land, water and energy are required, including an almost 50 per cent increase in agricultural yields compared with current trends, and a doubling of energy efficiency improvement.

Achieving the targets will require a broad portfolio of measures, including a mix of technological improvements, lifestyle changes and localized solutions. The many different challenges require dedicated measures that improve access to, for example, food, water and energy, while at the same time reducing the pressure on environmental resources and ecosystems. A key contribution may come from a redistribution of access to resources. From a production perspective, the changes would include elements such as cleaner production processes and decoupling of resource consumption from economic development. Also changes in demand-side efficiency and consumer behaviour should be considered. The latter may include dietary changes towards reduced ruminant consumption, but also changes in transport moving towards less energy-intensive transport modes.

Understanding interlinkages between measures and targets is crucial for synergistic implementation and policy coherence. Where measures generally aim at achieving specific targets, or a cluster of targets, the analysis showed some clear synergies between measures and targets in other areas. Examples include education, dietary change and air pollution control, with all three having positive impacts on both a Healthy Planet and Healthy People. This chapter also highlights important possible trade-offs, such as the impact of climate policy on the costs of energy and consequently energy access. In many cases, it is also possible to address these trade-offs by introducing mitigation measures (in the example above, specific policies to support energy access for the poor could prevent specific trade-offs).

The economic and technical potential is available to move towards implementation of the targets in Chapter 20. However, a full consideration also needs to account for social feasibility. The feasibility of the transformation processes can only be discussed in the light of current trends and ongoing innovation processes of citizens and businesses worldwide. Chapter 23 will do this. Finally, in Chapter 24, we will discuss how policy measures could induce the transformations presented here. In many cases, social feasibility can be enhanced by ensuring a proper consideration of possible synergies and trade-offs.

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