EU Resource Efficiency Perspectives in a Global Context

Policy Studies

PBL Netherlands Environmental Assessment Agency

EUROPEAN COMMISSION

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ISBN: 978-92-79-21329-8
doi: 10.2779/70659

ISBN PBL: 978-90-78645-82-5
PBL publication number: 555085001

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Acknowledgements
Nina Graus (Utrecht University) for providing access to the raw data of her PhD thesis on energy efficiency.
The OECD for permission to use the preliminary baseline of the 2012 OECD Environmental Outlook.
Villy Christensen (University of British Columbia, Vancouver) for permission to use their projections of future marine catches and marine depletion.
Mihai Tomescu and his colleagues from the European Commission (DG Environment) and many experts within the PBL, for their constructive comments on earlier versions of this report.

English-language editing
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Production co-ordination
PBL Publishers

Layout
Studio RIVM, Bilthoven

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Summary

Natural resources underpin the functioning of the European and the global economy and critically shape prospects for current and future quality of life. Increasing population and wealth are putting increasing pressure on key resources. The physical, economic and geopolitical accessibility, and the sustainable use of these resources, therefore, are of paramount concern. This study explores the relevance and implications of resource efficiency, an instrumental flagship initiative of the Europe 2020 Strategy.

This study considers five distinct, vitally important resource themes: (i) *Energy*, particularly with regard to scarcity associated with fossil fuels and their key role in climate change; (ii) *land* for agriculture/forestry and terrestrial biodiversity; (iii) *phosphorus*, especially with regard to its irreplaceable role in agricultural production; (iv) *fresh water* with attention to water stress in primary catchment areas; and (v) *fish stocks*. In order to assess the likelihood of problems arising from continued resource use, a global, model-based analysis is provided of the impacts of current and projected resource use up to 2050, in the assumed absence of additional, targeted policies. Subsequently, the report provides evidence of the potential for boosting resource efficiency, in different contexts of global and EU coordination, to determine the options for ambitious policy intervention. Interlinkages are identified between the issues considered and other resource issues. Specific attention is given to possible overlaps and complementarities with climate-change mitigation efforts.

Impacts of current and projected resource use

Looking a few decades ahead, there is ample justification for increasing global concerns in the areas included in the resource efficiency initiative. The model projections suggest, for example, that in the absence of additional targeted policies:

- Global annual energy demand will increase by almost 80% between 2010 and 2050, with 90% of the demand growth in developing and emerging countries. The share of fossil fuels in the total energy demand is projected to remain large (close to 80%). Targets for greenhouse gas emissions will be a long way from being met.
- Increase in agricultural productivity will lag behind increase in food demand, resulting in further expansion in land use for agricultural production in developing countries, notably in Africa and especially up to 2030. This would lead to substantial loss of nature and biodiversity and associated ecosystem services.
- Global annual use of phosphorus fertilisers will increase by 40% up to 2050. Although immediate scarcity of phosphorus in physical terms is unlikely, extraction of this irreplaceable non-renewable resource will concentrate more and more in northern Africa.
- The number of people living in areas affected by severe water stress[1] is projected to increase to 3.9 billion by 2050 (from 1.6 billion in 2000). Most of this increase will take place in South Asia.
- Commercially attractive fish stocks will continue to decline with some functional groups (of similar size and with similar feeding and habitat characteristics) approaching depletion.

Potential for enhanced resource efficiency

There is substantial potential to improve efficiency in the use of the resources analysed. Our analyses indicate that, with ambitious global efforts:

- The increase in global annual energy use between 2010 and 2050 could be limited to less than 25%. For greenhouse gas emissions, this would halve the gap between the situation of unchanged policy and the 450 ppm CO_2 eq mitigation scenario. This assumes accelerated adoption of best available technologies in industry, new buildings, household appliances, power and transport sectors. Further reduction in energy use than studied here is likely to require significant changes in consumer behaviour.
- Net global agricultural expansion between 2010 and 2050 may be halted, with expansion in Africa reduced by half, by improving the efficiency of agricultural production, consumption and food supply chains. Most industrialised countries and emerging economies would see a net reduction in their agricultural areas, after 2020.
- The global increase, up to 2050, in the use of phosphorus fertilisers from primary sources could be limited to 11%; mainly by making better use of manure and by recycling phosphorus from human excreta. Additional phosphorus savings could be achieved by improving animal feed and by banning the use of phosphorus in detergents.
- Globally, water efficiency, in all sectors combined, could be improved by 25%.
- Fish stocks may recover and marine biodiversity may improve, thus, sustaining higher catches in the long term, following a temporary reduction in fishing efforts.

Although these potential improvements are substantial, complementary measures will be needed to curb negative trends. To accomplish biodiversity goals, for example, in addition to halting the expansion of agricultural land, other pressures, such as from fragmentation and nitrogen compounds, also need to be addressed. The situation regarding fresh water appears to be most alarming. The efficiency gains will not be sufficient to offset the effects of strong population growth in water stressed river basins. As a consequence, some 3.7 billion people will still be living in areas affected by severe water stress by 2050.

Interactions and overlaps

The potentials for ambitious improvements that would lead to a more efficient use of the five resources in focus are interrelated, and our analysis revealed many synergies. However, there are also some trade-offs, such as additional amounts of water and fertilisers needed to sustain improved crop productivity, and the consequences of reduced deforestation when agricultural expansion is reduced. The latter may lead to an increase in forestry and logging activities in the existing forests, which would also add to the process of forest degradation. There is also a risk that an overly strong focus on short-term efficiency of marketed resources, for example, in intensive animal production, could jeopardise resilience in the long term.

With respect to the linkages with the current ambitions of EU energy and climate policies, this study indicates that the two policy strands are generally well in line. An exception is the production of bio-energy crops to accomplish climate goals, which could substantially reduce the potential resource efficiency gains regarding land use (-40%) and phosphorus fertilisers (-30%). Furthermore, specific decarbonisation of the energy supply remains a cornerstone of ambitious climate targets.

Without going into concrete policy options, this analysis confirms that ambitiously improving EU resource efficiency relates to numerous Commission portfolios, including those on the Environment, Research and Innovation, Agriculture, Fisheries, Energy, Climate, Development, and Transport.

The challenge of finding EU-wide goals for resource efficiency

The EU resource efficiency initiative appears to be multi-faceted and interconnected in terms of temporal and spatial scales, actors and institutions. Sustainable development requires that resource efficiency improvements are applied ambitiously, consistently and fully. This would go beyond mere adjustment of production technologies to include consumption incentives, behaviour and institutions. Rather than a goal in itself, resource efficiency should be regarded as an essential means to achieve sustainability goals.

This suggests that an overarching vision for the EU resource efficiency initiative may be easier framed in political-cultural terms ('the European way of managing resources') than in terms of physical indicators and targets. The role of governments in establishing international agreements, targets, policies and measures could be complementary to a role in more distributed initiatives by the private sector and supply-chain arrangements.

Priority issues for in-depth studies with specialised approaches

A number of issues emerged from our analysis as relevant for follow-up. We have recorded these without claiming to be comprehensive and without prioritisation. Many land-related issues were identified including efficiency of water management in agriculture worldwide and in areas of Europe, such as the Mediterranean; agricultural research aimed at land productivity; and large and influential uncertainties in future forest exploitation and wood demand. Major research issues will be the effectiveness of policy measures to enhance resource efficiency, including corporate social responsibility initiatives where stakeholders in the supply chain work together with NGOs, with or without government involvement; and the design and evaluation of coherent policy strategies that embrace the environment portfolio together with those on other subjects.

Main findings

This study explores in a fast-track mode the relevance and implications of resource efficiency, a flagship initiative of the Europe 2020 Strategy. The background is the European Commission's wish to address concerns about rising pressure on resources and to explore new ways of smart, sustainable and inclusive growth. In addition, opportunities and obstacles were considered for policies to achieve the benefits of boosting resource efficiency.

The key questions addressed are:
1. What are the impacts of current and projected resource use up to 2050 and in which parts of the world will they be felt most? What challenges do we face?
2. What are the potential effects of boosting resource efficiency in different contexts of global or regional co-ordination? Is policy intervention conceivable?
3. How would such interventions interact with other resources not targeted? Are there synergies and trade-offs, and how does resource efficiency relate to efforts to mitigate climate change?

These questions were examined for five resource themes:
- Energy, particularly with regard to the key role of fossil fuel combustion in climate change and scarcity associated with fossil fuels.
- Land, with attention to terrestrial biodiversity and the increasingly competing demands for land for the production of food, feed, fuel and forestry products.
- Phosphorus, especially with regard to its irreplaceable role in agricultural production, and the finite resource base with reserves concentrated in a few countries.
- Fresh water, with attention to water stress in primary catchment areas as affected by changes in demand and supply as a consequence of climate change and population pressure.
- Fish stocks, with attention to increasing demands for fishery products and rapidly depleting stocks.

The work centres on global, model-based analysis of the impacts of current and projected resource use up to 2050. The scarcity dimensions for each theme are summarised in Table 1. The set up and approach of the study, and its scope and limitations are outlined in Box 1.

The main findings of investigating the three key questions for the five resource themes are presented below. An overview of results in terms of projected changes in key indicators is given in Table 4. For each of the themes, more detailed background information is provided in the following chapters.

Q.1 What are the impacts of current and projected resource use, and where will they be felt most?

Looking a few decades ahead, there is ample justification for increasing global concerns in the areas included in the EU resource efficiency initiative. Although the greatest impacts are projected to occur outside the EU, especially in developing countries, serious direct and indirect consequences in the EU can also be expected. According to model projections in the absence of additional targeted policies:

Energy

Global primary energy demand[3] would increase by almost 80%: from just over 500 EJ/yr in 2010 to around 900 EJ/yr by 2050 (Figure 1, left). Final energy demand[4] would increase by almost 70% over the same period (from around 320 EJ/yr to 560 EJ/yr). Almost the entire increase in demand in the next 40 years would come from developing and emerging countries, accounting for 90% of the total. Even so, the per capita energy consumption will still be 2.5 times higher in OECD countries, by 2050, than in the rest of the world. Total energy demand would only be slightly reduced in a scenario of policies continued in line with those envisaged by the EU (see Table 2) as compared to the 'no new policies' *baseline* scenario (Figure 1, first two graphs on the left).

The share of fossil fuels in total primary energy use would remain large; remaining close to 80% in the *baseline*, while gradually decreasing to 70% in the *envisaged policies* scenario. As a consequence, greenhouse gas emissions will continue to rise. This also implies that the emission reductions needed to achieve the 2 °C global climate target by no means will be met.

EU dependency on fossil fuel imports would rise; for oil from 64% in 2010 to over 90% by 2040.

Land for agriculture/forestry and terrestrial biodiversity

The agricultural area would expand extensively in developing countries. Most of the expansion would occur in Africa especially up until 2030, leading to substantial loss of nature and biodiversity.

In most other regions including the EU, the agricultural area would slowly contract after 2020, but overall, terrestrial biodiversity would continuously decline as a consequence of continued pressure from forest exploitation and the effects of fragmentation, climate change and reactive nitrogen emissions.

Phosphorus

Phosphorus required in agriculture would increase by some 40% between 2010 and 2050. Phosphorus is an essential plant nutrient. The projected increase in phosphorus use is

Table 1
Scarcity dimensions of the themes addressed in this study

Physical	Economic	Political
Fossil energy		
Increased pressure on remaining fossil resources due to rising energy demand.	Exploitation and processing become increasingly costly; capacities lagging behind. Improperly functioning markets, resulting in strong price fluctuations. Underinvestment in production and refining capacity.	Concentration of available resources in a limited number of countries. Competition between OECD countries and emerging economies over remaining fossil reserves. Transboundary conflicts related to ownership of resources and conveyance systems (e.g., pipelines).
Land for agriculture/forestry and terrestrial biodiversity		
Competing claims on land for provisioning ecosystem services (food, feed, fibre, fuels and forestry products), leading to deterioration of regulating, cultural and supporting services, including loss of biodiversity and of agricultural land quality.	Improperly functioning land markets. Some land uses (e.g., for bio-energy) are in most cases still) not economically viable without strong government support.	High food prices leading to social instability; especially in low income countries. Scrambling for land (including by foreign states and investment funds). Implications for nature and/or food production, of imports (e.g., feed crops, biofuels) from other countries.
Phosphorus (P)		
Rising demands on finite resources, for which no alternative exists for agricultural production. Soil phosphorus depletion in many developing countries, causing soil degradation and productivity loss; one of the causes of deforestation. Eutrophication of surface waters.	High costs to restore phosphorus depleted soils. High prices for phosphorus fertiliser affects phosphorus use in developing countries.	Concentration of available resources in a few countries (the EU is almost completely dependent on imports). Agricultural expansion and intensification expected in developing countries, where high phosphorus fertiliser inputs are required to sustain yields.
Fresh water		
Increasing demand leading to increased pressure on freshwater resources. Adverse impacts of climate change could decrease resources availability.	Non-existent or improperly functioning markets and/or lack of infrastructure limit access to safe water, particularly for the poorest in developing countries. High cost of maintaining existing infrastructure and improving (inefficient) out-dated infrastructure.	Conflicts between parties in transboundary river basins limit access to water for downstream users. Sense of unfair competition between farmers who are subject to water pricing and those that are not.
Fish		
Rapidly depleting stocks of commercially exploitable fish species.	Increasing prices to consumers. High costs, including for fuel use, due to increasing efforts in fisheries (deeper, wider nets, larger distances). Fisheries sectors in jeopardy.	Disputes over fishing rights. Artisanal fisheries in developing countries harmed by industrial exploitation by fleets from other countries. Disputes over need (or not) to limit or ban fishing of certain species.

Based on Prins *et al.* (2011), and further elaborated in this study.

Box 1 Approach, scope and limitations of the study

The study has a global scope from an EU perspective with a time horizon up to 2050. It consists of a quantitative scenario analysis complemented by a qualitative analysis to provide the broader policy context.
The quantitative analysis was performed on six scenarios comprising various combinations with or without policy action on resource efficiency (RE) in a context with or without policy action on climate change in the EU, or globally. An overview of the scenarios is presented in Table 2. The baseline used is a preliminary version of the baseline currently being developed for the 2012 OECD Environmental Outlook, providing a context of socio-economic indicators. Assumptions for the resource efficiency scenarios are deemed to represent ambitious yet realistic developments, and are based on literature findings whenever possible.
The focus was on those aspects considered most important, and pragmatic choices were made regarding the analysis of the questions formulated. In each scenario, for example, all five resources are targeted simultaneously. Although this allows comprehensive analysis of the potential of the RE concept, and captures synergies and trade-offs, it inevitably limits the attribution of observed outcomes to the different resources. Furthermore, major disruptions could not be analysed and rebound effects could only partially be taken into accounted.
Some scenario assumptions are quite artificial, particularly for those scenarios that presume strong unilateral EU-level policy action while the rest of the world continues with 'business as usual'. Therefore, most results for these scenarios must be considered as crude indications.
Another inevitable limitation of the study is that only five resource themes were analysed. They were selected on the basis of (i) their importance as key resources; (ii) their distinctness; (iii) the availability of expertise and instruments to address them; and (iv) their link with the GLIMP study[2], also conducted by PBL, thus providing potential for synergies with that project. As a consequence, some resources receiving prominent public and policy attention, such as rare metals, could not be addressed.
Finally, the analysis took account of many interrelationships between themes and direct and indirect effects on numerous impact indicators. However, an economic analysis of impacts on GDP or other economic effects was not conducted beyond estimates of the direct effects of resource savings and/or the avoidance of greenhouse gas emissions and other quantifiable externalities considered by the models.
In spite of these restrictions, the conclusions reached by combining and cross-comparing the results of the quantitative scenarios with the insights from formerly published work are believed to be robust.

particularly high in developing countries where soils are currently strongly depleted of phosphorus.

Rapid depletion of rock phosphate is unlikely. However, in the very long term (200 to 300 years), phosphate resources that can be exploited with current technologies are likely to be depleted. As there is no substitute for phosphorus and resources are non-renewable, this could still be regarded as a long-term sustainability risk.

Primary production will increasingly concentrate in northern Africa. In addition to risks to supply (Figure 3), production costs are also likely to rise.

Fresh water

The number of people living in areas affected by severe water stress is projected to increase from 1.6 billion in 2000 to 3.9 billion by 2050. Most of this increase will take place in South Asia. The dominant cause is population growth in already water-stressed river basins.

Withdrawals of fresh water are bound to increase mostly for domestic, industrial and power production purposes. Freshwater demand for these purposes is projected to outweigh irrigation demands, which currently account for two thirds of total demand.

Fish stocks

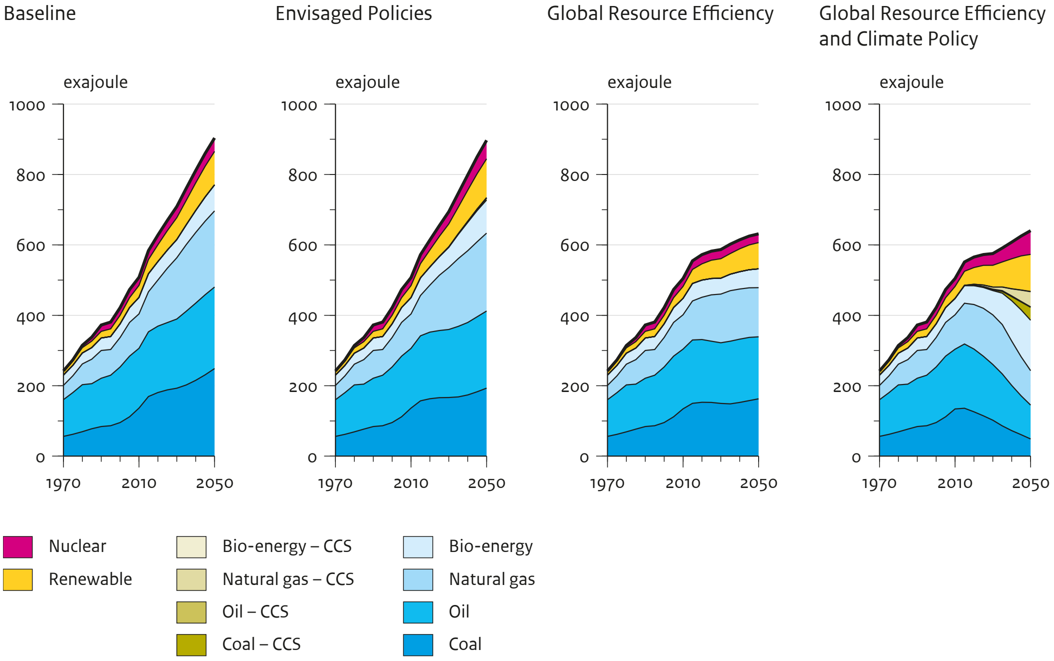
Commercially attractive fish stocks will continue to decline. Some functional groups would approach depletion in several fishing regions.

Aquaculture is projected to expand greatly, because the growing demand cannot be met by wild catch fisheries only. However, aquafeed is currently contributing to fish depletion, whereas crop-based aquafeed requires agricultural land.

Q.2 What are the potential effects of boosting resource efficiency in different contexts of global or regional co-ordination? Is policy intervention conceivable?

There is substantial potential to improve efficiency in the use of the resources analysed. According to our calculations, ambitious global efforts compared to policies continued in line with those envisaged by the EU (Table 2) could accomplish the following:

Figure 1
Global primary energy use per energy carrier



Source: PBL

Enhanced energy efficiency would break the rising trend in energy consumption. It would significantly help to mitigate climate change, but additional decarbonisation of the energy supply after 2030 would be needed to achieve the 2 °C target.

Energy

Global annual energy use may be reduced by around 30% by 2050 (Figure 1). This assumes accelerated adoption of energy efficiency in industry, new buildings, household appliances, power and transport sectors according to best available technologies. Major changes in consumer habits were not taken into account.

This efficiency improvement would lead to very substantial cuts in greenhouse gas emissions, closing about 50% of the gap between baseline emissions and those in the 450 ppm CO_2 eq mitigation scenario that corresponds to the 2 °C target. To fully realise the 450 ppm CO_2 eq scenario, energy efficiency improvements would require an additional strong shift to non-fossil renewables (including bio-energy) and nuclear energy, reduction in non-CO_2 gas emissions and use of carbon capture and storage. In the *global resource efficiency and climate policy* scenario (Figure 1, right), this was modelled on the basis of price signals, by introducing a carbon tax as a generic measure of climate policy.

The efficiency improvements would reduce EU dependency on fossil-fuel imports and lead to a slow down in the trend of depleting fossil fuel reserves, particularly of oil. Further introduction of climate policy may strengthen this effect, except for bio-energy imports that would increase.

Land for agriculture/forestry and terrestrial biodiversity

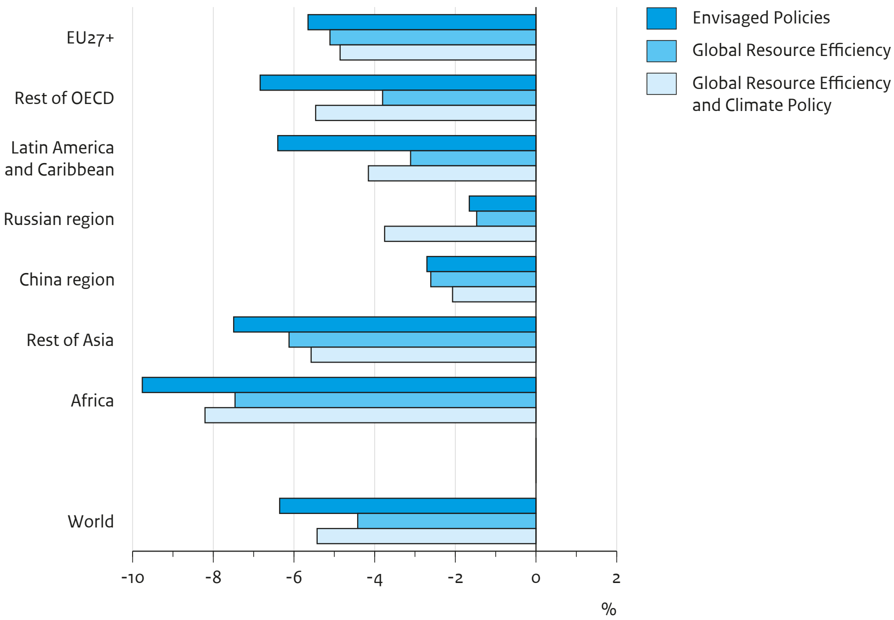
Agricultural expansion can be halted; after 2040 also in Africa. This would require ambitious global action to improve the efficiency of agricultural production, consumption and food supply chains. Food supply would also improve by these measures. However, such resource efficiency actions alone would not suffice to halt the increase in pressure on land resources and biodiversity loss if other pressures, such as reactive nitrogen emissions, climate change and forest exploitation remain unchecked.

Plantation forests could have a long-term beneficial effect on land resources and global biodiversity. Thus, expansion of forest plantations could be part of a resource efficiency strategy. However, the short-term effect is negative, because plantation establishment leads to additional land-use, while these forests will only deliver wood after decades of growth.

Deployment of bio-energy in strategies for climate-change mitigations puts additional stress on biodiversity. Overall, within the time-horizon of this study, the positive effects of

Figure 2

Net change in Mean Species Abundance, 2010 – 2050



Source: PBL

In the envisaged policies scenario between 2010 and 2050, the MSA biodiversity indicator presents a negative net change in all world regions. Africa is most seriously affected mainly because of agricultural expansion. The main causes of MSA decline in other regions are forest exploitation, climate change and fragmentation. In the global resource efficiency scenario, the decline in MSA is much less pronounced, mainly because of contraction or less expansion in agricultural land use. In the global resource efficiency and climate policy scenario, bio-energy crops put an additional constraint on MSA.

climate-change mitigation on biodiversity (as indicated by the MSA indicator) are offset by the negative effects of bio-energy crops that are deployed as part of the strategy, resulting in a net reduction of the MSA biodiversity indicator (Figure 2).

Phosphorus

The combined strategies for resource efficiency could reduce global phosphorus fertiliser use from primary sources by 22% by 2050, compared to envisaged policies. In EU27+, this reduction could amount to 32%. Strategies to improve phosphorus efficiency would address the scarcity issue as well as the negative environmental effects related to inefficient use. Most of the savings in phosphorus use from primary sources could be achieved by a better integration of animal manure in crop production systems, and by recycling phosphorus from human excreta. Improving animal feed, recycling P from biomass, and reduction in phosphorus use in detergents could further reduce phosphorus demand.

The case of phosphorus also reveals trade-offs. Resource efficiency policies that aim to improve land-use efficiency would seek to increase agricultural yields in developing countries. This would also increase phosphorous use, because in many of these countries, fertilizer inputs are currently too low to sustain agricultural production over longer periods. Furthermore, the additional use of bio-energy crops in policies on climate-change mitigation would substantially reduce the gains from efficiency improvements in phosphorus use.

Fresh water

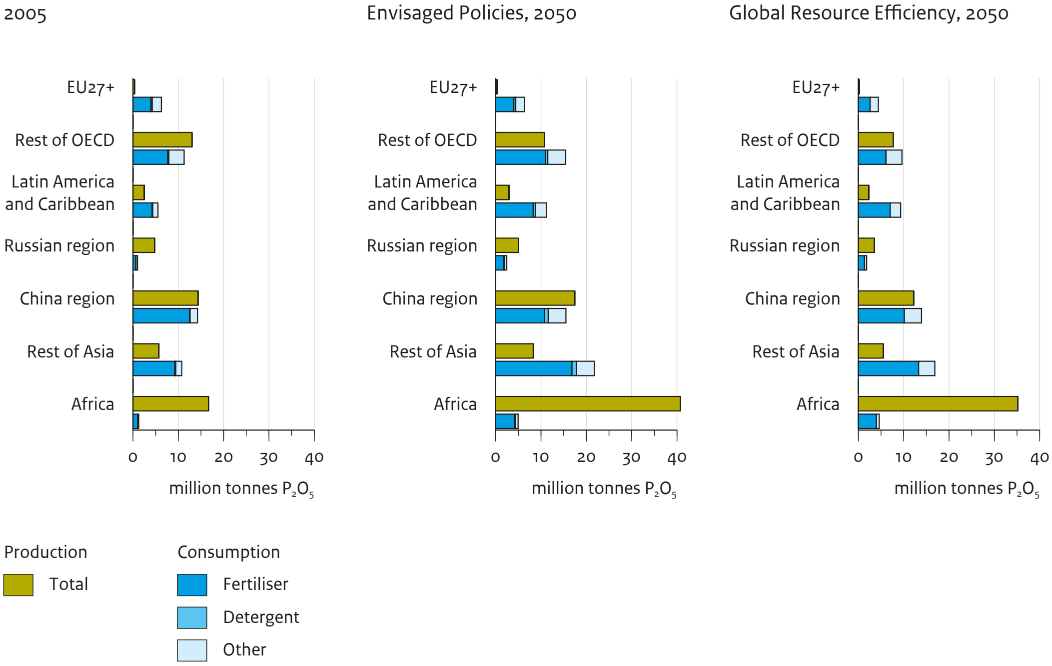
In all sectors and for all applications, significant water efficiency improvements may be achieved. Such improvement could reduce water withdrawals by some 25% by 2050, compared to the baseline.

Although this would mitigate water stress in all major river basins, it would hardly reduce the number of people living under severe water stress conditions: 3.7 billion people would still be living in areas affected by severe water stress by 2050 (Figure 4). This underlines that population growth in already water-stressed river basins is the dominant factor for this phenomenon. Matching the balance between demand and supply also coping with seasonal and inter-annual variations will continue to require improvements

Table 2
Overview of the scenarios

		Policy action targeting		Questions addressed in this study			
Scenario	**Abbreviation**	**Resource efficiency**	**Climate change**	*Problem with natural resources? Why? Where in the world?*	*How large potential for RE policies? Implications where in the world?*	*Can RE policies and CC policies mutually benefit?*	*Will problems remain under envisaged climate policies? Where in the world?*
Baseline	BL	None, beyond autonomous development	None beyond current formally enacted commitments	X	X		X
Envisaged policies	ENVISAG	Same as in BL	Current EU policies fully implemented and continued beyond 2020; low Copenhagen pledges continued beyond 2020 elsewhere				X
EU resource efficiency	E-RE	Ambitious, in EU only	Same as in ENVISAG		X	X	
Global resource efficiency	G-RE	Ambitious, worldwide	Same as in ENVISAG		X	X	
EU resource efficiency and climate policy	E-RE-CP	Ambitious, in EU only	Ambitious, in EU only; same as ENVISAG elsewhere			X	
Global resource efficiency and climate policy	G-RE-CP	Ambitious, worldwide	Ambitious, worldwide			X	

Figure 3
Production and use of phosphorus-based products



Source: PBL

The EU and several other world regions heavily depend on imports to meet phosphorus demand. Africa dominates the export market, with vast reserves in northern Africa and relatively limited own consumption. The combined phosphorus efficiency strategies would reduce extraction from primary sources by almost 25%, globally, by 2050, but this still implies an increase from the current level of extraction.

in integrated water management practices. Adequate pricing and other measures to provide incentives for more efficient use of freshwater resources would be important instruments.

Fish stocks

Stocks would recover and marine biodiversity improve. This would require a concerted, temporary and gradual reduction in fishing efforts.

In the long term, higher catches would be sustained without increasing efforts (Figure 5). However, fleet capacities would remain well above the level for sustainable catches, and will thus need to be reorganised.

Less land would be needed to produce feed for aquaculture (up to 18% compared to baseline, by 2050). Aquaculture would still expand substantially. However, with recovery of oceanic fish stocks, demand for aquaculture would rise less steeply than under current fisheries practices. Hence, fewer resources would be needed to supply feed for aquaculture, and both marine and terrestrial biodiversity would benefit from resource efficiency policies.

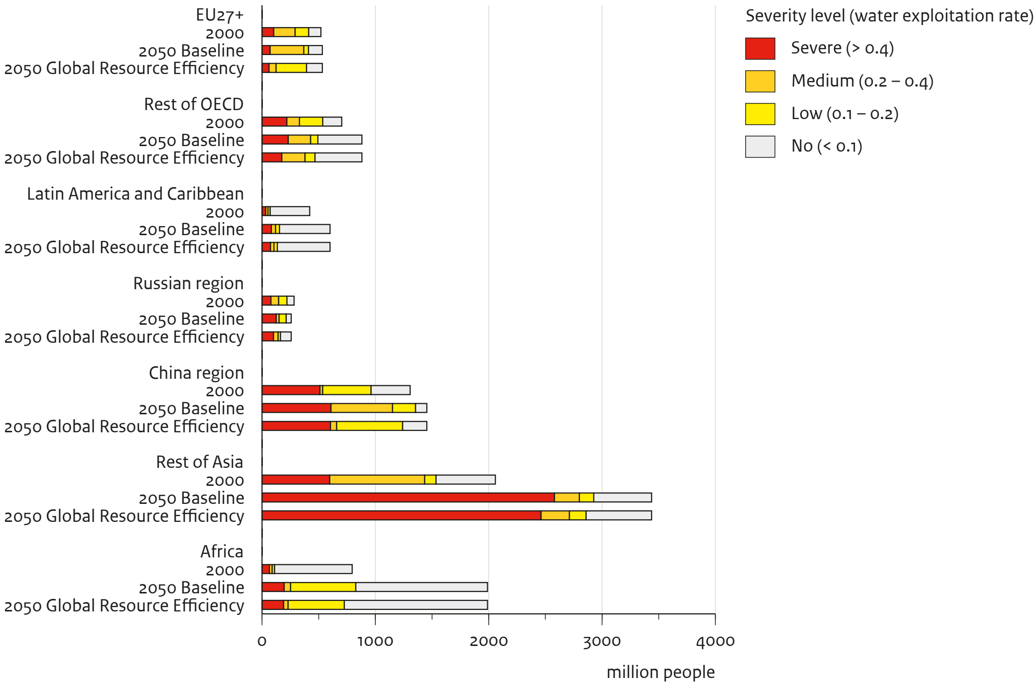
Q.3 How would resource efficiency interventions interact with other not targeted resources? Are there synergies and trade-offs, and how does resource efficiency relate to climate-change mitigation efforts?

Synergies between efforts to enhance efficient use of different resources and to mitigate climate change seem to be the rule. An overview is given in Table 3, for example:

- Irrigation water efficiency also contributes to land use efficiency, energy efficiency (less pumping) and phosphorus efficiency (less run-off losses).
- Efficiency in the fisheries sector contributes to energy efficiency (less fuel required) and land use efficiency (less land required to produce feed for aquaculture).
- Resource efficiency tends to contribute to climate-change mitigation. The strongest case investigated after energy efficiency is agricultural land because (i) less agricultural expansion as a consequence of yield improvements and better conversion of animal feed means less carbon dioxide emissions related to land conversion and even net absorption of CO_2 from the atmosphere as a result of forest regrowth; and (ii) improved feed conversion by ruminant livestock implies less methane emissions from enteric fermentation.

Figure 4

People living under water stress in major river basins



Source: PBL

The number of people living in areas affected by severe water stress is projected to increase from 1.6 billion in 2000 to 3.9 billion by 2050. This will occur mostly in Asia, primarily because of growing populations in highly stressed river basins, and to a lesser extent, because of an increase in the number of severely stressed river basins. Enhanced resource efficiency will have only a limited effect on this indicator.

There are also exceptions:

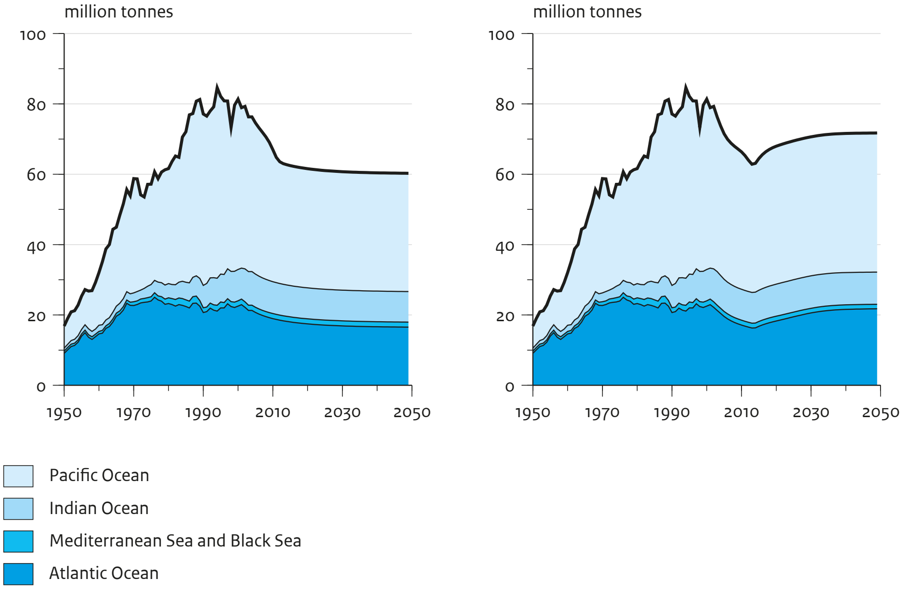
- Deployment of bio-energy in strategies for climate-change mitigation puts additional stress on biodiversity through increased land-use (including indirect land use change), and phosphorus.
- Carbon capture and storage (CCS), an important instrument to reduce green-house gas emissions, costs energy and has no interaction with any of the other resources studied.
- Synergy between phosphorus efficiency and other resources is not straightforward. Phosphorus efficiency in the EU requires transportation of manure over large distances involving high costs and fuel use because intensive livestock production systems are often concentrated in relatively small areas. For overall resource efficiency, crop–livestock systems need to be truly integrated at short distances or within the same farm, as is already the case in many developing countries.
- Some trade-offs are not easily detected, such as those between biofuels and marine biodiversity, as a consequence of competition between vegetable oil for (often subsidised) biodiesel and aquaculture which needs to increase to release the pressure from marine ecosystems.

Although taking advantage of synergies is crucial in any resource efficiency strategy, there is a risk of lock-ins and even into incentives for resource inefficiency. For instance, synergy between first generation biofuels from maize, soy and rapeseed, and their co-products used as livestock feed. Such synergies may help to make the production system more efficient, but once industries are established that benefit from them, their mutual dependence might evolve into lock-ins, hampering and delaying the introduction of second generation biofuels, which could be more efficient in terms of energy, land and phosphorus.

Leakage and rebound effects are not always perceived as negative, and some degree of rebound may even work as a stimulus for adoption. For example, improving land productivity in Africa would reduce the pressure to expand agriculture into biodiversity-rich areas, and would also contribute to food becoming more affordable and accessible. The

Figure 5

Marine fisheries catches



Source: UBC

Gradual reduction in marine catches over a ten-year period would help to restore fish stocks, enabling marine catches at a sustainably higher level than in the baseline.

latter effect could be seen as a co-benefit, even though the resulting increase in consumption would counteract some of the potential savings in land and biodiversity.

Policy opportunities and obstacles

The potential for resource efficiency policies depend on the type of resource and its scarcity dimensions. There is no single 'resource efficiency' policy. Often, physical scarcity is emphasised in discussions on the need for policies but, in reality, economic or geopolitical aspects may be more dominant. This will have consequences for the policy response.

A portfolio of policy instruments will be required to achieve the energy efficiency gains discussed in this report. These efficiency gains are mostly attained from the use of more efficient technologies. The main obstacles to their implementation are high initial investments and long payback times. Research indicates that different policy instruments are needed to overcome these obstacles depending on the situation (e.g., efficient buildings versus the transport sector). Measures promoting energy efficiency include efficiency standards, targeted subsidies and/or taxes; awareness campaigns, investments in infrastructure; and R&D to develop cheaper technologies and to raise the potential for further efficiency improvement. A portfolio of instruments will be more effective than instruments on their own. For instance, taxes could prevent rebound effects from efficiency standards. A significant part of the potential for energy efficiency is available at low and sometimes even negative costs. Further reduction in energy use than studied here is likely to require significant changes in consumer behaviour.

Enhancing efficient use of other resources requires more intricate policy instruments. The main barriers are socio-economic, political and cultural, not technical. Policy challenges are further complicated by large differences between regions and between sectors, and the need for global co-ordination in some policy areas. For example:

- The main obstacle to agricultural land use in the EU appears to be the lack of a shared vision on a desirable future for EU agriculture. The notion that resource efficiency leaves room for differentiated rural development according to regional ambitions could possibly help to gear more constructive discussion at regional level and to design a more goal-oriented Common Agricultural Policy.
- In developing countries, the underlying problems of inefficient land use are socio-economic factors, such as poor infrastructure and logistics, lack of access to credit,

Table 3

Interactions between resource efficiency interventions

Action on \ Effects on	Energy	Land / terrestrial biodiversity	Phosphorus	Fresh water (quantity)	Marine fish stocks	Climate-change mitigation
Energy		Less climate change[1)]	No response	Less need for water for power and industry[1)]	No response	Less greenhouse gas emissions from fossil fuels[1)]
Land / terrestrial biodiversity	Less field operations (tillage, harvesting etc.)		Soil conservation more fertiliser phosphorus needed in developing countries[1]	More gradual /uniform water flow to rivers More transpiration of permanent vegetation	Soil conservation: less sediments and pollutants After transition period, less crop-based feed required for aquaculture[1]	Less CO_2 emissions from land conversion and field operations[1)] Less CH_4 emissions from ruminant livestock due to shift in human diets[1)] Less CH_4 emissions due to improved animal feed
Phosphorus	Long distance transport of manure from surplus regions to recycle phosphorus	Soil conservation		Improved opportunities to re-use downstream water; reduced efforts needed in wastewater treatment	Less phosphorus (and nitrogen) loads	No response
Fresh water (quantity)	Less waste of pumped water	Less disturbance of stream flows / wetlands Potential for larger (high yielding) irrigated area	Less surface runoff		Less impact on hydrology of deltas and estuaries	Less energy waste on pumped water
Marine fish stocks	Smaller fish fleets, less need to fish deeper and remoter	Less need for aquaculture[1)]	No response	Less need for aquaculture due to more sustainable wild catch		Less energy required in fisheries and aquaculture
Climate	Climate Policy incentive for energy efficiency[1)] Promotion of (subsidised) renewables	Less impact of climate change on biodiversity[1] Effects of climate change on crop yields[1)] Additional land required for bio-energy crops[1)]	Additional phosphorus requirements for bio-energy crops[1)]	Effects of climate change on rainfall, potential evapo-transpiration[1]	Less change in sea temperature, polar ice, gulf streams Competition bio-energy vs feed for aquaculture	

[1)] Interactions that are addressed by the models used in this study.

Types of interactions: positive; negative; mixed positive & negative; No response: no significant interactions expected (until 2050).

lack of marketing opportunities and poor governance. These challenges require specific policy responses and actions at several levels simultaneously (local, regional, national), a notion that is only recently being accepted and responded to.
- The main challenge to fisheries is the strict rules that need to be imposed to allow fish stocks to recover. This is will almost certainly require reorganisation of the fisheries sector and firm international regulation. Fisheries reorganisation will lead to job losses and socio-economic problems, particularly in coastal villages, many of which have a proud cultural heritage of many generations of fishermen and long-standing fishery-related industries, but with few alternative livelihood opportunities.
- With respect to fresh water, pricing may be an effective and straightforward solution but is often perceived as biased against the poor and leading to unfair competition. More acceptable results might be achieved by using locally tailored solutions, such as community-based water resource management and flexible quota systems, such as water banking, designed with strong stakeholder involvement at the watershed and irrigation scheme level. Given the projected growth in non-agricultural water-using sectors, integrated water management is inevitable in matching supply and demands within river basins. This may include multilateral policy making and management bodies, such as already exist for major European river systems.

Therefore, to capture the full benefits of resource efficiency, multiple policy initiatives will be required simultaneously. Even when targeted at single resources, single-resource efficiency policies are unlikely to succeed. A mix of core and accompanying policies will be needed to target different actors and to avoid excessive leakage and rebound effects.

Some degree of global resource governance can be attained without government regulation. Most of the resource issues addressed have an international dimension. Numerous scholars argue that such issues would be best addressed by globally co-ordinated efforts in order to maximise coherence and to prevent free-rider behaviour. This is particularly the case with global public goods, such as ocean fish stocks, and regulating cultural and supporting ecosystem services provided by biodiversity rich conservation areas. The UN Convention on the law of the sea, the discussions on the succession of the Kyoto protocol and the Convention on Biological Diversity are examples of how difficult it is to establish and enforce ambitious international agreements to this end. This does not mean nothing can be done in their absence. There are many whole-chain initiatives and certification schemes governed by producers, local communities, bankers, traders and other supply chain stakeholders. Opinions vary regarding their successfulness; and the ideal role of governments and the EU within or alongside such schemes (e.g., observer, facilitator, co-funder, regulator) is still unclear.

Policy efforts luring the private sector to buy into resource efficiency can only be successful if information on resource use, stocks and reserves is transparent and accessible to public and private stakeholders. Currently, there is no international organisation monitoring resource use and providing transparent information on resource use and remaining reserves.

The challenge of finding common efficiency goals and other issues requiring further investigation

The EU resource efficiency initiative is multi-faceted and interconnected, in terms of temporal and spatial scales, actors and institutions. Sustainable development would require that resource efficiency improvements are applied ambitiously, consistently and fully. This would go beyond a mere adjustment of production technologies, but would also involve action with regard to consumption incentives, behaviour and institutional arrangements.

This suggests that an overarching vision for the EU resource efficiency initiative may be easier framed in political-cultural terms ('the European way of managing resources', and its aspirations to become a leading knowledge-based economy fostering smart sustainable growth) than in terms of physical indicators and targets.

Specific difficulties may arise with setting goals in terms of changes (regarding improved resource efficiency) that are not an ultimate goal in themselves, but rather as a means to achieve sustainability goals:
- Technical goals are often not easily understood and related to an understandable necessity.
- Measurement problems mean political problems on the way to common goals.
- Subsidiarity is a major issue if differences between countries are large. A way forward has been demonstrated in the EU energy efficiency discussion by combining joint policy attention for the issue at hand with periodic reports from most Member States, on the understanding that further policy discussion only occurs if a very large deviation from an indicative goal becomes apparent.
- A pitfall related to the setting of targets that are meant to induce a learning effect is that targets may be set on too short a time horizon. This makes it attractive to stick to the most limited, cheapest measures rather than to seize opportunities for investing in structural innovation. A way of integrating the learning objective has been demonstrated by the rules for carbon credits

Table 4

Key indicators according to model projections, 2010–2050

Potential objective	Indicator	2010		Baseline 'No new policies'		Envisaged policies		Global resource efficiency		Global resource efficiency and climate policy	
		World	EU27+	World	EU27+	World	EU27+	World	EU27+	World	EU27+
		Value		% change 2010 to 2050							
Efficient energy use	Primary energy use per unit of GDP (MJ/US$)	10.1	5.3	-51	-45	-51	-46	-65	-63	-65	-62
Efficient use of fossil energy sources	Primary energy use from fossil sources per unit of GDP (MJ/US$)	8.0	4.1	-52	-52	-56	-60	-67	-69	-78	-79
Decreasing dependency on fossil fuel imports	EU imports (EJ)		31.9		0		-16		-26		-54
	EU imports (fraction EJ of total use of fossil fuels)[1]		52		-3		-3		4		1
Climate change mitigation	Greenhouse gas emissions (energy, Gt C)	8.2	1.2	71	7	57	-18	19	-31	-37	-68
	Greenhouse gas emissions (total, Gt C)	12.0	1.4	55	6	37	-18	14	-30	-39	-70
Efficient agricultural land use	Agricultural land use (millions km^2)	52.5	2.3	4	-3	6	-2	-9	-13	-3	-12
	Agricultural land use (ha/capita)	0.76	0.44	-21	-2	-20	-1	-31	-12	-27	-11
Halting terrestrial biodiversity loss	MSA (%)[1]	67%	36%	-7	-6	-6	-6	-4	-5	-5	-5
	High quality nature (millions km^2)	60.6	0.6	-22	-43	-22	-40	-16	-39	-19	-37
	natural & semi-natural areas (millions km^2)	88.2	2.6	-3	1	-4	1	4	6	0	5
Efficient use of phosphorus in agriculture and food	Primary P fertiliser use (Mt P/yr)	16.4	1.9	41	-2	40	-2	9	-33	19	-32
Efficient use of fresh water	fresh surface water withdrawals (km^3/yr)[2]	3565	271	53	14	n.d.	n.d.	16	-18	n.d.	n.d.
Minimise the number of people living under water stress	People living under severe water stress (millions)[2]	1,608	103	142	-31	n.d.	n.d.	128	-40	n.d.	n.d.
Efficient fisheries	Average catches (Mt)[3]	67	14	-10	-11	n.d.	n.d.	7	6	n.d.	n.d.
Halting marine biodiversity decline	Marine depletion index (2004=1)[3]	1	1	-45	-38	n.d.	n.d.	32	12	n.d.	n.d.

1) Changes are expressed in percentage points
2) Reference year is 2000
3) Reference year is 2004. For the EU27+, the catches from the north-east Atlantic, central-east Atlantic and Mediterranean and Black sea FAO fishing regions were taken as representative
n.d. Not determined.

of renewable energy in transport, which provide a double financial advantage for electric vehicles' (carbon dioxide emissions avoided per distance driven), thus stimulating learning and innovation.

Many other issues were identified that require further investigation:

- Further research is required on the role of financial incentives and institutional arrangements for accelerated deployment of resource efficiency, as well as on the costs of such measures to societies, and the positive and negative implications of rebound effects.
- A more refined analysis is required to assess the potential of regionally differentiated resource efficiency policies.
- Research is required into the effectiveness of sustainable supply-chain initiatives by private stakeholders, local communities and NGOs, and the government role appropriate for such initiatives.
- Changes in water withdrawals for irrigation, which currently make up two thirds of the total, is subject to large uncertainty. Possible expansion of the irrigated area, the response of demand per hectare to climate change, and the efficiencies of irrigation systems and the fate of water required for cooling versus "real consumption" for industrial purposes all contribute to the uncertainty.
- Research is required for the development and even more effective deployment of water-saving production processes, household appliances and irrigation systems.
- In all scenarios, aquaculture will further expand to meet future fish demand. More sustainable aquaculture requires the support of research on technological innovations with less environmental impacts. Further research is required into the development of alternative feeds with less negative impacts on the environment and on human and fish health, and to decrease dependency on fish-based feed.
- Further research is needed to better understand the role of residual soil phosphorus, especially in strongly weathered tropical soils with high phosphorus fixation capacity. This aspect has been taken into account in this study, but to improve projections a more refined model is needed that accounts for soil properties and different soil phosphorus pools and can thus better address the issue of phosphorus use efficiency.
- The study results suggest considerable influence of future forest exploitation on land use and terrestrial biodiversity. However, there is considerable uncertainty about future demand for wood products and how it can be met. Possibilities other than the one studied here could be investigated, including resource efficiency on the demand side of wood products.

Notes

1 As defined by OECD (2008): areas with a ratio of annual withdrawals to available resources that exceeds 0.4.

2 Global integrated assessment to support EU future environmental policies. Service Contract No. 07.0307/2009/550636/SER/F1 (ENV.G.1/SER/2009/0061).

3 Primary energy refers to all energy used, including direct delivery to end-users plus the inputs in electric power and heat plants and other energy conversion processes such as refineries.

4 Final energy is energy as delivered to end-users, covering electricity, fossil and bio-energy carriers, heat and hydrogen.

FULL RESULTS

FULL RESULTS

ONE

Introduction

Increasing population and wealth are resulting in rising pressure on key resources to satisfy growing demand. The physical, economic and geopolitical accessibility of resources and the efficiency and sustainability of their use are of paramount concern worldwide and at European level.

Recognising these challenges, the Europe 2020 Strategy establishes resource efficiency as one of its flagship initiatives for ensuring smart, sustainable and inclusive growth. At EU level, the Commission is asked … 'to establish a vision of structural and technological changes required to move to a low carbon, resource efficient and climate resilient economy by 2050 which will allow the EU to achieve its emissions reductions and biodiversity targets; this included disaster prevention and response, harnessing the contribution of cohesion, agricultural, rural development, and maritime policies to address climate change, in particular through adaptation measures based on more efficient use of resources, which will also contribute to improving global food security.'

Resource efficiency is understood as making the best possible use of natural resources, using them wisely and sustainably throughout their lifecycle. This can contribute to ensuring that the environmental impacts of human activities remain within the physical and biological limits of the Planet.

This report presents the results and outcomes of Negotiated Procedure F.1/2010/Ref N°1 ARES (2010) 818226, a Complementary Contract to the GLIMP project (Global integrated assessment to support EU future environmental policies, Service Contract no ENV.G.1/SER/2009/0061).

The project objectives are to:
(a) *Assess current and future potential problems related to resource use* including scarcity risks in Europe due to EU resource consumption, as well as those induced by Europe elsewhere in the world, and to provide evidence of potential benefits of resource-efficiency policies.
(b) In the various contexts of climate efforts (no EU climate efforts beyond current commitments, isolated EU climate efforts, and global climate efforts); to identify and analyse *the potential benefits and trade-offs for Europe of policies aimed at improving resource efficiency*.
(c) Provide a suitable *basis for more in-depth work on resource-efficiency, suggesting*:

1. priority areas for further improvements in resource efficiency;
2. community policies that could be oriented or re-oriented to achieve the desired improvements;
3. ways to assess the improvement potentials in more depth with the help of dedicated modelling tools.

TWO

Approach

Because of the fast track nature of this study, only a limited number of resource efficiency themes or aspects were addressed, as presented in the overview in Section 2.1. In the study we performed complementary qualitative and quantitative analyses for each theme, as explained in Sections 2.2 and 2.3. Further elaboration on each theme including the results from the analyses is provided in Chapters 3 to 7.

2.1 Themes addressed

The following themes were selected for this study:

Energy particularly with regard to the key role of fossil fuel combustion in climate change, and the various aspects of scarcity (physical, economic and geopolitical) associated with fossil fuels particularly oil and gas.

Land with attention to the increasing competition between various types of land use for the production of food, feed, fibre, fuel and forestry products; the impacts of land use and land use change on other key ecosystem services (focusing mainly on terrestrial biodiversity and greenhouse gas mitigation); and the scope for enhanced efficiency through, for instance, sustainable intensification, reduced food chain losses and/or shifts in consumption patterns.

Phosphorus with attention to its critical and irreplaceable role in agricultural production; the consequences for phosphorus demand of agricultural expansion and intensification in regions dominated by phosphorus-depleted soils and phosphorus-fixing soils (in Sub-Saharan Africa and South America); the limited resource base with reserves concentrated in a few countries; and scope for achieving more efficiency through, for instance, improved farming practices, livestock feeding and recycling.

Fresh water with attention to river discharge in primary catchment areas and water stress indicators derived as affected by changes in demand and supply as a consequence of climate change and population pressure; and scope to enhance efficiency through, for instance, improved irrigation efficiency, reduced conveyance losses, and efficiency of water use for non-agricultural purposes.

Fish stocks with attention to increasing demands for fishery products and rapidly depleting stocks; and the scope for more efficiency through adapted fishing efforts and sustainable expansion of aquaculture.

2.2 Qualitative analysis

The qualitative analysis for this study was based mostly on reviews of published literature. For each theme, the physical, economic and geopolitical dimensions of resource issues (Prins *et al.*, 2011) were examined in order to address the following:

- How has resource use developed in the past and how is it expected to develop into the future?

Table 2.1
Overview of the approach to the quantitative analysis of each theme

Theme	Models used	Primary indicators	Impact indicators
Fossil energy including climate change	IMAGE Energy (TIMER)	Primary input of different types of fossil energy / GDP	• Greenhouse gas emissions • Reserve depletion in key geopolitical regions • Biodiversity indicators (Mean Species Abundance, areas of high quality nature in different biomes and geopolitical regions) • Production of agricultural and fisheries products • Land cover including natural biomes, agriculture, extensive grassland, bio-energy • Water stress in primary catchments
Land including terrestrial biodiversity	IMAGE land & climate GLOBIO3	Areas with different types of land use	
Phosphorus	Recently developed PBL model	Use of phosphorus from primary sources	
Fresh water	LPJmL extended with water reservoirs	Fresh water use	
Fish stocks	Calculations based on raw data of previous PBL/UBC work (PBL, 2010) and of GLIMP, where available	Wild catches, Depletion Index	

A detailed description of the model infrastructure available is given in the Appendix.

- What are the key drivers and actors in the chain from primary resource use/exploitation to final product consumption and in which geopolitical regions?
- What are the interlinkages with other Resource Efficiency themes and policies, for instance, with regard to climate change)?
- What are the impacts under continued practices, and what benefits can be projected from enhanced efficiency?
- What policies have been developed on the theme, and what are the effects and side effects?
- What is the physical, technological, economic and socio-cultural scope for enhancing efficiency and what are the main barriers?
- Which indicators are most suitable for expressing efficiency and impacts?
- Which options / policy instruments seem to be most promising to induce enhanced efficiency?

2.3 Quantitative scenario analysis

The study tested the hypothesis that increased EU focus on resource efficiency would be a 'cost-efficient strategy' for Europe in the context of (i) global climate action consistent with the EU 2 °C objective; and (ii) no concerted global climate action. The analysis was directed to assessing whether resource efficiency measures including measures to address rebound effects should receive highest priority.

Other issues addressed in the analysis are:

- The extent to which climate efforts may benefit from efforts on resource efficiency;
- The expected impacts on developing countries from increased focus on resource efficiency, especially with regard to poverty and food security.

An overview of the quantitative analysis for each theme is presented in Table 2.1.

The analysis provides the following:

- Global scope;
- A time horizon up to 2050;
- A context of aggregated demographic and economic indicators;
- Geographic explicitness, with analysis performed at the level of 24 world regions or at a 0.5 x 0.5 degree global grid, and with aggregated results presented for 7 major geo-political regions.

In order to safeguard consistency, the models indicated in Table 2.1 were used in packages. For example, output of IMAGE was used as input in GLOBIO3, LPJmL and the phosphorus model. This enabled assessment of the following interactions between the themes:

Land use *and* fossil energy:

- Greenhouse gas emissions related to land use, land-use change and ruminant production;
- Type and locations of bio-energy crops and their effects on land use and biodiversity (MSA indicator);
- Effects of CO_2 and climate change on crop yields.

Table 2.2
Scenarios analysed

		Policy action targeting	
Scenario	**Short**	**Resource efficiency**	**Climate change**
Baseline	BL	None beyond autonomous development	None beyond current formally enacted commitments
Envisaged policies	ENVISAG	Same as in BL	Current EU policies fully implemented and continued beyond 2020; low end Copenhagen pledges elsewhere
EU resource efficiency	E-RE	Ambitious, in EU only	Same as in ENVISAG
Global resource efficiency	G-RE	Ambitious, worldwide	Same as in ENVISAG
EU resource efficiency and climate policy	E-RE-CP	Ambitious, in EU only	Ambitious, in EU only; same as in ENVISAG elsewhere
Global resource efficiency and climate policy	G-RE-CP	Ambitious, worldwide	Ambitious, worldwide

Land use *and* phosphorus:
- Phosphorus fertiliser requirements in relation to crop production;
- Phosphorus excretion in livestock manure;
- Phosphorous fertiliser requirements for bio-energy crops.

Land use *and* fisheries:
- Crop-based feed requirements for aquaculture.

Climate change and energy *and* fresh water
- Change in rainfall patterns and irrigation water requirements as a consequence of climate change;
- Change in water use by industrial sectors engaged in energy efficiency.

The starting point for the scenario analysis is the macro-economic *baseline* scenario, constructed for the OECD environmental outlook, and shared with the GLIMP project. The *baseline* scenario is a 'no new policies' scenario, considering, for example, only the EU climate policies that had been formally approved by 2009; it does not include concerted global climate action.

Five additional scenarios were analysed as presented in Table 2.2.

The scenario *Envisaged policies* (ENVISAG) serves a purpose (within the practical constraints of this study) similar to that of the 'Reference' scenario in Annex 2 to the EU communication document *A resource-efficient Europe – flagship initiative under the Europe 2020 strategy*, of 26 January 2011 (EC, 2011b). In addition to the baseline, it assumes implementation of low-level Copenhagen pledges worldwide, and their continuation after 2020. For the EU, this implies that the EU energy and climate directives with a time horizon for 2020 are fully implemented and successful, and continued beyond 2020, as is explained in Chapter 3.

EU resource efficiency (E-RE) is a scenario of high policy ambitions on energy security and resource efficiency within the EU in the context of no global climate mitigation effort except for the low-level pledges under ENVISAG.

Global resource efficiency (G-RE) is a scenario of high policy ambitions on resource efficiency worldwide, and assessment of outcomes for climate in the absence of new policies targeting this issue.

The *EU resource efficiency and climate policy* (E-RE-CP) scenario has high policy ambitions for resource efficiency within the EU in the context of EU effort on climate change. This leads to approximately 80% domestic reduction in greenhouse gas emissions in the EU by 2050 on 1990 levels. There is *no* global climate mitigation except for the low-level pledges under ENVISAG.

Global resource efficiency and climate policy (G-RE-CP) is a scenario of high policy ambitions worldwide, and requires concerted global effort on resource efficiency and climate. This scenario is consistent with the 2°C objective, corresponding to approximately 80% reduction in domestic greenhouse gas emissions in the EU by 2050 on 1990 levels. This corresponds to the RCP 2.6 [1] scenario variant elaborated by (Van Vuuren *et al.*, 2010a).

A detailed description of the model and data infrastructure used is presented in the Appendix. Model parameter setting for the various scenarios including quantified descriptions of the assumptions on ambitious effort on resource efficiency was based on what is understood to be physically and technologically possible, socio-economically conceivable and potentially acceptable. Details of the assumptions made for each theme and the reasons are provided in the chapter addressing the individual theme. In many instances, the study had to assume certain beneficial changes (‘what if...?’) without being able to specify the policy levers that would have been actuated. In constructing the scenarios, such assumptions are made explicit.

Note

1 Representative Concentration Pathway. This particular pathway leads to radiative forcing of 2.6 W/m^2 by 2100.

Energy

3.1 Introduction

Energy is a crucial resource in the context of sustainable development. Energy consumption is a precondition for human activity. How it is currently produced and consumed is having significant environmental impacts, including those on climate change, and regional and local air pollution. Moreover, it is highly questionable whether current energy consumption patterns can be maintained in the long term. Fossil fuel energy sources are limited and very unevenly distributed throughout the world (Table 3.1).

For the EU, more than half of the total supply of fossil fuels is imported. Thus, limitations in supply on international markets may have direct impacts in the EU. The EU and several countries worldwide have expressed the ambition to reduce fossil fuel energy consumption both for environmental reasons and to improve security of supply. One way to reduce fossil fuel consumption is to reduce energy consumption. In this chapter, various measures to increase end-use efficiency are examined, with and without additional climate policy.

3.2 Resource efficiency mechanisms analysed

The analysis focuses on energy efficiency. The term is mostly used to indicate an improvement in the relationship between end-use services (e.g., heating) and the energy used for this service. At a more aggregated level, the energy intensity of the economy (the ratio between energy consumption and GDP) is also used as an efficiency indicator, although structural factors in the economy also play an important role.

The efficiency of energy use has been improving over the last decades and is expected to improve further in the future, even in the absence of specific policies for this purpose. The primary drivers are technology development and energy costs. However, energy efficiency can be improved further. Barriers to greater energy efficiency include, for instance, lack of information, alternative investment opportunities, and costs. Various studies have looked into specific measures to improve energy efficiency and their potential impact (for example Barker *et al*., 2007; de Beer, 1998; Graus *et al*., 2010; Interlaboratory Working Group, 1997). Cullen *et al.* (2011) indicate that the efficiency of energy use could be improved, through technical measures, by as much as 72% by 2050, although they caution that this is an extreme estimate. The (R)evolution scenario of Teske *et al*. (2010) indicates a global reduction potential of about 30% to 35% based on the reduction potential of Graus *et al.* (2010). The study of Graus *et al.*

Table 3.1
Scarcity dimensions of fossil energy

Physical	Economic	Political
Increased pressure on (remaining fossil) resources due to sharply rising demand.	Exploitation and processing become increasingly costly and capacities lagging behind. Improperly functioning markets. Under-investment in production and refining capacity.	Concentration of available resources in a limited number of countries. Competition between OECD countries and emerging economies for remaining fossil reserves. Transboundary conflicts related to ownership of resources and conveyance systems (e.g., pipelines).

(2010) mentions a technical reduction potential of 45% compared to baseline by 2050.

In the context of climate policy, efficiency measures are usually combined with measures to reduce the greenhouse gas intensity of energy supply (carbon factor), such as the use of renewable energy.

Measures to increase energy efficiency can be categorised as follows: 1) technical measures to increase energy efficiency (e.g., more efficient cars); 2) changes in consumption patterns (e.g., less car use); and 3) increases in material efficiency (e.g., more efficient use of steel). Our study concentrates on measures in the first category. Measures can be taken in different sectors including industry, transport, residential buildings, other end-use sectors, and energy supply.

3.3 Scenario assumptions

3.3.1 Baseline scenario

The *baseline* scenario of this study assumes no new, explicit energy efficiency and climate policies. Nevertheless, a similar rate of energy intensity improvement is assumed as in the past. For the 2000–2030 period, the *baseline* scenario loosely follows the IEA World Energy Outlook 2009, but corrected for new climate policies (IEA, 2009), leading to a final annual energy use of 560 EJ/yr by 2050 (compared to 320 EJ/yr today). Primary global energy use increases at a same rate from 508 EJ/yr to 904 EJ/yr. Most of the energy is supplied by fossil fuels (close to 80% in both 2010 and 2050)[1].

3.3.2 Envisaged policies scenario

The *envisaged policies* scenario (ENVISAG) assumes implementation of the low pledges submitted in the context of UNFCCC as part of the Copenhagen Accords based on the work by (den Elzen *et al*., 2010) (for details, see their Appendix A). The reduction targets assumed for developed countries are similar to those in the POLES scenario presented in the European Commission communication document *Analysis of options to move beyond 20% greenhouse gas emission reductions and assessing the risk of carbon leakage* (EC, 2010a). However, reduction levels for the major developing countries and emerging economies are different, as they critically depend on baseline assumptions and interpretation of the pledges (e.g. several targets are formulated as intensity targets). In the TIMER model (see description in the Appendix), the pledges are modelled by introducing a set of region-specific carbon taxes. Although pledges expire by 2020, the *envisaged policies* scenario assumes a continuation of a similar policy effort in the countries that have submitted their pledges. This is represented in the scenario by keeping the 2020 carbon price constant up to 2050. For regions in which the low pledges require considerable effort, this thus is assumed to continue beyond 2020, implying that the changes induced by the pledges will continue to be implemented at the rate of the turnover of capital goods.

3.3.3 Global resource efficiency scenario

The *global resource efficiency* scenario (G-RE) implements a set of ambitious energy efficiency measures worldwide over the coming 40 years. These measures are introduced at the capital turnover rate. Major behavioural changes, such as car-sharing or a shift from international to domestic tourism, were not considered in the analysis.

- In the steel and cement industries, the best-available-technologies in terms of energy efficiency are assumed to be implemented from 2011 at the rate of capital turnover. For steel, this implies a convergence in new technologies at around 17 GJ/t steel (electric arc furnaces are assumed to be limited by scrap availability). For other industries, the work of Graus *et al*. (2010) was followed. However, the potential is limited to 80% of the total potential (in order to exclude the most expensive measures) leading to a 30% to 40% improvement compared to the baseline by 2050.

Table 3.2
Scenario assumptions on energy efficiency

Scenario		For the EU	For rest of the world
Baseline	BL	No new policies and essentially follows the World Energy Outlook 2009 (IEA, 2009)	
Envisaged policies	ENVISAG	Low Copenhagen pledges implemented and continued beyond 2020	
EU resource efficiency	E-RE	Same as G-RE	Same as ENVISAG
Global resource efficiency	G-RE	Ambitious energy efficiency measures, including the use of best-available-technology in steel and cement production, prescription of energy efficient cars and planes, a moderate shift to high-speed trains, prescription of efficient technologies in the residential sector, efficient housing, more efficient power plants and generic efficiency measures in other industries and the service sector	
EU resource efficiency and climate policy	E-RE-CP	Same as G-RE-CP	Same as ENVISAG
Global resource efficiency and climate policy	G-RE-CP	Same energy efficiency measures as G-RE plus further introduction of a carbon price in order to reach the emission profile consistent with the RCP2.6 emissions trajectory	

- In transport, implementation of the most efficient cars and aircraft is assumed. Moreover, a moderate shift is assumed from aircraft to high speed train following transport patterns in Japan (Girod *et al.*, 2011). The assumption was that 80% of this technical potential could be implemented.
- In buildings, application of efficient technologies for all end-uses is assumed. This reduces energy use for appliances and lighting, and especially space heating. For the latter, building of highly efficient housing (mostly insulation measures) reduces energy use in temperate regions from 0.6 to 0.2 GJ/m^2.
- In the power sector, from 2011 onwards, new plants in all regions are assumed to be build on the basis of efficient technologies. Losses in power distribution and transformation are assumed to be reduced in low-income regions.
- In all other sectors, reductions in energy use are equal to 80% of the potential identified by Graus *et al*. (2010). This leads to a reduction of 20% to 30% in the services sector (based on the building estimate) and 30% to 40% in other sectors (based on industry).

3.3.4 Global resource efficiency and climate policy scenario

In addition to the efficiency measures above, a price for greenhouse gas emissions was introduced in order to induce measures that reduce emissions in the *global resource efficiency and climate policy* scenario (G-RE-CP). The price was set so that emissions would follow the RCP2.6 scenario leading to a mean probability of achieving the 2 °C target of between 60% and 70% (Van Vuuren et al., 2007; Van Vuuren et al., 2010a). In this calculation, climate policy mainly impacts the energy supply mix and measures to directly reduce greenhouse gas emissions (as efficiency measures have been accounted for according to the *global resource efficiency* scenario).

3.4 Results

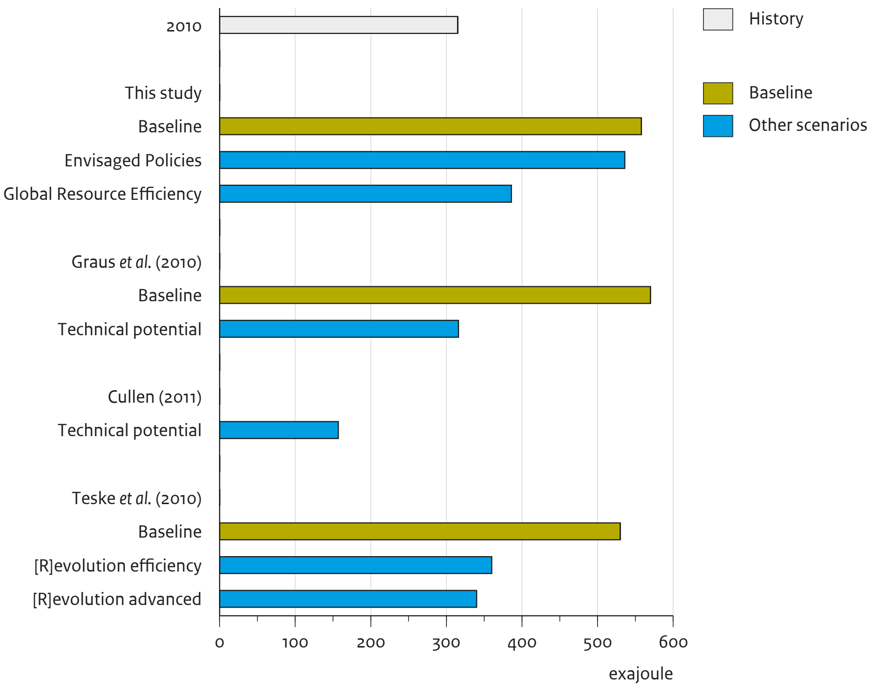
3.4.1 Overall energy consumption

Energy consumption is projected to increase significantly in the *baseline* scenario, driven by a growth in economic activities. Consistent with the trend over the last decades, most of this growth takes place in emerging and developing countries. In OECD countries, final annual energy use increases from 130 EJ/yr in 2010 to almost 150 EJ/yr by 2050, whereas energy use in the rest of the world doubles over the same period (from 200 to more than 400 EJ/yr). In per capita terms, this translates to a small relative decline in OECD countries (to around 150–200 GJ/yr per capita) but an increase in developing countries (in Asia, for instance, from around 20 GJ per capita in 2010 to between 50 and 60 GJ per capita by 2050).

The final energy consumption in the *baseline* scenario, the *envisaged policies* scenario and in the *global resource efficiency* scenario is compared with that in several other studies in Figure 3.1. The energy efficiency case in this study may be considered ambitious, but within the realm of possible outcomes considered by various studies on energy efficiency. It should be noted that the study by Cullen (2011) focused on the most advanced technical possibilities related to energy efficiency, thereby introducing very radical technologies. Graus *et al*. (2010), in contrast, identified the more conventional technical potential, thus limiting measures also because of practical constraints. For services and agriculture, however, our study in fact assumed a realisation of 80% of the potential identified in the Graus study, as we deemed this percentage to be more realistic. For the sectors of transport, industry and power, we introduced our own calculations, based on the same principles.

Jacobson and Delucchi (2011) estimated a baseline energy consumption of 530 EJ, annually, for 2030. They indicated

Figure 3.1
Final energy use in various studies, 2050



Source: various sources as indicated in the figure

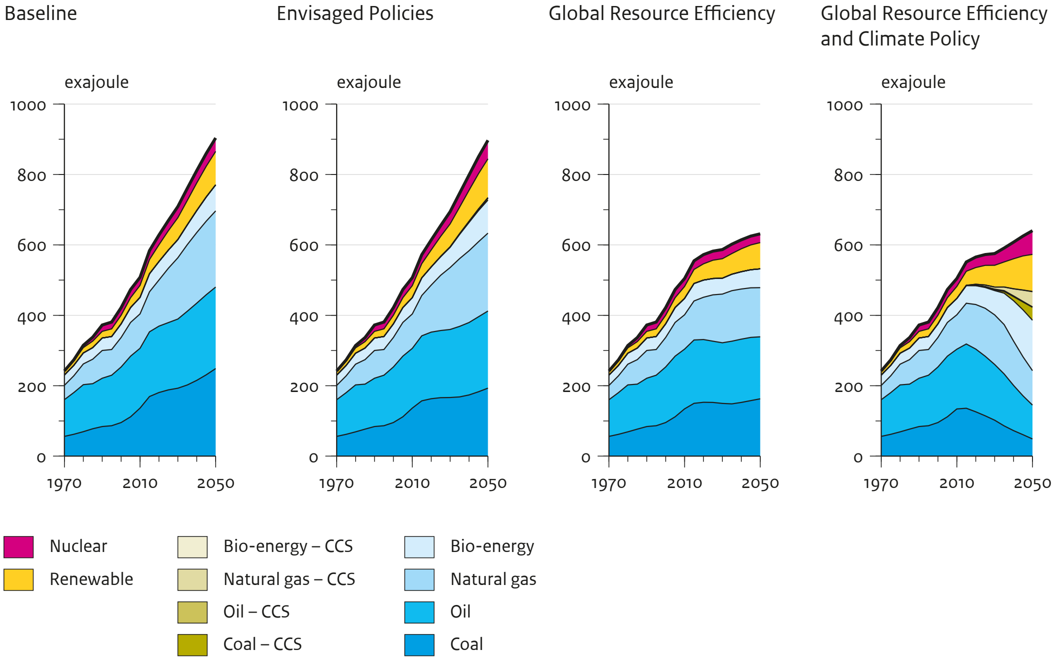
The effects of energy efficiency assumptions on final energy use, in this study looking at attainable accomplishments, are less pronounced than in other studies that focused on the full achievement of technical potentials.

that, under a scenario in which energy is supplied by wind, water, solar and hydrogen, efficiency may be improved, bringing the annual energy consumption down to 360 EJ/yr by 2030. This would translate to a 35% improvement in energy efficiency, which compares to the savings considered here. In our calculations for 2030, the *baseline* scenario would lead to an annual energy consumption of around 430 EJ/yr (final energy) and 700 EJ/yr (primary energy) while the *global resource efficiency* scenario would lead to 360 EJ and 585 EJ/yr, respectively.

The primary energy supply at a global level is presented in Figure 3.2. As shown, primary energy consumption remains dominated by fossil fuels in the *baseline* scenario. In 2010, oil had the largest share of the total energy consumption, whereas in our *baseline* scenario, consumption of both coal and natural gas will be greater than oil, by 2050. This is a result of depletion of most of the low-cost conventional oil resources leading to relatively high prices (with the category oil shown here, unconventional resources become increasingly important). In the *envisaged policies* scenario, the increase in energy consumption is slightly reduced, and the energy supply mix shifts somewhat at the expense of coal and oil in favour of bio-energy and renewables. In the *global resource efficiency* scenario, energy consumption is significantly reduced, compared to that in the baseline (similar to final energy consumption, with about a 30% reduction). However, the energy supply mix follows similar trends as in the *baseline* scenario. Introduction of ambitious climate policy in the *global resource efficiency and climate policy* scenario implies that the energy mix also changes significantly. A significant part of the remaining fossil fuels is used in combination with carbon capture and storage.

The scenario results for the EU27+ are shown in Figure 3.3. On a global scale, the differences are relatively small in the two scenarios in which policies are introduced in the European Union only (E-RE and E-RE-CP) as well as in the *envisaged policies* scenario. For the EU27+, the scenario results in energy consumption levels for the European efficiency cases (E-RE and E-RE-CP) are comparable to the *global efficiency* scenarios (by design).

Figure 3.2
Global primary energy use per energy carrier



Source: PBL

In the baseline scenario, primary energy consumption increases by nearly 80% between 2010 and 2050, and supply remains dominated by fossil fuels. Energy consumption is slightly reduced in the envisaged policies scenario, and the energy supply mix shifts somewhat to bio-energy and renewables. In the global resource efficiency scenario, energy consumption is reduced by about 30%, and in the global resource efficiency and climate policies scenario, the energy supply mix changes significantly and carbon capture and storage (CCS) becomes significant.
NB For accounting purposes, primary energy for solar, wind, hydro and nuclear power is reported assuming a 40% efficiency.

3.4.2 Energy efficiency trends

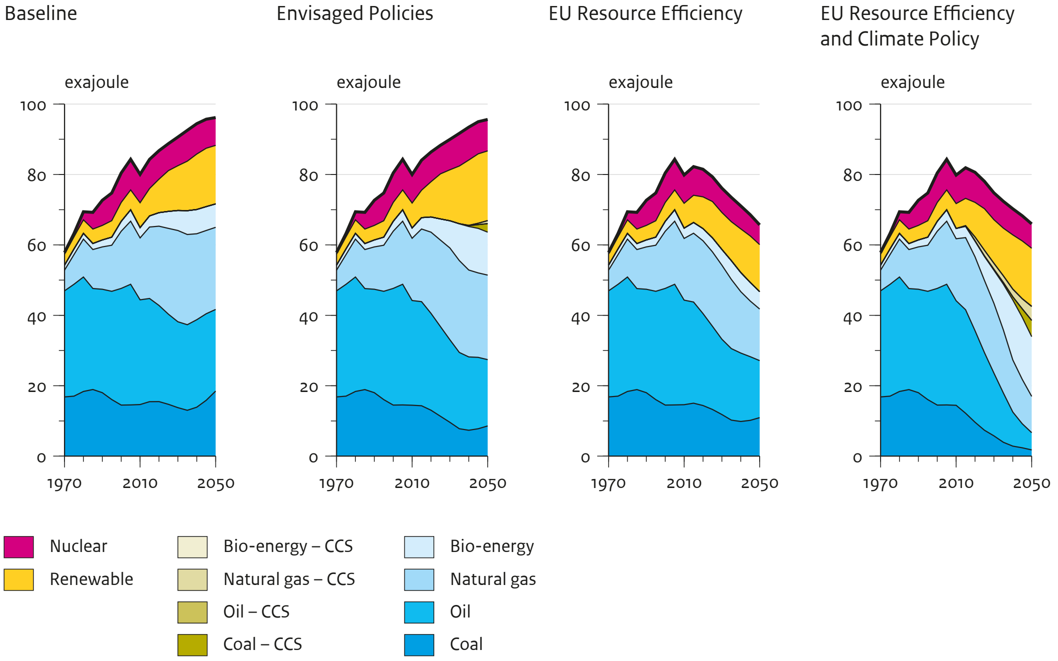
Future energy use and emissions can also be described by the different factors included in the Kaya identity (Kaya, 1989) [emissions = population x per capita income x energy intensity (energy per unit of income) x carbon factor (emissions per unit of energy)]. Energy intensity and the carbon factor are shown in Figure 3.4. Historically, improvement in energy intensity on a global scale has averaged 1% per year (with values varying between 0 and 2%). Improvement in energy intensity has been relatively slow in the 2000–2010 period. This is partly a result of high economic growth in areas with a low energy intensity, but other factors also play a role (van Vuuren and Riahi, 2008). In the *baseline* scenario, the energy intensity decline is assumed to be 1.7% annually, which is somewhat stronger than the historical rate. The higher rate partly results from the increasing share of regions with rapid economic growth in world GDP, and which are assumed to have a high rate of energy intensity improvement. In the *global resource efficiency* scenario, the improvement rate is projected to increase by 3% per year.

The carbon factor (based on the energy supply mix) has been nearly constant on a global scale. As would be expected, this factor remains more-or-less constant in the *baseline* scenario as well as in the *global resource efficiency* case. In the *envisaged policies* scenario and especially the *global resource efficiency and climate policy* scenario, the carbon factor is projected to reduce as a result of the penetration of low or zero carbon technologies.

3.4.3 Resource depletion

The total cumulative use of fossil fuels in the 2010–2050 period is compared with current reserves and resource estimates[2] in Table 3.3. It shows that cumulative consumption of oil and natural gas up to 2050 would be of the same magnitude as current reserve estimates of conventional resources. Total oil resources, including unconventional resources, are projected not to be depleted by 2050. However, a considerable part of these resource estimates is beset with uncertainty and still needs to be confirmed. Moreover, exploitation will need to be economically viable. Above all, the comparison with the

Figure 3.3
Primary energy use per energy carrier in EU27+



Source: PBL

For the EU27+, greenhouse gas reduction targets in the envisaged policies scenario are much more ambitious than global reduction targets (Figure 3.2), resulting in a stronger change compared to the baseline scenario. In the EU resource efficiency scenario, EU27+ energy consumption is reduced by over 30% (compared to the baseline and envisaged policies scenarios), which is complemented by a change in the energy supply mix in the resource efficiency and climate policy scenario.

resources columns indicate that, based on available data, it is unlikely that oil, gas or coal would be fully exhausted by 2050.

The calculations also show that efficiency and climate policy reduce the consumption of fossil fuels, thus also reducing the ratio between cumulative use and current reserves and resources estimates.

The policies also have an impact on the fossil fuel price. In the *baseline* scenario, oil prices are projected to increase significantly, whereas this is much less so in the *global resource efficiency and climate policy* scenario. It should be noted that lower prices would lead to less improvement in price-induced energy efficiency. The strength of such rebound effects is not exactly known.

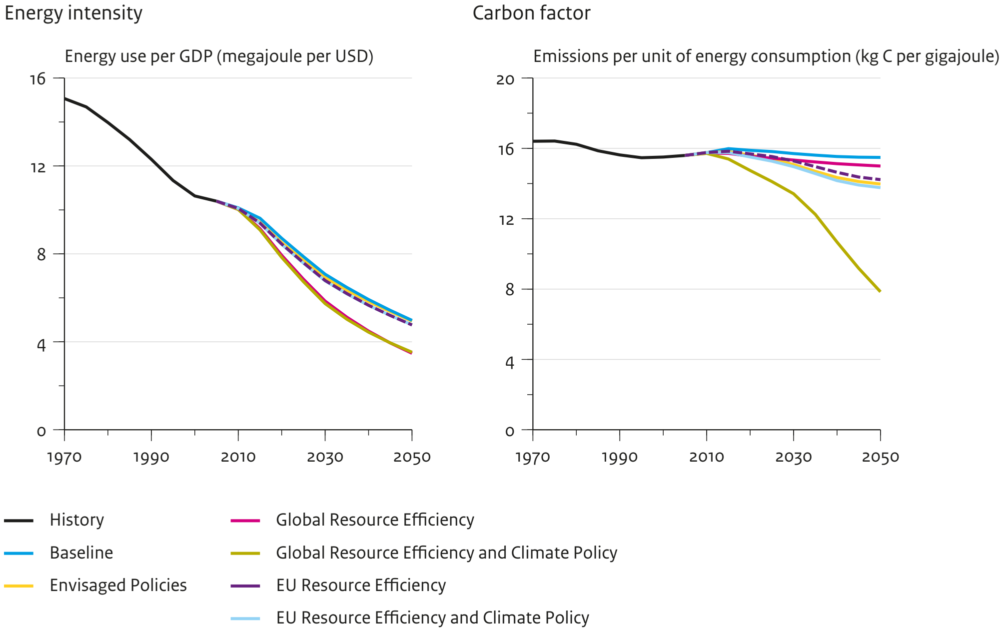
3.4.4 Energy imports

An important aspect of the energy security discussion relates to the dependency of the EU on the imports of fossil fuels (Figure 3.5). In the *baseline* scenario, the share of imports in the EU increases significantly because of depletion in low-cost resources within the EU. However, the absolute amount of oil imported is projected to increase only marginally and even to decline after 2040 because of a decline in oil use (mostly in sectors other than transport). The EU currently produces more than half of its natural gas demand; but also here imports are expected to increase to levels above 50% (mostly from the Russian Federation, northern Africa and the Middle East). In contrast to oil, absolute gas imports are projected to increase significantly up to 2030, followed by a gradual decline. For coal, around a third of supply comes from outside the EU – but from a wide range of countries. In the future, in the *baseline* scenario, coal imports decline, especially in the 2030-2050 period. In the scenarios that involve resource efficiency and climate policy, an additional reduction in coal consumption is projected, which further reduces import dependency.

3.4.5 Implications for climate policy

Under the *baseline* scenario, global greenhouse gas emissions are projected to increase (Figure 3.6). In the EU, emissions remain more or less stable, consistent with the trend over the last few decades. The *envisaged policies* scenario implements the low pledges and continues

Figure 3.4
Global Kaya factors



Source: PBL

The Kaya factor energy intensity (left) is projected to decrease considerably in all scenarios, but most steeply in the global resource efficiency scenarios. The carbon factor (emissions per energy consumption in kg C/GJ, right) is projected to remain fairly constant, except in the global resource efficiency and climate policy scenario.

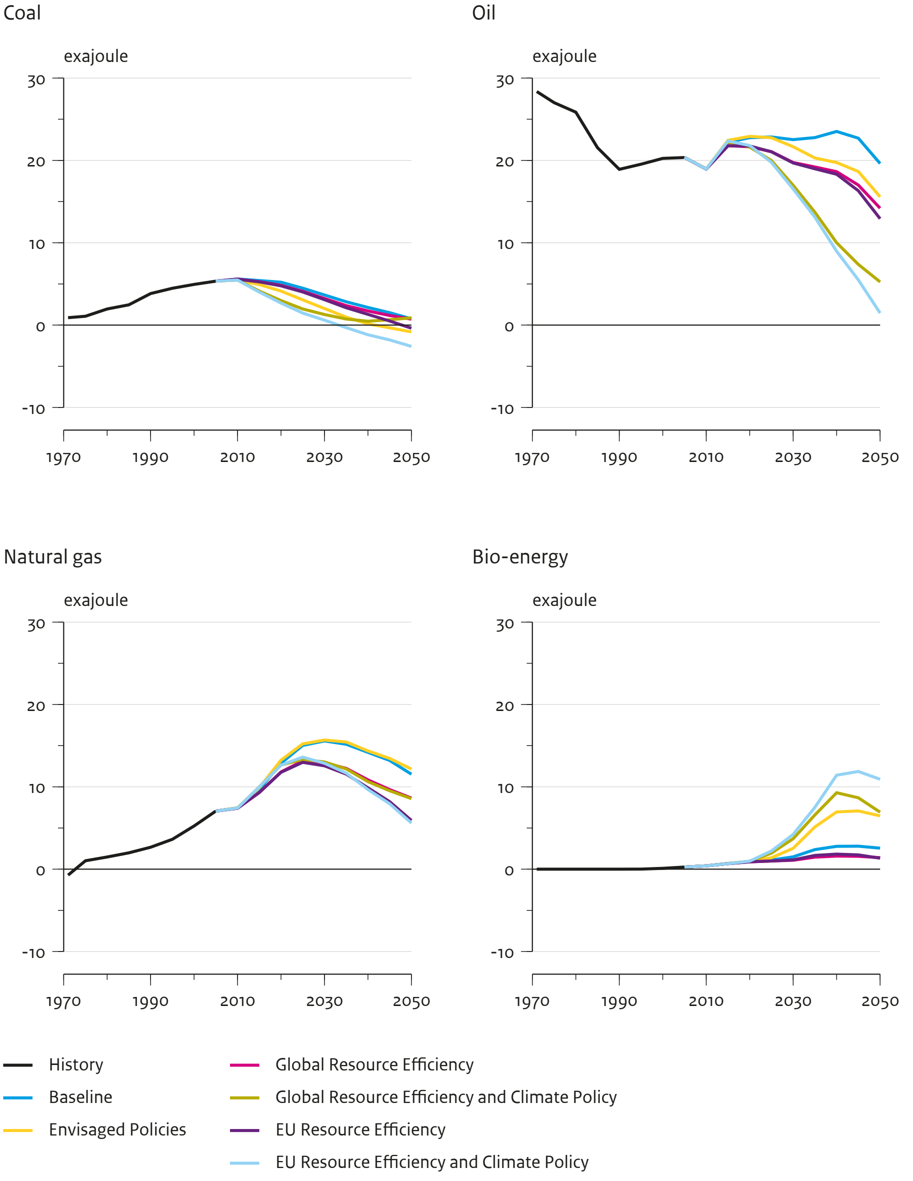
Table 3.3
Cumulative fossil fuel use and resource estimates

	Resource estimates (ZJ)			2010–2050 cumulative production (ZJ)			
Source	IMAGE	Global Energy Assessment (GEA, 2011)		BL	ENVISAG	G-RE	G-RE-CP
	Reserves + Resources	Reserves	Resources				
Coal	375.9	21.0	435.7	8.3	7.0	6.4	4.5
Conventional oil	11.1	7.6	13.8				
Unconventional oil	15.1	3.8	15.1				
Oil (total)	*26.2*	*11.4*	*28.9*	8.2	7.6	7.1	6.1
Conventional gas	11.6	7.1	16.0				
Unconventional gas	96.4	28.0	108.3				
Gas (Total)	*108.0*	*35.1*	*124.3*	6.7	6.6	5.3	5.3

similar policies after 2020. On the global scale, this implies that emissions are expected to continue to increase but at a considerably slower rate. In the EU, this scenario leads to a significant reduction of emissions.

Under the *global resource efficiency* scenario, EU emissions are further reduced and, globally, emissions will more or less stabilise. In order to have a high probability of holding temperature increases at a maximum of 2 °C, further reductions are needed. The results of the *global resource efficiency and climate policy* scenario (following the IPCC RCP2.6 emissions trajectory) show that, by 2050, global emissions from the energy system would be reduced by 40% to 50% compared to 2000. The *global resource efficiency* scenario by itself closes about half the gap between baseline and the emission reductions required.

Figure 3.5
Energy import into EU27+

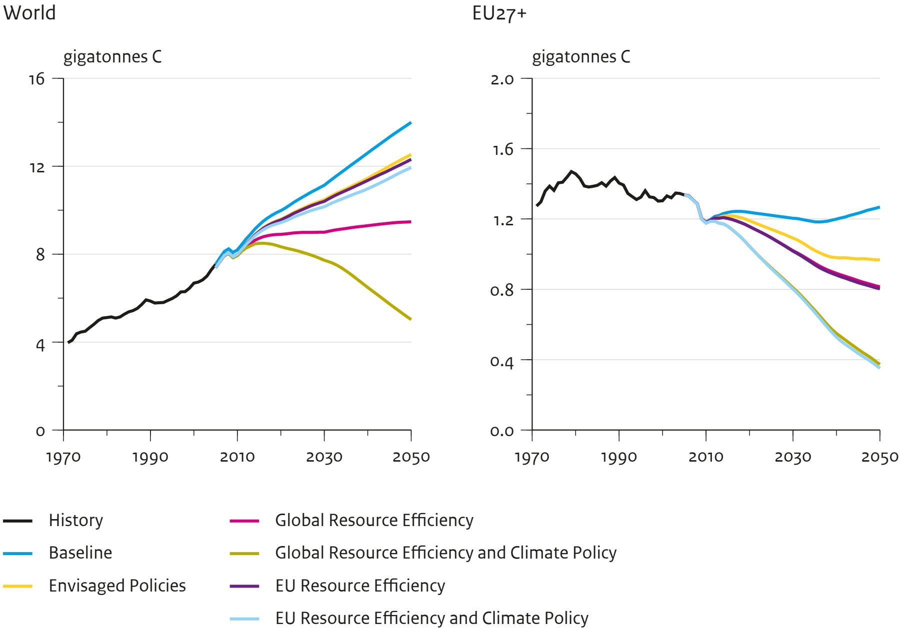


Source: PBL

In the baseline scenario, the EU increasingly depends on imports of fossil fuels, especially until 2030. In the EU resource efficiency and climate policy scenario, the EU is least dependent on imported fossil fuels, but depends more on imported bio-energy.

The effects of the European efficiency scenarios (E-RE and E-RE-CP) on a global scale are rather small because policies would only be introduced in the EU (a small part of global energy use). The *envisaged policies* scenario would have quite a strong effect in the EU27+ (Figure 3.6, right), because even the low-level Copenhagen pledges require substantial emission reductions in this region. Maintaining the carbon price level required to implement the pledges, would imply further reductions beyond 2020. Globally, the impact of these policies, compared to that under the *baseline* scenario, can clearly be seen in the left graph of Figure 3.6, although reductions will be smaller than in the EU27+ (right graph). Recent publications, such as the UNEP Emissions Gap Report (UNEP, 2010), also indicated that these reductions are insufficient to reach the 2 °C target.

Figure 3.6
CO_2 emissions from the energy system



Source: PBL

Global resource efficiency closes about 50% of the gap to attain the 2 °C global climate goal; currently envisaged policies only modestly contribute to this goal. For the EU27+, currently envisaged policies imply a more significant reduction in CO_2 emissions.

3.5 Limitations of the analysis

The analysis focuses on the impact of efficiency policies on several variables. However, there are certain limitations:

- How the efficiency measures should be implemented was not studied. The measures implemented are clearly not free of costs.
- Measures are implemented worldwide. No account was taken of international negotiations which are likely to allow less strict policies in developing countries.
- With regard to the *envisaged policies* scenario, there are several major uncertainties that could greatly affect emission reductions by 2020 resulting from the Annex I pledges (den Elzen *et al*., 2010). These relate to the contingency of the pledges, the use of surplus Assigned Amount Units (AAUs) 3, land use, land-use change and forestry rules and the potential double-counting of off-sets. The contingency of the pledges, in particular, may have a large effect on 2020 emissions for countries that only made a conditional pledge, such as Canada, Japan and the United States. If the preconditions of these pledges are not met, emissions from these countries may follow the *baseline* scenario, which, in turn, would lead to higher global emission levels. The impact of surplus AAUs, notably from Russia and the Ukraine, but also from Europe, could also cause a reduction in the mitigation effort, in the order of 6% to 8% of the 1990 emission levels of Annex I countries. Finally, there are risks of double counting of emission reductions, as non-Annex I parties are also looking for external finance for some of their reduction efforts.

3.6 Discussion and policy implications

The resource efficiency scenarios analysed lead to significantly less resource depletion and lower greenhouse gas emissions. In the scenario that also includes climate policy not only energy efficiency is increased, but emissions are reduced further by changes in the energy supply mix and application of carbon capture and storage.

The *global resource efficiency* scenario closes about half of the gap between the *baseline* scenario and the 2 °C case. There are several co-benefits of efficiency measures, including improvement in energy security, and reduction in air polluting emissions and greenhouse gases. Efficiency measures, therefore, could be regarded as more attractive than those that lack some of these co-benefits, such as carbon capture and storage and bio-energy use.

Efficiency measures can be implemented using various policy instruments. Research has shown that the choice of policy instruments involves trade-offs and that the final choice depends on the sector. Generic price-based instruments, such as greenhouse gas prices and taxes, have the advantage of flexibility for actors to weigh different measures (e.g., efficiency versus fuel switch), using locally available information in investment decisions. However, this assumes that actors have sufficient information and/or possibilities to invest, which is more likely to be the case for large companies than for individual consumers. Standards have proven to be very effective efficiency measures, such as for buildings (these standards can still be relatively generic). Other measures include information provision, stimulating investments via subsidies and/or soft loans and labelling. These measures have had various degrees of success in the past.

3.7 Conclusions

- In the absence of new policies, global annual final energy demand is projected to increase from around 330 EJ/yr in 2010 to over 550 EJ/yr by 2050. The largest part of the growth in demand (90%) would come from developing and emerging countries, even though per capita energy consumption will still be 2.5 times higher in OECD countries than in the rest of the world. The share of fossil fuels in the total energy demand would remain large (close to 80% by 2050), and greenhouse gas emission targets would be a long way from being met.
- The EU's dependency on imports of fossil fuel would rise; to up to over 90% for oil by 2040 (from around 60% in 2010), followed by a decline driven by high prices.
- Energy efficiency can significantly reduce energy consumption worldwide. The *global resource efficiency* scenario considered reduces energy use by slightly more than 30% compared to policies continued in line with that envisaged by the EU.
- The *global resource efficiency* scenario reduces the import of fossil fuels and bio-energy into Europe and reduces the use of fossil fuel reserves. Further introduction of climate policy may strengthen this effect, except for bio-energy imports which would increase.
- The *global resource efficiency* scenario closes about 50% of the gap between baseline emissions and the 450 ppm CO_2 eq mitigation scenario.

Notes

1 In this report, primary energy for solar, wind, hydro and nuclear power is reported assuming a 40% efficiency (for accounting purposes only).

2 Reserves are identified as that part of the resources considered to be economically exploitable at current prices and technology levels, and have a very high probability of being there. Other resources categories thus have higher production costs and/or a lower probability of being there.

3 Surplus Assigned Amount Units (AAUs) refer to the positive difference between the quantity of greenhouse gases that an Annex B country can emit in accordance with the Kyoto Protocol and the actual (projected) total greenhouse gas emissions by 2012.

FOUR

Land

4.1 Introduction

In the coming decades, substantial increases in agricultural productivity are needed in order to meet rising demand for food, feed, fibres and fuel at affordable prices, while limiting agricultural expansion into natural areas (Clay, 2004; Godfray *et al.*, 2010; Koning *et al.*, 2008; Smith *et al.*, 2010; Van Vuuren and Faber, 2009). In addition to population growth, increasing pressure on land also originates from diets becoming more meat intensive (Stehfest *et al.*, 2009; Steinfeld *et al.*, 2006) the advance of biofuels (Fischer *et al.*, 2009; Ros *et al.*, 2010) and increasing demand for wood products. Together with the vagaries of climate change, these developments are - in certain instances already today - leading to a chain of reactions including price spikes, rising interest in farm land by foreign investors, social unrest and rising pressures on natural ecosystems (Deininger and Byerlee, 2011; FAO, 2008; Harvey and Pilgrim, 2011; Koning and Mol, 2009; PBL, 2010). The area of unmanaged land suitable for agriculture offers potential for expansion (Figure 4.1). However, the unavoidable loss of biodiversity associated with this and the shrinking area of unaffected ecosystems are reasons for concern. Resource efficiency could possibly slow down, or even halt this trend (EC, 2011a). An overview of scarcity dimensions of land for agriculture/forestry and terrestrial biodiversity is presented in Table 4.1.

4.2 Resource efficiency mechanisms analysed

There are numerous ways in which the pressure on land could be reduced, or redirected, away from biodiversity-rich areas. The following resource efficiency mechanisms were included in this study:

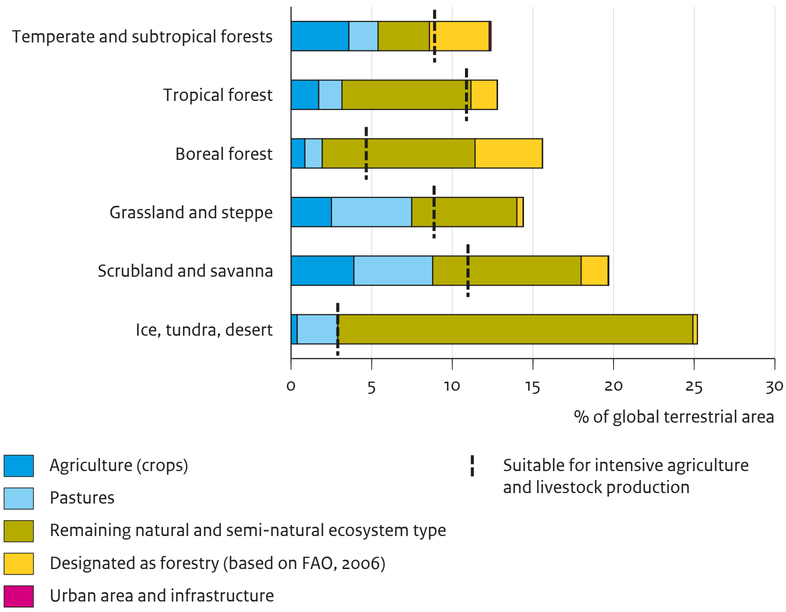
(i) Increasing crop yields;
(ii) Increasing animal feed conversion efficiency;
(iii) Reducing supply chain waste and losses;
(iv) Changing dietary preference in favour of less resource demanding food (e.g., less meat);
(v) Improving forest management;
(vi) Expanding biodiversity-rich conservation areas to protect biodiversity hot spots from being used for agriculture or being exploited in other ways, and to avoid rebound effects of yield efficiency measures.

With the exception of (ii), all of these measures were derived from Chapter 5 of the PBL study 'Rethinking global biodiversity strategies' (PBL, 2010). An overview of how they were implemented in the model is presented in Table 4.2. Potential measures not considered in the quantitative modelling analysis for this study include:

- Urban sprawl – urban areas were assumed to be constant in all scenarios analysed;
- Changing material use, such as increasing recycling in timber/paper industry and replacing wood with synthetic materials.

Figure 4.1

Land use and land cover per potential ecosystem type, 2000



Source: Based on Westhoek *et al.* (2010)

Today's world is facing competing claims by different types of land use. Expanding agricultural production is possible, especially in forest ecosystem types with rich biodiversity.

Table 4.1

Scarcity dimensions of land for agriculture/forestry and terrestrial biodiversity

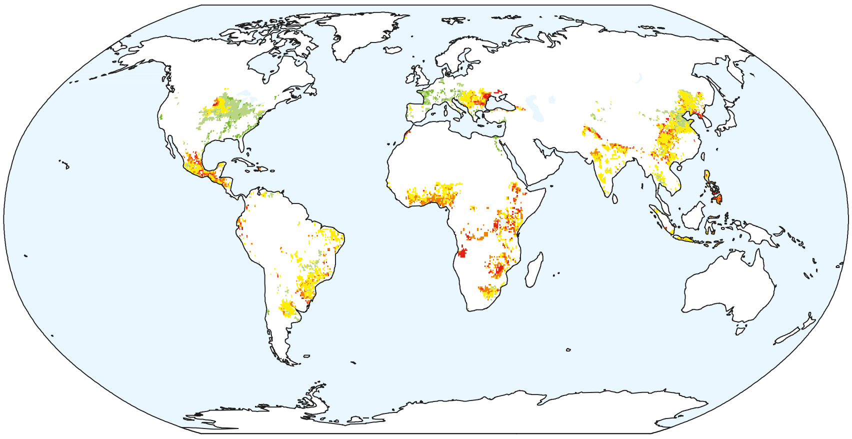
Physical	Economic	Political
Competing claims on land for provisioning ecosystem services including food, feed, fibre, fuel and forestry products ... ... leading to deterioration of regulating, cultural and supporting ecosystem services, including loss of biodiversity and of agricultural land quality.	Improperly functioning land markets. Some land uses (e.g., for bio-energy) are in many cases not economically viable without strong government support.	High food prices leading to social instability especially in low income countries. Scrambling for land, sometimes called 'land grab', including by foreign states and investment funds. Implications for nature and/or food production, of imports (e.g., feed crops, biofuels) from other countries (ecological footprint).

4.2.1 Increasing crop yields

Between 1970 and 2005, agricultural yields increased by about 1% per year on average, but yield increases especially of cereals appear to be levelling off, gradually (Bruinsma, 2003; Dixon *et al.*, 2009). Nevertheless, estimates of the differences between potential yields[1] and actual yields suggest that there is ample room for improvement (Figure 4.2). Such yield gaps are particularly wide in Sub-Saharan Africa (FAO and WorldBank, 2009; IAC, 2004; McIntyre *et al.*, 2009). Reasons for very large yield gaps include factors, such as low levels of agricultural inputs, lack of available location-specific technologies and inappropriate agronomic practices in general and are often caused by social, economic, infrastructural and institutional constraints (Bruinsma, 2003; IAC, 2004; Lobell *et al.*, 2009).

The yield assumptions for the baseline of this study were calibrated to FAO projections (FAO 2003; 2006), which are the most authoritative source for such projections. They imply some levelling-off of growth in agricultural productivity compared to the historic trend, and mostly

Figure 4.2
Yield gap maize, 2000



Yield gap (t/ha)

- Less than 1
- 1 – 2
- 2 – 4
- 4 – 5
- More than 5
- No significant grain maize

Source: Neumann *et al.* (2010)

Estimates of yield gaps between actual and potential yields suggest a large potential to increase agricultural production by improving management in areas already used for agriculture, especially in developing countries, particularly in Africa.

fall within the range of baseline or reference projections in other studies (Figure 4.3). For the EU, the increases are less than 0.5% per annum for most crop groups considered.

Assumptions regarding accelerated yield increases were inspired by the International Assessment on Agricultural Science and Technology for Development (McIntyre *et al.*, 2009). Acceleration (with yield growth rates being 50% higher than in the *baseline* scenario) would be possible, based on a boost in investment in agricultural research, development and extension, rural infrastructure, and enabling policies; particularly in developing regions.

4.2.2 Increasing animal feed conversion efficiency

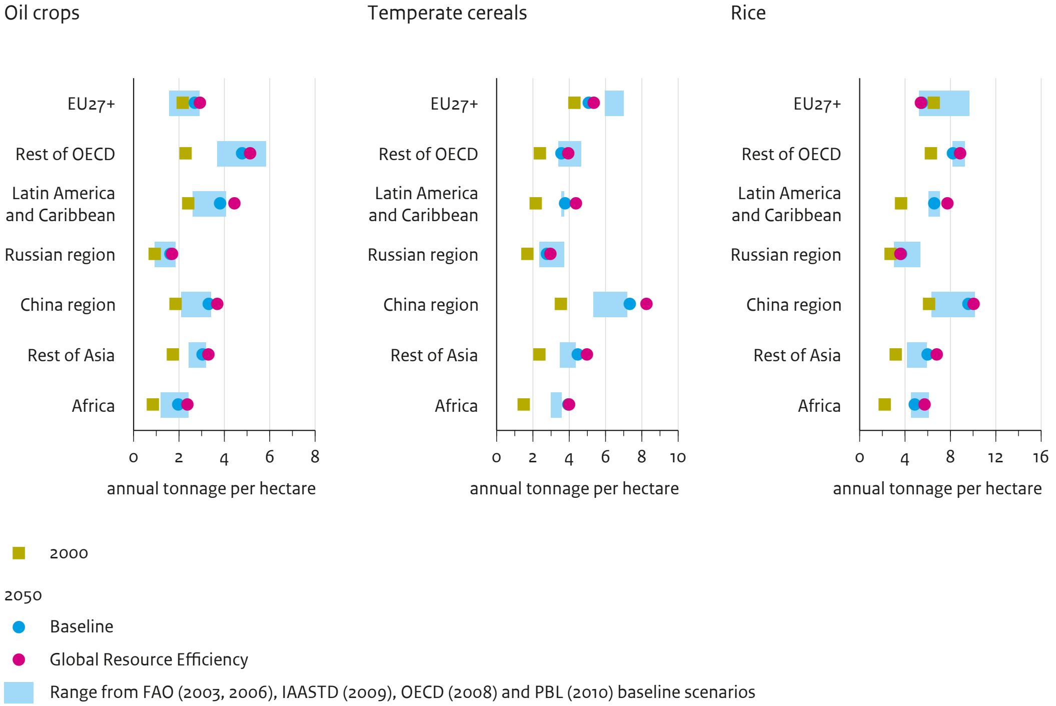
For the *baseline* scenario, gradual improvements are assumed in feed conversion efficiency for different animal categories based on historic trends of gradual shifts from roughage to feed concentrates and an increased share of animal production from pastoral to mixed and intensive systems (Bouwman *et al.*, 2005b).

For the global resource efficiency scenarios (G-RE-CP and G-RE), an additional 15% increase in feed conversion efficiency is assumed for the pig and poultry sectors. According to Oenema (2011) this is a realistic estimate considering the following:

- the large share of caloric value in feed currently used for maintenance (Oenema and Tamminga, 2005);
- the large variation in feed conversion across different countries (Lesschen *et al.*, 2011);
- the efficiency improvements achieved in the recent decades in intensive livestock systems.

In addition to improved feed quality (see assumptions for phosphorus, Chapter 5), these potential gains can be attributed to feeding practices that are more attuned to animal requirements, improved housing, improved sanitary and veterinary practices and more efficient animal breeds. To produce the improved feed quality needed to achieve these efficiency gains, a shift of 10% is assumed from the use of crop residues to feed concentrates in these sectors. For ruminant livestock (dairy, beef, sheep and goats), an additional 10% shift from extensive to mixed systems compared to the baseline was assumed.

Figure 4.3
Regional yields



Source: PBL and as indicated in the graph

Different agricultural outlooks project substantial yield improvements up to 2050 in most regions, under baseline conditions. The projected yields were calculated on the basis of the combined effects of projections for technological development, and environmental and economic conditions.

Table 4.2
Summary of land-use-related scenario assumptions

	***Baseline* and *envisaged policies* scenarios**	**Resource efficiency scenarios**
Crop yield increase	IMAGE/LEITAP model results used for OECD Outlook, which were calibrated against FAO projections.	Baseline yield increases are accelerated by 50% (in OECD countries to a maximum increase of 1.5% per year).
Feed conversion	Feed conversion efficiency improves according to historic trends.	Feed conversion efficiency increased by 15% above the baseline level (pigs and poultry). Shift of ruminant production from pastoral to mixed systems is accelerated.
Supply chain waste and losses	Continuation of current losses implicitly assumed.	Agricultural losses are assumed to be reduced by 7% of total produce.
Dietary preferences	Income elasticities are dynamically dependent on purchasing power corrected real GDP per capita.	Worldwide, meat consumption converges to a level of 50% above that suggested by Willett *et al.* (2001).
Share of timber from forest plantations	Increased production of forest products follows historical trend of exploitation from plantation/ natural forests.	Forest plantations are expanded to meet about 50% of timber demand by 2050. All selective logging is assumed to be based on Reduced Impact Logging (RIL).
Protected areas	Protected areas maintained at current level.	Globally, 20% of protected area covering a representative selection of the Earth's ecosystems, with a focus on threatened and endemic species.

The consequence of the latter shift would be a relative decrease in pasture compared to the baseline, but an increase in cropland.

4.2.3 Reducing supply chain wastes and losses

Large amounts of agricultural products – sometimes in excess of 50% – are lost in the supply chain from 'farm to fork'. Supply chain losses are caused by numerous factors, such as harvest inefficiencies (including poor timing), poor harvest conditions (e.g., too wet), losses during transport, deterioration during storage on-farm, on-market, and after purchase by consumers. Losses are poorly documented and estimates vary greatly but are always more than 20% of supplies. A 10% reduction in losses appears to be achievable. This would mainly require reductions in waste and losses at retail and household levels in developed countries, and mostly earlier in the supply chain (post-harvest and storage) in developing countries (Lundqvist, 2009; Parfitt *et al.*, 2010; Stuart, 2009). In the resource efficiency scenarios used in this study, a 7% reduction in losses of total agricultural production is assumed.

4.2.4 Changing dietary preferences

Numerous studies have demonstrated the negative environmental impacts of livestock production (FAO, 2009a; Stehfest *et al.*, 2009), and the potential environmental and health benefits of reduced consumption of animal products. However, historical evidence and country comparisons show strong relationships between prosperity and intake of animal products. This relationship is also expressed in the modelling suite, where income elasticities of demand for agricultural and food commodities are dynamically dependent on purchasing power corrected real GDP per capita, according to FAO 2003 World Food Model.

For the global resource efficiency scenarios (G-RE and G-RE-CP), meat consumption worldwide was assumed to converge at 50% above the level suggested by the healthy diet proposed by Willett *et al.* (2001). This corresponds to a weekly intake per person of 105 g beef, 105 g pork, and 460 g poultry and eggs. Consumption of fish and dairy products follows the *baseline* scenario. The Willett diet is in line with WHO recommendations (WHO, 2002, 2003), which are specified in terms of components, such as protein, fat, and saturated fat, rather than products. For developing countries, these assumptions imply that food consumption is not bound by restrictions until the level mentioned above is reached. For most OECD countries and several emerging countries, it implies a significant reduction of meat intake.

4.2.5 Improving forest management

In the *baseline* scenario, the regional expansion of forest plantations follows the FAO scenarios, described by Brown (2000). Spatial allocation is done according to a set of specific rules with preference for plantations on recently cut forests and land formerly used for agriculture. Increasing the share of timber from well-managed, highly productive forest plantations would result in less disturbance of natural forests with an overall positive net effect on biodiversity. Brown (2000) suggest that about 50% coverage of global wood demand from plantations would be consistent with a high resource efficiency ambition level [see also (Arets *et al.*, 2010)], which was therefore assumed as target for the global resource efficiency scenarios (G-RE and G-RE-CP).

4.2.6 Expansion of protected areas

Expansion of protected areas is a classical measure to protect biodiversity rich ecosystems. A political target of 17% protection per biome has recently been agreed (CBD, 2010). For the global resource efficiency scenarios, we assumed that currently protected areas (IUCN and UNEP, 2006) are complemented to 20% of each of 65 terrestrial ecoregions, using a combination of hotspots maps proposed for priority setting (Brooks *et al.*, 2006), consisting of WWF Global 200 priority ecoregions; amphibian diversity areas; endemic bird areas and Conservation International hotspots. The implications vary by region. Globally, about 10 million km^2 would be added to the existing 15 million km^2 of protected areas.

4.3 Impact indicators

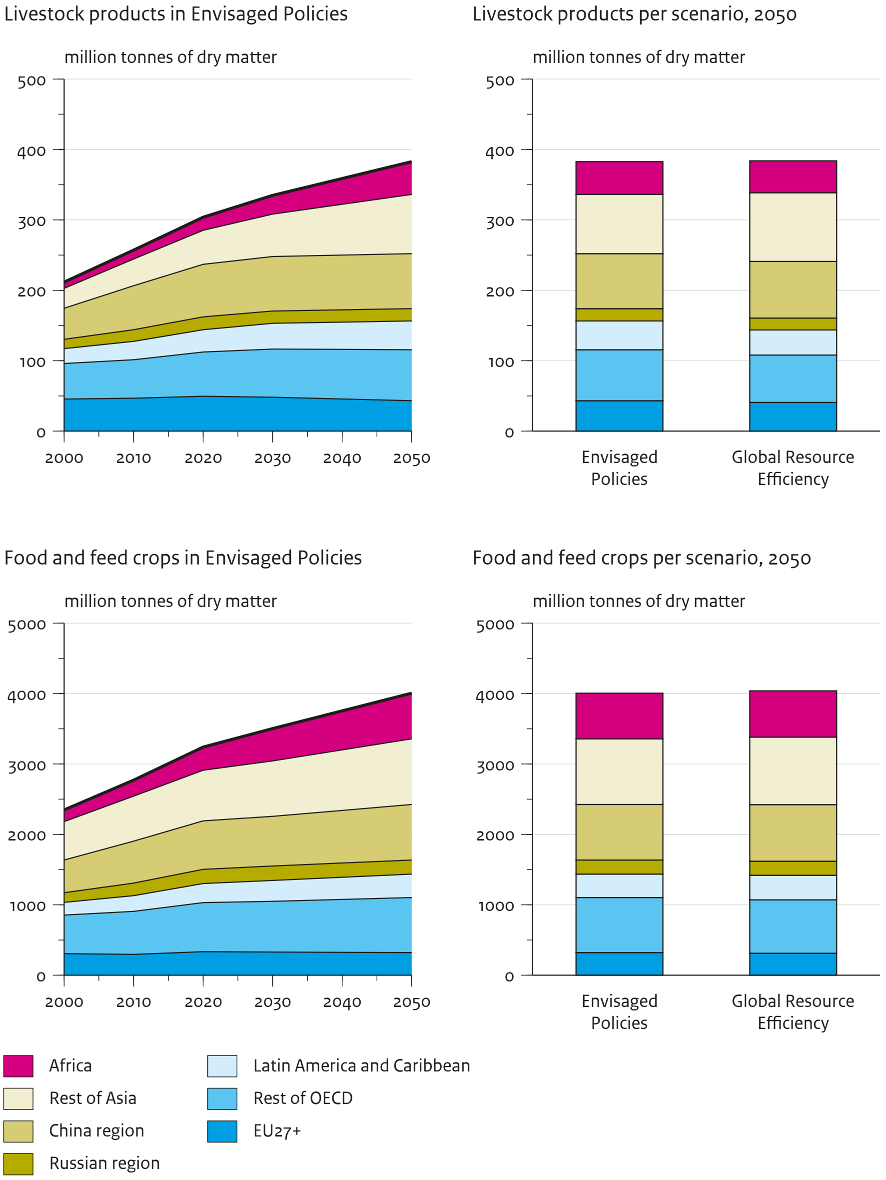
- Total area of different categories of land use and land cover per world region, and/or at 0.5 x 0.5 degree grid, allowing the identification of hotspots of pressure at sub-regional level.
- Biodiversity indicators: Mean Species Abundance in different geo-political regions, extent of natural and semi-natural areas, and extent of wilderness areas.
- Effects on input (phosphorus) use (discussed in Chapter 5).

4.4 Results

The results of the analysis are presented in a series of figures as follows: agricultural production in Figure 4.4; land use in Figure 4.5 (maps), and Figures 4.6 to 4.8 (diagrams); and the MSA biodiversity indicator in Figures 4.9 to 4.11.

Agricultural production (Figure 4.4) increases continually, however, more than 50% of the increase is projected

Figure 4.4
Agricultural production



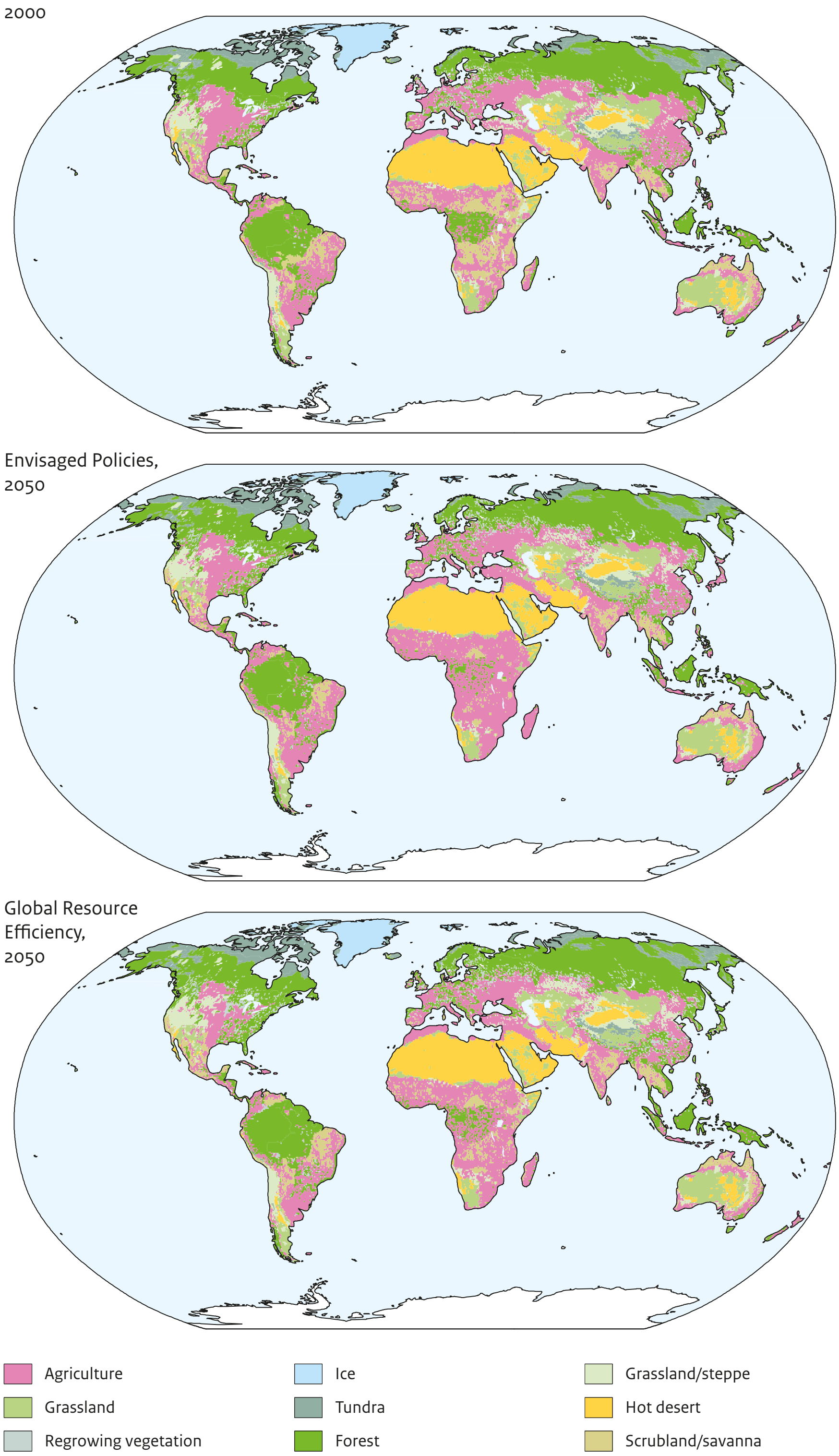
Source: PBL

Increase in agricultural production is projected to be particularly strong outside the EU. Overall differences between the scenarios are only marginal, because some scenario assumptions have opposing effects on production.

to occur before 2030. Furthermore, the differences between the scenarios are remarkably small in spite of improvement in supply chain efficiency and the diet imposed to OECD countries. The reason is that a major part of the efficiency gains is translated in lower consumer prices, stimulating a higher consumption in developing countries, rather than less production.

For land use in the *baseline* and *envisaged policies* scenarios, the results in Figure 4.6 show for the EU, an increase in agricultural area in 2020 compared to 2010, followed by a decline. A similar trend can be seen in other OECD countries and the BRIICS[2] (Figure 4.7), with the main difference that second generation biofuels play a more significant role in these countries. In developing countries (Figure 4.8), the tendency in the *baseline* and *envisaged policies* scenarios is continuous increase in agricultural land

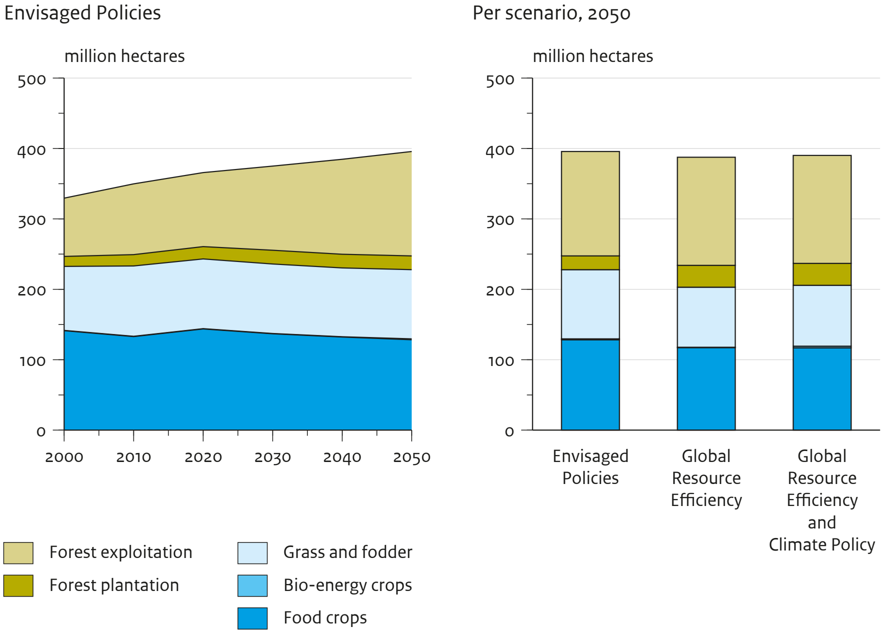
Figure 4.5
Land use



Source: PBL

A substantial part of the agricultural expansion in the envisaged policies scenario particularly in Africa is avoided in the global resource efficiency scenario.

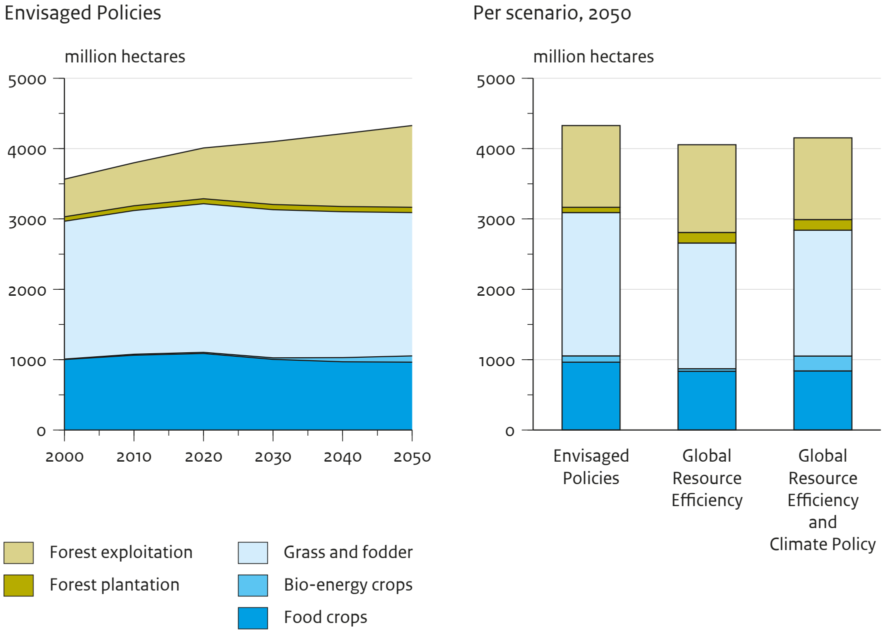
Figure 4.6
Land use in EU27+



Source: PBL

Agricultural land use in the EU27+ is projected to contract, gradually, after 2020, in the envisaged policies scenario. This contraction is somewhat more pronounced in the global resource efficiency scenarios. The area of exploited forests is projected to increase. Bio-energy crops are projected to play a minor role in the EU27+ (about 1% of the agricultural area, by 2050, in the global resource efficiency and climate policy scenario).

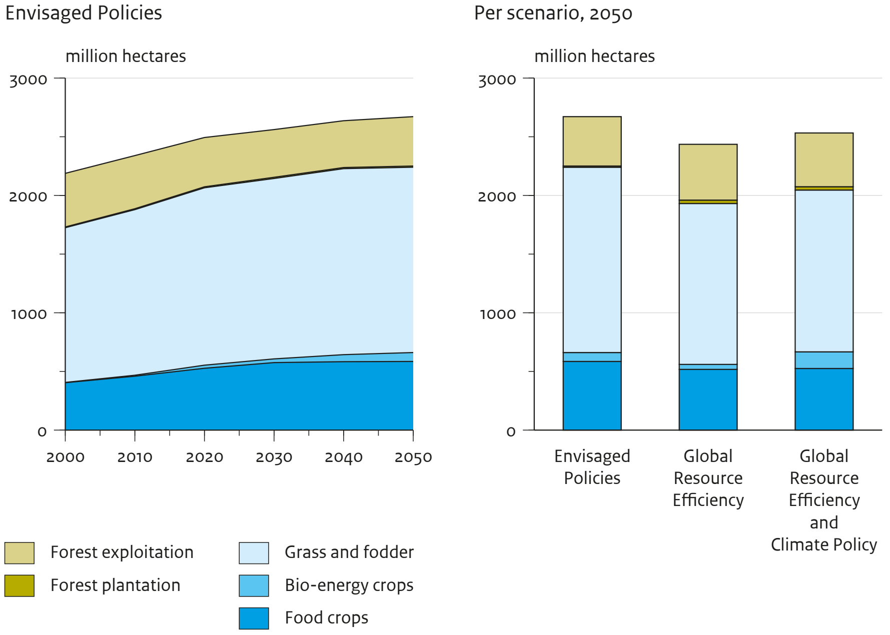
Figure 4.7
Land use in OECD (excl. EU27+) and BRIICS countries



Source: PBL

The projected land use trend in other (non-EU) OECD and BRIICS countries is similar to that in the EU27 + (Figure 4.6), but with a more pronounced share of bio-energy crops and with a stronger effect of resource efficiency policies.

Figure 4.8
Land use in developing countries



Source: PBL

Agricultural land use in developing countries is projected to increase, steeply. About half of the increases projected in the envisaged policies scenario are avoided in the global resource efficiency scenario. However, many of these efficiency gains would be claimed by bio-energy crops in the scenario with strong climate policy.

use. These changes occur mostly in Sub-Saharan Africa (Figure 4.5).

The results of the *global resource efficiency and climate policy* scenario suggest a significant contraction in agricultural land use in the EU, other OECD and BRIICS, and an approximate net stabilisation at 2020 levels in developing countries. Second generation biofuels are significant in the *envisaged policies* scenario and, especially in the *global resource efficiency and climate policy* scenario but not in the EU. Because of the rebound effects for agricultural production mentioned above, the effects of resource efficiency are much smaller than would be expected on the basis of the resource efficiency assumptions.

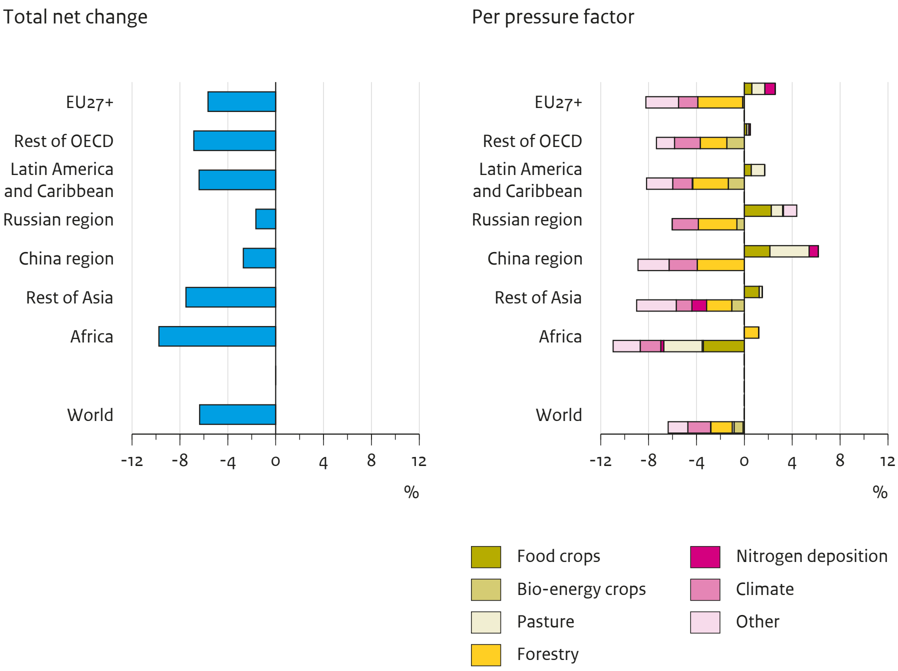
Aggregated results at world-region level mask the considerable variations that exist within regions, as shown in Figure 4.5, in which changes are shown to be most significant in Africa. Even in the *global resource efficiency* scenario, agricultural expansion would continue in Africa up to 2040, but would be about 50% less than in the *baseline* and *envisaged policies* scenarios.

The results for the MSA indicator for biodiversity (Figure 4.9) in the *Envisaged policies* scenario suggest a considerable decline in biodiversity in most regions. This is caused mainly by forest exploitation, climate change and other factors, such as fragmentation, infrastructure and encroachment. In Africa, agricultural expansion is the main cause of the MSA decline. As shown in Figure 4.10, these losses are only partly compensated in the *resource efficiency* scenarios. The strong pressure caused by forest exploitation in these scenarios suggests that, where agricultural expansion has ceased and forestry products thus are no longer available as a 'by-product' of land conversion, the demand for wood products will remain. In the *global resource efficiency and climate change* scenario (G-RE-CP, Figure 4.11), additional biofuel crops also appear as an important pressure on the land, approximately halving the effect of the *global resource efficiency* scenario; and in spite of the benign climate effects in G-RE-CP.

4.5 Limitations of the analysis

There is considerable uncertainty about future demand for wood products and how this will be met. Potential for resource efficiency on the demand side of wood products has not been investigated in this study. Demand from planted forests, currently based on Brown (2000), is being

Figure 4.9
Change in Mean Species Abundance in Envisaged Policies, 2010 – 2050



Source: PBL

In the envisaged policies scenario, between 2010 and 2050, the MSA biodiversity indicator presents a negative net change in all world regions. Africa is most seriously affected, especially, because of the expansion of cropland and pasture. The dominant factors exerting negative pressure on MSA in other regions are forest exploitation, climate change and other human-induced factors, such as fragmentation, infrastructure and encroachment.

updated according to (Carle and Holmgren, 2008), but is not yet available.

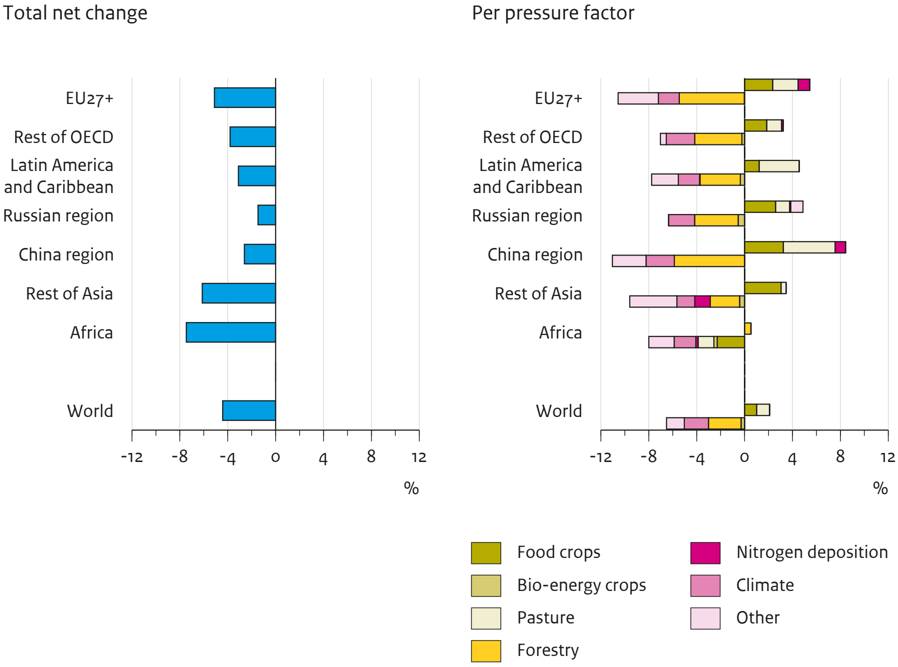
Furthermore, the focus of the analysis presented was on rural land use. Urban areas were assumed to be constant in all scenarios analysed and related aspects such as more efficient infrastructure development were not taken into consideration. This could have positive or negative effects on biodiversity.

The scenario assumptions were implemented world-wide. Regional differentiation does occur in the models because parameters are region specific, but opportunities for resource efficiency targeted to specific regions were not investigated. It could be interesting, for example, to analyse a scenario with focus on yield improvements and reduction of post harvest losses in developing countries, whereas the focus in industrialised countries could be on waste reduction at retail level and consumer level. Uncertainties related to some of the scenario assumptions are discussed in the following paragraphs.

4.6 Discussion and policy implications

Technological progress in agricultural systems is generally slow, particularly in ruminant livestock production systems. In other agricultural sectors, the response of farmers to change, and the adoption of new technologies are generally faster. Efficiency improvements have been about 1% per year over the last five decades in developed countries but technological progress has been much slower in many developing regions, such as Sub-Saharan Africa, where demand for agricultural products is rising steeply, whereas wide yield gaps suggest that there is still considerable room for yield improvements (Figure 4.2). Hence, progress in resource efficiency in crop and livestock production as assumed in the *global resource efficiency* scenario would need a redoubling of efforts and investments in many developing countries. Even the baseline assumptions, based on FAO projections (Bruinsma, 2003; FAO, 2006b) could be considered optimistic for a scenario without new policies, considering the high estimates of capital requirements to achieve

Figure 4.10
Change in Mean Species Abundance in Global Resource Efficiency, 2010 – 2050



Source: PBL

In the global resource efficiency scenario, the negative net change in MSA, up to 2050, is less pronounced than in the envisaged policies scenario (Figure 4.9), mainly because of contraction or less expansion in agricultural land use. A considerable part of the avoided MSA losses is offset by stronger negative pressure from forestry.

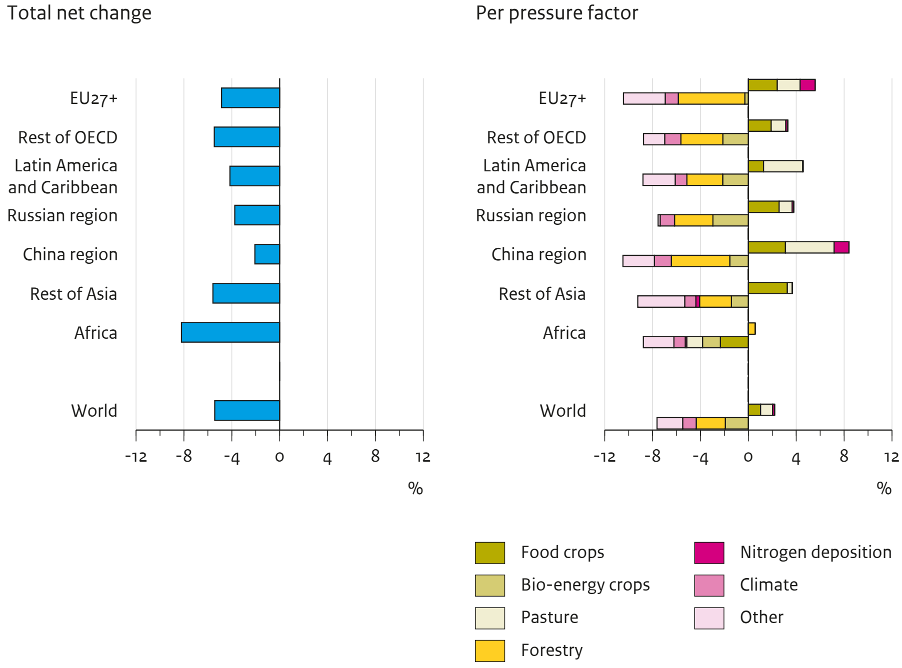
them as indicated by Schmidhuber *et al.* (2009). On the other hand, they appear modest compared to policy goals such as those stated in NEPAD's Comprehensive Africa Agriculture Development Programme (CAADP, 2011), which aims for an average annual growth rate of 6% in agriculture by 2015.

Numerous studies have been published on how agricultural yields and food supply could be improved sustainably (FAO and WorldBank, 2009; Gurib-Fakim and Smith, 2009; IAC, 2004; Izac *et al.*, 2009; OECD, 2011b; Pretty *et al.*, 2010; Pretty *et al.*, 2003). Most of these studies particularly focus on developing countries. On the ground, solutions appear to be mostly related to the introduction of new (high-yielding or more resistant) varieties or breeds and practices to enhance water and nutrient use efficiency, soil health or pest and weed control. In most cases, their implementation does not require cutting edge technologies. Main reasons why improvements tend to be so difficult to accomplish in real life are that (i) new tools and practices must be extensively tried, tested and adapted to local conditions first, before they can be fit into farmers' operational routine; and (ii) sustainable yield improvements usually require changes to production systems which are unattractive, difficult or impossible to implement by individual farmers under current social, institutional, infrastructural and political conditions. Addressing such issues requires an integrated approach and close participation between the different types of stakeholders, both at the local level as well as at national, regional and international level.

In regions, where potentially suitable land is abundant, it seems even more difficult to realise the potential of resource efficiency (including biodiversity gains) if policies to improve yields are not accompanied by measures to discourage the conversion of natural lands. In this study, this is partly achieved by the increase in protected areas. Other instruments, such as REDD have also been designed (in part) to address this issue, as well as whole-chain initiatives and certification schemes governed by producers, local communities, bankers, traders and other supply chain stakeholders, with little or no government involvement. Adherence to such schemes and new initiatives are strongly increasing. Identifying measurable, permanent impacts of such initiatives remains challenging, however, and the ideal role – if any - of governments (and the EU) within or alongside such schemes (e.g.,

Figure 4.11

Change in Mean Species Abundance in Global Resource Efficiency and Climate Policy, 2010 – 2050



Source: PBL

In the global resource efficiency and climate policy scenario, the negative net change in MSA is intermediate between the envisaged policies (Figure 4.9) and global resource efficiency (Figure 4.10) scenarios. The negative effect of climate change on MSA is much weaker, but bio-energy crops become a stronger factor affecting MSA.

observer, facilitator, co-funder, regulator) is still unclear (Biermann and Pattberg, 2008; Vermeulen *et al.*, 2010; WWF, 2010). Nepstad *et al.* (2009) provide a concrete example with a strong resource efficiency component, on how a combination of different initiatives from national and international governments, supply chain stakeholders and NGOs would have contributed to significantly reduce deforestation in the Brazilian Amazon.

In regions where agricultural land use is likely to contract, such as in the EU and most OECD countries, policy intervention could help to simultaneously enhance resource efficiency, facilitate ecosystem restoration and address socio-economic impacts. This could include, for example, the expansion of conservation areas, payments for environmental services on private lands, and/or measures to exploit alternative employment opportunities that will arise in high nature value areas. Such incentives could be targeted to restore pristine or semi-pristine ecosystems as well as very extensively used high nature value farmlands.

Resource efficiency appears to be a pre-requisite for sustainable land use as it would not only spare land for nature and the ecosystem services associated therewith, but also contribute to food security, energy efficiency, mitigating green-house gas emissions from land use and alleviating the competition for land. Such positive interactions are not automatically generated, however. Specific policies are required to avoid an overly strong focus on short-term efficiency of marketed resources and to address the effects of unavoidable negative externalities, which both could jeopardise resilience in the long term. Issues include, for example, the potential loss of job opportunities for unskilled workers, marginalisation of farmers (or entire communities) that are not able to adopt innovations; negative effects from additional amounts of water and fertilisers needed to sustain higher yields; and deterioration of animal welfare in intensive livestock production systems (OECD, 2011b; Wegner and Zwart, 2011; Westhoek *et al.*, 2011). Here again, complementary roles could apply for governments, private sector and multi-stakeholder arrangements.

4.7 Conclusions

- In the absence of strong resource efficiency efforts, the agricultural area is projected to expand extensively in developing countries. Most of the expansion would occur in Africa especially up until 2030, leading to substantial loss of nature and biodiversity.
- In most other regions including the EU, the agricultural area would slowly contract after 2020, but overall, terrestrial biodiversity would continuously decline as a consequence of continued pressure from forest exploitation and the effects of fragmentation, climate change and reactive nitrogen emissions.
- Ambitious global effort to improve the efficiency of agricultural production, consumption and food supply chains could reduce the agricultural expansion in developing regions by half, between 2010 and 2050, also in Africa, and virtually halt expansion after 2040. However, these efforts alone would not suffice to halt the increase in pressure on land resources and biodiversity loss if other pressures, such as reactive nitrogen emissions, climate change and forest exploitation remain unchecked.
- If managed adequately, expansion of forest plantations as part of a resource efficiency strategy could have a long-term beneficial effect on land resources and global biodiversity, but the effect is negative in the short-term. Likewise, within the time horizon of this study, use of bio-energy as part of mitigation strategies for climate change puts additional stress on biodiversity.
- These results suggest that efforts to increase yields sustainably are crucial in developing countries where increased food supplies are most needed. Most of these countries have a large untapped potential to increase yields. At the same time, the EU and other OECD countries have the potential to choose to pursue a balance between highly productive areas, extensively used farmland and restoration of pristine and semi-pristine conservation areas, such as broadleaf temperate forests that currently comprise the world's most endangered ecosystems.

Notes

1 Potential yields are agro-ecologically attainable yields, as demonstrated by top farmers or research trials under similar soil and weather conditions, or as calculated by simulation models calibrated to such conditions. See Lobell *et al.* (2009) for a discussion of the concepts involved.

2 Brazil, Russia, India, Indonesia, China and South Africa.

FIVE

Phosphorus

5.1 Introduction

Phosphorus (P) is used mainly in fertilisers, detergents, animal feed and chemicals (Figure 5.1). The first category is dominant in terms of volume with around 80% of global use of phosphate rock. Phosphorus plays a critical and irreplaceable role in agricultural production. Phosphorus fertilisers are needed to sustain current (high) crop yields. The increased yields as discussed in the previous chapter would require even higher amounts of phosphorus.

At present, phosphate rock is the most significant source of phosphorus. Phosphorus use has increased substantially over the last few decades (Figure 5.2). According to the International Fertilizer Industry Association (IFA), in 2008, 53.5 million tonnes (Mt) of $P_2O_5$1 was mined (IFA, 2008). World production is expected to further increase in the coming decades. Given the fact that production is based on non-renewable resources, consumption ultimately leads to depletion of high-grade phosphorus resources. High-grade ores are concentrated in only a few countries (USGS, 2011). With respect to pollution, the main issue is that excessive use of phosphorus fertilisers, phosphorus nutrients from other sources and phosphorus detergents lead to large flows of phosphorus into surface water, causing eutrophication of freshwater and marine ecosystems. In turn, this has a number of consequences, such as algal blooms, algal scum, enhanced benthic algal growth and massive growth of submersed and floating macrophytes and secondary problems, such as oxygen depletion in water and fish death (EEA, 2001; NLWRA, 2001; Vollenweider *et al.*, 1992). The scarcity dimensions of phosphorus resources are outlined in Table 5.1.

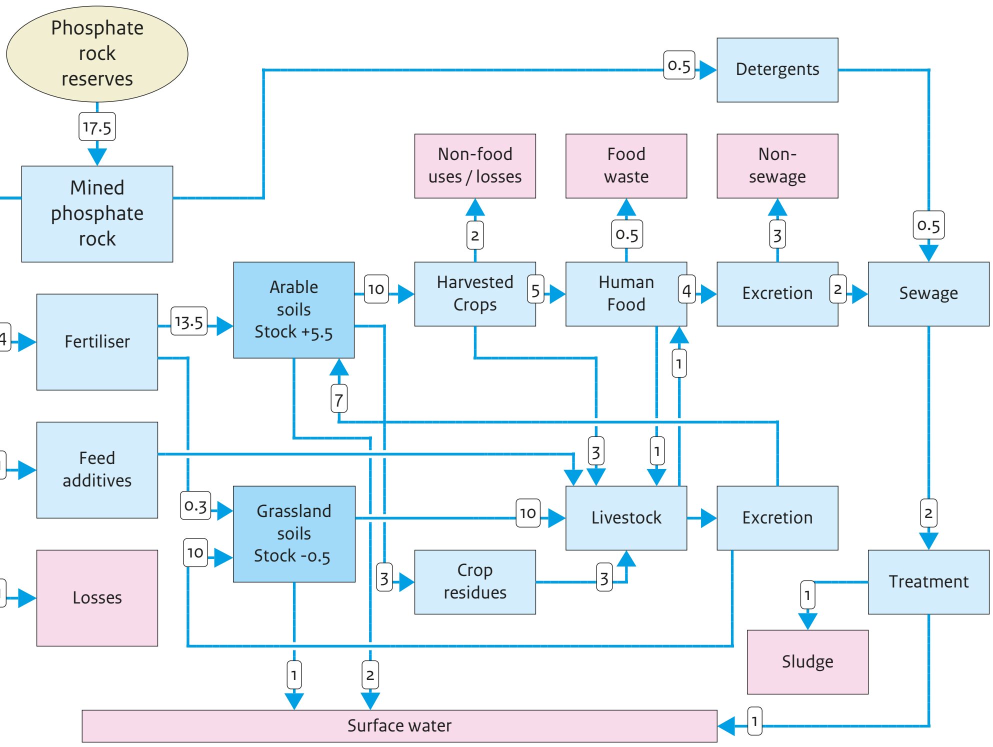
With the current increase in the use of phosphorus, particularly phosphorus fertilisers, it has been claimed that the global phosphate rock reserve may be depleted within decades (Cordell *et al.*, 2009). Other studies, however, indicate that depletion is only likely in the long-term (Bondre, 2011; Dawson and Hilton, 2011). Estimates of phosphorus resources are regularly updated.

Historical data on phosphorus fertiliser use show a number of important features (Figure 5.2). In industrialised countries, phosphorus fertiliser use peaked in the 1970s and has gradually declined since then. In the Russian region, phosphorus fertiliser was used very intensively until the early 1990s and then its use declined. Phosphorus fertiliser use in Africa is small and shows a decreasing trend. In Latin America, its use is also relatively small, but increasing, while in Asia there has been a dramatic increase since the 1970s. Short-term variations on these trends are related mainly to price fluctuations.

Part of the phosphorus added to soils as fertiliser and manure is used by the plant in the year of application. A varying but substantial part accumulates in the soil as ‘residual phosphorus’. This reserve can contribute to phosphorus in soil solution and be taken up by crops for many years. If the amount of readily available phosphorus is below a critical level, the rate of

Figure 5.1
Global phosphorus flows, 2000

million tonnes P per year



Source: Van Vuuren et al. (2010b)

Phosphorus is used mainly in fertilisers, detergents, animal feed and chemicals. The first category dominates in terms of volume (around 80% of global use of phosphate rock). Livestock also plays a pivotal role in the phosphorus cycle, even though little phosphorus originates from primary sources (feed additives).

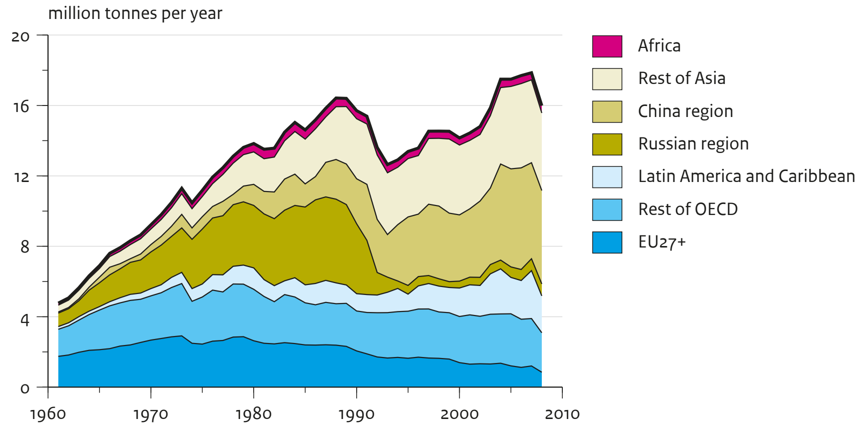
Table 5.1
Scarcity dimensions of phosphorus

Physical	Economic	Political
Rising demands on finite resources, for which no alternative exists for agricultural production Soil phosphorus depletion in many developing countries, causing soil degradation and productivity loss; one of the causes of deforestation Eutrophication of surface waters	High costs to restore phosphorus depleted soils High prices for phosphorus fertiliser affects phosphorus use in developing countries	Concentration of available resources in a few countries (the EU is almost completely dependent on imports) Agricultural expansion and intensification expected in developing countries, where high phosphorus fertiliser inputs are required to sustain yields

phosphorus release from residual soil phosphorus becomes insufficient to sustain optimal crop yields, such as in many parts of Africa. As the soil phosphorus status improves up to the critical level, crop phosphorus recovery may slowly increase to levels up to 90%. In an ideal situation, when an adequate amount of phosphorus is present in the readily available pool, annual phosphorus inputs from fertiliser equal to the plant phosphorus uptake may be adequate to maintain good crop yields (Syers *et al.*, 2008).

Cumulative phosphorus fertiliser applications in the United States (450 kg phosphorus / ha) and western Europe (1440 kg / ha) are large compared with developing

Figure 5.2
Phosphorus fertiliser use



Source: FAOSTAT (FAO, 2011a)

Since 1960, global use of phosphorus fertiliser has increased fourfold, and over the last decades mainly in emerging and developing countries.

countries (Africa, 90 kg/ha; South America, 380 kg/ha; Asia, 425 kg/ha). This explains the decline in phosphorus fertiliser use in most industrialised countries, while crop production is still increasing. Historic applications have contributed to the build-up of residual soil phosphorus, which can be taken up by crops in future years. In western Europe, for example, the annual phosphorus application today approximately equals the withdrawal by crop production (Figure 5.3). Further reduction at field level would lead to soil depletion because phosphorus inputs equal to withdrawal (maintenance) are required to sustain future food production.

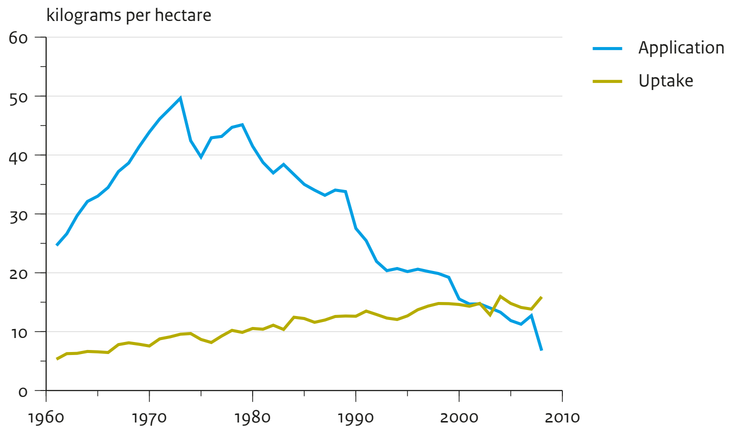
In developing countries, this residual soil phosphorus pool is still small. As a result, soils are rapidly depleted, and increased crop production and phosphorus supply must come from arable land expansion, whereas depleted soils are at risk of further degradation and abandonment. Therefore, increased phosphorus use is needed to sustain future food production and to maintain soil fertility.

Another important global user of phosphorus is monogastric livestock production. A large part of phosphorus in cereal grains is in the form of phytate, an insoluble compound. When grains are fed to non-ruminants, such as poultry and swine, most of the consumed phosphorus is excreted, because these animals cannot fully digest phytate. Thus, phosphorus is often added as a supplement to the feed. Globally, phosphorus supplemented to animal feed is about 1 million tones per annum (5% of global phosphorus use). The use of phosphorus feed supplement can be reduced by plant breeding to reduce the amount of phytate, or by pre-treating the feed, or by adding enzymes to improve the digestibility of phytate (Abelson, 1999).

The use of phosphorus-based detergents in washing machines and dishwashers currently amounts to 1.2 Tg phosphorus per annum (Global Phosphate Forum, 2008). This estimate probably includes domestic and industrial detergents, as well as other uses of phosphorus in industry. P-free detergents based on zeolites were introduced in Europe in the mid-1980s and progressively replaced detergents based on sodium tripolyphosphate ($Na_5P_3O_{10}$; STPP) through to the mid-1990s, when the markets stabilised (RPA, 2006). At present, phosphorus-free detergents based on zeolites make up 80% to 100% of all laundry detergents used in northern and western Europe. However, the use of automatic dishwashers is increasing in European households and no restrictions have yet been placed on the use of phosphorus-based detergents in these appliances.
Current phosphorus emissions from laundry and dishwasher detergents in the EU are about 0.4 kg per person per year. This corresponds to some 40% of the total phosphorus emissions from households of 0.9 to 1.0 kg per person per yr (Kristensen *et al.*, 2004). Most of these emissions are from laundry detergents (72%). However, there are large differences between European countries. At present, laundry detergents containing phosphorus are completely banned in some countries (Austria, Belgium, Germany, Ireland, Italy, Luxemburg, the Netherlands), while in countries such as Poland and the Baltic States,

Figure 5.3

Phosphorus fertiliser application and uptake by crops in western Europe



Source: Own calculations based on FAOSTAT (FAO, 2011a), USDA (2010) and Bouwman *et al.* (2005a)

In western Europe, application rates of fertiliser P have dropped below the uptake rates by crops, which leaves little potential for further reduction at the field level.

only 15% to 20% of laundry detergents are phosphorus-free (RPA, 2006).

5.2 Resource efficiency mechanisms analysed

A number of strategies are available to reduce the phosphorus use from primary sources:

(i) Reduce use of fertilisers in crop production by increasing the fertiliser use efficiency2 (FUE).

(ii) Improve the phosphorus conversion efficiency in livestock production systems by improving the overall feed conversion and by reducing the use of phosphorus supplements by adding phytase to feed primarily of monogastrics.

(iii) Close the agricultural phosphorus cycle by better integrating animal manure in crop production systems to reduce fertiliser use.

(iv) Recycle human excreta in agriculture to replace fertilisers from primary sources.

Outside agriculture, the following strategy is being considered:

(v) Replace phosphorus-based detergents with phosphorus-free detergents.

5.3 Aspects not considered

- With respect to recycling of human excreta, cultural taboos in various parts of the world have not been considered.
- The environmental impact of animal manure that currently (and in the baseline) ends up outside the agricultural system, such as manure used as fuel, has not been considered. For example, the burning of manure causes emissions. When this manure would be recycled in agriculture instead of being burned, data on emitted compounds and quantities would change in a resource efficiency scenario. This aspect has not been considered.
- Recycling of sewage sludge has not been accounted for in the *global resource efficiency* scenario. The amount of phosphorus lost via sewage systems is currently about 1.5 Mt globally of which almost 0.4 Mt in the EU.
- Use of bone meal has not been considered. Use of bone meal in animal feed has largely been abolished after the BSE crisis.
- Potential improvements in mining efficiency have not been considered.
- The measures assumed regarding detergent use include only domestic use and not industrial use of detergents, because data on industrial detergent use are not publicly available.

5.4 Scenario assumptions

An overview of scenario assumptions on phosphorus efficiency is presented in Table 5.2.

5.4.1 Fertiliser use efficiency

For constructing the *baseline* and *envisaged policies* scenarios (BL and ENVISAG), data from (Bruinsma, 2003) were used as a guide. Countries were divided into those with inputs exceeding the crop uptake (surplus countries) and those with current deficit (deficit countries). In deficit countries, PUE will gradually decrease to varying degrees. In contrast, fertiliser use decreased rapidly in eastern Europe and the former Soviet Union after 1990, leading to a strong apparent increase in fertiliser use efficiency.

In the *global resource efficiency scenario* (G-RE), in accordance with the assumptions on land use (Chapter 4), the growth of crop yields is 40% faster than in the *baseline* scenario. This has an effect on the fertiliser phosphorus input. With no further changes in technology, crop yield can be increased by improved management and increased phosphorus fertiliser inputs. At the same time, improved varieties will be introduced that show a higher phosphorus recovery. To assess the combined effect of these two developments, two cases were distinguished. Firstly, for countries with a phosphorus surplus, an increase of PUE of 50% of the additional aggregated yield increase was used in G-RE. This is an improved efficiency which is the combined effect of improved management and better crop varieties. Secondly, in countries with a phosphorus deficit, yield increases will not be possible without major increases in phosphorus fertiliser inputs. In the *baseline* and *envisaged policies* scenarios (BL and ENVISAG), phosphorus use in deficit countries increases rapidly (i.e. PUE will decrease, as has been the case in industrialised countries in the 1950–1970 period). In the *global resource efficiency scenario* (G-RE), a further decrease has been assumed in PUE in deficit countries of 50% of the aggregated additional yield growth relative to BL and ENVISAG.

5.4.2 Animal excretion

Improved feed conversion efficiency is part of G-RE scenario. It is difficult to estimate the impact of such major changes in livestock production systems on the use and recovery of phosphorus. The G-RE scenario, therefore, includes the simple assumption that phosphorus excretion per animal will decrease by 5%, by 2030, and by 10% by 2050, compared to the *baseline* and *envisaged policies* scenarios. This reduced phosphorus excretion is in addition to the improved recovery accounted for in the *baseline* scenario. The basic assumption is that this is achieved by fine-tuning feed rations and increasing the use of concentrates. Feed phosphorus additives in pork and poultry production and thus phosphorus excretion can be reduced by improving the capability of monogastrics to digest phytate, or by reducing the phytate contents of grain (Abelson, 1999).

5.4.3 Manure integration

Manure not used in the agricultural system in the *baseline* and *envisaged policies* scenarios (BL and ENVISAG) could be recycled in crop production systems to substitute mineral fertilisers. This would be an important process in many countries where manure currently is used as fuel or building material (as is common practice in India and many other countries), or in places where manure is unused, such as in the United States where it is currently stored in lagoons in CAFOs3. In situations where animal manure is already being used as fertiliser, it could generally be better integrated in crop production systems, particularly in industrialised countries. In the *global resource efficiency* scenario, the share of manure in nitrogen and phosphorus inputs determines where and how much fertiliser can be substituted by animal manure. In countries where this share is less than 25%, the assumption was made that fertiliser can be substituted by available manure. In countries where animal manure dominates the nutrient budget, the assumption was that manure integration cannot be improved. In general, these countries are phosphorus-deficit countries. The effectiveness of phosphorus in animal manure is assumed to be 100%.

5.4.4 Human excreta

In 2000, global human excretion of phosphorus was 4.3 million tonnes. This was 31% of the phosphorus fertiliser input. For the *global resource efficiency* scenario, part of the human excreta were assumed to be recycled in agricultural systems. The following assumptions were made to determine how much phosphorus from human excreta could be available for this purpose:

1. Human phosphorus from people with no access to improved sanitation cannot be made available for recycling.
2. Phosphorus from people with improved sanitation but no connection to sewage systems is completely available including urine and solid waste.
3. For households with a connection to a sewage system, urine is assumed to be collected separately from the solid waste and collected for recycling. For both sources, it was assumed that 25% of the phosphorus will be recycled by 2030, and 50% by 2050.

Data from Van Drecht *et al*. (2009) were used to estimate the quantity of recyclable P for all people with access to improved sanitation (WHO and UNICEF, 2000). Access to improved sanitation includes connection to public sewerage, but also to systems, such as septic systems, simple pit latrines, pour-flush, ventilated improved pit latrines and eco-sanitation. This was calculated for all

Table 5.2
Overview of scenario assumptions on phosphorus efficiency

Scenario	Scenario assumptions
Baseline and Envisaged policies	Fertiliser use efficiency (FUE), animal excretion and animal manure management as described in Bouwman *et al.* (2009). FUE is based on FAO's *Agriculture Towards 2030* (Bruinsma, 2003).
Resource efficiency scenarios	**1. Fertiliser use efficiency** (FUE, dry matter production in kg, per kg of phosphorus fertiliser): compared to ENVISAG, FUE is reduced (by 50% of the extra yield increase) in industrialised countries and phosphorus-surplus developing countries (India, China, Egypt); FUE is lower (by 50% of the extra yield increase) in developing countries with a phosphorus deficit. **2. Animal excretion**: 5% (2030) and 10% (2050) lower phosphorus (and nitrogen) excretion rates for beef cattle, dairy cattle, pigs, sheep, goats and poultry; this simulates the higher feed use efficiency compared to ENVISAG. **3. Manure integration**: manure that in ENVISAG ends outside the agricultural system (fuel use, lagoons) is recycled. Manure is better integrated in the agricultural system; this is important only in countries where animal manure spreading is less than 25% of total phosphorus or nitrogen input in crop production systems; in such cases phosphorus from animal manure is assumed to substitute fertiliser (100% of phosphorus is effectively available). **4. Human excreta**. Recycling of human phosphorus from households with access to improved sanitation but with no sewage connection, and urine from households with a sewage connection. For both sources, recycling is assumed to include 25% of available phosphorus by 2030, and 50% by 2050. This is calculated for all world regions, so no cultural taboos would hamper the re-use of human excreta. **5. Phosphorus-based detergents**. 100% replacement of phosphorus-based detergents with phosphorus-free detergents by 2050 (and 50% by 2030) in all world regions.

world regions, without cultural taboos for the use of human excreta. The effectiveness of phosphorus in human excreta was assumed to be 100%.

5.4.5 Phosphorus-based detergents

The resource efficiency scenarios are based on the simple assumption that 50% of phosphorus-based detergents will be replaced with phosphorus-free detergents by 2030, and by 2050 this will be 100%.

5.5 Results

5.5.1 Phosphorus fertiliser use

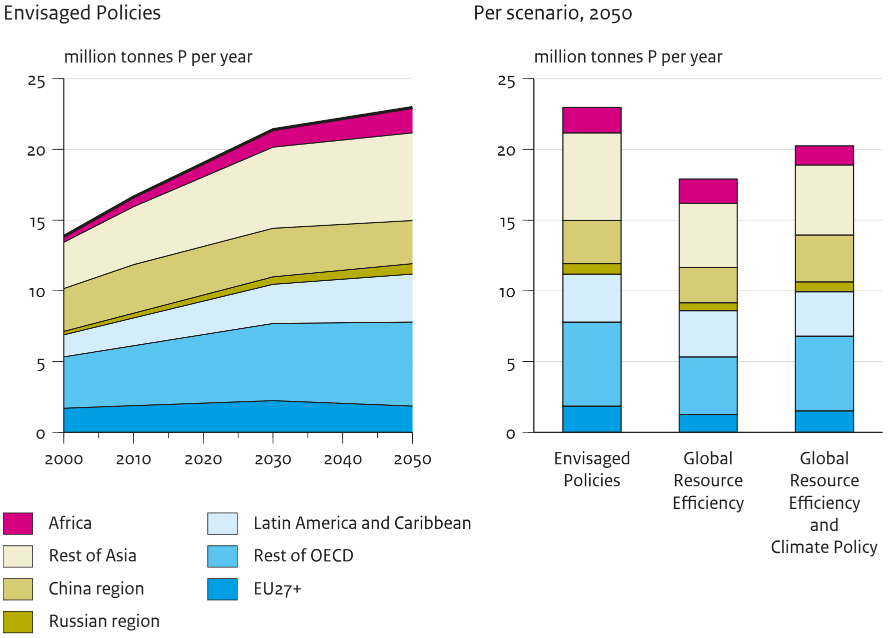
The *baseline* and *envisaged policies* scenarios show the results of a rapidly growing population and food production in developing countries. These vast increases lead to a rapid increase in phosphorus fertiliser use in phosphorus-deficit countries (by up to 100% in southern Africa) between 2010 and 2050 (Figures 5.4 and 5.5). The projected global increase is 40% between 2010 and 2050 (31% between 2010 and 2030). Annual global phosphorus fertiliser use is projected to increase from an estimated 16.4 million tonnes of phosphorus in 2010 to 23 million tonnes by 2050 (Figure 5.4). Phosphorus use in the *envisaged policies* scenario is marginally higher than in the *baseline* scenario (not shown), because of the increased production of bio-energy crops in the former (See Chapter 4).

In the *global resource efficiency* scenario, with all strategies to improve resource use efficiency, the annual global phosphorus fertiliser use from primary sources, by 2050, will be 17.9 million tonnes (Figure 5.4). The strategies considered have different impacts on phosphorus use. The increase in crop yields in the *global resource efficiency* scenario lead to significant increases in fertiliser use in phosphorus-deficit developing countries. The increased feed conversion together with reduction in phosphorus supplements in the feed of monogastrics leads to less phosphorus excretion. However, more feed crops are needed and thus also more phosphorus fertilisers to produce them. Hence, improved feed conversion leads to a shift in animal ratios from roughages to more concentrates, and the balance for phosphorus is close to neutral.

Better integration of animal manure is a very effective strategy to reduce fertiliser use in industrialised countries. Global phosphorus use is reduced by less than 4%, but reductions are much greater in industrialised regions; for example, just over 10% in North America and 12% in the EU27+. In developing countries with a phosphorus deficit, better integration is considered to be difficult, because fertiliser use is minimal and animal manure already plays an important role in sustaining crop production.

Recycling human excreta is potentially the most effective strategy for reducing phosphorus fertiliser use. By 2030, globally this would amount to an annual 1.1 million tonnes of recycled phosphorus, and by 2050, this would be 3.1 million tonnes. This would lead to a reduction in phosphorus fertiliser use of 6% by 2030 and 15% by 2050. Availability of human phosphorus varies per world region (Figure 5.6). In future decades, India and China could

Figure 5.4
Phosphorus fertiliser use



Source: PBL

In the envisaged policies scenario, global use of phosphorus fertiliser from primary sources is projected to increase by 40%, between 2010 and 2050. In the global resource efficiency scenario, the achieved phosphorus savings will be partly offset by additional phosphorus requirements for bio-energy crops, if ambitious climate policy is implemented.

recycle close to 40% of the globally available amounts of human phosphorus. North America and Western Europe could recycle 14% of the human phosphorus available globally, and this could lead to a reduction in their phosphorus fertiliser use of 12% in North America and almost 18% in Western Europe.

In the *global resource efficiency and climate policy* scenario (G-RE-CP), reduction in phosphorus use is less than in the *global resource efficiency* scenario (G-RE). Instead of a 22% reduction as in the G-RE scenario, there is a reduction of only 16% in the G-RE-CP scenario. This is related to the production of bio-energy crops on agricultural land. Similar to other crops, these crops require nutrients including phosphorus. In the EU27+, the difference between the resource efficiency scenarios is projected to be small, with reduction in phosphorus use of 32% in G-RE and 31% in G-RE-CP.

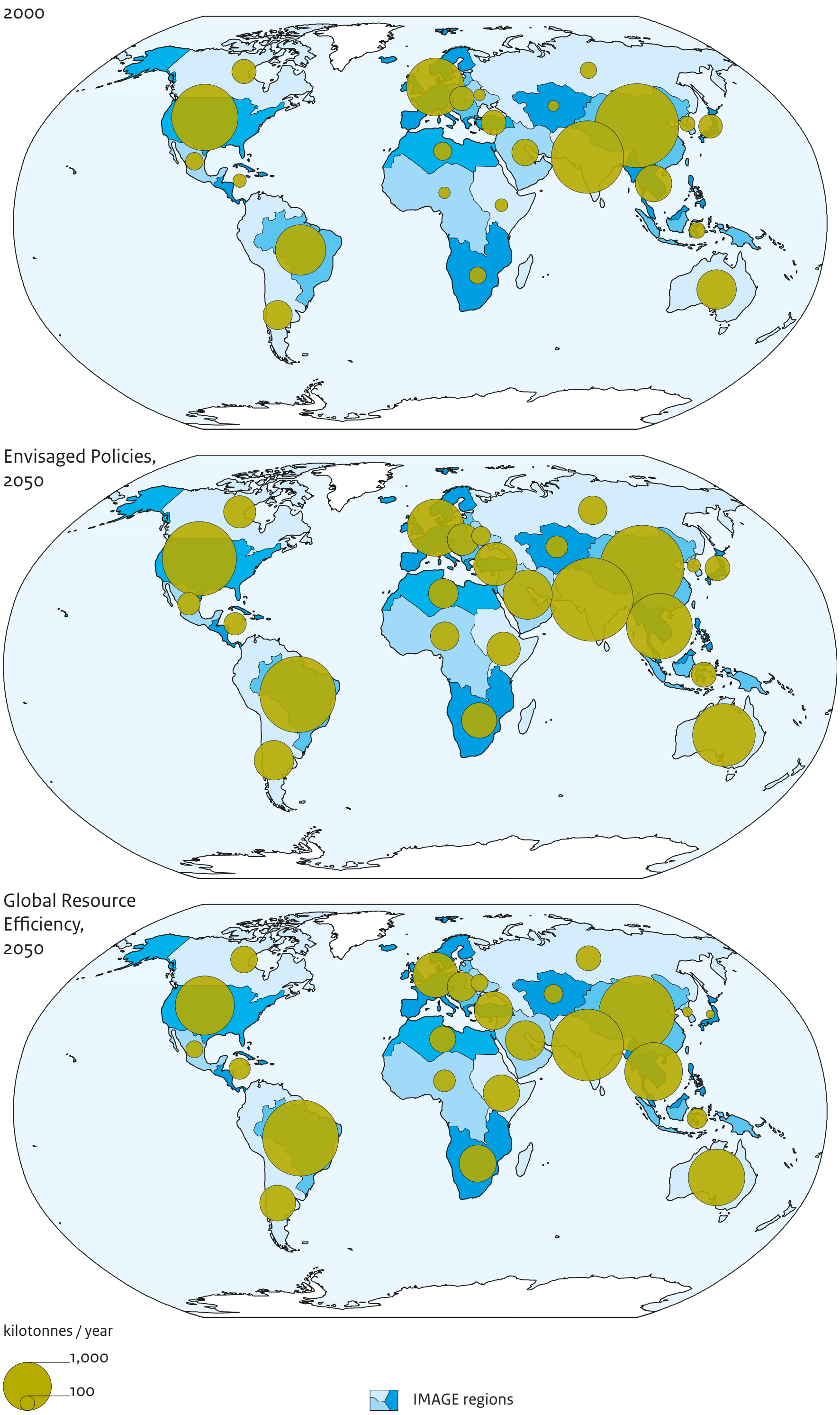
The conclusion is that global phosphorus fertiliser use will inevitably have to increase to sustain increasing food production. The increase is particularly strong in developing countries. The phosphorus required in agriculture will increase from current levels of 16.4 million tonnes, annually, to 23 million tonnes by 2050. In the *global resource efficiency* scenario, various strategies were combined to improve resource use efficiency. Strategies that aim to recycle phosphorus (human phosphorus, livestock phosphorus) seem to be most effective, particularly in industrialised countries. With all these strategies, annual phosphorus fertiliser use from primary sources could be reduced to 18 million tonnes by 2050. In the EU27+, use could be reduced from the current 1.9 million tonnes per year to 1.3 million tonnes by 2050.

5.5.2 Phosphorus detergent use

Data on global detergent use in the baseline (BL) indicate an increase from 0.4 million tonnes per year in 2000 to 0.6 million tonnes per year in 2010 (Figure 5.7). Since phosphorus is banned in laundry detergents in most western European countries, the European contribution comes mainly from dishwasher detergents. In general, the global increase over the 2000–2010 period was primarily in Asia, South and Central America and less so in Africa.

In future decades, this development will continue with a rapid global increase primarily in developing countries. In the *global resource efficiency* scenario, the use of

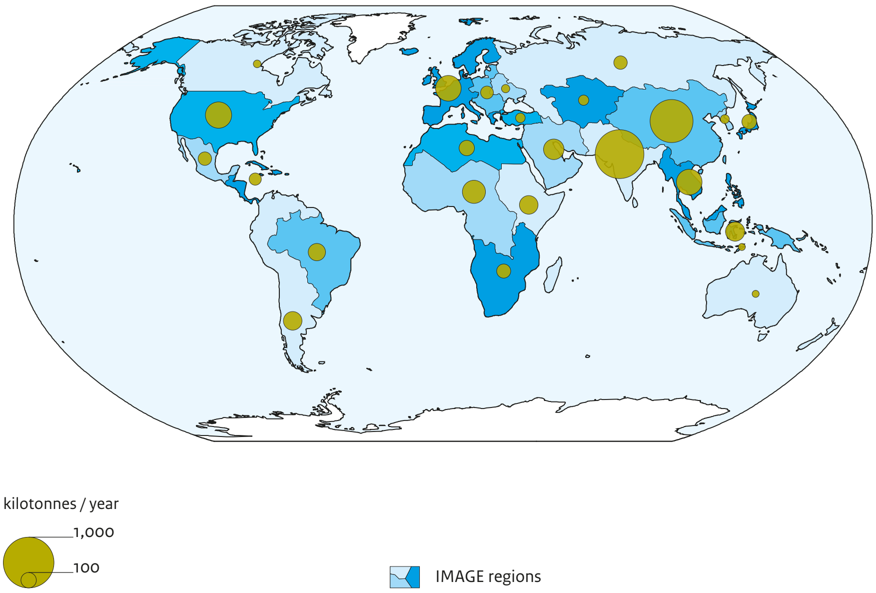
Figure 5.5
Phosphorus fertiliser use



Source: PBL

Global use of phosphorus fertiliser will continue to increase over the coming decades, most notably in developing countries and even in the global resource efficiency scenario.

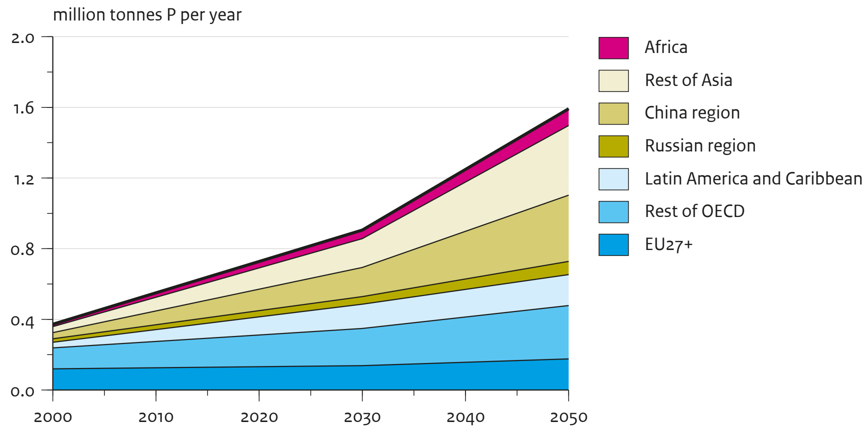
Figure 5.6
Human Phosphorus recycling in Global Resource Efficiency, 2050



Source: PBL

Phosphorus retrieved from human urine can contribute significantly to fertiliser supply.

Figure 5.7
Domestic use of phosphorus-based detergent in Baseline



Source: PBL

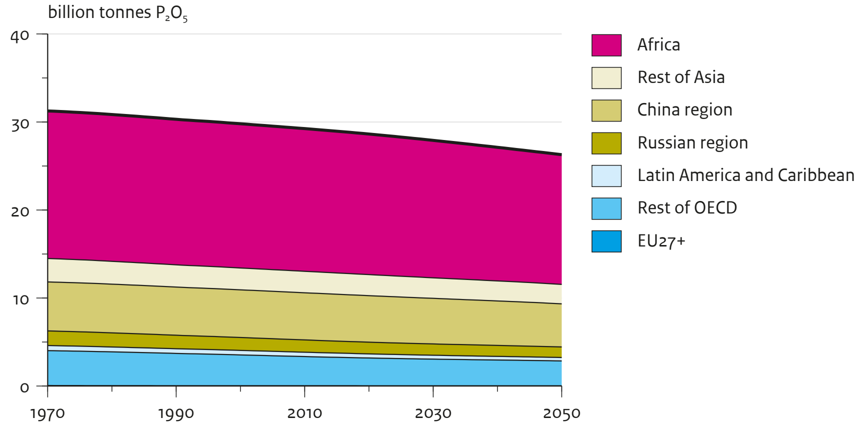
In the baseline and envisaged policies scenarios, the use of phosphorus-based detergent will almost triple between 2010 and 2050. Most of the increase will come from emerging economies and developing countries.

Table 5.3
Phosphorus resources and cumulative production in the *baseline* and *global resource efficiency* scenarios

	Resource estimates ($Gt\ P_2O_5$)[a]			**Cumulative production 2010–2050** ($Gt\ P_2O_5$)[a]	
	Reserve	Reserve Base	Additional	Baseline	Global resource efficiency
Medium	4.8	13.8	29.5	3.0	2.6
Range	4.0–6.0	7.6–21.8	15.4–83.7		

[a] 1.0 Gt P_2O_5 corresponds to 440 Mt of phosphorus.

Figure 5.8
Location of phosphorus resources in Envisaged Policies



Source: PBL

Global phosphorus resources are mostly located in Africa, especially in Morocco. Phosphorus reserves in the EU are insignificant.

phosphorus-based detergents will reduce by 50% by 2030, and by 100% by 2050. This implies an annual reduction in absolute terms of 0.5 million tonnes by 2030, and 1.6 million tonnes by 2050. This excludes all industrial uses of phosphorus-based detergents for which data are not available.

5.5.3 Depletion of reserves

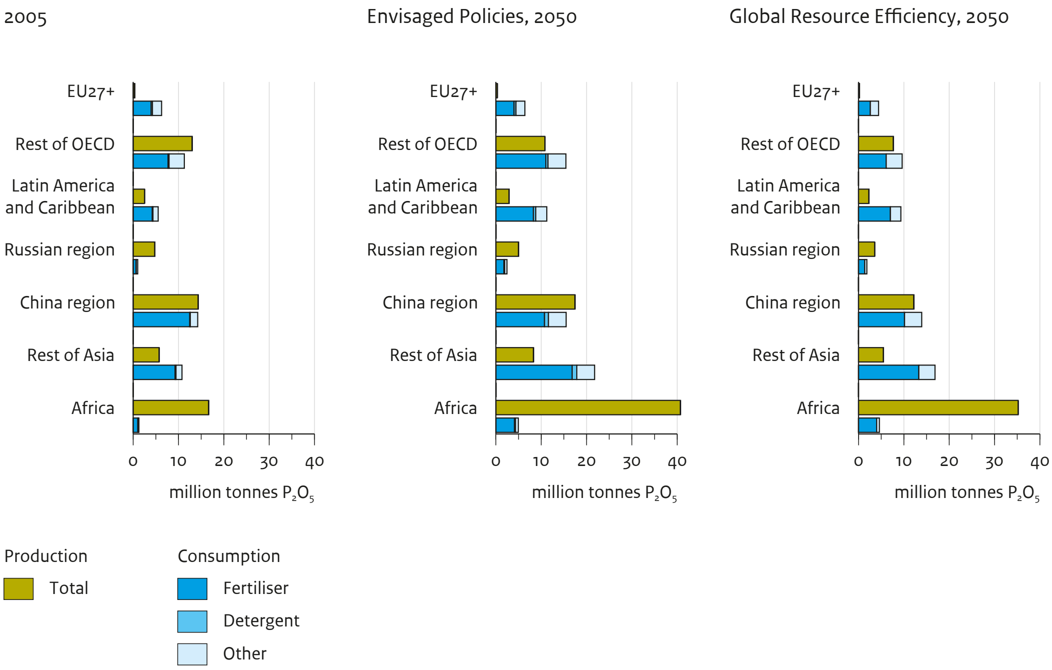
The term ‘reserves’ refers to known economically extractable resources, while ‘reserve base’ also includes resources that have a lower probability of being present, and/or carry higher extraction costs. The model developed by Van Vuuren *et al*. (2010b) was used in this study to explore the issue of phosphorus depletion.

The US Geological Survey (USGS), which is the most authoritative reference for global phosphate resource estimates, reported a reserve of nearly 18 Gt phosphate rock and a reserve base (including reserves) slightly above 51 Gt (USGS, 2008). This translates to 5 Gt P_2O_5 and 14 Gt P_2O_5, respectively. For additional phosphorus resources, estimates made by Smil (2000) were used.

Comparison between the cumulative phosphorus production from phosphate rock in the scenarios and the resource estimates (medium value of the reserve base, Table 5.3) suggests that about 20% of resources would be depleted by 2050. Even when the uncertainty in the resource estimates is taken into consideration, there are no indications of short-to medium-term depletion. In the long term, however, depletion of low-cost and high-grade resources will have consequences for future production trends. Although in the most optimistic case, considerable resources would remain, a more cautious viewpoint would emphasise the low resource estimate results, because there are no substitutes for phosphorus that support high agricultural yields.

Figure 5.9

Production and use of phosphorus-based products



Source: PBL

Some regions are self-sufficient in phosphorus, while others, such as the EU, depend heavily on imports. Africa dominates the export market and will increasingly dominate production. It has vast reserves and a relatively small use. The analysed combination of phosphorus efficiency strategies would reduce extraction from primary sources by some 25%, globally, by 2050. This still implies an increase in the current level of extraction.

5.5.4 Regional dimension

Resources are not evenly distributed. The phosphorus resource base by region and the projected production levels are presented in Figure 5.8. Global resources are mostly located in Africa, specifically in Morocco. In terms of production levels, the market is expected to continue to be dominated by northern Africa. Currently about 30% to 35% of global production originates from this region, whereas by 2050, this might be as high as 45% to 55% (Figure 5.9). Assuming that other phosphorus producing regions would mainly produce for their domestic markets, practically all exports to the EU27+ would originate from northern Africa.

5.6 Interactions

Synergy between phosphorus efficiency and the efficient use of other resources is not straightforward:

- Deployment of bio-energy in strategies for climate-change mitigation puts additional stress on phosphorus.
- After removal of phosphorus in harvested products, soil erosion is the second main mechanism of phosphorus removal from soils. Thus, soil and water conservation to sustain land productivity go hand in hand with phosphorus conservation. However, as argued above, large amounts of phosphorus are needed to enhance productivity of depleted soils in many developing countries.
- In regions with concentrations of intensive livestock production, phosphorus efficiency may require manure transportation over large distances, involving high costs and fuel use. In the EU, this happens irrespective of costs or fuel use, because environmental legislation prohibits manure dumping. For overall resource efficiency, crop–livestock systems need to be truly integrated within short distances from each other, or within the same farm, as is already the case in many developing countries.

5.7 Limitations of the analysis

One of the limitations of the analysis on phosphorus use efficiency in agriculture is the residual effect of past applications in industrialised countries. For example, current phosphorus fertiliser inputs in Europe equal the phosphorus withdrawal in harvested products. This is possible because historic inputs may have been as high as 700 kg phosphorus per hectare since 1960. However in some countries, current withdrawal exceeds the phosphorus fertiliser input. It is difficult to estimate future phosphorus fertiliser use in these regions and the associated crop yield.

An additional problem is the uncertainty about the effect of price fluctuations on phosphorus fertiliser use, as have occurred in recent years. This may be important in industrialised countries, where year-to-year phosphorus fertiliser use seems to follow price fluctuations. However, this price effect is more important in developing countries. Our analysis of fertiliser phosphorus use is thus a purely technical approach without consideration of the economic effects.

Data are limited on domestic use of phosphorus detergent use and there are no data on industrial detergent use, which may be as important as the domestic use.

5.8 Discussion and policy implications

The potential phosphorus efficiency gains suggested in this study are comparable to those suggested by Schröder *et al.* (2010) [see also Schröder *et al.* (2011)], but our scenarios generally project less global phosphorus fertiliser use than those of (Schröder *et al.*, 2010) which are based on a higher base-year consumption, somewhat simpler calculations (based on assumptions for fertiliser P to food P ratios), and much more extreme assumptions regarding future food consumption and bio-energy use. For example, their scenario with highest phosphorus consumption shows a 2050 use of almost 50 Mt P, assuming the adoption of western diets world-wide, 10% of transport fuel from biofuel crops; another 10% of transport fuel from algae, and 10% of global energy from bio-energy crops. This value drops to 26 Mt P (which is more similar to our *baseline* value of 23 Mt P) if bio-energy and dietary changes are excluded from the analysis.

Recycling of human excreta and better integration of animal manure in agricultural crop production systems are most effective in reducing phosphorus fertiliser use. This is not an easy task because it requires a change in sanitation systems to enable collection of urine and solid waste. It may also require a change of attitude to animal excreta. Handling human excreta is 'not-done' in many parts of the world. Thus, it is necessary to make people aware of excreta as a resource.

Reduction or a complete ban on the use of phosphorus-based laundry detergents is feasible, as is the case in the European Union. Similar regulations are needed for the phosphorus-based dishwasher detergents. The situation is different outside the European Union. Often, problems associated with eutrophication caused by increasing phosphorus discharge to surface water are considered to be of less importance than other problems, such as poverty reduction and malnutrition. Hence, the assumed reduction in phosphorus-based detergents (50% by 2030 and 100% by 2050) may be too optimistic.

Further research is needed to understand the role of residual soil phosphorus better, especially in strongly weathered tropical soils with high phosphorus-fixation capacity. This aspect has been taken into account but to improve projections a more refined model is needed that accounts for soil properties and different soil phosphorus pools and can thus better address the issue of phosphorus use efficiency.

5.9 Conclusions

- Phosphorus fertiliser use will almost inevitably increase to sustain increasing food production in the coming decades particularly in developing countries. Phosphorus required in agriculture will increase from current levels of below 17 million tonnes, annually, to 23 million tonnes by 2050 (*envisaged policies* scenario). To reduce phosphorus fertiliser use, considerable efforts are needed.
- Primary production will increasingly concentrate in one region (Morocco, northern Africa) which could lead to supply risks. Production costs are likely to rise.
- Depletion of phosphate extracted from phosphate rock is unlikely in the near term. In the long term (200–300 years), phosphate resources that can be exploited with current technologies are likely to become depleted.
- Strategies to improve phosphorus efficiency would address the scarcity issue and the negative environmental effects related to inefficient use. Recycling phosphorus from animal and human excreta seem to offer the best potential. Together, by 2050, such strategies could reduce the global use of fertiliser phosphorus from primary sources by 22%. In EU 27+, this reduction could be 32% compared to the *envisaged policies* scenario.

- Reduction in the use of phosphorus-based detergents will lead to an additional reduction in worldwide phosphorus demand in the *resource efficiency* scenario (-1.6 million tonnes annually).
- The case of phosphorus also reveals trade-offs:
  - Resource efficiency policies that aim to improve land-use efficiency would seek to increase agricultural yields in developing countries. These countries currently have unsustainably low fertiliser input levels that would need to go up to sustain yield increases.
  - Bio-energy crops, which are part of mitigation policies for climate change, would undo almost one third of the gains from efficiency improvements in phosphorus use.
- Together these results imply that, although increased use of primary phosphate resources is almost inevitable, efficiency policies are essential to prevent an even greater increase of their use. Efforts to improve domestic resource efficiency in the EU would be most effectively targeted at recycling phosphate and by further limiting the use of phosphate-based detergents. It would also be in the interest of the EU to assist developing countries to attain sustainable nutrient use, and to address dependency on a single supplier, for instance by exploring unconventional primary sources of phosphate.

Notes

1. This corresponds to 175 Mt of phosphate concentrates, averaging 30.7% P_2O_5 content, and containing 23.3 Mt of phosphorus.
2. Fertiliser use efficiency (FUE) represents crop production in kg dry matter per kg of a specific nutrient. This is the broadest measure of phosphorus use efficiency (PUE) and is also called the partial factor productivity of the applied fertiliser phosphorus (Dobermann and Cassmann, 2005). PUE is a very useful concept in scenario construction. It incorporates the contribution of indigenous soil phosphorus, phosphorus uptake efficiency, and the efficiency with which the phosphorus uptake is converted into the harvested product. PUE varies between countries because of differences in the crop mix, their attainable yield potential, soil quality, the amount and form of the application of phosphorus and other nutrients (such as, nitrogen) and management. For example, very high PUE values in many African and Latin American countries reflect current low fertiliser application rates. PUE values are much lower in many industrialised countries with intensive high-input agricultural systems.
3. CAFOs: Concentrated animal feeding operations.

Fresh water

6.1 Introduction

In a strictly physical sense, water is an abundant planetary resource, true to the popular term ‘the blue planet’ of no less than 1386 million km^3 (Gleick and Palaniappan, 2010). However, most resources are unsuitable for most applications because of the salt content. Oceans and saline groundwater together make up 97.5% of all planetary water. In addition, large volumes of water are currently inaccessible as they are frozen in ice caps, glaciers and permafrost, dominated by Antarctica and Greenland. Of the remaining fresh water in liquid form, more than 10,000 km^3 is stored in deep groundwater with varying but often very slow refill rates if exploited. As a consequence, the water available to sustain natural and human life on a renewable basis is a fairly scarce resource. An upper limit of globally accessible fresh water withdrawals[1] is put at 12,500 to 15,000 km3 per year (Rockström *et al.*, 2009b) with substantial variation between regions and water basins on an average annual basis. This is further aggravated by seasonal fluctuations in demand and supply, inter-annual variability and shifts in precipitation patterns.

Future climate change is bound to affect the availability of fresh water. On the global scale, precipitation is predicted to increase, because of elevated temperatures that cause higher evaporation levels. The geographical distribution shows patches with considerable increases and decreases in precipitation. Climate models are often not in agreement on local trends up to the point of indicating different directions of change, either wetter or dryer.

An overview of the scarcity dimensions of fresh water is given in Table 6.1.

6.2 Current freshwater extraction

In the model used in the analysis (LPJmL soft-linked with IMAGE; see the Appendix), the focus is on the interactions between precipitation, vegetation, soil moisture and surface and sub-surface flows to rivers and lakes. The resulting run-off per grid cell ends up in river systems, including lakes and dams, with volumes available for downstream extraction. Water extraction from deep groundwater reservoirs is not explicitly taken into account.

Water is extracted by humans to sustain a broad range of activities. Currently, on the global scale and in many regions and watersheds, the dominating demand is for irrigated agriculture. The area equipped for irrigation but even more the areas actually irrigated and the water volumes applied to the fields and extracted from river systems are all subject to considerable uncertainty. This is reflected in published data showing substantial differences even for relatively well monitored OECD member countries.

The ratio between the amount of water that effectively contributes to soil moisture for plant growth and the volume extracted from river systems, varies according to irrigation system and its management. Water evaporates from open canal systems and is lost through canal walls and cracks. Water does not evaporate from piped systems

Table 6.1

Scarcity dimensions of fresh water

Physical	Economic	Political
Increasing demand leading to increased pressure on freshwater resources Adverse impacts of climate change could decrease resources availability in certain regions	Non-existent or improperly functioning markets and lack of infrastructure limit access to safe water, particularly for the poorest in developing countries High cost of maintaining infrastructure and improving inefficient and out-dated infrastructure	Conflicts between parties in transboundary river basins limit access to water for downstream users Sense of unfair competition between farmers subject to different regimes (or not at all) of water pricing

but is lost from faults in joints and pipes on the way to the fields. Another source of inefficiency occurs in the fields, during application. Application methods vary, examples are sprinklers (losses caused by unequal distribution, evaporation, and drift by wind), surface irrigation (losses caused by evaporation, surface run-off, and non-uniform soil wetting), and drip irrigation close to plant roots. In the LPJmL model (Fader *et al.*, 2010), estimates have been made of the dominant systems in use in countries and regions, and their typical efficiencies. Globally, as much as 50% of the water extracted for irrigation is estimated to be lost from effective supply to the plants.

Based on the area per crop type distinguished in IMAGE/LPJmL, potential irrigation water requirements are calculated by comparing the amount of water needed for growth not constrained by water availability and the supply from precipitation. The gap is supplied by irrigation to the extent that sufficient water is available in the same or adjacent grid cells. Based on these assumptions, the water demand for irrigation is estimated at 2400 km^3 globally in the year 2000.

Another major water-demanding sector is domestic use for drinking, food preparation, sanitation, and cleaning. Driving factors are access to affordable and safe water supplies, connection to water supply systems, disposable income, climate and cultural influences. Based on an estimate made for the OECD Environmental Outlook to 2030 (OECD, 2008) and corrected for population, the estimate we used for the year 2000 is around 350 km^3. Geographical distribution follows from downscaled population projections corrected for urban/rural splits and income-dependent connection rates to tap water systems.

The OECD (2008) calculations were also used as the starting point for the manufacturing sector and for electricity production. Manufacturing uses are manifold and include process water and cooling water. The use per sector can differ enormously but an overall average relationship with total Industrial Value Added was assumed, and corrected downwards for structural shifts and autonomous technological progress. In 2000, the demand of the manufacturing sector is around 230 km^3.

After irrigated agriculture, the largest water demanding sector in 2000 was electricity primarily for cooling of thermal (steam cycle) based power generation. Differences per unit electricity can be significant depending on the overall efficiency of the plants, varying from less than 30% to around 60%, the type of plant (steam cycle or combined gas/steam cycle) and the cooling system (run-of-river, dry or wet cooling towers). Based on rough estimates for these factors, the OECD (2008) value is around 540 km^3.

Finally, relatively small but locally sometimes decisive amounts of water are needed for the livestock sector. This was estimated at around 25 km^3 for 2000. Demand in this sector is influenced by breed varieties, diets and climate.

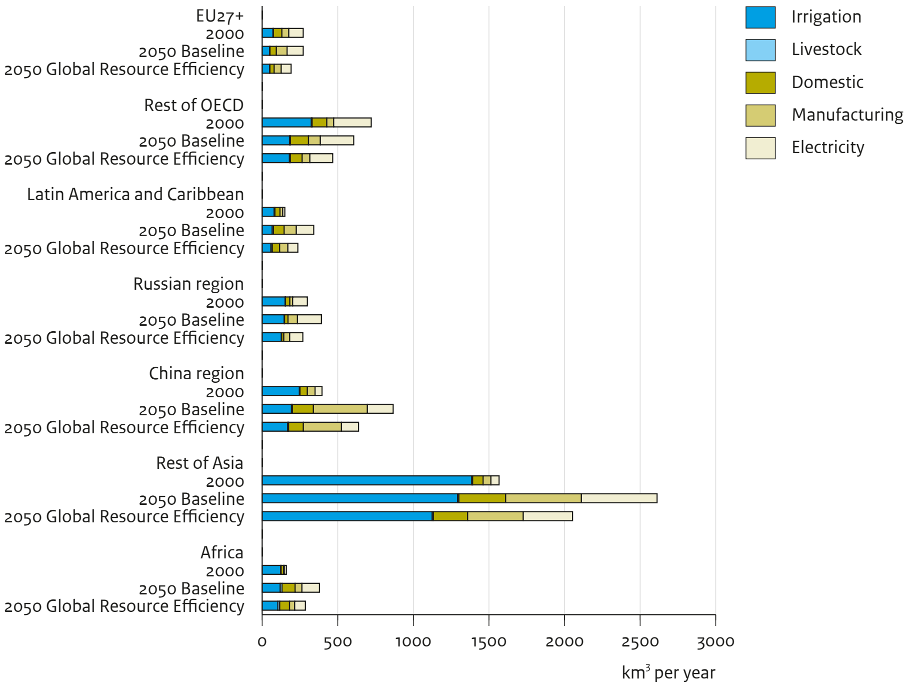
Total water demand, according to the analysis, in 2000 was thus 3,545 km^3 with irrigation making up two thirds of the total (Figure 6.1). This global value is well below the 5,000 to 6,000 km^3 level (set at 40% of the accessible volume) indicated by (Rockström *et al.*, 2009a), whereas resource availability per country, region and river basin is often tighter. This is reflected in the outcome for water stress analysis in Figure 6.2 (top panel) and the implications in terms of the number of people living and working in river basins already considered to be subject to severe water stress[2] (Figure 6.4)

6.3 Future freshwater demand and water stress

Under baseline conditions, future water demand is bound to increase strongly. A growing population with on average higher income requires more food, more industrial products and more electricity, and will tend to use more water for domestic purposes.

The baseline demand up to 2050 is adapted from the OECD (2008) projection, including the assumed

Figure 6.1
Water withdrawals



Source: PBL

Demands for fresh water up to 2050 (assuming no further expansion of the irrigated area) will increase due to strong growth in withdrawals for domestic purposes, manufacturing and electricity generation. In the baseline scenario, the share of withdrawals for irrigation drops from 67% in 2000 to 38% by 2050. In the global resource efficiency scenario, demands for all purposes are reduced, but are higher than in 2000, with the exception of the those in the OECD countries.

autonomous intensity and efficiency improvements. Regional adjustments to match the baseline for the next OECD Outlook 2012 are made for population (domestic), industrial value added (in PPP terms, manufacturing) and thermal electricity production (electricity). Livestock demand is not adjusted, as the volume is relatively small. The exception from OECD (2008) is irrigation demand, which is now calculated with the LPJmL model in conjunction with IMAGE.

In many river basins, population growth and increasing consumption of livestock products and other food commodities are projected to induce expansion of irrigated areas to enhance food security, and/or more intense irrigation to sustain productivity improvements, and/or possible demand increasing climate- change impacts. Attempts to estimate the future extent of the irrigated area range from using a simple rule of constant area per person so that the area grows with population (Shen *et al.*, 2008), to more sophisticated approaches combining potential demand (ratio of precipitation to evapotranspiration) and local availability of water resources to supply irrigation water (Fischer *et al.*, 2007). Neither of these methods could be applied in our analysis because that would have required further development of algorithms that are currently not available to assign areas to specific locations (grid cells) and to crops within these cells. Therefore, we calculated with constant irrigated areas, recognising that potential demand is underestimated. The potential impact on future water demands was estimated by applying the simple rule of Herold *et al.* (2008) to the assumed volumes and efficiencies in our projection. Irrigation demands range from 14% decrease in our projection between 2000 and 2050 and 25% increase resulting from a population-based expansion of the area with otherwise unchanged assumptions (see Figure 6.3). The biggest increase is in Asia where most of the global population growth is projected.

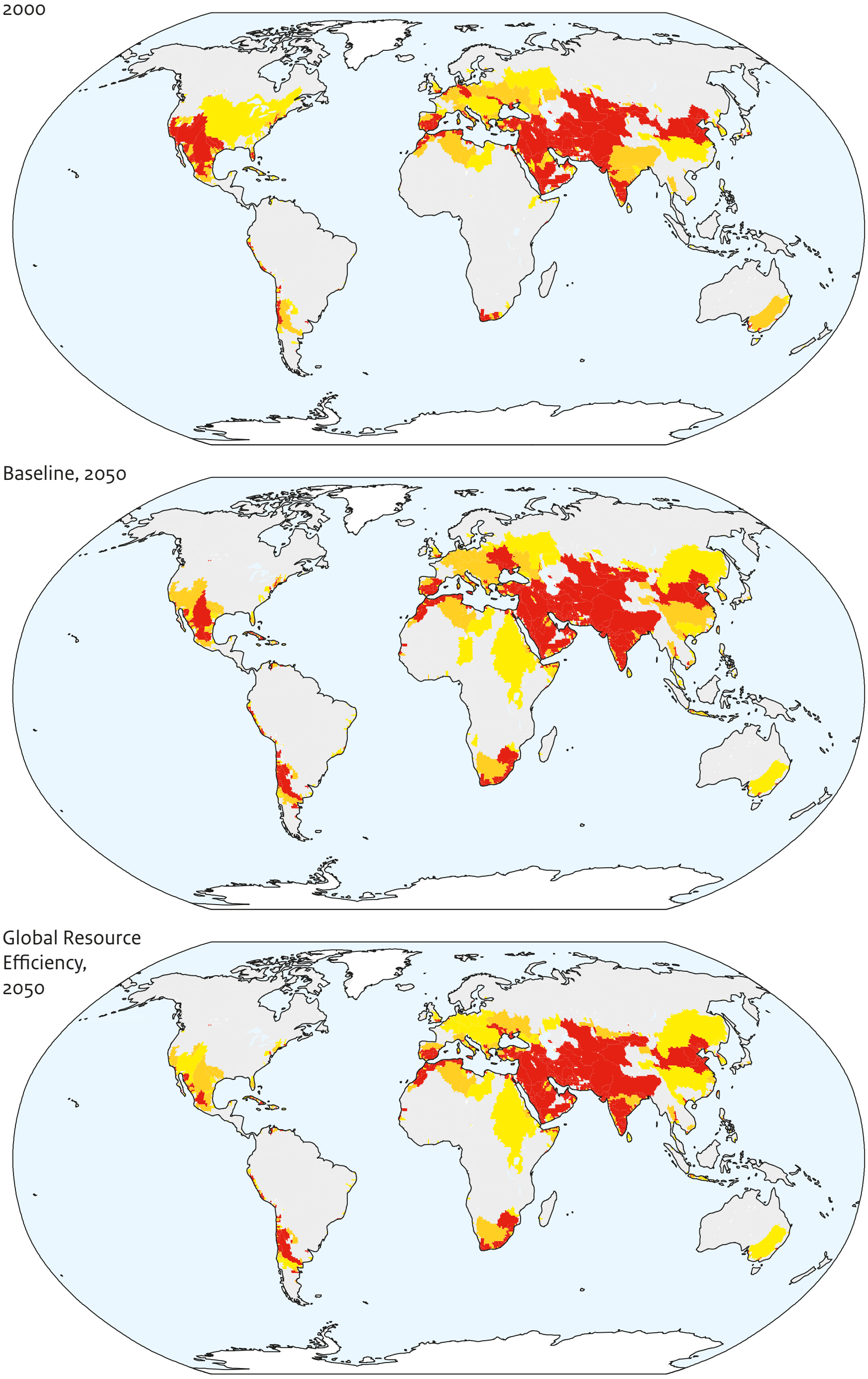
The impact of future climate change on irrigation water requirements is also uncertain. The compounded

Figure 6.2
Water stress in major river basins

2000

Baseline, 2050

Global Resource Efficiency, 2050



Severity level (water exploitation rate)

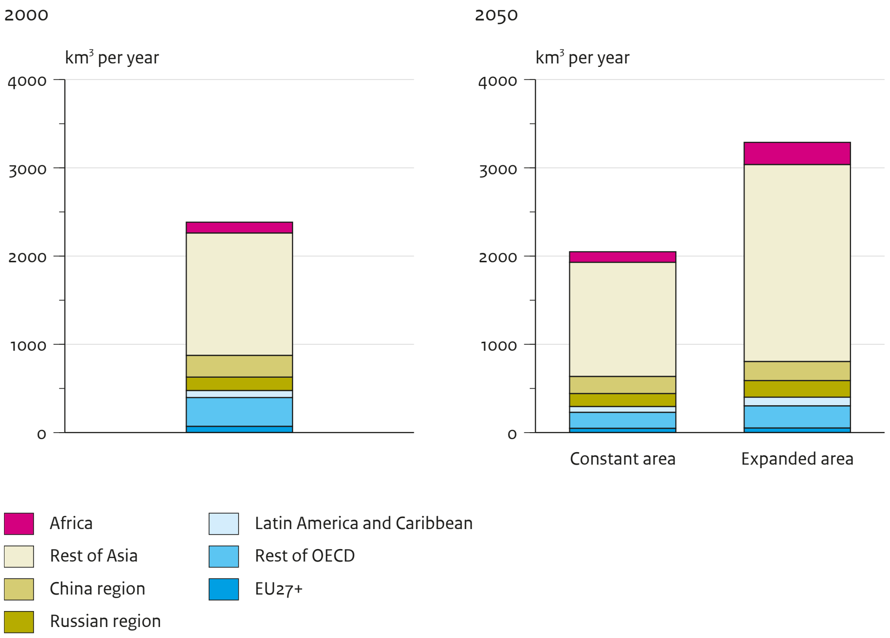
- No (< 0.1)
- Low (0.1 – 0.2)
- Medium (0.2 – 0.4)
- Severe (> 0.4)
- No data

Source: PBL

More river basins become subject to severe water stress in the baseline scenario, mainly as the result of growing water demand. With enhanced resource efficiency, the situation improves in many river basins (compare the United States, China, southern Europe, eastern Europe and Russia), but many others remain in the highest category (northern Africa, the Middle East, the India region and Central Asia).

Figure 6.3

Water demand for irrigation



Source: PBL

If the irrigated area is not expanded from the situation in the year 2000, as is assumed in this analysis, the irrigation water demand reduces by 14%, due to changes in precipitation, lower plant water requirements and efficiency improvements in irrigation systems. An area expansion of 45% in line with population growth as suggested by Shen et al. (2008) would lead to an increase in demand of 25%, between 2000 and 2050.

effects of higher evaporation with higher temperature, extension of the growing season at higher latitudes, and higher water use efficiency in response to higher CO_2 concentration have a positive effect (less water required) in some models, such as LPJmL, are assumed neutral as in Shen *et al.* (2008), or negative (higher water demand) as in Fischer *et al.* (2007). The latter does not mention the CO_2 fertilisation effect. According to the LPJmL model, the irrigation water requirements assuming a constant area will decline in future due to climate change.

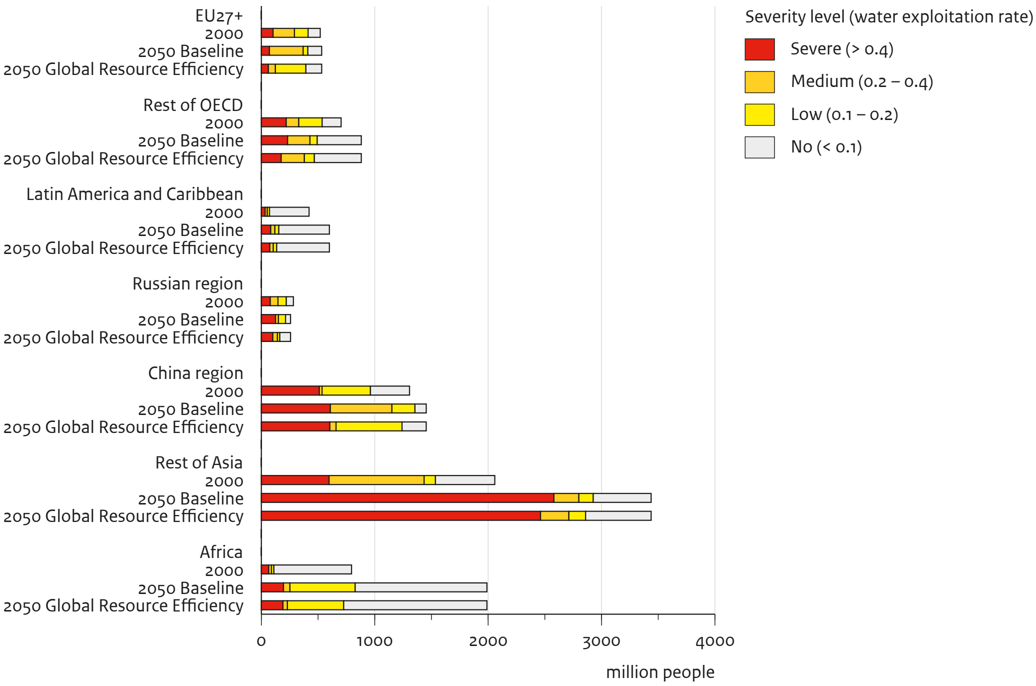
There is also significant scope to reduce losses of irrigation water with regard to the contributing factors mentioned above. Measures to enhance irrigation water efficiency include covering open canals, lining canals to make them waterproof, repair of pipe joints, repair and maintenance of nozzles, application of drip irrigation instead of spraying, and improved scheduling and overall management, both at reservoirs and in the fields.

At least part of this technical potential is assumed to be taken up in baseline projections, supported by insights from historical data presented in OECD (2011a). In our analysis, recommendations have been adopted for further efficiency improvement in OECD countries (personal communication, Kevin Parris, OECD) in line with the OECD Environmental Outlook 2012 (in preparation) based on assumed continuation of policies to foster more efficient water use. For other countries and regions, no further improvement in efficiency is assumed in the absence of knowledge about dedicated policies and their expected effect. Based on these assumptions and a constant irrigated area, by 2050 the calculated demand for irrigation water will be 14% lower than that of 2000. Including the estimated effect of the other approaches mentioned for area expansion and demand per ha imply an increase of 17% to 25% over the same period.

Despite the calculated decline in irrigation water use, the total global water demand in the *baseline* scenario increases substantially to 5,465 km³ because growth in other sectors outweighs increase in demand for irrigation (Figure 6.1). As a consequence, water stress increases in many river basins particularly in densely populated areas in rapidly developing economies. At the same time, water stress is somewhat reduced in parts of OECD countries, for example, the United States (see Figure 6.2; central panel versus top panel). Water stress would increase further

Figure 6.4

People living under water stress in major river basins



Source: PBL

The number of people living in river basins under severe water stress conditions increases sharply in the baseline scenario, and most in Asia (particularly India). In terms of number of people, the resource efficiency scenario has a greater effect on low and medium stressed river basins than on the severely stressed basins.

if expansion of the irrigated area were assumed. On the global level, the impact of these uncertainties on overall freshwater demand, and thus on water stress by 2050 would remain limited, because the changes in overall demand would be dominated by the strong increase in other sectors. Although the number of river basins with severe water stress would increase, the number of people living under severe water stress would increase much more (Figure 6.4). Almost the entire population of South Asia and the Middle East, and large proportion of China and north Africa are located in these river basins. Together, this is no less than 3.9 billion people, 43% of the global population, Whether or not they suffer the consequences in daily life cannot be answered because this also depends on adequacy of water management strategies.

6.4 Future water demand and water stress in a resource-efficient scenario

As already mentioned, the baseline development will lead to a serious increase in friction between demand for and supply of renewable water resources. If, and to what extent, non-renewable deep groundwater stocks are depleted cannot be assessed. Regionally, limits to extraction suggest a realistic prospect of ‘peak water’ situations (Gleick and Palaniappan, 2010), where extraction from deep aquifers is bound to stabilise and decline.

A range of options can be identified for improvement in the state of renewable water supplies, including the use and re-use of domestic and industrial wastewater directly or after treatment. Desalination of seawater is already in operation in some places including Australia and the Middle East but the costs and energy requirements are high and work against large-scale expansion. An important factor is technical and management training and in the long term, new technologies may result from R&D investment. In electricity production, an increasing share of more efficient cycles or systems requiring no cooling water can lead to major reductions in overall water demand. Relocation of water-demanding activities to less water stressed locations can be considered but the social cost may be prohibitive except in exceptional cases. The long history of the Middle East suggests that factors other than water availability weigh heavily. Water-saving devices (showers, flush toilets, industrial processes) are well known but are not yet standard practice. Awareness of water as an increasingly scarce resource may be instrumental, but lack of adequate metering and pricing do not provide financial incentives. In OECD (2011a), removal of harmful subsidies and introduction of realistic pricing, therefore, are strongly advocated.

In our study, a simple rule-based approach was used to test the potential to reduce the water stress observed in the baseline. For the electricity sector, major changes are brought about with the reduction in energy demand achieved in the *global resource efficiency* scenario (see Chapter 3) and this translates directly to lower water demand for cooling. Under the 2 °C climate scenario, additional reduction in water demand is predicted from larger shares for solar and wind-based generation. Up to 2050, the shift to thermal bio-energy and nuclear power plants (see Figure 3.2) would limit the water-saving potential.

The assumptions made are as follows:

- For irrigation, an additional efficiency improvement is assumed in all non-OECD countries, amounting to 15% higher efficiency than in the baseline; following Fischer *et al.* (2007). In OECD countries, further enhancement on the baseline is considered technically unlikely and therefore efficiencies are kept at their baseline level.
- For domestic and manufacturing uses, savings potentials are assumed to be comparable with those for energy consumption. Hence, compared to the baseline, the associated demands in each region are lowered in accordance with the energy savings in the *resource efficiency* scenario (see Chapter 3).
- As already mentioned for electricity production, demand reduction follows from using less thermal power production than in the baseline, implicitly assuming a similar development in technology performance.
- For the livestock sector, no adjustments were made. Demand may well be reduced somewhat from the assumed dietary and conversion efficiency improvements, but no attempt was made to quantify the effect. As baseline demand is so small compared to the other sectors, any adjustment is also small compared to the large uncertainties surrounding each of the larger demand categories.
- Efficiency improvements in agricultural production (Chapter 4), more efficient use of nutrients and recycling of phosphorus (Chapter 5) in the *global resource efficiency* scenario will improve opportunities to re-use downstream water and/or to reduce efforts needed in wastewater treatment. No attempt was made to capture these indirect effects on water demand.
- Finally, in the *global resource efficiency* scenario and even more so when combined with the climate target, climate change is contained below the *envisaged policies* scenario. Given the net response of the LPJmL model, this may end-up in slightly higher demand for irrigation water. Differences up to 2050 are relatively limited, and are not quantified here.

Taking all changes in the *resource efficiency* scenario together, annual water demand by 2050 would be 4,140 km^3, around 25% below that in the *baseline* scenario for the same year (Figure 6.1). The increase between 2000 and 2050 would drop from +53% to +16%. In comparison, improvements for people under water stress are less significant. The estimated 3.9 billion people living in areas affected by severe water stress would reduce only slightly to 3.7 billion. This underlines the notion that an increasing number of people are projected to live in already severely water stressed basins.

6.5 Limitations of the analysis

The analysis was limited to the supply/demand balance for renewable water resources, such as fresh water available in river systems. It does not address the state and prospects in practical terms for exhaustible deep aquifers.

Another limitation is that the current version of the tools does not allow for expanding irrigated areas in future, for lack of geographical and crop-specific operational allocation rules and algorithms.

Comprehensive assessments were not available of efficiencies in irrigation systems, water reducing household appliances and water sparing industrial processes. Hence, only crude, generic assumptions were tested for their effect on total water demand and water stress.

Options were not considered for reducing losses in rainfed agriculture aimed at improving 'water productivity' and thus run-off to river systems at a given precipitation level. Such measures may also lower demand for irrigation water because of more effective use of available precipitation. They would also affect water inflow to rivers but mostly during periods of peak supply.

6.6 Discussion and policy implications

Water demand is bound to increase substantially in the coming decades because all major driving factors are projected to grow: population, households, income, industrial output, electricity and livestock. In many regions and river basins, the ratio between water extracted annually and the available volume already exceeds 40%, which is considered to constitute risks of temporary shortages. The compounded effect of more people and more water demand per capita is a reason for concern.

In a stylised way, a more resource efficient future was tested for its implications on water demand, water stress in river basins and people living under water stress. Given the tight supply conditions in the baseline, policy interventions to reduce extractions are warranted. Given the differences between river basins and within river basins, policy actions will have to be tailored to local conditions. However, elements of a more resource efficient development are universal, and expertise and experience in the EU, for instance in connection with the Water Framework Directive, can inform other regions.

In the EU27, water scarcity is a serious issue in some river basins particularly in the Mediterranean Member States. According to climate models, freshwater supply is predicted to decrease further in the southern rim of the EU, putting further pressure on the already tight supply. Overall, the assumed improvements in resource efficiency tested will be important in improving the situation within the EU.

To a certain extent, the EU will contribute to water demand in other regions. For example, imports of consumer goods from China will lead to industrial water withdrawals. Indirectly, electricity used by those industries will use cooling water. Likewise, import of agricultural products may induce irrigation water use in the producing countries. Without further analysis, the extent of these ‘tele-connections’ cannot be estimated. Distinguishing agricultural water ‘use’ between irrigation water withdrawals and evapotranspiration from cultivated land is important in pinpointing problem areas.

Additional generic actions include support for the development and deployment of water saving equipment for households and industry, including re-use and recycling. For irrigation, often relatively simple improvements are available but are not fully deployed. A reason for this may be lack of awareness of water scarcity and another is relatively expensive labour cost for improvement and repairs. Development of robust, low maintenance, good quality and efficient irrigation systems can deliver improvements in this sector.

Another recurring issue is appropriate price signals and other means to resolve currently unpriced scarcity situations, such as (tradable) water use rights in river basins. This is expected to deliver significant improvements compared to un-administered practices where only investment in hardware is taken into account.

6.7 Conclusions

- The number of people living in areas affected by severe water stress is projected to increase from 1.6 billion in 2000 to 3.9 billion by 2050. Most of this increase will take place in South Asia.
- Enhanced water use efficiency will have only a limited effect on this indicator, as 3.7 billion people are projected to still be facing severe water stress, by 2050.
- The main reason for these developments is population growth in water-stressed river basins. Furthermore, demand for fresh water for purposes other than agriculture (domestic, industrial, and electricity) is projected to increase steeply and eventually outweigh irrigation demands, which currently account for two thirds of total demand.
- The above holds for all projections analysed, although estimating future demands for water for irrigation is subject to considerable uncertainty. Estimates range from close to the 2000 level to 25% above that level. Uncertainty factors include possible expansion of the irrigated areas, water demands per hectare as affected by climate change and efficiency improvements of irrigation systems.
- In all water-using sectors, substantial water efficiency improvements are technically conceivable, here combined in the *global resource efficiency* scenario. Full implementation would limit the projected increase of water withdrawals by 2050 to 16% compared to 2000 (implying a reduction by some 25% compared to the *baseline* scenario for 2050). Achieving these efficiency improvements requires large-scale adoption in the market. No or inadequate water pricing and/or management of locally available resources would hamper most improvements in resource efficiency.
- In the EU, the total number of people under pressure from water stress is relatively small. With ambitious water efficiency improvements, total freshwater demand in the EU (and other OECD regions) may be lower by 2050 than it was in 2000. However, the

situation in the southernmost Member States is often serious and aggravated by climate-change induced changes in precipitation.

- Hence, in addition to the important measures in resource efficiency, adaptation to a situation of relatively scarce water resources will continue to be a crucial element in integrated water management in many of the world's major river basins. This is also the case in the southern parts of the EU.

Notes

1 Referring to the annual amount of water in river systems accessible for extraction.

2 Water stress is a measure of the total, annual average water withdrawal from a river basin (or sub-basin) compared to the annual average water available in the basin. Often, the resulting ratio is grouped in one of four categories: less than 10% = no stress; 10-20% - low stress; 20-40% = medium stress; and more than 40% = severe stress. Given seasonal and inter-annual variability in water demand and supply, and the notion to maintain a minimum environmental flow level, high ratios are associated with increasing risks of recurring supply constrained periods.

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Fish stocks

7.1 Introduction

Current fishery practices are putting increasing pressures on global marine fish stocks resulting in overexploitation and depletion of many fish populations throughout the world (Figure 7.1). An estimated 27% of fish populations are overexploited and almost 80% of commercially fished stocks are fully fished or overfished (FAO, 2009b). Fish species are declining in numbers, the average fish size is getting smaller, and biodiversity as a whole is under pressure (Jackson *et al*., 2001; Watson and Pauly, 2001). The average population size of marine fishes and other marine animals has decreased by 24% since 1950 (Alder *et al*., 2007). Larger fish species have declined most. Only certain smaller fish species are able to flourish because the larger fish species have been removed.

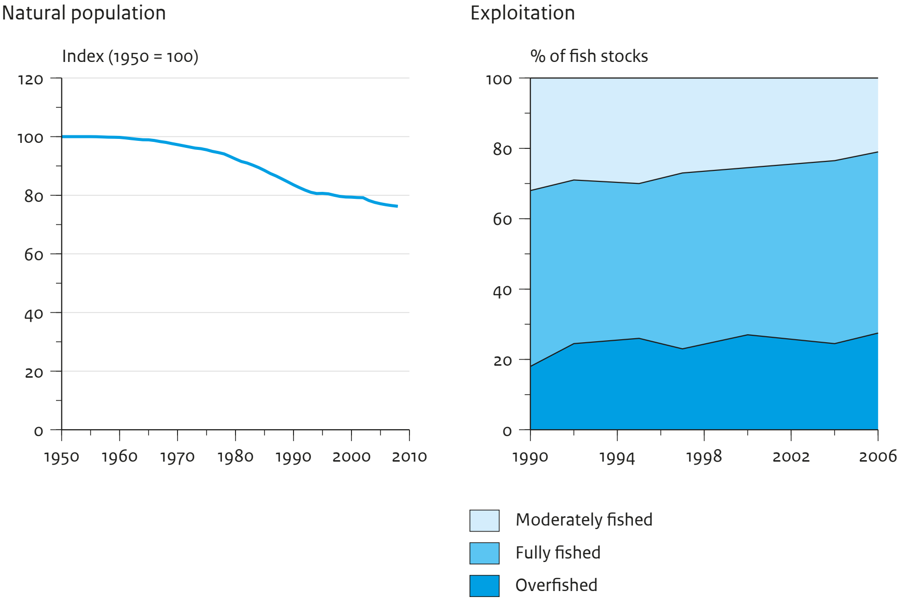
As fish stocks decline, fishermen have to travel further and fish deeper to maintain catch volumes. As a consequence, the effort and fuel needed to catch a given amount of fish is steadily increasing. Fishing vessels accounted for 1.2% of global oil consumption in 2000, which amounted to about 0.5% of global CO_2 emissions (134 Mt CO_2) (Tyedmers *et al*., 2005). Energy use depends heavily on the fishing method and varies for pelagic fisheries from 100 litres/tonne for herring and mackerel to more than 3000 litres/tonne for tuna. Demersal fisheries require about 500 litres diesel/tonne fish (Tyedmers, 2004).

Where global catches have stagnated, global fish consumption has increased in recent decades and will probably continue to rise (Delgado *et al*., 2003; FAO, 2009b). This expected rise in global demand for fish is largely driven by the increased purchasing power of a growing middle class in developing countries. Wild catches have reached their limits, whereas aquaculture is meeting the growing demand (Figure 7.2).

Nowadays, about 35% of world fish supply (finfish, shellfish and molluscs) comes from aquaculture (FAO, 2009b). However, current aquaculture practices also make a claim on wild catches. Approximately one fifth of the total fisheries catch is used as feed in aquaculture, especially for predatory species, such as salmon, either directly or after processing into fishmeal and fish oil (Westhoek *et al*., 2011). Since the 1980s, production of fishmeal and fish oil has been at the same level, but their use for aquaculture has greatly increased, while poultry and other livestock producers have increasingly switched to vegetable-based meals (Delgado *et al*., 2003). In 2006, about 60% of global fishmeal and 90% of fish oil were used for aquaculture (Tacon and Metian, 2008). A decline in the pressures on marine catches requires sustainable expansion of aquaculture with lower demand for fish-based feed.

An overview of scarcity dimensions of fish stocks is presented in Table 7.1.

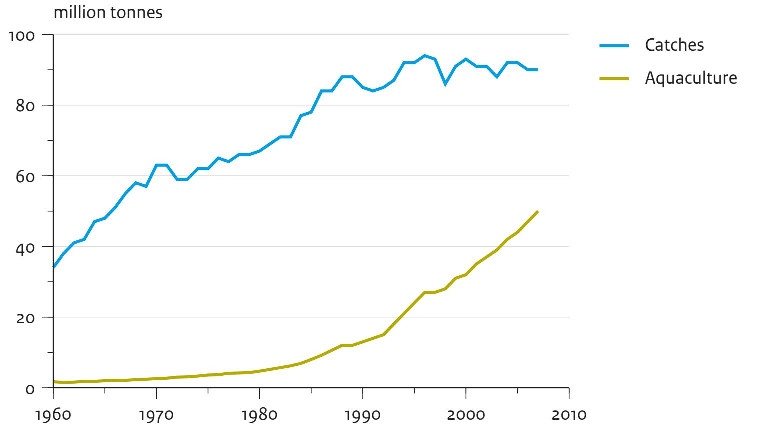
Figure 7.1
Global marine biodiversity



Sources: Alder *et al*. (2007) and FAO (2009b)

Globally, populations of marine fish species are estimated to have declined by more than 20%, since 1950. Nearly 80% of current fish stocks are fully exploited or overexploited.

Figure 7.2
Global fish production



Source: FAO (2009b, 2011b)

Global fish catches increased considerably, up to the mid-1980s, and since then have stagnated in spite of increasing efforts. Continued increase in demand has been met by aquaculture, mainly of freshwater fish in Asia.

Table 7.1
Scarcity dimensions of fish stocks

Physical	Economic	Political
Rapidly depleting stocks of commercially exploitable fish species	Increasing prices to consumers; decreasing returns to fishermen to the extent that fisheries sector in many countries in jeopardy High costs, including for fuel use, due to increasing efforts in fisheries (larger distances)	Disputes over fishing rights/licensing Artisanal fisheries in developing countries harmed by industrial exploitation by fleets from other countries in same or nearby waters Disputes over need to limit or ban fishing of certain species

7.2 Resource efficiency mechanisms analysed

Both supply (resource extraction stage) and demand (resource use stage) have major potential for improving resource efficiency. Supply-side opportunities for resource efficiency concern fisheries themselves (see opportunity 1). More sustainable fishing practices using organisational or technical solutions might decrease pressure on wild fish stocks. Demand-side opportunities concern the use of fish-based feed in aquaculture and livestock farming and the demand for human consumption. Opportunities 2 and 3 discuss shifts in fish diets to more vegetable-based meals and shifts in human diets to more herbivorous fish from aquaculture, respectively.

Opportunity 1: Restore catches to more sustainable levels
In 2006, the global catch (including shellfish) was 82 million tonnes from the sea and 10 million tonnes from fresh water (lakes and rivers). These catches are above maximum sustainable yield (MSY)[1] levels and depletion of fish stocks is a real threat. A temporary decrease in catches by reducing fishing efforts lowers pressure on fish stocks to a more sustainable level and restores stocks to produce higher catches.

Opportunity 2: Lower use of fishmeal and fish oil in aquafeeds
Fishmeal, fish oil and also by-catches and fish offal are used as feed for carnivore and omnivore fish species in aquaculture. In order to decrease the input of wild fish in aquaculture and livestock farming, alternative feeds with minimal or less use of wild fish are under development. Vegetable crops, such as soy, and to a lesser extent wheat and maize, have the highest share in alternative fish feeds for aquaculture. Other examples are feeds based on vegetable oils, algae, sandworms or single-cell proteins, and improved feeding techniques, helping to decrease the overall feed conversion ration (FCR, the ratio by mass of feed input to fish output).

Opportunity 3: Less wild fish consumption
Aquaculture might have a large potential for breeding highly productive nutritious and tasty 'domesticated' fish species. In order to decrease pressure on marine fish stocks, consumers have to use these alternative protein sources in their diets and notably shift fish consumption to herbivore fish from aquaculture.

7.3 Aspects not considered

- Fisheries are also associated with damage to marine life and habitats, for example by-catches, damage to coral reefs and damage to the seabed and bottom-dwelling organisms. Use of less disturbing fishing techniques might reduce these impacts on the marine habitat and the amount of by-catches. By-catch of target species concerns the catch of juvenile and undersized fish. By-catch of non-target species concerns mainly catches of other fish species and non-fish species, such as sea birds, turtles and dolphins.
- A considerable quantity of fish caught by fisheries is discarded. Fish are thrown back for various reasons: too small, of little or no commercial value or a species for which the fishery has no quota. It is estimated that worldwide the amount of fish thrown overboard corresponds to over 10% of the reported landed catch (FAO, 2009b). Most of the sea life thrown back does not survive. Reduction measures have been introduced to decrease discards of by-catches and by-catch is then used for local consumption and aquaculture (Garcia and Rosenberg, 2010). The European Commission has started discussions on banning discarding by-catches (Damanaki, 2011).
- Further changes in the use of fish-based feed in livestock farming other than aquaculture were not considered.
- Between extraction and consumption, there are other, intermediate links in the production chain, such as processing (sorting, gutting, cleaning, freezing, canning, filleting, breading, cooking and packaging)

Table 7.2
Overview of scenario assumptions

Scenario	Scenario assumptions
Baseline	**1. Fish demand**: Based on projections for aquaculture production for the 'global orchestration' scenario, by Overbeek *et al*. (2011) and Bouwman *et al*. (2011) and the assumption that global catches stabilise at a level of 95 million tonnes. Annual fish demand (based on supply) will increase from the current level of almost 140 million tonnes (in 2004) to reach almost 190 million tonnes by 2030 and more than 225 million tonnes by 2050.
	2. Wild catches: Marine catches: Based on the 'business as usual' scenario determined by UBC and described in section 4.8 of PBL (2010); 2002 fishing efforts in all years in period until 2050. Inland catches remain constant between 2000 and 2050.
	3. Fish supply by aquaculture: calculated as global fish demand minus marine and inland catches.
	4. Aquafeed: Feed conversion ratios and fish diets derived from Blonk *et al*. (2009) for salmon and catfish (as estimates for carnivore and herbivore finfish, respectively) and from Weimin and Mengqing (2007) for white shrimp (as estimate for shellfish). Future developments in diets and feed conversion ratios obtained from Overbeek *et al*. (2011) and Bouwman *et al*. (2011).
	5. Land use for crop based aquafeed: Based on crop requirements. Agriculture productivity growth in accordance with assumptions on trends in crop yield in the *envisaged policies* scenario (see the land-use section in Chapter 4)..
Global resource efficiency	**1. Fish demand:** Same as baseline.
	2. Wild catches: Marine catches: Based on the 'High Ambition with Ramp down' scenario determined by UBC and described in PBL (2010): gradual reduction in efforts in 10 years to reach optimal effort levels that maximise catches in the final year of the scenario run. Inland catches: same as in the *baseline* scenario.
	3. Fish supply by aquaculture: same calculation as for baseline, using the scenario-specific value for marine catches.
	4. Aquafeed: same calculations as for the *baseline* scenario, using the scenario-specific value for volumes of fish supplied by aquaculture.
	5. Land use for crop-based aquafeed: Agriculture productivity growth in accordance with assumptions on trends in crop yield in the scenarios on global resource efficiency (see the land-use section in Chapter 4).

and distribution. In these stages, losses may occur as well but they were not considered.

7.4 Scenario assumptions

An overview of scenario assumptions for this theme is given in Table 7.2.

7.4.1 Global fish demand

Projected global demands for finfish and shellfish up to 2050 were based on aquaculture projections plus global catches that were kept at a constant level of 95 million tonnes. Overbeek *et al*. (2011) and Bouwman *et al*. (2011) have compiled projections for aquaculture production of finfish and shellfish, respectively, for the four Millennium Ecosystem Assessment scenarios (Cork *et al*., 2005). In our study, the projections for their Global Orchestration scenario were used, which shows the highest fish supply based on a combination of low population growth, high income growth and high growth in per capita fish consumption. Projected global fish supply and hence demand in this scenario increases from almost 140 million tonnes in 2004 to almost 190 million tonnes by 2030 and to more than 225 million tonnes by 2050.

7.4.2 Marine catches

Two scenarios were distinguished for supply from marine catches for the fish theme. The first is the *baseline* scenario (BL), which for the purpose of this theme was considered equivalent to the *Envisaged policies* (ENVISAG). The second is the *global resource efficiency* scenario (G-RE), which for this theme was considered equivalent to the *global resource efficiency & climate change policy* scenario.

The projections for future marine catches in both scenarios were determined by the University of British Columbia (UBC) in their EcoOcean model. The same model was used to calculate the trend in species abundance in marine systems, as indicated by the depletion index (DI). A brief description of the model is presented in the Appendix. Marine catches were determined for 15 of the 19 marine statistical areas of the UN Food and Agricultural Organization (FAO). Together, these areas represent 99.8% of reported marine catches in 2000 (FAO, 2011b).

Table 7.3

Feed conversion ratio and fractions of fishmeal and fish oil in aquaculture feed for three fish species, in 2000 and 2050

	Salmon		Catfish		Shrimps	
	2000	2050	2000	2050	2000	2050
Feed conversion ratio (FCR, $kg.kg^{-1}$)	1.2	1.0	1.8	1.0	1.8	1.7
Fraction fishmeal + fish oil in feed	.56	.22	.12	.03	.25	.05

Source: Based on Blonk *et al*. (2009); Overbeek *et al*. (2011) for salmon and catfish; Weimin and Mengqing (2007) and Bouwman *et al*. (2011) for shrimps.

The *baseline* scenario applied the estimated 2002 effort levels for all marine fishing fleets to be constant into the future[2]. This scenario can be seen as 'business as usual'. In the ambitious *global resource efficiency* scenario, the fishing efforts of fleets were gradually ramped down to optimal levels in a ten-year period. The optimal effort level for a fleet was determined to be the level that maximised catches in the final year (2049). A gradual reduction seems to be more realistic than the immediate effort reduction in the 'High Ambition' variant as presented in section 4.8 of PBL (2010).

A scenario with increased European focus on resource efficiency without enhanced policies in other regions was not considered. Such a scenario should reduce efforts of European fleets, where other fleets are not disturbed. EU27 fish landings amounted to only 6% of the world total in 2008 (EC, 2010b), so effects of unilateral EU policies are expected to be small. Lower EU catches might lead to higher catches by non-EU fleets and higher EU fish imports to meet EU demand. This would mean that the EU would export its fishing footprint while restricting EU fishing.

7.4.3 Fish supply by aquaculture

For both scenarios in our study, the fish supply by aquaculture was calculated as the global fish demand minus the marine and inland catches. Since the demand for shellfish from aquaculture followed the projections of Bouwman *et al*. (2011), the demand for finfish was the difference with total supply form aquaculture. This also implies that the differences between the *baseline* scenario and the G-RE scenario concern only finfish but not shellfish.

Supply for finfish aquaculture was determined for carnivore plus omnivore fish species, and herbivore species separately, in order to facilitate feed and land-use calculations. In the scenarios, the share of carnivore plus omnivore species in total aquaculture finfish supplies would increase slightly from 22% in 2000 to 24% by 2050. The difference in production of aquaculture finfish between both scenarios was assumed to concern herbivore species only.

7.4.4 Crops required for aquafeed

We calculated the demand for feed in aquaculture for 2000 and for the growth in aquaculture in both scenarios using specific diets for carnivore and herbivore fish species and for crustaceans. Since molluscs feed on phytoplankton, crop-based feed use was not calculated for this group. The calculations were based on the diet of three fish species: salmon as an estimate for carnivore/omnivore species; pangas catfish as an estimate for herbivore species; and the pacific white shrimp as an estimate for shellfish. Information on the diets of salmon and catfish, (feed conversion ratio and feed composition) was obtained from Blonk *et al.* (2009) and for pacific white shrimp from Weimin and Mengqing (2007).

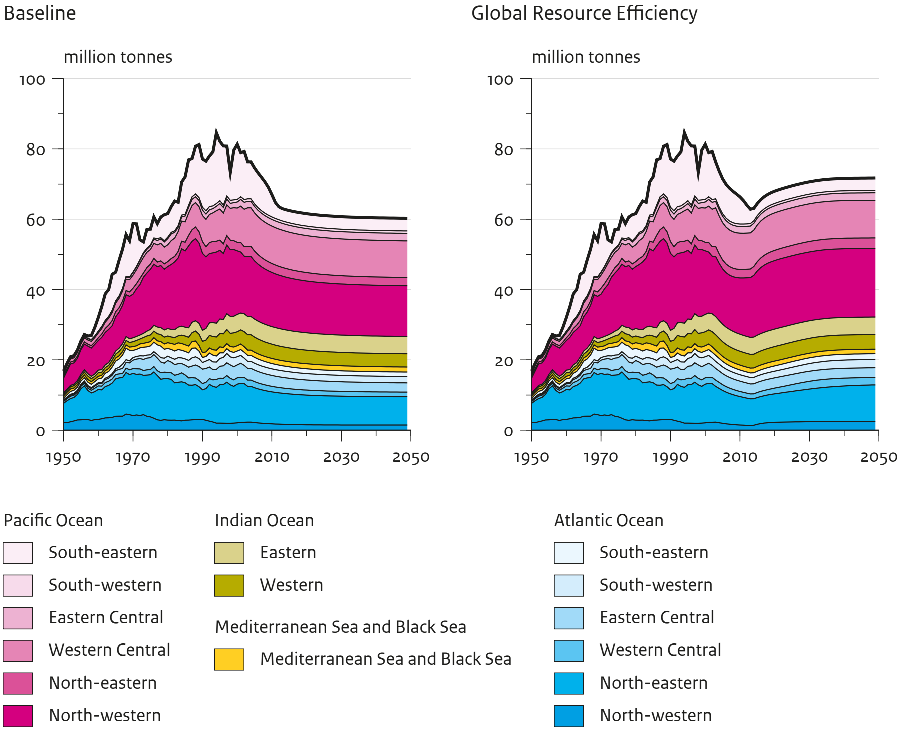
Determination of the extra feed requirements and land use to compensate for the temporarily lower catches in the G-RE scenario compared to the *baseline* scenario was based on the global difference between catches in these two scenarios. For the calculations, the year in which scenarios started to diverge was shifted from 2005 (the base year used by EcoOcean) to 2011. This implicitly assumes that the effects of the interventions in 2011 are similar to what they would have been in 2005. For the determination of feed requirements, in both scenarios, the assumption was made of a gradual improvement of feed efficiency over time, and an increase of the share of vegetable components in the feed, while the shares of fishmeal and fish oil are gradually reduced. The start and end values are presented in Table 7.3.

The crops quantities were based on conversion factors for the different feed ingredients to real crops. These conversion factors were obtained from Blonk *et al.* (2008).

7.4.5 Land requirements for aquaculture feed production

The land requirements for aquafeeds for 2000 were obtained from Blonk *et al.* (2009) for salmon and pangas catfish, and derived from data provided by Weimin and Mengqing (2007) and Blonk *et al.* (2008) for pacific white shrimp. Because these land requirement calculations were largely based on optimistic crop yields (for Europe and

Figure 7.3
Marine fisheries catches



Source: UBC

A gradual reduction in marine catches over a ten-year period would contribute to restoring fish stocks, enabling marine catches at a sustainably higher level than in the baseline scenario.

Brazil), they were adjusted to account for world average crop yields using FAO statistics (FAOstat).

For the scenario projections, the calculation of land requirements was based on FCRs and feed composition in 2000, and adjusted for future developments according to the assumptions in Table 7.3. The future decrease in the fractions of fishmeal and fish oil leads to a higher share of vegetable compounds in the feeds leading to increased demand for crop-based feed. Changes in crop yields followed the assumptions presented for the Land theme (Chapter 4). Differences in demand between the *baseline* and the *global resource efficiency* scenario were regionally allocated in proportion to the distribution of crop production in the baseline. Thus, for example, the extra soy would come mainly from the Americas and Asia.

7.5 Impact indicators

- Marine catches and fish stock depletion
- Share of aquaculture in total fisheries
- Crop production for aquaculture
- Impact of aquaculture on land use and terrestrial biodiversity

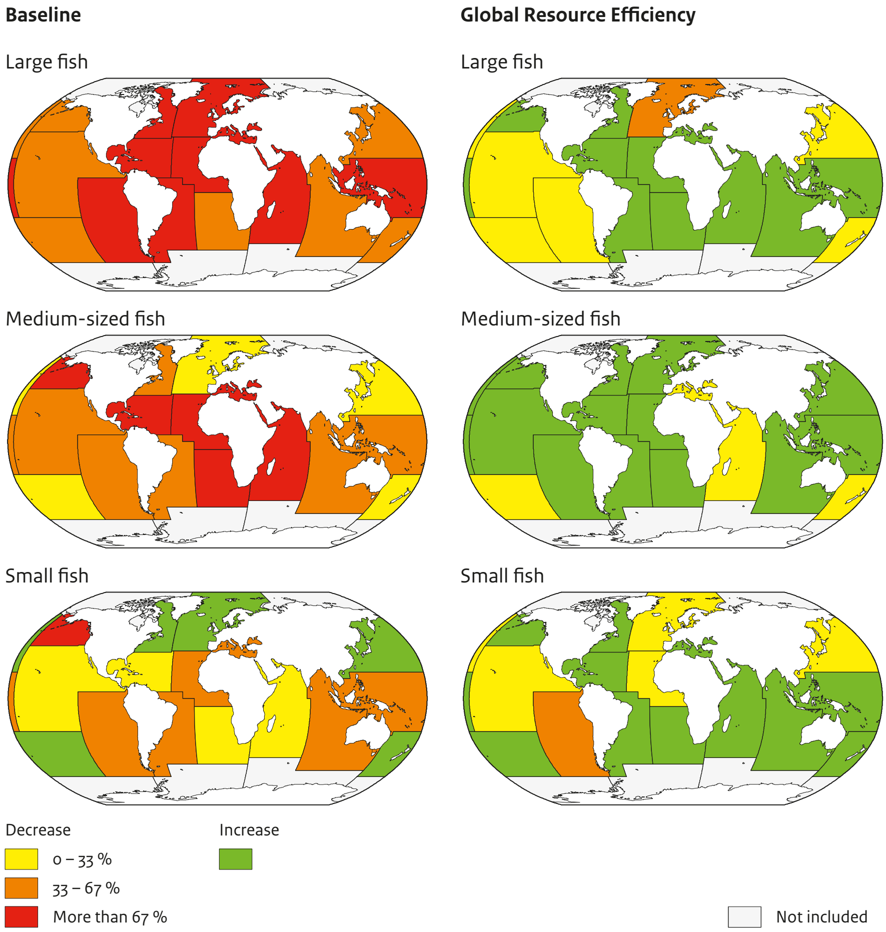
7.6 Results

7.6.1 Marine catches and fish stock depletion

Increase in marine catches in the past, and a projection for the two scenarios for the 2002-2050 period determined with the EcoOcean model are presented in Figure 7.3.

In the *baseline* scenario (Figure 7.3, left), the net result for 2050 would be a decline in total catches of over 20%, compared to 2002 levels. In the *global resource efficiency* scenario (Figure 7.3, right), stocks would be restored to higher levels after the 10 year ramp-down in fishing effort. Marine catches would recover to levels of just above 70 million tonnes by 2050, which is 9% below the 2002 level, but 19% higher than catches in the *baseline* scenario for the same year. Nevertheless, the ramp-down period may not be sufficient for some functional groups to recover. Therefore, the model results suggest a somewhat lower level of final catches in this scenario than for the more

Figure 7.4
Change in biomass of fish groups, 2004 – 2050



Source: UBC and PBL

The Marine Depletion Index (stock indicator for fish populations, based on the change in total biomass per species between 2004 and 2050) presents substantial improvement in the global resource efficiency scenario as compared to the baseline scenario, especially for large and medium-sized fish populations.

ambitious policy with steeper reduction presented in PBL (2010).

According to the model results, from the 2004 reference level onwards, the marine depletion index (DI) will decrease by 38% on average in the *baseline* scenario. The *global resource efficiency* scenario shows a clear improvement, compared to both the *baseline* scenario and the 2004 situation (Figure 7.4). The overall DI increases by 24% by 2050.

7.6.2 Aquaculture and its share in total fisheries

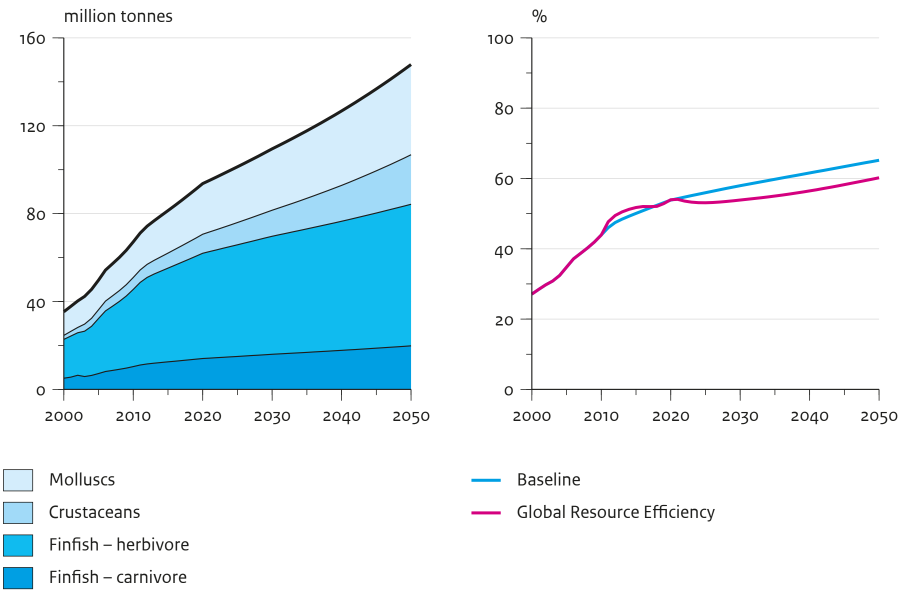
In the *baseline* scenario, total annual aquaculture production of finfish, crustaceans and molluscs will increase from 35 Tg in 2000 to almost 110 Tg by 2030, and to over 145 Tg by 2050. In the *global resource efficiency* scenario, total aquaculture production during the ramp-down period is higher than in the *baseline* scenario. After this period, marine catches return to a substantially higher level than the baseline level and consequently, demand for aquaculture production drops below the baseline level (Figure 7.5).

7.6.3 Feed for aquaculture

The amounts of crops for feed depend on developments in aquaculture production, the composition of fish diets and the FCRs. Assumptions on feed were the same in both scenarios, and thus the differences are the result of differences in aquaculture production developments. In the *global resource efficiency* scenario, total crop production

Figure 7.5
Aquacultural production

Baseline | Share in global fish supply

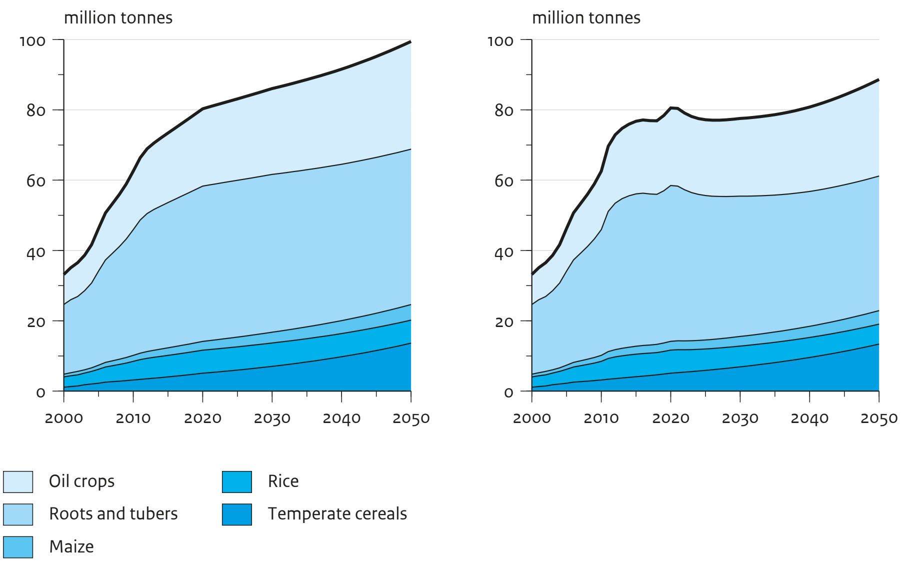


Source: left: Overbeek *et al*. (2011) and Bouwman *et al*. (2011); right: PBL

Aquacultural production is projected to increase almost fourfold, between 2000 and 2050, and to become the main source of global fish supply, before 2020. After the ramp-down period, more aquaculture is needed in the baseline scenario than in the global resource efficiency scenario.

Figure 7.6
Feed for aquaculture

Baseline | Global Resource Efficiency



Source: PBL

The larger sustainable marine catches in the global resource efficiency scenario imply that, in the long run, less feed, and thus less land will be needed for aquaculture than in the baseline scenario.

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for aquaculture is almost 7% higher in 2013 than in the *baseline* scenario, but in 2050, it is 11% lower than in the same year in the *baseline* scenario (Figure 7.6).

7.6.4 Impacts of aquaculture on land use and terrestrial biodiversity

The calculated land use for feed for aquaculture is about 0.08 million km^2 (8 million ha) in 2000, which corresponds to about 2% of the global crop area for feed production. In the *baseline* scenario, land use for aquafeed increases to 0.16 million km^2 by 2030 and 0.18 million km^2 by 2050. The extra land required for crops to compensate for the lower catches in the *global resource efficiency* scenario between 2010 and 2020 is up to 3.5% (in 2012). After this period, land for aquafeed in the *global resource efficiency* scenario would drop below the levels required in the *baseline* scenario by almost 15% by 2030, and almost 18% by 2050. The changes in crop area have a very small positive effect on terrestrial biodiversity (+0.01 percentage point by 2050, as indicated by the global Mean Species Abundance (MSA)) because increased wild fish catches reduce the need for aquaculture and thus for agriculture to produce aquafeed.

7.6.5 Conclusion on scenario outcomes

In conclusion, marine catches in the long term will be higher in the *global resource efficiency* scenario than in the *baseline* scenario, in which some functional groups approach depletion in several fishing regions. In the *global resource efficiency* scenario, stocks have the opportunity to return to more sustainable levels leading to higher catches and lower demand for aquaculture than in the *baseline* scenario. Thus both marine and land biodiversity will improve in the long term.

7.7 Limitations of the analysis

- Additional aquaculture developments were assumed to be on the global scale without regional specification.
- Direct use of water and land areas in aquaculture, such as coastal areas, basins and ponds, was not included in the calculations. Studies for catfish and tilapia production in ponds showed that the land requirements for feed ingredients are larger by a factor of 2 to 3 than the land requirement for culture facilities (Boyd *et al*., 2007). However, direct land use for shrimp production might be equal to or even higher than land requirements for feed production depending on the intensiveness of production. Furthermore, extensive shrimp cultures have resulted in physical degradation of coastal habitats, such as mangroves and wetlands (FAO, 2011c).

7.8 Barriers for resource efficiency and policy implications

The scenario results presented are computational explorations of three resource efficiency options for the resource fish without defining explicit policies. However, there are several physical, technological, economic and socio-cultural aspects concerning these options. Some of the main barriers and possible policy responses for the three resource efficiency opportunities are discussed in this study from an EU perspective.

7.8.1 Reducing catches

A temporary reduction in catches as shown in the *global resource efficiency* scenario might be achieved by restricting fishing efforts or restricting fish landings. Policy instruments to restrict fishing efforts include regulating fishing periods, zoning, limited entry or fishing days, and licensing. Establishments of Marine Protected Areas (MPAs), for instance, may restrict fishing activities temporarily during the spawning season or permanently. There are potential benefits of marine reserves where fishing is prohibited, but negative consequences in the form of increasing pressures on surrounding fishing areas and socio-economic impacts on local fishing communities are a real risk (Hilborn *et al*., 2004).

A decrease in the number of vessels will not automatically lead to reduced fish catches. When improvements in fishing efficiency go faster than reductions in fleet capacities, overall the effective harvest capacities of fleets is not reduced. In this sense, the EU Common Fisheries Policy (CFP, see Box 7.1) stimulating technological efficiency in fishing undermines the measures to reduce fishing fleet capacities (Villasante and Sumaila, 2010). Fuel subsidies in European countries (mostly in the form of fuel tax exemptions) do not stimulate reducing fishing activities either(Binet, 2007). Technical measures, such as fish sonar and the use of wider nets have at least partly counteracted the effect of decreasing fleets. However, technologies, such as satellite remote sensing and other information technologies can help monitor fishing activities. Vessel monitoring systems can provide information on vessel movements in order to enhance enforcement of regulations.

A policy instrument for restricting fish landings is a system of fish quotas per country and per fish species. Quotas are based on the total allowable catch (TAC) that can be harvested per fishing area. The International Council for the Exploration of the Sea (ICES, Box 7.2) gives advice on TACs to the EC on the basis of fish stocks, carrying capacity and regeneration rates. Individual shares based on quotas are allocated to fishers per country. Where

Box 7.1 The EU Common Fisheries Policy (CFP)

The main EU policy framework for fishing is the Common Fisheries Policy (CFP). In 1970, fishery policy started by the then six Member States with setting rules about equal access to all EEC fishing grounds and in 1976, rights over marine resources were extended. In 1983, the first CFP was launched with the introduction of a system of total allowable catches (TACs), quotas on a species-by-species basis and distribution of TACs over countries. A revised CFP was agreed in 2002 with new elements including reduction of fleet capacity and greater involvement of fishermen in the CFP management process. Up until now, structural problems in EU fisheries, such as fleet overcapacity and overfishing have not been resolved (see EC Green Paper on CFP, 2009). Therefore, a reformed policy is planned for 2012 with attention to sustainable fisheries, the principle of MSY, an improved quota system, by-catches, implementation and control, and the economic position of the fisheries sector. Furthermore fishermen would be given more responsibility for managing stocks.

Box 7.2 International Council for the Exploration of the Sea (ICES)

Founded in 1902, the International Council for the Exploration of the Sea (ICES) coordinates and promotes research on oceanography, the marine environment, the marine ecosystem, and on living marine resources in the North Atlantic (ICES, 2011). The ICES community consists of 20 member states including all coastal states bordering the North Atlantic and the Baltic Sea. A number of countries in the southern hemisphere are affiliated with ICES. ICES provides information on the status of stocks of finfish and shellfish in the North Atlantic Ocean and advises on catches per species.

quotas are transferable, fishers might buy or sell these shares. In practice, however, the functioning of quotas is not optimal because of lack of trust between the fisheries sector, scientists (marine biologists), and governments. Sympathies for one another positions have increased since the establishment of Regional Advisory Councils (RACs). Differences between the fishing quotas and the TACs recommended by ICES were about 20% in the 1992–2008 period (Villasante *et al.*, 2011). Proposals for sustainable catch levels were revised upwards for political reasons. Fishermen often blame the EC that quotas are too low with the argument that current catches indicate an abundance of fish. Furthermore, quotas have the side effect that fish are caught that are not covered by the species quota, or that are not considered optimal are thrown back into the sea. Quotas have also generated a considerable volume of illegal fishing. The Green Paper (EC, 2009b) suggests increasing effectiveness of inspections and more heavy penalties for rule breaking.

A reduction in fishing efforts or catches will have further impact on incomes of individual fishermen in the short term. The fisheries sector is struggling with poor economic returns due to the declining fish stocks and rising costs. At the same time, it is facing increasing competition from alternatives, such as farmed pangasius and tilapia in Asia. Employment in fisheries in the EU Member States fell from about 190,000 fishermen in 2003 to about 126,000 in 2007 (JRC-IPTS, 2009). Alternative job opportunities for fishermen are scarce; fishermen are not fish farmers. Many coastal communities in Europe depend on small-scale recreational and coastal fishing for their income. Thus, the fisheries sector also has an important cultural heritage function in these coastal areas.

It is more difficult to limit fishing capacity in developing countries where fishing operations are dominated by disperse, small-scale activities. Marine fisheries are an important component of food security and income in coastal nations and limiting catches would have significant impacts on those depending on fisheries for their food and livelihoods. The EU made bilateral fisheries partnership agreements (FPAs) with countries in western Africa and around the Indian Ocean in order to give European fisheries access to fish stocks in remote seas. These agreements also intend to support regional fisheries management organisations in strengthening fishery policies in the partner countries. There is a risk that EU fish catches in the fishing areas of developing countries take away an important protein source from the population in those countries.

The EC realises that reform of the CFP is necessary to resist the problems in the EU fishing industry partly caused by unwanted side effects of policy instruments. Debate on this reform was stimulated by preparing a Green Paper with a vision on future EU fisheries and a consultation round with stakeholders (EC, 2009b, 2010c). The Green Paper states that emphasis should be on the future sustainability of the industry with long-term socio-economic benefits instead of increasing short-term fishing opportunities. Fishermen have to be encouraged to develop methods of sustainable management from a long-term perspective. A potential policy instrument for more sustainable management of stocks is the use of transferable quotas with rights for many years. The Green Paper also suggests differentiating between the rights of small-scale community-based coastal fishing boats and large industrial concerns.

7.8.2 Alternative feeds in aquaculture[3]

For the EU, where about 85% of aquaculture production concerns carnivore fish species, a shift to more sustainable feeds that depend less on wild fish catches is a challenge. Fish oil is a more immediate constraint than fishmeal, but nutrition research confirms that complete substitution of fish oil with vegetable oils is possible (Bostock *et al*., 2008). Several developments in alternative feeds are underway, but often in early stages. As aquaculture expands further, it is not clear whether sufficient amounts of alternative feeds can be developed and produced in time. The use of krill for aquaculture feeds has to compete with increasing use of krill for direct human consumption and for production of pharmacological krill oils (Bostock *et al*., 2010). There are also risks of harmful effects on ecosystems, such as the Antarctic waters, and a potential impact on marine food webs. Feed of vegetable origin, such as soy, requires land for production that competes with land for food production and nature. The growing demand for vegetable oils in fish diets also has to compete with an increased demand for biofuels, for instance based on rape seed oil that is stimulated by EU policies. An integrated approach with aquaculture and feed production at the same location might be a plausible option. Waste products of aquaculture might then be used as fertiliser in crop production.

An economic barrier is that the production costs of fish feed alternatives, such as algae and worms are higher than the production costs of fish oil and fishmeal. Higher prices for fish-based feeds will make alternative feeds for aquaculture more competitive. Higher prices might also prevent fishmeal and fish oil becoming attractive again for other uses, such as components in animal feeds in livestock farming. A decline in production of fishmeal and fish oil will have negative socio-economic impacts on the producers but offers opportunities for development of new industries in feed production.

Fish feed alternatives have to take into account effects on human and animal welfare. Carnivore fish species contain omega-3 fatty acids to which positive effects on human health are attributed (see option 3). The fish receive these acids from algae via the food chain by eating small edible fish or crayfish. Since resources of vegetable origin contain only small amounts of omega-3 fats or none at all, substitution with vegetable feed will decrease the amount of these fats in fish from aquaculture. Furthermore, not all fish oil and fishmeal in feed for carnivore fish can be replaced with vegetable alternatives because several species exhibit lower growth rates and higher mortality.

Research is advancing to increase the share of vegetable feed while minimising the negative effects on fish growth and health and the content of omega-3 fats. For instance, salmon can be fed with vegetable oils during most of the production cycle, and a switch to fish oils in the last months for harvesting is sufficient to produce omega-3 fats (Bostock *et al*., 2008). Genetic modification (GM) might also increase the production of healthy fats in fishes and plants, but this technology is not well accepted by European consumers.

In the framework of the CFP, the EC developed strategies for sustainable development of the aquaculture sector in the EU (EC, 2002, 2009a, c). These strategies identified actions with regard to aquaculture feeds, such as stimulation and promotion of research on feed substitution and optimisation of feed regimes.

7.8.3 Shift in fish consumption

A shift from marine fish production to aquaculture has to be achieved in a situation where overall fish consumption is stimulated. There are recommendations to eat more fish in Europe (EFSA, 2010), but also in other countries, such as China (Ge *et al*., 2007). Fish and shellfish are sources of essential vitamins, minerals and in particular, fatty fish contains omega-3 fatty acids. These substances have a positive effect on human health by decreasing the risk of cardiovascular diseases (Kromhout *et al*., 1995; RIVM, 2004). Consumption of more freshwater fish and less saltwater fish might decrease the health advantages of fish because omega-3 fats are lower in freshwater fish. An option is to recommend the use of nutritious supplements based on microalgae, which are the original source of the healthy fats in fish. However, consumers prefer fat carnivore and omnivore fish species to herbivore species not only for health reasons but also for the taste. Furthermore, there may be a shift in developing countries from herbivore fish to carnivore fish as incomes increase.

Aquaculture systems also have environmental impacts. The land use required for fish feed has been discussed above (opportunity 2). Other environmental issues related to aquaculture include:

- Greenhouse gas emissions: most emissions related to aquaculture come from fossil energy use and direct greenhouse gas emissions in crop farming, energy use in feed production (crops, fishmeal, fish oil, etc.) and direct energy use in aquaculture (fish farming).

Although there are differences per species, energy use per kg farmed fish is similar to fisheries (see Blonk *et al.* (2009).
- Eutrophication: aquaculture in or near coastal areas and rivers may lead to over-fertilisation of these waters due to nitrogen and phosphorus loading.
- In aquaculture, fishes live (relatively) close together leading to disease. Where the farming areas are connected to natural ecosystems, antibiotics used to control these diseases may pollute ecosystems. The use of chemical products in aquaculture may also pollute the surrounding waters. Furthermore, farmed fishes might escape and bring diseases to wild fish populations.
- Loss of habitats when farming occurs in natural areas, such as mangroves and coastal marshlands. Saltwater use in coastal ponds may render these areas unusable for agriculture for decades.
- Freshwater use for controlling the salt level in aquaculture basins. This use is at the expense of drinking water in developing countries.
- Competition of (escaped) invasive species with natural species may result in displacement of original species. For instance, introduction of the Nile perch for sport fishery in Lake Victoria in the 1960s decreased the native fish population dramatically.

Better management of aquaculture systems can counter some of the environmental impacts mentioned. The EU strategies for sustainable aquaculture (EC, 2002, 2009a) in the framework of reform of the CFP have set out policy directions to ensure environmental sustainability, safety and quality of EU aquaculture production. Other aspects concern the growth and competitiveness of the aquaculture sector in the EU, and the health and well-being of fish. The strategy on environmental aspects is directed at supporting sustainable development of aquaculture by stimulating research on technological innovations to reduce environmental impacts in farming systems. Adequate monitoring of the aquaculture sector is needed to support policies. Boyd *et al.* (2007) proposed a set of indicators of resource use efficiency and environmental performance in aquaculture that could be used in monitoring and comparing the impacts of different aquaculture production systems. Where EU aquaculture cannot fulfil demand, product and quality standards have to be defined for aquaculture products from abroad.

When decreasing fish consumption is not a realistic option for health reasons, consumption, production and trade of certified fish could be stimulated. Certification via schemes, such as the Marine Stewardship Council (MSC) label is directed to achieving effective fisheries management without overfishing and with limited environmental impact. Governments do not organise certification, but only encourage initiatives by NGOs and private sectors. The MSC was initiated by Unilever and WWF in 1999, but is now a broad partnership. Certification for aquaculture products is under development in the form of the establishment of the Aquaculture Stewardship Council (ASC) directed to inspection of effective management of nature, food security and social circumstances. Several international NGOs have criticised the establishment of the ASC for its association with industrial aquaculture and alleged lack of regard for local environments and indigenous communities (SeafoodSource, 2009). Effects of certification have to be studied further to determine the effectiveness of this instrument.

7.9 Conclusions

- In the absence of strong diversion from recent trends, commercially attractive fish stocks will continue to decline with some functional groups approaching depletion in several fishing regions. A concerted, gradual reduction in fishing efforts would lead to recovery of stocks and improvement in marine biodiversity that can sustain higher catches in the long-term without ever increasing efforts.
- Current instruments based on total allowable catches (TAC) are not optimal in restoring fish stocks. New instruments have to be developed that stimulate fishermen to manage fish stocks more sustainably from a long-term perspective. In any scenario, current fleet capacities are well above the level of sustainable catches, and will need to be reorganised accordingly. The most serious challenges are the social implications of structural reform and the need for agreements between communities (or countries) competing for the same stocks.
- Given that wild catch fisheries cannot supply growing demands, aquaculture is projected to expand strongly. Reduced fishing efforts would initially require even more fish supplies from aquaculture (+3.5%). When oceanic fish stocks recover, demand for aquaculture will rise less steeply than under current fisheries practices, and less land area would be needed to produce feed for aquaculture (aquafeed) (-18% compared to *baseline* scenario for 2050). Hence, both marine and terrestrial biodiversity would benefit from resource efficiency policies.
- Currently, aquafeed tends to contribute to fish depletion. In order to decrease dependency on fish-based feed, alternative crop-based feeds need to be developed further that will not affect the content of omega-3 fats in fish from aquaculture. Higher production costs of alternatives are still a barrier in a transition to alternative feeds.

- The EU currently lags behind with aquaculture and is becoming increasingly dependent on fish imports.
- The building of more sustainable aquaculture requires the support of research on technological innovations with less environmental impacts. Establishment of quality and sustainability standards for aquaculture products from EU production and abroad might accelerate implementation of more environmentally sound aquaculture production practices.

Notes

1 MSY is theoretically the largest average catch that can be taken from fish stocks over an indefinite period.

2 The scenarios were based on model calculations carried out by UBC for the 'reduced marine fishing efforts' option of the PBL study on Rethinking global Biodiversity Strategies (PBL, 2010, section 4.8). The Baseline scenario of this study corresponds with the 'business as usual' variant of PBL (2010); and scenario G-RE with the 'High ambition with ramp down' variant of PBL (2010).

3 Main part of the information in this section is based on Rood, G.A., D. Nagelhout, J. Ros and H. Wilting (2006) Duurzame viskweek voor behoud van de visvoorraad. Evaluatie van transities op basis van systeemopties. Bilthoven: Milieu en Natuur Planbureau.

Glossary

BRIICS: Brazil, Russia, India, Indonesia, China and South Africa.

Feed Conversion Ratio (FCR): the number of kilograms of feed (dry mass) required to produce a kilogram of animal weight gain.

Fertiliser use efficiency (FUE): crop production in kg dry matter per kg of a specific nutrient applied. This is the broadest measure of nutrient use efficiency and is also called the partial factor productivity of the applied nutrient (Dobermann and Cassman, 2005).

Final energy: energy as delivered to end-users, covering electricity, fossil fuel and bio-energy carriers, heat and hydrogen.

Marine Depletion Index (DI): the weighted mean of the ratios of the biomass estimated for 2050 and that of 2004, per species. It was adapted from the original depletion index described in (Alder *et al.*, 2007).

Maximum Sustainable Yield (MSY): this is theoretically the largest catch, per fish population, over an indefinite period, keeping the size of this population at its maximum growth rate by harvesting the numbers of fish that would normally be added to the population, allowing it to continue to be productive indefinitely.

Mean Species Abundance (MSA): an indicator of biodiversity intactness and defined as the 'mean abundance of original species relative to their abundance in undisturbed ecosystems'. See the Appendix, section on GLOBIO3.

Natural and semi-natural area: is the original area of a region or biome minus the area converted for human use by agriculture (arable land and land for permanent grazing), forestry plantations, infrastructure and built-up area. This includes both entirely intact and degraded areas.

P: Phosphorus

Primary energy: the energy used, including direct delivery to end-users plus the inputs in electric power and heat plants and other energy conversion processes, such as refineries.

Primary sources: original, raw, not recycled. From primary sources: from agricultural products or mining.

RCP2.6: a greenhouse gas trajectory (RCP=Representative Concentration Pathway) leading to radiative forcing of 2.6 W/m^2 by 2100, with a mean probability of achieving the 2 °C target of between 60% and 70% (Van Vuuren *et al.*, 2007; Van Vuuren *et al.*, 2010a).

Total Allowable Catch (TAC): a catch limit set for a particular fishery, generally for a year or a fishing season. TACs are usually expressed in tonnes of live-weight equivalent, but are sometimes set in terms of numbers of fish.

Water stress severity classes: as adopted from the OECD Environmental Outlook (OECD, 2008): Water stress is a measure of the long-term average withdrawal-to-availability ratio in a river basin. The ratio is grouped in one of four categories: No stress, less than 10%; low stress, 10% to 20%; medium stress, 20% to 40%; severe stress, more than 40%. These inferred severity levels refer to the river basin (its management, ecosystem and local economy). Class boundaries were determined on the basis of experience and expert judgement.

Wilderness areas: natural areas with a low degree of human influences. These areas are mainly areas where large animals can roam freely and vegetation is untouched by humans. In this study, wilderness areas are defined as the natural area with high MSA values, arbitrarily set higher than 80%.

Appendix

Model infrastructure and data used

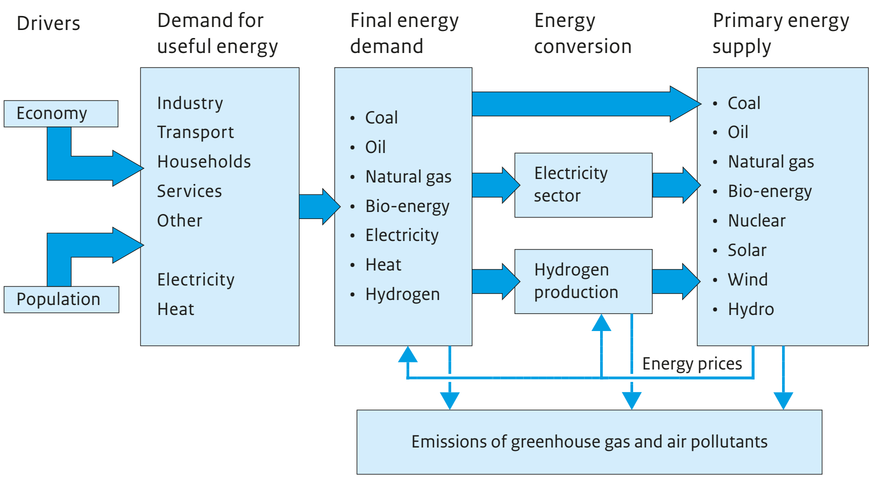
IMAGE

IMAGE Energy (TIMER)
The global energy system model TIMER (The IMage Energy Regional Model) (Van Vuuren *et al.*, 2007) has been developed to simulate long-term energy baseline and climate change mitigation scenarios. The model describes the investments in and use of different types of energy options influenced by technology development (learning-by-doing) and resource depletion. Inputs to the model are macro-economic scenarios and assumptions on technology development, preference levels and restrictions to fuel trade. The model output demonstrates how energy intensity, fuel costs and competing non-fossil supply technologies develop over time. It generates primary and final energy consumption by energy type, sector and region, and capacity build-up and utilisation, cost indicators and greenhouse gas and other emissions. Thus, the TIMER model provides regional energy consumption, energy efficiency improvements, fuel substitution, supply and trade of fossil fuels and renewable energy technologies. On the basis of energy use and industrial production, TIMER computes greenhouse gas emissions, ozone precursors and acidifying compounds.

In TIMER, implementation of mitigation is generally modelled on the basis of price signals (a tax on carbon dioxide). A carbon tax is used as a generic measure of climate policy and induces additional investments in energy efficiency, fossil fuel substitution, and investments in bio-energy, nuclear power, solar power, wind power, and carbon capture and storage. Selection of options throughout the model is based on a multinomial logit model that assigns market shares on the basis of relative production costs of competing options, modified for observed preferences (De Vries *et al.*, 2001).

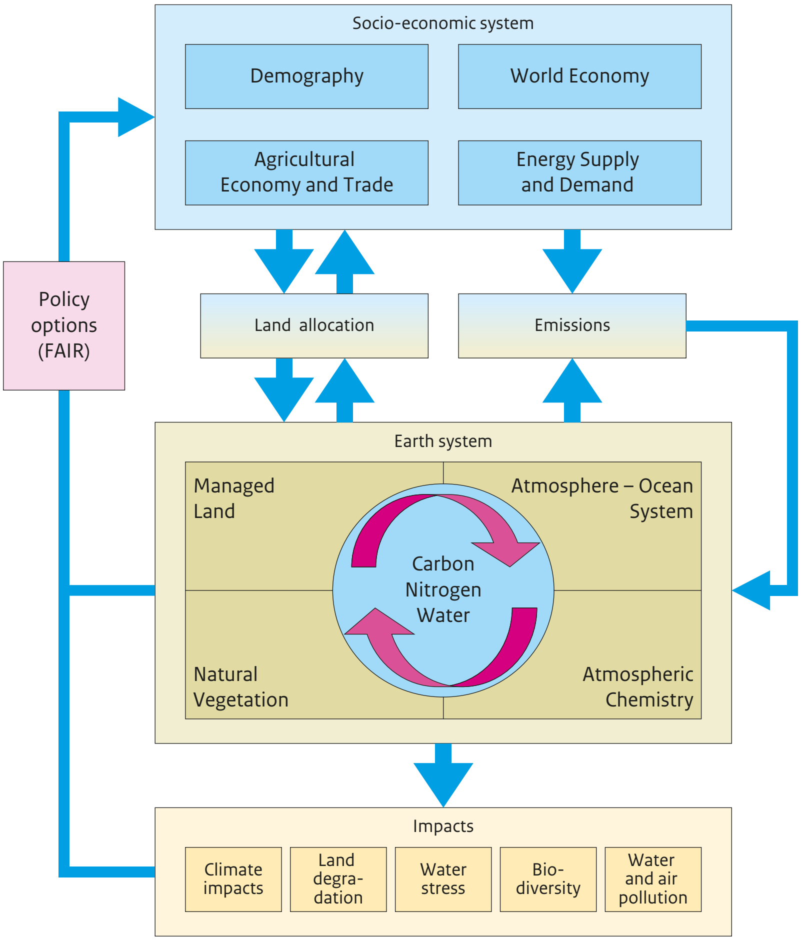
The TIMER model covers the chain from demand for energy services (useful energy) to the supply of energy by different primary energy sources and related emissions (Figure A-I.1). The steps are connected by energy demand (from left to right) and by feedbacks mainly in the form of energy prices (from right to left). The TIMER model has three types of sub-models: (i) the energy demand model;

Figure A-I.1
Overview of the TIMER model



Source: MNP (2006)

Figure A-I.2
IMAGE 2.4 Framework



Source: MNP (2006)

three types of sub-models: (i) the energy demand model; (ii) models for energy conversion (electricity and hydrogen production); and (iii) models for primary energy supply. Input data for TIMER and IMAGE on energy use and historic emissions are derived from the EDGAR (Emission Database for Global Atmospheric Research) information system (Olivier *et al.*, 2001).

IMAGE land & climate

The Terrestrial Environment System (TES) of IMAGE (Alcamo, 1994; Bouwman *et al.*, 2006) computes land-use changes based on regional production of food, animal feed, fodder, grass, bio-energy and timber, with consideration of local climatic and terrain properties (Figure A-I.2). Climate change affects the productivity of crops and induces changes in natural vegetation with consequences for biodiversity.

TES represents the geographically explicit modelling of land use, one of the outstanding characteristics of IMAGE. The potential distribution of natural vegetation and crops is determined on the basis of climate conditions and soil characteristics on a spatial resolution of 0.5 degree latitude x 0.5 degree longitude. It also estimates potential crop productivity, which is used to determine allocation of cropland to different crops. First, constraint-free rainfed crop yields are calculated that account for local climate and light attenuation by the crop considered (FAO, 1981). These climate-dependent crop yields are adjusted for grid-specific conditions by a soil factor that accounts for nutrient retention and availability; level of salinity, alkalinity and toxicity; and rooting conditions for plants. In addition, the fertilisation effect of changes in the atmospheric concentration of carbon dioxide is taken into account. The resulting crop productivity is used in the land cover model (LCM, which aims to simulate changes in global land use and land cover by reconciling land-use demand with land potential. The basic idea of LCM is to allocate crop production on grid cells within a world region until total demand for this region is met. The results depend on changes in demand for food, feed and bio-energy. Land-use types are allocated at grid cell level on the basis of specific rules, such as crop productivity, distance to existing agricultural land, distance to water bodies, and a random factor (Alcamo *et al.*, 1998). Bio-energy crops are only allocated to contracting agricultural lands and natural grasslands and savannahs.

Emissions from land-use changes, natural ecosystems and agricultural production systems, and the exchange of carbon dioxide between terrestrial ecosystems and the atmosphere are also calculated. The Atmospheric Ocean System (AOS) part of IMAGE calculates changes in atmospheric composition using the emissions from the TIMER model and TES, and by taking oceanic carbon dioxide uptake and atmospheric chemistry into consideration. Subsequently, AOS computes changes in climatic parameters by resolving the changes in radiative forcing caused by greenhouse gases, aerosols and oceanic heat transport.

IMAGE uses historical data for the 1765–1970 period to initialise the carbon cycle and climate system. Simulations cover the 1970–2050 period. Data on the 1970–2000 period were used to calibrate the IMAGE model with FAO data. For the 2001–2050 period, the simulations were driven by input from the TIMER model and agroeconomic model (mostly LEITAP), and by additional scenario assumptions, such as those on technology development, yield improvements and efficiencies of animal production systems.

On the consumption side, it is assumed that the relative contribution of commodities not covered by the IMAGE crop and animal product groups to the diet remains constant. This group includes fish and can be adjusted to reflect constraints in regional fishery output.

The parameterisation of the climate model included in IMAGE (called MAGICC) follows the IPCC fourth assessment report (see Meinshausen *et al.*, 2011). Concerning the terrestrial carbon cycle, the parameterisation of the IMAGE 2.4 model follows recommendations of IPCC (2007), with reduced fertilisation factor of natural vegetation compared to earlier versions. The estimation of CO_2 fertilisation remains uncertain because many other growth factors may constrain the effect in many regions.

GLOBIO3

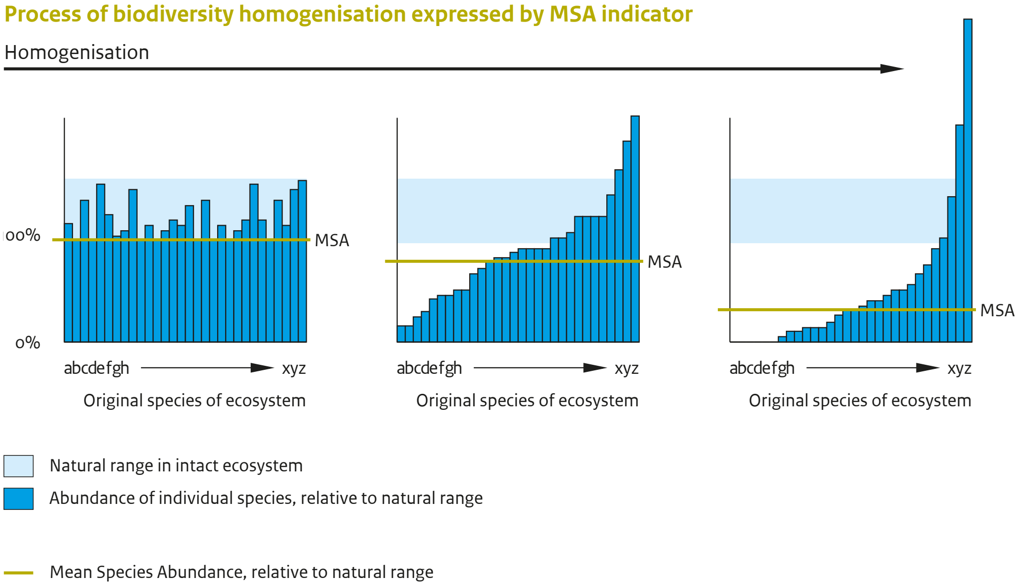
According to the Convention on Biological Diversity (CBD), biodiversity encompasses the overall variety found in the living world and includes variation in genes, populations, species and ecosystems. Several complementary indices are used within the CBD framework. In the GLOBIO3 model (Alkemade *et al.*, 2009), biodiversity loss is expressed for each biome by the mean relative abundance of the original species (MSA). In this index, the abundance of individual species is compared with their abundance in the natural or low-impacted state. Therefore, this aggregated indicator can be interpreted as a measure of 'naturalness' or 'intactness', and is similar to the Biodiversity Intactness Index BII (Scholes and Biggs, 2005). The difference between an intact (left) and a degraded ecosystem (right) expressed by the MSA indicator are illustrated in Figure A-1.3.

Mean species abundance is not an absolute measure of biodiversity. For instance, if the indicator value is 100%, the biodiversity is similar to the natural state, and if the indicator value is 50%, the average abundance of original species is 50% of the natural state. By definition, the abundance of exotic or invasive species is not included in the indicator, but their impact is shown by the decrease in the abundance of the original species they replace.
One of the advantages of 'mean species abundance' is that it can be measured and modelled relatively easily. In a straightforward multiplicative approach, the GLOBIO3 model (Alkemade *et al.*, 2009) combines estimates for key pressures on biodiversity. These pressures include climate change, nitrogen deposition, land-use change (agriculture, forestry, urban), fragmentation, infrastructure and human settlement.

The core of GLOBIO3 is a set of regression equations describing the impact on biodiversity of the degree of pressure using dose-response relationships. These dose-response relationships are derived from a database of observations of species response to change. The current version of the database includes data from approximately 500 peer-reviewed studies, about 140 studies on the relationship between species abundance and land cover or land use, 50 on atmospheric nitrogen deposition (Bobbink, 2004), over 300 on impacts of infrastructure (UNEP, 2001) and several literature studies on minimal area requirements of species. Dose-response relationships for climate change are based on model studies (Bakkenes *et al.*, 2002; Leemans and Eickhout, 2004).

The pressures on biodiversity considered with GLOBIO3 include land-cover change, land-use intensity (partly taken from IMAGE), atmospheric nitrogen deposition, infrastructure development, fragmentation and climate change.

Figure A-I.3
Process of biodiversity homogenisation expressed by MSA indicator



Source: PBL

Indirect drivers of biodiversity change, such as human population density and energy use, are not used explicitly in the GLOBIO3 framework, but impact biodiversity through their influence on direct drivers. For example, changes in direct drivers (land use, climate, atmospheric nitrogen deposition and forestry) due to changing demography and socio-economic developments are calculated with IMAGE (Bouwman *et al.*, 2006). Changes in infrastructure are calculated with the GLOBIO2 model (UNEP, 2001; UNEP and RIVM, 2004).

For land-use change, the MSA value of a human influenced land-cover type depends on the local pristine or reference situation. For instance, a forest converted to intensively used grassland has a lower remaining MSA than natural grassland converted to the same land cover, because the converted grassland more closely resembles the original situation. The fragmentation effect is related to the size of natural continuous land-cover types, and their capacity to sustainably house viable populations of species. The combination of multiple impacts results in estimates for changes in species abundance and extent of natural areas on a detailed spatial grid of 0.5 x 0.5 degree, in conformity with IMAGE.

The effect of infrastructure is based on the GLOBIO2 model (UNEP and RIVM, 2004), which treats infrastructure as a proxy for a range of pressure factors. The GLOBIO3 model treats these pressure factors independently but still uses the infrastructure knowledge base of GLOBIO2 to estimate the impact of infrastructure expansion.

LPJmL model, extended to include water reservoirs

The assessment of freshwater resources in this study is performed with an extended version of the LPJmL model, as described by (Biemans *et al.*, 2011):
The LPJmL model was designed to simulate global carbon and water balances in conjunction with the dynamics of natural vegetation (Gerten *et al.*, 2004; Sitch *et al.*, 2003) and agricultural land (Bondeau *et al.*, 2007; Fader *et al.*, 2010), including a global routing and irrigation module (Rost *et al.*, 2008). LPJmL has been validated against discharge observations for 300 globally distributed river basins (Biemans *et al.*, 2009) and irrigation water use and consumption (Rost *et al.*, 2008). The net irrigation demand of an agricultural field is defined as the amount of water needed either to fill the soil to field capacity, or the amount needed to meet the atmospheric evaporative demand. The gross water demand is determined by multiplying the net irrigation demand with a country-specific irrigation efficiency factor, which depends on the irrigation system [estimated by Rohwer, *et al.* (2007)]. This gross irrigation demand is first fulfilled by taking water from the cell's lakes and rivers. If the local cell cannot meet the demand, water is taken from the adjacent grid cell with the highest discharge. In the extended LPJmL model, if there is still a remaining irrigation demand, water is requested from the reservoir. Finally, depending on the

input assumptions, any remaining demand can be met assuming unlimited supply (e.g., from fossil groundwater).

Not all water extracted reaches agricultural fields. Transport losses are accounted for by applying a country-specific conveyance efficiency factor. This factor varies between 0.7 and 0.95 depending on the irrigation system used (lined canals, unlined canals, or pipeline systems; see Rohwer *et al.* (2007); Rost *et al*. (2008). About 50% of the water lost during conveyance is assumed to evaporate and 50% is assumed to return to the river.

The reservoir scheme of the extended LPJmL model is based on a combination of algorithms developed by Hanasaki *et al.* (2006) and Haddeland *et al.* (2006). A reservoir is considered in the model from the simulation in which it was built. This makes the model suitable to study the impacts of dams over time. Water enters the reservoir on a daily basis with discharge from upstream and precipitation. The calculation of discharge from the reservoir varies according to its primary purpose (irrigation, hydropower, flood control, navigation). If the reservoir is not built for irrigation purposes, the water is released directly into the river. Otherwise, part of the released water can be diverted to irrigated land, except for the water needed to fulfil environmental flow requirements, for which a minimum release was set at 10% of the mean monthly inflow.

All cells requesting water from a reservoir must be at lower altitudes than the cell with the reservoir. Further, they must either be situated along the main river downstream of the reservoir, or within reach of this main river at a distance of a maximum 5 cells upstream (approximately 250 km at the equator). Consequently, an irrigated cell can be supplied by two or more reservoirs, in which case the irrigation demand of that cell is shared between the reservoirs proportional to their mean volumes.

The mean volume of water stored in a reservoir can change from year to year, and hence shares are updated annually. Irrigation demands vary from day to day and water released for irrigation is made available for a five-day period. If the water is not used within these 5 days, it is released into the river, and hence storage possibilities in the conveyance system are simulated. A reservoir's total water demand is compared with the water released from the reservoirs for irrigation. If the total demand can only partly be fulfilled, all cells get the same fraction of the water they requested.

Carbon and water pools are initialised by running the model for the 1901–2000 period, after a 990 year spin-up period (forced by repeating 1901–1930 climate and without irrigation and reservoirs). Weather data input include monthly gridded values for temperature, precipitation, number of wet days and cloud cover from the CRU TS 2.1 climate data set (Mitchell and Jones, 2005). Daily weather data are generated by linear interpolation for temperature and cloud cover; and by applying a stochastic distribution method using the number of wet days for precipitation (Sitch *et al.*, 2003). The land use input consists of annual fractions of irrigated and non-irrigated crop types within each grid cell for the 20th century. This global crop and irrigation input dataset was developed by combining recently compiled datasets on rainfed and irrigated agriculture (Portmann *et al.*, 2010), current crop distributions (Monfreda *et al.*, 2008; Ramankutty *et al.*, 2008), and historic land-use information (Klein Goldewijk and Van Drecht, 2006). Information on natural lakes was obtained from the global lake and wetland database, GLWD (Lehner and Döll, 2004); and the locations of the reservoirs from the GRanD database (Lehner *et al.*, 2011). This global database contains geographical locations for approximately 7,000 dams, including information on construction year, maximum storage capacity, surface area and functions. The representation of the river system is simplified to a 0.5° grid network (Vörösmarty *et al.*, 2000). As a consequence, not all reservoirs (which have exact geographical locations) are placed on the right tributary of the modelled river system. However, the locations of all (190) reservoirs with a capacity larger than 5 km^3 have been checked and relocated on the network, if necessary.

Phosphorus

Phosphorus depletion is currently not explicitly modelled in IMAGE. Therefore, a recently developed model at PBL was used to explore depletion of phosphorus resources by directly connecting primary phosphorus production and final phosphorus consumption. The model uses exogenous region-specific demands for phosphorus resources (e.g., from the USGS) and considers trade in phosphorus products (e.g., phosphorus fertiliser and animal feed) between regions. The phosphorus flow into a certain region is the net result of trade in ore and phosphorus-containing products. Globally, 14 world regions are considered. The model applies seven different resource types, such as historic production between 1970 and 2000, reserves, reserve base, and additional resources (e.g., seabeds). Different types of phosphorus-containing products are not considered in the model.

Phosphorus depletion is a function of the cumulative production from the initial resource base and the consumption of other resource types. Each of the seven resource types has a region-specific base production cost used as an indicator for depletion. Hence, depletion of phosphorus resource types is cost related. For the initial year (2000), these costs are taken from literature. The production cost of each resource type is assumed to increase linearly with the progressive depletion to the production cost of the other resource types. Trade flows are included in a way that all production regions together produce sufficient phosphorus to met phosphorus demand domestically and elsewhere. The market share of a producing region per market is based on relative costs (including transport) compared to all producing regions. Market share and regional demand determine the regional production level.

Fisheries (EcoOcean)

Catch projections under various effort scenarios were made using a slightly modified version of the global EcoOcean model detailed in Alder *et al.* (2007). Projections were determined by UBC in their EcoOcean models for 15 of the 19 marine statistical areas of the UN Food and Agricultural Organisation (FAO) covering the non-polar regions of the world oceans. The polar regions were excluded because of data deficiencies and very low achieved and potential catches. The model was constructed using 43 functional groups common to the world's oceans. The groups were selected with special consideration for exploited fish species, but are intended to jointly include all major groups in the oceans. The fish groups are based on size categories, and feeding and habitat characteristics. Fishing effort is the most important driver for the ecosystem model simulations. Five major fleet categories (demersal, distant-water, baitfish tuna (purse seine), tuna longline and small pelagic) were used to distinguish different fishing effort based on historic information. A description of catch and effort reconstructions can be found in Alder *et al.* (2007).

Although the base models and fitting criteria were similar to those described in Alder *et al.* (2007), some modifications were made to improve model fits and more realistically capture changes in fishing effort. The most notable difference in the new models was the application of a 'technology creep' factor to the previously used effort-time series. The use of gross tonnage as a metric of fishing effort is unlikely to capture modernisation of fishing technology since 1950. To capture this effect, a 'technology creep' of 3% per year was applied. The net result was notably different effort-time series that necessitated model refitting. The model tuning procedures used were similar to those outlined in Alder *et al.* (2007) with some additional alterations to the diet composition matrix. These changes were necessary because fisheries only target a sub-component of each functional group and may represent some fraction of a predator's diet. The net result of these model refinements were better fits to the observed catches.

Given that effort levels have increased beyond the sustainable in all areas of the world, as indicated by declining catches over the last decades, the optimal effort levels by fleet were estimated by incrementally reducing effort on all fleets and projecting catches forward through 2049. The optimal effort level for a fleet was determined to be the level that maximised catch in the final year. Although such a procedure does not necessarily maximise the total (summed over all fleets) catch in 2049, it does prevents all effort from being allocated to a single fleet when gear compete, which is common in effort optimisation exercises where trade off is a factor.

Simulating forward in time under a constant effort implicitly assumes either no 'technology creep' or a corresponding decrease in capacity. Thus, in all scenarios presented, 'technology creep' over the projections to 2050 was assumed not to occur.

Biomass changes due to fisheries in various functional groups of fish, crustaceans and molluscs were also calculated using the EcoOcean model. For each functional group and region, the estimated biomass was divided by the biomass calculated for 2004. The depletion index (DI) is the weighted mean of these ratios per species and has been adapted from the original depletion index described in Alder *et al.* (2007).

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This study explores the relevance and implications of resource efficiency for five distinct, vitally important resource themes: energy, land, phosphorus, fresh water and fish stocks. Natural resources underpin the functioning of both the European and the global economy. They critically shape prospects for current and future quality of life over the coming decades. Key questions addressed in this study are: What are the impacts of current and projected resource use up to 2050 and in which parts of the world will they be felt most? What are the potential effects of boosting resource efficiency in different world regions? Is policy intervention conceivable? How would such interventions interact with other resources not targeted; and how does resource efficiency relate to efforts to mitigate climate change?

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November 2011