PBL Netherlands Environmental
Assessment Agency

Exploring future changes in land use and land condition and the impacts on food, water, climate change and biodiversity

Scenarios for the UNCCD Global Land Outlook

Policy Report

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Executive summary

Land is a major overarching theme connecting the three Rio Conventions covering climate change (UNFCCC), biodiversity (CBD), and desertification and land degradation (UNCCD). Land management plays a key role in attaining their goals and targets. Furthermore, a large number of the Sustainable Development Goals have strong links to land and land management, and trade-offs between sustainability ambitions often materialise on land.

This study provides scenario projections for the Global Land Outlook, which is developed by the secretariat of the UN Convention to Combat Desertification (UNCCD). The aim is to explore how various demands on land are expected to change under alternative future developments up to 2050, how that will affect the challenges facing global sustainability ambitions, and to what extent land degradation may exacerbate these challenges. The study provides policymakers with quantitative information on the order of magnitude of future change to the land system, and can support discussion on policy priorities and interventions, within the UNCCD and other institutions.

Scenarios help to explore future changes to land use

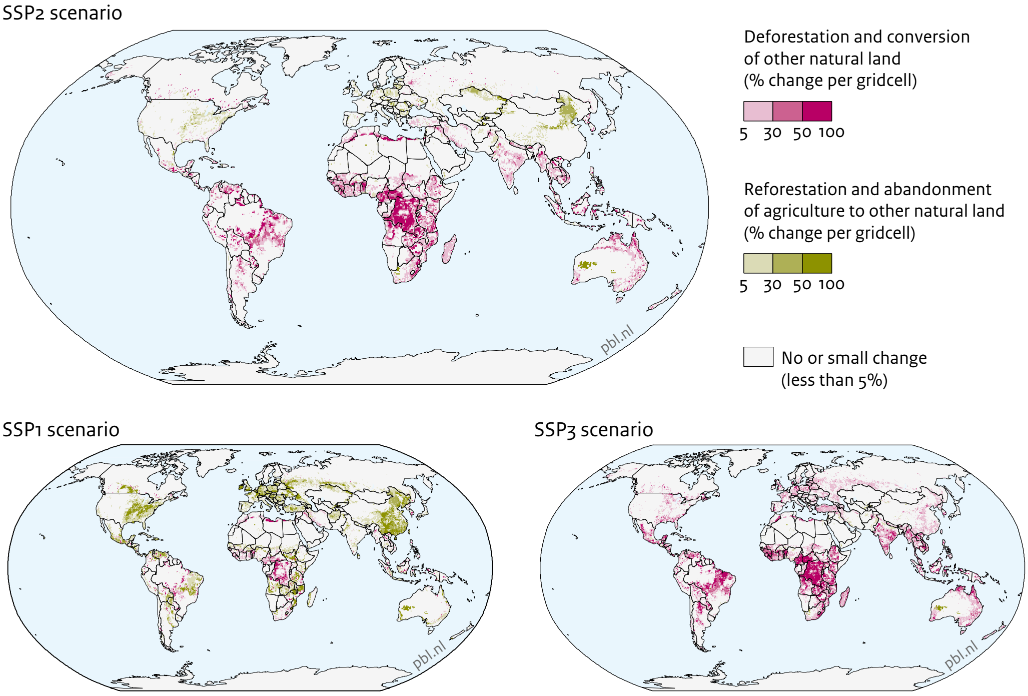
Three scenarios reveal the scope of potential future changes in land use up to 2050. The three scenarios each assume a different path along which the world may develop over the coming decades. The SSP2 scenario assumes a continuation of current trends in population, economic development and technology. The SSP1 scenario assumes lower population growth, higher economic growth and an emphasis on environmental protection and international cooperation. The SSP3 scenario assumes high population growth, lower economic growth, and less technological change, environmental protection and international cooperation.

In all three scenarios, the pressure on land is projected to increase in Sub-Saharan Africa. Larger and more affluent populations will drive an increase in demand for food and fibre, with projections ranging from 25% to 75%, depending on the scenario being considered. Sub-Saharan Africa and South Asia are the regions that will bear the brunt of population growth and, together with South America, are expected to see the fastest increase in pressure on land resources. All three scenarios expect the most significant regional expansion of agricultural land to take place in
Sub-Saharan Africa, taking over savannahs and tropical forests, in particular (Figure 1; see Annex 4 for a map of geographical regions).

The amount of land available to expand agriculture is becoming more and more limited and expansion increasingly takes place on marginal lands. Agriculture currently occupies approximately 35% of the global land area, and is forecast to reach 39% by 2050 in the SSP2 scenario. In several regions, the best lands are already in use and expansion will increasingly take place on marginal lands which include less fertile soils, steep slopes and less-favourable climatic conditions, resulting in lower yields. Land for agriculture is especially scarce, or expected to become so, in the Middle East and Northern Africa, South Asia, China, and Japan and Oceania.
The projected expansion of agriculture in tropical areas is especially worrisome since soils there are, generally, more prone to erosion and nutrient depletion when not managed carefully.

Future agricultural land use depends greatly on efficiency increases. Over the past decades, the largest contribution to the rise in food production has come from efficiency increases in agriculture, in both yields and conversion steps in the livestock sector. Although to varying degrees, the three scenarios assume enhanced efficiency will continue to play a dominant role in future production increases. However, the opportunities for future efficiency improvements differ markedly

Figure 1
Land-use change per scenario, 2010 – 2050



Source: PBL/IMAGE

among regions. Where yields are currently far below those achieved elsewhere, such as in Sub-Saharan Africa, there is, in theory, room for progress, although local constraints on water and nutrients or governance-related issues may complicate the picture. Limited availability of land creates an incentive to improve productivity on land already in use, but this can only be achieved if the means to do so are available. It seems technically possible to triple crop yields in Sub-Saharan Africa but infrastructural and institutional constraints make this a huge challenge.

The unsustainable use of groundwater presents a risk for agricultural production, potentially leading to shifts in land use. Agriculture takes the largest share of global water use. Vast areas of the Middle East, South Asia and North America rely for large proportions of their water withdrawals on aquifers that are non-renewable and will therefore certainly be depleted, the only uncertainty being *when* that will happen. The result will be shifts in land use and agricultural production to other locations. Moves towards more sustainable agricultural output must include high irrigation efficiency and improved rainwater use.

Beside agriculture, other demands on land are expected to increase as well. Urban expansion, the demand for bio-energy, forestry, and the conservation of areas for biodiversity and climate mitigation lead to more and more intensely competing claims on limited land resources. Urbanisation increasingly displaces agricultural activity. While urban settlements take up relatively little land, compared to the land area used for agriculture or forestry, there are concerns that urban expansion is increasingly crowding out agriculture from fertile areas, forcing it onto less productive lands. Populations which become more and more urban also affect land use in other ways, since the growing disconnect from production locations influences flows of land-based products, and makes it more difficult to close production and consumption cycles.

In the scenarios, the demand for bio-energy is expected to increase due to high energy prices and the policy targets to increase the share of bio-energy in national energy mixes. The demand for wood and timber products is expected to increase by approximately 20% in the SSP2 scenario. The use of fuelwood, representing about 50% of global wood use, is expected to decrease though, as a result of shifts to more modern cooking methods in developing countries. In the scenarios, the surface area required for forestry is projected to grow modestly, although at the cost of changes in production methods towards more intensive monoculture plantations.

Protected areas are assumed to maintain their surface area of approximately 14% of the global land area in the SSP3 projection. In the other scenarios, they are foreseen to expand, reaching the Aichi target of 17% in SSP2, and significantly more in SSP1, where agriculture and forestry areas increasingly include land set aside from production. With these increases, and depending on the location of new or expanded protected areas, the competition between conservation and other land uses is likely to intensify.

The effects of climate change on future agricultural land use are especially uncertain, but likely to be negative, on a global level. At the global level, for 2050, increases in agricultural yields are projected to be slower with yields about 10% lower than would have been the case without climate change, mostly due to water shortages and extremely high temperatures, although some temperate regions are expected to see increasing yields due to higher temperatures and longer growing seasons. Agriculture in tropical and sub-tropical regions, such as India and Sub-Saharan Africa, will be the most negatively affected by climate change. Lower yields due to climate change would result in more land (around 10%) having to be used for agriculture. However, current knowledge as it is applied in crop models, is still limited, such as on extreme weather events and pests and disease pressures and on the capacity of farmers to adapt to climate change. This may result in significant underestimations of the impacts of climate change on agriculture.

Land degradation is a global phenomenon that is expected to affect key ecosystem functions, over the coming decades

Estimations on the current amount of degraded land, its global occurrence, the considerable financial costs, and the negative effects on low-income and vulnerable populations in particular, make that policymakers should account for the future effects of land degradation. Especially when it comes to agriculture, there is much uncertainty about the degree to which current management practices degrade soil resources in the long term and thus put their continued use at risk. Land degradation and its consequences have in general not been included in prior quantitative scenario studies assessing global environmental change and their scale and severity are therefore largely unknown to policymakers.

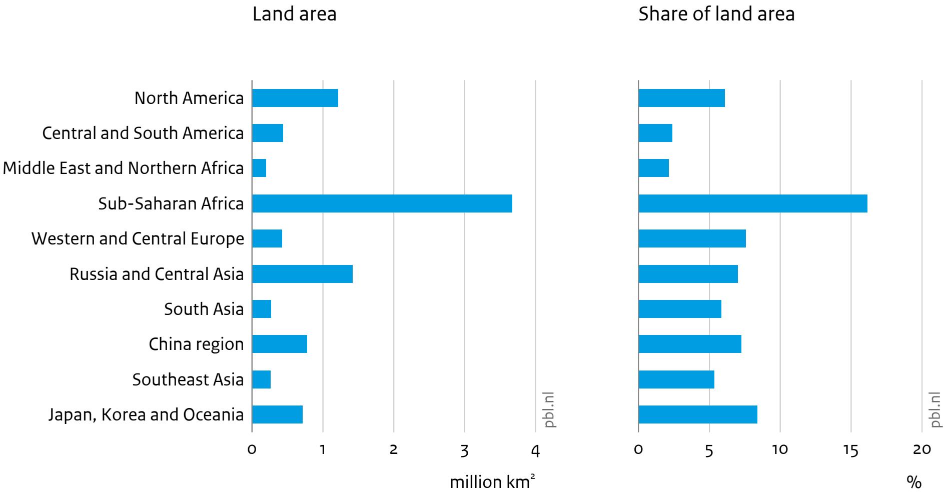
Estimates on the scale and severity of land degradation vary significantly. This is due to differences in definitions, applied methodologies and even the perception of what constitutes land degradation. This study therefore uses the concept of *land condition,* expressing it in quantifiable indicators, and assessing how these indicators have changed over time and are expected to change up to 2050. Many of these link directly to the indicators in the UNCCD Strategic Plan and the Land Degradation Neutrality target, including land cover, land productivity, soil organic carbon, species abundance, and number of people affected. Future estimates based on these indicators are made in a variant of the SSP2 scenario that includes the effects of changes in land condition on ecosystem functions.

Future changes in land condition are projected to be widespread, as a result of both continued changes in land use, such as conversion of natural land into cropland, and of land management practices in croplands, grazing lands and forests. The consequences are a loss of net primary production over large areas, a decline in soil organic carbon, and a loss of biodiversity.

Nearly a quarter of the global land area shows current biomass productivity that is lower than it would be in an undisturbed state. On 28 million km², or 23% of the global terrestrial area, current biomass productivity is estimated to be lower than what it would be in an undisturbed situation; in other words, without human interference. This includes an estimated 36% of all cropland, pasture and forestry systems and an estimated 15% of natural areas. Much of this change is inherent in the conversion of natural land to managed land.

Worldwide, on more than 9 million km² of land, there is a persistent, significant decline in net primary production (excluding the effects of climate change), showing decades-long negative effects of human activities and land management practices. Climate-corrected productivity decline is a proxy for the detrimental effects that human disturbance or land management practices have on the biomass productivity of an ecosystem. Filtering out the effects of climate change from biomass productivity trends allows for an approximation of the effects of land management. The most dramatic developments are taking place in Sub-Saharan Africa, where over 15% of the land area is affected. In most other regions, the figure lies between 5% and 10% (Figure 2). More than half of the 9 million km² affected, worldwide, is cropland and pasture, an area of 4.7 million km², corresponding to about 12% of all

Figure 2
Area with negative productivity trend, corrected for climate change, 1982 – 2010



Source: PBL

agricultural land on the planet. Sub-Saharan Africa and Russia and Central Asia are the regions with the highest percentages of agricultural areas with negative trends in biomass productivity associated with land management.

Soil health, in terms of the soil organic carbon content, is projected to further decline in many regions. Globally, soils contain about three times the amount of carbon that is stored in vegetation and twice the amount present in the atmosphere. An estimated 8% or 176 Gt of soil organic carbon has been lost due to past changes in land use, such as the conversion of natural land to cropland, and due to land management practices. Losses between 2010 and 2050 are projected to amount to an additional 27 Gt of soil organic carbon as a consequence of land conversion and land management. Figure 3 shows the distribution of these past and expected losses. This may affect agricultural yields through the reduced water holding capacity and loss of nutrients, and will have wider effects on hydrology, biodiversity and carbon emissions. Given that soil restoration is a long-term process, prevention of further soil organic carbon losses is crucial to avoid these effects.

Biodiversity loss was at an estimated 34% in 2010 compared to an undisturbed state and is projected to continue with some 10 per cent point of additional loss up to 2050. The major causes are conversion of natural areas into agricultural land and forestry, climate change, encroachment from expanding human settlements, infrastructure development, and habitat fragmentation. Up to now, the largest losses have occurred in developed countries , but most current and expected future loss is concentrated in developing countries, much in line with trends in changes in land use and more intensive land management.

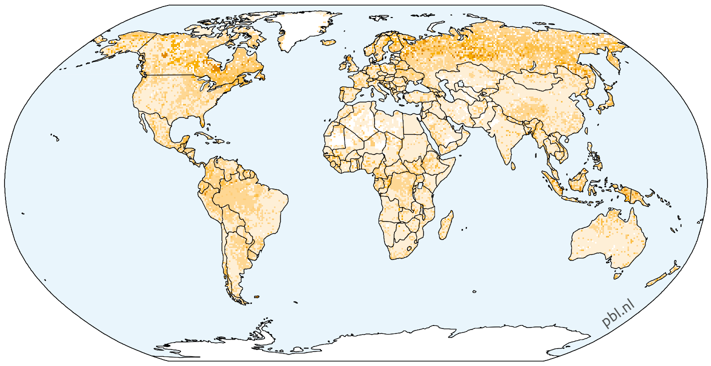
By 2050, human populations in drylands are projected to increase by 40% to 50%, under the SSP2 scenario, which is far more than the 25% increase in non-drylands. Soils in drylands are generally more vulnerable to erosion and disturbance from conversion, and the effects of future land-cover change and soil organic carbon loss will exacerbate the challenge of managing water in these regions. The largest increases in populations are projected to take place in semi-arid and arid drylands. Regional projections of the number of people living in drylands see South Asia having the largest increase, over 500 million, and Sub-Saharan Africa experiencing a doubling (Figure 4). The overall challenges in drylands will be much more aggravated by increased demands from larger populations than by climate change. However, the effects of climate change, such as a heightened risk of drought and more erratic weather patterns, will consequently affect many more people in drylands, in the future.

Change in land condition affects ecosystem functions and is expected to further exacerbate the challenge of managing increasing pressures on land. Agricultural yields, soil nutrient stocks, water availability and flows, and carbon emissions are all affected by a deterioration of land condition. Land degradation, similar to climate change, is therefore expected to exacerbate the challenge of managing increasing pressures on land.

The scenario variant projects an additional 5% in agricultural area will be needed by 2050, if the current

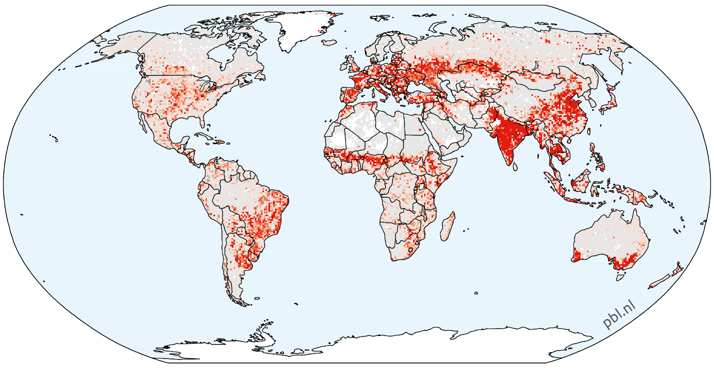
Figure 3
Soil organic carbon

2010



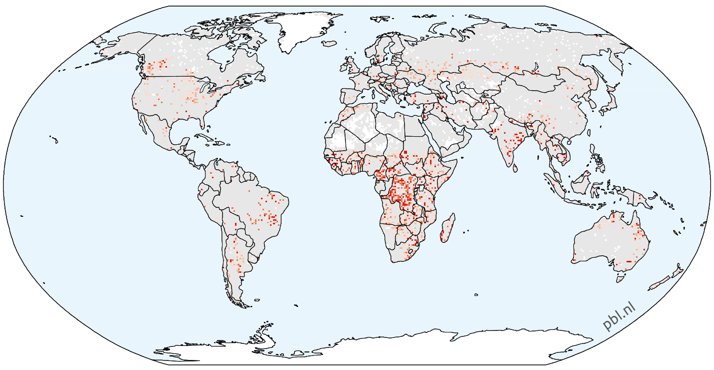
Percentage in top 30 cm soil
- Low (1.5% or less)
- Moderate (1.5 – 3.0%)
- High (3.0 – 5.0%)
- Humose (5.0 – 12.0%)
- Organo-mineral (12.0 – 35%)
- Organic (More than 35%)

Change compared to natural situation, 2010



Percentage loss
- 50 and more
- 30 – 50
- 20 – 30
- 10 – 20
- 2 – 10
- 2% loss – 2% growth
- More than 2% growth

Change under the SSP2 productivity-decline scenario, 2010 – 2050



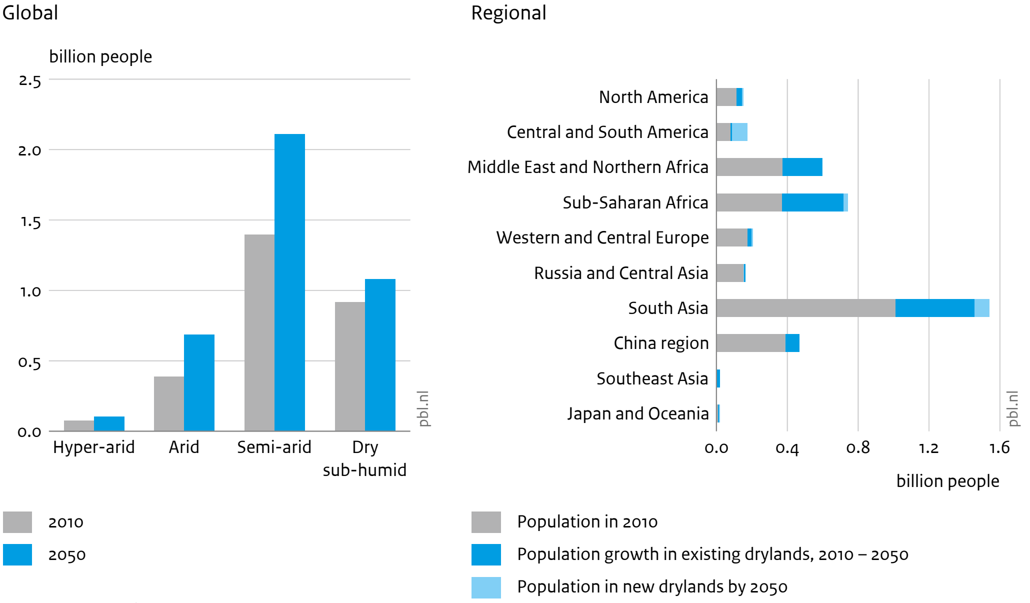
- No data

Source: Stoorvogel et al. 2017; Schut et al. 2015; PBL

negative trends associated with human disturbance and land management continue. This is a rather large figure compared to the 8% increase in agricultural area due to rising demand for land-based products over the same period. This additional need for agricultural expansion will in turn lead to further losses of natural areas, biodiversity, and carbon stored in vegetation and soils.

Water cycles, the likelihood of flooding and drought, and the navigability of rivers are not only affected by climate change, but also by changes in land cover and soils. The scenarios show that, depending on the characteristics of the water basin, the effects of climate change and changes in land cover and soils can either reinforce or counteract each other. Especially in areas prone to water stress, land use and land management can bring about changes to water regulation that may affect future water security.

Figure 4
Population in drylands, under the SSP2 scenario



Source: PBL/IMAGE

The projected carbon losses associated with changes in land use and land management, up to 2050, will amount to the equivalent of about eight years of current global carbon emissions from fossil fuel use, a sizeable share when regarded in the context of international climate ambitions. The carbon storage potential of agricultural land is high, but requires the development of high-yielding agricultural systems with near-natural soil carbon levels.

Regional risks and potential lines of response

Risks associated with increasing pressures on land and with land degradation differ per region. The 10 world regions assessed in this report fall roughly into three categories with respect to current and future pressures on land. Five regions are deemed relatively stable and face a limited number of challenges. In contrast, three are confronted with a daunting combination of land-related challenges that will be difficult to manage.
The other two fall somewhere in-between.

Five regions face comparably minor challenges related to land: North America, Western and Central Europe, the Russian region and Central Asia, the China region, and Japan and Oceania. These regions are relatively prosperous or quickly becoming so, and will need to deal with a limited number of challenges, scattered over several areas. Only North America is expected to see its population grow significantly, in the period up to 2050. There is a limited amount of remaining available agricultural land in the regions of China and Japan and Oceania, and Russia and Central Europe see extensive negative impacts associated with land management in agricultural areas, but the population projections and corresponding demands for land-based products for these regions suggest these pressures on land are manageable. Water stress is a challenge in all five regions, in terms of both the currently affected proportion of the population and the projected increase in this group.

Three regions face the most difficult challenges: Sub-Saharan Africa, South Asia, and the Middle East and Northern Africa. These regions are characterised by a combination of current and future land-related challenges that are much more serious than those faced in other regions and concern high levels of population growth up to 2050, including in drylands, low current levels of GDP per capita, generally low crop yields, intense pressure to expand agricultural land, marked increases in water stress, and, to a large degree, a dependence on imports from other regions for their food supply. Losses in productivity and soil condition are projected to be most severe in Sub-Saharan Africa, but, in all three, the strongly increasing pressure on land makes land management key in maintaining ecosystem functions for the benefit of agriculture and the water cycle.

Two regions fall in-between: Central and South America, and South-East Asia. South-East Asia is characterised by a marked rise in water demand, high increases in agricultural area, and a low current GDP per capita. GDP per capita is set to grow fourfold by 2050, and the increasing demands associated with this increase can be expected to further put pressure on the limited amount of potentially available cropland, leading to high levels of biodiversity loss. Central and South America is mostly expected to face challenges related to projected increases in land use for agriculture and livestock, and to the competition for land resources for various uses. Both regions can be said to be at a tipping point. The land-related challenges are not particularly daunting, nor are many of them strongly increasing, and economic projections indicate that governments will have the means to manage them. However, these challenges should not be underestimated, and if countries within these regions fail to implement appropriate management of natural resources, the outlook may become more serious.

Institutions and governance influencing land use and land management, and the lines of response that are available, will determine the way regions cope with these challenges. These aspects are briefly covered in this explorative study and are of growing importance. A particularly pressing question is how land governance can best reconcile the wide range of interests involved in land-related developments and challenges. In other words, what determines the *quality* of land governance, and how do institutions shape decision-making on land use and land management? Beyond that, institutions, such as trade agreements and certification schemes driving sustainability in supply chains, also influence land use and land management, showing that management of land-related challenges can be viewed from a much wider perspective.

Four fundamental lines of response can be distinguished that address different parts of the human–land system interactions and can mitigate the pressure coming from multiple claims on land:

1. *Spatial and land-use planning*, at local, national and regional scales – 'doing the right thing in the right place'. This line of response also highlights the need to look for synergies between agricultural production, forestry, the provision of ecosystem functions and the protection of natural capital.
2. *Sustainable land management and restoration.* The prevention of the deterioration in land condition through more sustainable land management practices, along with rehabilitation and restoration of ecosystem services and biodiversity in line with the use of the land.
3. *Limiting and reducing the demand for land-based products* by reducing waste, shifting consumption patterns, limiting bio-energy use and, and increasing efficiencies in supply chains.
4. *Sustainably increasing the yields* of all commodities, increasing the efficiency of production per hectare, volume of water, and nutrients.

In conclusion, this study explores the extent of global, land-related challenges over the coming decades. A next step would be a detailed assessment of the potential of these lines of response, and of their interaction with governance and institutions influencing land use and land management, to develop strategies to attain sustainability ambitions, particularly for the most challenged regions.

FULL RESULTS

Introduction

1.1 Increasing demands on a limited resource

An understanding of the future of land is required to inform policy on sustainable development
Land is a limited resource that provides food, fibre, shelter and important ecosystem services to humanity. As a key element in attaining many global ambitions for sustainable development, policymakers require insight into what future land use might look like and how this affects the ability of the land system to continue supplying ecosystem goods and services. Many forms of land use are limited by local biophysical conditions, influenced by multi-level institutions and governance and hampered by ongoing land degradation and climate change.

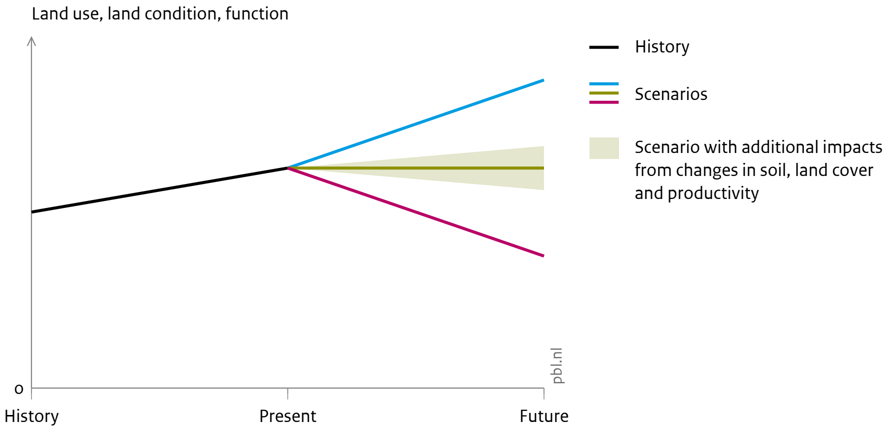
Growing pressures on land: increasing demands are exacerbated by climate change and land degradation
Agricultural land has expanded by some 12% since the 1970s to the detriment of natural forests and grasslands. Demands on land continue to increase but the magnitude is uncertain, since it depends on a large number of factors, including population growth, economics, trade, and changes in agricultural productivity. Increased competition for land and water originating from various types of land use and the demand for land can add to existing threats to human securities – food, water, energy and physical security (FAO, 2011). The first people to be affected are those who are highly dependent on natural resources for their livelihoods, who have little political power to influence the distribution of resources, have limited alternatives, or for whom the options for optimising their own resource management are severely restricted.

Pressures on land resources are exacerbated by climate change and land degradation. Higher global temperatures are altering the suitability of regions for agriculture and in many places the overall condition of the land is deteriorating. Land degradation limits productivity and reduces the ability of the land to regulate climate, water and nutrient cycles. Many forms of land degradation are slow processes, only manifesting themselves over decades, which makes it difficult to maintain land degradation on political agendas and create long-term policy responses. Global policy responses to land degradation have been further hampered by uncertainty about the current state of land and soils, at the global level, and the extent of various forms of land degradation, and by a lack of estimates of the potential future impacts of land degradation.

The management of land resources is key to many of the Sustainable Development Goals
With over 9 billion people inhabiting the planet by 2050, demands for land will increasingly lead to choices between functions, such as food, fibre and bio-energy production, conserving biodiversity and natural areas, and expanding housing and infrastructure. Many responses to the challenges of long-term food and water security, biodiversity loss and climate change depend on land and the way it is managed. When it comes to decisions on land use, management and planning, pathways towards a more sustainable future require balancing these increasingly competing claims. Looking at global sustainability ambitions from the perspective of the use and management of land also urges the consideration of cultural values, the dependencies of people on their land and the methods and means used to govern rights, access to and distribution of land resources. Land features particularly in the Sustainable Development Goals addressing poverty, food security, water security, energy security, gender equality, responsible consumption and production, climate change and life on land.

Figure 1.1

Explorative scenarios to analyse future changes in land and ecosystem function



Source: PBL

Schematic representation of the scenarios used in this study

1.2 Purpose of the study

The study had two objectives. First, it explored how land use may change up to 2050, on global and regional levels, under various scenarios of future development, and how this affects the extent of the challenges facing land-related sustainability ambitions. Second, it explored the extent to which land degradation will exacerbate these challenges as it affects essential functions of land.
That naturally puts the growing competition for the various uses of land at the forefront, along with the resulting trade-offs between various uses. It also requires an estimate of how climate change and continued deterioration of the condition of land and soils complicate future land use and may compromise ecosystem functions and services.

The consideration of future changes to the condition of land is especially relevant as, typically, aspects of land degradation are not included in scenario analyses on global land-use change (UNEP, 2012). An advisory report to the UNCCD noted that the poor understanding of the complexity of feedback processes involving climate change and land degradation processes, including the interactions within various socio-ecological systems and how they may change in the future, 'limits our capacity for anticipatory adaptation' (Reed and Stringer, 2015). The study presented here includes a first attempt at estimating the future effects of several such feedback processes.

The examined scenarios provide storylines of plausible alternative futures. The variables used in these storylines are quantified through integrated modelling, which enables an exploration of the demand for land and the drivers shaping future land use, with a focus on the interactions between the various drivers and pressures on land and the directions and orders of magnitude of the changes they undergo.

1.3 Scenarios for the Global Land Outlook

The results of this scenario study serve as input for the UNCCD Global Land Outlook. The UNCCD initiated the development of an outlook against the background of increasing pressures on land resources around the planet. The outlook is intended to signal challenges and solutions regarding the use of land resources, with specific attention for the consequences of land degradation and the potential for land restoration and sustainable management. The value of an outlook study lies in the perspective it provides to decision-makers dealing with land-related issues, helping them to evaluate and position policies more fittingly in the light of recent trends and expected future developments. In addition, it can signal new challenges to land management given future change, help estimate the distance towards policy goals, and provides analyses of potential responses and solutions.

Using scenarios to assess the future challenges facing land

This study uses scenario analyses combined with quantitative modelling. Scenario analyses can help in exploring potential future pathways that incorporate many uncertainties. They employ internally consistent storylines on potential future developments to establish a set of plausible alternative futures. This study concentrates on three explorative scenarios and a variation on one of them (Figure 1.1). The scenarios examine the degree to which demands for land might develop and how that may affect land use, the efficiency of the use of land resources and products, trade and food self-sufficiency, climate change, and biodiversity. A variant of one of these scenarios includes an estimate of the change in the condition of land in terms of land cover, biomass productivity, soil, and the consequential impacts on ecosystem functions.

The value of an integrated approach

The various demands placed on land are highly interlinked. For example, a growing demand for food and fibres can push up prices and encourage an expansion of agricultural use into natural areas, depending on the availability and suitability of the land. However, higher prices also spur investments in the efficiency of the use of land resources. Given the many feedback loops in these processes, an integrated approach that takes these feedbacks into account is necessary to assess future changes to land.

Since the scenario analyses are explorative, they do not aim to evaluate the benefits of options that can improve land-use efficiency and manage competing claims on land under future scenarios. Reports that deal with options include PBL (2010), PBL (2012) and PBL (2014).

1.4 Report structure

Chapter 2 presents the current challenges on land deriving from increasing demands, land degradation and climate change, summarises a number of key trends that have influenced land use over the past decades, and highlights the global sustainability ambitions related to land. It also introduces the problems in assessing land degradation and the conceptual approach used to quantify it. Chapter 3 describes the results of three scenarios to explore land-use change from the present until 2050, and shows that differences in the magnitude of future demands on land lead to a diverging range of implications for global sustainability ambitions. Chapter 4 shows how continued land degradation could affect ecosystem functions and exacerbate the pressure on land for various uses. Finally, Chapter 5 presents the results from Chapters 3 and 4 from a regional perspective, summarising the various combinations of land-related challenges faced by the major geographic regions of the world and highlighting potential lines of response.

TWO

Land: availability, trends and goals

Three main forces challenge the sustainable use of global land resources: increasing demands for various uses of land, the degradation of land and soils through poor management, and climate change. This chapter introduces these three forces, explores a number of current trends that influence land, provides a short overview of the position of land in the Sustainable Development Goals, presents the conceptual approach used in this report to assess land degradation, and ends with a schematic representation of the changes to land that are quantified under the various scenarios in the next chapters.

2.1 Global land resources are set to become scarcer

Over the coming decades, land faces increased competition from various uses fuelled by rising demands for food and fibre, urban expansion, and ambitions for climate change mitigation and biodiversity conservation. In addition, increasingly interconnected markets, the limited availability of land for expansion in some regions, and investment capital in search of returns are all slowly making land more of a global resource, as evidenced by the rise in cross-border investments in land (Land Matrix, 2016). With increasing demands on a limited stock, land resources are set to become scarcer. Whether that poses a problem depends on how that stock and its revenues are managed.

Land harbours biodiversity, interacts with the global climate system, provides ecosystem functions and services that humanity depends on, and can have important cultural values (Box 2.1). Changes to the global land system can therefore have negative effects on current and future human wellbeing. An important challenge for sustainable development in the 21st century, therefore, is how to sustainably use global land resources. Understanding what drives scarcity of land resources helps to find out where challenges will most likely converge, where they may negatively affect human development, and where potential solutions can be found (Seto and Reenberg, 2014).

The increasing policy attention for land is underscored by a number of recent reports that assess land-related issues from various angles. Reports by the UNEP International Resource Panel discuss balancing production and consumption from the perspectives of cropland use and expansion (UNEP, 2014), the potential of land resources (UNEP, 2016a) and the sustainability of the food system (UNEP, 2016b). *Assessment of the Status of the World's Soil Resources by the Intergovernmental Technical Panel on Soils* (FAO and ITPS, 2015) provides a worldwide evaluation of the global and regional status of soils, their functions and the pressures affecting them. The Economics of Land Degradation (ELD) report, The Value of Land (2015), highlights the importance of valuing ecosystem services, and the potential of sustainable land management in mitigating land degradation. The OECD has analysed the interconnections between land, water and energy, from a resource scarcity perspective, with a time horizon until 2060 (OECD, 2017). The periodical FAO report *State of Global Land and Water Resources* (FAO, 2011) highlights that modernisation of land and water institutions is not keeping pace with developments in agriculture and water use. Other reports and assessments cover the use of land for agriculture, such as the *Agricultural Outlook* published by the OECD and the FAO (OECD and FAO, 2015) or the state and change of ecosystems in the *Global Biodiversity Outlook* (CBD, 2015). This report adds to these studies by providing estimates of the extent of future land challenges under alternative future scenarios and quantitatively describing how the deteriorating condition of land may influence future land use and ecosystem functions.

Box 2.1 Perspectives on land-use

Land-use is primarily local in nature but becoming increasingly global, through trends in urbanisation, trade, cross-border land acquisitions and global environmental change. These trends may affect the opportunities and constraints on sustainable land-use in the future. Land-use can be considered from many angles, and, depending on the chosen perspective, particular issues may be identified and various courses of action devised. Four possible perspectives are presented below (Seto and Reenberg, 2014):

- one that emphasises local and regional *competition for land-related resources*, such as food, biofuels, and space for urban expansion;
- another highlights the *long-distance connections*; how distances between centres of production and consumption affect pressure on land;
- a third perspective is based on the way *decision-makers and institutions* implement forms of land management, including how land is accessed and allocated to various actors;
- and finally, there is a *normative perspective* that looks at land from the point of view of norms, values, equity and justice and their impact on land-use decision-making.

This report mostly reflects the first perspective, and part of the second. It provides a predominantly economic and biophysical outlook on the future of land-use with a global focus on competition for land resources. There is less attention for other aspects, such as governance and land management institutions, the cultural and spiritual values of land, and debates on ethics and justice in the allocation of land and its benefits. These aspects are obviously no less important. Rather, the projections in this report provide a starting point for discussions on these topics, given the possible future changes to land use.

2.1.1 The global distribution of land use

The demand for land-based products

Most of the demand for land-based products is agricultural, such as food, fodder, and livestock. However, it also includes fibres, such as cotton, timber for construction and the paper industries, and fuel – either firewood or other forms of biomass used in traditional energy systems, or more modern forms, such as pellets in coal-fired power plants or feedstock for bioethanol. Besides satisfying the demand for these products, land is also used for urban development and infrastructure and increasingly for the protection of forests and other natural areas to promote biodiversity conservation and climate change mitigation. Alongside this increasing demand is the growing demand for freshwater for drinking, sanitation, industry and irrigation.

The current global distribution of land use

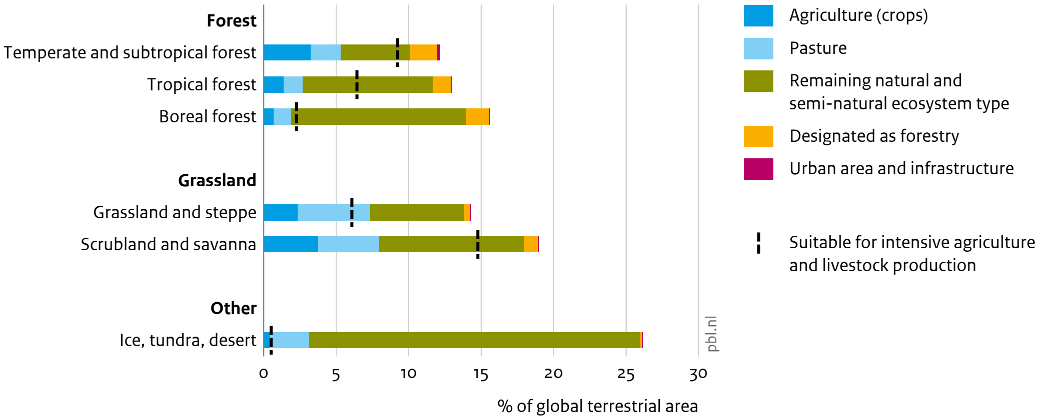
The Earth's land surface is estimated to be approximately 132 million km^2, of which around 15 million km^2 are in use as cropland and 25 million km^2 as grassland for livestock. While the figure for cropland is quite precise with published estimates differing little, rangeland figures vary more, with higher estimates ranging up to 34 million km^2, in part depending on whether or not extensively used grasslands are included in the calculation. A substantial surface area is also taken up by forestry, including 12 million km^2 designated for production, and a further 10 million km^2 which is exploited under multiple-use management (FAO, 2015). Urban areas and infrastructure account for a very small part of global land use.

Figure 2.1 shows the estimated use of land in 2010, for agriculture, pasture, forestry and urban areas, per original natural ecosystem type, globally. Most of the current land in use for crop and livestock production is part of what used to be grasslands and savannah systems, and about one third has taken the place of former forested areas. Mixed-use forests are not included in the figures, and part of the forests that are designated for production may occupy areas suited for intensive agriculture.

Land potentially available for agriculture

Excluding existing protected areas, the land available for agriculture is estimated at 53 million km^2 (Mandryk et al., 2015), out of the planet's approximate total land area of 132 million km^2. Other estimates are often lower. For example, the global database of agro-ecological zones classifies 31 million km^2 as good to very suitable for growing five key crops (IIASA/FAO, 2012). Determining factors in the range of estimates are the decisions on whether or not to include less fertile land and whether or not to exclude forests. The suitability of land for agricultural production depends on the type of crop, with some crops better suited to certain areas. It also depends on the ability of land to provide attractive returns in the case of market-oriented agriculture, or on the needs of subsistence farmers, who may have few other options besides expanding into marginal areas. Technology and crop price increases may make previously marginal land

Figure 2.1
Land use and land cover per original ecosystem type, 2010



Source: PBL/IMAGE

attractive for development, while social and political factors can mean the development of land carries considerable risks in certain regions. In other words, the potential availability of agricultural land is not an absolute concept. Working with the higher estimate for potentially available agricultural land, which implies including marginal land, is appropriate for this study as the model framework makes it possible to create a balance between agricultural expansion depending on the suitability of land, intensification of production on existing land and crop price levels (see Chapter 3 for further details).

Due to agricultural expansion and other land uses, the amount of land still available for agriculture has declined over past decades. In some regions, such as Japan and Northern Africa, there is little land left for cultivation (Mandryk et al., 2015). For the world as a whole, many of the most productive areas are already in use and expansion will increasingly have to take place on less productive land, with correspondingly lower yields or requiring more inputs.

Conversion of forests and wetlands
Agricultural expansion has had a dramatic effect on the world's forests and wetlands. The global forest area declined by 1.3 million km^2 between 1990 and 2015, pushing the total forest area below 40 million km^2 (FAO, 2016). Wetlands are estimated to have declined by 64% to 71%, since the beginning of the 20th century (Davidson, 2014). These ecosystems contain a large proportion of the world's biodiversity, and contribute to water regulation and carbon sequestration – benefits that are local as well as global.

2.1.2 Land degradation

The pressure on land and in particular its conversion and exploitation for agriculture have led to adverse impacts on the environment through the degradation of the soil and the ecosystems it supports, the pollution of waterways and the deterioration of forests. If left unchecked, land degradation can have negative effects on the continued delivery of ecosystem services, in the long term. Services affected by land degradation include biomass and crop production, water storage and regulation, nutrient regulation and carbon sequestration in soils and vegetation. Soil erosion may lead to landslides and clog waterways, limiting navigation, and hampering hydropower generation. Estimates by the Economics of Land Degradation project (ELD, 2015) suggest that at least a third of global agricultural land has already been affected to some degree by degradation. The trend is worrying given that soils are, on a human timescale, a non-renewable resource (Lal, 1994).

The effects of degradation most directly threaten the rural poor who depend, more than any other group, on land for their basic needs and livelihoods (Nachtergaele et al., 2010; Reed and Stringer, 2016). An estimated 1.3 to 1.5 billion people worldwide are affected by land degradation (Bai et al., 2008; Barbier and Hochard, 2016). More indirectly, degradation may compound the effects of increasing demands on land if declines in crop, grass and fibre production lead to the need for additional land conversion or an increase in inputs to compensate for reduced production. Degradation can also have remote effects, such as the consequences of erosion on water systems. The indirect impacts of degradation and poor

Table 2.1
Estimates of global extent of land degradation

Source	Calculation method	Estimate	Estimate breakdown	Regional focus
GLASOD (Oldeman et al., 1990)	Expert opinion	15% of land is degraded	22.5% of agricultural land, pasture, forest and woodland has degraded, since the 1950s (20 million km²)	
Drenge & Chou (1992)	Expert opinion	70% of drylands affected by degradation (36 million km²)	Affected: 73% of rangelands, 47% of rain-fed croplands, 30% of irrigated croplands	
FAO TerraSTAT (Bot et al., 2000)	Expert opinion	65% (60 million km²) of the world's land is slightly to severely affected by degradation	26% severely to very severely degraded (35% of which due to agricultural activities), 21% moderately degraded, 18% slightly degraded	
FAO GLADA (Bai et al., 2008)	Satellite-based approach (NDVI)	Over the 1981–2006 period, about 24% of land was degraded, substantially (27 million km²)	19% of degrading land is cropland, 24% is broad-leaved forest, 19% needle leaved forest	Africa, Southeast Asia, China, North central Australia, the Pampas, Siberia and North America
Cai et al., (2011)	Biophysical Models	Almost 10 million km² of degraded and abandoned lands		50% of all degraded lands are in China and India
Ramankutty & Foley (1999)	Based on land abandonment	Cropland abandonment increased from 0.6–22 million km², 1950–1990		North America, China, Southern South America, Europe
HYDE Database (Campbell et al., 2008)	Based on land abandonment	3.8–4.7 million km² abandoned land (over the last 300 years)		
FAO Pan-tropical Landsat	Based on land abandonment	0.8 million km² of cropland and pasture was abandoned temporarily or permanently, in the 1990s		Latin America, Tropical Asia and Africa
Le et al., (2014)	Satellite-based approach (NDVI)	29% of land contains degradation hotspots	Human-induced biomass productivity decline found in 25% of croplands 25% of shrublands 33% of grasslands	

Source: PBL, drawing on data from (Caspari et al., 2014; Gibbs and Salmon, 2015; Nkonya et al., 2016).

land management can transcend local, district and national boundaries, and affect food prices, food security and the provision of ecosystem services further afield.

Land degradation has various effects and is difficult to measure

Land degradation is used as an umbrella term for multiple types of undesired and more or less irreversible processes, including salinisation, desertification, wind and water erosion, compaction, human encroachment and invasions of exotic species (Gibbs and Salmon, 2015). Efforts to measure land degradation regard it as both a state and a process, but there is disagreement on whether calculations should take into account data on natural processes or should only consider data on human-induced processes (Wiegmann et al., 2008). Further dissent exists on the need to include changes to vegetation, which are potentially short-term, and degradation of the soil, which takes place over longer periods of time (Lambin and Geist, 2010). As a result, no consensus exists on the extent of degraded land, either globally or at the country level (Bindraban et al., 2012; FAO, 2008; Lepers et al., 2005). Estimates of land degradation worldwide differ considerably, ranging from 15% to 66% of the world's land area depending partly on methods of measurement and partly on the applied concepts, definitions, baselines and thresholds (Table 2.1) (Caspari et al., 2014; Gibbs and Salmon, 2015). There *is* agreement, however, that land degradation occurs globally, in all biomes and regions (Le et al., 2014).

These difficulties in defining the concept of land degradation mean that its operationalisation in quantitative scenario analyses is not straightforward.

Box 2.2 Conceptual approach: assessing changes to land condition and ecosystem services instead of land degradation

Estimates of land degradation differ considerably worldwide, depending on measuring methodologies, on the applied concepts and definitions (Table 2.1), and partly even on perception (Meyer, 1996). To move beyond these discussions, land degradation is not further defined or quantified as such in this report. Instead, changes to the condition of land resulting from human intervention are expressed in various indicators, which are used in future scenarios to estimate the effects of those changes on ecosystem functions and services.

Land condition reflects the state of the terrestrial surface of the Earth, including both the vegetation on the surface and the soils underneath. It is therefore similar to *land cover* as defined in Lambin & Geist (2010) but given the common use of that term to only refer to vegetative cover, *land condition* is used to explicitly include soils. *The condition of the land* determines its potential to provide people with various types of services. Land condition can be assessed according to many indicators, including soil organic carbon and topsoil depth, vegetative cover, soil nutrient balance, aridity, and biodiversity. To provide a fixed reference point against which to compare changes in land condition indicators, this study uses a constructed natural (i.e. without human intervention) state (Kotiaho et al., 2016; UNEP, 2003).

Land condition can change due to changes in land use (e.g. the conversion of natural land into cropland, or cropland into a built-up area) but also through changes in the management of a land-use system (e.g. increased use of fertilisers or irrigation of existing croplands). Furthermore, climate change may affect land condition through changes in temperature and precipitation patterns, affecting plant growth and soils. Changes in land condition result in alterations to ecosystem functioning and ecosystem services, such as productivity for crops and grass, water regulation, and carbon storage. Figure 4.1 in Chapter 4 shows a schematic representation of these relationships.

Changes in land use and land condition reflect trade-offs between various ecosystem goods and services supplied by the land system. Figure 2.2 shows a stylised representation of these trade-offs for two land-use systems. Various intensities of land use can result in varying compositions of ecosystem services provided by that land. Assessing potential future changes in land use and land condition provides information on the extent of these trade-offs over the coming decades, and the effects on ecosystem functions and services.

Therefore, this study quantifies changes in soils, land cover, biodiversity and ecosystem functions, comparing them to their natural, undisturbed state, and showing the trade-offs between them (Box 2.2).

2.1.3 Climate change affecting land

Multiple connections exist between climate change and land systems. Climate change affects the condition of land and soils, while changes in land use and land cover can contribute to greenhouse gas emissions. Policies that aim to mitigate climate change require land for the large-scale implementation of bio-energy and REDD[1] projects, and adaptation policies may result in the need to transfer certain types of land use to elsewhere.

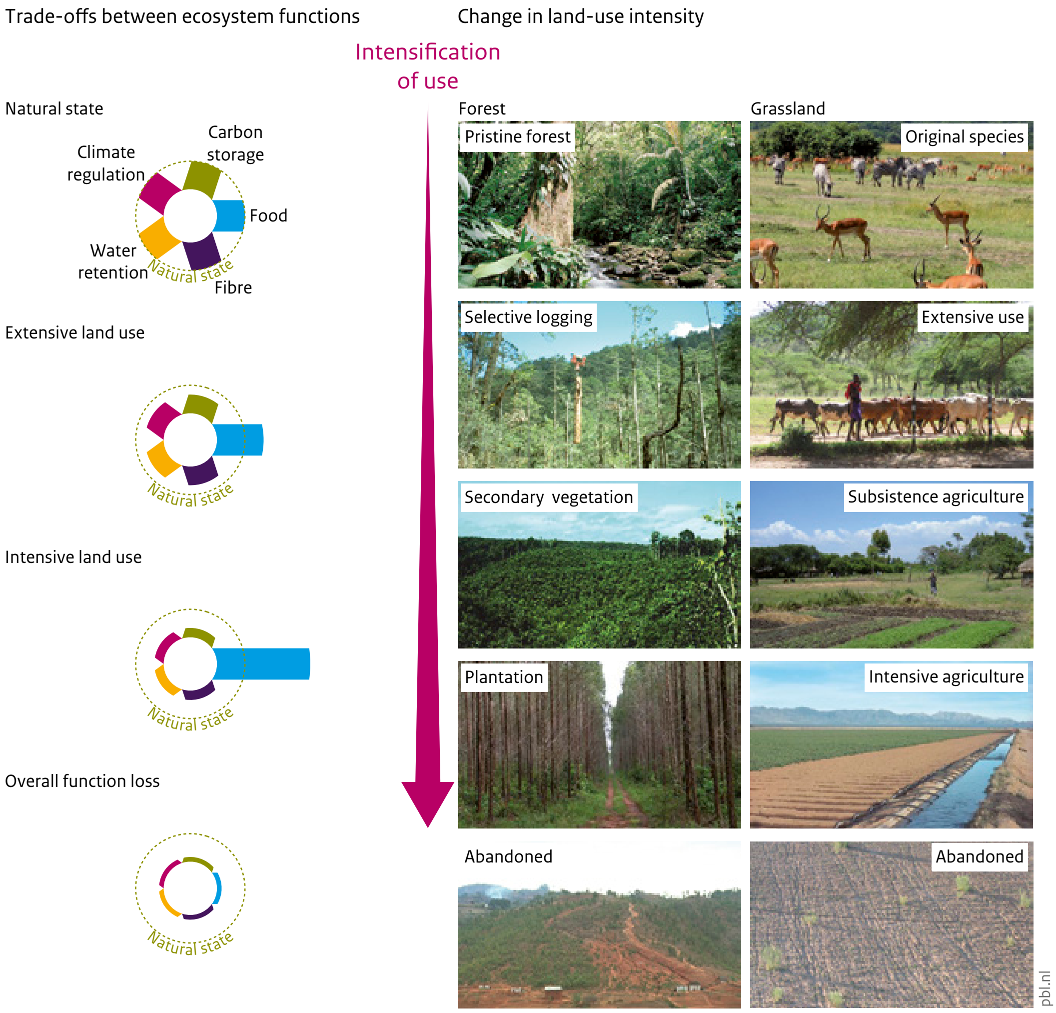
Climate change can produce changes in temperature, precipitation, growing seasons and carbon dioxide fertilisation, affecting agricultural production (World Bank, 2015). The effects will differ per region, with some regions becoming more productive while others see productivity decline. In combination with altered growing seasons and shifts in seasonal water availability, this could result in agriculture being displaced to new areas (UNEP, 2014). Rising sea levels could also lead to a loss of agricultural land (OECD & FAO, 2015). Drought, heatwaves and variability in rainfall are likely to increase, resulting in water scarcity issues, vegetation and soil loss and decreased crop yields (FAO, 2016), particularly in drylands. Climate change accelerates the decomposition of soil organic matter, putting pressure on the condition of soils in warming regions and adding to further carbon emissions. More frequent and higher intensity rainfall may increase erosion and the occurrence of natural disasters (Nearing et al., 2004).

Greenhouse gas emissions from land use, including agriculture and livestock farming, are estimated at just under a quarter of total anthropogenic greenhouse gas emissions, 10 to 12 $GtCO_2$ equivalents per year. These emissions are mainly attributed to deforestation, livestock, and poor soil and nutrient management (Smith et al., 2016). Land use and land management present many options to contribute to climate change mitigation,

Box 2.2 *Continued*

Figure 2.2

Stylised representation of change in ecosystem functions and trade-offs per land-use intensity



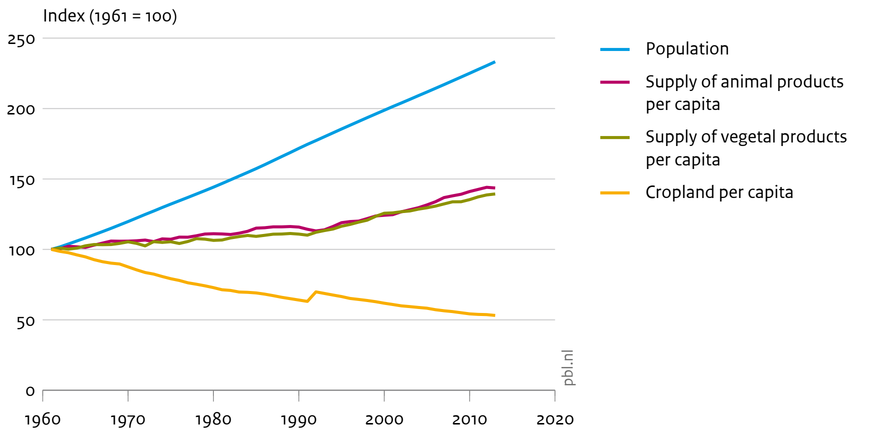
Source: PBL

most clearly by conserving and increasing carbon stocks in vegetation and soils and employing bio-energy. However, the latter presents a challenge as bio-energy expansion may itself contribute to emissions from land conversion, in addition to potentially affecting food prices, putting more pressure on water availability, and coming at the cost of loss of biodiversity.

2.2 Global trends influencing land use

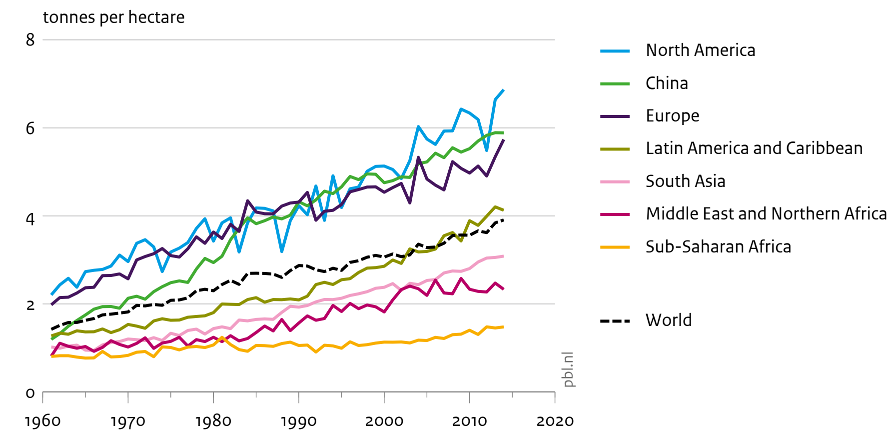
The demand for land has increased rapidly, following global trends in population growth, wealth and changing diets, and coinciding with a decrease in cropland per capita (Figure 2.3). The world population grew from 3.7 billion in 1970 to 7.3 billion in 2015, of which the majority (54%) now live in urban areas (UN, 2014). This growth has resulted in a rising demand for land-based products, such as food, feed, fibre and fuel, which leads to increasing pressures on land, from both local and more distant sources (Lambin and Meyfroidt, 2011). While demands on land are increasing, there are various trends that show how the availability of land is becoming increasingly limited. Against this backdrop, there are a number of other global trends that can be expected to play a role in future changes in land use. These include agricultural productivity gains, variations in food prices, urbanisation, trade, and increasing international investments in land.

Figure 2.3
Global population, cropland and food supply



Source: FAOSTAT; World Development Indicators 2017

Figure 2.4
Cereal yield per region



Source: FAOSTAT; World Development Indicators 2017

Agricultural productivity gains account for most of the increase in production

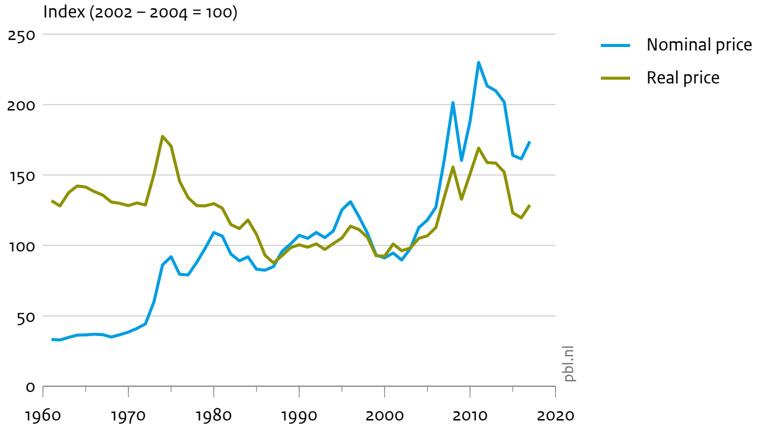
In order to meet the growing demand for food, the productivity of agricultural land has been improved significantly over the past 50 years, primarily through irrigation, fertilisation and the use of pesticides to increase yields, rather than through expansion onto new land. Since 1960, cropland area has increased by 12% while, over the same period, global crop yields have almost tripled (Figure 2.4). The variation in trends across regions depends on agricultural practice (Grassini et al., 2013; Licker et al., 2010; Neumann et al., 2010). In the future, further increases in crop yields and improved efficiency in livestock production will be important in limiting the need for agricultural land expansion.

There are however indications that in some regions the rate of yield increases has slowed down or even reached zero (Bruinsma, 2011; Von Witzke, 2008).

Food prices remain relatively low but show more volatility

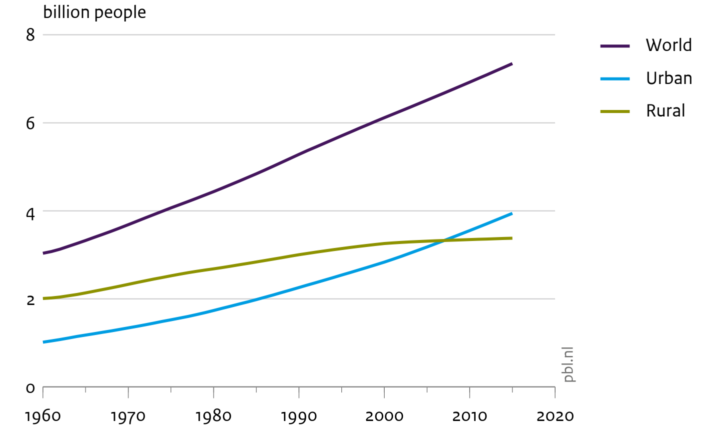
Food prices have been high and more volatile over the past decade as a consequence of a complex combination of factors including rising food demands, oil prices, weather shocks, rapid economic growth or recession and competing demands from biofuels (FAO, 2016). Figure 2.5 shows the trend from 1960 to the present. This has a direct effect on poverty rates and on countries with a high share of food imports (FAO, 2016; UNEP, 2014). Recent spikes in food prices, such as those of 2007–2008, were in part attributed to the increased demand for biofuels but

Figure 2.5
Food price



Source: FAOSTAT 2017

Figure 2.6
Global rural and urban population



Source: United Nations Urbanization Prospects 2017

another factor was the growing involvement of financial institutions seeking investment opportunities at a time of financial turbulence in many areas of the agri-food system where speculation and trading can impact prices (Burch and Lawrence, 2009; Wahl, 2009). Increased price volatility makes it harder for farmers to anticipate the markets for their products and therefore investments in agriculture become more risky and costly. Current prices are almost at pre-1985 levels and, corrected for income, historically low; the average share of household income spent on food is on a downward trend. The expectation is that this will continue in the future. However, low-income households that have not benefitted from the increase in average incomes will be affected by relatively higher price levels and increased price volatility.

Urbanisation at the expense of prime agricultural land
The world is becoming increasingly urbanised. Figure 2.6 shows how the proportion of the global population living in cities grew from 30% in 1960 to 54% in 2015 (UN, 2014). The highest relative increase in urban population was the 12-fold growth which occurred in Africa (UNEP, 2014) though most of the population remains rural there (UNEP, 2012). Internal migration is increasingly dominated by rural–urban flows which are expected to continue (Sommers, 2010).

Urbanisation directly and indirectly affects land use. The expansion of urban areas often comes directly at the expense of prime agricultural land as human settlements have historically developed in the most fertile areas (d'Amour et al., 2016; Del Mar López et al., 2001; Seto et al., 2010). Therefore, while urban expansion is small relative to global land use, its effects on production may be larger (d'Amour et al., 2016). In China, more than 70% of the increase in urban land took place on previously cultivated land (Hao et al., 2011). Growth is mainly in *peri-urban areas* – the fragmented landscape around cities – which expand at four times the rate of urban areas (Piorr et al., 2011). Pressure on agricultural land from urbanisation partly results in displacement of agriculture to other locations, at the expense of grasslands, savannahs and forests (Holmgren, 2006; Seto et al., 2002). In addition, urban-based demand for agricultural commodities is an indirect driver of land-use change in other, more distant areas (DeFries et al., 2010). As nations urbanise and wealth increases, calorie intake and the consumption of resource intensive foods and other products also increase (IFPRI, 2016), a process which can drive agricultural production and deforestation in other regions and is defined as *urban teleconnections* (Seto et al., 2012).

Market integration and trade drive changes in land use

Economic flows worldwide are growing and globalising rapidly due to market liberalisation and information technology (Reardon and Barrett, 2000). Global trade quadrupled between 1980 and 2011, growing about twice as fast as global production, with the share of developing countries' exports increasing from 34% to 47% in the same period (WTO, 2013).

Trade over vast distances has created a disconnect between consumption and production of natural resources (Erb et al., 2009), and has given rise to the concept of *environmental footprints*. The global integration of markets has also resulted in changes to commodity market structures: there is a drive towards large-scale agriculture, monofunctional landscapes and trade with distant markets in which supply chains, supermarkets and international agribusinesses are increasingly involved. Trade can improve the efficiency of land use, while land-use decisions are coming under the influence of factors in distant markets (DeFries et al., 2010). These factors include the demand for high-value commodities, such as coffee, cocoa and beef (Le Polain De Waroux and Lambin, 2013), along with agricultural and wood products (Anderson, 2010). The land use at the origin of these trade flows can therefore be affected by changes in demand as well as by market price fluctuations and changes to trade tariffs. However, impacts can be felt in the opposite direction too: local biophysical changes, such as those caused by climate change, affect the suitability of land and lead to shifting agricultural zones, with consequences that are felt globally. As a result of these connections, a large percentage of deforestation today is due to the production of commodities for global markets (Lambin and Meyfroidt, 2014).

Growing international investments in land

Land is increasingly becoming an international asset class. Flows of trade, finance and investments, which are higher than ever, are both indirect and direct drivers of land-use change (Marcotullio, 2014). Also termed *the land rush* or *land grabbing* (Anseeuw et al., 2012), large-scale transnational land acquisition has increased dramatically since 2000, totalling 1,204 deals covering approximately 0.4 million km^2 (42.4 Mha), which is roughly the size of Spain, focussing primarily on food and agro-fuel crops in Africa and the southern hemisphere (Land Matrix, 2016). While this surface area is small compared to the global land use by agriculture, the potential impacts on smallholders and concerns about fairness have drawn attention.

This increase in cross-border acquisitions or leases is triggered by many issues, including food security, economic recession, biofuel targets and national concerns to secure safe and profitable assets (Friis and Reenberg, 2010; Mann and Smaller, 2010). The 2007–2008 spike in food prices resulted in greater investments in land for food production and export (Toulmin et al., 2011). Examples include Saudi Arabia, which aims to move agricultural investments abroad due to water scarcity in its own territory (Mann and Smaller, 2010) by buying land in Ethiopia (Lippman, 2010) and Chinese investors seeking to buy agricultural land in Africa (Hofman and Ho, 2012). This supports the trend away from investments in domestic agriculture for domestic and global markets, to investments in land abroad to supply domestic markets (De Schutter, 2011; Mann and Smaller, 2010).

However, it is not only national governments and sovereign wealth funds that are investing in land abroad. Land as an asset class brings with it an array of new agents that are increasingly international in nature. At present, most deals are sealed by private companies, both listed and non-listed, including large multinationals involved in food and livestock production (Land Matrix, 2016). There are many unsolved issues around transparency of deals, land ownership and tenure. In many cases, these deals result in large scale industrial monocultures, such as oil palm plantations (Novo et al., 2010; Richardson, 2010) and in some countries, such as the Democratic Republic of the Congo, agricultural investments have forced local farmers into the national park areas (Deininger, 2011).

Figure 2.7
Sustainable development goals (SDGs) with a strong relation to land

Source: UN; PBL

2.3 Global goals for land

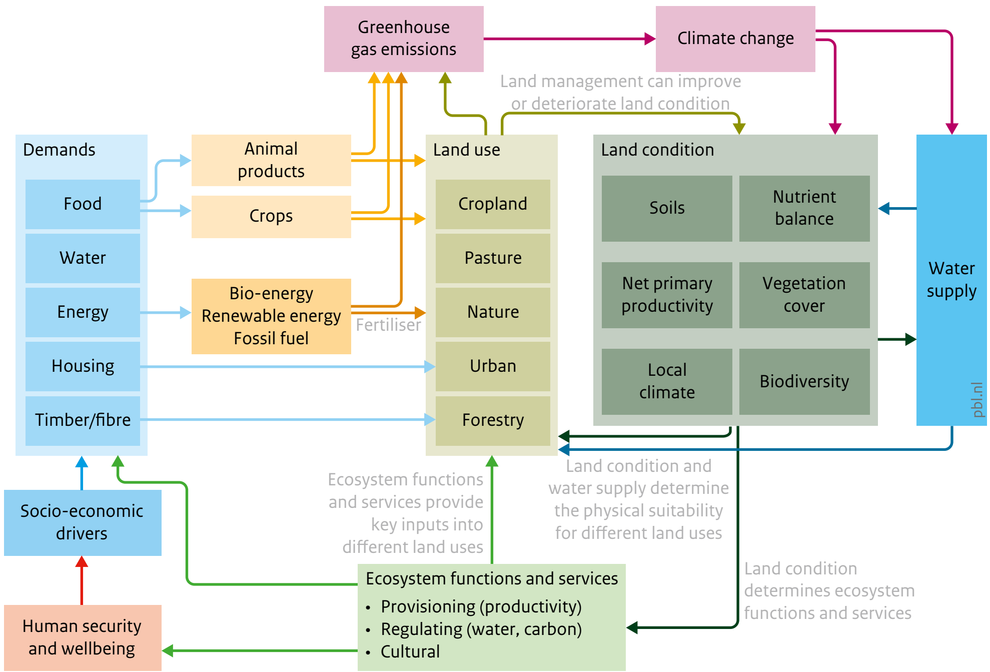
The management of land resources affects human securities
Changes in the use and quality of land and soils affect human and national securities, both positively and negatively, at the local, regional and global levels. Land degradation is said to be a contributor to social destabilisation, migration and conflict, in agreement with observations in Sub-Saharan Africa and the Middle East although the relationships are difficult to prove (Van Schaik and Dinnissen, 2014). Over the past 60 years, 40% of all intrastate conflicts have been linked to the use of natural resources (UNEP, 2009) and over 70% of all countries affirm that climate change impacts, including land degradation and drought, are regarded as national security issues (EJF, 2014). The effects of poor resource management and degradation may be felt both locally and elsewhere in the world, indicating that the sustainable management of land resources plays a critical role in addressing many sustainable development challenges. This is recognised and reiterated in various global ambitions and goals for land.

Global ambitions and goals for land
A number of international ambitions have been formulated that directly or indirectly target land and the way it is managed and governed. These are found among the specific goals and targets of the three *Rio Conventions*[2], in voluntary guidelines and multilateral environmental agreements (MEAs), and they also appear repeatedly in the Sustainable Development Goals (SDGs). The Rio Conventions form part of international law and became legal instruments after they were ratified, although they include only few precisely defined obligations for specific countries aside from reporting requirements (the Kyoto protocol being an exception).

Multilateral declarations by governments, such as the Bonn Challenge and the New York Declaration on Forests, are generally statements of intent rather than legal commitments. These declarations set ambition levels and harness support in a desired direction. The *Voluntary guidelines on responsible governance of land tenure, fisheries and forests in the context of food security*, developed by the FAO, are an example of international soft law that lays out the ground rules for reporting on secure tenure rights and equitable access to land (UNEP, 2012).

The *Sustainable Development Goals* are statements of ambitions rather than legal obligations, but are unique in their strong integrated view on global challenges and their universal applicability. Among the 17 goals and 167 targets of the SDGs, the focus on land varies. The eight goals that are most closely connected to land can be grouped into four categories: *conservation and restoration of land resources, sustainable and efficient management of land, ownership and access to land, and sustainable consumption and production of natural resources* (Figure 2.7). The eight goals underscore the notion that land and land management are of key importance to at least half of the SDGs through multiple perspectives and connections.

Figure 2.8
Interlinkages between key themes in global land systems



Source: PBL

2.4 Assessing future changes in land systems

Given the limited availability of land, the increasing demands, and the role of land in many of the SDGs, it is relevant to obtain a sense of the direction of developments determining future changes in the land system. The report continues with the various factors that drive those changes, with Chapter 3 focusing on projections of future land use and Chapter 4 on the extent to which land condition may change and how that may affect ecosystem functions and services. Figure 2.8 shows a diagram of the connections that are quantified in the following chapters and for which projections to 2050 are explored through the use of scenarios. Chapter 5 briefly summarises the changes by region, showing where the biggest changes and challenges are expected.

Notes

1 Reducing Emissions from Deforestation and Forest Degradation.
2 The three Rio Conventions are the United Nations Framework Convention on Climate Change (UNFCCC), the United Nations Convention to Combat Desertification (UNCCD) and the Convention on Biological Diversity (CBD).

THREE

Land-use change under various futures

3.1 Future demands on land

Explorative scenarios to study future land-use dynamics
As mentioned in Chapters 1 and 2, there is concern that trends in global population, economic growth and technological development, coupled with stronger ambitions for biodiversity protection and land-based climate policies will lead to strongly increased competition for land. Climate change and the degradation of land and soils put further strains on the suitability of land for various purposes. Land as a resource is therefore likely to become scarcer from a global perspective, making sustainable and efficient use even more important. This chapter describes the explorative scenario approach used to quantify the potential scale of changes in future land use under alternative futures, providing an array of possible future changes for which relevant responses can be formulated.

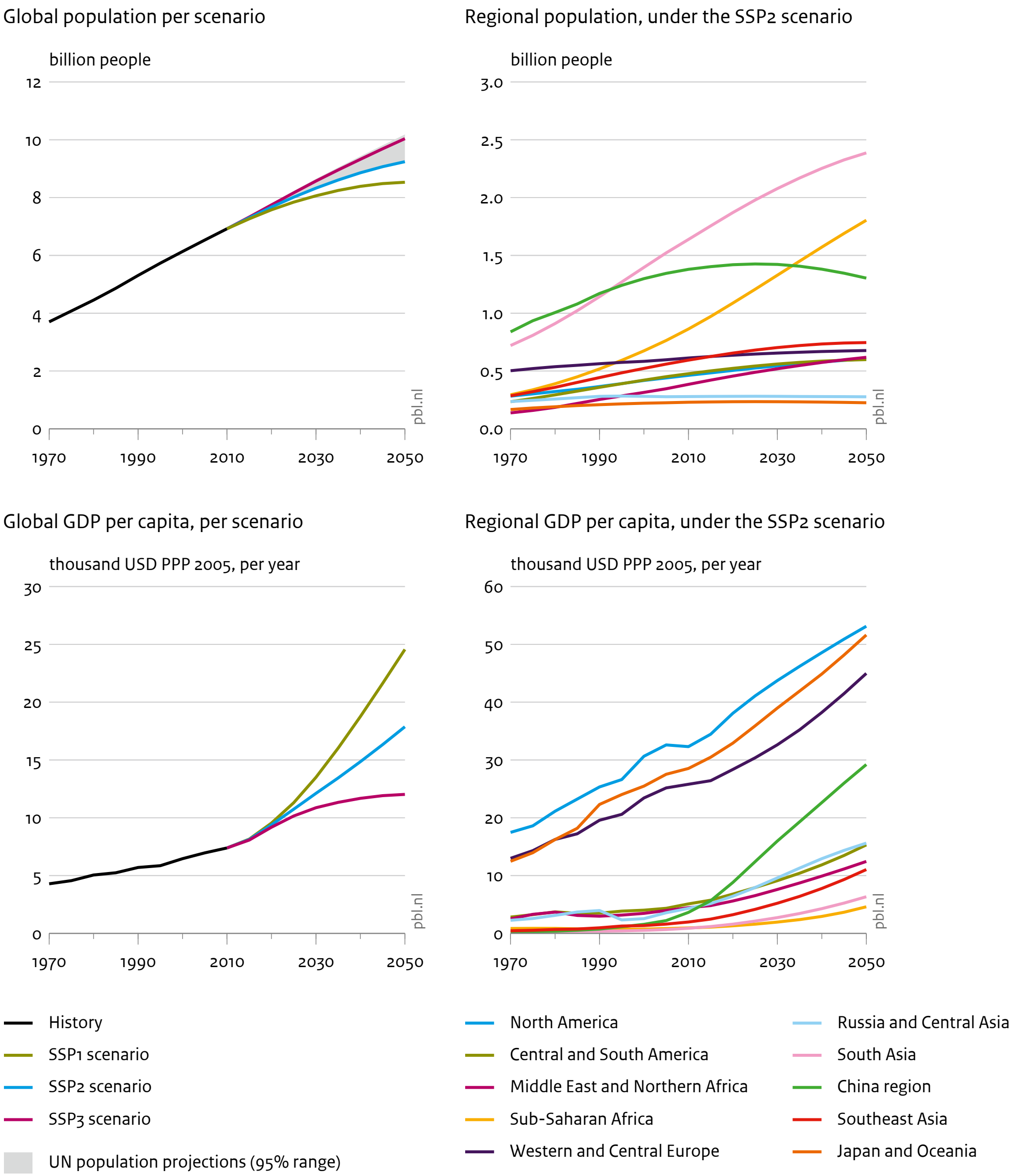
3.2 Three scenarios

The storylines of the Shared Socio-economic Pathways describe overall socio-economic trends
Over the past few years, the scientific community has developed a set of scenarios, known as *Shared Socio-economic Pathways* (SSPs). Initially, they were developed to serve the climate research community in their assessment of climate change. They cover a broad range of aspects of future land use, including land-use regulation (e.g. protected areas), agricultural technology, dietary preference, and trade. Due to their broad coverage of global trends, the SSPs are also useful outside the climate research community, making it possible to carry out assessments of plausible, contrasting futures of the global land system. The SSP storylines describe overall developments, which are characterised by various trends in key determinants of global environmental change and social development, such as population growth, economic growth, technological change, level of environmental protection, and level of cooperation across countries and regions (O'Neill et al., 2017). The storylines are used to subsequently derive demographic (KC and Lutz, 2014) and economic scenarios (Dellink et al., 2015). Other elements of the original storylines are only described in qualitative terms and had to be quantified to enable the creation of quantitative scenarios. Several integrated assessment models, including the IMAGE model (Stehfest et al., 2014), have recently implemented the SSP scenarios (see Popp et al., 2017 and Riahi et al., 2017). This study uses the SSPs that have been implemented in the IMAGE model.

Three storylines: a short description of SSP1, SSP2 and SSP3
For the study reported here, SSP1, SSP2 and SSP3 were selected from a larger set of SSPs, as they represent the full range of possible outcomes for the land system (see Doelman et al., in review). The three storylines are described briefly below (see also Table 3.1) with SSP2 being mentioned first as it best represents a continuation of current trends. SSPs 1 and 3 reflect scenarios with lower and higher levels of challenges respectively. The descriptions include quotations from (O'Neill et al., 2017):

SSP2 – Middle of the road: medium population growth, medium economic growth, medium technological change; in all aspects, current trends are continued.
'In this world, trends typical of recent decades continue, with some progress towards achieving development goals, reductions in resource and energy intensity at historic rates, and slowly decreasing fossil fuel dependence. Development of low-income countries proceeds unevenly, with some countries making relatively good progress while others are left behind.'

Figure 3.1
Socio-economic drivers



Source: PBL/IMAGE

SSP1 – Sustainability: low population growth, high economic growth, medium fast technological change, emphasis on environmental protection and international cooperation
'The Sustainability SSP1 describes a world that makes relatively good progress towards sustainability, with sustained efforts to achieve development goals, while reducing resource intensity and fossil fuel dependence. Elements that contribute to this are an open globalised economy, rapid development of low-income countries, a reduction of inequality (globally and within economies), rapid technology development, low population growth and a high level of awareness regarding environmental degradation. More environmental awareness reduces food waste, the appetite for meat as well as making land use regulation stricter.'

SSP3 – Regional rivalry: high population growth, low economic growth, less technological change, little environmental protection and reduced international cooperation.
'The Regional Rivalry SSP3 describes a world which is separated into regions characterised by extreme poverty, pockets of moderate wealth and a bulk of countries that struggle to maintain living standards for a strongly growing population. Regional blocks of countries have re-emerged with little coordination between them.

Table 3.1
Characteristics of major land-use components in the SSP storylines. These qualitative assumptions are quantified for the IMAGE SSPs (see Annex 2).

	SSP1 Sustainability	SSP2 Middle of the Road	SSP3 Fragmentation
Globalisation of trade	High	Medium	Low
Meat consumption and waste in the food chain	Low	Medium	High
Land-use regulation (e.g. protected areas)	Strict	Moderate	Low
Crop yield improvement	High	Medium	Low
Livestock system efficiency	High	Medium	Low

Countries focus on achieving energy and food security goals within their own region. The world has de-globalised, and international trade, including energy resource and agricultural markets, is severely restricted. Population growth in this scenario is high as a result of the education and economic trends.'

Contrasting population and economic growth across the three scenarios
The trends in GDP and population development vary substantially, with the global population in 2050 ranging from 8.5 billion in SSP1 to 10 billion in SSP3 (Table 3.1; Figure 3.1). The global average GDP per capita in 2050 is about USD 12,000 in SSP3 and USD 25,000 in SSP1, in 2005 PPP USD, with considerable variation across regions.

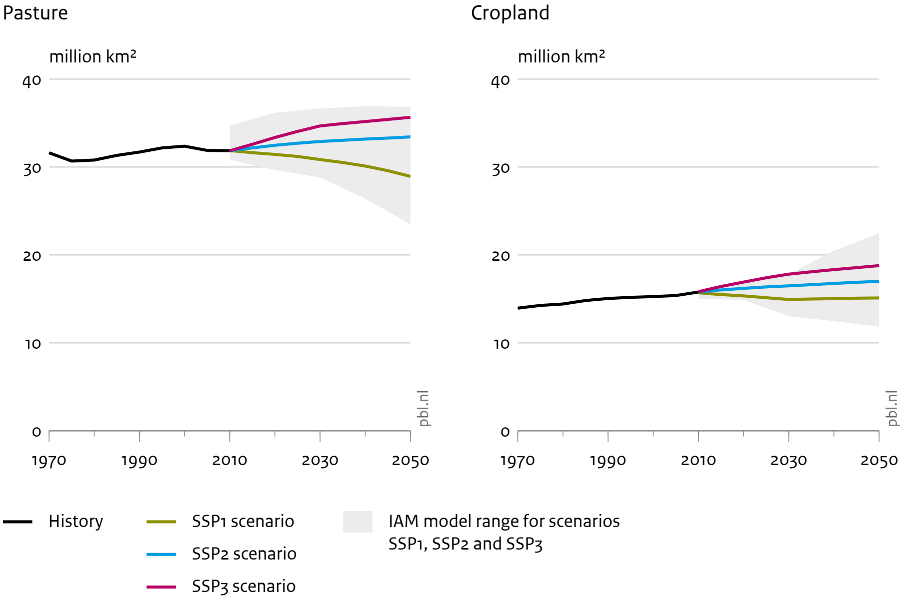
For the population increase, historic growth patterns are projected to continue, but start to diverge from 2010 onwards, with the scenarios eventually differing by 1.5 billion people by 2050. A levelling off of population growth by the middle of the century is assumed in the SSP1 and SSP2 scenarios. Income levels, gender policies, maternity health and education levels are key determinant factors in these global projections. At the regional level, SSP2 foresees for both Sub-Saharan Africa and South Asia strong population growth continuing well into the 21st century, while China's population will start declining due to the effects of previous population control policies.

For GDP per capita, the SSP2 scenario assumes an increase to at least twice its starting value, but the variation among the scenarios is larger than in the estimates for population. Important determinants of economic growth are population, labour, physical capital, natural and energy resources, and long-term technological change, known as 'total factor productivity' (Dellink et al., 2015). Technologies are at least partially assumed to spill over to other countries, accelerating convergence of income levels. The Chinese region shows the fastest growth and many developing regions have growth rates that lead to a doubling or tripling of GDP per capita by 2050. While these growth rates mean that incomes per capita in these regions are converging toward those of more developed regions, their low starting levels prevent them from coming anywhere near the average income per capita in the richer countries by the middle of the century, with China getting the closest. Still, these figures are not forecasts but rather quantifications of possible future growth paths to be used for policy analysis, and a number of effects and shocks may happen that can change this outlook. Furthermore, a number of aspects, including feedback from the environment to the economy, are not included in these projections.

While SSP2 is closest to the typical UN population projections for 2050, SSPs 1 and 3 envisage opposite trends for population and income growth: SSP1 foresees a much slower growth in population with much higher income levels per capita and SSP3 is based on faster population growth combined with lower average incomes per capita. These differences affect the future of land in multiple ways: higher incomes trigger increased animal protein consumption, and higher population growth in less-developed regions with limited availability of land can put strains on resource use.

Translating storylines to quantitative scenario assumptions
The qualitative description of the storylines was translated to specific assumptions and model input for IMAGE. Important scenario assumptions that are specifically relevant for the land-use system relate to resource efficiency of food consumption, trade, policy on land-use change, and climate mitigation (Table 3.1). Trade, including trade in agricultural commodities, is projected to become freer and more globalised in SSP1, but more restricted in SSP3. Food consumption is characterised by higher meat intake and increased generation of waste in the consumption-oriented world

Figure 3.2
Global agricultural area per scenario



Source: PBL/IMAGE

The shaded areas show the range of values according to other models (Popp et al., 2017)

of SSP3, as opposed to the environmental awareness in the world of SSP1.

Whereas land-use regulation is strict in SSP1, limiting expansion into many existing natural areas, SSP3 has few restrictions to conversion of natural land. Improvements in crop yield and efficiency of the livestock sector are significant in SSP1 compared to the small improvements in SSP3. The SSP baselines have been designed to exclude the effect of climate change (see for example Popp et al., 2017). Therefore, the SSP baselines elaborated by the IMAGE model exclude the effect of climate change on the agro-economic system and land-use patterns.
However, the results on biodiversity and water, presented in Chapter 4, do include the effect of climate change as calculated by IMAGE (corresponding to global temperature increases of about 2.1, 2.3 and 2.4 °C, by 2050, in the SSP1, SSP2 and SSP3 scenarios, respectively), and reflect corresponding impacts. The time horizon of this assessment is 2050, while the original SSP scenarios continue on to 2100.

3.3 Projected land-use changes

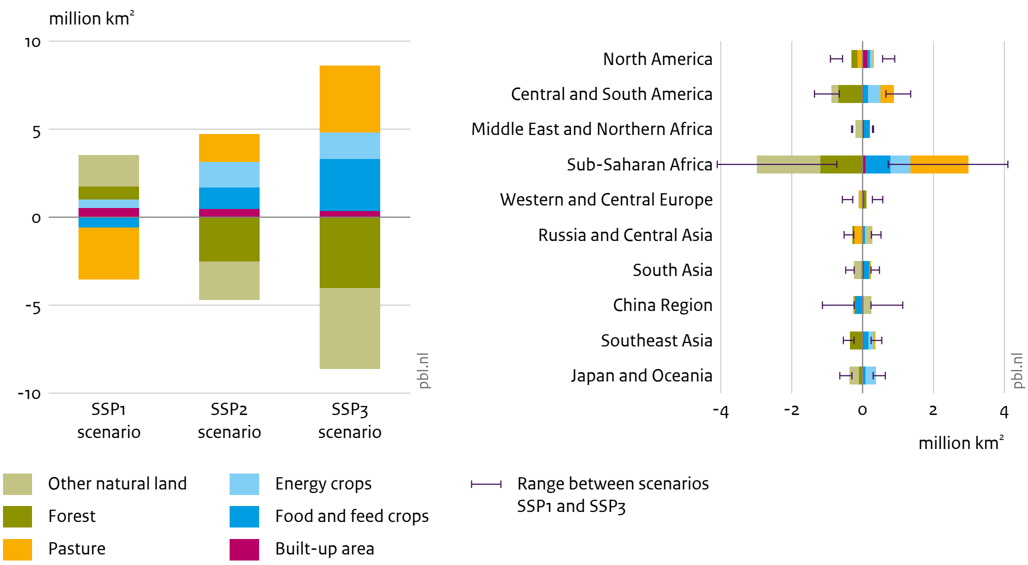
3.3.1 Globally aggregated land-use changes

The implications of the various scenario characteristics for land use, up to 2050
Global land-use change is expected to continue in the *Middle of the Road scenario* (SSP2), with expansion of cropland from 13 million km² in 2010 by about 0.9 million km² up to 2030 and a further 1.2 million km² between 2030 and 2050. In addition, 1.4 million km² is to be dedicated to energy crops by 2050 (Figure 3.2; Figure 3.3). Pasture area is projected to increase by about 1.6 million km² until 2050. Built-up areas, which often expand into the most fertile agricultural lands, (see Section 3.4.6) are projected to increase significantly, by almost 80% (0.50 million km²). SSP3 shows a more dramatic expansion of the categories cropland, bio-energy and pasture than SSP2, which is mostly due to the slower pace of technological development. In the SSP1 scenario, on the global level a net decrease of agricultural area is projected, as a result of its combination of lowest increase in global population, more attention for sustainability (lower levels of meat consumption and less food waste), and high efficiency of crop and livestock systems.

Figure 3.3
Land-use change, 2010 – 2050

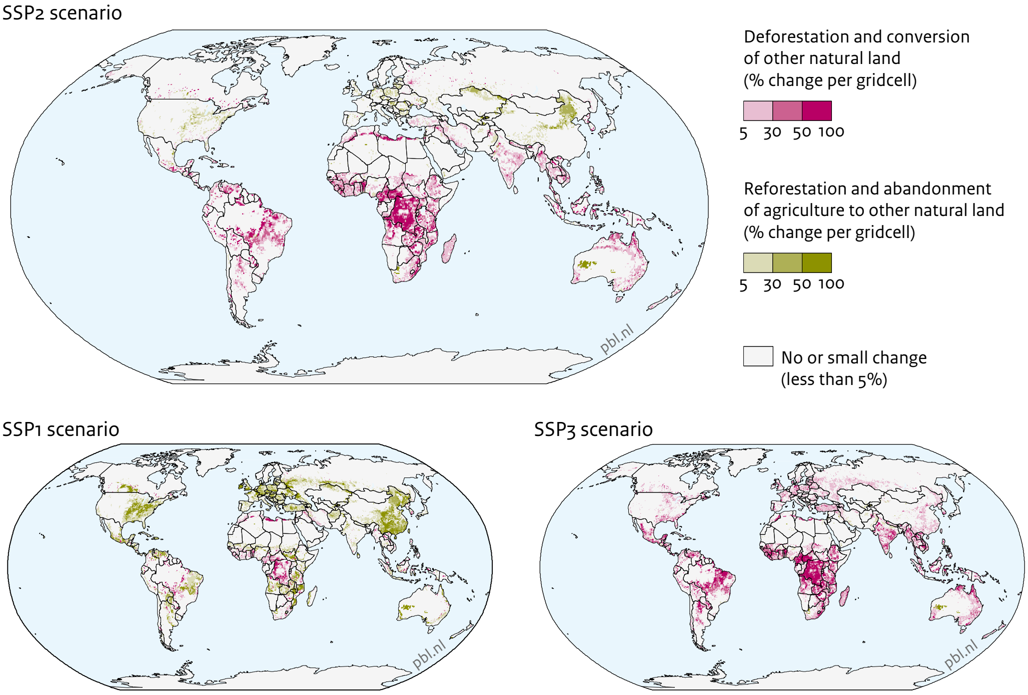
Global per scenario

Regional change under the SSP2 scenario



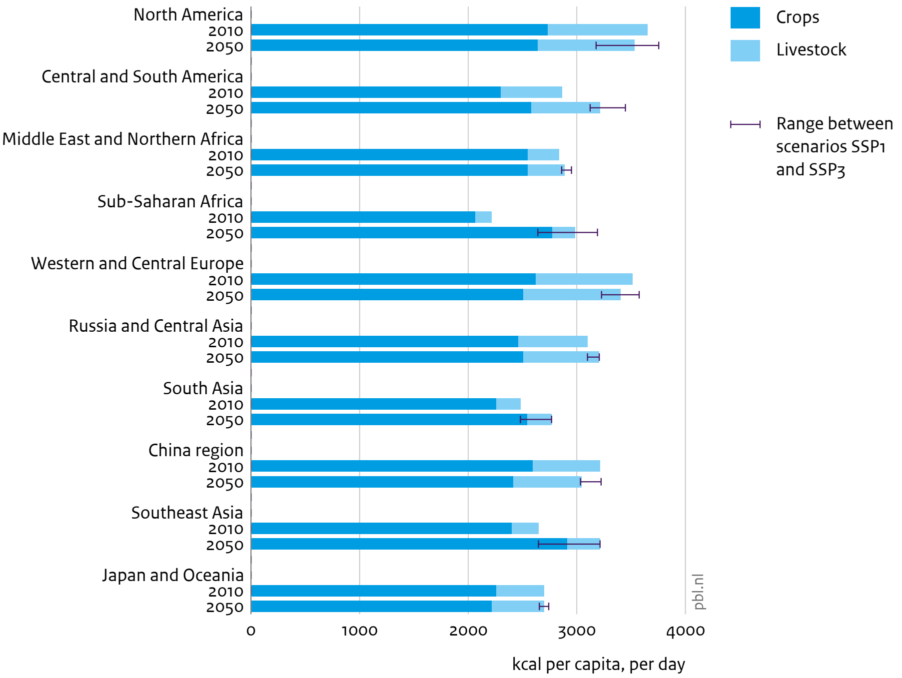
Source: PBL/IMAGE

Figure 3.4
Land-use change per scenario, 2010 – 2050



Source: PBL/IMAGE

Figure 3.5
Regional demand for crops and livestock products, under the SSP2 scenario



Source: PBL/IMAGE

The graph shows food use for consumption, excluding waste at household level (definition based on food balance sheets from FAOSTAT, 2016)

Large differences in future land use
The projections for land use by humans in 2050 (food and feed crops, pasture, bio-energy, built-up areas) differ widely among the three SSPs (Figure 3.4). SSP1 foresees a net decrease in land use, due to a reduction in cropland and pasture, though bio-energy plantations and built-up areas are set to grow. SSP2 suggests a moderate increase in land use of 4 million km² and SSP3 points to the largest increase of about 8 million km² (Figure 3.3).
These projections fall well within the range of other integrated assessment models for the same scenarios, without reaching their upper and lower limits. A more detailed discussion can be found in Popp et al. (2017).

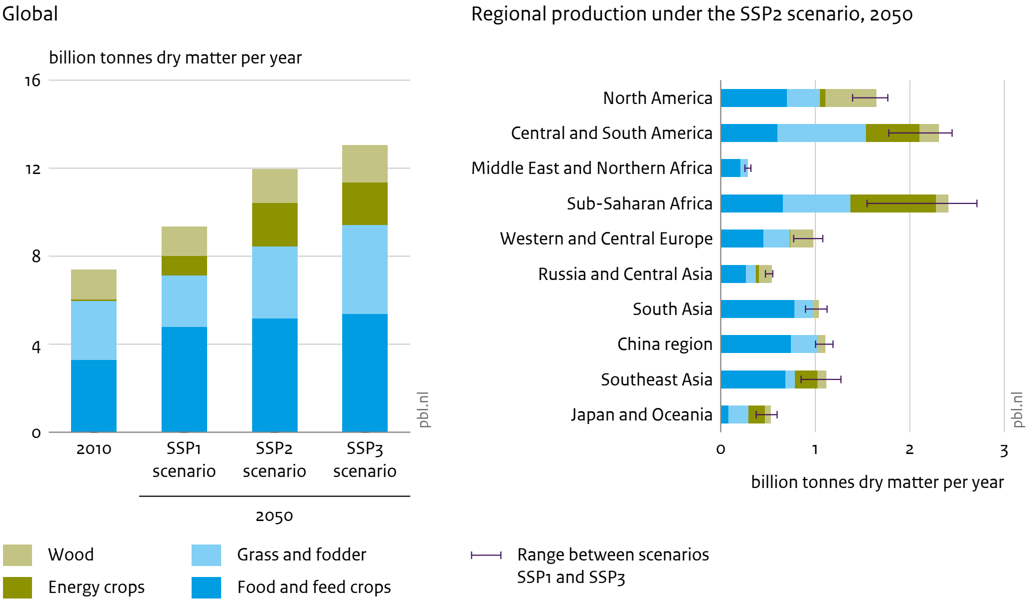
3.3.2 Projected regional land-use changes
The projections for future change in land use vary significantly across regions, since each SSP uses specific trends in population and economic growth, and in the subsequent domestic demand for land-based products (Figure 3.5). In SSP2, agricultural land is set to decrease in China, and remain more or less stable in Russia, Europe and North America, but SSP3 foresees slight increases for these regions. In SSP2, the largest absolute increase is projected to occur in Sub-Saharan Africa, with about 3 million km² of additional agricultural land expanding into forests and other natural lands (Figure 3.3; Figure 3.4). A similar projection, yet lower, is made for Latin America, South Asia and Southeast Asia. In SSP3, agricultural expansion in these three developing regions is projected to increase more than in SSP2. In SSP1, all regions are projected to have less cropland in 2050 than in 2010, except for Sub-Saharan Africa, where the net increase in cropland is presumed to continue at the expense of pasture and forests.

3.4 Projections for the main drivers of land-use change

3.4.1 Demand for food and fuel

A major increase in the demand for agricultural products, due to population growth and higher incomes
The three scenarios foresee a 25% to 75% increase in the demand for and production of agricultural products and timber until 2050, as a result of population growth and higher incomes. This is in line with findings in recent literature on similar models and scenario assumptions (Popp et al., 2017). SSP2 and SSP3 show similar figures for

Figure 3.6
Agricultural production per scenario



Source: PBL/IMAGE

demand and production of food and feed crops (around 5,500 Mt dry matter). SSP3 foresees a larger population, but this is compensated for by lower economic growth, resulting in a reduced food demand compared to SSP2 (Figure 3.5; Figure 3.6). SSP1, in contrast, is characterised by both low population growth and an assumed shift towards environmentally friendly consumption patterns, which results in a smaller increase in food production, and even a reduction in the demand for pasture land, due to a downturn in beef production and marked increases in the efficiency of livestock farming.

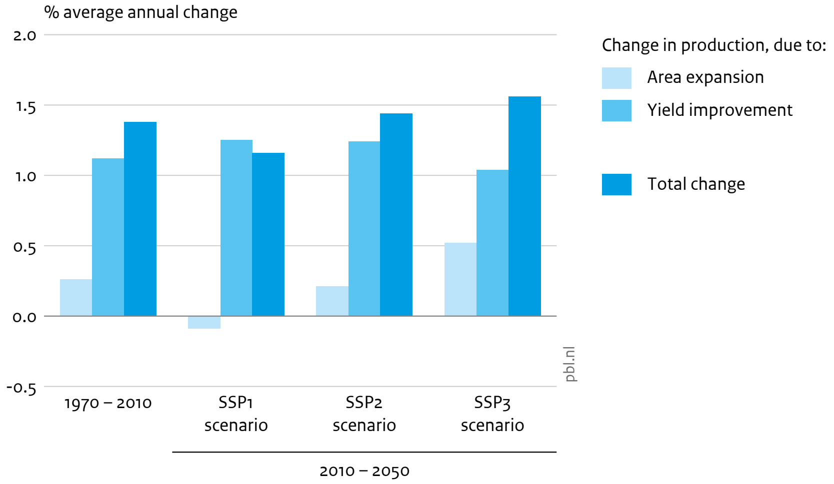
The demand for bio-energy is also expected to increase due to high energy prices and policy targets
Next to the demand for food and feed crops, additional demand will arise from the energy system. To increase their energy security or as a contribution to climate change mitigation, many countries have adopted stimulating policies and made plans to increase the share of bio-energy in national energy consumption. Nevertheless, the main forces behind increased demand for bio-energy are higher energy prices (with rises of 30%, 40% and 130%, for oil, coal and natural gas, respectively, in SSP2) and technological progress in bio-energy conversion, which make bio-energy more competitive. Compared to food crops and their share in agricultural area, biomass production at bio-energy plantations is relatively high for two reasons: first, vegetation on bio-energy plantations is harvested as a whole, while for food crops only a specific part (e.g. the seed) is harvested and counted as yield; second, bio-energy plantations have a high potential to increase attainable yields and most scenarios therefore count on a significant increase in bio-energy crop yields. Bio-energy plantations are assumed not to compete with food and feed crops for fertile lands, and only non-forest areas can be used to reduce the impacts on biodiversity and carbon emissions caused by land-use change. Thanks to the large areas of shrubland still available in Latin America and Sub-Saharan Africa, and the relatively low local labour costs, these regions are projected to be attractive for bio-energy production. It is assumed that the production of bio-energy is typically introduced in large-scale initiatives or by companies producing for the global market – rather than through smallholders – and therefore characterised by more efficient management.

3.4.2 Crop yields and efficiency of livestock systems

The surface area dedicated to agriculture will depend on developments in crop yield and the efficiency of feed production
Over the past decades, the largest contribution to the increase in food production has come from efficiency improvements in agriculture, such as enhanced feeding efficiency in livestock production and increased crop yields per hectare (Figure 3.7). The extent to which this trend continues will therefore strongly influence future agricultural land use.

Figure 3.7

Change in global crop production

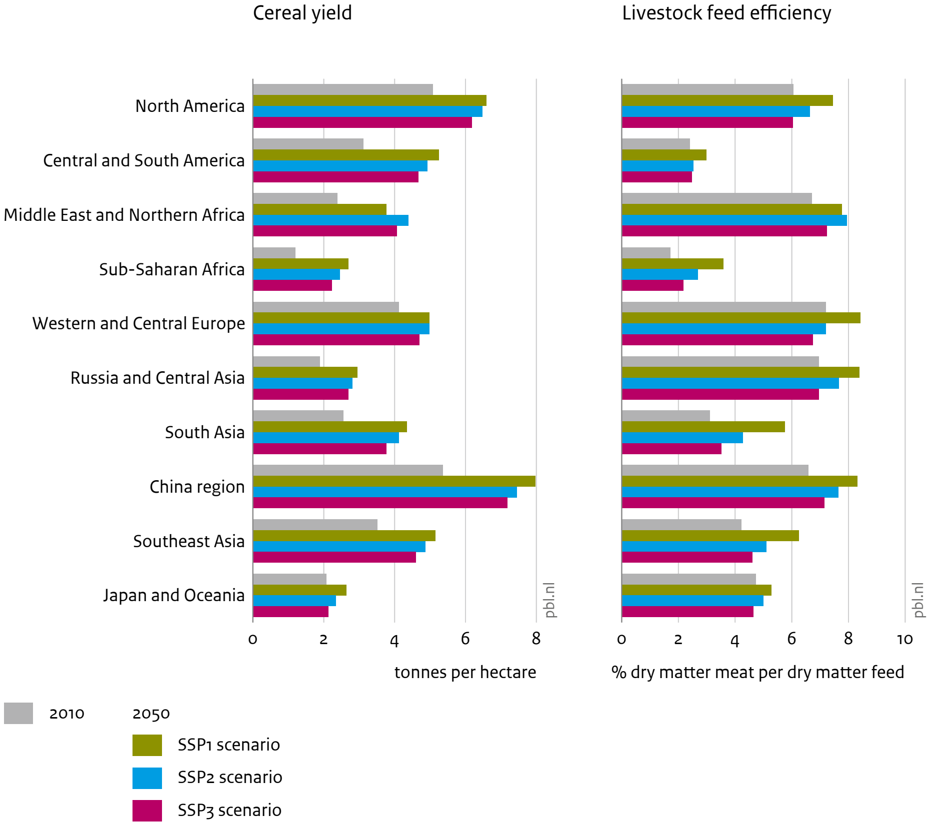


Source: PBL/IMAGE

Yield improvement is derived from total crop production and total cropland area, and, as such, shows yield per physical area, not per harvested area. It therefore includes increases in cropping intensity (number of harvests per year, per hectare) and a reduction in fallow periods. All changes have been evaluated relative to 2010 levels.

Figure 3.8

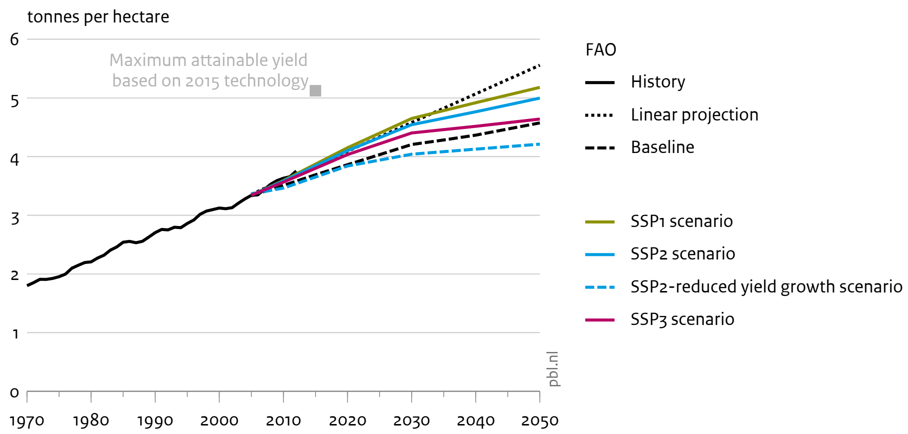
Crop yield and livestock efficiency per region



Source: PBL/IMAGE

Box 3.1: The consequences of slower increases in agricultural efficiency
To show the consequences of more pessimistic assumptions about crop yield increases, this study evaluates a variant of the SSP2 scenario, the SSP2 Reduced yield-growth scenario, which factors in severely limited increases in agricultural efficiency. This is achieved by assuming that the progress in potential yields due to research and development and plant breeding is zero. Figure 3.9 shows the results of the global cereal yields for this scenario, and compares them with those of the other scenarios and FAO projections (Alexandratos and Bruinsma, 2012) and with current attainable yields (Mueller and Binder, 2015). The resulting yields from this pessimistic scenario fall below the FAO projection, while the three SSP scenarios produce results that lie between the FAO projection and a linear extrapolation of historic trends.

Figure 3.9
Cereal yield



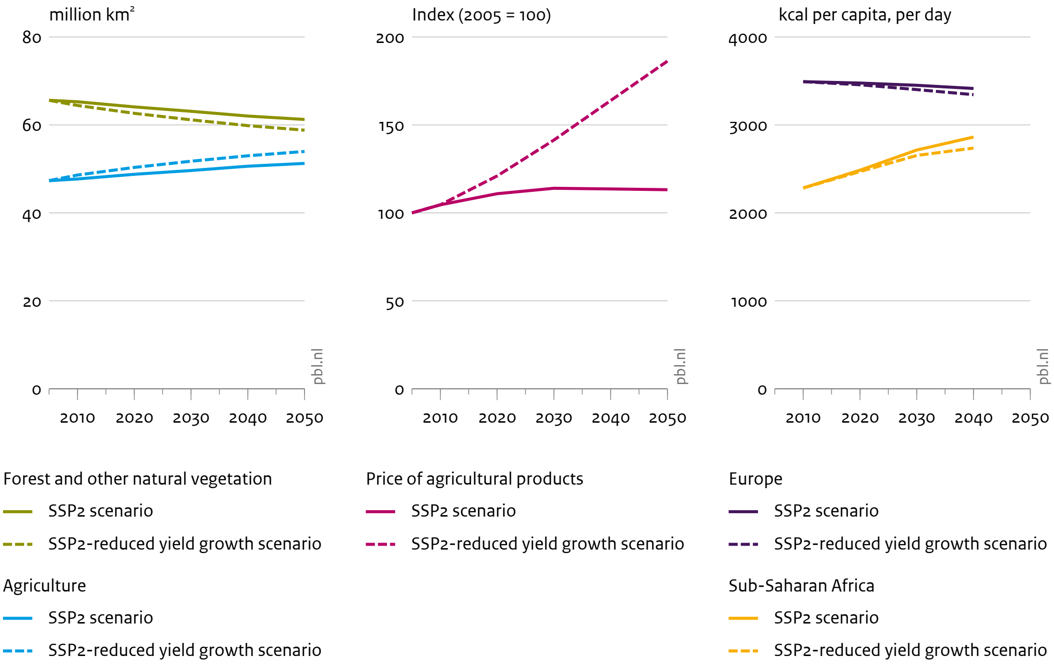
Source: FAO; PBL/IMAGE

In the pessimistic scenario, the more modest increase in crop yield results in higher demand for agricultural land, and consequently, a decrease of natural vegetation area (Figure 3.10). Across all regions, prices of both livestock and crops increase. Not surprisingly, food consumption is reduced in 2050, with the overall calorie supply almost 200 kcal/cap/day lower than in SSP2, and some regions more heavily affected than others (Figure 3.10).
An important effect is that in regions such as Sub-Saharan Africa, food imports increase because the less efficient regional agricultural production cannot keep up with demand. The self-sufficiency of the region therefore decreases as well. In fact, all regions which are unable to be self-sufficient in the SSP2 projections, will become even less self-sufficient if yield improvements stagnate, leading to increases in food exports from regions which are already self-sufficient (North America, Europe, Brazil).

Opportunities for increased future efficiency differ strongly per region. In regions where yields are currently far below the levels that are achieved elsewhere, there is in theory room for improvement, although local constraints related to water and nutrients may complicate the picture (Figure 3.8). In other regions, such as the United States or Western Europe, yields are much closer to their maximally attainable levels. Increases in such regions will have to come from new technologies and even more efficient land use. In the three scenarios, increases in crop yields and livestock efficiencies are realised through a combination of assumed technological change and economic processes which achieve more efficient land use by substituting land with capital, labour or inputs, such as fertiliser. In all three scenarios, the projected crop yield changes lie between the figures published by the FAO and extrapolated values of historical trends and currently attainable yields. This means that the crop yields as projected by the scenarios are possible at least from a technical point of view, especially as currently attainable levels are likelyto increase further in the future through breeding and improved crop varieties (see e.g. Van Ittersum, 2016). In addition to yield increases, the reduction of post-harvest losses shows great potential for improvement.

Box 3.1: *Continued*

Figure 3.10
Effects of reduced yield growth

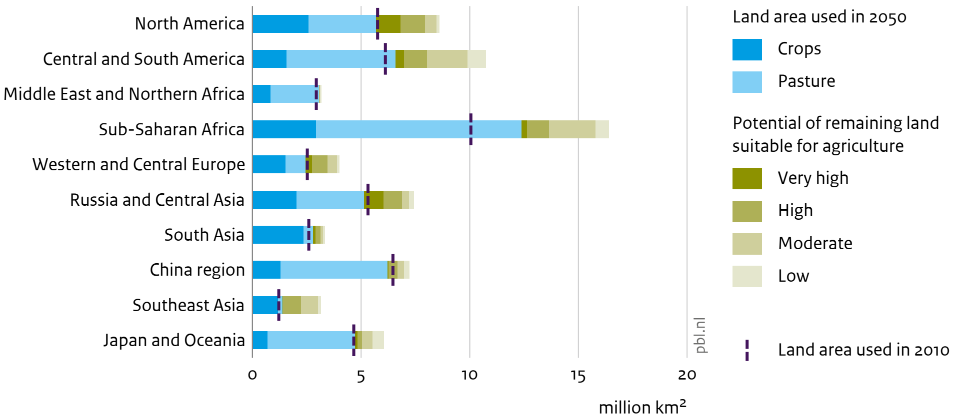


Source: PBL/IMAGE

Efficiency in the agricultural sector involves more than crop yields: large gains can also be made in the livestock sector through more efficient use of fodder and feed crops, indirectly resulting in a reduced pressure on land. In all scenarios, both crop yields and livestock efficiencies increase in all regions, driven by technological change and economic processes. To provide an order of magnitude for the sensitivity of the scenario outcomes, Box 3.1 shows what would happen to agricultural land use under much more pessimistic assumptions about yield increases.

Agricultural management differs across the scenarios as a result of a wide range of drivers and feedback processes
The degree to which increased demand for land-based products will affect land use worldwide is determined by agricultural management and the ability of farmers and farming organisations to use natural, physical and financial resources in their production systems. These in turn are influenced by a wide range of factors, such as rural infrastructure, education, general economic development and the demand from the supply chain. A combination of land scarcity and higher market prices creates incentives for farmers to intensify production. This happens especially in SSP3 for regions such as China, where demand is high and land is increasingly a constraint on agricultural expansion, boosting agricultural efficiency above the low levels assumed initially in SSP3. Similarly, the low demand for agricultural land in SSP1 removes the incentive to intensify further, and therefore leads to more extensive production. In all three scenarios, Sub-Saharan Africa is projected to see high absolute increases in cereal yields, more or less tripling. Despite this, yields are only expected to attain the 2010 world average by 2050, rather than converge to the yields of other regions. Given that Sub-Saharan Africa will see strong increases in population and food demand along with a loss of natural areas, further accelerating yield increases here seems both possible and important. However, while tripling yields by 2050 is technically and economically feasible – and therefore projected here and in other assessments – it will require overcoming the current infrastructural and governance barriers.

Figure 3.11
Agricultural land use and remaining suitable land, under the SSP2 scenario



Source: PBL/IMAGE

3.4.3 Availability and suitability of land

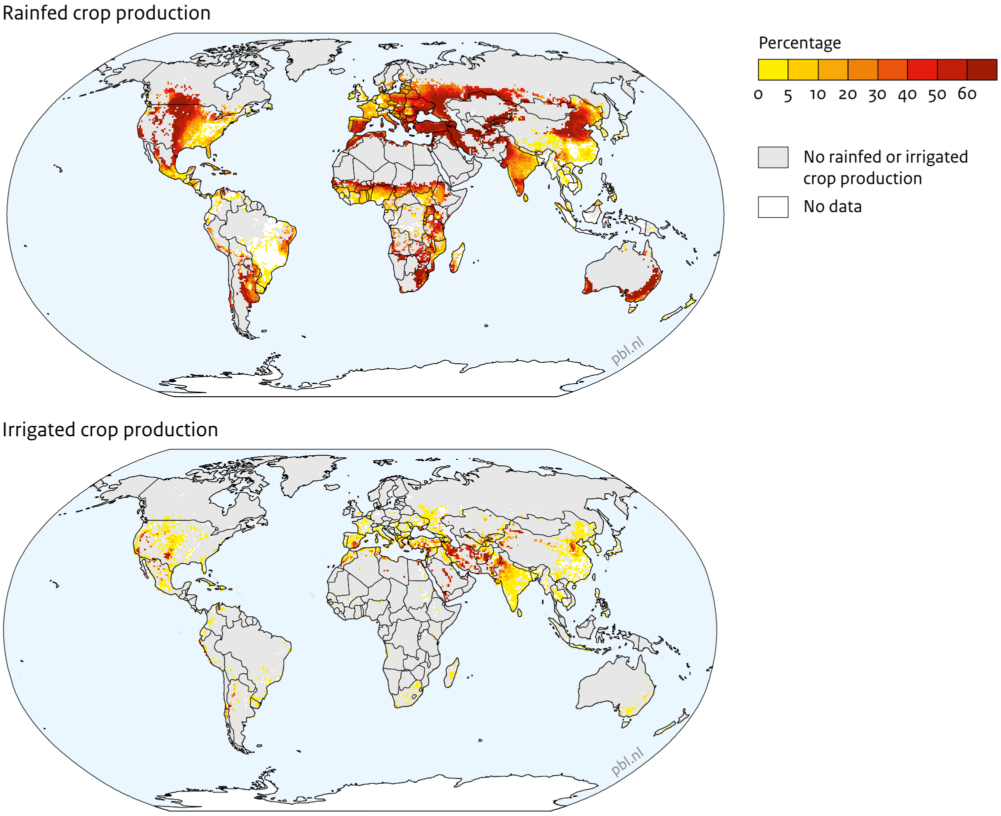
Land availability depends on biophysical suitability, regulation and productivity levels
Future land use does not only depend on the changes in demand, trade and efficiency of production, but also on the availability of land, and the local suitability of land with regard to soil, climate, socio-economic and environmental factors. Overall, the availability of land (i.e. its scarcity or abundance) influences intensification processes and trade, through price signals. The availability of suitable potential agricultural land is estimated in the IMAGE model and determines land supply in the future (Mandryk et al., 2015). Next to the biophysical suitability constraints (slope, wetlands, climate and potential crop yields), protected areas and land-use regulations are taken into account to determine the remaining available land (Figure 3.11). In SSP2, protection levels are assumed to increase consistently with the Aichi targets to a global protected area of 17% of the Earth's total land surface in 2050. SSP1 foresees a significantly greater protection of natural land by expanding officially protected areas and ensuring the inclusion of more natural areas for conservation and recreation in agricultural and urban environments. SSP3 on the other hand, assumes that protected areas will remain at their current level of approximately 14% of the Earth's land surface. Annex 2 provides detailed information on the assumptions made for each scenario.

Most of the highly productive soils are already in use
In SSP2, land for agricultural expansion is still rather abundant in many regions although 9 out of 10 regions have already taken a major share of suitable agricultural land into production. Only in China, South Asia, the Middle East and Northern Africa does current agriculture occupy more than 80% of the land available and suitable for agriculture. It is important to note that *available* does not necessarily mean that the land is not in use and can easily be converted. It may be in use for informal activities, such as hunting and gathering, or for forestry, and it may be important for ecosystem services, which means that conversion would be to the detriment of natural areas and biodiversity. Furthermore, a large share of the remaining available land has low or moderate potential crop productivity, as the highly productive soils are already being exploited. On the other hand, a large share of suitable agricultural land is currently in use as pasture and part of this could be converted to cropland if livestock systems become more intensive.

3.4.4 The influence of water on land use and land-use change

Gains in agricultural output can be achieved by increasing irrigation and improving rainwater management
The suitability of land for agriculture depends on the availability of water from rainfall and irrigation and therefore the water system is strongly interlinked with human land use and the food sector. Irrigated agriculture only accounts for a small share, about 17%, of cropland worldwide, but it provides a substantial share of global crop production, about 40%. Globally, most rain-fed agriculture delivers lower yields due to water deficits, and irrigated areas also show a certain level of shortfall (Figure 3.12). Irrigated areas in the Middle East, the western United States, southern Europe and parts of South Asia, Africa and China are not attaining their full potential yields due to water shortages. Nevertheless, improved rainwater management can contribute

Figure 3.12
Reduction in crop production caused by local water shortages, 2010



Source: PBL/IMAGE

substantially to increasing agricultural output (Jägermeyr et al., 2016) while reducing the amount of cropland needed to meet the required crop production.

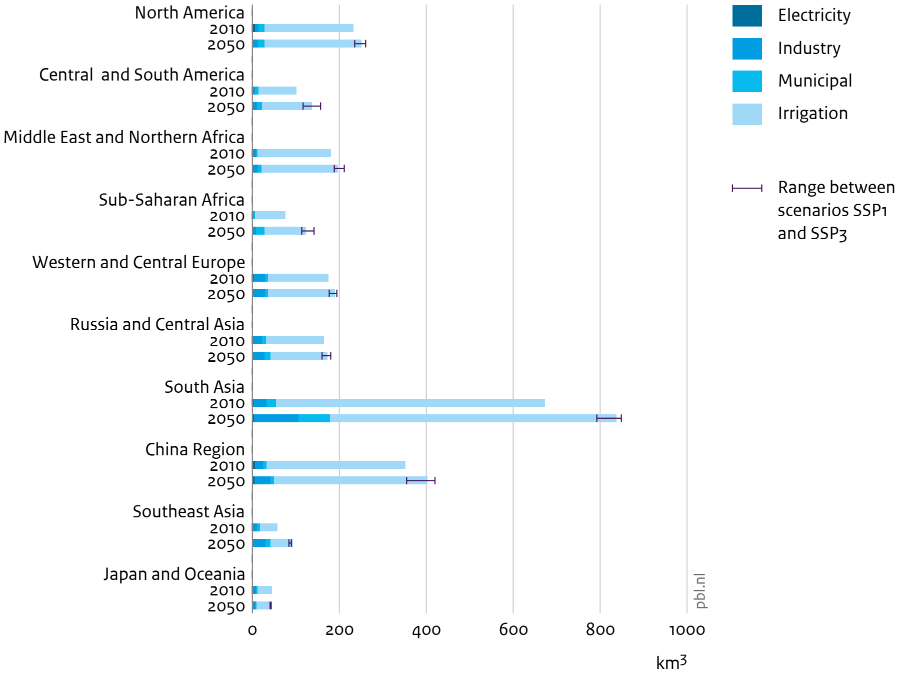
Areas under irrigation and irrigation efficiency are projected to increase in the future

Both the extent of irrigated areas and the efficiency of water use in irrigation are projected to increase in the future. In irrigated agriculture, the demand for water will grow proportionally less than the total production area because the related technology is becoming more efficient and more and more widespread, particularly in those regions where the practice of irrigation is expanding. In SSP2, projections for irrigated areas are taken from the FAO *Agricultural Outlook towards 2050* (Alexandratos and Bruinsma, 2012) and improvement in irrigation efficiency is introduced as a gradual reduction in water losses – the difference between water withdrawal and actual water consumption (for details see Doelman et al., under review). In SSP1, the expansion of irrigated areas is assumed to be lower than in SSP2 in all regions because of increased concern about unsustainable water and energy use by irrigation agriculture, but also because of improved irrigation efficiency. In contrast, SSP3 assumes a more substantial expansion of irrigated areas than SSP2, as a result of high population growth combined with easing environmental concern and stagnation in efforts to improve irrigation efficiency.

Agriculture takes the largest share of global water use, with some regions relying heavily on non-renewable sources

Currently, agriculture claims the largest share of global water use, but thanks to efficiency improvements in several regions, the increase in demand is smaller than in other sectors (Figure 3.13). To meet the water demand, water is abstracted from surface waters and from groundwater. Depending on the source, the abstracted water is categorised into renewable and non-renewable stocks. When withdrawals from renewable groundwater exceed the recharge, natural flows are disrupted, threatening water security for agriculture and natural systems.
As water resources for irrigation are limited, some areas derive substantial amounts of irrigation water from non-renewable aquifers which are not recharged. Such

Figure 3.13
Regional water demand, under the SSP2 scenario



Source: UU/PBL

unsustainable use also occurs when other groundwater sources are used at higher rates than they are recharged. Areas where water resources are overexploited run a risk of future water shortages and consequently declining yields (Box 3.2). Climate change adds to the complex dynamics of the land–water nexus, through changing temperature and precipitation patterns, and with plants increasing their water use efficiency under elevated levels of CO_2.

3.4.5 Demand for timber and forest products

The demand for wood and wood-related products is expected to increase
An often-underestimated factor in the demand for land is the provision of wood and wood-related products. The demand for timber has risen steadily over the past decades and the SSP2 baseline scenario projects a further increase of 35%, though for the demand for wood as a traditional biofuel it foresees a decrease (Figure 3.16). Large amounts of timber are used in construction and for furniture, but a substantial share is also used in the paper industry and for fuelwood for cooking and heating, mostly in countries where access to modern energy is limited. Firewood can be used directly but it is often converted to charcoal first, a practice that often takes advantage of residual wood from logging activities.

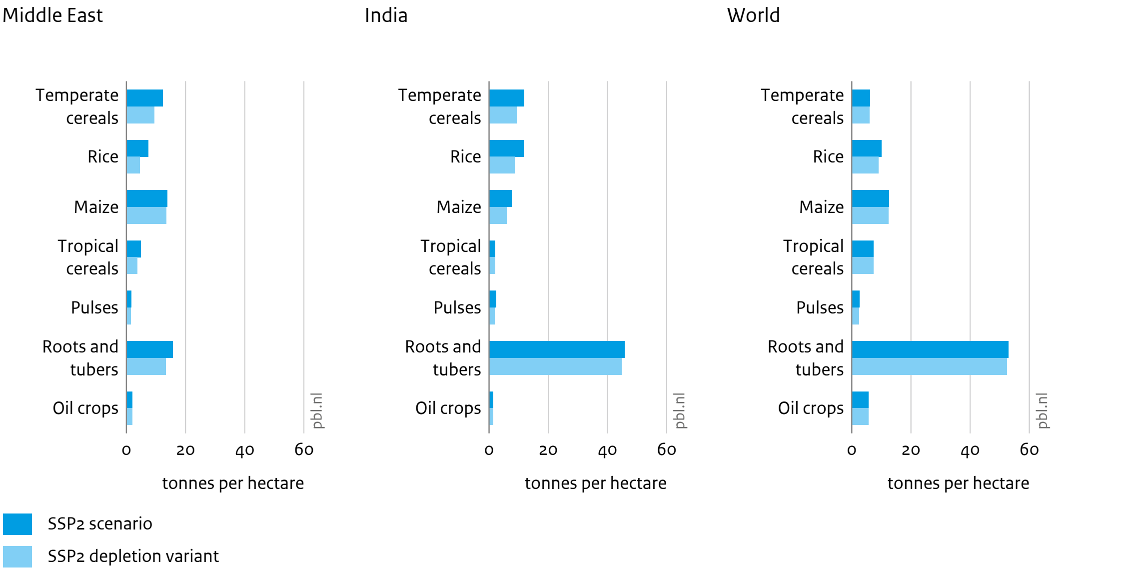
The scenarios might be underestimating the demand for fuelwood from forestry. The use of fuelwood is around 49% of the total global wood use (FAO, 2015), with an unknown proportion attributed to informal collection. This study assumes that about 50% of the traditional fuelwood comes from informal sources (e.g. collection along roads or in gardens) which does not add to the demand from forest management. The past decades have also seen a strong increase in the demand for wood pellets in response to bio-energy use targets in Europe (FAO, 2014). Most wood products are used domestically and a large proportion of that consumption is not included in official statistics. A modest share of wood products is internationally traded (UNECE, 2014) with increases seen especially in the trade of industrialising countries, such as Vietnam and China (Hudson et al., 2013).

The area needed for timber production depends on the forest management system
To fulfil the demand for timber, slightly under a third of the world's 40 million km² of forests is designated as production forest (FAO, 2016). However, the exact use and production intensity are difficult to estimate and model due to a lack of sufficient detailed and historical forest use data. Various management systems are employed for timber harvesting, depending, for instance, on the wood species available, market demands, and

Box 3.2: Water for irrigation and aquifer depletion

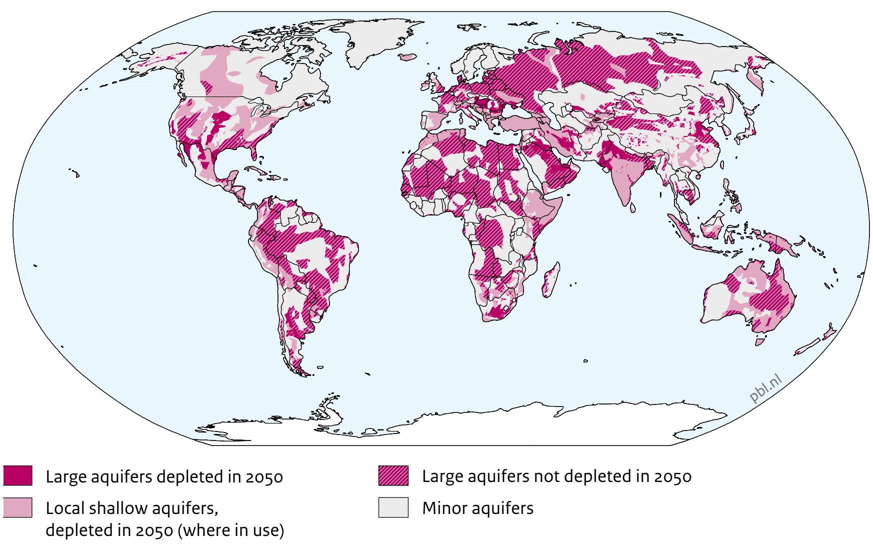
While worldwide only about 17% of agricultural land is irrigated, these areas provide about 40% of the global crop production. In some regions, especially arid and semi-arid zones, groundwater is used intensively for irrigation (Famiglietti, 2014; Gleeson et al., 2012; OECD & FAO, 2015; Wada et al., 2010), along with surface water and water stored in reservoirs. There are concerns that part of this groundwater use may not be sustainable in the long run, as extraction rates exceed the natural recharge rates. A recent study carried out with the IMAGE model evaluates in which water basins and regions depletion of aquifers could be a fact by mid-century (Figures 3.14 and 3.15) (OECD, 2017), and what this would mean for global food production. In the Middle East and India, more than 59% of irrigation water is groundwater, and if the aquifers in these regions are depleted, crop yield will drop by up to 20%, requiring additional cropland areas to make up for the decline.

Figure 3.14
Crop yield affected by potential depletion of aquifers, 2060



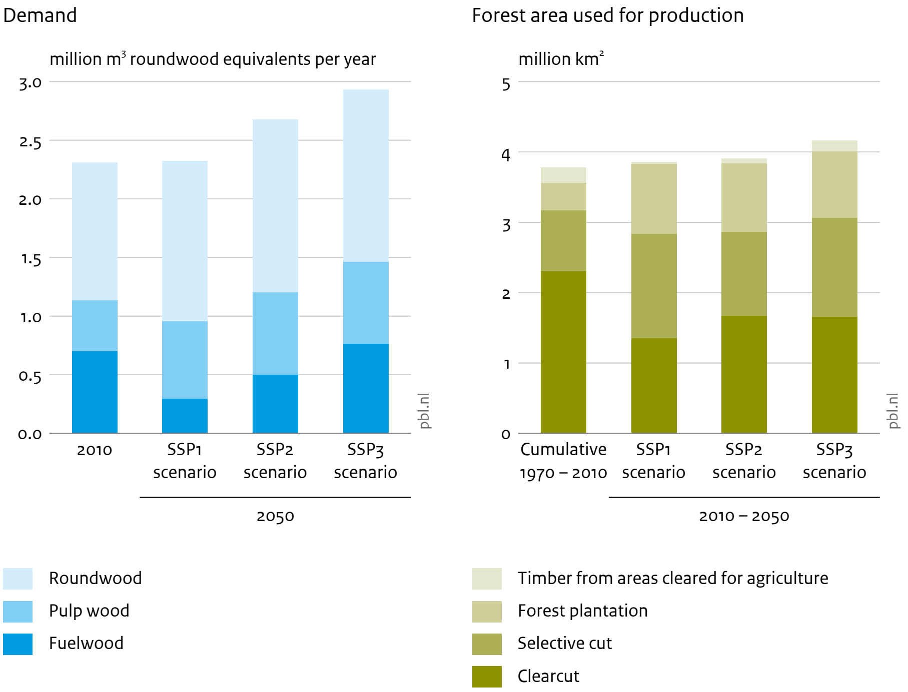
Source: OECD 2017

Figure 3.15
Depletion of aquifers



Source: OECD

Figure 3.16
Global wood demand and production



Source: PBL/IMAGE

For fuelwood, only the contribution from formal forest management is shown, whereas an estimated 50% of fuelwood is assumed to come from informal collection. The graph only shows forest management area harvested for timber, cumulative between 2010 and 2050, not the entire forest area which is under management.

accessibility of an area. Management and production vary considerably (Carle and Holmgren, 2008) but can be grouped into three main systems: clearcutting of forest areas, selective logging of commercially valuable trees only and the use of intensively managed timber plantations. There are large differences in the land areas required for the systems to operate. Plantations are the most efficient and use the smallest land area per produced tonne of wood, but they are usually monocultures and not forests with high levels of biodiversity. Selective logging, in contrast, which has lower productivity levels and causes considerable damage to the remaining forest, is a major driver of forest degradation. Moreover, some timber originates from areas that, subsequently, are converted into agricultural land. The share of timber from this source is also difficult to estimate, due to under-reporting of a practice that is often of an illegal nature. The recent broad availability of remote sensing data shows that deforestation for the benefit of infrastructure and development contributes significantly to forest degradation and a further opening up of forest areas, making them more readily accessible for the informal activities and agriculture which inevitably follow (Kissinger et al., 2012).

In the SSP2 baseline, the area required to fulfil wood demand is projected to grow slightly between 2010 and 2050, with an increasing proportion dedicated to timber plantations (Figure 3.16).

3.4.6 Projections for built-up areas

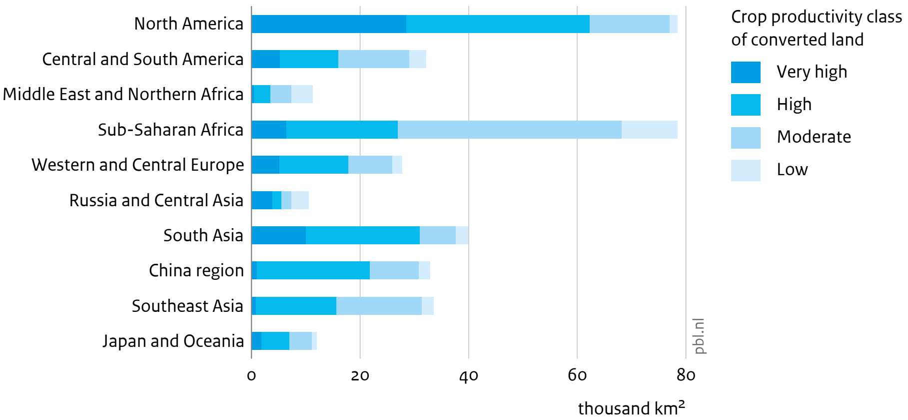
Urbanisation and urban sprawl

The total land surface dedicated to built-up areas is small compared to the amount used for cropland and pasture. However, in some regions, urban areas are expected to grow substantially in the future and, while still being relatively small, will greatly affect agriculture.

Urban expansion is likely to occur on the most fertile agricultural lands

Human settlements have historically developed in the most fertile areas. At present, urban growth is threatening to crowd out fertile agricultural land. In China, more than 70% of new urban development has taken place on previously cultivated land (Hao et al., 2011). Urban expansion is mainly taking place in peri-urban areas, slowly fragmenting and taking over agricultural landscapes. As a result, agriculture is displaced to other,

Figure 3.17
Regional expansion of built-up areas on land suitable for agriculture, under the SSP2 scenario, 2010 – 2050



Source: PBL/IMAGE

sometimes less productive locations. The *Middle of the Road* scenario projects built-up areas to increase by 0.5 million km² with the largest increases driven by population growth and economic development in North America, Sub-Saharan Africa and Asia. Much of this expansion is expected to occur on highly productive agricultural areas (Figure 3.17), triggering displacement of agriculture to less productive regions, and the subsequent requirement for larger cropland areas. This finding is, along general lines, consistent with other literature, but the process is complex, and other sources project the largest cases of urban expansion to occur in other regions, such as China (d'Amour et al., 2016).

3.4.7 The impacts of climate change and climate change mitigation on land use

Neither climate change impacts nor climate change mitigation are integral parts of the SSP baseline scenarios, but it is generally accepted that both will increase the demand for land.

The impacts of climate change on land use

Climate change alone could lead to the need for additional cropland since it is likely to lead to a decrease in average yields and to negatively affect suitable agricultural land in some regions, influencing trade patterns, expansion of agricultural areas, food prices and food production and consumption. The uncertainty about the range of impacts on agriculture is considerable, both in terms of the effects on crop yields and in terms of the required adjustment processes in local and global agricultural systems (Nelson et al., 2014). Impacts differ widely between regions: while some temperate regions are likely to benefit from higher temperatures and longer growing periods, others, such as Sub-Saharan Africa and South Asia, are expected to see yield declines due to increased water shortages from changes in precipitation patterns and – even more importantly – extremely high temperatures. Higher productivity due to additional CO_2 fertilisation of plants may compensate for some of the adverse effects but it is still unclear to what extent these benefits can be realised in practice. At the global level, yields are projected to be about 10% lower, by 2050, compared to SSP2; which, in turn, would result in about 10% increase in the demand for cropland and a few percentage points decline in production (JRC, 2017) (Box 3.3). On a regional level, however, the range is much more diverse and the negative effects can be limited through trade.

The impacts of climate change mitigation

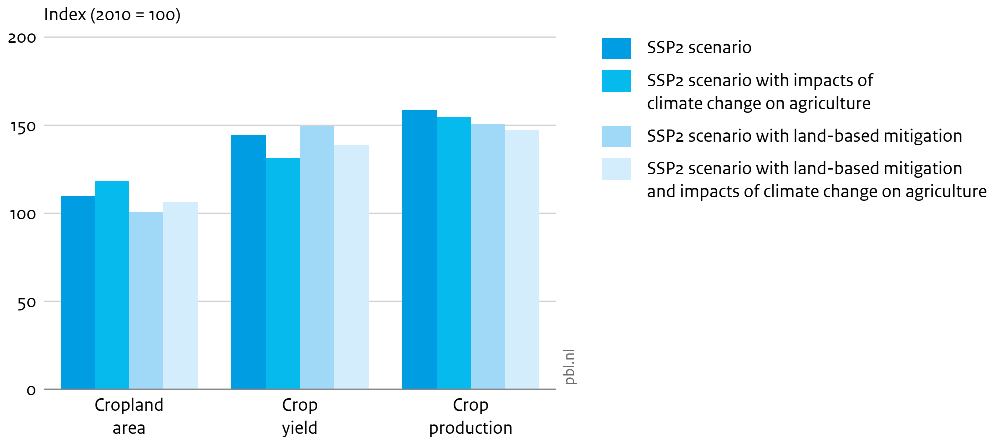
In most projections of climate policies, the ambition to keep the global temperature rise below 2°C relies on a substantial contribution from land-based mitigation in the form of bio-energy in combination with carbon capture and storage (BECCS), and on afforestation, which are practically the only options to achieve negative emissions. Both options require land, with bio-energy occupying about 3 million km² in 2050, under an SSP2 2 °C scenario (Box 3.3). Because of a 'food first' assumption in the modelling, and to avoid emissions from deforestation, the three SSP scenarios assume that the expansion of bio-energy production is achieved by establishing plantations on non-agricultural, non-forest land. In addition to afforestation, REDD programmes require the conservation of forests and natural lands. Climate change affects biodiversity and the living conditions of species, meaning they require larger and better-connected natural areas to be able to cope with the changes to their habitats.

Box 3.3: The impacts of climate change and land-based mitigation on agriculture
The implementation of the SSP2 scenario in various integrated assessment models, including IMAGE, is designed for the purposes of experimenting without taking into account the impacts of climate change on agriculture. If climate change impacts were factored in into land-use patterns, then it would not be possible to make a correct assessment of the combined effects of land-use change and climate change based on SSP results in a dedicated impact model, e.g. for biodiversity and water. However, both climate change impacts and land-based mitigation efforts (such as bio-energy, REDD – reduction of emissions from deforestation and forest degradation, afforestation) will probably have a dramatic impact on land use.

This box shows a variant of the SSP2 scenario, which includes the impacts of climate change on agriculture along with the effects of climate change mitigation efforts on cropland (adopted from JRC, 2017). Land-based mitigation, under this scenario, is assumed to be in competition for land with food and feed production. At the global level, in 2050, yields are projected to be about 10% lower than they would have been without climate change, on average, according to modelling results (JRC, 2017), though some temperate regions are expected to see increasing yields due to higher temperatures and longer growing seasons. The results also show that in general, a decline in yields will probably lead to a proportionately larger expansion of cropland area and also to a small reduction in crop production. Agriculture in regions such as South Asia and Sub-Saharan Africa is most negatively affected by climate change, which can partly be compensated for by increased trade.
These results may be an underestimation of the potential climate change impacts, as most crop models used to calculate the yield changes, only take into account a limited number of relevant processes and mostly ignore weather variability and heat stress, and do not provide a detailed representation of sensitive stages of plant development.

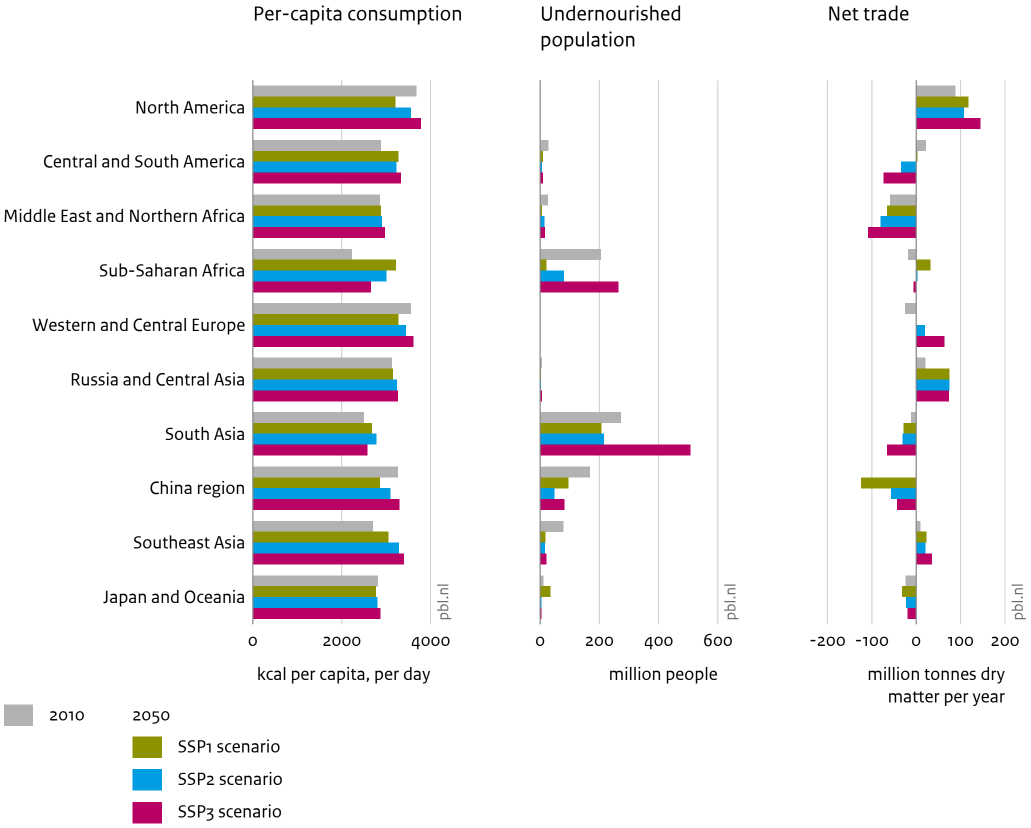
The effect of land-based climate mitigation, which requires additional areas for bio-energy or afforestation, on agricultural production is similar to that of climate change. This variant of SSP2 foresees a decrease in the area for food and feed crops due to the other competing demands and a slight increase in crop yields due to higher prices.

Figure 3.18
Impacts of climate change and land-based mitigation on agriculture, 2050



Source: PBL/IMAGE

Figure 3.19
Food security



Source: PBL/IMAGE

3.5 Implications for food security and environmental sustainable development goals

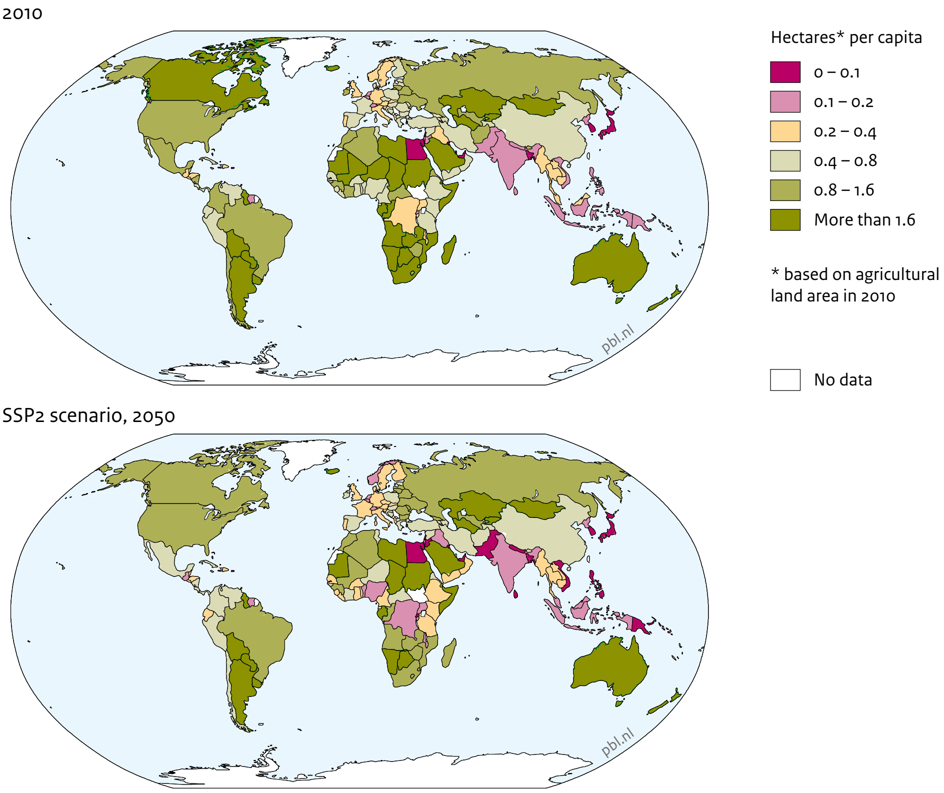
The previous sections have discussed the projections of the extent of future land use along with the underlying drivers. These changes in the land system have important implications for a range of sustainable development issues. Chapter 2 puts forward the central role of land for sustainable development goals. Here, some implications are highlighted of the dynamics in the scenarios with regard to land-related SDGs. As the scenarios are explorative, they are not specifically designed to meet the SDGs. Rather, the scenarios show the various futures under which the SDGs might have to be attained. A more challenging future, such as that described in SSP3, will, for instance, make it more difficult for goals to be reached. The scenarios can also be used to explore the extent to which land-related SDG ambitions are likely to be met in various future contexts, and where additional efforts would most likely be required given the expected developments. Fulfilling the SDGs might lead to additional claims on land use beyond what is assumed in the scenarios. For instance, halting biodiversity loss is an issue that virtually requires a complete stop to further land conversion and forest loss.

3.5.1 The implications for food security

While food security is improving, it remains insufficient to meet sustainable development goals
A wide range of indicators has been proposed to assess the complex issue of food security[1]. Figure 3.19 presents scenario results on consumption per capita, the number of people undernourished, net trade (import dependence) and cropland per capita as proxies that give an idea of how the components of food security are projected to develop under the three scenarios.

Most regions are projected to continue in their roles as net importers or net exporters. This is particularly the case in Sub-Saharan Africa, which has been a net importer of food since 2010 and for which, given the considerable changes in demand, an increase in imports is foreseen, which is more marked under SSP3 than under

Figure 3.20
Agricultural land per capita



Source: PBL/IMAGE

The cropland area in 2010 is assumed constant up to 2050, in order to show the effect on cropland, per capita, if biodiversity and climate mitigation concerns would halt cropland expansion.

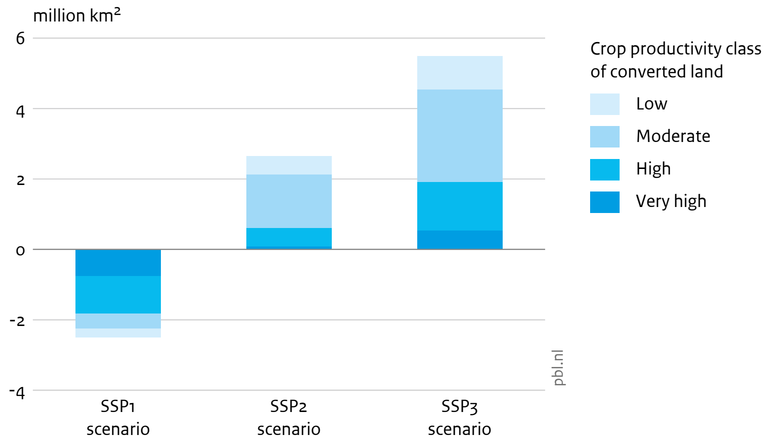
SSP2. Only Latin America shows a picture of substantial change, as it is currently an exporting region, but projected to become a net importer. Of the three scenarios, SSP3 projects the largest increases in average food prices in almost all regions, especially in regions which already suffer low levels of food security, such as Sub-Saharan Africa and South Asia. For food security, the availability of land for food production per capita is a relevant parameter, with various sources suggesting that at least 0.5 ha per capita are needed (Lal et al., 1989), and that values of less than 0.3 or less than 0.15 ha per capita indicate high or very high pressure on land (Wiebe, 2003). Figure 3.20 shows the total area of agricultural land per capita for 2010 and the projection for 2050 (accounting for population increase, not for increase in cropland). While agricultural expansion might lead to an increase of cropland area, the ambition to reduce biodiversity loss, and limit climate change requires stabilisation of the current extent of agricultural areas. Assuming such stabilisation is actually achieved, the amount of agricultural area per capita will decrease further in several African and Asian countries, due to population growth (Figure 3.20).

3.5.2 The implications for the use of marginal lands

Agricultural expansion increasingly takes place on low and moderately productive soils
As a consequence of the land-use dynamics described above, the loss of natural areas is expected to continue under SSP2, and even more markedly under SSP3. Under SSP1, however, the loss is substantially lower. The remaining land available for agricultural expansion is becoming limited and expansion increasingly takes place on more marginal lands (Figure 3.21). With much of the land that is suitable for agriculture already in use, either for crops, livestock, or urban areas and infrastructure, additional land for agriculture has to be found in areas that are less productive. Using less productive land obviously requires a larger area to achieve the same level of production, and also partially drives the intensification of production on existing land as described in Section 3.4.2. Moreover, marginal lands are often more difficult to manage as they include, for instance, sloped terrain, fields with thinner layers of topsoil, areas that are more

Figure 3.21

Change in agricultural area, per scenario, 2010 – 2050



Source: PBL/IMAGE

difficult to plough, contain fewer nutrients, have limited water supply or have adverse climate conditions. Farmers therefore need to devote more effort and provide more inputs on top of working under conditions that are less favourable than elsewhere.

As has been shown, two out of the three scenarios project an increase in agricultural land use. SSP3 projections that approximately 50% of the expansion is to take place on lands with low or moderate productivity, and SSP2 puts the estimate even higher, at 80%. In contrast, SSP1 projects the precise opposite, seeing mostly highly to very highly productive lands being abandoned. In this scenario, agricultural activity is discontinued due to lower demands, especially in European and Russian regions, which have a large proportion of the world's more fertile lands. Therefore, from a perspective of globally efficient use of land, more trade in land products would help allocate production to those regions best suited to it. However, there are many other concerns beyond globally efficient land use, such as political aims for domestic self-sufficiency, agricultural livelihoods and employment in the agricultural sector.

Tropical and subtropical soils are vulnerable to erosion and land degradation

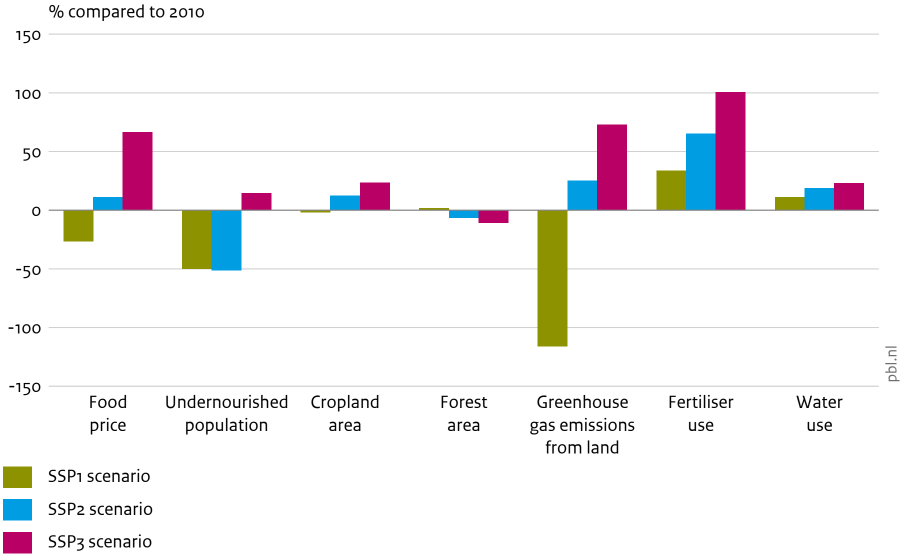
Projections show a significant expansion onto tropical soils that are vulnerable to erosion and land degradation if not managed sustainably. All scenarios, especially the baseline and SSP3, show that a significant share of the additional land conversion will take place in tropical forest systems (Figures 3.3 and 3.4). Tropical forest soils are generally weathered, with year-round rains having leached out most nutrients from the topsoil.
The vegetation is sustained in a closed cycle in which almost all nutrients are found in the layer of decaying organic matter on the forest floor instead of in the soil.
A recent study shows that the tropical climate zone has the highest rainfall erosivity, it being almost double that of the humid temperate zone and four times higher than that of the Mediterranean zone (Panagos et al., 2017). Given the marked increase in demand from Sub-Saharan Africa, even under the baseline assumptions of a tripling of its agricultural productivity, the largest agricultural expansion is projected to occur in the Congo basin. However, without appropriate soil management and conservation systems in place, clearing these lands for agriculture entails the risk of diminishing yields after a few years of exposure to water erosion and the ensuing lack of nutrients.

3.5.3 The implications for land-related Sustainable Development Goals

The trade-offs between various sustainable development ambitions in the scenarios

The key ambitions for the sustainable development goals (SDGs) focus on providing food and water security for all, while halting biodiversity loss and limiting climate change to safe levels. The three scenarios present alternative futures within which these goals might have to be attained. It is clear that this is much easier under the SSP1 scenario than under the SSP3 scenario. In short, the fulfilment of sustainability ambitions and the additional effort required depend greatly on future developments in populations, incomes, trade patterns, the spread of technology, and individual motivations and behaviour patterns, which include for instance, dietary preferences, the desire to conserve nature, and attitudes towards globalisation and international cooperation.

Figure 3.22
Changes in variables as indicators of SDG achievement, per scenario, 2010 – 2050



Source: PBL/IMAGE

To give an idea of the order of magnitude of the differences in the challenges facing the land-related sustainability ambitions under the three scenarios, Figure 3.22 presents projections for a number of indicators related to these ambitions:

- *Food security (SDG 1 'Zero hunger'): food prices and undernourishment*
- *Biodiversity (SDG 15 'Life on land'): cropland expansion and forest areas*
- *Climate change (SDG 13 'Climate action'): Greenhouse gas emissions from land-use change*
- *Water (SDG 6 'Clean water and sanitation' and SDG 14 'Life below water'): Water consumption and fertiliser use*

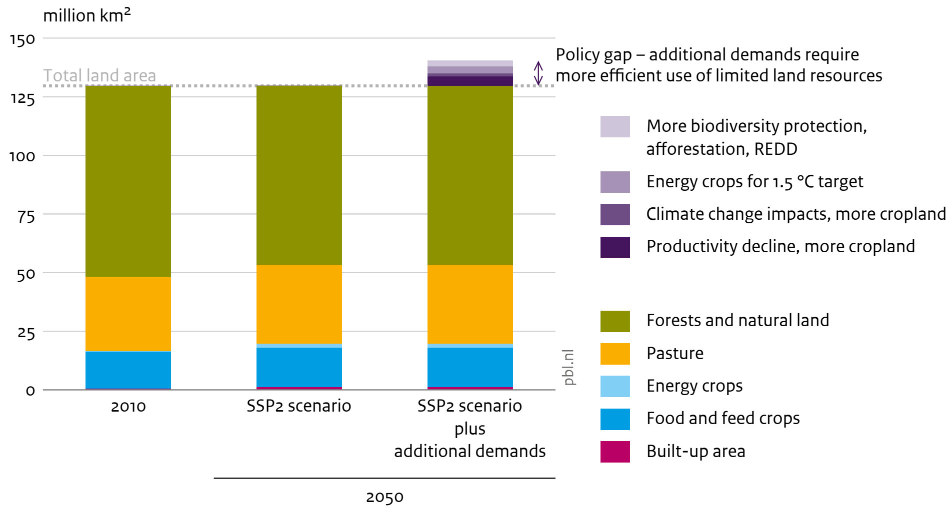
There are multiple connections between these SDG's and land-use dynamics, and some indicators in fact relate to several SDG's. For example, fertiliser use affects both water quality and agricultural greenhouse gas emissions. While the world fares worst in all categories under SSP3, SSP2 shows trade-offs between food and environmental aspects in some regions. Per capita food consumption is an indicator that is problematic to interpret at the global level, because in SSP1 it is also influenced by falling levels of meat consumption in developed countries and in SSP3 by high levels of meat consumption. Therefore, this study uses the level of undernourishment as an indicator for food security.

3.5.4 The question of whether and where land scarcity is increasing

Whether increasing land scarcity is problematic depends on the effects it produces, which may differ between regions
In all three scenarios, the demand for agricultural products and the related demand for land cannot exceed the availability of suitable agricultural area, as internal dynamics – in the models and in the real world – do not allow more land to be used than is available. However, when substantial proportions of the available land are given over to agriculture due to increasing demands for land-based products, the resulting situation can be described as a condition of increased scarcity, which is mostly reflected in higher prices of land and land-based products. These increased prices will lead to adjustments to consumption and trade patterns, can trigger further intensification of agriculture if the farmers have the means to do so, and put downward pressure on the demand.
If much of the fertile land is already in use, this often means that the intensity of human activity will increase further, leading to additional environmental pressures and loss of biodiversity in existing agricultural areas.

Whether this involves a higher risk of land degradation remains to be seen, as higher prices make investments in

Figure 3.23
Competing land claims



Source: PBL/IMAGE

land more attractive but also encourage the exploitation of water resources, eventual intensive unsustainable use of soils, and the development of land that may be more prone to erosion, such as fields on slopes.

Scarcity is not a problem in itself. It can even trigger more efficient use of the land, and is reflected in increasing land prices. In recent years, land acquisition practices indicate that land is already a scarce resource in some regions. For example, land scarcity in China has recently prompted acquisitions in Africa, which are often flagged as *land grabbing*. Another indicator is the fact that these investments are becoming financially attractive, either due to expected price rises in the future (speculation), the current low costs of capital, or the ready access investors have to technology and capital, which enables them to boost productivity to make the investment profitable.

A policy gap to accommodate all future demands for land
Land scarcity can become more acute due to higher demands from economic activities (e.g. for food and feed production, for urban areas, or bio-energy production), or due to a decrease in available land after substantial amounts have been set aside for biodiversity protection and conservation of carbon stocks, or to compensate for the loss of fertile land as a result of land degradation or climate change. Here, the outcome of the SSP2 scenario is combined with additional claims that are not covered in the default model setup. Next to the demands explicitly modelled in the scenario (food, feed, fibre and fuel), additional claims will arise for biodiversity protection and climate mitigation, to offset climate change impacts and to compensate for soil degradation. To calculate these additional demands, the study assumes that no further loss of biodiversity and thus no further loss of natural areas occurs after 2030, and factors in the impacts of climate change mitigation and land-based climate mitigation from Box 3.3, and the additional demand for agricultural land due to continued decline in soil productivity from Chapter 4.

As a result of these additional claims, the demand for land will outweigh the amount of land available (Figure 3.23), creating a policy gap, and indicating that interventions will be necessary to accommodate all demands on the limited land resource. Some regions will find themselves under high pressure in the default SSP2 scenario, due to rising food prices and growing net food import levels (Figure 3.22). In such situations, the additional demand to cover certain matters, such as energy crops or nature conservation, or the loss of fertile land to soil degradation, will make land shortages more critical, thereby further increasing food prices, unless appropriate measures are taken.

3.6 Conclusions and uncertainties

The demand for land will increase in the future and there will be trade-offs and synergies between sustainable development issues
Claims on land are likely to grow in the future and competition – and possibly conflicts – between these claims will become more intense. The regions where this

is most likely to occur are Sub-Saharan Africa, the Middle East, Northern Africa and Asia. Several aspects of the sustainable development goals are related to land, and there is a clear range of trade-offs, such as competition between the demand for food products, nature conservation, bio-energy production and afforestation to promote climate change mitigation. Achieving several sustainability goals at the same time will require considerable effort, but many synergistic alternatives, or win-win options, exist to promote steps in this direction. The global trends reflected in the storylines strongly affect the effort required to achieve food security, nature conservation and climate targets.

Among all regions, Sub-Saharan Africa is, quite obviously, the region which will be facing the most daunting land-related challenges in the coming decades. Population growth and the related increase in the demand for land will exert intense pressure on further expansion of agricultural areas. Moreover, vast areas in the region are drylands and tropical forests, which are particularly vulnerable to land degradation when brought under intensive use.

Uncertainties in land-use projections arise from socio-economic development and the characteristics of the employed models

The three scenarios and the various demands for land show that future land use may develop along widely differing paths. Explorative scenarios help to quantify part of this uncertainty, provide a range of contexts within which future changes might take place and establish the extent to which the changes depend on future socio-economic developments.

An important source of uncertainty in projecting future land use, besides socio-economic drivers, is the dynamics and the parameters of the assessment models. Five integrated assessment models (Popp et al., 2017), have been used to quantify the recently published SSP scenarios and the results show there is a wide range of model-related uncertainty. One of the employed assessment models is IMAGE and its findings fall well within the overall range of projections. Key uncertainties across the models are the level of future agricultural intensification (in crops and particularly in livestock farming), and the dynamics of trade (Popp et al., 2017). Timber demand is also an important driver of global land-use change, but currently wood demand, trade and production are not included at all in most models or only marginally.

Several drivers and feedback loops are not covered in current global land-use scenarios

In addition to the uncertainties described above, the scenarios employed in this study and the SSPs implemented by other models do not take into account a number of drivers, processes and feedback loops, which further widens the spectrum of possible outcomes. Matters that are not yet being considered include the effects of climate change on agriculture, degradation processes in land and soils and new societal ambitions to protect biodiversity or limit climate change. All these factors will further increase the demand for land and eventually contribute to land scarcity.

The study uses dedicated sensitivity analyses to explore the possible effects of some of the uncertainties. These are highlighted in Box 3.1, Box 3.2 and Box 3.3 and provide estimates on increases in agricultural efficiency, water depletion, and the impact of climate change and land-based mitigation.

The degradation of land and soil is a key process affecting future land system dynamics but its sphere of influence is not fully understood. The reduction of crop yields on agricultural land as a result of unsustainable use and degradation, and, possibly, the loss of these lands for agricultural production will cause an additional demand for agricultural land elsewhere. None of the global integrated assessment models currently include land degradation in their scenarios. The effect of future land degradation is explored in Chapter 4, as a variation on the standard SSP2 scenario presented in this chapter.

Notes

1 See for example FAO, http://www.fao.org/economic/ess/ess-fs/ess-fadata/en/#.WDDO_k3fMug.

FOUR

Future changes in the condition of land and ecosystem services

4.1 Changes in land condition and ecosystem functions

Concern about the global effects of land degradation is warranted
Global estimates identify a significant share of terrestrial area as degraded or degrading land. Severe forms of land degradation can, on a human timescale, irreversibly reduce the potential of land to provide certain services. Furthermore, land degradation occurs in all regions, can entail high economic costs (ELD, 2015), and often disproportionally affects poor landholders, contributing to poverty traps and food insecurity. Several international conventions and agreements have therefore set targets or ambitions to reduce land degradation and restore degraded lands:

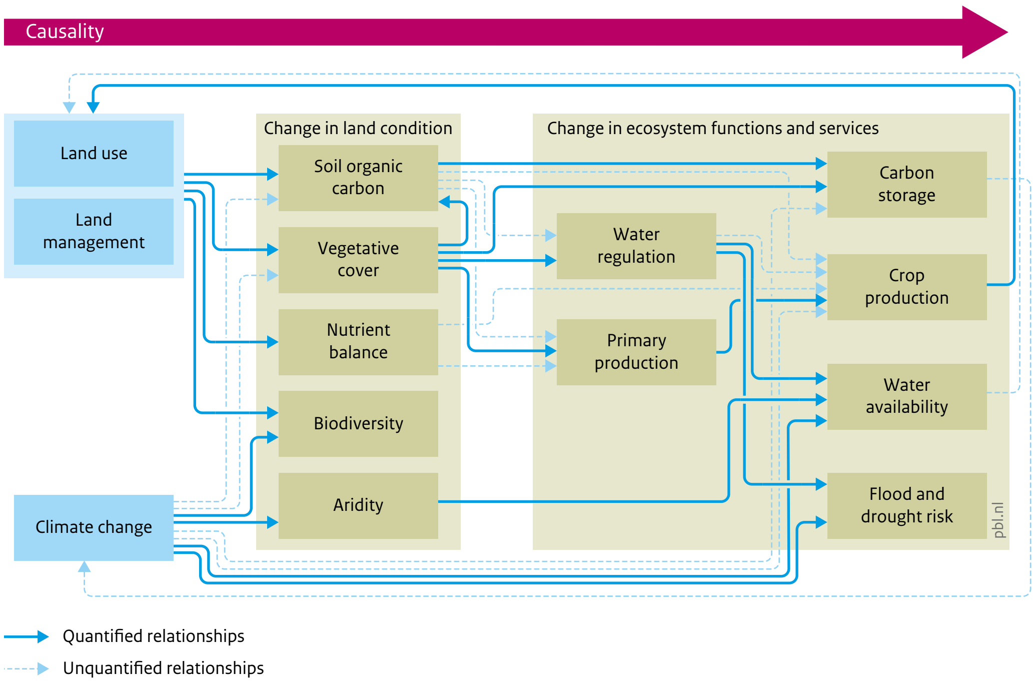
- In 2010, the UN Convention on Biological Diversity (CBD) adopted the Aichi target 15: 'By 2020, ecosystem resilience and the contribution of biodiversity to carbon stocks has been enhanced, through conservation and restoration, including restoration of at least 15 per cent of degraded ecosystems, thereby contributing to climate change mitigation and adaptation and to combating desertification.'
- In 2015, the UN Convention to Combat Desertification (UNCCD) agreed to support the Land Degradation Neutrality target and develop national plans towards this goal.
- Most recently, goal 15 of the UN Sustainable Development Goals aims to sustainably manage forests, combat desertification, and halt and reverse land degradation, and halt biodiversity loss.

Indicators for the SDG target on land degradation
Progress towards the SDG 15 target on reducing the degradation of land and soils is indicated by the *proportion of land that is degraded globally*. More specific indicators are under discussion, most prominently *land cover, land productivity, and soil organic carbon* (UNCCD, 2016). To assess the need for policy measures and cooperation at the global level, it is imperative to have an understanding of the current state of, and expected future changes in these indicators. This chapter therefore presents current and future estimates for these indicators, and provides several important additions.

The extent of future impacts of land degradation is unknown in global assessments
Land degradation and its consequences are typically not explicitly taken into account in global assessments that explore future environmental change. Especially when it comes to agriculture, there is much uncertainty about the degree to which unsustainable practices degrade soils in the long term. The question is to what extent land degradation will compromise agriculture, water availability and flows, and other ecosystem functions over the longer term future.

Assessing change in land condition and ecosystem functions instead of land degradation
As outlined in Box 2.2 in Chapter 2, this report does not directly quantify 'land degradation'. Instead, it assesses changes in land condition and ecosystem functions relative to the natural or undisturbed state to determine human impact. Land condition includes soils, land cover (i.e. vegetation) and biodiversity. Land condition can change as a consequence of land-use change (conversion from one use to another), land management (more intensive or extensive land management systems), climate change and natural processes. Land condition can be expressed in indicators such as soil organic carbon, soil depth, soil nutrient balance, vegetation cover, biodiversity, and aridity (Figure 4.1). The extent to which changes in these indicators qualify as land degradation is not assessed in this report given the differences among definitions and the subjectivity of the term itself. Instead, changes in land condition and related ecosystem functions and services are estimated and expressed in a number of quantitative indicators, which makes it possible to identify the trade-offs that result from human transformation of landscapes which are key to present-day sustainability challenges.

Figure 4.1
Effects from change in land use, land management and climate on land condition and ecosystem services



Source: PBL

Land condition determines the potential of land to provide people with various types of services. Land condition has changed in many areas across the globe, in part due to the intentional conversion of ecosystems to boost certain services, such as food and fibre production, and in part due to 'unnecessary' degradation from poor management practices or indirect human causes (FAO, 2011).

Figure 4.1 shows the relationships that are quantified in this chapter and for which future projections to 2050 are presented, as well as those that are not quantified any further here. There are many more functions and services than those presented here, with model and scale constraints limiting their inclusion. The connections quantified in this study are indicated by straight lines, with the dotted lines representing connections that are not quantitatively included in the projections. Annex 3 presents the methodology behind the results presented in this chapter.

Two scenarios to assess future land condition and ecosystem functions

The projections in this chapter are based on two scenarios:

1. *SSP2 scenario* [1]
   This scenario is described in the previous chapter. This chapter assesses for the SSP2 scenario the impacts of changes in land use and climate on land condition and ecosystem functions. In this scenario, climate change is assumed to correspond to a global average temperature increase of 2.3°C by 2050, but the results do not include the effects of climate change on agriculture (same as in Chapter 3, see also box 3.1).
2. *SSP2 productivity decline scenario*
   This is a variant of the SSP2 scenario which also takes into account the impact of a persistent decline in the production of biomass caused by land management and the ensuing impacts on land condition.

The second scenario is a variant of the SSP2 scenario, designed to explore the impacts on land condition from poor land management. These impacts are derived from the ongoing decline in net primary production (NPP) as observed with remote sensing techniques (see Section 4.2.1 for further details).

Section 4.2 first presents net primary production projections for 2050, followed by projections for soil organic carbon, nutrient balances, biodiversity and aridity. Section 4.3 translates these land condition projections to future impacts on the ecosystem functions of carbon storage and climate mitigation, crop production, water scarcity, and low and high river discharges. Section 4.4 discusses the uncertainties of the projections that should be taken heed of, and Section 4.5 presents the main conclusions of this chapter.

4.2 Projected changes in land condition

4.2.1 Satellite-observed trends in net primary production

Biomass productivity as a key indicator of land condition
Net primary production represents an ecosystem's ability to produce biomass from water, carbon dioxide, nutrients and solar energy. Terrestrial net primary production (NPP) represents the total annual growth of biomass on land. Biomass production is the most elementary property of any ecosystem and the basis for life. The current biomass productivity is therefore a key indicator for land condition when expressed relative to productivity in an undisturbed situation or when seen against changes over time.

Many factors may cause the productivity of the land to decline
Various impacts on soils – erosion, nutrient mining, compaction, pollution, and salinisation – can cause a decline in productivity. Changes in productivity can be induced by many other factors as well, including climatic fluctuations, land management, land-use change, disruptive events such as fires and flooding, changes in species compositions and natural processes.

As this study aims to single out the long-term changes to productivity attributable to land management, productivity observations are corrected for the effects of long-term climate change to arrive at a residual which approximates the effects of land management.
Climatic changes can have multiple effects on productivity depending on location. Positive effects on productivity can be expected in more northern latitudes where warming reduces the climate constraints on photovoltaic activity, and enhances the atmospheric fertilisation effect.
Reductions in water availability due to more frequent incidences of drought or changing rainfall patterns can negatively affect productivity. To correct for these climatic changes, the observed trends in productivity over the 1982–2010 period have been adjusted for climate effects (see Annex 3 and Schut et al., 2015).

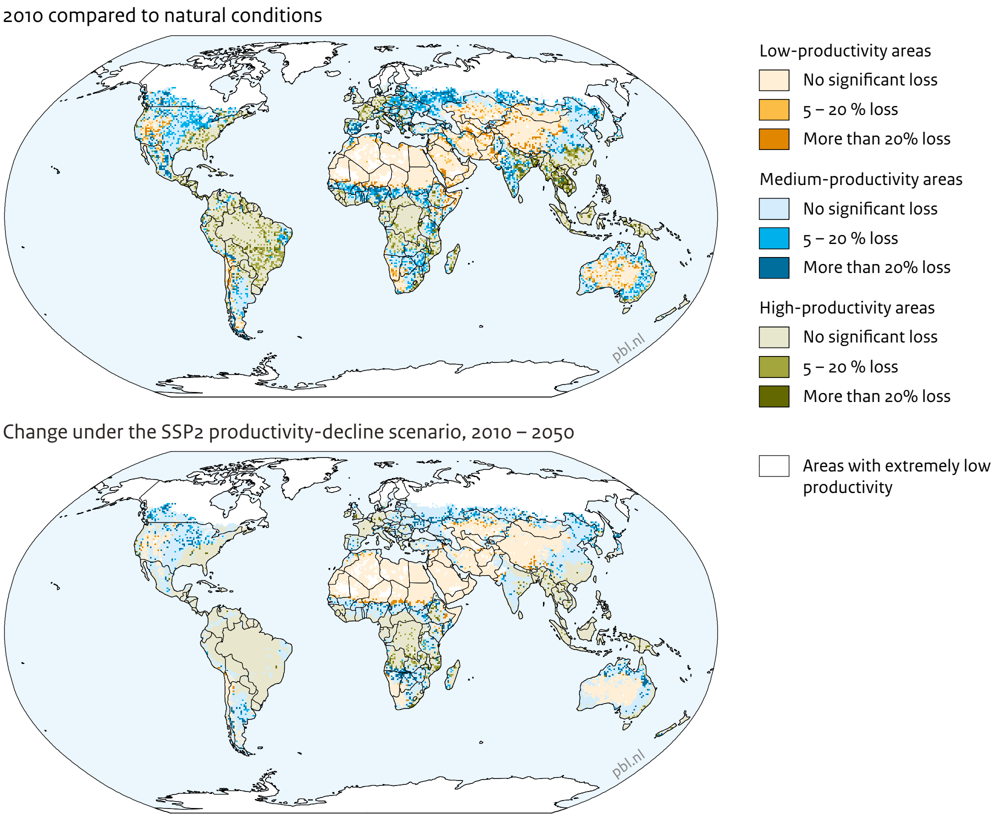
This study uses detailed global satellite data (Normalised Difference Vegetation Index or NDVI) as proxy for photosynthetic activity and biomass productivity.
To determine how human activity has changed biomass productivity up to the present day, current values are compared with NDVI values of an undisturbed situation as reconstructed by Stoorvogel et al. (2017a) and (2017b).
In order to develop the SSP2 productivity decline scenario, the satellite-observed productivity change in a given area over the period from 1982 to 2010 is corrected for the effects of long term climatic change. Negative trends are extrapolated to 2050, based on Schut et al. (2015) and Conijn et al. (2013). It should be noted that this scenario only intends to assess future impacts of land degradation; positive trends were therefore omitted. Annex 3 elaborates on the methodology, including the correction of the observed trends for climatic change.

Nearly a quarter of the global land area shows a productivity which is lower than it would be under undisturbed conditions
Compared to an undisturbed situation, current productivity is estimated to be lower on 28 million km^2 or 23% of the global terrestrial area[2]. The absolute global reduction of net primary production is estimated at 5% of that of the natural state, similar to the value reported by Smith et al. (2016). Of the total terrestrial area found to have reduced productivity, 48% is located in areas of medium natural productivity and 33% in areas with high natural productivity (Figure 4.2).

Of the areas used for cropland, forestry and pasture (excluding extensively used rangelands), some 16 million km^2 or 36%, distributed over all regions, show productivity below that of an undisturbed situation (Figure 4.3). For these cultivated areas, productivity decline is not necessarily an indication that something is wrong, as the conversion of natural systems to managed systems inherently changes the ecosystem composition and land cover. It would become worrisome though, if productivity continued to drop over a longer period of time while the land use remained the same. There are also agricultural areas with productivity above that of the natural situation. Typically, these are irrigated areas which have little vegetation growing under natural conditions and where the supply of irrigation water and fertilisers leads to a significant increase in the vegetative cover and productivity (derived from Stoorvogel et al. 2017a and 2017b). These areas with a higher productivity cover approximately 8.5 million km^2.

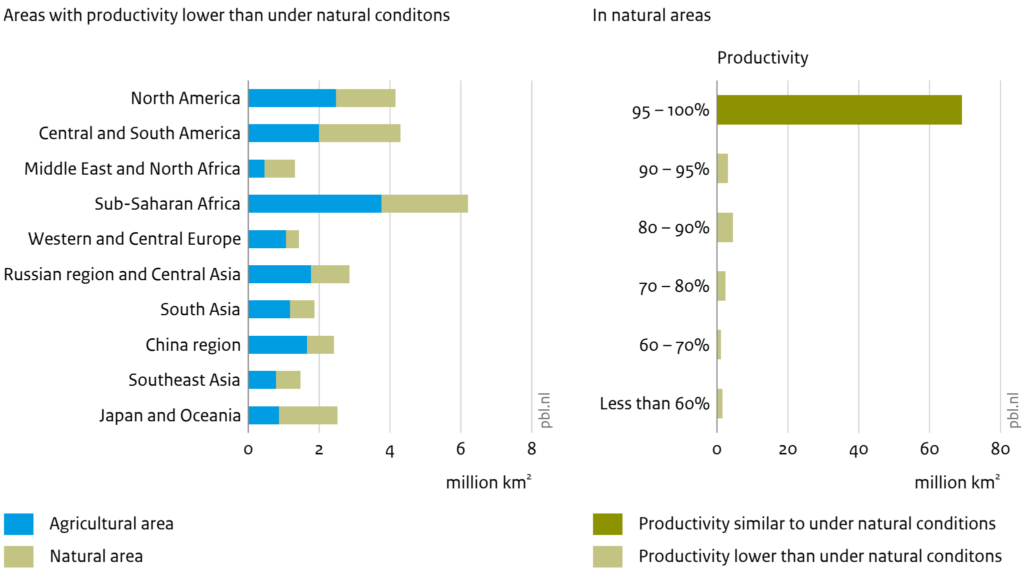
Of the natural areas, an estimated 15% have a level of productivity that is significantly lower than expected in an undisturbed situation, given their climate, topography and soil type (Figure 4.3). This could be the result of former types of land use, but also be caused by natural disturbances, such as fires, or by unrecorded land use, such as shifting cultivation, extensive forms of livestock grazing, collection of wood and fodder and anthropogenic fire regimes.

Figure 4.2
Net primary production



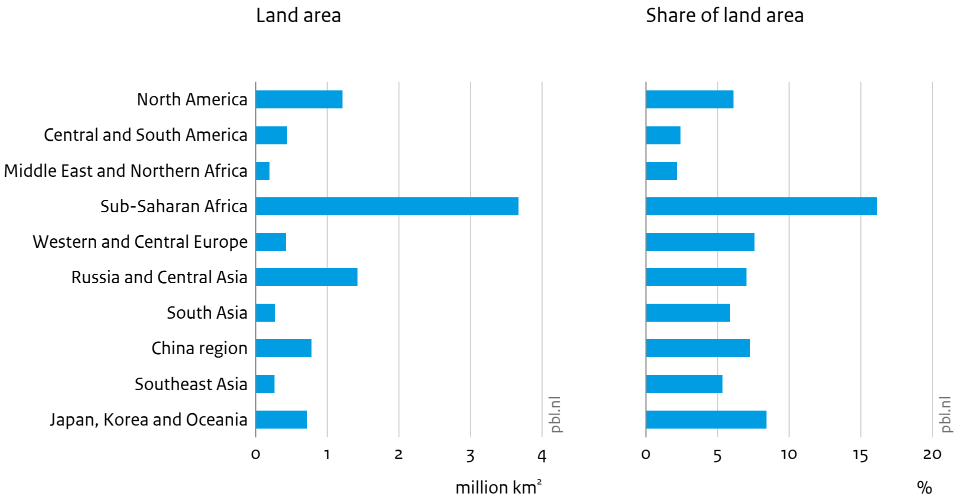
Source: Stoorvogel et al., 2017; Schut et al., 2015; PBL

Figure 4.3
Net primary production compared to natural situation, 2010



Source: PBL

Figure 4.4
Area with negative productivity trend, corrected for climate change, 1982 – 2010



Source: PBL

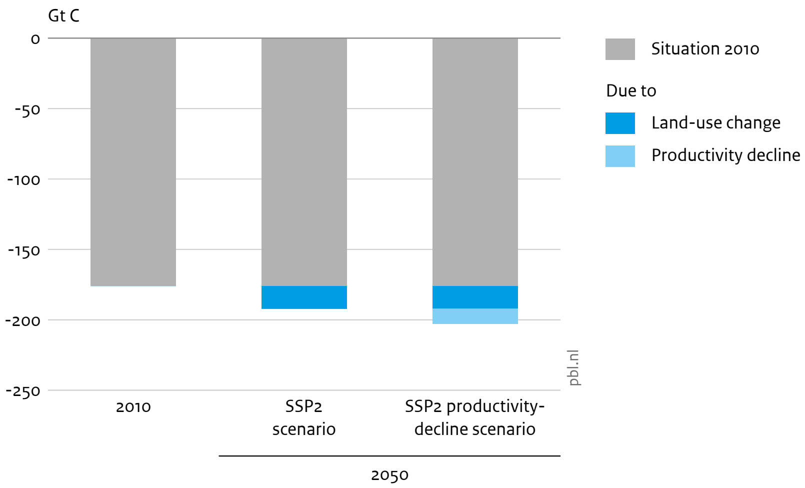
Table 4.1
Percentage of area showing declining, climate-corrected trends in productivity over the 1982–2010 period, per region

	Percentage of area showing declining trends	
Region	**Agriculture area**	**Natural area**
North America	10%	5%
Central and South America	4%	2%
Middle East and Northern Africa	12%	0%
Sub-Saharan Africa	23%	13%
Western and Central Europe	9%	6%
Russian region and Central Asia	19%	4%
South Asia	6%	5%
China region	10%	5%
Southeast Asia	7%	5%
Japan, Korea and Oceania	12%	7%
World	**12%**	**5%**

More than 9 million km² of land saw ongoing downward trends in productivity over the period from 1982 to 2010, when corrected for climatic change
Drawing on the work of Schut et al. (2015), ongoing negative trends in productivity over the period from 1982 to 2010 have been determined after correcting for the effect of climate change. In most regions, about 5% to 10% of the land shows continuing downward trends (Figure 4.4). Note that these figures are not corrected for any decline in productivity that may be artificially maintained by anthropogenic fertiliser application. Sub-Saharan Africa stands out as having a proportion of land with declining trends that is almost twice that of other regions, and as having the largest overall surface area affected.

More than 9 million km² of land show persistent, significant decline in climate-corrected productivity, half of which is agricultural land (cropland and pasture), about 12% (4.7 million km²) of worldwide agricultural land. Sub-Saharan Africa and the Russian region have the largest shares of agricultural area with negative trends in climate-corrected productivity (Table 4.1).
Land management may persistently affect the capability to produce food, fibre or fodder in these areas.

Figure 4.5
Change in soil organic carbon, per scenario, compared to natural situation



Source: PBL/IMAGE

4.2.2 Soil organic carbon

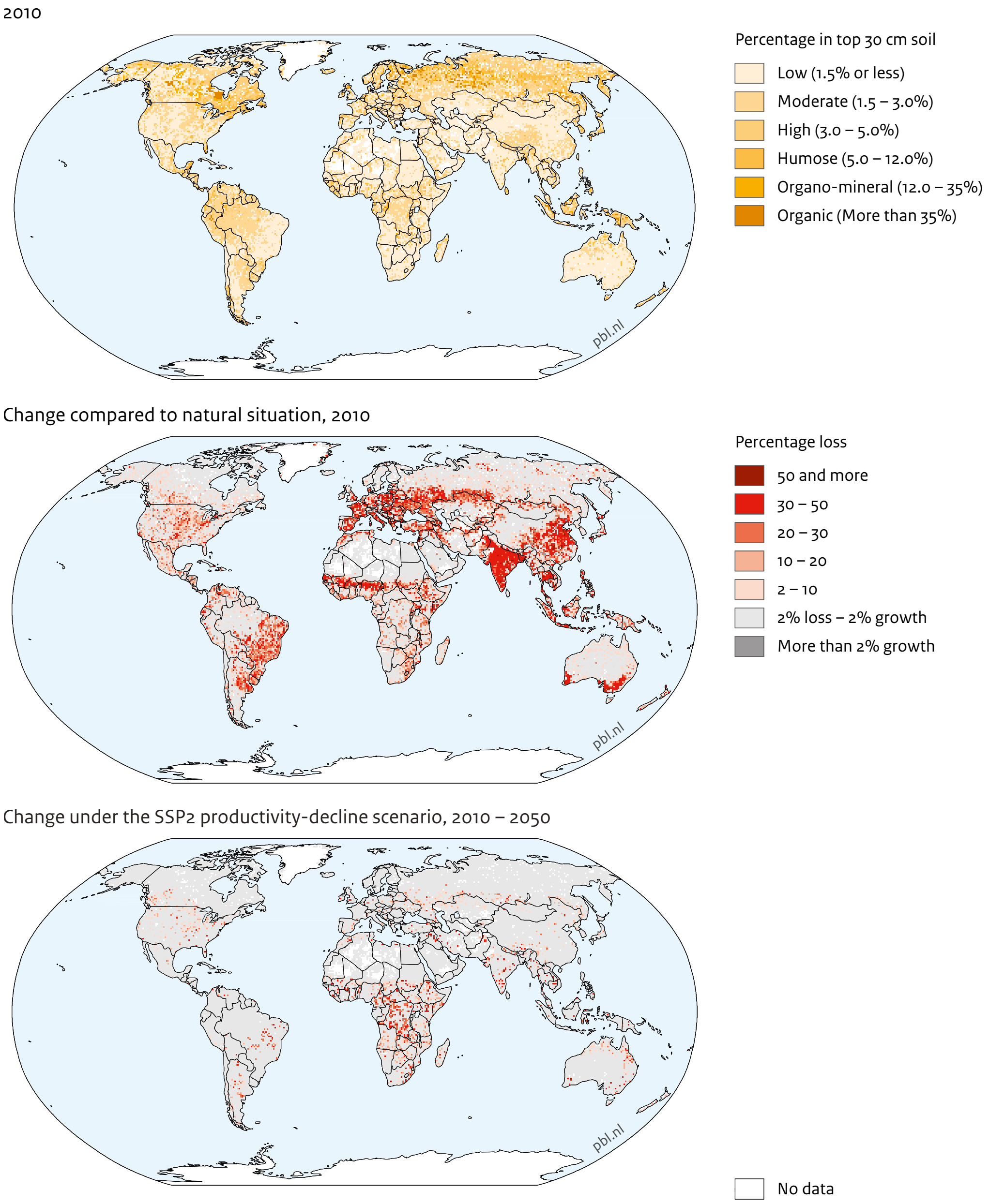
Soil organic carbon directly influences key ecosystem services
Soil organic matter is composed of carbon, hydrogen, oxygen and a small share of nutrients and is central to the chemical, physical and biological functioning of the soil. It directly relates to the maintenance and provision of many ecosystem goods and services: agricultural production, nutrient cycling, water regulation, and carbon storage (Banwart et al., 2014). Organic matter, generally, takes up between 2% and 10% of the total soil mass, but is difficult to measure with any precision. The carbon component, or soil organic carbon (SOC), however, can be measured more easily, and is therefore usually used as an indicator of the amount of soil organic matter. A loss in SOC indicates lower soil fertility levels, a decline in soil water holding capacity and soil stability, all of which in turn negatively impact ecosystem services (UNEP, 2012).

Soils are a large global terrestrial carbon pool
Globally, soils contain about three times the amount of carbon that is stored in vegetation and twice the amount present in the atmosphere (IPCC, 2000). The size of the global soil organic carbon pool is estimated at between 1,500 and 3,000 Gt of carbon (Scharlemann et al., 2014), with the higher estimates including deeper soil layers. More recently, Batjes (2016) reported a range of 1,408 Gt to 2,060 Gt for respectively one and two meters of soil depth. In this study, the global SOC pool in the upper 1.2 meter of soils is estimated at 2,000 Gt (Stoorvogel et al., 2017a).

Soil organic carbon content is a balance of biomass input and decomposition
The stock of organic carbon that builds up in a soil depends on the balance of input from biomass production and net losses from the soil as carbon dioxide emissions from decaying biomass, dissolved organic carbon, and loss through erosion. As a result, the organic carbon content in soils is typically high in cold regions where lower temperatures prevent quick decay. In warm areas biomass production is much faster but the decomposition rate is higher as well, often resulting in lower soil organic carbon contents. Peatlands, which have developed in both cold and warm regions, are very rich in soil organic carbon, because the waterlogged conditions strongly reduce the decomposition of dead biomass and soil organic carbon into carbon dioxide. When natural areas are converted into cropland or grazing lands, carbon inputs into the soil decrease because crops are removed from the system. SOC decomposition also tends to increase due to tillage. As a result, the conversion of natural land to a conventional cropping system will generally cause soil organic carbon stocks to decrease by 30% to 50% (Guo and Gifford, 2002).

Past and future losses of soil organic carbon
An estimated 8% or 176 Gt of soil organic carbon has been lost due to past changes in land use, such as the conversion of natural land into agriculture and overgrazing in grasslands (data derived from Stoorvogel et al. 2017a and 2017b; Figure 4.5). The greatest part of the loss originates from agricultural land in northern regions (Figure 4.6). This estimate is in line with previously published data (Houghton, 2003; Kaplan et al., 2011; Levy et al., 2004).

Figure 4.6
Soil organic carbon



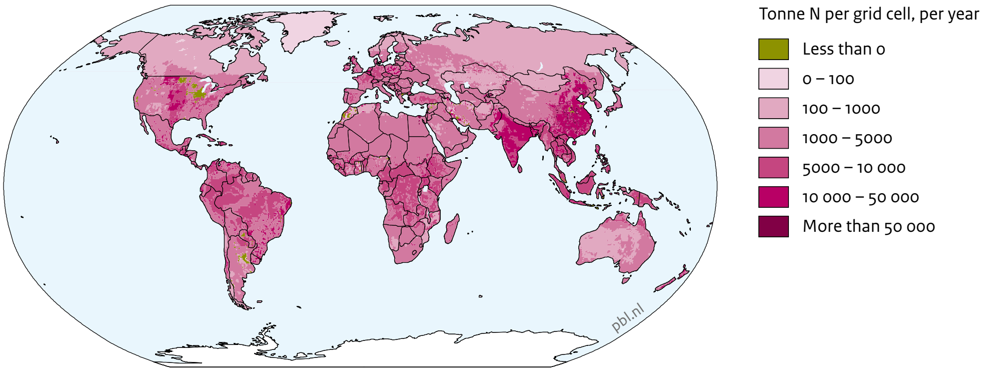
Source: Stoorvogel et al. 2017; Schut et al. 2015; PBL

Under the SSP2 productivity decline scenario, two effects play a role. The first is the loss of soil organic carbon resulting from future expansion of agricultural land, which amounts to some 16 Gt between 2010 and 2050. The second effect is the result of the declining productivity trends associated with land management, resulting in a projected additional loss of 11 Gt over the same period. This second effect, however, may be countered by productivity increases from climate change, the future effects of which are uncertain and not estimated here. The 11 Gt estimate may therefore be lower when positive climate effects on biomass productivity (and consequential increases in soil organic carbon) are taken into account, and vice versa.

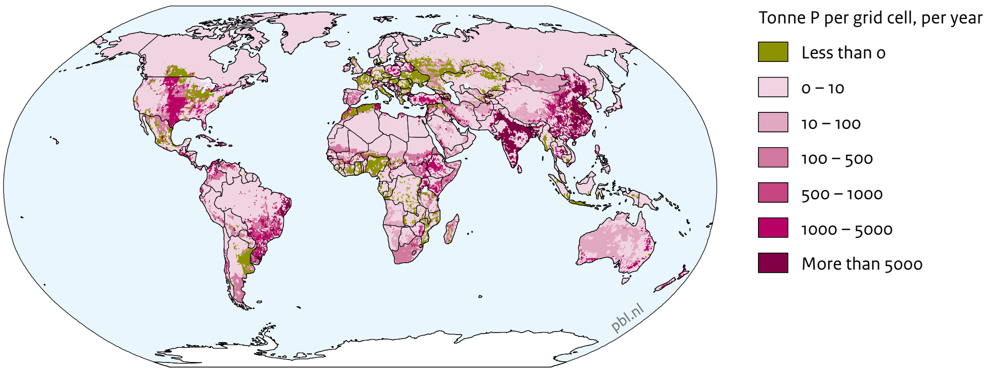
Soil health, indicated by soil organic carbon, is thus projected to further decline in many regions of the world. This may affect agricultural yields through the decrease in nutrients (Section 4.2.3) and in water holding capacity (Section 4.3.3). Losses of soil organic carbon also have

Figure 4.7
Nitrogen and phosphorus budget, 2010

Nitrogen



Phosphorus



Source: PBL

wider effects on hydrology, above- and below-ground biological diversity, and carbon emissions (FAO, 2011). Continued loss of soil organic carbon in African soils has already rendered many soils 'non-responsive', which means that the fertilisers that may be available simply do not work (Tittonell and Giller, 2013). For smallholder farmers in Africa this may constitute a poverty trap, requiring investments to rebuild soil organic carbon levels and restore the soils to a responsive state.

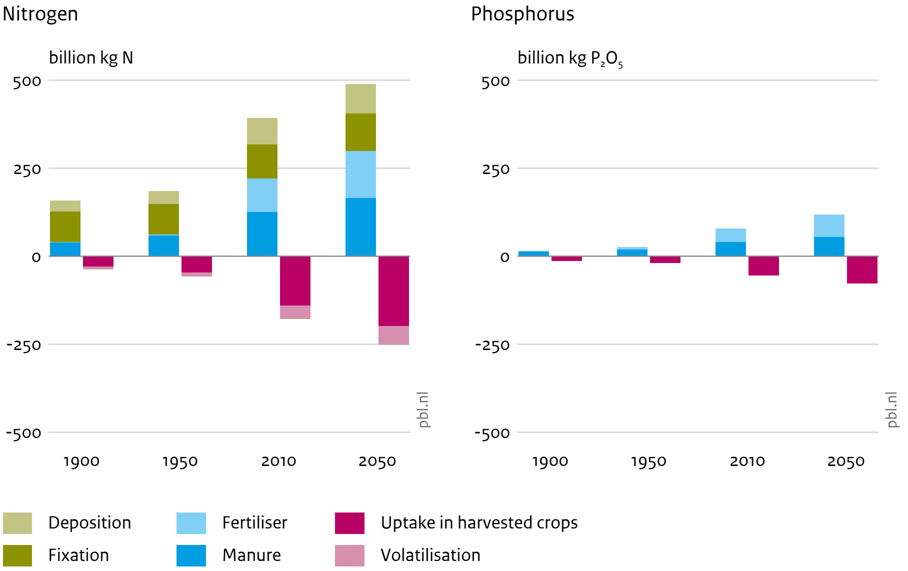
4.2.3 Soil nutrient budgets

Next to organic matter content and water availability, the productivity of soils strongly depends on the availability of nutrients, especially phosphorus (P) and nitrogen (N). There are about 14 other nutrients (or minerals), which are not only essential for crop production but also for humans and livestock. These include macro-elements as potassium and calcium, and micronutrients, such as iron, zinc, molybdenum and boron. The difference between macronutrients and micronutrients is the amount absorbed by crops: macronutrients are typically measured in kg/ha and micronutrients in g/ha (Box 4.1). As the nutrient availability is a limiting condition for crop production, the use of mineral fertilisers has enabled farmers worldwide to vastly increase crop yields.

Soil nutrients are enriched in some regions and depleted in others

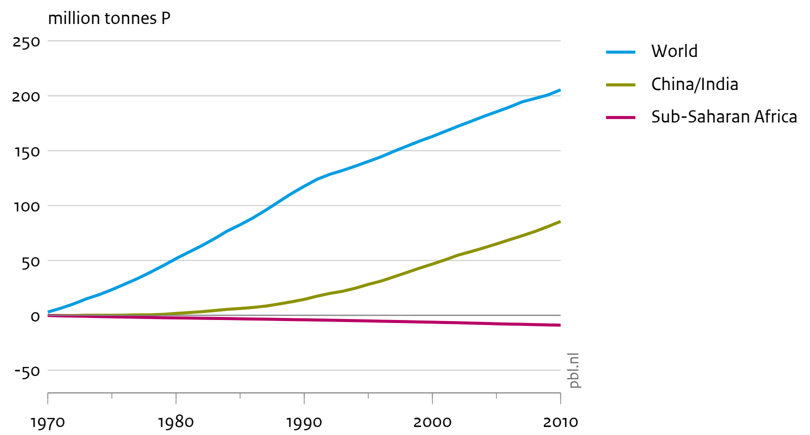
The availability of nutrients in the soil depends on its nutrient content and additional inputs it receives, such as fertiliser, manure, compost and atmospheric nitrogen deposition. Further nitrogen inputs may come from biological fixation, mainly by leguminous crops, such as beans and clover. Outputs consist of nutrients in the harvested parts of crops, and losses. Losses are mainly due to nutrient run-off, leaching or wind erosion. However, they can also occur in the form of emissions of ammonia, nitrous oxide (one of the major greenhouse gases) or inert nitrogen gas. Depending on the budget of inputs and outputs, soils can be stable in nutrient availability, enriched with nutrients (due to positive budgets) or depleted (due to negative budgets).

Figure 4.8
Global nitrogen and phosphorus budget, under the SSP2 scenario



Source: PBL

Figure 4.9
Accumulation of phosphorus in soil

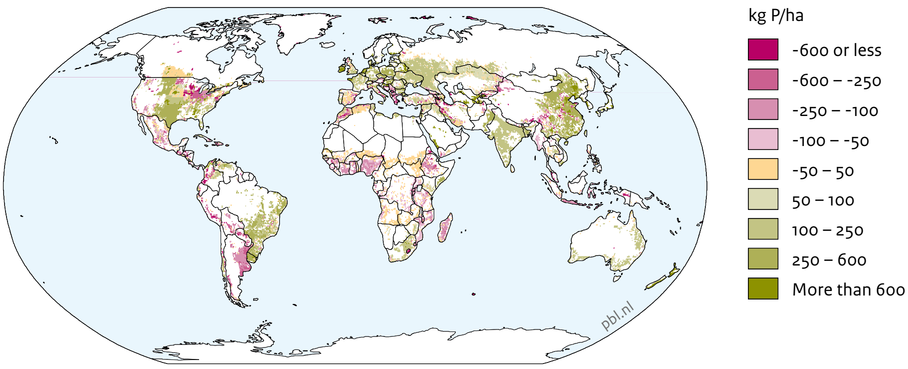


Source: PBL

At present, almost all soils around the world have a positive nitrogen budget, with hotspots of surpluses in India, China and parts of Europe and the United States (Figure 4.7). For phosphorus, a more diverse pattern exists, with positive budget hotspots in parts of Europe, North and South America and China, and large areas with negative budgets in Africa, North and South America, Central Asia and Europe (Figure 4.7). Residual soil budgets are the accumulation of nutrients in soils over multiple seasons. This applies mainly to P, as much of the residual N can be considered an environmental burden; after the growing season, the soil will be denitrified, or surplus N will be leached or taken up by the next crop. In contrast, P is chemically absorbed by soil particles. P can be lost from soils in run-off in the form of dissolved reactive P and particulate P and will leach into water systems only after long periods of excessive application.

Farmers in high-income countries and in China and India have built up a large reserve of residual soil P in cropland in recent decades. This residual soil P stock can be mobilised for use by crops, and consequently, the use of

Figure 4.10
Cumulative residual phosphorus, 1970 – 2010



Source: PBL

mineral P fertiliser has been decreasing in many industrialised countries in recent years. Soil P budgets are even negative in Europe to date. Large amounts of N surpluses are lost to the environment through emissions to air and water and are transported in groundwater with long travel times (decades and longer). Increasing efficiency in the use of N and the utilisation of accumulated residual soil P makes it possible to achieve continued increases in crop yields with decreasing losses to the environment (Bouwman et al., 2017).
However, with aquifers continuing to release N in many landscapes, concentrations in many rivers do not respond to the increased efficiency of fertiliser use. As a result, in Europe, water quality is threatened by rapidly increasing N–P ratios (Bouwman et al., 2017). Farmers in developing countries can avoid these legacy problems by integrating management of N, P and other nutrients and accounting for residual soil P.

In the SSP2 scenario, the increase in food production will lead to rises in the use of nitrogen and phosphorus fertiliser (Figure 4.8), especially in regions where use is currently still low. On a global scale, this leads to a massive accumulation of fertiliser in soils and groundwater up to 2050.

Phosphorus depletion implies a risk of decreased soil productivity
While the overall phosphorus and nitrogen flows have increased over time (Figure 4.9), there are also large areas with a negative phosphorus budget over the 1970–2010 period. Large areas with significant negative phosphorus budgets are found in Africa, North and South America, the Mediterranean area and China (Figure 4.10). Under the SSP2 scenario, the soil depletion in these areas is projected to continue. In areas with a negative budget for phosphorus, the risk of decreasing crop production depends on the available nutrient stock in the soil.
As those nutrient stocks in the soil are poorly known, the potential future impact on crop yields cannot be assessed.

Nutrient enrichment and depletion entail risk of environmental damage
Positive budgets for nitrogen lead to enriched soils and increased groundwater pollution, and nutrient loading of streams and rivers, lakes, reservoirs, and coastal seas. Phosphorus is lost from soil-crop systems by surface run-off, and accumulation of P in soils can lead to high P content in the run-off (Beusen et al., 2016). Phenomena like harmful algal blooms, oxygen depletion and hypoxia, and fish kill are well-known impacts from increased nitrogen or phosphorus application (Diaz and Rosenberg, 2008).

4.2.4 Biodiversity

Up to the present day, global biodiversity has declined by one third in terms of mean species abundance
Biodiversity is declining due to a series of drivers and pressures. By 2010, global biodiversity had declined by around 34% in terms of mean species abundance (MSA)[3], compared to an undisturbed natural state. The major causes are conversion of natural areas into agricultural land, forestry, climate change, encroachment from expanding human settlements, infrastructure and fragmentation (Figure 4.12). The largest losses have occurred in countries that are now developed.
Most current and expected future loss is concentrated in developing countries, much in line with land-use expansion and more intensive land management.

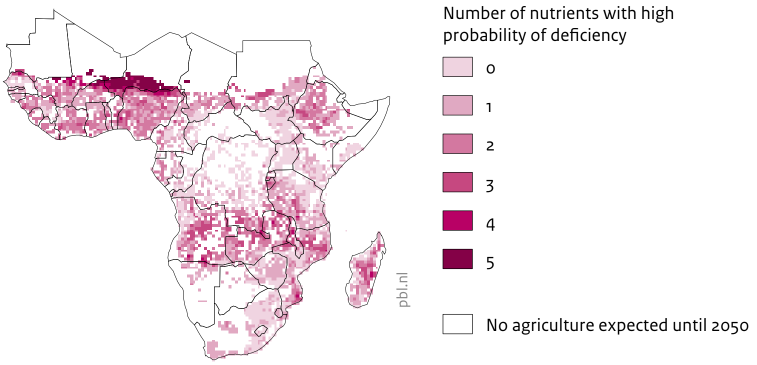
Biodiversity decline is expected to continue in the future
Biodiversity loss is projected to increase from 34% in 2010 to 38%, 43% and 46% under SSP1, SSP2 and SSP3,

Box 4.1 Three strategies to reduce micronutrient deficiencies

There is a growing appreciation of the role of micronutrients, such as zinc, iron, copper, manganese, boron and selenium in soils (Vanlauwe et al., 2015; Voortman, 2015). Concentrations of these nutrients in soils may be naturally low, or become deficient through the continuous removal of harvested crops (Figure 4.11).

Figure 4.11

Estimated distribution of soil micronutrient deficiencies across Sub-Saharan Africa



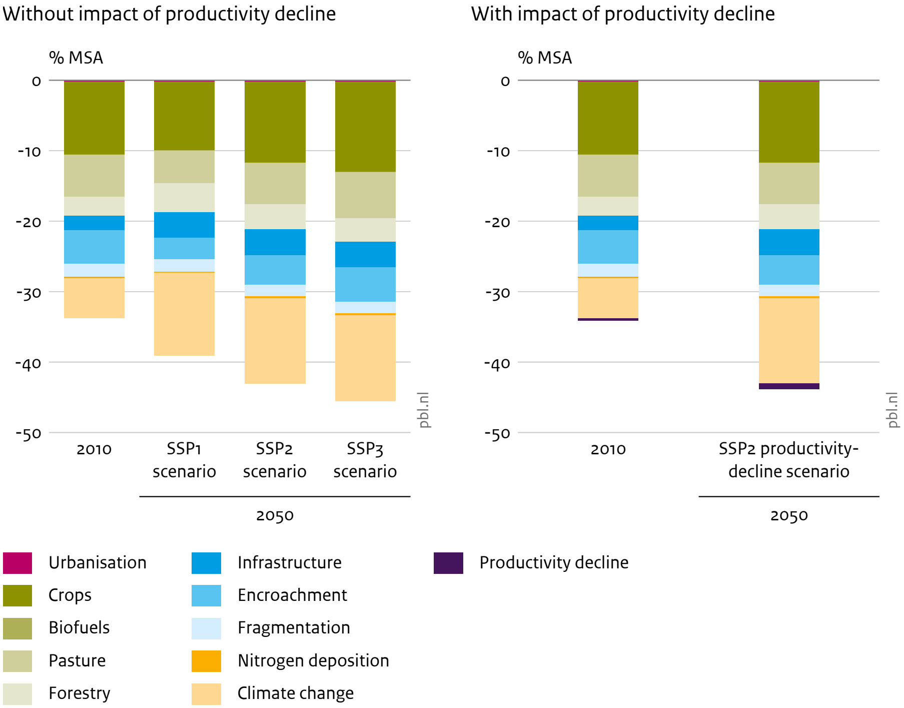
Source: Hengl et al. 2017; PBL/IMAGE

Estimated distribution of soil micronutrient densities (B, Cu, Fe, Mn, Zn) across Africa, for locations where agricultural activity is expected under the trend scenario used for the fourth Global Biodiversity Outlook (PBL, 2014). The map displays the number of micronutrients that fall within the lower 25% range of each nutrient distribution. At these locations, the likelihood of multiple nutrient deficiencies is the greatest, which may hamper developments towards more intensive agricultural production.

Low levels of micronutrients may limit crop yields and nutritional quality, which in turn negatively affects human health. Micronutrient deficiency affects approximately two billion people worldwide (Black et al., 2013). Micronutrient deficiencies could, at least partly, be prevented by properly recycling the removed micronutrients. This recycling is carried out mainly by applying manure, crop and food waste. Currently, this is often not possible due to the spatially segregated feed and animal production, and that of rural food production and urban consumption.

One way to reduce existing micronutrient deficiencies is by agronomic fortification (fertilisation). To date, fertilisation has been most effective with Zn and Se (De Valença et al., 2017). One of the most celebrated cases comes from Finland, where the addition of Se to NPK fertilisers increased crop Se contents and the Se status of the whole Finnish population (Ros et al., 2016). However, insufficient evidence hampers definite conclusions about the effectiveness of fertilisation in alleviating micronutrient deficiencies among humans (De Valença et al., 2017). Other options are increasing the concentration of micronutrients through breeding and genetic engineering (biofortification) and through food supplements (food fortification). However, neither address low micronutrient stocks in soils.

Figure 4.12
Pressures on global biodiversity, per scenario, compared to natural condition



Source: PBL/IMAGE

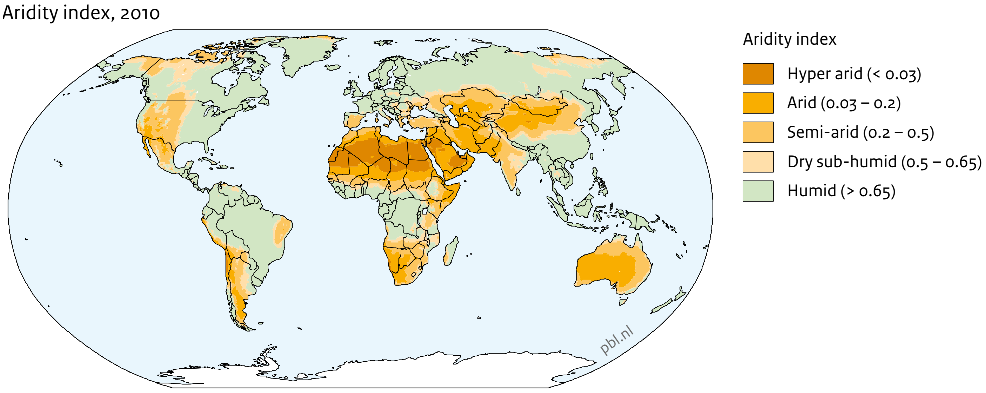
Table 4.2
Mean species abundance in 2010 and projections by the SSP2 productivity-decline scenario

		2010	2050, SSP2 productivity decline scenario
Regions	**Area, in million km²**	**MSA**	**MSA**
North America	20	65%	56%
Central and South America	18	65%	53%
Middle East and Northern Africa	11	81%	77%
Sub-Saharan Africa	24	70%	56%
Western and Central Europe	6	37%	29%
Russian region and Central Asia	21	73%	65%
South Asia	5	44%	35%
China region	11	56%	49%
Southeast Asia	7	55%	43%
Japan, Korea and Oceania	8	71%	57%
Polar	2	96%	91%
World	**132**	**66%**	**56%**

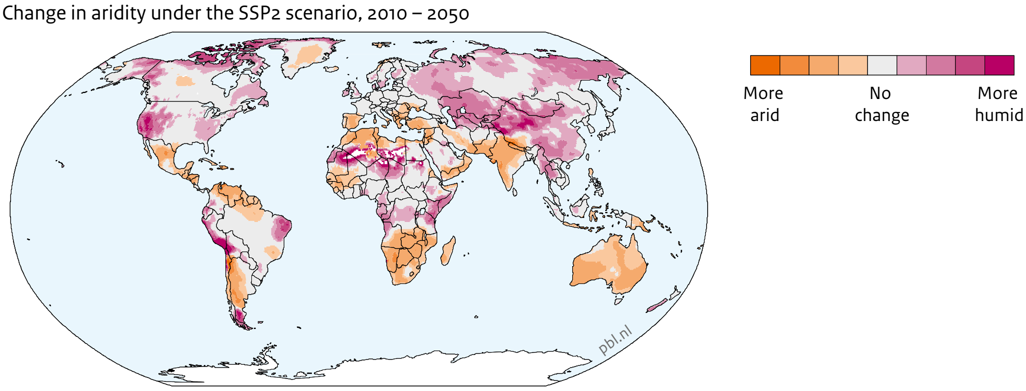
respectively (Figure 4.12). In SSP1, the rate of loss is slowed down by halting the expansion of cropland although this leads to a higher impact from forestry. This is a typical example of trade-offs between various sector developments: under SSP1, the forestry area has to expand more than in SSP2 and SSP3 to compensate for the absence of timber produced by clearing forests for cropland expansion. SSP2 and SSP3 foresee the most considerable biodiversity losses as a cumulative effect of the increase in cropland, including bio-energy crop plantations, infrastructure, encroachment from human settlements, forestry and climate change. In these scenarios, the rate of loss recorded in the 20th century is projected to continue or even accelerate.

Figure 4.13
Aridity

Aridity index, 2010



Change in aridity under the SSP2 scenario, 2010 – 2050



Source: PBL/IMAGE

The SSP2 productivity-decline scenario projects an additional biodiversity loss of about 1% by 2050 (Figure 4.12), equivalent to a complete loss of the original biodiversity (entire populations of all original species) of an area about 2.4 times the size of France. About one third of this additional loss takes place in natural areas that suffer the effects of a former type of land use, such as desertified and abandoned land, and areas for which the use is unrecorded, such as extensive grazing, fodder and wood collection, and land that has been cleared by fire. The biodiversity loss related to this unrecorded land use has been ignored in previous global assessments (Annex 3). The other two thirds of the additional biodiversity loss is caused by agricultural expansion to compensate for the loss in productivity, as elaborated in Section 4.3.2. Regional projections are given in Table 4.2.

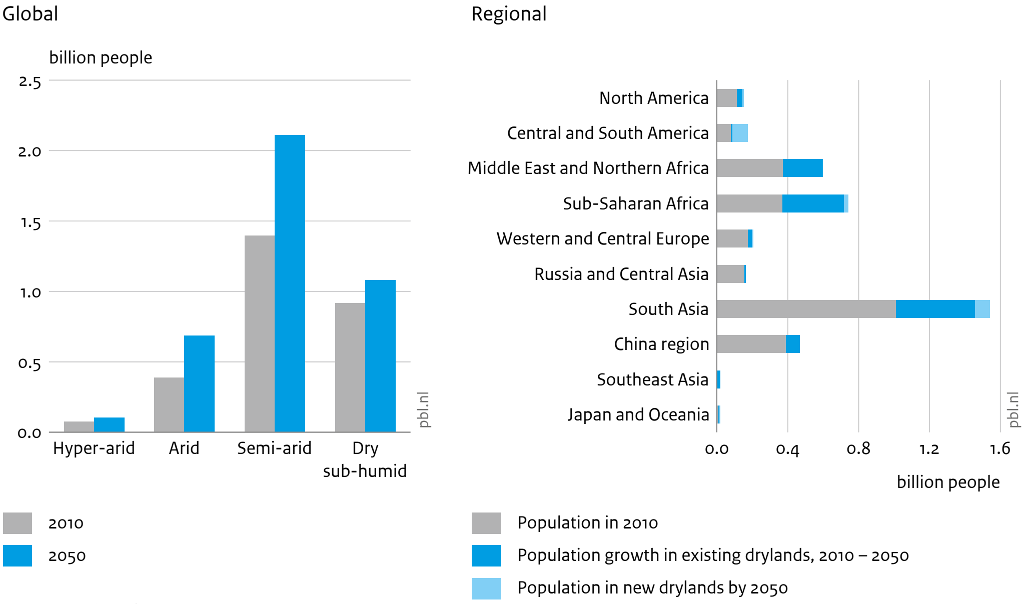
Biodiversity loss is expected to continue after 2050
The aim of the Convention on Biological Diversity that biodiversity loss will come to a halt by 2050, is not achieved in any of the scenarios. Between 2050 and 2100, an estimated additional 9 per cent point of MSA is projected to be lost under the SSP2 scenario.

4.2.5 Aridity

The UNCCD defines desertification as the degradation of land in arid, semi-arid, and dry sub-humid areas. While climate change can reinforce land degradation in drylands in the long run, for the most part drylands have always experienced drier and wetter periods, lasting from one to several years, or even decades. Natural systems have adapted to these patterns. Drought events, for instance, occur about every 30 years in the Sahel and the Horn of Africa, and in the dry plains in the United States (MA, 2005; Montgomery, 2012). El Niño and La Niña events also lead to changes in the periods of drier and wetter weather.

These fluctuations over longer timeframes pose an additional challenge to sustainable land use in drylands. Traditional systems, such as nomadic grazing practices, have adapted to longer periods of drought. However, severe dry spells combined with increasing pressures from overgrazing and cropland expansion – the latter inducing erosion and putting greater pressure on remaining land – increasingly strain local abilities to cope with drought. At the same time, drylands are currently home to an estimated 2.7 billion people who are among

Figure 4.14
Population in drylands, under the SSP2 scenario



Source: PBL/IMAGE

the most vulnerable in terms of food and water security. Figure 4.13 shows the regions that are becoming drier and wetter under the SSP2 scenario, with climate change projections equivalent to a global warming of 2.3 °C by 2050 and 3.9 °C by 2100, although there is uncertainty regarding the specific pattern that could be explored by using multiple climate models.

Dryland populations are projected to increase considerably by 2050

Overall, populations in drylands are projected to increase by 40% to 50%, from 2.7 billion in 2010 to around 4.0 billion by 2050, which is a far higher population growth rate than that in non-drylands, with around 25% under the SSP2 scenario (Figure 4.14). In drylands, water, generally, is a limiting factor for plant growth and is often scarce. With the projected population increases, water scarcity is bound to become an even more pressing issue in many of these regions, let alone if populations grow faster; for instance, at a rate that is more in line with the SSP3 scenario.

The largest increases in populations are projected to take place in semi-arid and arid drylands (Figure 4.14). South Asia is projected to see the largest increase in number of people living in drylands, over 500 million, and Sub-Saharan Africa is estimated to see its dryland population almost doubling. Though smaller, a doubling is also projected for Central and South America, although, whereas in Sub-Saharan Africa the increase is mainly driven by population growth in existing drylands, in Central and South America the main cause is the projected expansion of drylands due to climatic changes. Therefore, while many regions will become somewhat dryer and several others will get wetter, the overall challenges in drylands will be much more aggravated by increased demands from larger populations than by climate change. However, the effects of climate change, such as increased risks of more erratic weather, especially drought, will be felt by many more people in drylands, in the future.

4.3 Impacts on ecosystem functions and services

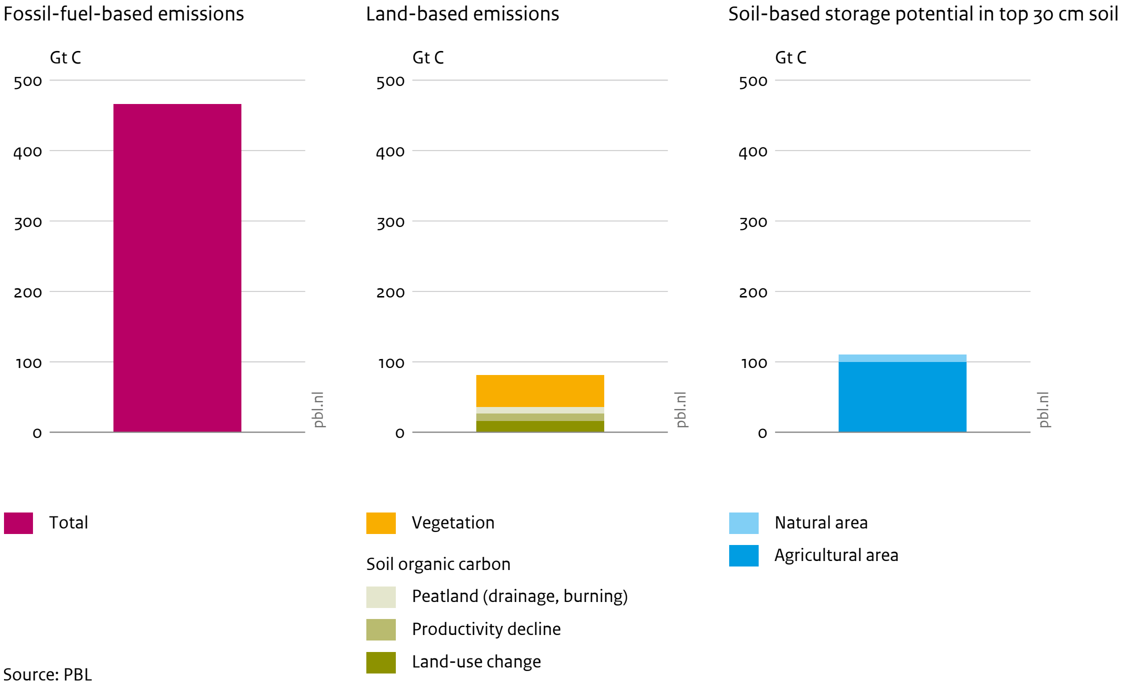
This section summarises the projected impact of the changes in land condition and land use as estimated in the previous sections on carbon emissions, water regulation, agricultural productivity and cropland area.

4.3.1 Impacts on carbon emissions

Current and future land-based contributions to carbon emissions

Compared to the carbon emissions from fossil fuel use and the cement industry, the amount of carbon emissions from land-use change is more uncertain. Current global net carbon emissions from land-use change are estimated at 0.9 GtC/y (±0.8) (IPCC, 2014). This average estimate is derived by comparing various methods

Figure 4.15
Carbon emissions from fossil fuel and land use, under the SSP2 productivity-decline scenario, 2010 – 2050



Source: PBL

(Houghton et al., 2012) and includes processes, such as deforestation and forest regrowth, as well as soil carbon released when converting forest into cropland.

As stated in Section 4.2.2, under the SSP2 productivity-decline scenario, cumulative emissions from soil organic carbon are estimated at around 27 GtC over the 2010–2050 period. Of this amount, 16 GtC originate from the future conversion of natural land into agricultural land, and 11 GtC from continued decline in land cover and productivity, other than that stemming from land conversion (Figure 4.15). This decline may come from inappropriate management practices that cause erosion, insufficient replenishment of the soil with organic matter and the soil being left bare for prolonged periods.

The continued drainage of peat soils and subsequent peat fires are estimated to contribute cumulatively about 9 GtC (±2) emissions between 2010 and 2050. This estimate is based on projections of emissions in Southeast Asia (Hooijer et al., 2010) and the extrapolation of current emissions in Europe, including European Russia (Drösler et al., 2008). Cumulative carbon emissions from vegetation loss under the SSP2 scenario are estimated at around 45 GtC by 2050 (Figure 4.15). This biomass loss originates from agricultural expansion, forest degradation and forest management, and is the net balance of, in particular, afforestation in the northern regions and continued deforestation in the southern regions.

The land-based contribution to carbon emissions is small compared to emissions from fossil fuel use
The anthropogenic land-based emissions mentioned above add up to around 80 GtC by 2050, equivalent to about eight years of current carbon emissions from fossil fuel use at 9.9 GtC/y (Olivier et al., 2015). Cumulative emissions of carbon from fossil fuel use and cement production between 2010 and 2050 are estimated about 465 GtC. These estimates do not include the feedback effects from climate change (temperature and precipitation) on soil organic carbon stocks or the impacts from CO_2 fertilisation. The former may have positive and negative impacts on carbon storage in soil, depending on local conditions. Crowther et al. (2016) estimate a global net loss of soil organic carbon of 55±50 GtC in case of 2°C warming.

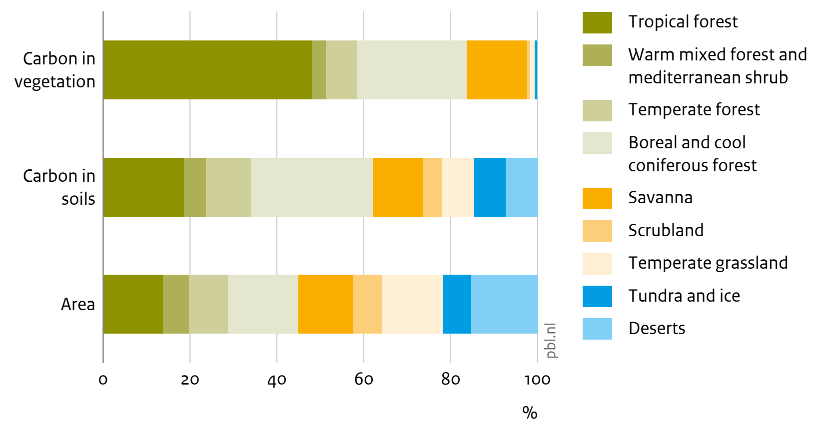
Restoration and prevention of land-based emissions are interesting from a climate mitigation perspective
Since the greatest part of the historical loss in soil organic carbon originates from the top 30 cm of soil in current or former agricultural land, agriculture is also where the

Box 4.2 Carbon stocks in vegetation and soils

Carbon stocks in soils amount to about 2,000 GtC whereas in vegetation stocks are about 450 GtC. Figure 4.16 shows the carbon stored in soils and in vegetation per biome, compared to each biome's terrestrial area. The ratio between carbon stored in soil and in vegetation is, to a large extent, linked to climatic zones. High soil carbon stocks per hectare are found in wetlands, boreal forests, temperate grasslands and tundra, which are all regions with relatively low temperatures and often high rainfall. In these biomes, the amount of carbon in the vegetation is low compared to the soil carbon. Relatively low soil carbon stocks per hectare are found in deserts and semi-deserts, croplands and in temperate forests. Forests, especially tropical and boreal forests have the highest carbon stocks in vegetation per hectare. Tropical forests are unique in having about equal stocks per hectare in soils and vegetation. Boreal and cool coniferous forests and the tundra occupy 20% of the global land area but hold 35% of all carbon in soils and only a very modest share of the carbon in vegetation.

For policies dealing with carbon storage in soils and vegetation it is useful to understand these ratios. The biomes in the northern latitudes are particularly sensitive since restoration of lost carbon takes a very long time. In tundra, the only option to keep carbon stored is preventing climate change, something that is beyond local management and regional policies. In boreal forests and peatlands, maintaining stored carbon is achieved by preventing drainage, fires and logging. Restoration of peatlands involves raising groundwater to levels nearer to those of the natural situation but the net result from sequestering carbon and the additional release of methane is modest. In the deserts, semi-deserts and savannahs, prevention of erosion and nutrient depletion in particular can limit emissions.

Figure 4.16
Carbon stocks in vegetation and soils, per biome, 2010

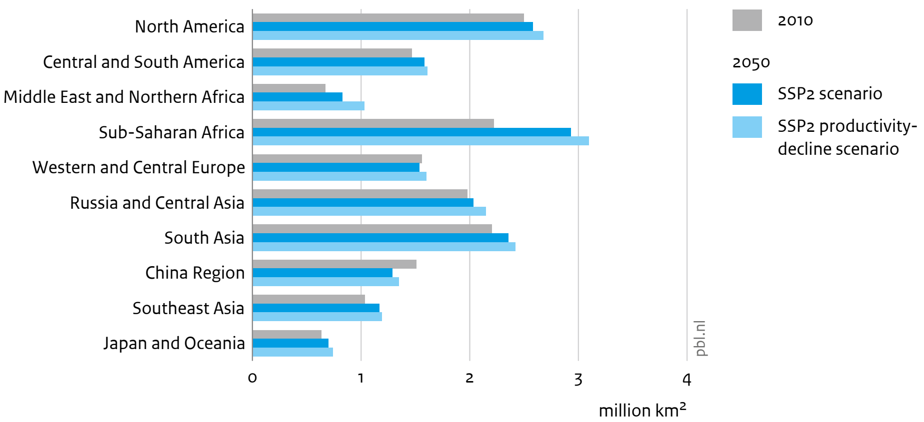


Source: PBL

greatest restoration potential lies (Stoorvogel et al. 2017a and 2017b) (Figure 4.15). This global potential is considerable – in the order of magnitude of 100 GtC – but requires the development of agricultural systems that combine high yields with near-natural soil organic carbon levels. It should be stressed that restoration over a few decades is confined to the top soil. At greater depths, where about one third of the total historical loss is estimated to have occurred, restoration requires much longer periods.

The share of future land-based carbon emissions is small compared to fossil fuel emissions. However, reducing land-based emissions and utilising the carbon sequestration potential of agricultural land would bring significant gains from a climate change mitigation perspective (Box 4.2). They would leave more of the available global carbon budget intact. Estimated at 170–320 GtC, this budget is the amount of CO_2 emissions that can still be generated without jeopardising the target[4] of keeping the average global temperature increase below 1.5 °C to 2 °C (IPCC, 2014; Rogelj et al., 2016; UNFCCC, 2015).

Figure 4.17
Cropland area



Source: PBL/IMAGE

Table 4.3
Mechanisms of changes in land condition and their impacts on agricultural production

Process	Description	Cause / aggravated by	Impacts on agriculture, crop growth and yields
Land clearing	Removal of trees, stumps, brush, stones and other obstacles from an area to increase the size of crop land	Increased demand for agriculture or forestry products Loss of (and reduced productivity of) existing agricultural land	Essential to provide space for agricultural production Loss of supporting ecosystem services associated to pollination, pest predation and other functions; Loss of genetic diversity to help plant breeders develop better crops using wild varieties At large scale, disturbance of water basin hydrology
Erosion	Removal of topsoil by run-off or wind	Poor vegetation cover (e.g. after ploughing) Unstable surface soil structure (e.g. due to loss of soil organic matter) In case of water erosion: Steep or long slopes Slow infiltration of surface water into the soil (e.g. due to dense surface soil) In case of wind erosion: High wind speed; no wind breaks (e.g. trees) Drought	Loss of topsoil, i.e. the part of the soil that is richest in plant nutrients and organic matter and has the most favourable physical properties. Reduction of the volume of soil that can be explored by roots, thus reducing the availability of soil water and nutrients to plants In its extreme form, gullies formed by water erosion make the land totally unfit for agricultural practice Large volumes of sediments damaging or covering crops In areas where sedimentation is gradual, agriculture can benefit from the high nutrient content and favourable physical properties of sediments
Soil crusting	Formation of hard (when dry) and dense surface layer due to impact of rain drops	Poor vegetation cover Unstable surface soil structure (e.g. due to ploughing or loss of soil organic matter or sodification)	Poor germination and emergence of seedlings that have to break through the crust Reduced availability of water to plants due to water loss by run-off over crusted surface
Soil compaction	Reduced soil porosity (loss of large pores in particular) due to heavy machinery, slipping wheels or trampling livestock	Soil disturbance during wet conditions Frequent use of heavy machinery High livestock density Unstable soil structure (e.g. due to sodification, loss of soil animals)	Reduced root functionality due to lack of oxygen in the soil Stagnation of water in top soil increasing the risk of disease Difficulty of roots to penetrate compacted soil layers, thus limiting the plants' access to soil water and nutrients Slight compaction in sandy soils can benefit yields by increasing water holding capacity
Soil sealing	covering of the ground by an impermeable material	Urbanisation	Reduction of cropland area, often leading to a displacement effect

Table 4.3 (continued)
Mechanisms of changes in land condition and their impacts on agricultural production

Process	Description	Cause / aggravated by	Impacts on agriculture, crop growth and yields
Salinisation	Accumulation of salts in rooted part of the soil	Arid or semi-arid climate Irrigation with poor quality water Shallow groundwater level with high salt content	Physiological drought Nutrient imbalances Toxicity of salts to crops
Sodification	Replacement of exchangeable Ca++, Mg++ and K+ in the soil by Na+	Irrigation with water with high sodium content Shallow groundwater level with high sodium content	Nutrient imbalances Toxicity of sodium to crops Effects of soil crusting
Nutrient depletion	Net loss of plant nutrients from the soil over time	Removal of nutrients from the land in crops at harvest or by foraging livestock without replacing them with fertilisers or manure Leaching of nutrients with draining soil water Limited capacity of the soil to store or retain nutrients (e.g. due to low clay and soil organic matter content)	Loss of essential plant nutrients
Soil contamination	Contamination of soils with toxic materials (heavy metals, persistent organic compounds)	Use of certain agro-chemicals (pesticides, polluted fertilisers) By water or air pollution from other sources	Lower crop yields Contaminated crops or livestock products
Soil organic matter loss	Net loss of soil organic matter from soils	Ploughing Artificial drainage Decreased input of fresh organic matter (e.g. due to poor crop growth, burning, harvesting, excessive grazing)	Reduced ability of soils to store nutrients and water loss in structural soil stability, thus making the soil more vulnerable to erosion and compaction
Groundwater depletion	Lowering groundwater levels as water withdrawals exceed influx	Increasing water withdrawals for irrigation and non-agricultural use Decreased rainfall as a consequence of climate change	Increasing costs to satisfy water demands for crops eventually resulting in decreased supplies with yield penalty or abandonment

4.3.2 Impacts on crop yields and agricultural area

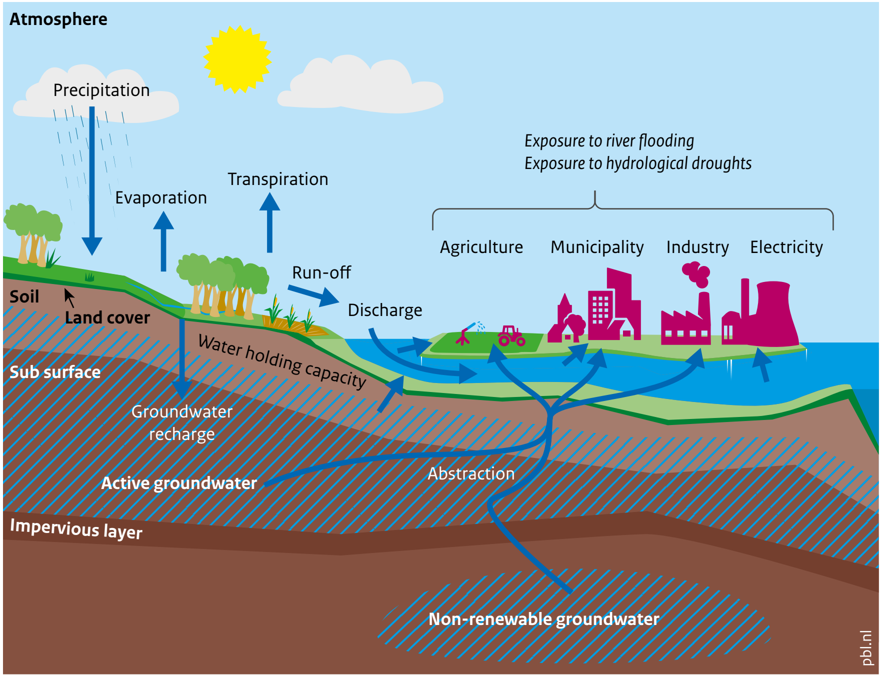
Impact of change in land condition on global crop production is poorly known

Local change in land condition can negatively affect agricultural productivity. The effects are well understood at the local level but their global scale and extent have not been thoroughly studied and are highly uncertain (Lambin and Meyfroidt, 2011). Crop growth and yields can be disturbed due to numerous factors ranging from salinisation, soil erosion, poorer soil water retention, nutrient depletion, soil crusting and compaction (Table 4.3). When yields decline, loss has to be compensated for by agricultural land expansion or intensification elsewhere to maintain the same overall production level.
Severe declines in yields can lead to land abandonment if further exploitation becomes unprofitable or impossible. This potentially creates a negative spiral, as in general the most suitable lands have already been put to use.
If expansion takes place onto more marginal land, larger land surfaces are needed to maintain production levels (see also Chapter 3). One reason for the uncertainty at the global level is that in most regions crop yields are still increasing and any negative effects on yields are more than matched by the positive effects of increased use of fertilisers, irrigation or improved crop varieties. This means that local changes in land condition have effects on yields which, to a large extent, remain invisible on the national or regional scales until yields start to decline rapidly as soil conditions approach the tipping points (Bindraban et al., 2012; FAO and ITPS, 2015).

Declining trends in crop area productivity due to inadequate land management practices result in an additional expansion of cropland by 5%

The SSP2 assumptions on cropland yields in Chapter 3 do not account for the effect of declining productivity trends or smaller productivity increases than would be expected given climate change effects over the period from 1982 to 2010, as estimated in Section 4.2.1. These negative effects on productivity are assumed to be related to land management and soil fertility, and to continue at a

Figure 4.18
Water cycle and water use



Source: PBL

decreasing pace under the projection for 2050 of the SSP2 productivity decline scenario (see Annex 3 for method). A rough estimate of the future displacement effects due to land management under this scenario is a 5% increase in land use for cropland by 2050 on top of the expected increase of around 8% in cropland under SSP2 (see Figure 4.17). The regions that show the biggest additional expansion by 2050 under these assumptions are the Middle East and Northern Africa, Sub-Saharan Africa, Russia and Central Asia. This is a combination of a) the negative effects on productivity in existing cropland which are assumed to be related to land management and soil fertility, b) expansion onto other land which is often less productive, and c) compensation of the production loss in a region by cropland expansion within the same region (Annex 3).

It should be noted that the effects that climate change may have on agricultural production are not included in this analysis and may be positive or negative depending on the degree of climate change and geographic location. This implies that the 5% cropland expansion reported above is not a net figure, but rather the estimated size of the effect from land management practices decreasing the productivity of land. Adding climate effects might result in a net effect of reducing or further expanding agricultural area in a region, but the climate effects on agriculture are highly uncertain (Box 3.3). The results do suggest, however, that improving land management to maintain productivity and soil fertility can save considerable amounts of land from agricultural expansion, keeping it available for other uses.

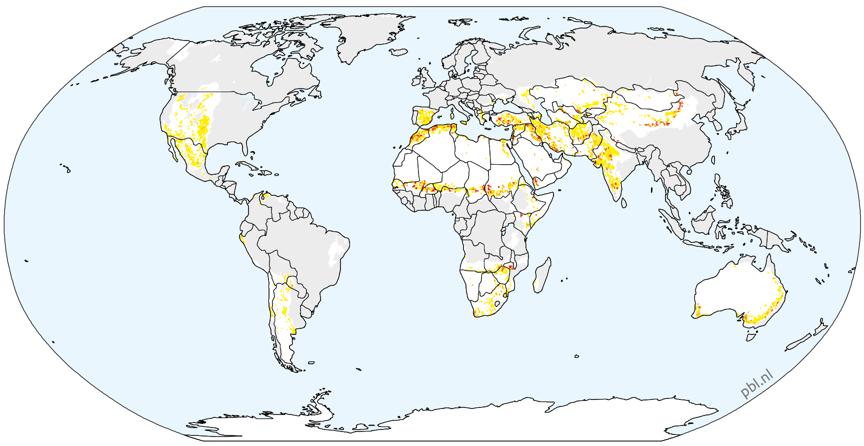
4.3.3 Impacts on river flows and water scarcity

Changes in land cover and soils alter water cycles and influence the probability of flooding and drought
Major changes in global land cover and land use, and climate change affect the water cycle in various ways. These impacts occur in multiple processes that play out on various spatial and temporal scales, changing the run-off, the water that flows over the surface of land directly into rivers (Figure 4.18):

- **Evaporation and transpiration:** More evapotranspiration decreases run-off. Evapotranspiration increases with growing vegetation. Inversely, run-off increases when the amount of vegetation growth declines, for instance outside the growing season.
- **Changes in land cover and soils:** The absence of a protective vegetation cover and soil compaction can lead to soil sealing which increases run-off. Loss of soil organic matter reduces the water holding capacity of the soil, and leads to a wetter land surface and more run-off during the rainy season, and to a dryer surface during the dry season.

Figure 4.19

Decrease in water holding capacity in arid areas under SSP2 productivity-decline scenario, 2010 – 2050



Decrease in water holding capacity

Small Large

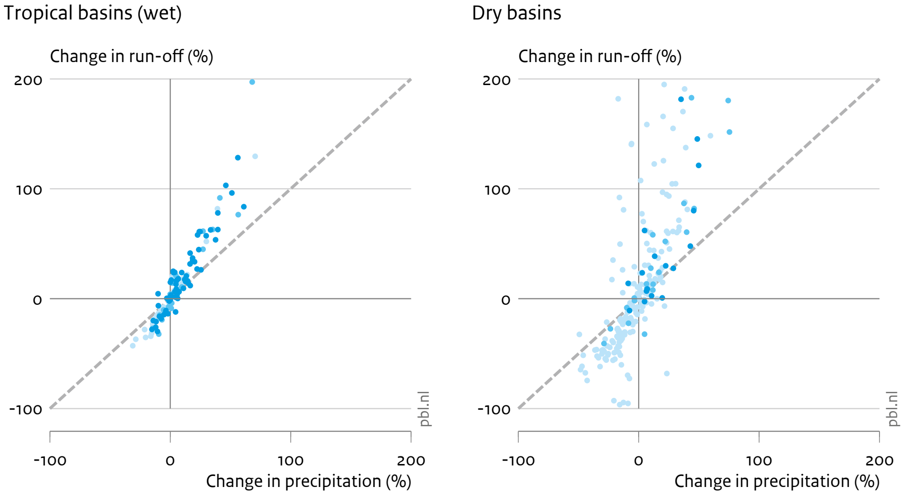
No decrease

Non arid areas

Source: UU; PBL

Figure 4.20

Change in run-off due to changes in climate and land cover, under the SSP2 scenario, 2010 – 2050



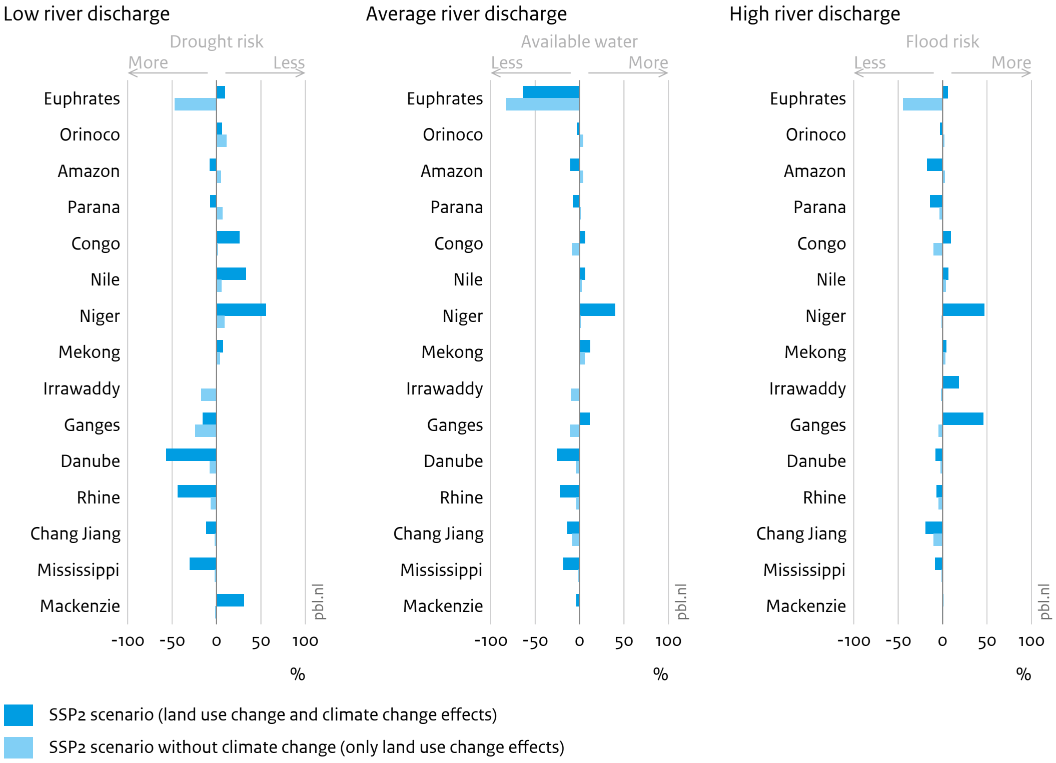
Waterbasins with

- Little land-cover change
- Moderate land-cover change
- Strong land-cover change

Change in precipitation = change in runoff

Source: UU; PBL

Figure 4.21
Change in major river-basins discharge, 2010 – 2050



Source: UU; PBL

Loss of soil organic matter affects the water holding capacity of soils, reducing local water availability especially in drylands
The water holding capacity of soil is especially relevant for rain-fed agricultural production in arid areas, where rainfall can be erratic and the buffering capacity of soils to store water is an important factor for plants to bridge dry spells. Low yields in semi-arid systems, for instance, are often ascribed to excessive soil evaporation, a situation in which higher proportions of soil organic matter and mulching could improve productivity (Jägermeyr et al., 2016). Especially in arid areas, a decrease in water holding capacity might be the tipping point for crop failure. Under the SSP2 productivity-decline scenario, changes in water holding capacity are expected in areas where agriculture could be affected, such as the plains in North America, Spain, and parts of India, Pakistan, Sahel and the Maghreb (Figure 4.19).

Under a warmer climate scenario, arid zones are most at risk of land-cover change affecting run-off
In a warmer climate, evapotranspiration increases. A decline in land cover, such as that occurring in cultivated areas, leads to a local decrease in evapotranspiration and therefore more run-off. Figure 4.20 shows the projected change in run-off in river basins due to changes in precipitation, temperature and land cover and land use in tropical (wet) and arid climate zones.

In the SSP2 scenario, many river basins that are expected to see increasing precipitation due to climate change show an increase in run-off that is larger than expected. The decline in vegetation appears to be a major cause, reducing the buffering of water flows and leading to extra run-off. The most striking increase in run-off is projected to take place in small basins in the arid climate zones, where a minor reduction in land cover may cause a marked increase in run-off (Figure 4.20). A disproportionate decrease in run-off due to a decrease in precipitation can also be seen in the arid climate zones. In a few basins, an increase in precipitation is accompanied by a decrease in run-off. Here, increasing evapotranspiration caused by higher temperatures is the dominant factor.

Land-use change may amplify or moderate the effects of climate change on water flows and on the risks of flooding and drought
As discussed above, changes in climate and land cover influence the run-off and discharge of rivers.
To distinguish whether these effects are exerted by

changes in land cover or by climate change, the data of an SSP2 variant without climate change has been added. Figure 4.21 shows the relative changes in low, average and high discharge volumes projected by the SSP2 scenario for large river basins. The average discharge is informative about the projected change in the availability of water. The maximum and minimum discharge levels within a year are informative about change in flood and drought hazards. Low volume is defined as a discharge that is surpassed 90% of the time; average volume is surpassed 50% of the time and high volume 10%.
A downward change in low discharge indicates that a river basin will be more susceptible to hydrological drought, and less susceptible in the case of an upward change.
An upward change in high discharge indicates that a river basin will be more susceptible to flooding.

Effects on water discharge in major river basins under the SSP2 scenario
The individual effects of climate change and land-cover change may amplify or moderate one another.
These interactions and their intensity vary per river basin and are related to the following processes:
- Climate change leads to more intense and often more variable precipitation, increasing run-off and average discharge;
- Climate change leads to a temperature increase, potentially increasing evapotranspiration and reducing run-off and discharge;
- Climate change leads to higher temperatures and an earlier onset of snowmelt, increasing discharge extremes in temperate and arctic rivers;
- An increase in cultivated area reduces vegetation and evapotranspiration and increases run-off and discharge;
- Land management that reduces the water holding capacity of the soil or increases soil sealing increases run-off and discharges;
- Expanding agriculture usually increases water withdrawals, with irrigation in particular leading to declining stream flows.

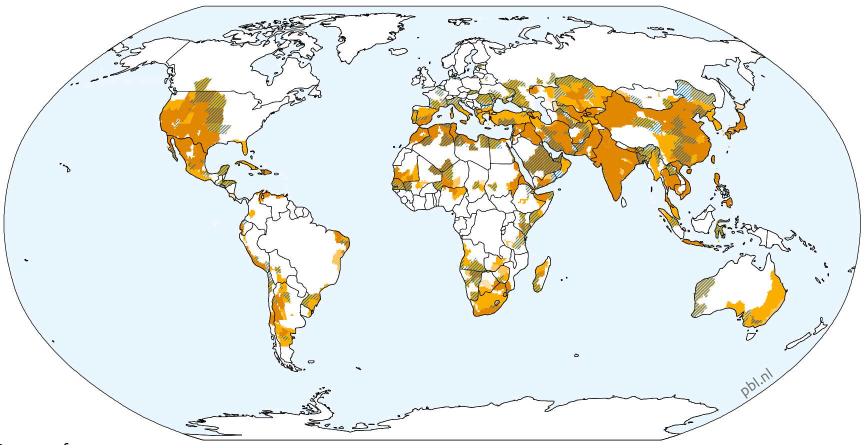
Figure 4.21 shows the amplification or moderation of the effects of climate change and of land cover and land use for various basins. In the Euphrates, an increase in precipitation is expected but this is insufficient to offset the growing water demand in the river basin, resulting in lower overall discharge and increasing drought risk.
The South American rivers Orinoco, Amazon and Parana show opposite trends with declining land cover leading to higher discharge volumes and increasing temperatures leading to less discharge. The Congo – the second largest river in the world, covering 3% of the global run-off – also shows opposite trends in discharge with land cover and climate change resulting in net higher discharges. A more intense hydrological cycle caused by climate change is projected for the Nile and Niger where low, average and high discharges will increase.
Generally, the flood hazard for the Irrawaddy and Ganges will increase due to climate change, while increasing water demand will lead to lower average and low-volume discharges. Temperate river basins, such as the Danube, Rhine, Chang Jiang and Mississippi, all show sharply decreasing discharges following changes in climate, land use and land cover. Land abandonment in the Rhine and Danube basins is expected to cause increased evapotranspiration and thus reduce average discharge levels.
The Mackenzie is the only arctic basin assessed here. Overall, it shows little change, as land-use change is marginal and climate change does not affect the total discharge.

The sheer size of the projected changes in some rivers gives cause for concern. The low-volume discharges of the Rhine and Danube are expected to further decrease to half their current volumes under the SSP2 scenario. This means that water will become scarce in summers with possible consequences for inland shipping and agriculture. High flows in the Niger and Ganges projected to increase by 50% give concern for the probability of flooding. Especially in the heavily populated Ganges basin this may have severe consequences. Overall, the future changes by 20% or more seen in various river basins may signal serious increasing risks of flooding and drought. Land use and land cover play a significant role in these effects in many of these river basins.

Changes in river discharges and future water scarcity
With water demand increasing greatly (Chapter 3), water scarcity may become a growing risk. Uncertainty on the availability of non-renewable groundwater resources, changing rainfall patterns, land-cover change and loss in soil properties will all affect water availability.
Water quality, not addressed here, is an additional concern. The arid areas in particular, with their low volume of fresh water, are sensitive to deterioration of water quality.

Water scarcity is the limited availability of water for various users. It is calculated as the ratio of water demand to available water in a certain area (Van Beek et al., 2011). Under the SSP2 scenario, the global water demand increases by 19%, approximately from 2100 km^3 to 2,400 km^3 in 2050. The domestic and industrial water demand will double, while the water demand for cooling energy plants is assumed to decrease due to new techniques. The water demand for irrigation will increase and Asia and Sub-Saharan Africa show a large increase in demand from industry and households (Chapter 3).

Figure 4.22
Water scarcity under the SSP2 scenario, 2050



Source: UU
The dynamic water scarcity index map is based on a monthly timescale and accounts for how often and how persistent water scarcity conditions occur, per year.

Figure 4.22 shows that, by 2050, water scarcity may occur frequently in densely populated regions, such as India, Asia, the western United States and Spain, which are mostly arid regions. It also shows in which regions water scarcity is likely to worsen, compared to 2010. The change may be caused by increased scarcity over the whole year or by more frequently occurring periods of scarcity within a year. Whether local water scarcity will be problematic also depends on measures taken, such as local storage, pumping of groundwater from aquifers, or upstream initiatives to prevent deficits downstream. The projections explored here are only a rough outline of the risks and do not include these potential mitigation and adaptation measures.

4.4 Uncertainties

This chapter first explores direction, size and location of potential changes in land condition and then estimates the extent to which land degradation can compromise ecosystem functions and services in the future. These outcomes are inevitably uncertain due to the large number of interacting factors, the spatial variability, a structural lack of globally consistent data and the early stage of development of the employed type of quantitative scenario analyses. This section summarises key uncertainties and omissions resulting from the methodology.

Problem framing and conceptual approach
The conceptual approach does not define land degradation. Instead, the approach explores historical changes and potential future changes in a number of indicators of land condition, caused by human intervention. It does not judge whether the state of these indicators, or the past and future changes to it, reflect land degradation.
By sidestepping the question of what land degradation is and what it is not, and providing quantitative estimates which are globally consistent, and comparable and scalable over time and space (Box 2.2), this approach allows others to decide whether or not these changes and trade-offs represent land degradation.

The conceptual framework views the state or condition of land as a determinant of ecosystem functions. The analysis of ecosystems functions carried out here resembles the approach in LADA-GLADIS, which focuses on the state of and trends in land resources in terms of biomass, water resources, soil health, above-ground biodiversity, and economic and social provisions contributing to ecosystem goods and services (FAO and ITPS, 2015). It is also in line with the scientific conceptual framework for land degradation neutrality published by the UNCCD (Orr et al., 2017).

Scenarios
This chapter uses the SSP2 scenario as a 'middle of the road' scenario out of three scenarios, with moderate projections of population growth, demand, land use and climate change. A variant, the SSP2 productivity-decline scenario, has been developed to assess the effects of future decline in soil properties, productivity and land cover on ecosystem functions.

The projections in the SSP2 scenario have considerable uncertainties, as discussed in Chapter 3. By only changing the land condition in the SSP2 productivity-decline scenario, the impacts relative to the SSP2 scenario become clear while the majority of uncertainties across the two remain the same. However, this chapter lacks the bandwidth estimates for changes to land condition and the robustness of the relative size of changes could thus be tested further.

The land-management effect in the SSP2 productivity-decline scenario is based on a combination of satellite observed long-term trends and climate modelling: Major uncertainties exist in i) the original NDVI data-set as a basis for productivity and land cover (Guay et al., 2014); ii) the limited time period for which observations are available (28 years) compared to the length of extrapolation (40 years); iii) the reliance on a single NDVI metric (Schut et al., 2015); iv) the correction of observed trends for climate change going beyond the hotspots reported in Schut et al. (2015) and Conijn et al. (2013); v) derivation of soil properties from changes in land cover and land use (Chapter 3) with the S-World model (Stoorvogel et al., 2017a and 2017b); and vi) the application of the outcomes to soil, productivity and land cover in the models IMAGE, GLOBIO and PCR GLOBWB to estimate the impact on cropland area, water regulation, land-based carbon emissions and biodiversity.

The lack of data on underlying causes of change in land condition
Not explicitly included are causes and mechanisms of land degradation, such as erosion, salinisation, sealing, compaction and the chemical pollution of soils. The SSP2 productivity-decline scenario is, however, assumed to approximate their effects as these processes affect biomass productivity. A possible verification step would be to check the observed trends in biomass productivity against areas known to be undergoing these types of degradation. This is challenging, however, given the lack of systematic inventories of institutional, socio-economic and biophysical causes of land degradation at national or regional levels (FAO & ITPS, 2015).

Given the lack of globally consistent field data, it is obviously difficult to assess the uncertainties of the individual steps. In addition, it is much more difficult to assess the uncertainties over the entire effect chain. A few reflections can be offered, though. Firstly, most individual steps concern cause-and-effect relationships based on empirical data, being generalised for global application. The derivation of land cover and productivity from NDVI observations are two examples. Secondly, most steps and all models have been published in peer-reviewed articles, but the correction of the biomass productivity trends for climate change effects in order to determine the land-management effect has not. The separation of the effects and the spatial distribution has been published in Schut et al. (2015), but the precise adjustment of the trend has not, making it a weak point in the analysis. Nevertheless, the decision has been made to filter out the effects of climate change, since they are a potentially serious distorting factor in assessing the impact of changes in land condition caused by land management. Thirdly, soil property results from the S-World model inherently stay within the ranges of field observations, as the model does not allow higher and lower values than the 90th and 10th percentile, respectively. Given the considerable uncertainties described above, the direction of the effects is considered to be more robust than the relative changes.

Temporal and spatial scales
The long term of the projections, to 2050, is appropriate for the analysis, because the key processes explored (i.e. changes in socio-economy, land use, land management, land condition and climate) unfold rather slowly. The level of spatial resolution (see Annex 3) may lead to an underestimation of the impacts on land condition and ecosystem functions. More extreme local impacts might be 'diluted' because of aggregation of detailed maps to a coarser resolution, to accommodate model projections.

Choice of indicators for land condition and ecosystem functions
This chapter selected a number of indicators to explore changes in the condition of land. The indicators of land cover, soil organic carbon and productivity correspond to those discussed under the UNCCD, the mean species abundance is one of the indicators used in the Global Biodiversity Outlooks under the CBD for terrestrial biodiversity, and aridity is used under the UNFCCC. Nutrient budgets are common indicators in agriculture, while and water holding capacity and river discharge are common indicators in hydrology. Taken together, they

cover a spectrum that includes key biophysical processes and provides links to the Rio Conventions. Finally, Figure 4.1 shows that several relationships between the main drivers of change (change in land use, land management change, and climate change), land condition, and ecosystem functions and services are not quantified in the projections. Including these connections may affect the results, for instance in the case of soil organic carbon losses affecting water regulation.

4.5 Conclusions

The future impacts of changes in land condition are generally not included in global assessments of environmental change. However, the estimates on the amount of degraded land, its global distribution, related economic costs, and negative effects on poor and vulnerable populations in particular make this an important oversight. Especially when it comes to agriculture, there is much uncertainty on the degree to which unsustainable practices degrade soil resources in the long term and thus put their continued use at risk.

Future changes in the condition of land are projected to be extensive, as a result of both continued land-use change and detrimental land-management practices. The region most affected is Sub-Saharan Africa, with many of the other regions also showing considerable signs of land and soils degrading as a consequence of land management. Over 15% of the land area in Sub-Saharan Africa shows declining productivity trends, when corrected for climate effects, while in most other regions the figure lies between 5% and 10%. On top of that, the projections discussed in Chapter 3 show significant future agricultural expansion on tropical soils that are vulnerable to risks of erosion and land degradation if not managed sustainably (FAO and ITPS, 2015).

Agricultural yields, soil nutrient supply, water availability and flows, and carbon emissions are all affected by deterioration of land. The rough estimate of an additional 5% of agricultural area needed by 2050 if current productivity declines continue is large when compared to the 8% increase in agricultural area due to rising demand to 2050. Further agricultural expansion will in turn lead to additional losses of remaining natural areas, biodiversity, and carbon content. Water cycles, crop yields, the likelihood of flooding and drought, and the navigability of rivers are not only affected by climate change, but also by changes in land cover and soils. Projected carbon losses up to 2050 associated with land-use change, land cover and productivity loss will amount to about eight years of current global carbon emissions from fossil fuel use, a sizeable share, compared to international climate ambitions. The carbon storage potential of agricultural land is high, but requires the development of high-yield agricultural systems with near-natural carbon levels.

While the indicators in this chapter point to land management negatively affecting productivity and ecosystem functions as a global phenomenon, dryland areas are projected to be especially affected. Their soils are generally more vulnerable to erosion, and the effects of future land-cover change and soil organic carbon losses will exacerbate the challenge to manage water in these regions. To make matters worse, populations in drylands are projected to increase strongly, by 40% to 50%, under the SSP2 scenario, which is considerably more than the increase outside drylands. Adequate systems of land management and governance will be required to manage these challenges.

The estimates presented here are a first attempt at including changes in land condition in a global scenario analysis. Nevertheless, the results underscore the need for policymakers to give due attention to sustainable land management. While the impacts of land degradation are multiple and have both local and global effects, restoration and prevention of further losses will likewise yield multiple benefits. Restoring soil organic carbon levels improves yields and water management, and contributes to climate change mitigation. Stimulating the adoption of more sustainable land management in land-use sectors, such as agriculture, livestock farming, and forestry, appears to be a direction of intervention with few downsides, especially when developed in the regions that are projected to see considerably increased pressure on land and water, and where people rely disproportionately heavy on land for their livelihood.

Notes

1 The results of the SSP1 and SSP3 scenarios with regard to biodiversity are also presented.

2 Changes in NPP could not be assessed for the entire planet. In an area of about 29 million km^2, NPP trends could not be derived from NDVI measurements, either due to a lack of a significant correlation between NPP and NDVI, absence of vegetation or lack of data. This area is included in the No significant loss in net primary production fraction.

3 Mean species abundance has been defined as the average population size of the original species relative to their population size in the undisturbed state (Alkemade et al., 2009; Stehfest et al., 2014; www.globio.info).

4 UNFCCC Paris agreement Article 2 p.: Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. Scenarios with a likely (>66%) probability of keeping global temperature increase below 2 °C should limit future cumulative CO_2 emissions to 630–1180 $GtCO_2$ (170–320 GtC).

Regional risks and lines of response

Chapters 3 and 4 have shown that there are significant global and regional trends affecting land that will impinge on the efforts necessary to attain many of the Sustainable Development Goals. For these trends, Chapters 3 and 4 provide scenario projections per indicator in the various regions. This chapter pivots the analysis of the results to the regional perspective. As much of the results have already been presented in the previous chapters, the discussion here is kept brief. The chapter ends with an overview of the main lines of response to bring land use and land management in line with sustainability ambitions, given expected future developments.

5.1 Regional challenges related to land

This study uses a subdivision of the world into 10 geo-political regions, for which the scenario results are presented in Chapters 3 and 4 (see Annex 4 for a map of the regions). For each of the 10 regions, this section provides a summary of those results to assess the challenges related to land and land management, both in the current situation and for the period up to 2050. The future results for each region are based on projections from the SSP2 and the SSP2 productivity-decline scenarios.

Table 5.1 provides an overview of most of the indicators dealt with in previous chapters, by region. They are subdivided into four categories corresponding loosely to the chapters of this report: socio-economic issues, demand for land-based products, land use (Chapter 3) and land condition (Chapter 4). For each region, the results are further specified for both the 2010 situation and the SSP2 projection of change towards the 2050 situation. While the 2010 situation provides an idea of the current land-related pressures in a region, the change to 2050 indicates the additional pressure that a region will come to bear and the dimension of the adjustments or accommodation required.

Some regions face a larger set of land-related challenges than others. The 10 regions are divided into three groups, according to the number and relative size of socio-economic and environmental challenges facing them. Five regions appear to be relatively stable and are expected to face only a small number of land-related challenges that require specific managing. Three regions see a combination of current and projected future challenges that – if the projections materialise – can become extremely difficult to manage. The two remaining regions are somewhere in between, one currently facing a more complex set of challenges – though many are expected to become smaller towards 2050 – and the other seeing challenges relating particularly to current and future land use. This categorisation of regions is somewhat arbitrary, compares challenges of various sizes and shapes for the current and projected future situations, and disregards indicators of institutional capacity and potential responses. Nevertheless, the pattern that emerges points to a number of critical situations in each region that warrant attention.

Five regions face challenges that are relatively small in number or size: North America, Western and Central Europe, the Russian region and Central Asia, the China region, and Japan and Oceania. These regions are relatively wealthy or quickly becoming so, and see challenges scattered over several areas. Of these regions, only North America is expected to see its population grow significantly up to 2050, and both North America and Japan and Oceania are expected to see sharp increases in dryland populations. There is limited remaining available agricultural land in the China region and Japan and Oceania, but their population projections show modest increases or even decreases, making this less of an issue. The one challenge that stands out is water stress, affecting all five regions, both in terms of the currently affected proportion of the population and the projected increase in this group.

Three regions, Sub-Saharan Africa, South Asia, and the Middle East and Northern Africa, face the most difficult challenges. These regions are characterised by a combination of challenges which are much more serious than those faced in other regions: high levels of population growth, including in their drylands, low current levels of GDP per capita, marked increases in water stress, limited protein intake, dependence on imports for their food supply, low crop yields, intense pressure to expand agricultural land use, and high levels of historical and ongoing productivity loss. Even with sufficient institutional capacity, it would be difficult for any region to overcome and adapt to this combination of challenges.

Two regions fall somewhere in between: Central and South America, and Southeast Asia. The Southeast Asia region is characterised by a marked rise in water demand, dependence on food imports, high increases in agricultural area and a low GDP per capita. Though GDP is set to grow fourfold by 2050, the accompanying increase in demands will likely put further pressure on the limited amount of potentially available cropland, leading to high levels of biodiversity loss. Central America and South America are different, and are mostly expected to see challenges related to projected increases in land use for agriculture and livestock, and to the likelihood of competition for land for various uses and between various interest groups. Both regions can be said to be at a tipping point. The challenges are not overly daunting, nor are many of them dramatically increasing, and the projected economic development indicates governments will have the means to manage the situation. But these challenges are not to be underestimated, and if countries within these regions fail to implement appropriate management of natural resources it is easy to see how the situation can deteriorate.

No analysis has been made of the possible consequences of these combinations of challenges for specific regions. This requires improved accuracy of the projected outcomes, and a better understanding of the related uncertainties and the interactions between them, at the level of the regions. More detailed analyses also require a specific look at two aspects that have not been covered in detail in this study. The first is the ability of regions to cope with current challenges and future changes through institutional action and governance to regulate competing claims on land resources, distribute the benefits, and stimulate sustainable management (Section 5.2). The second is the extent to which regions are able to develop lines of response to the challenges (Section 5.3). Both are introduced below but require much deeper analysis to assess what they can mean for the addressing of regional challenges.

5.2 Institutions and governance relating to land

This section provides a brief introduction to discussions around land governance. Future analyses would do well to see if scenario assessments can be combined with research on institutions and land governance. This is particularly relevant when it comes to assessing potential response lines to land-related challenges (Section 5.3).

The increasing importance of land governance

Land governance is becoming more and more important as cumulative pressures from the demands for food, feed, biofuels, nature conservation, and urban expansion lead to increasing competition for land. This may be either direct competition between various types of land use within countries, or competition spurred by international trade between countries.

Land governance refers to how interactions between actors shape 'decisions that are made about the use of and control over land, the manner in which the decisions are implemented and enforced, and the way that competing interests in land are managed' (Palmer et al., 2009). Put differently, land governance is about the various ways in which political and societal steering in relation to the use of land takes place (see Peters and Pierre, 2016). In the context of the abovementioned pressures, a particularly pressing question is how such steering can come to accommodate the wide range of interests and ideas involved in land-related developments and challenges; in other words, what determines the *quality* of land governance?

The central role of institutions in land governance

In principle, governance interactions are structured by institutions but they also create and change them. Understanding the constraining and enabling effects of institutions –defined broadly as the rules, norms and meanings that, together with the related activities and resources, provide stability and meaning to social life (Scott, 2008) – and how changes may affect them is therefore of vital importance.

The list of institutions that have been identified as affecting land-use change is a long one (e.g. see Broadhead and Izquierdo, 2010; Keys and Mcconnell, 2005; Roy Chowdhury, 2006), whereby distinctions can be made between those that are formal and informal, those that emerge bottom-up or top-down, and those that interact on different levels (local, national, global). *Land tenure* regimes have traditionally attracted much scholarly interest (e.g. Angelsen, 2007; Keys and Mcconnell, 2005).

Table 5.1
Overview of selected indicator outcomes, per region

Category	Indicator	Unit	North America 2010	North America Change 2010–2050	Central and South America 2010	Central and South America Change 2010–2050	Middle East and Northern Africa 2010	Middle East and Northern Africa Change 2010–2050
Socio-economic	Population	*billion*	0.46	31%	0.48	25%	0.38	61%
	Dryland population	*million*	113	36%	79	123%	373	60%
	GDP per capita	2005 USD PPP	32,304	64%	5,105	200%	4,455	180%
	Water stress[a]	*number of people exposed (millions)*	183	46%	214	11%	262	67%
Demand	Food crops	*kcal/cap/day*	2,733	-3%	2,300	12%	2,549	0%
	Livestock products	*kcal/cap/day*	917	-3%	562	12%	289	17%
	Water	*km^3*	233	8%	102	34%	181	9%
	Import dependence (net trade in agricultural products)[b]	*million tonnes of dry matter per year*	88	18% (2010), 15% (2050)	22	6% (2010), -3% (2050)	-59	-36% (2010), -26% (2050)
Land use	Cropland[c]	*million km^2*	2.5	5%	1.5	32%	0.7	24%
	Pasture	*million km^2*	3.3	-5%	4.6	8%	2.3	-1%
	Potential Available Cropland (PAC) per capita	*hectares per capita*	1.8	-24%	2.1	-20%	0.9	-38%
	Remaining PAC	*million km^2*	2.9	0%	4.5	-8%	0.2	-38%
	Remaining High Quality PAC	*million km^2*	2.3	0%	1.5	-6%	0.0	-2%
	Average crop yield	*tonnes per hectare*	5.1	27%	3.1	58%	2.4	84%
Land condition	% of natural land with reduced productivity compared to natural situation	%	13%		20%		11%	
	Area with land management-related productivity decline[d]	*million km^2*	1.2		0.4		0.2	
	Additional cropland required to compensate for productivity loss	*% of 2010 cropland area*		2%		1%		22%
	Soil organic carbon loss[e]	GtC	28	2.5	20	2.0	4	0.7
	Biodiversity	*Mean Species Abundance (MSA)*	65%	-13%	65%	-18%	81%	-5%
	Dryland areas	*million km^2*	8.7	-5%	5.1	-1%	10.9	0%

[a] Includes categories from low to very high water stress.
[b] Positive figures indicate the region is a net exporter. Negative figures indicate the region is a net importer. The two figures in the 'Change 2010–2050' column show the net trade as a share of demand for agricultural products, for 2010 and 2050.
[c] Includes cropland for energy crops.
[d] See Chapter 4. Long-term trends in net primary production, corrected for climatic effects, are a proxy for the effects of land management and human disturbance on ecosystem biomass productivity.
[e] Loss up to 2010, compared to undisturbed conditions and projected losses over the period from 2010 to 2050, in GtC. Does not include climate-change-related changes in SOC.

	Sub-Saharan Africa		Western and Central Europe		Russian region and Central Asia		South Asia		China region		Southeast Asia		Japan, Korea and Oceania	
	2010	Change 2010–2050	2010	Change 2010–2050	2010	Change 2010–2050	2010	Change 2010–2050	2010	Change 2010–2050	2010	Change 2010–2050	2010	Change 2010–2050
	0.86	109%	0.61	11%	0.28	-1%	1.64	46%	1.38	-6%	0.59	26%	0.23	-2%
	371	100%	176	17%	163	-5%	1010	53%	468	-17%	19	-91%	10	106%
	963	378%	25,802	74%	4,338	260%	898	607%	3,634	704%	1,974	460%	28,537	81%
	234	109%	146	88%	70	73%	1533	46%	1256	-4%	414	29%	177	-2%
	2,068	34%	2,624	-4%	2,460	2%	2,260	13%	2,594	-7%	2,403	21%	2,261	-2%
	149	41%	891	1%	639	9%	221	0%	621	2%	244	24%	438	10%
	76	63%	174	9%	165	4%	673	24%	351	15%	57	62%	44	0%
	-18	-6% (2010), 0% (2050)	-25	-5% (2010), 4% (2050)	21	12% (2010), 30% (2050)	-12	-2% (2010), -4% (2050)	-1	0% (2010), -6% (2050)	9	2% (2010), 2% (2050)	-24	-24% (2010), -8% (2050)
	2.3	55%	1.6	-1%	2.0	4%	2.2	7%	1.5	-15%	1.0	26%	0.6	56%
	7.8	21%	1.0	-6%	3.3	-7%	0.4	10%	5.0	-1%	0.2	26%	4.0	0%
	1.8	-52%	0.6	-10%	2.6	1%	0.2	-31%	0.6	6%	0.5	-20%	2.5	2%
	6.1	-34%	1.5	3%	2.1	7%	0.7	-24%	0.9	14%	1.9	-9%	1.4	-8%
	1.7	-26%	1.0	4%	1.7	6%	0.5	-24%	0.4	8%	0.9	-9%	0.4	-11%
	1.2	105%	4.1	21%	1.9	48%	2.5	62%	5.4	39%	3.5	39%	2.1	13%
	18%		17%		7%		35%		14%		23%		27%	
	3.7		0.4		1.4		0.3		0.8		0.3		0.7	
		7%		3%		4%		4%		3%		2%		5%
	30	12.0	13	1.2	29	2.5	14	1.7	17	0.8	13	2.0	8	1.6
	70%	-20%	37%	-21%	73%	-10%	44%	-21%	56%	-13%	55%	-22%	71%	-19%
	16.3	2%	2.0	5%	7.6	-11%	3.9	5%	6.9	-1%	0.1	-57%	7.2	2%

Other institutional factors that recur throughout the literature include *incentive structures* that affect individual decision-making (e.g. subsidy schemes or regulations), *social norms* (e.g. societal acceptance of forests being burned down to create fertile land for agricultural purposes, or the opposite: a shared sense of forest stewardship), *market access and demand, information systems, conflict resolution systems* and *practices, and donor policies by foreign governments* (Angelsen, 2007; Broadhead and Izquierdo, 2010; Keys and Mcconnell, 2005; Lambin et al., 2003) – with some of these factors possibly representing a variety of institutions, themselves.

It is important to note that such institutions impact decision-making and, ultimately, land-use change in ways that are complex and ambiguous (Lambin et al., 2001). Indeed, the impact of institutional factors can run in opposite directions; institutions can either hinder or contribute to sustainable land-use management (Keys and Mcconnell, 2005; Rockson et al., 2013). Impacts are highly context-specific (Angelsen, 2007), and institutions can therefore have a *direct* effect on individual decision-making and local adaptation strategies concerning land. However, often, they either mobilise direct causes or mediate these (Angelsen, 2007; Broadhead and Izquierdo, 2010; Lambin et al., 2003). For example, although deforestation in Southeast Asia may be partly the result of illegal logging, such illegal practices are in fact enabled by the underlying institutions that facilitate corruption amongst overseers (Jepson et al., 2001). Perhaps the most fundamental aspect is that institutions determine the level or type of access of individuals and groups to land as a production factor (Lambin et al., 2003) as well as to political resources (Borras Jr and Franco, 2010). Through the latter, institutions may have an effect on who is involved in decision-making about land use, on how they are involved, and therefore also on the outcome of such decisions.

The literature on land governance has identified various recurring flaws in these governance processes that can result in unsustainable or unjust land-use practices; particularly, in developing countries:

- Decision-making power often tends to be concentrated in the hands of a powerful few; generally, resulting in a bias towards short-term economic interest, at the expense of pro-poor, sustainable development (Borras Jr and Franco, 2010; FAO, 2011; Palmer et al., 2009).
- Land governance is often affected by general characteristics of poor governance, including corruption, lack of consultation, and lack of transparency (Broadhead and Izquierdo, 2010). In this context, land governance is obviously influenced by national or regional broader quality of governance (Broadhead and Izquierdo, 2010; Palmer et al., 2009).
- Frequent mismatches and frictions occur between top-down and bottom-up institutions and governance processes. Such mismatches may arise, for example, when customary and traditional land-use rights are not included in national policy-making; something that has attracted particular criticism in relation to large-scale land acquisitions (FAO, 2011). Sanderson (1994) formulates this as ‘outside institutions dominating inside institutions’, referring to situations in which institutions from the outside introduce reform at the expense of local land-use managers and institutions (whereby what is outside and inside depends on one’s perspective).
- Fourth, administrative capacity and formal governmental institutions are often weak in the least-developed countries; particularly, in the domains that are relevant for sustainable development (FAO, 2011; Lambin et al., 2001). As a result, problems outpace governance efforts (FAO, 2011), whereby environmental problems affecting local populations are insufficiently estimated and acted upon at higher levels (Lambin et al., 2003). In addition, fragmentation and a lack of transboundary institutions hamper the development of integrated approaches (FAO, 2011). This lack of capacity has been reinforced by a decline in public and private investments in basic infrastructure and institutions, over the last two decades (FAO, 2011; GIZ, 2016).

Gaps, debates and recommendations

Although the image that arises gives cause for concern, some more optimistic observations and arguments can be discerned, as well. Miccolis et al. (2014), for example, observe that a strengthening of high-level coordination has resulted in an improvement in environmental governance in Brazil, although wide gaps remain. Others pose that appropriate land-use policies can contribute to the recovery or restoration of land (Lambin et al., 2003), and that collaborative land governance may help the adaptation to emerging challenges, such as climate change (GIZ, 2016).

The literature provides a wide range of recommendations to improve the quality of land governance. The World Bank has developed a diagnostic tool, the Land Governance Assessment Framework (LGAF), which can be used for analysing shortcomings and the avenues for improvement in existing land governance arrangements (Deininger et al., 2012). Strengthening democratic and/or collaborative institutions in land governance is repeatedly mentioned as a desired form of intervention (Borras Jr and Franco, 2010; FAO, 2011; Palmer et al., 2009). The German Institute for Development Cooperation, in this respect, uses three guiding principles that are largely based on the LGAF: i) efficiency and the promotion of economic development, ii) equity and social justice, and iii) accountability with clear responsibilities and transparent processes (GIZ, 2016).

Table 5.2
Overview of concrete land governance recommendations in the literature

Authors and year	Recommendations
Deininger (2003)	– Formal titles will increase tenure security in many situations, but are not always necessary and often not a sufficient condition for the optimum use of land.
FAO (2011)	– Remove distortions that encourage land and water degradation by changing incentive structures. – Appropriate regulations to address land acquisition. – Better integration and scaling up of international initiatives dealing with land and water management. – Invest in three areas within countries: i) public goods at the national level (e.g. roads and storage), ii) institutions that regulate and promote sustainable land and water management (e.g. research and incentive systems), iii) integrated planning approaches at basin or irrigation scheme level. – Strengthen land and water administration institutions to improve systems for land and water rights where shortcomings inhibit improved productivity. – Adapt common-property systems to provide secure land tenure by legal recognition and protection, or by negotiated and legalised conversion to individual rights. – Promote and regulate land markets to improve allocation efficiency and equity.
GIZ (2016)	– Improve the legal security of property rights in land and assure the application of the rule of law in case of land acquisition. – Ensure transparency in land sale and rental markets. – Enable the delivery of ecosystem services. – Ensure gender equality with regards to land acquisition, use and transfer. – Further develop the harmonisation between statutory and customary land-related rules and the statutory legal framework. – Collaborate with international organisations and regimes. – Cooperate with international agencies in case of financial and human capacity constraints.
Miccolis et al. (2014)	– Mainstream climate-change and conservation policies into wider rural-development and economic policies
Palmer et al. (2009)	– Blur the distinction between design and implementation of reform, to enable reformers to take advantage of new information generated through the reform process.

This, ideally, would result in a more balanced weighing of interests and perspectives in the management of land and other resources (Lambin et al., 2003), whereby trade-offs and unintended consequences are discussed and addressed (FAO, 2011; Roy Chowdhury, 2006). In addition, including a wider range of stakeholders in land governance could enhance a timely identification of, and ability to act upon, new trends and challenges and, in this way, result in more adaptive governance (FAO, 2011). Palmer et al. (2009) distinguish a number of factors that are key for the success of such governance reform: i) political will, ii) a broad coalition for change, iii) sustained grassroots engagement, iv) a shared understanding of land problems, and v) national ownership during the implementation.

Apart from these general recommendations, more concrete suggestions have been made. These are presented in Table 5.2. It is important to stress that these recommendations will not work in every setting and that many of them are subject to academic debate. For example, some scholars and organisations believe that privatised tenure rights contribute to sustainable land use (e.g.Deininger and Jin, 2006; Holden and Otsuka, 2014), whereas others have argued in favour of land governance on community level (e.g. Mckean, 2000; Ostrom, 2015).

5.3 Response lines

This study uses a number of explorative scenarios to examine how land use and land condition may change over the coming decades, as a consequence of changes in populations, income levels and the demand for land-based products. These scenarios do not include an exploration of potential lines of response to improve the management and use of land resources, or of the extent to which these responses can reduce pressure on land and mitigate a series of challenges as discussed in Section 5.1. This section provides an overview of four main lines of response that address various components of the human–land system interactions (Figure 2.8) and can mitigate the pressure of multiple claims on land.

1. Sustainable land management and restoration
Many biophysical interventions exist to help enhance the sustainable use of land and soils. Given the large variety in environmental and socio-economic conditions, as well as land-use types, solutions need to be tailored to the local context. Options for more sustainable management of land include the prevention of unwelcome changes in land condition along with rehabilitation and restoration of ecosystem services and biodiversity, where this is compatible with the use of the land.

- For agricultural and forested land for instance, the maintenance of soil organic matter content is important, due to its pivotal role in soil biodiversity, water regulation, carbon storage and nutrient adsorption. Soil organic matter content can be maintained or enhanced by avoiding run-off (erosion), by avoiding lowering the water table (especially in peat areas) and, especially in the case of crop production, by delivering a regular supply of organic substances (plant residues, manure, compost, etc.).
- At the landscape level, maintenance or reintroduction of landscape elements and other 'natural' areas, which can provide valuable ecosystem services, such as pollination, pest control and water and nutrient regulation (Scherr and McNeely, 2008);
- Prevention of soil erosion, such as by keeping the soil covered (e.g. with growing plants or mulching with leaves), by contour ploughing, by maintaining landscape features, such as hedges, tree rows and ditches, as these usually help to prevent erosion, as well as by preventing overgrazing of pastures;
- Restoration of degraded areas, for example by reforestation, lowering livestock density and the construction of terraces.

The main challenge is for theory to occur in practice, and in such a way that land managers see and profit from the benefits, and thereby safeguard a continuation of sustainable land-use practices. Mechanisms to stimulate this involve strong stakeholder participation, improved tenure systems, legislation, as well as payments for environmental services.

2. Limiting and reducing the demand for land-based products by reducing waste, shifting consumption patterns, limiting bio-energy use and, and increasing efficiencies in supply chains

One important route to reduce the pressure on land is to reduce the demand for products that are produced on land, such as food, bio-energy and timber. For food production, two important pathways exist; the reduction of food waste and losses, as well as dietary shifts towards less resource-intensive products. The latter implies a shift from livestock to plant-based products, while respecting dietary guidelines.

Reducing food waste and losses. According to the FAO, one third of food produced for human consumption is lost or wasted globally, which amounts to about 1.3 billion tonnes per year. Reducing food waste and losses could therefore significantly reduce the demand for agriculture products, and thus lead to a lower demand for land. Food losses and waste have many causes, and effective solutions are very context dependent.
In developing countries, reducing food losses often involves improving infrastructure, particularly storage, transport, energy and market facilities.

- **Shifts in diets.** The production of meat, dairy and eggs is very land demanding. According to Mottet et al. (2017), the production of global feed requires 2.5 billion ha of land, which is about half of the global agricultural area. Livestock use 2 billion ha of grassland, of which 700 million could be used as cropland. Therefore, a shift to more plant-based diets would implicate that less land is needed for food production.

An increase in feed efficiency in livestock systems could also lead to a reduced demand for feed crops and therefore to reduced pressure on land needed for crop production. Globally, there are still large differences in feed efficiency (Gerber et al., 2013), and therefore 'Closing the feed efficiency gap' is one of the three focal points of the FAO-led Global Agenda for Sustainable Livestock. The focus should not be on farm-based feed efficiency by itself, but on the larger food and feed system.
The inclusion of certain by-products or waste streams might even lower the feed efficiency at the farm level, but will also make it possible to replace the input of cultivated feed. Increasing the productivity of pastoral systems is another important effort in certain regions.

Limiting the use of biofuels has multiple sides. Governments that subsidise bio-energy and impose minimum levels of bio-energy use, for instance in transport fuels, should take heed of the trade-offs that increased bio-energy use involves, such as increased land use for their production. In the case of traditional forms of bio-energy, such as fuelwood, efforts to accelerate the transition to modern energy can limit the pressure on forests and woodlands from harvesting, and improve public health at the same time.

3. Increase the efficiency of agricultural land use by sustainably increasing the yields of all commodities with regard to exploited land area, and volume of consumed water and nutrients

Increasing the productivity of the land in a sustainable way is possible for land-use types where production plays a role in reducing the area of land required. This is mainly the case for agricultural land (both cropland and pastures), as well as for managed forests.

To limit, and ultimately, avoid agricultural expansion into nature areas, higher yields on existing agricultural land are required. In many regions around the world large gaps still exist between attainable and actual production, prompting the need for larger investments in agricultural productivity. The risk of more intensive production is that this could lead to higher local pressures on ecosystems. Therefore, a balanced approach should be promoted, aiming at increased productivity of all inputs (including fertilisers), which would also reduce the environmental impact. For this, the term 'sustainable intensification' is often used, which is usually defined as ‘simultaneously improving the productivity and sustainable management of natural resources’, although overlapping definitions exist (Buckwell et al., 2014; Garnett et al., 2013; Pretty et al., 2011). There are many ways to increase crop productivity. These include higher soil fertility (integrated nutrient management), improved crop varieties, better water supply or utilisation of rainwater and improved pest and weed management (for example by biological or integrated pest management).

Increasing long-term crop productivity will require investments – either financial or in terms of labour. An enabling environment is key in order to stimulate these investments (PBL, 2012):

- Proper infrastructure (transport, power, Internet, mobile phone) to lower transaction costs by ensuring optimum connection between producers, suppliers, buyers and consumers;
- Access to credit against affordable conditions, for example, through cooperative banks and micro-credit schemes.
- Transparent and fair price formation for produce and inputs, and minimal price volatility.
- Secure land tenure, for example, through formalised property rights and respect for the rule of law, so that farmers do not risk losing the fruits of their investments
- A fair balance of power between governments, producers and their buyers and suppliers; promotion of transparency and up-to-date market information.

In forestry, the production efficiency per unit of land can be improved, but this brings along trade-offs. Plantations are generally more productive than natural forests and require less land for the same production, but, in contrast, they are much less relevant in terms of biodiversity.

4. Spatial and land-use planning, at local, national and regional scales – ‘doing the right thing in the right place’. This line of response also highlights the need to look for synergies between agricultural production, forestry, the provision of ecosystem functions and the protection of natural capital. Planning options may involve the expansion of protected areas, urban zoning, integrated landscape management and forest moratoriums.

This line of response requires institutions that are capable of developing, implementing and monitoring planned land-use systems.

Annex

A1. Land-related SDGs, targets and indicators

Overview of SDGs, targets and indicators most closely related to land

Table A1.1
Land in the SDGs

SDG	Target	Indicator
Conservation and restoration of land resources		
Life on land	**15.1 Conservation and restoration of ecosystems** *By 2020, ensure the conservation, restoration and sustainable use of terrestrial and inland freshwater ecosystems and their services, in particular forests, wetlands, mountains and drylands, in line with obligations under international agreements*	1. Forest area as a proportion of total land area 2. Proportion of important sites for terrestrial and freshwater biodiversity that are covered by protected areas, by ecosystem type
Life on land	**15.3 A land degradation neutral world by 2030** *By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and flooding, and strive to achieve a land degradation-neutral world*	1. Proportion of land that is degraded over total land area
Life on land	**15.5 Halting loss of biodiversity** *Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species*	1. Red List Index
Clean water and sanitation	**6.6 Restoring water-related ecosystems** *By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes*	1. Percentage of change in water-related ecosystems extent over time
Sustainable and efficient land management		
Zero hunger	**2.3 Doubling agricultural productivity and improving access to land** *By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment*	1. Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size
Zero hunger	**2.4 Sustainable land management** *By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality*	1. Proportion of agricultural area under productive and sustainable agriculture
Climate action	**13.1 Resilience and climate adaptation** *Strengthen resilience and adaptive capacity to climate-related hazards and natural disasters in all countries*	1. Number of countries with national and local disaster risk reduction strategies 2. Number of deaths, missing persons and persons affected by disaster per 100,000 people

Table A1.1 (continued)

Land in the SDGs

SDG	Target	Indicator
Life on land	**15.2 Sustainable management of natural resources** *By 2020, promote the implementation of sustainable management of all types of forests, halt deforestation, restore degraded forests and substantially increase afforestation and reforestation globally*	1. Progress towards sustainable forest management
Ownership and access to land		
No poverty	**1.4 Equal rights and ownership of land** *By 2030, ensure that all men and women, in particular the poor and the vulnerable, have equal rights to economic resources, as well as access to basic services, ownership and control over land and other forms of property, inheritance, natural resources, appropriate new technology and financial services, including microfinance*	1. Proportion of total adult population with secure tenure rights to land, with legally recognized documentation and who perceive their rights to land as secure, by sex and by type of tenure
Gender equality	**5.a Equal rights and ownership of land for women** *Undertake reforms to give women equal rights to economic resources, as well as access to ownership and control over land and other forms of property, financial services, inheritance and natural resources, in accordance with national laws*	1. (a) Proportion of total agricultural population with ownership or secure rights over agricultural land, by sex; and (b) share of women among owners or rights-bearers of agricultural land, by type of tenure 2. Proportion of countries where the legal framework (including customary law) guarantees women's equal rights to land ownership and/or control
Sustainable production and consumption of natural resources		
Affordable and clean energy	**7.1 Access to modern, clean energy** *By 2030, ensure universal access to affordable, reliable and modern energy services*	1. Proportion of population with primary reliance on clean fuels and technology
Responsible consumption and production	**12.1 Sustainable consumption and production** *Implement the 10-Year Framework of Programmes on Sustainable Consumption and Production Patterns, all countries taking action, with developed countries taking the lead, taking into account the development and capabilities of developing countries*	1. Number of countries with sustainable consumption and production (SCP) national action plans or SCP mainstreamed as a priority or a target into national policies
Responsible consumption and production	**12.2 Sustainable management and efficient use of natural resources** *By 2030, achieve the sustainable management and efficient use of natural resources*	1. Material footprint, material footprint per capita, and material footprint per GDP 2. Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP
Responsible consumption and production	**12.3 Halve per capita global food waste** *By 2030, halve per capita global food waste at the retail and consumer levels and reduce food losses along production and supply chains, including post-harvest losses*	1. Global food loss index
Clean water and sanitation	**6.4 Water-use efficiency** *By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity*	Percentage change in water use efficiency over time Level of water stress: freshwater withdrawal in percentage of available freshwater resources

A2. Detailed scenario assumptions for the three scenarios in Chapter 3

Table A2.1
Scenario assumptions for SSP1, SSP2 and SSP3

	SSP1	SSP2	SSP3
Land-use change regulation*	**Strong**	**Medium**	**Weak**
Forest protection	Protected areas are extended to achieve the Aichi target of 17%. Additional areas are also protected to provide essential services in line with Aichi targets 14 and 15, adding up to a total 30% of terrestrial area being unavailable for agricultural expansion.	Current protected areas extended to Aichi target (17%), introduced gradually between 2010 and 2050	Maintain current protected areas
Deforestation	Deforestation for reasons other than agricultural expansion is decreased to zero in 2020	Deforestation for reasons other than agricultural expansion is decreased to zero in 2040	Deforestation for reasons other than agricultural expansion is decreased to zero in 2060
Urban area	Expansion of built-up area as a function of population growth and urbanisation	Expansion of built-up area as a function of population growth and urbanisation	Expansion of built-up area as a function of population growth and urbanisation
Land productivity growth**	**Rapid (for low and medium-income countries) or medium (for high-income countries)**	**Medium**	**Slow**
Crop yield increase	Future crop yields as a function of GDP per capita; see Doelman et al. (in review).	Future crop yields as a function of GDP per capita; see Doelman et al. (in review).	Future crop yields as a function of GDP per capita; see Doelman et al. (in review).
Irrigation	Smaller increase in irrigated area than in SSP2 due to growing sustainability concerns; large increase in irrigation efficiency.	FAO projection on irrigated area expansion (Alexandratos and Bruinsma 2012); medium increase in irrigation efficiency.	Greater expansion of irrigated areas than in SSP2 due to higher food demand and fewer constraints; small increase in irrigation efficiency.
Livestock farming intensification	Faster efficiency increase than in SSP2, approaching SSP2 intensity levels earlier, e.g. in 2030 instead of in 2050, and in 2050 instead of in 2100.	FAO projection as far as possible with the available data, and own expert estimate.	Slower efficiency increase than in SSP2, approaching SSP2 intensity levels later e.g. only in 2100 instead of in 2050.
Environmental impact of food consumption***	**Low**	**Medium**	**High**
Food demand	Less meat and dairy: consumption 5%, 10%, 20% and 30% lower than initial outcome, in 2020, 2030, 2050, and 2100 respectively, for high and medium-income regions.		More meat and dairy: consumption 5%, 10%, 20% and 30% higher than initial outcome, in 2020, 2030, 2050, and 2100 respectively.
Waste	Reduce food waste by 1/3 (current waste is about 33%): implemented as an 11% total efficiency increase in production and consumption of agri-food products. This 11% will be achieved in equal shares by agriculture, intermediate processing stages and final consumption.		Increase of food waste by 1/3 (current waste is about 33%): implemented as an 11% total efficiency decrease in production and consumption of agri-food products. This 11% will be achieved in equal shares by agriculture, intermediate processing stages and final consumption.
Nitrogen fertiliser use	20% increase in the efficiency of nitrogen use relative to FAO projection	Nitrogen use based on FAO projection	20% reduction in the efficiency of nitrogen use relative to FAO projection

Table A2.1 (continued)
Scenario assumptions for SSP1, SSP2 and SSP3

	SSP1	SSP2	SSP3
International trade ****	**Globalised**	**Regionalised**	**Regionalised**
Agricultural trade barriers	Abolishment of export subsidies and gradual reduction of import tariffs for all sectors. In 2020, a 50% reduction on 2010 rates; in 2030, all tariffs abolished.		
Regional preference	Preference for products from own region; implemented by the introduction of import taxes on all agri products. 2030: 5%, 2050: 10%, 2100: 10%.		Food security concerns leading to the introduction of import taxes on all agri products. 2030: 5%, 2050: 10%, 2100: 10%.

* This describes the level and the quality of governance of land use. Strong = high level of forest protection, low availability of non-agricultural land for conversion; weak = low level of forest protection, ready availability of non-agricultural land for conversion.

** SSP2: land productivity trends following largely FAO projections, with declining land productivity growth rate for high-income countries, and medium rates for low-income countries; SSP1 sees low-income countries catching up more quickly, and also takes sustainability issues into account; SSP3: lower land productivity growth rates in all regions.

*** This describes preferences and consumer behaviour, and is on top of endogenous effects resulting from GDP development. Low = relatively low caloric intake, relatively low animal calorie share, low waste; high = relatively high caloric intake, relatively high animal calorie share, high waste.

**** This not only refers to abolishing or maintaining current agricultural trade regulations, but also to a generalised emergence of more or less integrated and globalised world markets.

A3. Methodological information on Chapter 4

A3.1 Introduction

This annex presents the calculation procedures of the change in land condition as elaborated in Chapter 4. Section 3.2 of this annex elaborates on changes in soil properties, in particular soil organic carbon. Section 3.3 discusses the impact on water scarcity and fluctuations in river discharges of changes in soil properties and land cover. Section 3.4 deals with the loss in productivity and the impact on the extent of cropland, and Section 3.5 with the loss of biodiversity resulting from land-cover loss in natural areas and productivity loss in cropland. Figure A3.1 provides an overview of the calculation procedures in 11 Steps which will be referred to in the text below.

A3.2 Soils

This section describes the methodology used to construct global, high-resolution maps of soil organic carbon, soil depth, soil texture and productivity in the undisturbed state, and in the present and future states. The first part, Section 3.2.1, briefly describes a soil model (S-World), mapping present soil conditions. The second part, Section 3.2.2, describes the methodologies to map soil conditions in the undisturbed state and for the projected state in 2050, and the adaptation of the S-World model to make it compatible with the IMAGE model and enable integrated scenario studies. The result is a first estimate of soil properties at three points in time: a hypothetical original situation where soils are undisturbed, not affected by anthropogenic land use and land-cover changes; the situation in 2010 ('the present'); and the projected situation in 2050. The undisturbed state is hypothetical and functions as a natural baseline. It enables, for instance, the formulation of estimates of future change in comparison to historical changes, shows the anthropogenic impact on land, provides a first estimate of the theoretical restoration potential of soil under natural conditions, and forms the basis for a fair comparison between regions in various stages of socioeconomic development (Kotiaho et al., 2016; UNEP, 2003).

3.2.1 S-World, mapping of present soil properties

The S-World model (Stoorvogel et al., 2017a) has been developed to draw global maps of soil organic carbon, soil depth and soil texture (soil properties).
Existing global soil information was compiled at too coarse a resolution to be useful in gridded projections of land-use change. Moreover, no information was available on historical conditions to assess the loss of soil properties, nor on plausible futures to assess risks. Therefore, the S-World model was designed to map the soil properties at grid cell resolution (30 arc-seconds) by combining existing soil information with soil-forming factors.
The assessment of the impacts on ecosystem functions requires compatibility of the S-World model with other, integrated assessment models, such as IMAGE and GLOBIO, and the water model PCR GLOBWB, as worked out in the next sections.

The S-World model consists of two components, elaborated in Step 1 and Step 2 (Figure A3.1). Step 1 describes the development of a global map of single soil types. Step 2 describes how the S-World model determines levels of local soil organic carbon, soil depth and soil texture as a function of the soil type, and the soil-forming factors climate, topography, land cover and land-use intensity.

Step 1: Constructing a Global Soil Type map

The Harmonised World Soil Database (HWSD) (FAO et al., 2012) provides a rough spatial representation of complex soil units that are present at the earth surface. The soil units of HWSD have been disaggregated into a Global Soil Type map that depicts single soil types. Standardised topographic rules (topo sequences) and a global digital elevation model are used for the spatial allocation of the soil types (Danielson and Gesch, 2011). This procedure is part of the S-World model and has been described in (Stoorvogel et al., 2017a).

Step 2: Constructing maps of the present (2010) state of soil properties

In the S-World model (Figure A3.1), the local value of each soil property is a function of the following soil forming factors (Jenny, 1941):

i **Soil type**
ranges of soil depth, soil organic carbon and soil texture are derived for each individual soil type, based on empirical values from a global soil-profile database (ISRIC-WISE 3.1)(Batjes, 2009);

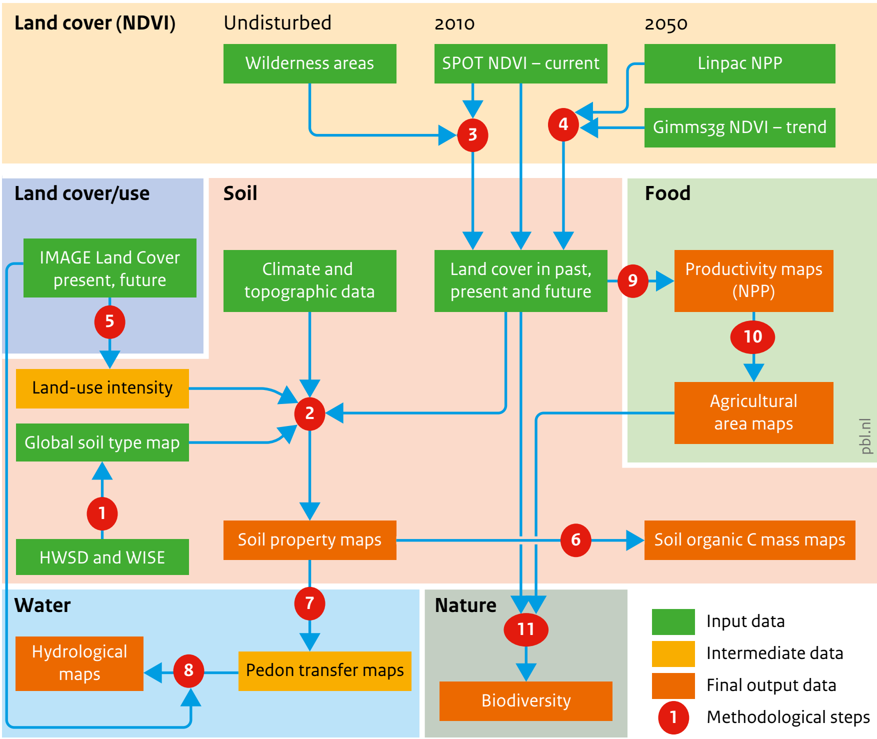
ii **Climate**
the factors used are the mean annual temperature and precipitation from the WorldClim database (Hijmans et al., 2005);

iii **Topography**
this concerns information on terrain slope, derived from Danielson and Gesch, 2011;

iv **Land-use intensity**
this value ranges from 0% for natural areas to 100% for areas under very intensive use, such as cropland; derived from (Bontemps et al., 2011);

v **Land cover**
or vegetation cover protects the underlying soil

Figure A3.1
Procedure for the calculation of changes in land condition and functions



Source: PBL

against erosion and is a source of soil organic carbon. Land cover is derived from a five-year average of SPOT NDVI image ('greenness') data over the 2006–2010 period (http://free.vgt.vito.be).

Applying these global data in S-World generates maps of the present state of soil properties at a resolution of 30 arc-seconds. S-World is extensively described in Stoorvogel et al. (2017a).

3.2.2 S-World, mapping soil properties in the undisturbed state and for 2050

Soil maps of past and future states are important for the following reasons. Maps of soil properties in the undisturbed state enable assessment of how much was lost, in the past, at various locations, and, in the case of soil organic carbon, assessment of a soil's restoration potential under natural, undisturbed conditions. Maps of soil properties for 2050 make it possible to assess how much may be lost in the coming decades, where this might happen, and what the corresponding risks are for key ecosystem functions. For the purpose of this analysis, the first Global Land Outlook, the focus is on estimating loss in soil condition resulting from detrimental land and soil management, rather than other factors, such as climate change.

Constructing soil property maps of the undisturbed state and for 2050 requires the determination of the two anthropogenic factors in the S-World equation: land cover and land-use intensity.

Land cover:

- For a reconstruction of the state of undisturbed soil, the present land-cover map (expressed in terms of NDVI from the SPOT satellite) is replaced by a natural land-cover map. This procedure is elaborated below in *Step 3*. For the 2050 projection, the present land-cover map is replaced by a map derived by extrapolating significant negative NDVI trends over the period from 1982–2010 to 2050. This procedure is detailed below in *Step 4*.

Land-use intensity:

- For the undisturbed state, land-use intensity is set at zero to reflect the absence of anthropogenic land use. For 2050, the land-use map is generated by the IMAGE model for the SSP2 scenario. To ensure compatibility between depictions of present and future land-use intensity, the 2010 map of S-World is replaced by the one derived from the IMAGE model for SSP2 for the year 2010. The assessment procedure of land-use intensity is elaborated in *Step 5*.

Table A3.1
IMAGE model crop types and weighting factors used for generating Land-Use-Intensity maps which served as input for S-World

Crop #	Crop type	Weight	Crop #	Crop type	Weight
01	Grass (rain-fed)	0.5			
02	Temperate cereals (rain-fed)	1.0	13	Temperate cereals (irrigated)	1.0
03	Rice (rain-fed)	1.0	14	Rice (irrigated)	0.75
04	Maize (rain-fed)	1.0	15	Maize (irrigated)	1.0
05	Tropical cereals (rain-fed)	1.0	16	Tropical cereals (irrigated)	1.0
06	Pulses (rain-fed)	1.0	17	Pulses (irrigated)	1.0
07	Roots and tubers (rain-fed)	1.0	18	Roots and tubers (irrigated)	1.0
08	Oil crops (rain-fed)	1.0	19	Oil crops (irrigated)	1.0
09	Biofuel sugar cane	1.0			
10	Biofuel maize	1.0			
11	Woody biofuels	1.0			
12	Non-woody biofuels	1.0			

The other soil forming factors, soil types, topography and climate, are assumed to remain constant over time. Soil types and topography hardly change on timescales of millennia. The impact of climate change is filtered out in this analysis assuming that climate conditions in the undisturbed state and future state are equal to those in the present (2010) situation. The resulting undisturbed-conditions map of soil organic carbon shows a real restoration potential under current climate conditions, instead of climate conditions of the past that do not exist anymore, and thus are politically irrelevant.

Step 3: Deriving a land-cover map for an undisturbed state

The reconstruction of a global land-cover map (expressed in terms of NDVI) for the undisturbed state, keeping climate (temperature and precipitation), soil types and topography constant, is described in detail in Stoorvogel et al. (2017b). To derive a natural-state NDVI map, a space-for-time-replacement approach was applied. A spatially representative sample was collected of locations around the world that have a high probability of being undisturbed. The sample was taken from two global databases, the Data-set of the Last of the Wild Project (Version 2, 2005) (WCS and CIESIN, 2005), and the World Database on Protected Areas (UNEP and WCMC, 2016). The NDVI map of these undisturbed locations have served as a reference, using multiple regression kriging.

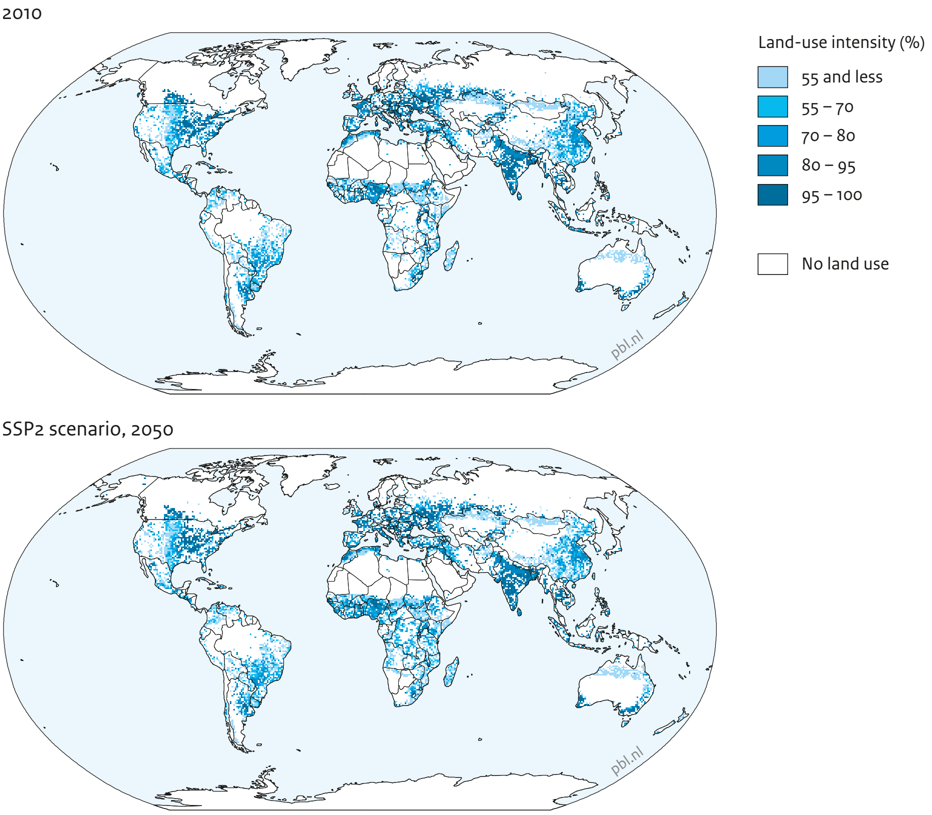
Step 4: Deriving a land-cover map for 2050 by trend extrapolation over the 1982–2010 period

To explore loss in soil properties up to 2050 due to land management, projections have been made for land-use change and land-use intensity. For the land-cover map for 2050, current negative NDVI trends were extrapolated to 2050 (*Step 4*, Figure A3.1), assuming those trends represent the impact of detrimental land management and will continue in the future.

Schut et al. (2015) determined global trends in NDVI to obtain a first estimate of areas that show significant, long-term, negative trends related to land management. They compared six methods for determining NDVI trends in each 5 arc-minute pixel, over the 1982–2010 period, using data from the GIMMS3g data set (Tucker et al., 2005). Based on statistical analyses, they selected the annual sum in combination with a piecewise regression (2 segments) as the most robust approach.
These methods are not dependent on the start and finish of growing seasons of crops which are especially difficult to estimate in areas with two cropping cycles. This approach is also followed in this Global Land Outlook assessment.

The GIMMS3g database was preferred over the shorter but higher resolution time series (2000–2010, 30 arc-seconds) to avoid – insofar as possible – the inclusion of trends from natural climate fluctuations lasting one or two decades, that would compromise the detection of steady negative trends resulting from land management practices. Because NDVI trends are also influenced by structural climate change, Schut et al. (2015) compared these observed NDVI trends with (LINPAC) modelled trends of net primary production (NPP) resulting from actual climate change over the same period, following a method analogous to those described by Bai et al. (2012) and Conijn et al. (2013). In this analysis, these modelled climate-related trends in NPP are used to correct the GIMMS3g NDVI trends for the impact of structural climate change, which is described in the next two paragraphs.

Figure A3.2
Land-use intensity



Source: PBL

The LINPAC model (Jing et al., 2012) calculates and maps the production of annual total biomass weight (TBW) over the 1982–2010 period, given actual weather conditions. These annual maps are used to calculate linear trends for TBW for the same time periods (one or two segments) as the piecewise NDVI trends from GIMMS3g as determined by Schut et al. (2015). For those grid cells without a significant breakpoint in the trend analysis, the full period between 1982 and 2010 is considered. For each grid cell, the trends in TBW are converted into NDVI trends by using biome-specific curvilinear relationships between TBW and NDVI, and then subtracted (as rate) from the NDVI trends to obtain climate-corrected NDVI trends. These NDVI trends are finally converted into yearly climate-corrected changes in NDVI.

The result is a grid map with annual changes in NDVI corrected for the effects of climate change. For each grid cell, the annual trend is extrapolated to 2050. Only those grid cells (of a 5 arc-minute resolution) are selected that fulfil at least one of the following criteria:

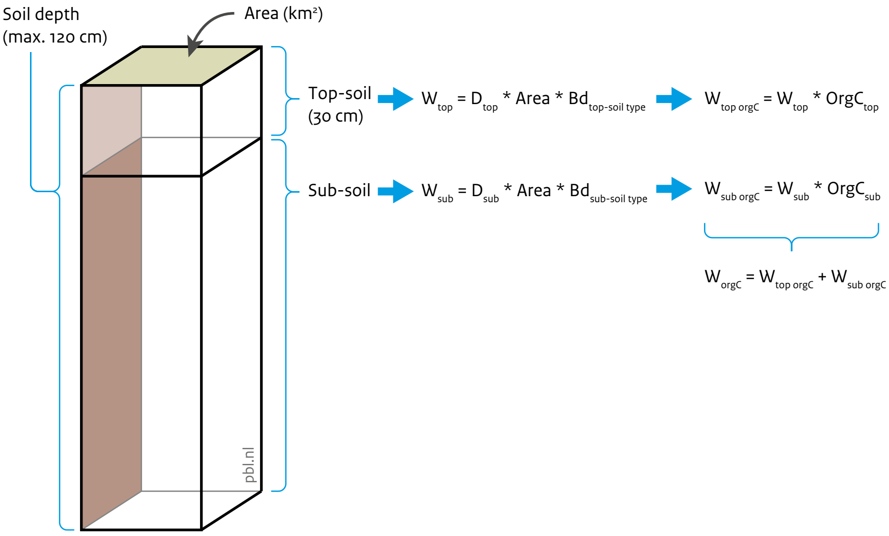
i) a significant negative monotonic trend;
ii) a negative NDVI trend in both segments of the piecewise regression;
iii) a negative trend in the second segment only and an NPP value for 2010 below the initial NPP value for 1982.

The NDVI trend per pixel is extrapolated using the following equation:

$$\mathrm{NDVI}_{\mathrm{year}_{end}} = \mathrm{NDVI}_{year_{start}} \cdot \left(\frac{100 - \%\ \text{annual decline}}{100}\right)^{(year_{end} - year_{start} - 1)}$$

In this equation, year_{end} is equal to 2050, $\text{year}_{\text{start}}$ is equal to 2010, and % annual decline is derived from the climate-corrected NDVI change over the period from 1982 to 2010. Applying a power function, the negative 1982–2010 NDVI trends in the selected grid cells continue to 2050, though at a slowly declining rate. The resulting NDVI map for 2050 is used as input for the land-cover factor in the S-World model to generate soil-property maps for 2050, in combination with the 2050 land-use-intensity map derived from SSP2 scenario projections.

Figure A3.3
Calculation of the total mass of soil organic carbon



Source: PBL

Step 5: Replacing S-World data by IMAGE data for land-use intensity in 2010 and 2050

Coupling the S-World soil model with IMAGE is necessary to create projections of future change in soil properties. This is achieved by substituting the land-use-intensity map of S-World with an IMAGE-based one (*Step* 5 in Figure A3.1). One of the outputs of the IMAGE model is a set of maps describing the proportion of land occupied by a given crop type in a grid cell. Using the S-World methodology as a guide, the following equation was derived to convert the crop-fraction maps of IMAGE into a land-use intensity (LUI) map:

$$LUI_c = \sum_{i}^{19} C_i * W_i$$

In this equation, LUI_C stands for the crop-based land-use intensity, C_i stands for crop type i, and W_i stands for the weighting factor for crop type i (see Table A3.1 for crop types and weights). For this report, two LUI maps have been created (Figure A3.2) to enable tracking changes over time: one depicting the present state (2010) and one to illustrate the SSP2 projections for a future state.[1]

Step 6: Constructing soil organic carbon maps for the undisturbed, present and future states

The total mass of soil organic carbon was calculated using the output from the IMAGE-coupled S-World model on a 30 arc-second resolution (Step 6, Figure A3.1). Besides information about the depth of the soil layers and percentage of soil organic carbon in each layer, data on the bulk density per soil type and the area of each column of soil were worked into the equation (Figure A3.3). The S-World model provides information about the soil depth, soil texture and soil organic carbon content of each grid cell. The bulk density was derived from the Harmonised World Soil Database which provides data on the average bulk density for the top and sub layers (FAO et al., 2012); data from columns labelled T_BULK_DENSITY and S_BULK_DENSITY in the HWSD_DATA table). This means that fixed bulk density values, per soil type, were used for the topsoil and sub soil. As a consequence, changes in mineral composition of the soil, e.g. soil organic matter, clay or sand, will therefore have had no impact on the bulk density used in the calculation of the total mass of soil organic carbon. We chose not to calculate the bulk density from the S-World outcomes, for example, with formulas from Balland et al. (2008), because this would have meant that we also should have made assumptions about the particle density. The calculated total mass of soil organic carbon highly depends on the bulk density, see Figure A3.3. Consequently, variations in the chosen average bulk density estimates led to associated changes in total soil organic carbon.

The area of a grid cell depends on its latitudinal position on the globe. The total area for each 5 arc-minute grid cell is calculated using that position and it is assumed that each 30 arc-second cell within that raster has an area equal to one-hundredth of the area of the 5 arc-minute raster. The mass of soil organic carbon per grid-cell layer, per grid cell and for the world as a whole is calculated as presented in Figure A3.3.

Table A3.4

Soil organic carbon per biome, for certain points in time and various scenarios

		Soil Organic Carbon (Gt)			
Description	**Area, in million km²**	**Undisturbed**	**2010**	**SSP2, in 2050**	**SSP2 productivity decline, in 2050**
Tundra and Ice	8.2	158	149	149	149
Boreal and Cool coniferous forest	20.3	584	567	567	565
Temperate forest	11.4	242	206	205	203
Warm mixed forest and Mediterranean shrub	7.5	122	104	103	103
Temperate grassland	17.5	165	147	146	145
Desert	19.1	149	147	146	146
Scrubland	8.4	105	90	88	87
Savanna	15.8	264	230	223	221
Tropical forest	17.2	400	374	369	369
Total*	**125.4**	**2,188**	**2,013**	**1,997**	**1,986**

* Soil organic carbon figures are rounded to Gt
Column SSP2: The impact from land-use change on soil organic carbon under the SSP2 scenario
Column SSP2 productivity-decline scenario; as SSP2, but also including the impacts of continuing land-cover loss on soil organic carbon, and of the additional expansion of cropland to compensate for productivity loss.

Table A3.5

Land-cover types in PCR-GLOBWB

#	PCR-GLOBWB land-cover types
1	Urban
2	Rain-fed crops
3	Non-paddy irrigation
4	Paddy irrigation
5	Pasture and rangeland
6	Short natural vegetation (grassland)
7	Tall natural vegetation (forest)

The total stock of soil organic carbon and changes over time (*Step 6*) can be calculated by applying the S-World model according to Steps *1 to 4* in combination with the 2010 and 2050 land-use-intensity maps generated by IMAGE for the SSP2 scenario in *Step 5*. For 2050, the figures are adjusted by first including changes in soil properties from the land-use change that is projected to take place between 2010 and 2050 according to the SSP2 scenario (column ‘SSP2’ in Table A3.4). In addition, the changes in soil properties resulting from the negative trends in land cover (NDVI) related to (detrimental) land management (Step 4) are also taken into account (column ‘SSP2 productivity decline’ in Table A3.4).

A3.3 Water

The global hydrological model PCR-GLOBWB (Sutanudjaja et al., 2014; Van Beek and Bierkens, 2009; Van Beek et al., 2011) is applied to calculate water scarcity and changes in river discharge characteristics resulting from changes in land use, land cover, climate and soil properties. Section 3.3.1 briefly describes the technical features of the PCR-GLOBWB model. Section 3.3.2 describes the implementation of the soil-property maps from S-World in the PCR GLOBWB model, enabling the assessment of changes in land condition on water holding capacity, water scarcity and river discharge. In this study, the impact of change in soil properties is determined for water holding capacity only, given the limitations of the modelling at this stage. However, the impact of climate change (precipitation and temperature) and land cover *is* determined under the SSP2 scenario.

3.3.1 PCR-GLOBWB, modelling changes in water scarcity and river discharge

PCR-GLOBWB is a 'leaky bucket' type of model that is applied on a cell-by-cell basis to all land cells on the grid map. For every grid cell and for every time step, the water storage is calculated for two stacked soil layers and an underlying groundwater reservoir. Changes in storage arise because of the exchange of water between these layers (percolation, capillary rise), depletion (interflow and base flow), and processes in the atmosphere (rainfall, snowmelt and evapotranspiration).
Soil hydrology is strongly influenced by land use and land cover and, to take this into account, the land area in each cell is further subdivided into certain land-cover types. The 7 land-cover types distinguished for this study are listed in Table A3.5.

Each of these land-cover types is represented by its fractional contribution to the total land surface as cell-specific values for vegetation and soil parameters. The distribution of these land-cover types is compiled from various sources, and is, in this case, largely conditioned by land-cover and land-use information from the IMAGE model for the SSP1, SSP2, and SSP3 scenarios. Of the land-cover types in Table A3.5, the first five can be considered as intensively modified by humans, whereas the other two are only extensively used and are considered as natural. The standard soil parameterisation in PCR-GLOBWB is derived from the FAO Digital Soil Map of the World (FAO, 1974, 2007)(1: 5,000,000). This data set uses pedons, assemblages of larger soil units, which cannot be accurately linked to single land-cover units. Hence, the default PCR-GLOBWB does not distinguish between soil conditions for different land-cover types within one cell. By coupling S-World to PCR-GLOBWB, it is possible to incorporate changes in soil properties.

3.3.2 Incorporating soil maps of S-World into PCR-GLOBWB

In order to improve the information on the distribution of individual soil types and to generate scenarios of changing soil conditions in the PCR GLOBWB model, the study uses S-World (Stoorvogel et al., 2017a and b). Maps from S-World are sufficiently fine (30 arc-seconds, approximately 1 km²) to make a theoretical link between soil conditions and land cover, and amalgamate this in the soil parameterisation per land-cover type in every grid cell in PCR-GLOBWB (Sutanudjaja et al., 2014; Van Beek and Bierkens, 2009; Van Beek et al., 2011). Moreover, S-World directly estimates the effects of land cover, and any other changes there may be, on soil properties, by applying a land-use-intensity map. This requires, however, a means to transfer the soil information of S-World into the soil properties applied in PCR-GLOBWB and the use of a unified land-cover map.

Step 7: Pedon transfer maps: applying soil-property maps into PCR-GLOBWB.

The PCR-GLOBWB model cannot directly use the soil information of S-World, which has a finer spatial resolution and only specifies some general attributes. In *Step 7*, the soil attributes of S-World are transformed into the soil hydraulic properties, such as water holding capacity, field capacity and wilting point, which are applied in PCR-GLOBWB using the pedotransfer functions from Balland et al. (2008). These functions are chosen because they are sound and compatible with the information supplied by S-World. Overall, these functions provide good results with high coefficients of determinations, and minimise bias. Moreover, they were originally developed for soils with high organic matter content and therefore overcome the limitation of many other pedotransfer functions that have been developed for agricultural soils with limited soil organic matter content (e.g. Saxton and Rawls, 2006). The pedotransfer functions developed by (Balland et al., 2008) allow the estimation of bulk density and related soil-hydraulic properties at any given depth, which is required to link the layer information from S-World to the two-layer schematisation in PCR-GLOBWB.

In the application of the pedotransfer functions, first all relevant properties are calculated per 30 arc-second cell and at the centre of each layer as originally provided by S-World for each scenario. This information is then scaled to the layer configuration of PCR-GLOBWB. In this study, the choice is made to use a fixed topsoil depth of 30 cm for the first layer in PCR-GLOBWB. To reach the maximum depth of 150 cm, the second layer covers an interval of 120 cm. In PCR-GLOBWB, the total depth in a particular grid cell can be greater than the maximum soil depth in S-World (120 cm), in which case a virtual, third layer is introduced there that does not contain organic matter but has the same textural composition as the soil above. The soil properties of the three layers are then averaged proportionally by depth to provide an incipient soil parameterisation for PCR-GLOBWB at 30 arc-seconds. In places where the S-World soil layer is thin, the third virtual layer emulates an additional layer of parent material that is incorporated in the soil mantle. It should be stressed that, as a result of the choice of the corresponding layer depths, the top soil properties in PCR-GLOBWB at the original resolution of 30 arc-seconds are always identical to those derived directly from S-World.

Step 8: Applying IMAGE land-use maps into PCR GLOBWB

At the 30 arc-minute resolution of the PCR-GLOBWB model, the grid-map cells can contain a number of 30 arc-second cells, ranging from 100 to 3600. For each soil property, the average value of those 30 arc-second

cells is assigned to the corresponding cell in the coarser PCR-GLOBWB map. In principle, these soil properties can be calculated per land-cover type within each grid cell. Unfortunately, this level of correspondence between soil and hydrological model cannot be achieved as no harmonised 30 arc-second land-cover distribution is available on the basis of the desired IMAGE scenario information. IMAGE simulates land cover at 5 arc-minutes and assigns a single land-cover type to cells as a whole, whereas, PCR-GLOBWB uses fewer and differing types of land cover and assigns them to fractions of cells to simulate a more accurate hydrological response.
The resulting mismatch is even more serious as the applied land-use-intensity map of S-World is derived from the IMAGE land-use map from the SSP2 scenario. Consequently, on the basis of the IMAGE land-cover map, this land-use-intensity mask reads all 30 arc-second cells in a 5 arc-minute cell as having either intense land use (classes 1 – 5 from Table A3.5) or no land use, at all (classes 6 and 7 from Table A3.5). To overcome this limitation, the following adjustments are made in *Step 8*:

1 For the SSP2 scenario, without changes in soil properties, all S-World derived soil properties at 30 arc-seconds are averaged jointly, giving a single, homogeneous soil parameterisation that is applied to all land-cover types in a PCR-GLOBWB cell and that does not vary over time;
2 For SSP2 productivity-decline scenario, which takes into account changes in soil properties from land use and land-cover change, a broad distinction is made between cells depicting land use by humans (classes 1–5 in Table A3.5) and cells representing natural states (classes 6 and 7 in Table A3.5). For the former, the current S-World soil properties are used and averaged, working with the land-use-intensity map. This produces general land-use-dependent soil properties for most cells on the world map which have all five land-cover types modified by land use assigned to them. For the natural land-cover types, often no information is available and to remedy this, an S-World parameterisation under fully natural, *pristine* land-cover conditions is used. As the fractions of the seven land-cover conditions change over time in the simulation in PCR-GLOBWB in accordance with the IMAGE scenarios, the soil conditions change too. Moreover, an additional dynamic component is added in those cases where the NDVI extrapolation, the SSP2 productivity-decline scenario, is included. Here, the soil properties projected for 2050 are blended proportionally for both land-cover groups (land-use modified and natural) although the effect of the NDVI changes is biased towards the land-use modified land-cover types as these dominate both in surface area and trends of change in large parts of the world.

Just as IMAGE, PCR-GLOBWB has origins and objectives that differ from those of S-World. It therefore requires considerable effort to link them and make them fully compatible, in terms of resolution, dynamics, variables and parameterisation. Despite the still partial compatibility between the models and a better capture of land-cover effects than of soil changes in the PCR GLOBWB model, the scenarios do reveal the dominant trends in causal factors (soil, land cover, temperature and precipitation) and show the direction and order of magnitude of the major effects in terms of water scarcity and river discharge.

A3.4 Food

Change in natural primary productivity will probably affect crop and grass production. For the SSP2 productivity-decline scenario, the same food supply at the regional level is assumed as in the SSP2 scenario. In cases of locally declining yields, agricultural area will need to increase to compensate for the loss in productivity. In *Step 9* (Figure A3.1), the change in productivity is derived from the change in NDVI. In *Step 10* the additional expansion of agriculture is derived from the decline in productivity.

Step 9: Deriving NPP from NDVI

It is not yet possible to model, at the global scale, the effects of future changes in soil properties on the production of crops and grasses. Therefore, an indirect approach is chosen to link soil-related productivity loss to food production and agriculture. The expected impacts of declining productivity are that yields per pixel will decline and additional cropland is needed to compensate for the losses. The projected reduction in climate-corrected NDVI up to 2050 (SSP2 productivity-decline scenario), as elaborated in *Step 4*, is used as a first proxy for crop yield losses. The correlation of NDVI with net primary production (Zhu & Southworth, 2013) is used to convert NDVI maps into NPP maps (*Step 9*). The methodology developed by Schut *et al.* (2015) to determine NDVI-NPP relations is also used in this study, but instead of relying on GIMMS3g NDVI maps it takes advantage of the spatially more detailed NDVI maps based on SPOT NDVI images (http://free.vgt.vito.be/) from the S-World model.

Because the MODIS-NPP grid cells (MOD17A3 data-set) (Zhao et al., 2005), covering about 1 km^2, have been resampled to 5 arc-minutes, the SPOT NDVI map for the present situation (averaged over the 2006–2010 period) with a 30 arc-second resolution is also resampled to 5 arc-minute cells by assigning the mean value to each.

Table A3.6

Regression coefficients for the relationship between NPP (MODIS-NPP) and NDVI

		NPP = Int + a * NDVI + b * NDVI2				
Biome	**N**	**Correlation coefficient**	**Intercept**	**A**	**b**	**R2**
Overall	1,957,341	0.8321727	381.6874	0.980692	0.266152	0.7187
1 Trop. & subtrop. moist broadleaf forests	229,281	0.496007	1684.386	20.36989	0.152784	0.2472
2 Trop. & subtrop. Dry Broadleaf forests	43,064	0.650633	-4273.08	56.70037	0.064652	0.4236
3 Trop. & subtrop. Coniferous forests	8,715	0.599972	3096.207	-47.1059	0.421325	0.2992
4 Temperate broadleaf & mixed forests	199,395	0.724949	945.7899	1.794254	0.228735	0.5374
5 Temperate conifer forests	64,265	0.786138	-1428.61	48.52161	0.005072	0.618
6 Boreal forests/taiga	347,132	0.879883	-2241.4	78.22091	-0.18345	0.785
7 Trop. & subtrop. grasslands, savannas & shrublands	208,233	0.729478	-4464.8	77.28349	-0.04956	0.5326
8 Temp. grasslands, savannas & shrublands	150,623	0.727768	-405.58	28.72473	0.051772	0.5309
9 Flooded grasslands & savannas	12,479	0.661786	-1651.11	48.44325	-0.00729	0.4379
10 Montane grasslands & shrublands	53,442	0.917992	-1133.16	15.98763	0.300922	0.8608
11 Tundra	187,572	0.809207	-3184.75	98.97078	-0.32921	0.6637
12 Mediterranean forests, woodlands & shrub	35,671	0.86348	1389.296	-26.0036	0.410559	0.7822
13 Deserts & xeric shrublands	107,698	0.842208	-369.365	7.961838	0.219536	0.7277
14 Mangroves	2,310	0.64465	4495.458	-38.5308	0.373489	0.4319

These cells are correlated with the MODIS-NPP cells using the following function:

$$NPP \approx NDVI + NDVI^2$$

This results in several regression equations, one overall global relationship and other biome-specific equations (Kier et al., 2005). Table 6 shows the regression model coefficients.

Applying the regressions on the NDVI maps for the *present state* and the SSP2 productivity-decline scenario generates two global NPP maps. Table A3.6 shows the calculation method used to create the NPP maps.

Step 10: Deriving agricultural productivity from NPP

Annual NPP reduction maps are calculated using the NPP maps from *Step 9*. These maps are subsequently used within the IMAGE model to assess the effects of changes in NPP, as a proxy for yield reduction on cropland. In step A in Figure A3.4 the biome-specific regressions from Table A3.6 are used to calculate NPP maps for the present, and future scenario situation. The 30 arc-second NPP maps, about 1 km^2 on the equator, are averaged to a 5 or 30 arc-minute resolution map for use within the IMAGE model (Step B in Figure A3.4). These aggregated NPP maps are converted into annual NPP reduction maps (Step C in Figure A3.4) using the following equation:

$$Annual\ reduction = \left(\frac{NPP_{Agr-Sc}}{NPP_{Agr-current}}\right)^{1.0/40.0}$$

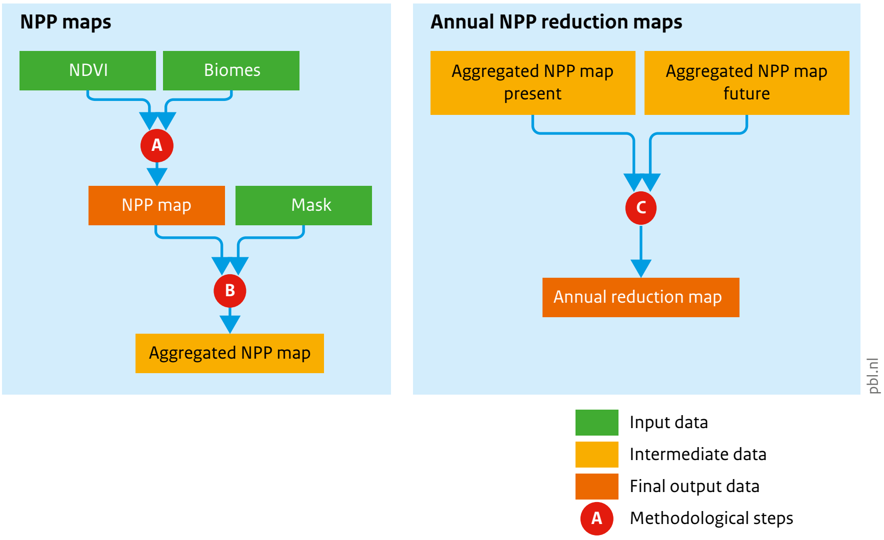
Here NPP_{Agr-Sc} stands for one of the averaged aggregated NPP maps for a scenario year, and $NPP_{Agr-present}$ stands for the averaged aggregated NPP map for the present situation (i.e. the year 2010).

In *Step 10* in Figure A3.1, for each cropland grid cell with declining NPP, the annual NNP reduction value is superimposed on the 2010 NPP value.
Potential crop yields and grassland productivity in the dynamically coupled IMAGE-LPJmL model are calculated by LPJmL (Bondeau et al., 2007). The effects of soil degradation on crop yields and grassland productivity are not modelled as a process in LPJmL. However, the estimated reduction due to soil degradation is subtracted from the potential yield in the IMAGE model depending on the number of years of agricultural use established by the following formula:

$$Y_{actual} = Y_{potential} \cdot AnnRed^{n\ years}$$

After the soil-degradation effect on crop yields and grassland productivity has been taken into account, the IMAGE land-use model assesses the loss in crop or livestock production. If demand for crops or livestock products is not met due to the production loss, cropland or grassland expansion takes place.

Figure A3.4
Calculation of net primary production (NPP) and annual NPP reduction maps



Source: PBL

A3.5 Nature

Step 11: Including change in land cover and productivity as new drivers of biodiversity loss in GLOBIO

Biodiversity impacts are expressed in changes in mean species abundance (MSA), a measure regularly applied in global and regional biodiversity assessments. MSA is defined as the *mean abundance*[2] of original species relative to their abundance in undisturbed ecosystems (Alkemade et al., 2009). The IMAGE-GLOBIO model combination, applied to integrated global environmental assessments, calculates impacts on the mean species abundance of the drivers: land-use change, climate change, infrastructure, disturbance, fragmentation and nitrogen deposition (Alkemade et al., 2009; Stehfest et al., 2014) (www.globio.info). Former assessments have not included the impact of land-cover loss in natural areas due to overexploitation in the past, such as that seen in desertified regions. Nor have they addressed the projections made by scenarios for the future which refer to productivity loss in agricultural areas leading to additional agricultural expansion to compensate for the loss and meet human demand. The development of the land-cover and productivity maps of the past, present and future for the Global Land Outlook is a great opportunity to fill these gaps with a noteworthy and reliable estimate, worked out in *Step 11* in Figure A3.1.

Land-cover loss in natural areas

Human-caused land-cover loss in natural areas may occur for two reasons. Firstly, it may originate from *former* land use that was detrimental to the production capacity and the vegetation. Causal factors are, for example, soil erosion and nutrient depletion, which lead to land being abandoned. To date, this lost or deteriorated land cover has not been regenerated yet. A second reason may lie in *current* types of land use that have not been mapped in GLC2000 (Bartholomé and Belward, 2005). Examples are forms of extensive use, such as livestock herding, wood and fodder collection, and fire regimes that reduce vegetation cover and therefore biomass.

In a literature review, Pettorelli et al. (2011) showed that change in NDVI has proven extremely useful in predicting change in species abundance, productivity (NPP) and biomass. Consequently, as a first-order estimate for this unknown kind of impact from land-cover change, this study assumes that the loss of vegetation cover in natural areas is proportional to the average loss in populations and thus MSA, according to the formula:

$$MSA_{t-natural\ areas} = MSA_{t-original\ formula} * {}^{NDVI_t}/_{NDVI_{natural}}$$

The first part of the equation is the original formula for MSA (Alkemade et al., 2009) and the second part serves to include productivity loss as a supplementary driver, where $NDVI_t$ stands for land cover in year t, and $NDVI_{natural}$ stands for land cover in a natural situation. Cold areas with low productivity levels are excluded to avoid the inclusion of 'noise'; pastures and areas affected by human settlements (encroachment) are also excluded to avoid the possibility of double counting with other drives which are already taken into account (disturbance and extensive grazing).

The NDVI in S-World, ranging from 1 through 255, is truncated at 50 and 200, given the impact characteristics of vegetation cover on NDVI. The NDVI values are subsequently transferred to values between 1 and 150. The loss of land cover per pixel is derived by comparing present and future NDVI maps with the natural (undisturbed) NDVI map, as elaborated in *Steps 2, 3 and 4* in Figure A3.1. It is not expected this will lead to double counting with the traditional drivers in GLOBIO, infrastructure, disturbance and fragmentation which also may occur in natural areas. These drivers mainly lead to a shift in abundance of the original species, not to a loss in land cover or biomass. Further, nitrogen deposition as an existing driver in GLOBIO will probably lead to an increase of land cover or biomass, not a decline, and the impact of climate change on land cover (NDVI) does not apply, for it is filtered out following the method elaborated in Step 4.

Biodiversity loss from agricultural expansion as compensation for productivity loss.

Next to the direct effect of land-cover loss on biodiversity discussed above, there is also an indirect effect from productivity decline, leading to losses in agricultural yields over the 2010–2050 period. Local productivity loss is not foreseen in the SSP2 scenario. In the SSP2 productivity-decline scenario, however, ongoing productivity loss over the 1982–2010 period is extrapolated to 2050 as a scenario assumption to enable an exploration of the impact on carbon, land area occupied by agriculture, water (in this stage limited to water holding capacity) and biodiversity. The indirect impact on biodiversity is related to the additional expansion of agriculture in natural areas to compensate for production loss in existing agriculture. This indirect effect of land-use change is determined according to the regular GLOBIO procedures and derived from Step 10, which deals with the expansion of cropland area.

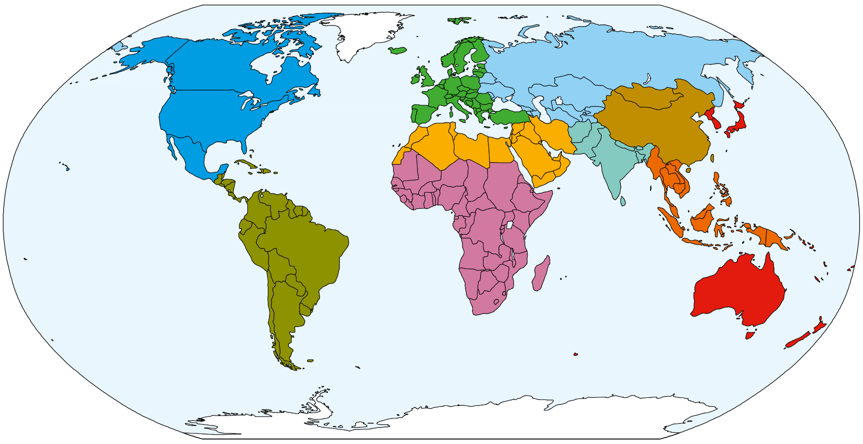
Notes

1. For Chapter 4, the IMAGE SSP2 Scenario V_15 was used, which is a slightly older version of the SSP2 scenario applied in Chapter 3. Time constraints prohibited applying the use of the latest version in Chapter 4. The latest version has a slightly larger LUI change. However, this did not affect the direction or the order of magnitude of the projected changes.
2. With 'abundance' is meant 'population size'.

A4. Map of the 10 world regions

Figure A4.1

The 10 IMAGE regions used in this report



North America	Western and Central Europe	Japan, Korea and Oceania
Central and South America	Russian region and Central Asia	China region
Sub-Saharan Africa	South Asia	
Middle East and Northern Africa	Southeast Asia	Polar

Source: PBL

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