Chapter 3

Projections of economic growth and impacts of outdoor air pollution

This chapter outlines the main socioeconomic trends that are projected to emerge in absence of environmental policies other than those that are already in place. It presents the projections of the air pollutant emissions as linked to the economic projections of the ENV-Linkages model. The chapter also presents results on the concentrations of key pollutants that are the drivers of impacts on health and crop yields. Finally, it presents results on the biophysical impacts related to premature deaths, increasing cases of illnesses, and changes in crop yields.

3.1. Trends in economic activity and growth

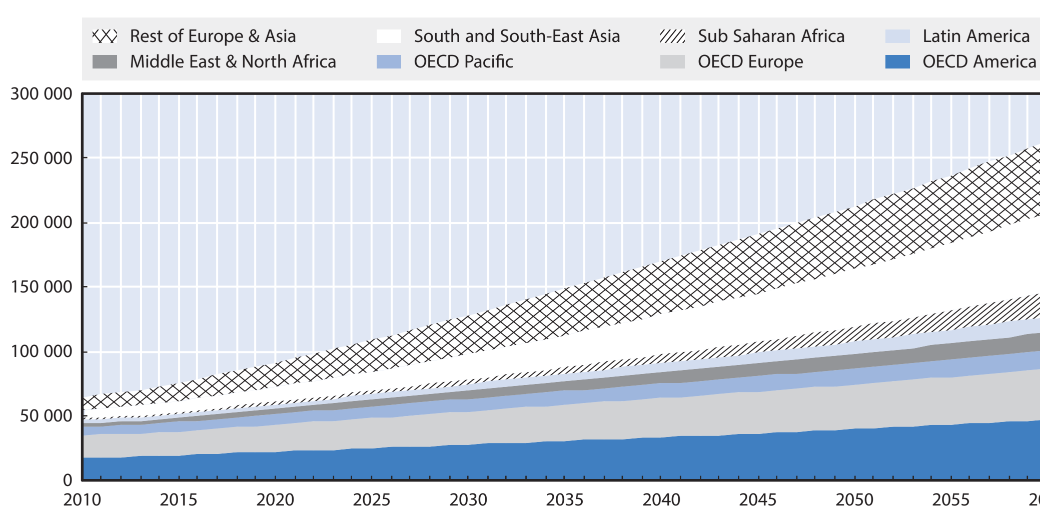
The projections of future economic activity are based on a modelling framework, the OECD's ENV-Linkages model (Chateau et al., 2014), which provides trends in sectoral and regional economic activity. These projections of GDP and other economic indicators are driven by a multitude of factors, including assumptions on so-called megatrends, such as developments in demography and technology. These megatrends are country-specific. For example, the age structure in the People's Republic of China (henceforth "China") and in India are different: aging will become a major force in China in the coming decades, while India has a much younger population. Similarly, while the average annual growth rate of technological progress is currently highest in the emerging economies, such as China, India and Indonesia, growth rates in these countries are projected to decline, while they are projected to increase in many developing countries.

The regional projections of GDP indicate that global economic activity will continue growing in the coming decades. While long-run global economic growth rates are gradually declining, Figure 3.1 shows that GDP levels in the projection without economic feedbacks from air pollution are still projected to increase significantly over time. The largest growth is projected to be outside the OECD region, especially in Asia and Africa, where a huge economic growth potential exists. The share of the OECD in the world economy is projected to decline from 64% in 2010 to 38% in 2060. These projections are fully aligned with the OECD Economic Outlook (OECD, 2014) and include the main effects of the financial crisis as they emerged until 2013. They are also consistent with the central scenario of the OECD@100 report on long-term scenarios (Braconier et al., 2014).

Figure 3.2 shows how the sectoral structure evolves in the regional economies. The shares of the various sectors in OECD economies tend to be relatively stable, with the services sectors accounting for more than half of GDP (i.e. value added). However, there are undoubtedly many fundamental changes at the sub-sectoral level that are not reflected here.

Figure 3.1. **Trend in real GDP, no-feedback projection**

Billions of USD, 2010 PPP exchange rates



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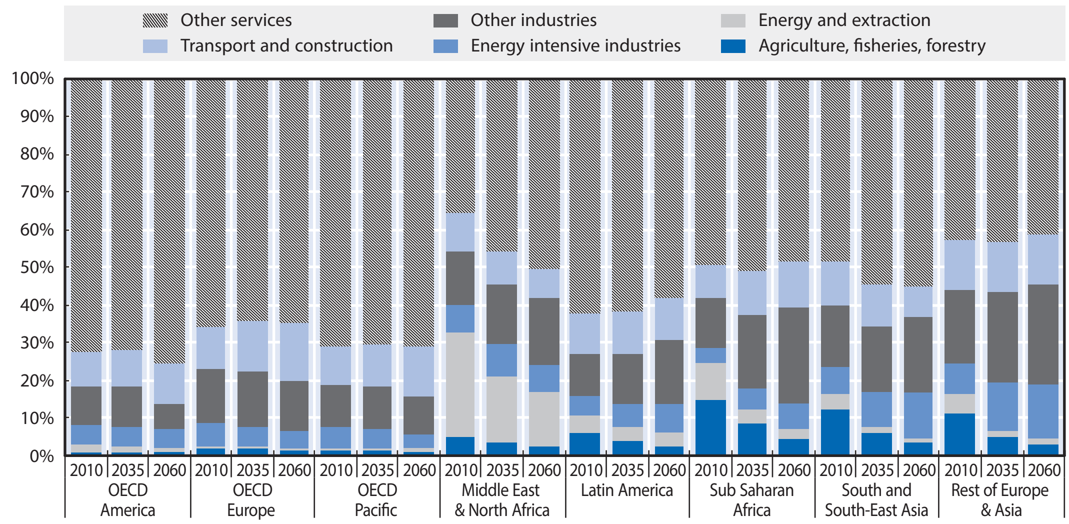
Source: OECD (2014) for OECD countries and ENV-Linkages model for non-OECD economies.

Figure 3.2. **Sectoral composition of GDP by region, no-feedback projection**

Percentage of GDP, 2010, 2035 and 2060



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Source: ENV-Linkages model.

The major oil exporters in the Middle East and Northern Africa are projected to gradually diversify their economies and rely less on energy resources. In developing countries the decline of the importance of agriculture is projected to continue strongly. Given the high growth rates in many of these economies, this does not mean an absolute decline of agricultural production, but rather an industrialisation process, and, in many cases, a strong increase in services. Energy and extraction increases especially in the South and South-East Asia and Rest of Europe and Asia regions, reflecting a higher reliance on fossil fuels and a strong increase in electricity use. This has significant consequences for emissions of air pollutants.

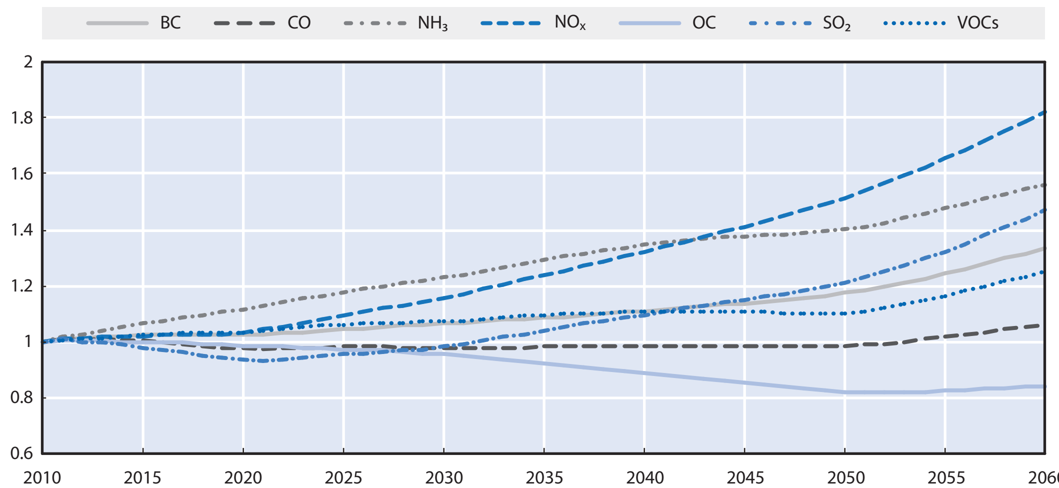
3.2. Projections of air pollutant emissions

For most air pollutants, emissions are projected to increase in the coming decades, as illustrated in Figure 3.3. Rising emissions reflect the underlying baseline assumptions on economic growth, as presented in Section 3.1. With increasing GDP and energy demand, especially in some fast growing economies such as India and China, emissions of air pollutants rise at global level.

Emissions of nitrogen oxides (NO_x) and ammonia (NH_3) are projected to have a particularly strong increase, with NO_x emissions almost doubling by 2060. These large changes are due to the projected increase in the demand for agricultural products and energy (incl. transport and power generation) and a rather limited control of NO_x emissions from power plants and industrial boilers in the developing world. Emissions of all other pollutants also increase with the exception of organic carbon (OC). The slight emission decrease for OC corresponds to lower emissions from energy demand from households, which reflects technology improvements in energy efficiency, the use of cleaner fuels, and the switch from biomass in open fire to cleaner energy sources including LPG, ethanol, or enhanced cooking stoves. Interestingly, emissions of sulphur dioxide (SO_2) are projected to initially decrease but increase again after 2030. The initial decline is due to current policies that require flue gas desulphurisation even in several developing countries (primarily in the power sector), but is later offset by the continuing increase in energy demand, which eventually leads to higher emissions.

Figure 3.3. **Emission projections over time**

Index with respect to 2010



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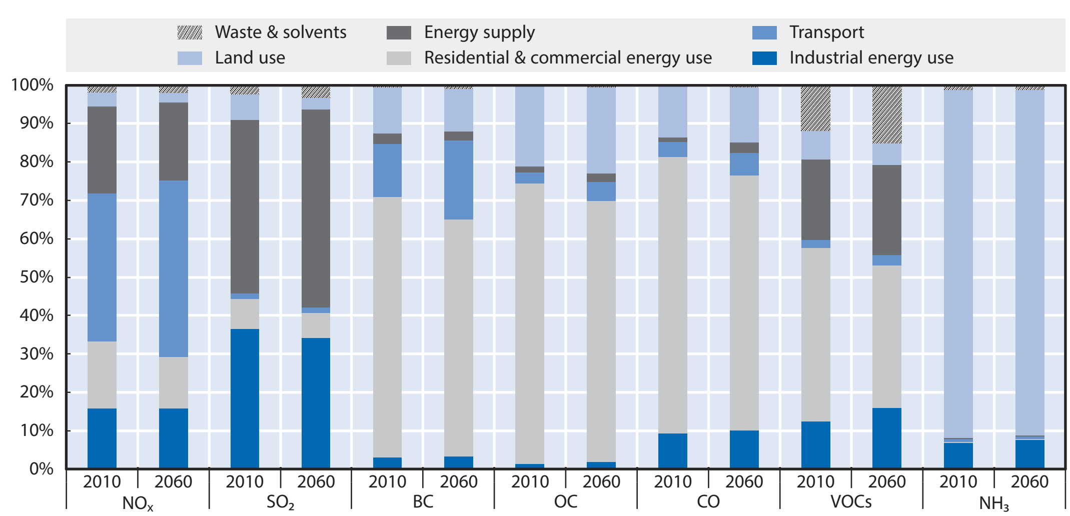
Source: ENV-Linkages model, based on projections of emission factors from the GAINS model.

Each gas has a unique profile of different emission sources, as illustrated in Figure 3.4. The emission sources considered are grouped into energy demand from industrial sectors, from residential and commercial services and from transport, energy supply, land use, and emissions from waste, wastewater treatment, and solvents.

With the exception of emissions of NH_3, which are mostly caused by livestock production and land use with associated application of manures and mineral fertilisers, the energy sector is the main source of air pollutant emissions (IEA, 2016). More specifically, the main emission sources are linked to combustion processes and energy use.

Figure 3.4. **Sectoral shares of emissions**

Percentage of total emissions



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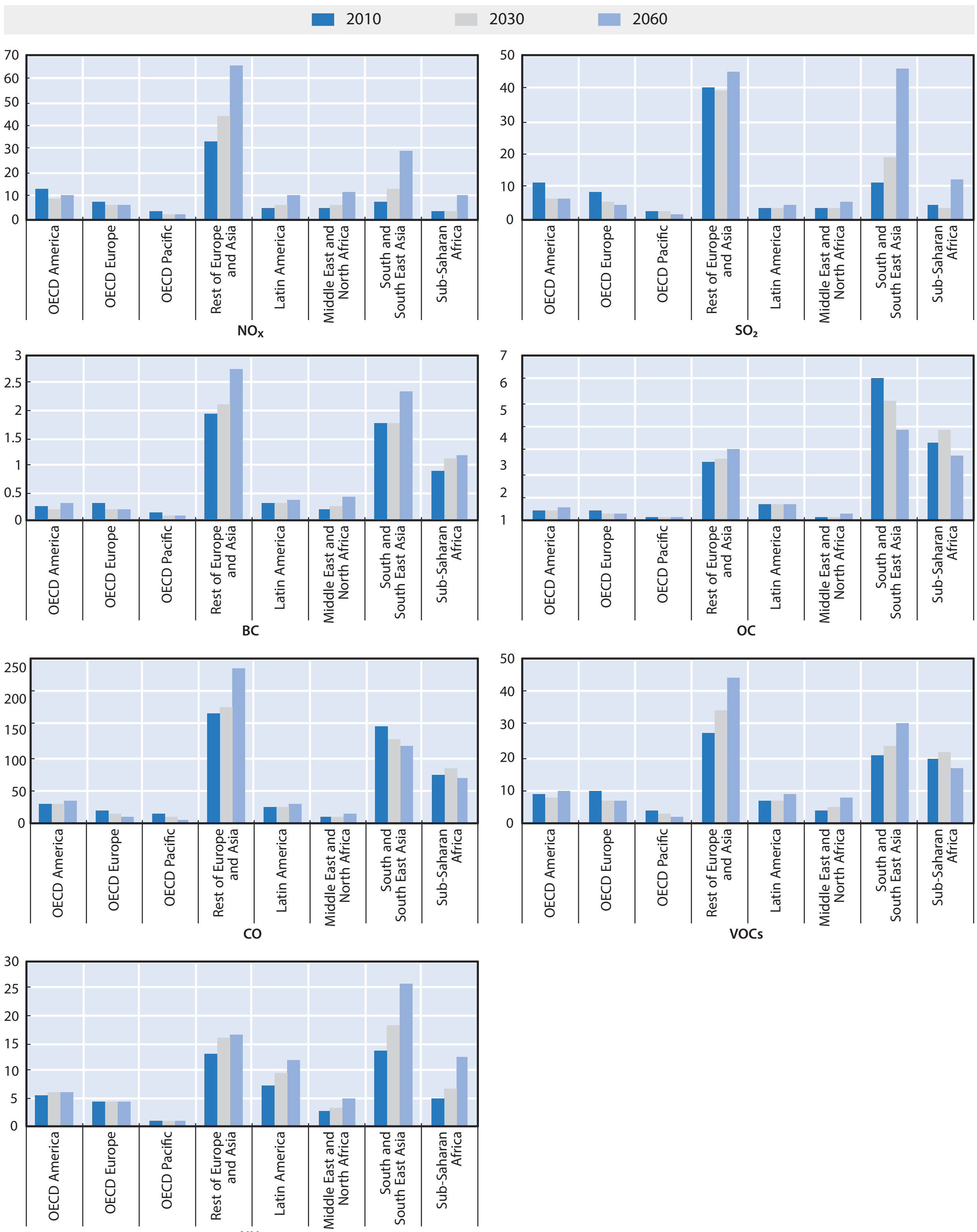
Source: ENV-Linkages model, based on projections of emission factors from the GAINS model.

Figure 3.5. **Emissions by region and by pollutant**

Megatonnes



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Source: ENV-Linkages model, based on projections of emission factors from the GAINS model.

Most emissions of NO_x and SO_2 come from combustion processes in respectively transport and energy supply (power generation). However, the majority of emissions of NO_x originate from transport and industrial sources, whereas emissions of SO_2 are almost completely from industrial sources including power generation. In the United States, for instance, in 2010 a large source of NO_x emissions (around 33%) was road (and rail) transport and around 70% of SO_2 emissions were from coal power plants. Primary sources of black carbon (BC) and OC emissions are caused by the transport sector, which dominates emissions in OECD countries, and by residential and commercial use of solid fuels (cooking and heating in developing countries). Locally, informal industries, such as brick making, and land use, such as open burning of biomass, can be significant sources. Emissions of carbon monoxide (CO) and volatile organic componds (VOCs) stem from all sources, with only a small contribution from energy supply. The largest share of VOCs emissions is from waste and solvents.

While the sources of emissions are largely unchanged over time, they do not all grow at the same rate over time. The contribution of emissions from industrial sources is projected to increase for all pollutants. The contribution of emissions from land use is by contrast projected to decrease.[1] The contribution of emissions from residential and commercial services for CO is projected to remain relatively stable. Emission reductions from the residential sectors, thanks to technological improvements, are offset by higher emissions from transport and industrial energy demand. Finally, emissions from other sources, including waste and solvent use, are projected to increase, especially for OC and VOCs.

There are large differences among countries and regions in emissions of the different pollutants, as illustrated in Figure 3.5. NO_x emissions are particularly high in the Rest of Europe and Asia region (which includes China) but also high in South and South East Asia. Emissions of SO_2 are also high in the Rest of Europe and Asia region for the reference year 2010. However, by 2060 emissions in the South and South East Asia region become equally high. This is mostly due to emissions rapidly rising in India and Indonesia. Emissions of BC and OC, CO and VOCs are highest in Rest of Europe and Asia, South and South East Asia and in Sub-Saharan Africa. Finally, emissions of NH_3 are highest in Rest of Europe and Asia and in South and South East Asia, although they are projected to increase particularly in the South and South East Asia region.

Emissions are generally projected to increase in non-OECD economies, with the highest increases taking place in the South and South East Asia region. The exception to this is emissions of OC and CO that decline in South and South East Asia and Sub-Saharan Africa. This is mostly thanks to improvement in the residential sectors, i.e. access to cleaner energy for households, linked to general megatrends, including urbanisation and electrification. Emissions from OECD countries tend to be stable or to slightly decline, although the projections show a small increase in emissions of all gases but NO_x and SO_2 in the OECD America region.

3.3. Projections of particulate matter and ozone concentrations

With emissions of air pollutants generally rising over time, the concentrations of $PM_{2.5}$ and ozone are also projected to increase in most regions, although, as discussed in Chapter 2, climatic conditions and several other factors influence concentrations. The maps in Figure 3.6 illustrate the annual average of anthropogenic $PM_{2.5}$ concentrations in the reference year (2010) as well as in the projected years 2030 and 2060 (maps for overall emissions, including the natural components of dust and sea salt, are presented in the right panels). In the reference year, $PM_{2.5}$ concentrations are highest in South and East Asia, and particularly in China and India. They are also high in some areas of North America, Europe and Africa. According to the projections, the average concentrations will increase significantly in South and East Asia, as well in some areas of Africa. Concentrations are projected to slightly decrease in North America and Europe.

The projections of average $PM_{2.5}$ concentrations show that several areas are already well above the reference levels recommended by the WHO air quality guidelines (WHO, 2006) (see Box 3.1). The WHO guidelines recommend annual mean concentrations below 10 $\mu g/m^3$ but also specify interim targets that reflect achievable levels with abatement measures. The highest interim target is set at 35 $\mu g/m^3$ and is estimated to correspond to 15% higher long-term mortality risk relative to the recommended target.

The WHO guideline level of 10 $\mu g/m^3$ should not be interpreted as a cut-off point below which there are no health impacts. The epidemiological literature is not yet grounded on a reached consensus on what happens at low concentration levels. Recent literature, e.g. Shi et al. (2016), suggests that there is no lower cut-off level regarding impacts, and even concentration levels below 10 $\mu g/m^3$ may lead to health impacts. The calculations of the health impacts in this report do not include a cut-off point and allow for impacts also at lower concentration levels. Nevertheless, the WHO guidelines provide an insightful reference point to shed light on the severity of the outdoor air pollution problem.

Box 3.1. **WHO global air quality guidelines**

The WHO global air quality guidelines (WHO, 2006), specify target levels for concentrations of particulate matter (both PM_{10} and $PM_{2.5}$) and ozone concerning the health impacts associated with each of the targets. The guidelines are useful in identifying levels of concentrations that do not lead to low effects on human health. Table 3.1 summarises the characteristics of the guidelines and targets for $PM_{2.5}$ and ozone.

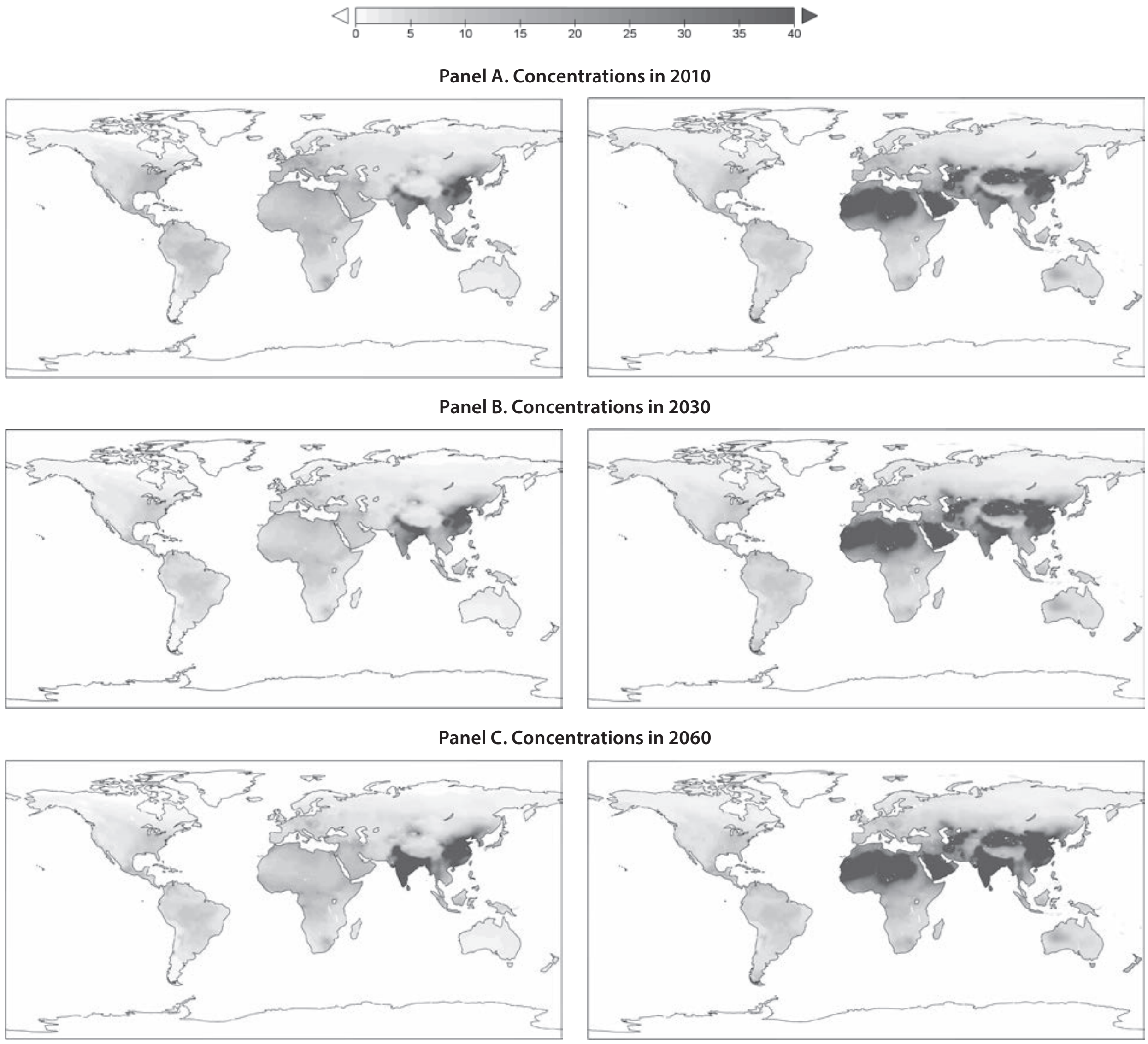
Table 3.1. **Targets specified in the WHO air quality guidelines**

Targets		Basis for selected level
$PM_{2.5}$ (Annual mean $PM_{2.5}$, $\mu g/m^3$)		
Interim target 1	35	About a 15% higher long-term mortality risk relative to guideline level.
Interim target 2	25	In addition to other health benefits, these levels lower the risk of premature mortality by 2-11% relative to the Interim target 1 level.
Interim target 3	15	In addition to other health benefits, these levels reduce the mortality risk by 2-11% relative to the interim target 2.
Air quality guideline	10	These are the lowest levels at which mortality due to long-term exposure to $PM_{2.5}$ has been shown to increase with more than 95% confidence.
Ozone (Daily maximum 8-hour mean, $\mu g/m^3$)		
High levels	240	Significant health effects; substantial proportion of vulnerable populations affected.
Interim target 1	160	Important health effects; does not provide adequate protection of public health.
Air quality guideline	100	Provides adequate protection of public health, though some health effects may occur below this level.

Source: WHO (2006).

Figure 3.6. **Particulate matter concentrations**

Annual average total $PM_{2.5}$; anthropogenic on left panels and total on right panels, $\mu g/m^3$



Note: The maps are based on concentrations specified at a 1°×1° resolution.

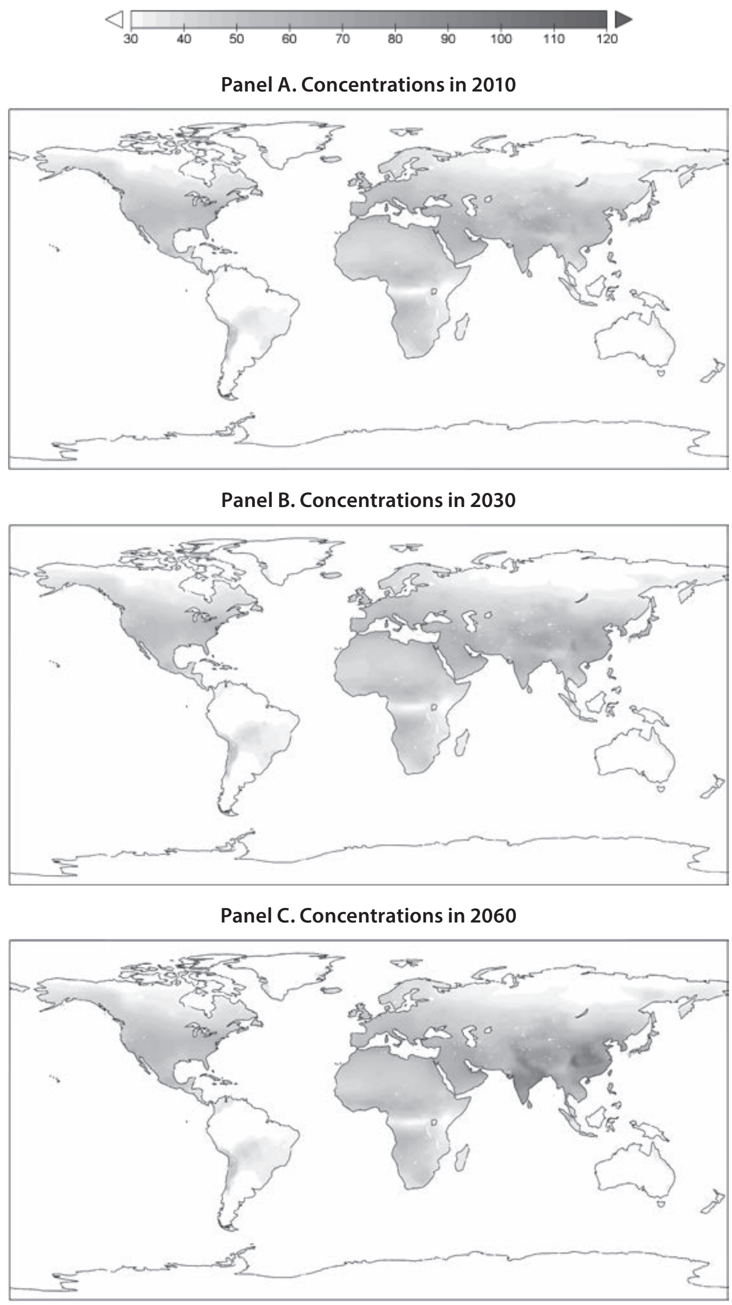
Source: TM5-FASST model, based on projections of emissions from the ENV-Linkages model.

As illustrated in Figure 3.6, several world regions, and especially China and India, were already above the highest interim target in 2010 and are projected to reach even higher levels by 2060. While the maps in Figure 3.6 show lighter colours for OECD regions, these levels are above the recommended WHO guidelines in most areas, implying that there are still strong impacts on human health and the environment.

Less than 4 people out of 10 around the globe live in areas that respect the levels of $PM_{2.5}$ concentrations recommended by the WHO Air quality Guidelines (10 $\mu g/m^3$). Even below this threshold, there may still be impacts on human health. The population exposure also changes over time. The percentage of population exposed to annual mean concentrations of $PM_{2.5}$ higher than 35 μg/m³ is estimated to be 15% in 2010, while it is projected to increase to 30% by 2060. The increase is even higher in China and India where emissions and concentrations increase the most. In China the percentage of population exposed to annual mean concentrations of $PM_{2.5}$ higher than 35 μg/m³ is projected to

Figure 3.7. **Ozone concentrations**

Maximal 6-month mean of daily maximal hourly ozone, M6M, in ppb



Note: The maps are based on concentrations specified at a 1°×1° resolution.

Source: TM5-FASST model, based on projections of emissions from the ENV-Linkages model.

increase from 40% in 2010 to 65% in 2060 while in India from 15% in 2010 to 60% in 2060. While in China the percentage is already currently very high, the worsening of the population exposure is particularly strong in India.

Average concentrations of ground level ozone are presented in Figure 3.7. They are particularly high in parts of Asia (not least Korea), the Middle East and the Mediterranean, but they also exceed air quality guidelines in many other OECD and non-OECD regions. These areas are most affected not only in the reference year but also in the projections at both 2030 and 2060. While there are hardly any changes by 2030, there are some more significant changes by 2060. According to the projections, by 2060, some areas, including parts of the Middle East and Asia (including China and India) could reach very high levels of concentrations (above 120 ppb maximal 6-month mean of daily maximal hourly ozone).

For ozone concentrations, the WHO guidelines recommend levels below 100 ($\mu g/m^3$) daily maximum 8-hour mean, with the highest interim target set at 240 ($\mu g/m^3$) daily maximum 8-hour mean. These are respectively approximately equivalent to 50 and 120 ppb 6-month mean daily maximum levels. As illustrated in the maps, considering average concentrations there are no areas above the highest interim target in 2010. However, by 2060, the projections show that several areas will reach levels above the interim target, especially in China and India. Such high concentrations will lead to significant health effects and environmental impacts, including reductions in crop yields that will affect agricultural output.

For the scope of this report, concentrations of pollutants are only an intermediate step for the calculations of the economic consequences of air pollution. Nevertheless, the average numbers presented are themselves an indicator of the severity of the air pollution problem. High average numbers mean that in many areas – and especially in large cities – air pollution levels are permanently above recommended levels and that there are several days per year where they reach levels that are extremely dangerous for human health. This has already happened in the past years in several cities around the globe, affecting health but also leading to restrictions on human activities. This type of situation is projected to increase in the absence of further policies to reduce air pollutant emissions.

3.4. Projections of the impacts of outdoor air pollution on health and agriculture

3.4.1. Premature deaths

The number of premature deaths due to outdoor air pollution have already been estimated to be high in recent years (see e.g. Lim et al., 2012 and Forouzanfar, 2015), with elderly people and children being most affected (WHO, 2014). The fundamental issue in estimating the number of premature deaths due to air pollution is the shape of the concentration-response function over a wide range of observed concentrations. For the base year 2010, the calculations of premature deaths are based on the Global Burden of Disease work reported by Forouzanfar et al. (2015) for $PM_{2.5}$ and Lim et al. (2012) for ozone. For future projections, the concentration-response function for $PM_{2.5}$ in particular becomes more uncertain as the population-weighted concentrations of $PM_{2.5}$ become much higher in some countries. To reflect this uncertainty two different functions are used for $PM_{2.5}$: *(i)* a linear function showing a simple linear relationship between concentrations and the number of premature deaths adjusted for changes in mortality rates, and *(ii)* a non-linear function, which considers that the incremental number of deaths decreases as concentrations become higher. Annex C outlines in more detail the two different formulations of the concentration-response function.

According to the calculations, premature deaths caused by outdoor air pollution in the reference year 2010 amounted to almost 3 million people globally (in line with the results of Forouzanfar et al., 2015). Premature deaths from outdoor air pollution are projected to reach a global total of 6 to 9 million people in 2060 (considering a non-linear and a linear concentration-response function respectively). This large increase is not only due to higher concentrations of $PM_{2.5}$ and O_3, but also to an increasing and aging population and to urbanisation (which also leads to higher exposure).

High concentrations of $PM_{2.5}$ account for most of the premature deaths. In 2010, PM is linked to around 95% of premature deaths from air pollution at the global level. The contribution of PM to mortality varies across regions. This fraction is lowest in India (89%) and highest in regions such as Canada where PM is responsible for almost all premature

Table 3.2. **Premature deaths from exposure to particulate matter and ozone**

Number of premature deaths caused by outdoor air pollution, thousands of people

		2010	2030		2060	
			Non-linear	Linear	Non-linear	Linear
OECD America	Canada	8	10	10	13	14
	Chile	3	4	4	7	6
	Mexico	14	21	21	42	42
	USA	93	92	99	122	128
OECD Europe	EU large 4	111	97	98	89	95
	Other OECD EU	90	87	84	99	97
	Other OECD	28	37	35	65	64
OECD Pacific	Aus. & New Z.	2	2	3	3	4
	Japan	60	78	76	77	80
	Korea	17	31	30	52	54
Rest of Europe & Asia	China	905	1 374	1 492	2 065	2 711
	Non-OECD EU	33	26	25	23	22
	Russia	119	106	107	93	93
	Caspian region	44	69	69	111	116
	Other Europe	74	57	56	49	49
Latin America	Brazil	36	48	48	73	73
	Other Lat. Am.	38	52	53	87	87
Middle East & North Africa	Middle East	52	85	95	191	229
	North Africa	52	65	62	107	112
South and South-East Asia	ASEAN 9	102	152	155	286	343
	Indonesia	57	80	81	113	116
	India	613	788	926	1 553	3 351
	Other Asia	202	253	253	509	811
Sub-Saharan Africa	South Africa	12	8	9	11	11
	Other Africa	167	178	180	323	334
OECD		*428*	*459*	*460*	*569*	*584*
Non-OECD		*2 505*	*3 339*	*3 610*	*5 593*	*8 459*
World		*2 933*	*3 799*	*4 070*	*6 162*	*9 043*

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Note: Due to the curvature of the functions and rounding, the effects of the non-linear projection can in some cases be reported to be slightly higher than the linear projection; this only affects the results for low and modest concentration levels.

deaths linked to outdoor air pollution. Whilst PM accounts for the highest share of deaths, mortality due to ozone is projected to increase over time as ozone concentrations become higher and more dangerous for human health. By 2060, premature deaths due to ozone are projected to increase to 7-10% of the total. In India, they could account for up to 20%.

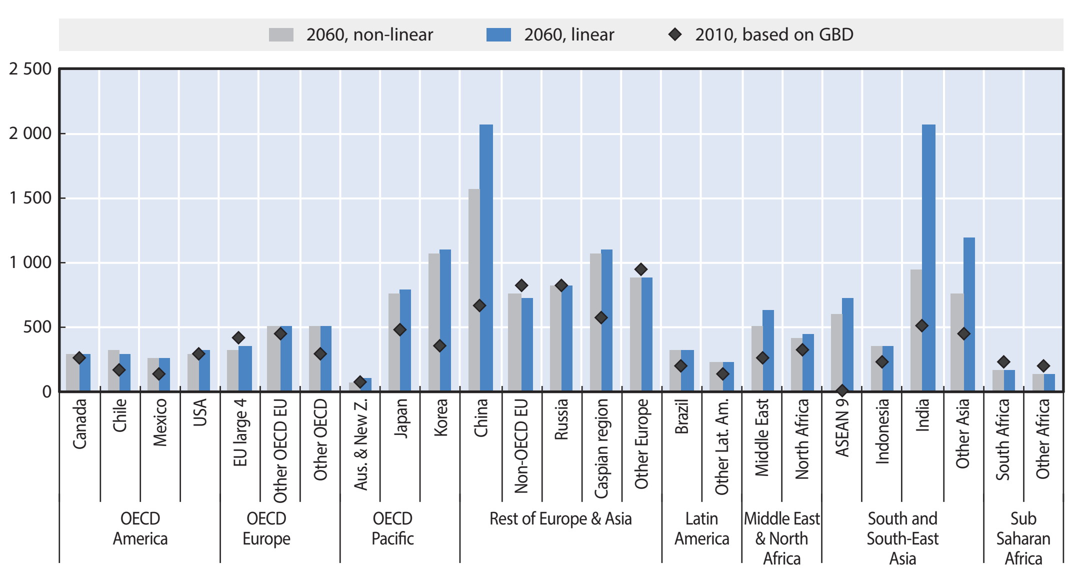
The number of premature deaths is unequally distributed across the world. As illustrated in Table 3.2, the highest number of deaths takes place in non-OECD economies and particularly in China and India. These regions also experience the highest increase in the number of premature deaths to 2060. China's premature deaths account for 31% of the global total in 2010 and for 30-34% in 2060. While China's share of premature deaths is rather stable over time, premature deaths in India increase substantially over time and increase from 21% of the global total in 2010 to 27-35% in 2060. A smaller increase is projected in OECD countries, with the number of premature deaths increasing from around 430 thousand people in 2010 to around 570-580 thousand in 2060. The share of premature deaths caused by outdoor air pollution in OECD countries decreases over time (from 15% of the global total in 2010 to 6-9% in 2060). In particular the share of premature deaths of the United States decreases from 3% of the global total in 2010 to 1-2% in 2060, and from 8% in 2010 to 2-3% for the EU.

The range of projected results in 2060 is larger in some regions than in others. For regions where the increase in concentrations is limited, there is hardly any difference between the results obtained with the two alterative functions. For regions with high increases in concentrations, such as India and China but also South and South East Asia, the range can be quite large. The projected concentrations are larger with the linear function as it considers that premature deaths will continue increasing strongly even with high concentrations of PM.

As already discussed, the increasing number of deaths is partly due to increasing populations, which also lead to a higher number of people being exposed to air pollution. Some of the most affected areas are also highly populated. Nevertheless, even considering the number of premature deaths per million people (Figure 3.8), India and China are projected to have an extremely high number of deaths. Africa, Oceania and Latin America are by contrast the regions with the lowest number of premature deaths per million people.

Figure 3.8. **Premature deaths from exposure to particulate matter and ozone**

Number of deaths caused by outdoor air pollution per year per million people



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3.4.2. Illness

As previously discussed, increasing concentrations of $PM_{2.5}$ and ozone will also lead to a higher number of cases of illness, which will imply more hospital admissions, health expenditures and sick or restricted activity days, which lead to labour productivity losses.

Table 3.3 presents an overview of the health impacts at the global level. The number of cases of bronchitis is projected to increase substantially going from 12 to 36 million new cases per year for children aged 6 to 12, and from 3.5 to 10 million cases for adults.[2] Children are also affected by asthma, with an increasing number of asthma symptom days for children of age 5 to 19.

These increasing cases of illnesses have been translated into an equivalent number of hospital admissions and then into their corresponding healthcare costs (see Annex C). According to the calculations, hospital admissions are projected to increase from 3.6 in 2010 to 11 million in 2060.

The additional cases of illnesses also lead to an impact on normal work activities. In 2060, lost working time at the global level will be of the order of 3.75 billion days. But there will also be an increasing number of (minor) restricted activity days.

While Table 3.3 presents results at the global level, there are regional differences, which reflect the levels of concentrations of pollutants, the exposure in the different areas and the demographic characteristics of the population. The additional health costs associated with these impacts also vary across the world, reflecting the differences in the capacity and financing of the health systems and the average costs of hospital admissions.

As discussed in Section 2.6, the number of additional cases of illness and of hospital admission is used to calculate overall health expenditures using the established unit values for each endpoint. Lost working days are used to calculate labour productivity changes, as described in Section 2.7. Overall additional health expenditures and changes in labour productivity are then used as inputs in the ENV-Linkages model to calculate the related market costs. Results on market costs are presented in Chapter 4.

The results for additional cases of illness, hospital admissions and (minor) restricted activity days are also used to calculate the welfare costs (e.g. related to pain and suffering) by multiplying results for each endpoint with the appropriate unit value, as explained in Section 2.8. These non-market costs will be presented in Chapter 5.

Table 3.3. **Health impacts at global level**

	2010	2060
Respiratory diseases (million number of cases)		
Bronchitis in children aged 6 to 12	12	36
Chronic bronchitis (adults, cases)	3.5	10
Asthma symptom days (million number of days)		
Asthma symptom days (children aged 5 to 19)	118	360
Healthcare costs (million number of admissions)		
Hospital admissions	3.6	11
Restricted activity days (million number of days)		
Lost working days	1 240	3 750
Restricted activity days	4 930	14 900
Minor restricted activity days (asthma symptom days)	630	2 580

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3.4.3. Agricultural yield impacts

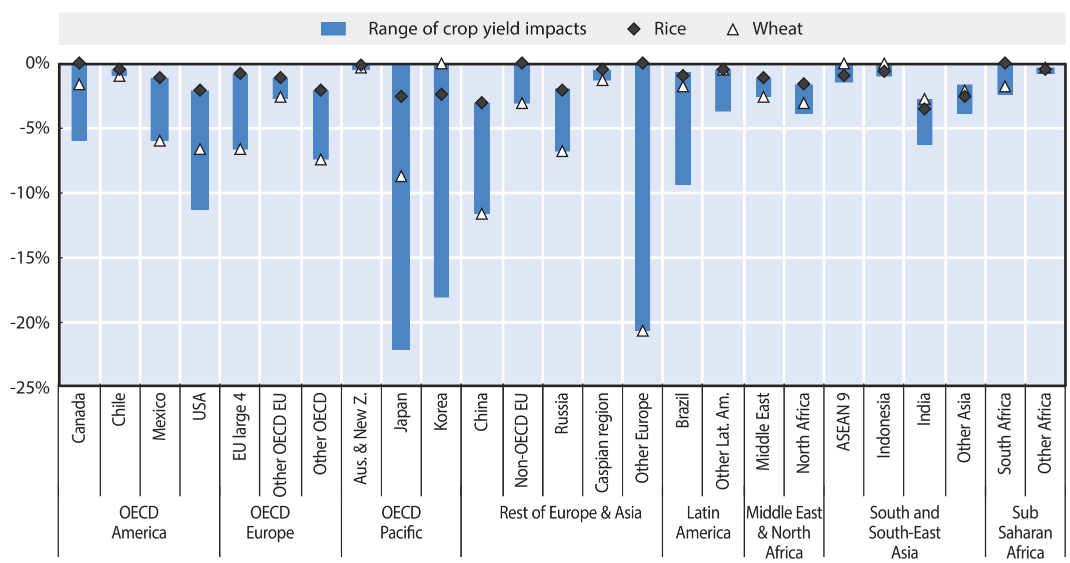
High levels of concentration of pollutants, and particularly of ozone, reduce crop yields and thus affect agricultural productivity. Figure 3.9 presents the crop yield changes by region for 2060, expressed as a percentage change from the no-feedback crop yield projections. The graph presents the full range across different crops, and, separately, impacts on rice and wheat.

According to the TM5-FASST calculations, and in line with the larger literature (e.g. Mills et al., 2007; Chuwah et al., 2015), crop yields are negatively affected in all regions, with big differences between regions and crops. In many regions, wheat and oil seeds are more affected than the other crops, with high losses in several OECD countries, including Japan, Korea and the USA for oilseeds, and China and Other Europe for wheat.

In some regions the effects of outdoor air pollution on crop yields are small. For instance, Chile, the Other OECD and Other Africa regions, Australia and New Zealand, and Indonesia have much smaller impacts than the other regions. The impacts on crop yields are included in the ENV-Linkages model for the assessment of market costs. Results are presented in Chapter 5. The regional differences illustrated can lead to changes in competitiveness so that regions that are less affected can even have economic benefits.

Figure 3.9. **Impacts of outdoor air pollution on crop yields**

Percentage change w.r.t. no-feedback projection, 2060



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Source: Own calculations, based on the TM5-FASST model and Mills et al. (2007).

Notes

1. This may in part be due to the underestimation of emissions from forest, savannah and agricultural burning.

2. Childhood bronchitis and adult bronchitis persist for different periods. The illness in children typically lasts for only about 2 weeks, whereas in adults, bronchitis may be permanent once initiated.

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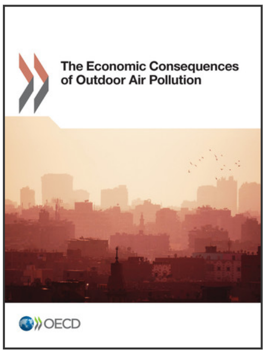

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