PBL Netherlands Environmental Assessment Agency

THE GLOBAL POTENTIAL FOR LAND RESTORATION: SCENARIOS FOR THE GLOBAL LAND OUTLOOK 2

Policy Report

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Colophon

The global potential for land restoration: Scenarios for the Global Land Outlook 2

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Contents

Acronyms and Glossary of terms for this report

Acronyms

Acronym	Description
CBD	Convention on Biological Diversity
GDP	Gross domestic product
LDN	Land Degradation Neutrality
NBSAPs	National Biodiversity Strategies and Action Plans under the CBD
NDCs	Nationally Determined Contributions under the UNFCCC
NDVI	Normalised Difference Vegetation Index
SDGs	Sustainable Development Goals, a collection of 17 interlinked goals for 2030, building on the Millennium Development Goals and agreed on by the UN General Assembly in 2015.
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change

Glossary of terms

Term	Description
Biodiversity	The biological diversity and variability of life.
Carbon stocks	Carbon stocks in soils and vegetation (above and below ground).
Conservation agriculture	A system of managing agricultural lands based on farming practices that aim to achieve sustainable agricultural production through the preservation of soil quality and improvement of soil biodiversity.
Ecological restoration	Where degraded or managed land is aimed to be restored to its natural condition/state.
Ecosystem functions	These include the ability to regulate water and nutrients and produce biomass and are themselves dependent on the biological diversity and condition of the ecosystem.
Improved land management (including sustainable land management)	Improving the management and/or sustainable use of land to reduce trade-offs between ecosystem functions.

Land condition	This reflects the state of the terrestrial surface of the Earth, including both the vegetation on the surface and the soils underneath.
Land degradation	A negative trend in land condition and persistent loss of ecosystem functions that cannot be reversed unaided. Quantified through a set of indicators: land use, primary productivity, soil organic carbon and biodiversity (for land condition); and agricultural yields, water regulation and carbon stocks (for changes in ecosystem functions).
Natural land/area	Land not under direct human use such as agriculture, forestry, urban areas.
Natural condition/state	This study uses a constructed natural (i.e. without human intervention) state to provide a fixed reference point with which to compare changes in land condition indicators.
Nature-based solutions	Actions to protect, sustainably manage and restore ecosystems that simultaneously provide human well-being and biodiversity benefits, such as agroforestry, conservation agriculture and grazing management.
Primary productivity	In this report, primary productivity refers to vegetation vigour, using satellite observations of the normalised difference vegetation index (NDVI) from 2001 to 2018 and correcting for long-term climatic effects.
Protection	The safeguarding and conservation of natural areas that are important for water regulation, biodiversity, carbon stocks and the prevention of soil erosion through protection measures. This assumes that these areas will not be converted for human use in the future.
Rehabilitation	Restoration measures focused on improving production systems for human use.
Restoration (including land restoration, ecosystem restoration)	Restoration covers a range of measures that improve land condition through changes to the physical land management, and includes improved land management on land under human use, rehabilitation of degraded lands to a productive status, and ecological restoration, where degraded or managed land is aimed to be restored to its natural condition.
Restoration measures	Restoration measures included in this report are: conservation agriculture, agroforestry on cropland, agroforestry on grazing land, grazing management, grassland improvement, forest plantations on degraded land, assisted natural regeneration, and cross-slope barriers.
Rio Conventions	These are the UNFCCC, CBD and UNCCD conventions agreed at the Earth Summit held in Rio de Janeiro in 1992.
Soil organic carbon	Soil organic carbon, or SOC, is an important indicator of soil health as it contributes positively to soil fertility and water-holding capacity. SOC is the carbon component of soil organic matter.
Water regulation	There are many indicators for water regulation; in this report, we use the water-holding capacity in rain-fed cropland areas.

Main messages

Land restoration has the potential to deliver multiple benefits simultaneously, making it a highly integrated solution for sustainable development. The way that land is used, managed and protected is central to achieving the goals of the UN Conventions on land degradation and desertification, climate change and biodiversity, as well as many of the Sustainable Development Goals. This is because the choices, synergies and trade-offs between sustainability ambitions often materialise on land. Over the past years, attention to and ambitions for restoration have gained momentum, culminating in the UN Decade on Ecosystem Restoration (2021–2030).

This study quantifies the potential effects of land restoration at the global and regional levels. Three global land-use scenarios up to 2050 were constructed and analysed to provide a view of the extent and risks of land degradation, and to estimate the potential of land restoration compared to a future without restoration. These three scenarios are the *Baseline*, *Restoration* and *Restoration & Protection* scenarios. The effects of land restoration were assessed for natural area, biodiversity, soil organic carbon, agricultural yields, water regulation and carbon storage.

The *Baseline* scenario shows what would happen between 2015 and 2050 without land restoration measures. Land management negatively affects soil and biomass productivity on an estimated 12% of the global land area. Agricultural productivity is projected to increase, but current land management practices have an average negative effect of 2%, rising to 6% to 10% in some regions. Cropland expands by about 20% (~300 million ha), at the expense of natural areas. Of the remaining biodiversity, 6% is lost due to land-use change, intensive production and climate change. Average annual carbon emissions between 2015 and 2050 from land-use change and land management amount to 16% of current annual emissions.

In the *Restoration* scenario, around five billion hectares are restored using potential land restoration measures. Land condition and ecosystem functions improve between 2015 and 2050 due to the implementation of these measures. The measures include agroforestry, conservation agriculture, silvopasture, grazing management, grassland improvement, forest plantations, assisted natural regeneration and cross-slope barriers. Restoration boosts agricultural yields globally by 2% and by up to 10% in some regions, compared to the *Baseline* scenario. Conversion of natural land to agriculture is reduced and biodiversity loss is 11% less in 2050 compared to the *Baseline* scenario. Carbon storage in soils increases and loss of carbon in vegetation is reduced, resulting in a net gain of 17 GtC between 2015 and 2050. This can make a substantial contribution to meeting climate ambitions, when compared to current global emissions of 11 GtC/yr.

In the *Restoration & Protection* scenario, restoration measures are combined with protection of areas that are important to maintain ecosystem functions. This translates into 400 million hectares more natural land, and the prevention of one third of the global biodiversity loss in the *Baseline* scenario. However, food prices increase relative to the *Restoration* scenario and agriculture is required to intensify faster due to limited available land. Compared to the Baseline scenario, an additional 83 Gt of carbon is stored in soils and vegetation, equivalent to more than 7 years of current global emissions.

Current global restoration commitments cover around one billion hectares and therefore one fifth of the potential for restoration in the scenario projections. Almost half of all commitments are found in sub-Saharan Africa. There are also large commitments in South Asia and Central and South America, relative to the total land area. Other regions report much smaller commitments to land restoration.

Implementing the current commitments requires investments estimated at 0.04% to 0.21% of annual global GDP for 10 years (USD 300 billion to USD 1,670 billion). Estimated costs are highest for sub-Saharan Africa due to the large restoration commitments in this region. The costs of implementing the restoration commitments are likely to be prohibitive for developing countries, unless international cost-sharing mechanisms for restoration are developed.

The benefits of agricultural restoration measures to household incomes remain without firm evidence. Better land management by landowners is hoped to deliver higher agricultural productivity and improved farmer household incomes. Too few studies exist to firmly assess the direct benefits of land restoration to farmer household incomes, and the existing studies provide little to no evidence of short-term effects on household income. Given the large land restoration commitments by countries, this knowledge gap is problematic.

The multiple benefits of restoration draw in a variety of actors but can result in fragmentation, making investment decisions complex. Fragmented planning, funding and implementation are underscored by the lack of coherence between national plans for land restoration. While private investors need to rely on bundling of projects to attain profitable scale and reduce risks, transaction costs increase with the number of actors involved. Knowledge on effective policy and governance approaches to bridge this complex distribution of costs and benefits remains scarce.

Restoration measures can prevent future land degradation, and this should be accounted for when assessing investment in restoration measures. Not accounting for prevented impacts would underestimate the potential benefits of land restoration. Prevention is crucial because land restoration is generally a long-term process.

The stimulation of land restoration measures requires countries to integrate restoration into existing policies and institutions. Given the large commitments that countries are making, in particular in improved land management, effective governance requires policy interventions across multiple levels and sectors. While there are many different policies and institutions to build on or to newly develop, there is no one-size-fits-all policy. Policymakers require evidence of what works under which conditions, and such information is imperative for making the UN Decade of Restoration a success.

Combining land restoration and protection measures with changes to production, supply chains and consumption patterns can achieve larger benefits. These measures can have synergy with land restoration, as reducing pressure on land can further improve the potential for land restoration.

Executive summary

Land, and the way it is used, managed and protected, is central to achieving global sustainability ambitions and the goals of the three Rio Conventions covering land degradation and desertification (UNCCD), biodiversity (CBD) and climate change (UNFCCC). Many of the Sustainable Development Goals have clear links to land, and the choices, synergies and trade-offs between sustainability ambitions often materialise on land. Land restoration is seen as a means to provide multiple benefits. Restoration measures can contribute to better soil quality, higher agricultural productivity and improved water regulation, as well as to biodiversity conservation and climate change mitigation and adaptation.

This study provides a quantitative estimate of the global and regional potential of land restoration until 2050 using a comparative scenario analysis. This restoration potential is expressed in terms of changes to a set of biophysical indicators for land and soils, biodiversity, climate, water and agriculture, and is subsequently compared to projected future changes to land over the coming decades, in the absence of restoration. The current restoration commitments made by countries, and the costs of and policies required for their implementation, are compared to the restoration potential.

The scenarios presented in this study provide a first approximation of the global potential of land restoration. The quantitative results are based on a large set of assumptions, a combination of models, and a limited set of scenarios, resulting in a high degree of uncertainty. Furthermore, the study's objectives and method require a focus on biophysical effects and agro-economics at global and regional scales, which means that limited attention is paid to local complexities and governance of land rights, land distribution and access. These are, obviously, also highly important, but fall outside the scope of this scenario study. Still, the findings of this study can provide a background to discussions on the future of land governance and land markets.

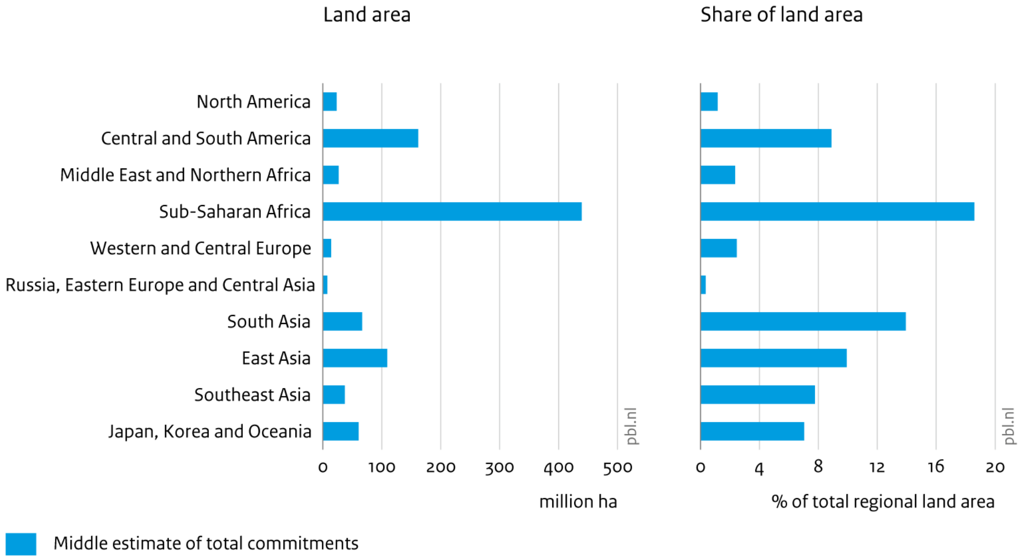
Land restoration and current restoration commitments

Land degradation is defined as a negative trend in land condition and persistent loss of ecosystem functions that cannot be reversed unaided. This study quantifies changes in land condition and ecosystem functions, using a set of indicators. The indicators for changes in land condition include land use, primary productivity, soil organic carbon and biodiversity. Agricultural yields, water regulation (in terms of water-holding capacity) and carbon stocks are used as indicators for changes in ecosystem functions. This report provides estimates of future trends for each of these indicators, but no estimate of the total degraded area, as decisions on land management often result in a trade-off between individual ecosystem functions, rather than a negative trend across all indicators (Section 2.1.1).

Land restoration provides multiple potential benefits and thus draws interest from various stakeholders. Over the past years, attention to and ambitions for restoration have gained momentum. This has culminated in the UN Decade on Ecosystem Restoration (2021–2030), an array of global and regional restoration goals, and the inclusion of land restoration measures in many countries' national policy plans. In this report, *restoration* covers a range of measures that improve land condition through changes to physical land management, including improved management of land under human use, rehabilitation of degraded lands to a productive status, and ecological restoration, where the aim is to restore degraded land to its natural state (Section 2.1.2).

Countries' restoration ambitions are already significant. At least 115 countries have committed a total of close to 1 billion hectares to land restoration. Commitments are combined from national plans under the UNCCD, CBD and UNFCCC conventions and the Bonn Challenge. Almost half of all restoration commitments are found in sub-Saharan Africa. South Asia and Central and South America also have large commitments relative to their land area (Figure 1) (Sections 2.2 and 2.3).

Figure 1
Total restoration commitments per region, 2020



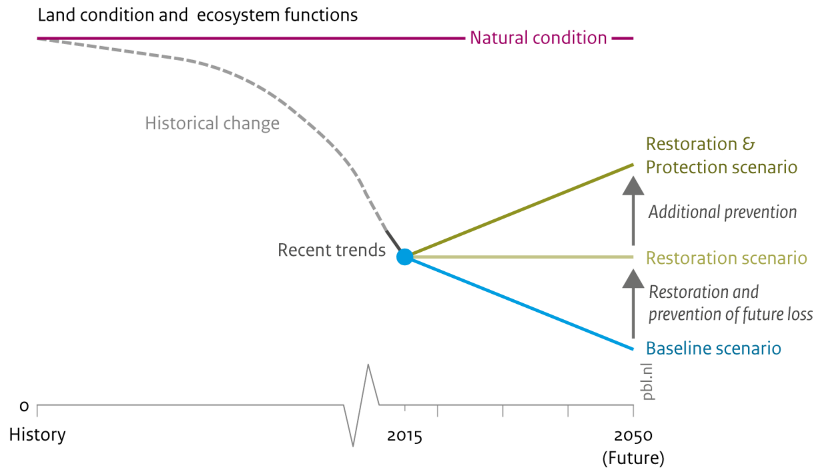
Source: UNCCD, UNFCCC, CBD, Bonn Challenge, FAO; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

Countries' current restoration commitments cover natural areas and areas under human use, in equal measure. Total commitments are almost equally divided between the ecological restoration and protection of natural areas on the one hand, and improved land management and the rehabilitation of degraded land on the other. The current commitments cover roughly about one fifth of global cropland, one tenth of all forest area, and a small share of pastures (Section 2.3.3).

Three scenarios to explore the potential of land restoration

Three global scenarios up to 2050 provide a view of the future impacts of land degradation and the potential benefits of land restoration and prevention of future land degradation. The scenarios include a *Baseline* scenario, a *Restoration* scenario, and a *Restoration & Protection* scenario (Figure 2). The effects of restoration measures can take a long time to fully materialise, which is why the restoration potential is assessed in scenarios up to 2050. Meanwhile, demographic, economic and environmental factors continue to develop (Section 2.4).

Figure 2
Illustration of scenarios to assess potential benefits of land restoration



Source: PBL

The *Baseline* scenario projects future changes in land condition and ecosystem functions up to 2050, without land restoration. In the *Baseline* scenario, there are three main factors that affect land condition and ecosystem functions: land-use change (due to the increasing global demand for food, feed, fibre and bioenergy crops), climate change effects, and the impact of current land management practices. The *Baseline* scenario provides the reference against which the effects of the restoration scenarios are compared. This makes it possible to estimate the potential of land restoration measures to prevent losses in land condition and ecosystem functions that would otherwise take place (Figure 2 and Section 2.4).

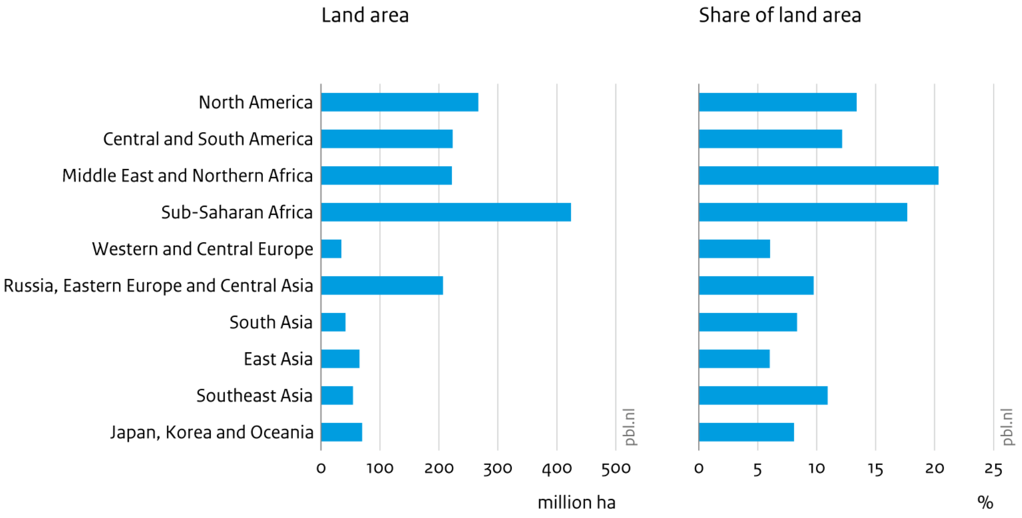
The two restoration scenarios project the potential effects of land restoration measures and the protection of ecosystem functions up to 2050. The *Restoration* scenario assumes the implementation of eight potential land restoration measures on cropland, grazing land and natural land. The *Restoration & Protection* scenario assumes the same potential restoration measures and adds the safeguarding of natural areas that are important for water regulation, biodiversity, carbon stocks and the prevention of soil erosion through protection measures, and assumes that these natural areas will not be converted for human use in the future. This scenario shows to what extent the future decline in land condition and ecosystem functions can be prevented if key areas are protected (Section 2.4).

The *Baseline* scenario projects a continued global decline in land condition and most ecosystem functions

Worldwide, a persistent decline in primary productivity is taking place, attributed mainly to land management practices on an estimated 1.6 billion ha (12%) of the total land area. This estimate is based on satellite observations of the normalised difference vegetation index (NDVI) between 2001 and 2018 and is corrected for long-term climatic effects. The regions that are most affected are sub-Saharan Africa, the Middle East and Northern Africa, and North America (Figure 3).

This decline in NDVI affects 14% of the total cropland area, 13% of all grazing land and 12% of all natural areas (Section 3.2.2).

Figure 3
Areas with a negative productivity trend, corrected for climate change, 2001 – 2018



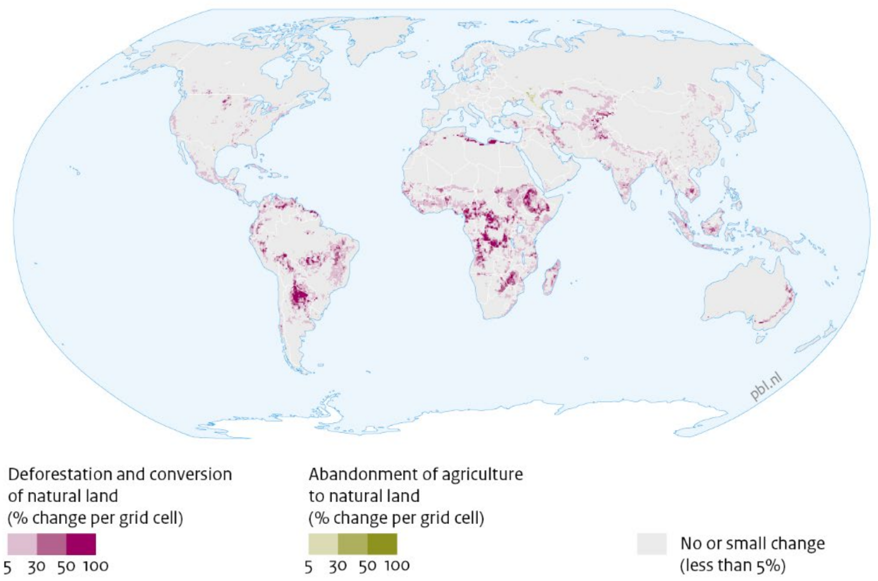
Source: PBL, NASA/MODIS

In the *Baseline* scenario, pressure on land increases at the expense of natural areas. Land use for agricultural production increases, in particular in sub-Saharan Africa and Central and South America (Figure 4). In most other regions, the availability of natural land suitable for agricultural expansion is very limited and food production increasingly relies on intensification. Under this scenario, the global demand for crops increases by some 45% and cropland expands by close to 20% (~300 million hectares), between 2015 and 2050. Agricultural expansion comes at the expense of natural areas, with biodiversity declining by an estimated 6% compared to 2015 (in mean species abundance), mainly due to more intensive production in existing agricultural areas and climate change (Sections 3.2.1 and 3.2.5).

Soil health is projected to further decline in many regions, under the *Baseline* scenario. Soil organic carbon is an important indicator of soil health as it contributes to soil fertility and water-holding capacity. Most regions have already seen significant losses of soil organic carbon due to the conversion of natural land to agriculture. The majority of losses have occurred in highly productive agricultural regions, most notably in North America, Europe, India and China. An estimated 7%, or 140 Gt, of soil carbon has been lost due to historical changes in land use, such as the conversion of natural land to cropland and land management practices (Section 3.2.4).

Under the *Baseline* scenario, projected soil carbon losses amount to 32 GtC between 2015 and 2050, as a consequence of land conversion and ongoing land management practices. Declining soil health increases vulnerability to dry spells, as it reduces water-holding capacity and may also negatively affect agricultural yields through the loss of nutrients, as well as having wider effects on hydrology, biodiversity and carbon stocks.

Figure 4
Land-use change under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

Deterioration in land condition affects agricultural yields, water regulation and carbon storage in soils and vegetation. This exacerbates the challenge of attaining the goals of the three Rio Conventions and the SDGs. While average agricultural yields are projected to increase globally, degradation processes reduce these increases in all regions. This is most pronounced in the Middle East and Northern Africa, sub-Saharan Africa and Central and South America, with a 6% to 10% negative impact on yields attributed to land degradation. Compensating these losses by taking more land into production is responsible for about 20% of agricultural land expansion, under the *Baseline* scenario. In addition, climate change has a negative impact on yields in tropical regions, due to reduced precipitation and higher average temperatures, with an up to 4% reduction in yields in sub-Saharan Africa. Both of these effects reinforce the existing need to significantly improve agricultural yields, especially in sub-Saharan Africa. Both effects also come with high uncertainties. There are few other estimates of the impact of land degradation on agricultural yields and projections of climate change impacts vary greatly. Livestock areas are projected to become increasingly densely used, increasing the risk of overgrazing, especially in the Middle East and Northern Africa as well as in South Asia (Sections 3.2.1, 3.2.2 and 3.3.1.2).

The water-holding capacity of soils is particularly important for the cultivation of rain-fed crops and grazing land in dryland areas, which require moisture to be stored for long periods without rain. Under the *Baseline* scenario, areas where crop production is already limited by low water availability are projected to be particularly affected, including large areas in East and West Africa and in South America (Section 3.3.2).

Average annual carbon emissions from land-use change and land management, over the period covered by the *Baseline* scenario, amount to 17% of current annual emissions. Changes in carbon stocks in soils and vegetation affect carbon dioxide concentrations in the atmosphere. Under the *Baseline* scenario, the amounts of emissions from soil and vegetation are comparable. Average annual emissions due to loss of soil organic carbon amount to 8% of current global annual emissions (total of 32 GtC over the 2015–2050 period), about a third of which in sub-Saharan Africa.

Estimated average annual emissions from vegetation loss due to land-use change, over the *Baseline* scenario period, amount to some 7% of current global emissions (total of 27 GtC over the 2015–2050 period). Continued agricultural activity on peat soils, mostly in Europe and Russia, as well as further conversion of peatlands in tropical regions, results in substantial carbon emissions from degrading peatlands, and amount to 2% of current emissions when averaged per year (total of 10 GtC over the 2015–2050 period). In total, projected average annual carbon emissions from land-use change and land management amount to 17% of current annual emissions (Section 3.3.3).

The benefits of improvements in land management and prevention of land degradation

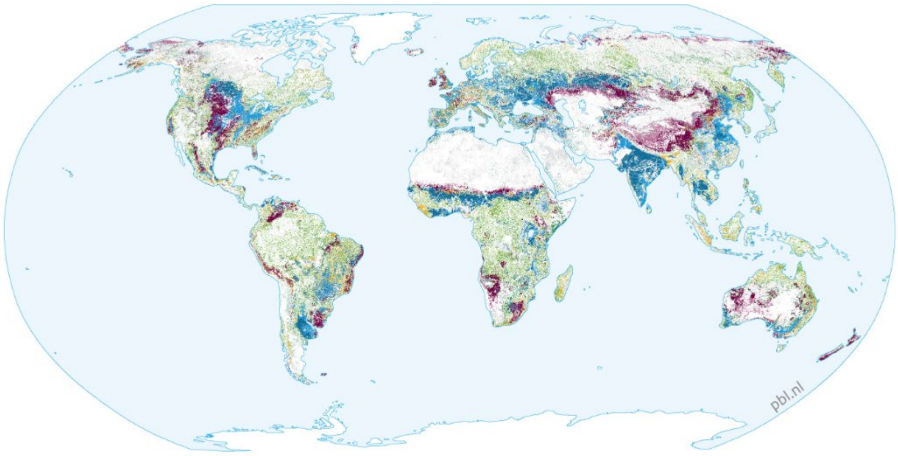
Under the *Restoration* scenario, land is restored where there is potential to do so, and part of the future negative impacts on land condition as projected under the *Baseline* scenario is prevented, through the implementation of eight types of restoration measures. Under the *Restoration & Protection* scenario, the same measures are implemented and, in addition, natural areas that are important for specific ecosystem functions are protected from land conversion. Under both restoration scenarios, restoration measures are assumed to be appropriate for current and future land use. This means that, for instance, measures for conservation agriculture are taken on croplands, and measures for grazing management on pastures. No agricultural or forest land is assumed to be taken out of production for restoration. Agroforestry measures are not applied in intensive production areas where there is little productivity potential left to compensate for possibly reduced agricultural yields.

Under both restoration scenarios, land restoration measures are implemented on around five billion hectares. On this land area, soils are estimated to have potential to be restored and one or more restoration measures are applicable. The measures include conservation agriculture, agroforestry on cropland and grazing land, grazing management, grassland improvement, forest plantations on degraded land, assisted natural regeneration, and cross-slope barriers. In many areas, multiple measures are possible and, in practice, could be combined (Figure 5). Restoration measures are estimated to be possible on 1.6 billion ha of cropland, 2.2 billion ha of grazing land, and 1.4 billion ha of natural areas. The regions with the largest area with restoration measures are sub-Saharan Africa and Central and South America.

Natural areas serve both biodiversity and key ecosystem functions, indicating the multiple benefits of conserving and protecting these areas. Under the *Restoration & Protection* scenario, there is no conversion of areas that are important for biodiversity and the provision of key ecosystem functions. This is in line with proposals by Parties to the CBD and other stakeholders for the post-2020 global biodiversity framework to protect 30% or more of land by 2030. Implementation of protected areas under the *Restoration & Protection* scenario reaches close to 50% of the terrestrial area by 2050, based on assumptions regarding which areas are important for water regulation, biodiversity, carbon stocks and prevention of soil erosion. Such far-reaching protection of areas for ecosystem functions significantly limits agricultural expansion in Southeast Asia, South Asia and East Asia (Section 4.2.3)

Figure 5

Locations of improved land management and restoration measures, as applied in the Restoration scenarios



Measures and combinations of measures

- Agroforestry; Conservation agriculture
- Conservation agriculture
- Cross-slope barriers; Agroforestry; Conservation agriculture
- Cross-slope barriers
- Grazing management; Silvopasture
- Grazing management; Grassland improvement
- Grassland improvement
- Assisted natural regeneration
- Forest plantation
- Assisted natural regeneration; Forest plantation
- Other combinations
- Restoration potential, but no measure possible
- No restoration potential

Source: PBL/WUR

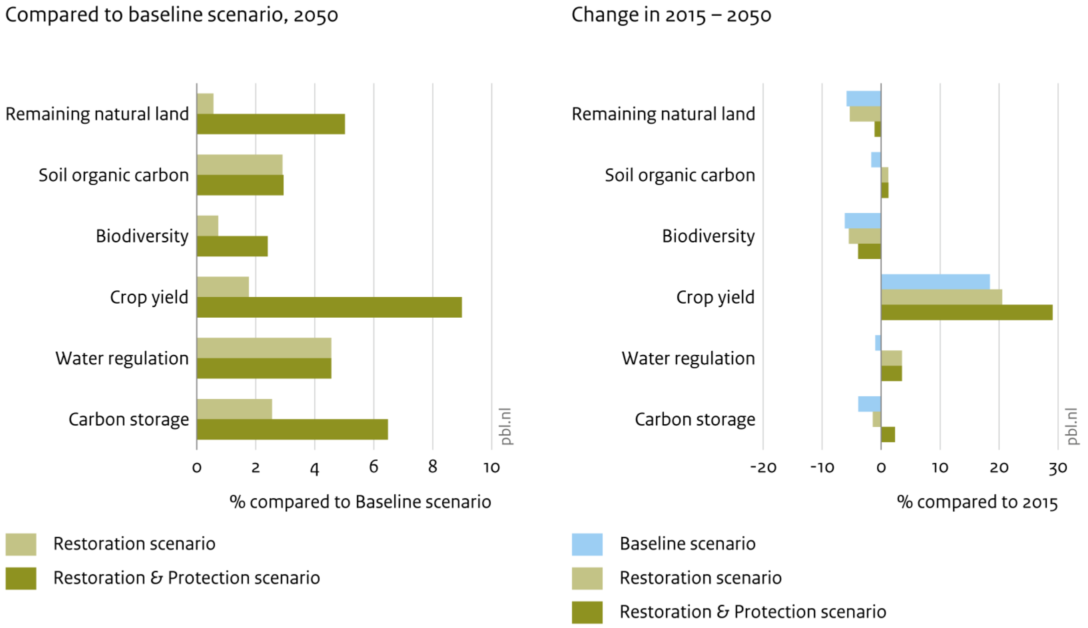
The *Restoration* scenario shows significant gains from the restoration measures by 2050, compared to under the *Baseline* scenario. The type and size of impacts differ per region. Under the *Restoration* scenario, land condition and ecosystem functions are projected to improve between 2015 and 2050. Restoration of soil health leads to crop yields that are, averaged globally, about 2% higher by 2050 than they are under the *Baseline* scenario (Figure 6). Benefits to crop yields by 2050 are the greatest in the Middle East and Northern Africa, Central and South America and sub-Saharan Africa, with increases of 10%, 5% and 5%, respectively, compared to under the *Baseline* scenario (Section 4.3.4).

The extent of natural land continues to decline under the *Restoration* scenario, due to the expansion of agricultural land and urban areas. This expansion is slightly less than under the *Baseline* scenario, due to improvements in agricultural productivity from restoration measures. By 2050, the largest effects are in Central and South America, where natural areas are some 3% larger, compared to under the *Baseline* scenario. Biodiversity also continues to decline, but restoration measures prevent some 11% of the loss under the *Baseline* scenario. This is due to reduced conversion of natural land and increased agroforestry. The effect on biodiversity is underestimated in this analysis, as the *Restoration* scenario does not quantify the biodiversity benefits of the 1.4 billion hectares of natural area that are restored, due to difficulties in estimations (Sections 4.3.1 and 4.3.3).

Under the *Restoration* scenario, wide-scale implementation of land restoration measures has a large effect on soil organic carbon. This leads, globally, to an additional 55 GtC stored in soils by 2050, compared to under the *Baseline* scenario. When measured in tonnes, the largest gains are projected in the regions of Russia, Eastern Europe and Central Asia and in Central and South America, while the strongest prevention of soil organic carbon loss takes place in sub-Saharan Africa. Particularly large relative improvements in soil organic carbon are projected for West Africa, India, Southeast Asia and parts of Brazil. Restoration can be crucial in areas with lower levels of natural soil organic carbon, such as marginal agricultural areas where smallholder livelihoods depend on the sustainable use of soils. Here, maintaining soil fertility, water-holding capacity and soil stability may do less in absolute terms of storing carbon, but be all the more important in sustaining livelihoods and small-scale agriculture. Restoring soil organic carbon requires input of organic matter, but this is also used for fuel or fodder in many areas. The use of fertiliser seems therefore necessary in many cases, to produce organic matter at high enough levels for soil carbon restoration, while avoiding trade-offs with biomass use required for livelihoods (Section 4.3.2).

Figure 6

Global effect of Restoration scenarios on land condition and ecosystem functions



Crop yield increases under the Restoration & Protection scenario beyond the impact of the Restoration scenario are caused by the additional protection of areas constraining agricultural expansion. Therefore, this additional increase in yields is a requirement in this scenario, not a benefit of restoration.

Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017, Utrecht University

As a consequence of soil carbon improvements, soil water-holding capacity increases. This is especially relevant for rain-fed agriculture in arid areas, where the buffering capacity of soils can help plants to bridge dry spells. Under the *Restoration* scenario, the average water-holding capacity in rain-fed croplands improves by over 4%. The effect is strongest in parts of East and West Africa and in parts of South America, as well as in parts of South and Southeast Asia. The effects on water-holding capacity are only projected for current rain-fed croplands, and are thus the same under both restoration scenarios (Section 4.3.5).

Compared to 2015, carbon storage on land leads to a net increase of 17 GtC under the *Restoration* scenario. This is the balance of a net increase in soil organic carbon, increased carbon in agroforestry and a continued loss of vegetation carbon due to land conversion, although this loss is smaller than under the Baseline scenario. With global emissions from all sources currently at 11 GtC/year, this increased storage can make a substantial contribution to achieving climate ambitions. The difference between the *Restoration* and the *Baseline* scenarios is 66 GtC in 2050, a much higher figure as this includes the carbon emissions that are prevented by the restoration measures compared to a situation without restoration. Carbon storage on land is improved by restoring soils and vegetation, and by limiting land conversion (Figure 6; Section 4.3.6).

The *Restoration & Protection* scenario shows larger gains than the *Restoration* scenario, especially for remaining natural areas, biodiversity and carbon storage. However, this requires much larger yield increases and pushes up food prices. By conserving natural areas for their biodiversity and ecosystem functions, space for agricultural expansion is much more limited under the *Restoration & Protection* scenario than it is under both the *Baseline* scenario and the *Restoration* scenario. As a consequence, agriculture is forced to intensify. This requires yields of some 9% above levels under the *Baseline* scenario, in 2050. This is significantly beyond what is achieved through the restoration of soils. Contrary to the *Restoration* scenario, this has an upward effect on food prices, implying reduced food security, especially in South Asia and Southeast Asia where agricultural land is already scarce.

The extent of natural land by 2050 is much larger under the *Restoration & Protection* scenario than under both the *Baseline* and the *Restoration* scenario. Compared to the *Baseline* scenario, in 2050, there are close to 400 million hectares more natural land. The largest gains are in South Asia, Southeast Asia and Central and South America. Biodiversity is still projected to decline up to 2050, under the *Restoration & Protection* scenario, but the combination of restoration measures and protection prevent over a third of the biodiversity loss that occurs under the *Baseline* scenario. There are also potential biodiversity benefits in the restored 1.4 billion hectares of natural area, but as previously noted, these are difficult to quantify and have therefore not been included.

For soil organic carbon, the effects under the *Restoration & Protection* scenario are comparable to those under the *Restoration* scenario. Under the *Restoration & Protection* scenario, the combination of restoration measures and protection leads to a difference of 56 GtC with the *Baseline* scenario, over the period between 2015 and 2050. This small difference has three reasons: (1) most of the improvements in soil carbon come from restoration measures on existing agricultural or natural lands, (2) any agricultural expansion is mostly on soils that are lower in soil carbon, and (3) new agricultural land is assumed to be managed under the best available land management practices, under both restoration scenarios.

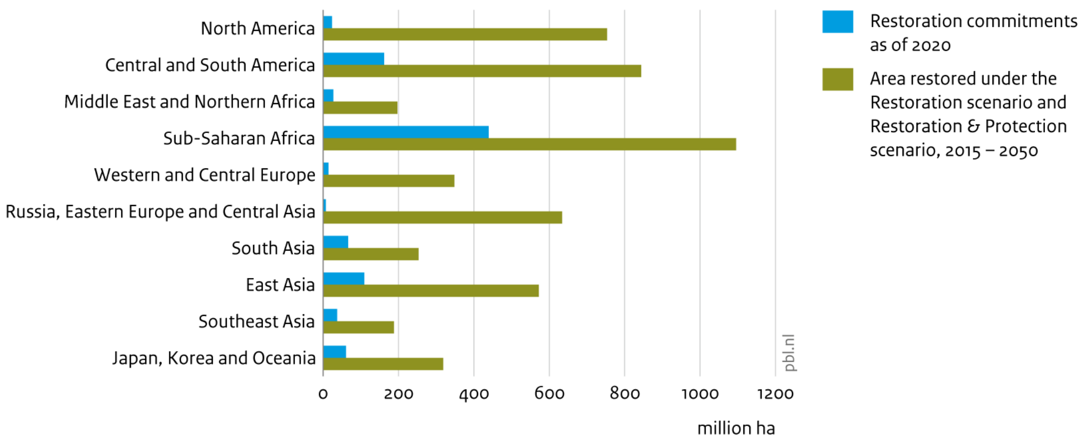
Carbon storage in above-ground vegetation is 16 GtC higher under the *Restoration & Protection* scenario than under the *Restoration* scenario. Crucially, while soil organic carbon levels hardly differ between the two restoration scenarios, the protection of peatlands and high-carbon forest areas in particular leads to a significant positive change in vegetation carbon under the *Restoration & Protection* scenario. As under the *Restoration* scenario, this estimate includes the effect of restoration measures and agroforestry, but does not account for the potential of forest restoration. Compared to the *Baseline* scenario, the *Restoration & Protection* scenario projects 83 Gt more carbon storage in soils and vegetation, by 2050. This is also the result of emissions under the *Baseline* scenario that are prevented through restoration measures and reduced land conversion.

Restoration can increase resilience to sudden environmental shocks and contribute to longer term climate change adaptation. Environmental shocks, such as drought, flooding, pests and diseases, may increase in intensity or frequency, as a result of climate change. The effects of restoration on agricultural yields and water-holding capacity may serve as a first estimate of how, where and to what extent land restoration can help to mitigate environmental shocks and adaptation to a changing climate. In most regions, climate change is projected to negatively affect yields, which may be counterbalanced through restoration. The degree to which these changes might mitigate the impacts of environmental shocks is not further quantified.

Of the potential area under the restoration scenarios that is suitable for restoration measures, around 20% is covered under countries' current restoration commitments. Globally, these restoration commitments cover about a billion hectares, and potential area for restoration is estimated at 5.2 billion hectares, under the restoration scenarios. In sub-Saharan Africa, current restoration commitments add up to about half of the estimated area with potential for restoration (Figure 7). Sub-Saharan Africa is one of the regions with the largest share of land showing negative trends in primary productivity caused by land management, and it is also the region that is projected to have the highest degree of land-use change up to 2050. These commitments, therefore, appear to be focused on the right place. The other regions show much lower coverage by current commitments relative to the potential restoration area. Countries' commitments to land restoration and the expansion of protected areas could increase in response to ambitious targets in the CBD post-2020 framework for biodiversity restoration.

Figure 7

Restoration commitments compared to areas restored under the Restoration scenarios



Source: UNCCD, UNFCCC, CBD, Bonn Challenge; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

Global costs of land restoration and benefits to households

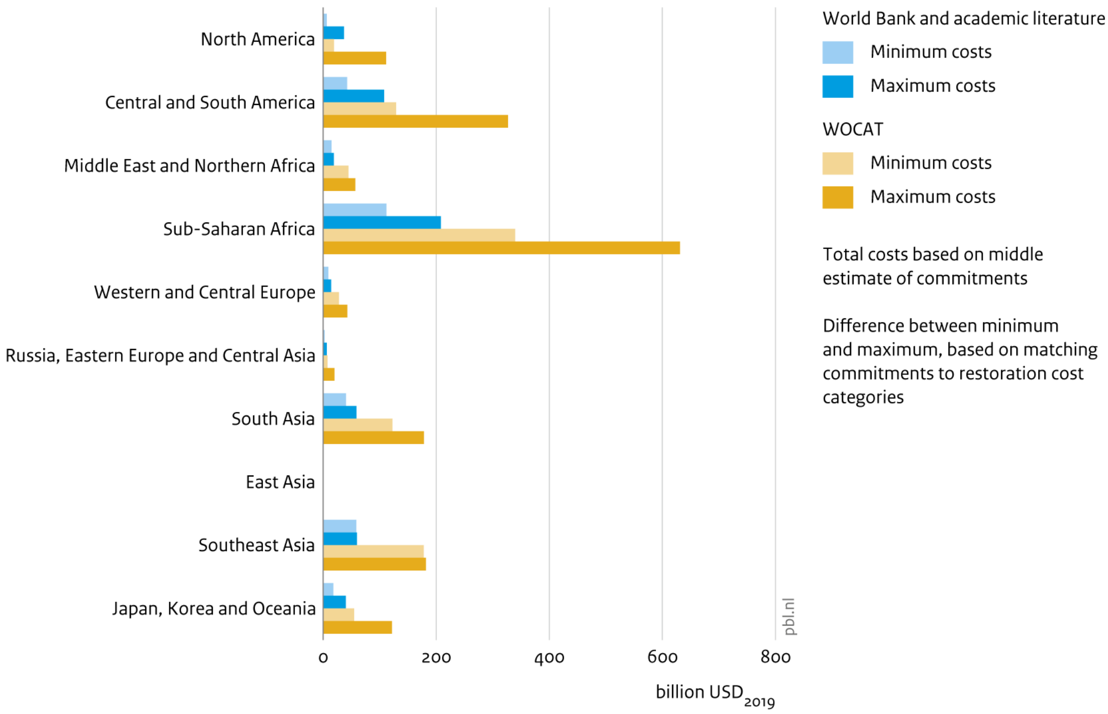
The benefits of land restoration are significant, but implementation of measures is complex due to high costs and their distribution. The potential benefits of restoration as shown by the *Restoration* scenario are significant, although some potentially negative effects could not yet be incorporated in the modelling. However, implementing current commitments, or going beyond that, requires addressing how such implementation should be financed, how to balance private and public costs and benefits, and how to enable effective governance mechanisms.

Implementing current land restoration commitments requires investments that are estimated at 0.04% to 0.21% of annual global GDP, if implementation would be spread out over 10 years. The total costs range from USD 300 billion to USD 1,670 billion. The large spread is mainly due to large differences in the cost data available from various data sources. The estimate accounts for differences in labour and investment costs between countries, based on their GDP. It also accounts for specific types of restoration measures. The median restoration cost for all restoration types comes to USD 1,464/ha, with the highest median restoration costs found in cross-slope barriers, irrigation, silvopasture and agroforestry, and with the lowest median costs recorded for forest management, grazing management and passive regeneration. Not included are learning curve effects, the potential benefits of scale and opportunity costs. The costs are only calculated for the current commitments by countries, not for the restoration scenarios (Section 5.3).

Most restoration costs for current commitments will be incurred in developing countries, where costs are likely to prohibit full implementation. The largest share of restoration costs appears to occur in sub-Saharan Africa (USD 112–631 billion) and Central and South America (USD 43–327 billion), in part due to the higher level of commitments made in the global south (Figure 8). The costs of implementing the restoration commitments in sub-Saharan Africa, with estimates of 0.8% to 3.7% of GDP, annually, up to 2030, are likely to prohibit implementation in this region. Unless international cost-sharing mechanisms for restoration are developed, such as through climate, biodiversity or private finance measures, it seems likely that countries that have made a large part of the current commitments will lack the required resources (Section 5.3).

Figure 8

Total costs of restoration commitments as of 2020



Source: PBL, Verhoeven et al. in prep.

The large ambitions related to land restoration and improved land management make it imperative to know how restoration can benefit land users. Better land management is viewed as the key to unlocking multiple benefits for land users, including better soil quality, higher levels of agricultural productivity and higher incomes. Many of the interventions are based on a plausible theory of change. However, the empirical evidence based on private benefits of land restoration by landowners is ambiguous. If restoration practices increase on-farm productivity and farm income but also demand more labour and thus lock out other sources of income, the overall effects on farmer household income could be negligible (Section 5.1).

The benefits of agricultural restoration measures to farmer household incomes remain without firm evidence. Too few studies are available to firmly assess the direct benefits of land restoration for household incomes. Existing studies provide little to no evidence of short-term effects on household income, and many studies report no findings on the impact of restoration on households and provide little information on the institutional and governance environment in which the measures were implemented. Given the large land restoration commitments by countries, policymakers need advice on incentivising land restoration by landowners to create net societal benefits, especially in agricultural land management. This is a key knowledge gap to be addressed (Section 5.2).

Restoration measures can prevent future land degradation, and this should be taken into account when assessing investments in restoration measures. The negative impacts that are avoided by preventing future land degradation are a benefit of the implementation of restoration measures. This requires an estimate of the potential future impact in the absence of restoration measures. Not accounting for prevented impacts would underestimate the potential benefits of land restoration. Prevention is also crucial because, while deterioration of land condition can be rapid (in the case of land conversion) or slow (in the case of slow but persistent degradation processes), land restoration is generally a long-term process (Section 5.4).

Land restoration's strength in creating multiple benefits for many actors is also its weakness. How private actors, such as smallholders, can be rewarded for providing public benefits, in the short or long term, is a key challenge. Adding to the complexity is the number of actors involved. Scaling up restoration projects requires engaging millions of smallholders across many regions of the world. While private investors need to rely on bundling of projects to attain profitable scale and reduce risks, transaction costs increase with the number of actors involved. Knowledge of effective policy and governance approaches to bridge this complex distribution of costs and benefits remains scarce (Sections 5.5 and 5.6).

Balancing the public and private benefits of land restoration requires effective governance

Effective governance of land restoration efforts requires policy interventions at micro, meso and macro levels. While land restoration often starts with micro-level restoration projects, there is scope for enhancing the incentives by landowners by considering complementary national policies. Such policies may further leverage private investment by providing better safeguards and legal certainty for private investors.

The stimulation of land restoration measures requires countries to integrate restoration into existing policies and institutions. There is a large variety of policies and institutions to support and shape incentives for land restoration, such as agricultural and land-related policies, nationwide economic policies, and policies in several non-agricultural sectors. These policies include the implementation and enforcement of local rules and regulations, participatory decision-making, capacity building for cooperatives to implement restoration, responsive extension services, effective land policy frameworks that govern tenure and land markets, and agricultural taxes and subsidies. For some of these instruments and institutions, it is clear under which conditions they can help to provide enabling conditions for restoration — for others, much less so.

Fragmentation amongst actors makes public or private investment decisions complex. Because restoration can provide a range of benefits, rather than being a focused solution for a single goal, it can result in fragmented planning, funding and implementation. The onset of the UN Decade on Ecosystem Restoration, and the inclusion of a complementary and consistent set of restoration targets in the Rio Conventions and the SDGs that are subsequently translated into the national plans (LDN, NDCs, NBSAPs), may help create more coherence between various goals and ambitions.

Combining land restoration and protection measures with changes in production and consumption patterns can achieve larger benefits and enable implementation. The restoration scenarios account for changes in land restoration and management, and the protection of key ecosystem functions. Larger improvements to land condition, biodiversity and ecosystem functions could be achieved by avoiding ongoing degradation and conversion. Scenarios can be designed where restoration and protection are combined with concurrent food system transformations, such as consumption shifts to less meat-intensive diets, reductions in food waste, and the more sustainable sourcing of agro-commodities. Increasing efficiencies in production chains, for instance through improved livestock efficiency or reduced losses of food in the supply chain, would reduce the pressure on land. If less land would be needed for the production of land-based products and, thus, would become abandoned, this land could be restored.

There are no silver bullets for choosing the right mix of policies or projects to incentivise land restoration at scale. There is a paucity of empirical evidence on combinations of policies and projects that have proved successful for land restoration. Such information is urgently needed as the required interventions are site- or country-specific, and also as benefits take decades to materialise. This finding implies a need for more policy experimentation and evaluation to better understand how land restoration can be achieved at scale, at the lowest possible cost to societies. Such information is imperative for making the UN Decade of Restoration a success.

1 Introduction

1.1 Land restoration attracting increasing attention

Increasing global attention to and ambitions for the restoration of land and ecosystems

Increasing attention is being paid to the possible role of ecosystem restoration, including improved land management, in realising global sustainability ambitions (Suding et al., 2015; Chazdon et al., 2017). These ambitions are expressed in the goals and targets of the United Nations Convention to Combat Desertification (UNCCD), the Convention on Biological Diversity (CBD), and the United Nations Framework Convention on Climate Change (UNFCCC). Restoration ambitions are also included in the Sustainable Development Goals (SDGs) and in various other international and regional agreements and initiatives.

The increased interest in restoration follows a number of high-level reports that highlight the extent and impact of climate change, land degradation, deforestation and biodiversity loss. This is exemplified by the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) Assessment Report on Land Degradation and Restoration (2018), the Intergovernmental Panel on Climate Change (IPCC) Special Report on Climate Change and Land (2019), and the first edition of the UNCCD Global Land Outlook (2017), as well as much-discussed journal articles on reforestation potential and the role of nature-based solutions in tackling climate change and biodiversity loss (Bastin et al., 2019; Griscom et al., 2017; Roe et al., 2019; Strassburg et al., 2019).

The UN Decade on Ecosystem Restoration

A number of initiatives have arisen to build knowledge networks and capacity development, such as the Global Partnership on Forest and Landscape Restoration (2003), the Bonn Challenge (2011) and the New York Declaration on Forests (2014). Most recently, the UN has declared the years 2021 to 2030 as the UN Decade on Ecosystem Restoration, jointly led by the Food and Agriculture Organization of the United Nations (FAO) and the UN Environment Programme (UNEP), and supported by collaborating agencies, including the three Rio Conventions, other international conventions, and regional partners including IUCN.

Restoration and improved land management are recognised as cross-cutting instruments for the Rio Conventions (Rio Conventions, 2012) and sustainable development (Navarro et al., 2017). They can simultaneously contribute to the goals of all three conventions on biodiversity, desertification and land degradation, and climate change (IPBES, 2018) and can have significant co-benefits for nearly all the SDGs, though these may occur on different temporal scales and also feature trade-offs (IRP, 2019). This high level of synergy across goals and targets makes restoration attractive in an era in which trade-offs and difficult choices are becoming increasingly clear. Harnessing such synergies could aid the development of integrated frameworks of restoration measures, policy alignment and cost-effective action (Akhtar-Schuster et al., 2017).

1.2 Purpose of the study

This scenario study is a background study for the Global Land Outlook 2 and quantifies the potential global and regional benefits of land restoration. The scenario study for the first Global Land Outlook (GLO1) was purposed to assess the potential future impact of continued land degradation, in light of the ongoing pressures on land and a changing climate (Van der Esch et al., 2017; UNCCD, 2017a).

This study quantifies the potential of land restoration, while taking into account continuing developments in the demand for land and land-based products, climate change and land degradation. Land restoration in this study includes ecological restoration, rehabilitation, improved land management and partial restoration of land used for agriculture (Box 2.1). The long-term perspective of scenarios (in this case, up to 2050) is necessary, as many land restoration measures require long-term perseverance to yield their full potential, and because potential future developments have to be taken into account when planning restoration and land management improvements and when estimating their potential benefits.

A crucial aspect of land restoration is the delivery of multiple benefits. This requires the scenario analysis to cover a broad range of indicators. This report includes indicators to cover the three Rio Conventions (land degradation and desertification, biodiversity, climate) plus aspects of agriculture/food and water security.

The study compares the scenario ambitions to the current commitments by countries on land restoration, reviews the evidence of benefits of land restoration for livelihoods and households, estimates the costs of land restoration commitments and thus the investment necessary to implement them, and reviews the institutions and policies that could enable the uptake and implementation of land restoration measures.

1.3 Scope and contributions of the study

This study addresses several knowledge gaps on land degradation and restoration. First and foremost, this study estimates the future global potential of land restoration in terms of its contributions to a range of sustainability ambitions, including to mitigate climate change, limit biodiversity loss, and improve the sustainable use of land and water for agriculture. This report compares this potential not only to the present situation, but also to a business-as-usual scenario in which degradation processes are allowed to continue and there is an absence of restoration, based on the scenario report for the GLO1 (Van der Esch et al., 2017). This makes it possible to estimate the potential of land restoration and improvements in land management to prevent future impacts.

A second knowledge gap is addressed in this report with the estimate of the current commitments of countries to restore, rehabilitate and improve land management. Thirdly, an estimate of the order of magnitude of the costs of current commitments on land restoration is made, and finally, an assessment is carried out of the evidence base on the benefits of improved land management for household incomes.

Filling these gaps required the construction of four new databases, the analysis of satellite data, and multiple model developments, improvements and combinations. The technical and scientific

underpinning of these results will be published separately in technical reports or articles (Sewell et al., 2020a,b; Malan et al., in prep.; Verhoeven et al., in prep.; Fleskens et al., in prep.).
This study does not provide a complete overview of the current state of the relevant science, as this was recently covered by two big assessments: the IPBES Assessment Report on Land Degradation and Restoration, and the IPCC Special Report on Climate Change and Land (IPBES, 2018; IPCC, 2019).

The study's objectives and method required a focus on biophysical effects and agro-economics at the global and regional scales, which means that less attention is paid to local complexities, land rights, and perspectives on land distribution and access other than through land use and competition for land from different demands. These are, obviously, also highly important, but fall beyond the scope of this study as they are addressed in the chapters of the upcoming Global Land Outlook 2 by the UNCCD. Neither is specific attention paid to the impacts of the COVID-19 pandemic or large-scale pests, droughts or diseases that are hampering land users in different regions of the world. The long-term impact of these shocks is not yet clear and could therefore not be accounted for in the scenarios.

1.4 Report structure

Chapter 2 presents the way in which this report understands land degradation and restoration, provides an overview of the global goals on restoration and the extent of commitments made by over 100 countries on land restoration, and introduces the scenarios. Chapter 3 describes the results of the baseline scenario, exploring the projected changes in land use, climate change and land degradation up to 2050 and the effects on key ecosystem functions. Chapter 4 then shows the potential of an array of land restoration measures and increased preservation of ecosystem functions, compared to the baseline scenario. Finally, Chapter 5 presents the current state of knowledge on how land restoration may affect livelihoods in agricultural situations, the costs of land restoration commitments, and the ways in which governance, institutions and policy instruments can help or hinder the implementation of these commitments.

2 Global land restoration goals and commitments

The year 2021 will see the kick-off of the United Nations Decade on Ecosystem Restoration, which represents a culmination of growing global attention to and agreements and ambitions for restoration and improved land management. Measures that help to restore land and improve its management can offer multiple benefits to society simultaneously — contributing to food and water security and helping to address biodiversity loss and mitigate and adapt to climate change. This diversity of benefits has resulted in restoration commitments submitted by countries across international conventions on climate, biodiversity and desertification, and through voluntary initiatives such as the Bonn Challenge.

This chapter introduces the understanding of land degradation and restoration (2.1), the current state of goals (2.2) and quantitative commitments for restoration (2.3) at the start of the restoration decade, and their relevance for global scenarios on land degradation and restoration (2.4) (also see Chapters 3 and 4) as well as for governance, institutions and restoration costs (Chapter 5). Sections 2.2 and 2.3 draw extensively on a policy brief developed for this report (Sewell et al., 2020a).

2.1 Understanding land degradation and restoration

2.1.1 Land degradation

Land has been changed by humans for their use for centuries. However, the pressure on land has increased exponentially over the last century, in line with increasing populations, expanding infrastructure, and the wider and more intensive development of agriculture. This has translated into adverse impacts on the environment through the loss of soils and vegetation and the loss of functions provided by ecosystems for the regulation of water, nutrients and climate. The recent IPBES report on land degradation and restoration estimates that about one quarter of the world's terrestrial area remains free from substantial human impact (IPBES, 2018).

Land degradation is used as an umbrella term for multiple types of undesired and more or less irreversible processes, including salinisation, wind and water erosion, compaction, human encroachment, and invasions of exotic species (Gibbs and Salmon, 2015) (also see Chapter 3). Past efforts to measure land degradation (Table 2.1) have been hampered by disagreements on whether calculations should take into account natural or human-induced processes (Wiegmann et al., 2008), or which baseline (Herrick et al., 2019) or time period to use (Prince et al., 2018). 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).

The IPCC (2019) conclude that, while current evidence is limited and inconsistent due to differences in definitions and measurements of land degradation, it does suggest that about one quarter of the ice-free land area is subject to some form of human-induced land degradation. Estimates of land degradation worldwide differ considerably, ranging from 15% to 75% of the world's land area, due to differences in definitions, applied methodologies and concepts (Table 2.1) (Caspari et al., 2014; Gibbs and Salmon, 2015).

The UNCCD, in both its strategic objectives and its Land Degradation Neutrality (LDN) approach, use three indicators to assess land degradation: land cover and land use, primary productivity, and soil organic carbon. The SDGs, which include halting and reversing land degradation in Goal 15, depend on the same three indicators in Target 15.3. Such a limited set of indicators is practical, and they are available for and comparable across countries. While the UNFCCC does not include indicators for land degradation or restoration except for carbon sequestration, the CBD has a large number of indicators for the Aichi Targets, which are being redeveloped under the post-2020 framework. These indicators include the extent, quality and distribution of natural ecosystems, the rate of loss of natural ecosystems, biodiversity loss, and protection of key ecosystems.

Moving to a broader set of indicators

The previous scenario report for the Global Land Outlook and the World Atlas of Desertification were published around the same time and did not attempt to estimate the extent of degraded land (Van der Esch et al., 2017; JRC, 2018). Instead, they assessed an array of indicators to consider multiple aspects of land degradation and its consequences, focusing more on land condition, on pressure factors that affect land condition and include socio-economic drivers, and on the potential impact of changes to land condition. These reports worked from the premise that what is relevant is not the extent and severity of land degradation itself, but the causes and consequences, or impacts, of the changes to land use and land condition.

Land degradation is about a decline in land condition and persistent loss of ecosystem functions due to direct or indirect human-induced processes that cannot be reversed unaided

The recent IPBES and IPCC reports on land and land degradation used different but similar definitions, on which the previous sentence is based. This is in line with the move to more indicators, attention for land condition, and a focus on the consequences of changes to land. The reports make it clear that biodiversity and ecological integrity should be part of land condition. Also, climate change, as an indirect human-induced process, is a driver of land degradation, affecting land condition and ecosystem functions.

Table 2.1
Estimates of the global extent of land degradation

Source	Calculation method	Estimate	Estimate breakdown
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 Mkm^2)
Drenge and Chou (1992)	Expert opinion	70% of drylands affected by degradation (36 Mkm^2)	Affected: 73% of rangelands 47% of rain-fed croplands 30% of irrigated croplands
Ramankutty and Foley (1999)	Based on land abandonment	Cropland abandonment increased from 0.6 to 22 Mkm^2, 1950s–1990	

FAO TerraSTAT (Bot et al., 2000)	Expert opinion	66% (60 Mkm^2) of the world's land affected by degradation	26% severely degraded 21% moderately degraded 18% lightly degraded
FAO GLADA (Bai et al., 2008)	Satellite-based approach (NDVI)	About 24% of land degraded substantially (27 Mkm^2) over the 1981 to 2006 period	19% of degrading land is cropland 24% is broadleaved forest 19% is needle-leaved forest
HYDE database (Campbell et al., 2008)	Based on land abandonment	3.8–4.7 Mkm^2 abandoned land (over last 300 years)	
Cai et al. (2011)	Biophysical models	Almost 10 Mkm^2 of degraded and abandoned lands	
FAO Pan-tropical Landsat	Based on land abandonment	0.8 Mkm^2 of cropland and pasture was abandoned temporarily or permanently in the 1990s	
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
Van der Esch et al. (2017)	Combined satellite-based / modelling approach	9 Mkm^2 globally showing a persistent, significant decline in net primary production (excluding the effects of climate change), covering 12% of global agricultural land. Net primary productivity is lower than natural state on 23% of global terrestrial area	
IPBES (2018)	Literature review	Less than one quarter of the Earth's land surface remains free from substantial human impacts (established but incomplete). By 2050, it is estimated that less than 10% of the Earth's land surface will remain substantially free of direct human impact	
Atlas of desertification (JRC, 2018)	Satellite-based approach	Between 1999 and 2013, about 20% of the global ice-free land area showed persistent declining trends in land	22% in Africa 37% in Australia and Oceania 27% in South America 18% in North America 14% in Asia

		productivity, with regional differences	12% in Europe
IPCC (2019)	Literature review	About a quarter of the ice-free land area is subject to human-induced degradation (limited evidence, medium agreement), affecting about 3.2 billion people (low confidence)	

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

2.1.2 Land restoration

Restoration includes the improvement of natural ecosystems and the rehabilitation and sustainable management of lands under human use

In this report, land and ecosystem restoration covers the full or partial restoration of an ecosystem (Box 2.1). An area that has scope for restoration can be fully restored to its natural state (ecological restoration) or rehabilitated to serve a specific land use (rehabilitation or sustainable land management) (Figure 2.1) (IPBES, 2018). This is in line with the restoration continuum by Gann et al. (2019). Areas do not have to be completely degraded or abandoned for them to have restoration potential. Agricultural areas that are still in use but have suffered from erosion or other degradation processes have scope for restoration. There is, therefore, a clear link between restoration and land management. Improved land management, or sustainable land management, can reduce or avoid degradation processes and, over time, lead to ecosystem recovery. Preventing degradation or reducing further degradation through improved land management can help to avoid restoration costs further down the line. For instance, applying grazing management may help grasslands and their soils to recover from overgrazing and erosion and prevent further erosion. Restoration therefore covers efforts aimed at restoring ecosystems to their natural state and rehabilitating and improving systems that are under human use and management.

Restoration and improved land management are recognised as cross-cutting instruments for the Rio Conventions (Rio Conventions, 2012) and sustainable development (Navarro et al., 2017). They can simultaneously contribute to the goals of all three conventions on biodiversity, desertification and land degradation, and climate change (IPBES, 2018) and can have significant co-benefits for nearly all the SDGs, though these may occur on different temporal scales and also feature trade-offs (IRP, 2019). This high level of synergy across goals and targets makes land restoration attractive in an era in which trade-offs and difficult choices on land use are becoming increasingly clear.

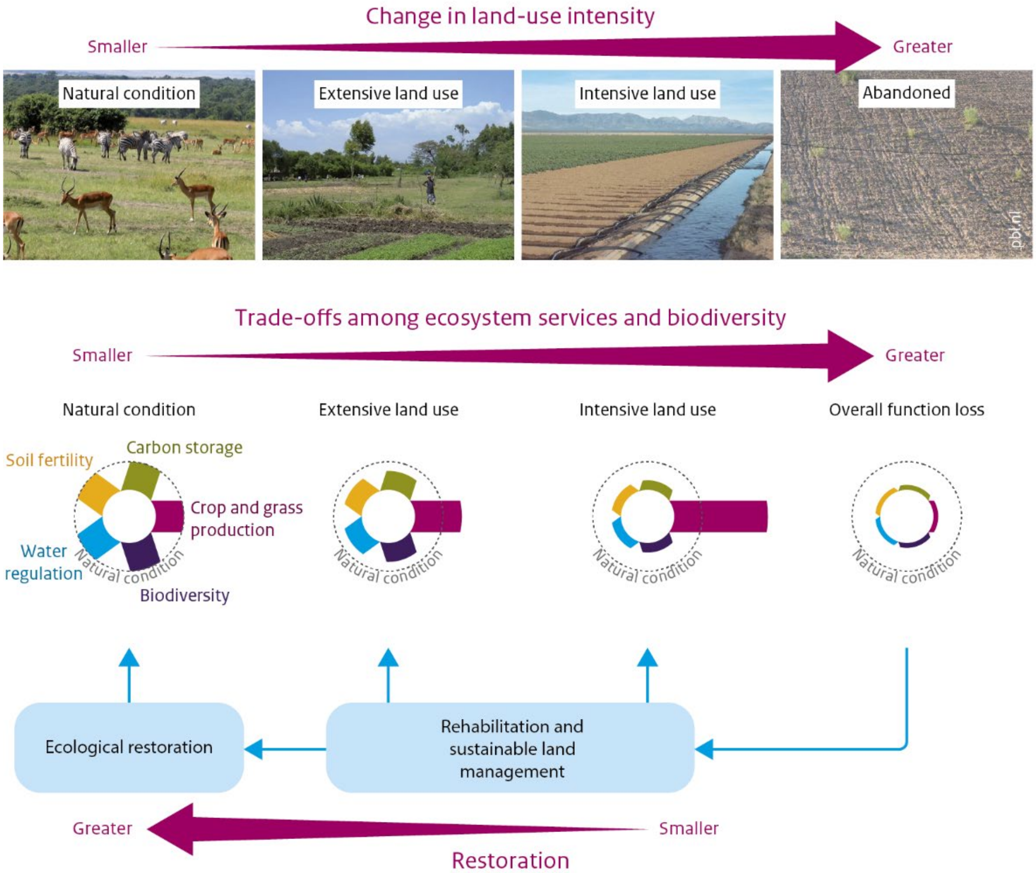
For example, restoration and improved land management efforts have, alongside conservation, the potential to benefit climate change mitigation in various ways, such as by increasing terrestrial carbon storage (IPBES, 2018; Griscom et al., 2017; Strassburg et al., 2019) and climate change adaptation, and by increasing ecosystem resilience to natural and climate change-related hazards, such as flash flooding and landslides (Sanz et al., 2017). Furthermore, improved soil quality supports resilience and adaptation to climate change and extreme weather events such as flooding and drought (Abhilash et al., 2016; Edrisi and Abhilash, 2016; Dubey et al., 2019).

Restoration can provide co-benefits for food security by safeguarding ecosystem services such as soil protection, pollination, nutrient cycling and soil water-holding capacity, which are crucial for both short- and long-term agricultural productivity (Foley et al., 2011; Tilman et al., 2011; Bommarco et al., 2013; Bossio et al., 2010; Stavi et al., 2015; Tripathi et al., 2017), as well as biodiversity benefits including avoided species extinctions (Strassburg et al., 2019). Strategic planning can help to achieve multiple benefits and to avoid trade-offs between conservation and food security needs, in both the short and the long term, such as when land is taken out of production for restoration purposes (Dudley et al., 2005; IRP, 2019).

Healthy and productive landscapes and the benefits they provide can tackle further human security concerns, such as regarding employment, health and education, while providing other socio-economic conditions that foster peace (Abhilash et al., 2016; IRP, 2019; Lonergan, 2012). For example, restoration and more secure land tenure can help to support food and livelihood security and economic diversification beyond agricultural livelihoods, thereby contributing to more stable environments (Mach et al., 2019).

Figure 2.1

Understanding land degradation and restoration through changes in ecosystem function and trade-offs



Source: PBL

Box 2.1 Conceptual approach: assessing changes to land condition and ecosystem functions instead of land degradation

This report uses *land condition* and *ecosystem functions* as its core concepts. It does not attempt to estimate the extent and severity of land degradation according to a specific definition. Changes to the condition of land resulting from human activity are expressed in a set of indicators, which are used in a baseline and two restoration scenarios (Section 2.4) 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. The condition of the land determines the potential of its ecosystem functions to provide people with various types of ecosystem 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 state (i.e. without human intervention) (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, which influence plant growth and soils. Changes in land condition result in alterations to ecosystem functions and services, such as productivity for crops and grass, water regulation and carbon storage. Figure 2.5 in Section 2.4 shows a schematic representation of these relationships.

Ecosystem functions include water regulation, nutrient regulation and biomass production, and are themselves dependent on the biological diversity and condition of the ecosystem. Changes to ecosystem functions can be intentional, for instance when a natural system is converted into an agricultural system, or unintentional, and some functions can increase while others decrease (Van der Esch et al., 2017; IPBES, 2018). Restoration aims to increase ecosystem functions where possible, generally without reducing other functions. In this report, restoration covers a wide range of measures that restore land through changing its physical management, and include ecological restoration, rehabilitation of degraded lands for human use, and improved management of land under existing use. Measures therefore often overlap with sustainable land management (SLM).

Changes in land use and land condition reflect trade-offs between various ecosystem functions and services supplied by land. Figure 2.1 shows a stylised representation of these trade-offs. 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.

2.2 Global land restoration goals

The multiple benefits of restoration, from local to global scales, are reflected in the array of global and regional goals for restoration

There are a large number of agreements and initiatives that include goals or objectives on land restoration and improved land management. These include multilateral environmental agreements (MEAs) and multi-actor initiatives by public, private and civil society actors. Table 2.2 provides an overview of international and large regional agreements and initiatives.

Multilateral environmental agreements (MEAs)

Several MEAs include goals or objectives on restoration at the international level. These goals are found across a spectrum of conventions with different environmental and sustainability ambitions, including the three Rio Conventions (UNFCCC, CBD, UNCCD) on climate change, biodiversity loss, desertification and land degradation, the Ramsar Convention on Wetlands, the Sendai Framework for Disaster Risk Reduction, and the UN Forum on Forests (UNFF). Links to restoration are also found in the SDGs (Appendix A1), including with particular relevance to this report: SDG 2 (zero hunger), SDG 6 (clean water and sanitation), SDG 13 (climate action) and SDG 15 (life on land).

Multi-actor initiatives for restoration

There are many other ambitions for restoration among public, private and civil society actors that are more hybrid in nature than their MEA counterparts, not only at the international level but also regionally. These include initiatives centred around tree planting (Trillion Tree Campaign), soil restoration (4 per 1000) and forest and landscape restoration that aim to address climate change, human well-being and biodiversity loss by restoring landscapes (Bonn Challenge and the New York Declaration on Forests). These initiatives were intended as a means to get governments, companies and a wide range of public, private and non-state actors to commit to restoration and to implement existing international commitments at national and regional levels.

Within the Bonn Challenge, the majority of voluntary commitments for action are made by national governments or national regions, and very seldom by private companies or other non-state actors. The New York Declaration on Forests is a political declaration and a partnership of governments, multinational companies, civil society, indigenous peoples and local communities. While the declaration was signed by 190 organisations (including 57 transnational companies), few have submitted official commitments on these platforms with respect to land restoration (Jopke and Schoneveld, 2018).

Table 2.2
Agreements and initiatives with goals or objectives for restoration and improved land management

Category	Agreement or initiative	Goals or objectives
Multilateral	Paris Agreement (UNFCCC)	Report on mitigation activities including agriculture, forestry and other land use (AFOLU) (Article 4; NDCs), conserve and enhance forest carbon stocks through sustainable management of forests (Article 5; REDD+) and enhance adaptive capacity, strengthen resilience and reduce vulnerability to climate change (Article 7.1; climate adaptation).

Multilateral	Aichi Biodiversity Targets (CBD)	Halve the rate of loss of forests and other ecosystems and where possible reduce it to zero, ensure at least 17% of terrestrial areas are conserved through effectively and equitably managed protected areas or comparable approaches, restore at least 15% of degraded ecosystems, enhance resilience and contribution of biodiversity to carbon stocks, sustainably manage productive areas to also conserve biodiversity, and conserve and restore ecosystem services. Targets 2, 5, 7, 11, 14 and 15 primarily (though there are others that link more indirectly).
Multilateral	Achieving Land Degradation Neutrality (LDN) (UNCCD)	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. Aligns with SDG Target 15.3, using the indicator 'Proportion of land that is degraded over total land area'.
Multilateral	Sustainable Development Goals (SDGs)	SDG Targets 2.4, 6.6, 13.1, 15.1, 15.2, 15.3, 15.4, 15.5, 15.7. Covering: conservation and restoration of ecosystems, land degradation neutrality, halting loss of biodiversity, sustainable land management, resilience and climate adaptation, and sustainable management of natural resources.
Multilateral	UN Strategic Plan for Forests 2030 (UNFF)	Six Global Forest Goals including sustainable forest management, halt deforestation and forest degradation, and a 3% increase (120 million hectares) in forest area worldwide by 2030.
Multilateral	EU Green Deal/ Biodiversity Strategy	Protect 30% of land in Europe, increase organic farming and biodiversity-rich landscapes, halt or reverse the decline of pollinators, plant 3 billion trees by 2030, restore 25,000 km of rivers and reduce the use and risk of pesticides by 50% by 2030.
Multilateral	Ramsar Convention on Wetlands	Four goals, addressing drivers of degradation and loss of wetlands; effectively conserve and wisely use wetlands.
Multilateral	Sendai Framework for Disaster Risk Reduction	Seven global targets that aim to substantially reduce disaster risk and losses in lives, livelihoods and health and in the economic, physical, social, cultural and environmental assets of persons, businesses, communities and countries, for example through ecosystem-based adaptation.
Multi-actor, international	The Bonn Challenge	Restore 150 million hectares of the world's deforested and degraded lands by 2020, extended by 200 million hectares by the New York Declaration on Forests to 350 million hectares by 2030.
Multi-actor, international	New York Declaration on Forests	Reduce and halt deforestation by 2030, restore degraded landscapes and forest lands (adding 200 million hectares by 2030 to the initial 150 million hectares of the Bonn Challenge goal, see Bonn Challenge above), reduce emissions from deforestation and degradation and strengthen forest governance.
Multi-actor, international	Trillion Trees Campaign	Restore and conserve one trillion trees globally by 2030 to restore biodiversity and address climate change.
Multi-actor, international	Ark 2030	Restore and regenerate 500 million hectares of land across five critical landscapes worldwide.

Multi-actor, international	4 per 1000	Increase soil carbon stocks by 0.4% per year in the first 30–40 cm of soil up to 2050.
Multi-actor, regional	AFR100	Bring 100 million hectares of degraded and deforested land in Africa into restoration by 2030.
Multi-actor, regional	Great Green Wall	Restore 100 million hectares of currently degraded land, sequester 250 million tonnes of carbon and create 10 million jobs in rural areas by 2030.
Multi-actor, regional	ECCA30	Build on the Astana Resolution (2018) to bring 30 million hectares of degraded and deforested land in Europe, the Caucasus and Central Asia into restoration by 2030.
Multi-actor, regional	Initiative 20x20	Restoration initiative in Latin America and the Caribbean to bring 20 million hectares of deforested and degraded land into restoration by 2020.
Multi-actor, regional	Agadir Declaration	Restoration initiative in the Mediterranean region by Silva Mediterranea to restore 8 million hectares of degraded and deforested land by 2030; endorsed by 10 countries.
Multi-actor, regional	Regreening Africa	Reverse land degradation among 500,000 households on 1 million hectares by 2022, in 8 countries in sub-Saharan Africa: Ethiopia, Ghana, Kenya, Mali, Niger, Rwanda, Senegal and Somalia.
Multi-actor, regional	1000 landscapes	Achieve regenerative landscape and livelihood ambitions in 1,000 landscapes for 1 billion people by linking currently fragmented efforts, building capacities and unlocking investment finance, by 2030.

2.3 Global overview of current national restoration plans and commitments

Most countries have submitted commitments on restoration to the three Rio Conventions and the Bonn Challenge

Both qualitative and quantitative voluntary country commitments related to restoration are published in the national plans or as voluntary commitments that countries submit to the Rio Conventions or via the Bonn Challenge or related initiatives. 115 countries have put forward restoration commitments under at least one of the three conventions or the Bonn Challenge. In general, the commitments are to be achieved between 2020 and 2030, and in a small number of cases by 2040. All of the quantitative commitments, publicly available as of August 2020, have been collected and categorised in the Global Restoration Commitments (GRC) database, for all countries that have submitted restoration plans or commitments under at least one of the conventions or the Bonn Challenge.

Box 2.2 The Global Restoration Commitments (GRC) database

The analysis of quantitative country restoration commitments is based on a new database on global restoration commitments that was developed by PBL for UNCCD’s Global Land Outlook 2.

Purpose
The GRC database provides information on the type of restoration measures that countries plan to implement, and on the order of magnitude of restoration commitments in various countries, regions and the world. The primary purpose of the database is to inform PBL's work on global scenario analysis covering land-use change, land degradation and land restoration for the UNCCD's Global Land Outlook, second edition. Data outputs from the GRC database (on the order of magnitude, regional location and restoration category of commitments) make it possible to estimate how scenario projections on land degradation, or scenario assumptions on restoration policies, compare to the current level of ambition, and therefore how relatively ambitious a scenario is compared to current plans. The database can also inform policymakers on the extent of current global and country commitments and facilitate discussions on possible improvements to commitments. Other potential uses include monitoring (progress on restoration can be compared to the national commitments in the database), policy coherence discussions (i.e. on synergies between different convention commitments within countries), informing global restoration cost estimates (Verhoeven et al., in prep.), identifying countries that require capacity building to improve the quality and measurability of commitments, and analysing best practices in reporting styles between countries and conventions.

Method
The method used for data collection and categorisation for the database builds on existing work by Arts et al. (2017), Lewis et al. (2017), Wolff et al. (2018), Climate Focus and IUCN (2018), Gichuki et al. (2019) and other reports linking the various Rio Conventions (CBD and FERI, 2016) and outlining restoration categories (Global Mechanism of the UNCCD, 2019). The database covers all commitments (as of August 2020) by countries on the restoration and sustainable use of land and terrestrial ecosystems that are:

publicly available through nationally submitted plans under the Rio Conventions and under the Bonn Challenge and associated regional initiatives, and
quantifiable in hectares with a clear reference year, or in a percentage that is translatable into hectares, such as increase in forest area.

For the UNCCD, the quantitative commitments are extracted from the publicly available Land Degradation Neutrality (LDN) national voluntary targets. For the CBD, the commitments are extracted from the latest National Biodiversity Strategies and Action Plans (NBSAPs). For the UNFCCC, the most recent Nationally Determined Contribution (NDC) country reports were used. For the Bonn Challenge, commitments were sourced from the Bonn Challenge website and the AFR100, Initiative 20x20 and ECCA30 websites.

The GRC database in its current form is not an exhaustive overview of all global restoration commitments. There are regional or national plans that are not reported to the Rio Conventions or the Bonn Challenge, but these are not included (e.g. the EU's Green New Deal plans on reforestation), and the same applies to commitments that could exist under other conventions or ambitions (e.g. the Ramsar Convention or the UNFF Global Forest Goals). Nevertheless, the database is estimated to include the majority of commitments globally and thus provide a useful order of magnitude estimate.

2.3.1 The size of current commitments under the Rio Conventions and the Bonn Challenge

The total of all restoration commitments by countries is close to one billion hectares

Adding up all the commitments by the 115 countries that have been submitted under the Rio Conventions and the Bonn Challenge or associated regional initiatives provides a total global range of commitments from 765 million to 1 billion hectares[1], to be restored or undergoing restoration by 2030 (Figure 2.2). The low, middle and high total estimates, and the closeness of the middle and high estimates (Figure 2.2) are the result of different assumptions on how country commitments overlap between the various conventions and/or the Bonn Challenge, or across restoration categories. The middle estimate is probably closest to reality, as it is based on removing overlaps within restoration measure sub-categories. The reasoning is that countries may make multiple mutually inconsistent commitments on a restoration measure that can be expected to have a high overlap (e.g. restore forest land), but that a different measure (e.g. increase land productivity in agricultural areas) will be an additional commitment. Also, these figures probably represent the bulk of current commitments globally, though they do not include some conventions, ambitions and regional and national plans (Box 2.2).

Countries have committed to restoring about 450 million hectares across various forms of land restoration and according to national needs and circumstances through the Land Degradation Neutrality national voluntary target-setting programme. About 250 million hectares are committed in the Nationally Determined Contributions, and some 90 million hectares are committed in the National Biodiversity Strategies and Action Plans under the CBD. The current commitments under the Bonn Challenge and associated regional initiatives add up to some 210 million hectares.

The assumptions behind the total range of estimates in Figure 2.2 are explained in Appendix A2. In an effort to address the uncertainty behind the overlap between the various commitments and sources, a high, low and middle estimate are expressed.

2.3.2 The geographical distribution of restoration commitments

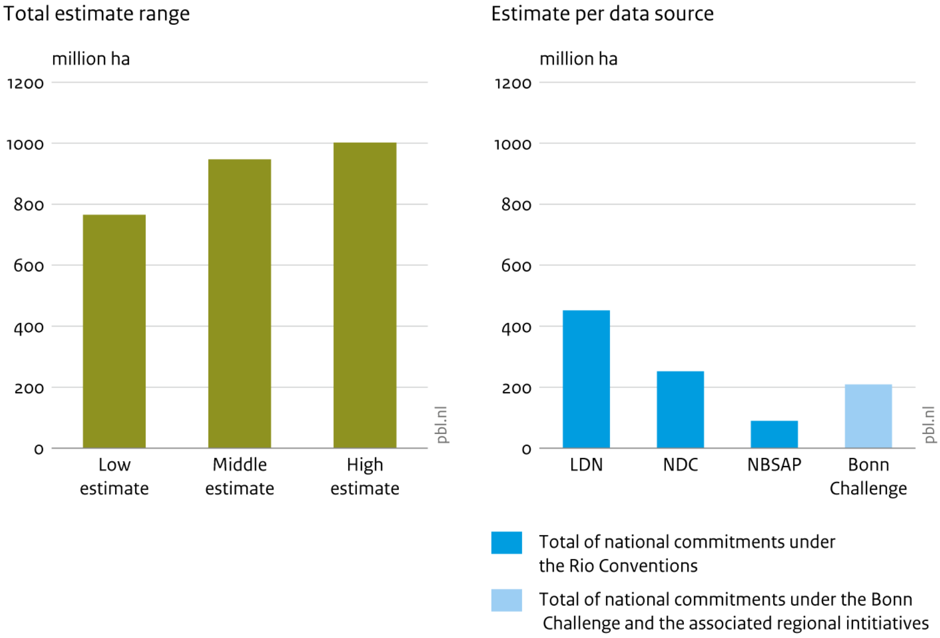
Almost half of all restoration commitments are found in sub-Saharan Africa, followed in size by Central and South America and East Asia

When aggregated into the 10 geographical regions[2] used in this report, the largest share of commitments is found in sub-Saharan Africa, in part due to the large share of countries submitting commitments under LDN and AFR100. This is followed by Central and South America, though here the commitments primarily come from NDC and Initiative 20x20 commitments. Relatively small commitments are found in Western and Central Europe, Russia, Eastern Europe and Central Asia, North America, and the Middle East and Northern Africa regions. When comparing the area covered by a commitment in a region to that region's total area, sub-Saharan Africa (19%), South Asia (14%) and East Asia (10%) see the largest share of their terrestrial area under restoration commitments (Figure 2.3).

[1] One billion hectares compares roughly to the size of Canada, the United States or China.

[2] 10 world regions used in this report. For a breakdown of countries in regions, see Appendix A4.

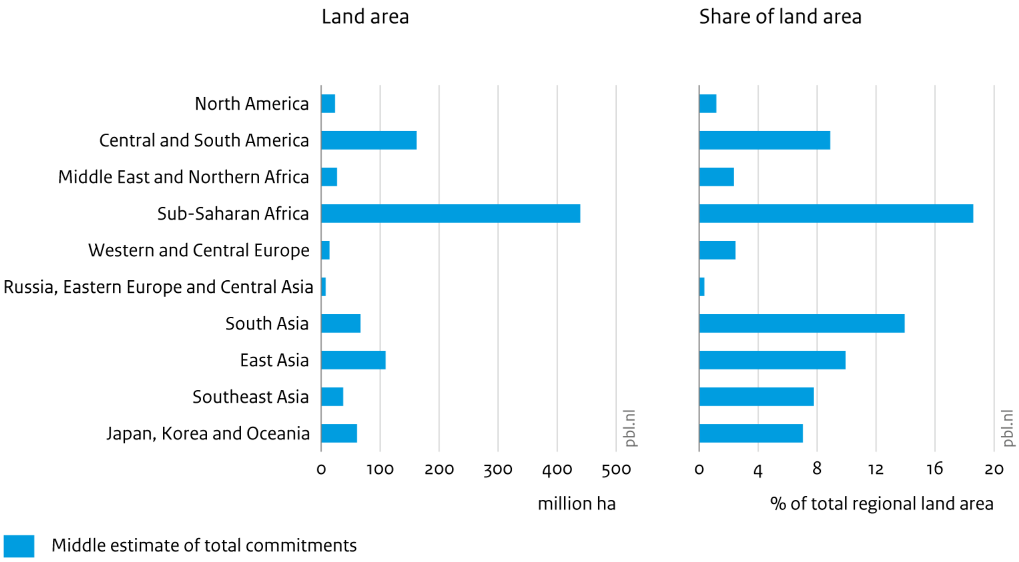
Figure 2.2
Global restoration commitments, 2020



Source: UNCCD, UNFCCC, CBD, Bonn Challenge; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

Figure 2.3

Total restoration commitments per region, 2020



Source: UNCCD, UNFCCC, CBD, Bonn Challenge, FAO; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

Relatively few commitments in North America, Western and Central Europe, and Russia, Eastern Europe and Central Asia

Relatively few quantitative commitments have been made under the Rio Conventions and the Bonn Challenge by countries in the North America, Western and Central Europe, and Russia, Eastern Europe and Central Asia regions. This is in part due to a lack of participation in the Bonn Challenge and associated regional initiatives, as well as those countries not having declared themselves as affected parties under the UNCCD. However, this does not mean that these regions do not experience land degradation, as changes to the use and condition of land also occur here (JRC, 2017; Van der Esch et al., 2017) (also see Chapter 3). Restoration and improved land management may have a role to play in these regions to achieve national, regional or global benefits and sustainability ambitions. For instance, the intensely farmed lands in these regions could have a large potential for improving soil carbon stocks. Many countries have commitments under only one or two of the conventions, which often translates into an emphasis on one type of restoration (e.g. only reforestation under an NDC). There is scope for countries to consider additional measures on restoration or improved land management that complement existing commitments, for example to address biodiversity as well as climate objectives through rewilding.

Regions with the largest commitments are also projected to see the strongest continued pressure on land

Sub-Saharan Africa, South Asia, and Central and South America are regions that will continue to experience strong pressure on land resources over the coming decades (Van der Esch et al., 2017) (also see Chapter 3). The largest restoration commitments are also in these regions, and could turn out to be reinforcing, with rehabilitation and improved land management helping to alleviate pressure on land by restoring productivity, and high demands on land making restoration more worthwhile. However, they could also turn out to be competitive, with more competition from agriculture for land, making protection and conservation efforts more difficult.

2.3.3 The distribution of restoration measures under the national restoration commitments

Country commitments address both restoration and protection, and management and rehabilitation

Commitments can be divided into two overarching categories, broadly covering ecosystem restoration and protection, and improved land management and rehabilitation[3], based on the specific restoration measures included in plans or target-setting reports. When aggregated into these two main categories, overall commitments are evenly divided across these two categories, covering 522 million hectares and 480 million hectares, respectively.

The conventions place different emphases on restoration measures

The LDN commitments emphasise improved land management and rehabilitation measures, which aligns with the LDN response hierarchy to avoid, reduce and reverse land degradation (UNCCD,

[3] Restoration and protection include measures that aim to bring ecosystems back to a natural state or that aim to conserve and prevent degradation. Management and rehabilitation include measures that aim to rehabilitate areas that are under human use but are degraded, or rehabilitate degraded areas for human use, or improve the management of used areas to at least partially restore the natural condition and functions (e.g. restore soils in agricultural areas) while maintaining the area for human use. For more information on this categorisation, see technical note (Sewell et al., 2020b).

2016). The NBSAPs generally place more emphasis on ecological restoration and protection, in line with the objectives of the CBD. The Aichi Biodiversity Targets related to sustainable agriculture and forestry (e.g. Aichi Target 7) were generally not translated into area-based commitments by the Parties (GBO5, 2020). Commitments under the NDCs are balanced between improved land management and rehabilitation on the one hand, and ecological restoration and protection on the other (mostly forest restoration and reductions in deforestation).

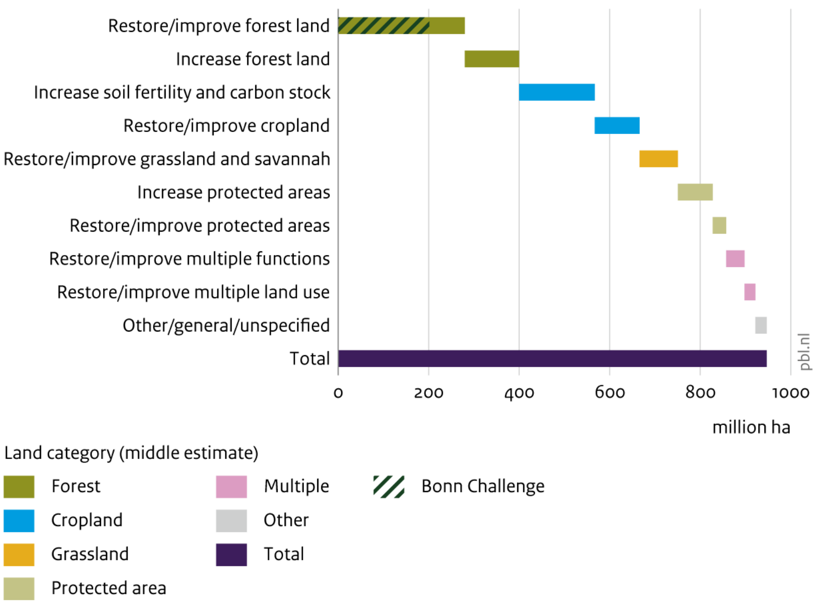
Commitments cover a wide range of land-use types

Figure 2.4 shows that the commitments cover a wide range of land-use types, but predominantly forest (42%) and agricultural land (cropland and grassland, 37%). The category *restore/improve forest land* includes all the Bonn Challenge commitments (see technical note, Sewell et al., 2020b); these are likely to also be partly agriculture-based measures, but this information was not available at the time of reporting. Commitments for restoring and improving wetlands, peatlands, mangroves, coastal areas, mining areas and artificial urban areas are small, and fall under 'other/general/unspecified'. The one billion hectares of restoration commitments cover a variety of land uses, including roughly 10% of all forest area, perhaps 20% of cropland (assuming soil fertility measures on cropland only) and a small share of pastures (Figure 2.4).

Countries have proposed different restoration measures for their commitments under different conventions

A country may plan to increase soil fertility in cropland on a specific number of hectares under the LDN commitments, while the same country may also plan another number of hectares of reforestation under its NDC for the climate convention. In some cases, areas for restoration under different commitments might also have an overlap, but it does point to the potential for countries to align their commitments between conventions and the Bonn Challenge.

Figure 2.4
Global restoration commitments, per restoration measure category, 2020



Source: UNCCD, UNFCCC, CBD, Bonn Challenge; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

2.3.4 Insights for future plans and commitments on restoration

Efforts are required to improve the alignment, measurability and geographical specificity of commitments

National plans do not in general appear to be aligned between conventions when it comes to quantitative restoration commitments. Improving the alignment could enhance planning and implementation. Also, many countries have additional qualitative commitments for restoration that lack specificity and are difficult to measure and, therefore, to evaluate or monitor. Commitments need to be measurable, geographically specific and transparent to create realistic targets and to help monitor progress, as well as provide transparency for land users.

Commitments generally fail to clarify what constitutes successful implementation in terms of quality

A few LDN commitments discuss both area and improvement in ecosystem functions such as carbon stock, but this is limited. In general, it can be assumed that restoration of natural areas implies a restoration to its natural state even though this may take decades or longer; for agricultural or mixed-use areas being clear about the specific ambition beyond the number of hectares is important. Differences in reporting styles also pose a challenge for comparing restoration commitments and progress on restoration within and between countries and conventions.

2.4 Including land degradation and restoration in the global scenario analysis

How do the current commitments by countries compare to the global potential of land restoration?

The current commitments for land restoration appear significant in size, as shown in Section 2.3. However, it is unclear what share of the global potential area for restoration they cover. In addition, the commitments are as yet relatively poor in terms of specific effects, or impacts, as they focus mostly on area size and type of land use. This report employs scenario analysis to estimate the potential of land restoration in terms of area as well as effects on land condition and ecosystem functions.

Scenario analysis to assess future changes to land

The scenario analysis in this study assesses what may happen to land over the coming decades, given the multiple demands made of land, ongoing climate change and the impact of land degradation. There are multiple types of approaches to a scenario analysis. The scenario report for the Global Land Outlook 1 (GLO1) used an exploratory approach, assessing four different scenarios to explore the order of magnitude of potential future changes under different assumptions as well as estimating the potential contribution of land degradation to those changes. The analysis in this report comes closer to the approach known as the policy-screening scenario approach, in the sense that it evaluates the potential of a policy focus on land restoration (IPBES, 2016). This approach evaluates the effects of certain policies (in this case, land restoration and extended protection of areas important for key ecosystem functions) against what is projected to happen in the future in the absence of those policies (a baseline).

As with the scenarios for GLO1, the analysis is mostly done using quantitative, integrated modelling, for a number of reasons. Firstly, this method makes it possible to account for many of the key interactions in the systems that ultimately drive land dynamics at the global and regional scales. Accounting for these interactions is important for such an analysis, given the large amount of feedback between economics, consumption patterns, land availability and prices, climate change and more. Second-order effects may diminish or enlarge first-order effects, potentially making a significant difference.

Secondly, the world is developing rapidly and any land restoration at scale will take decades to implement, bear fruit and have major effects. It is therefore important to take potential future land changes into account when estimating the potential effects of land restoration ambitions.

Thirdly, to fully assess the potential effects of large-scale land restoration, it is not enough to estimate the benefits compared to the current situation. It also requires estimating what would have happened in the absence of the measure. If a land restoration measure taken now yields benefits compared to the situation now, but also prevents a potentially worse future situation, both effects are required for an adequate estimate of the potential effect of the measure.

Indicators assessed in the scenarios

Section 2.1 outlined the move to multiple indicators to assess land degradation, and to assessing both land condition and the consequences, or impacts, of land degradation. Sections 2.2 and 2.3 have shown that there are multiple angles and approaches to restoration, anchored in different global goals and with slightly different aims. This report, in line with the earlier scenario analysis for GLO1, uses a set of indicators covering change in land condition and change in a set of key ecosystem functions, reflecting the different global goals and land restoration's relevance to each (Table 2.3). Note that some of the indicators overlap for different goals; for example, soil organic carbon is both an indicator for Land Degradation Neutrality and for climate change mitigation, and land cover/use is an indicator for Land Degradation Neutrality and for halting biodiversity loss (remaining natural area).

Table 2.3
Overview of indicators in this report

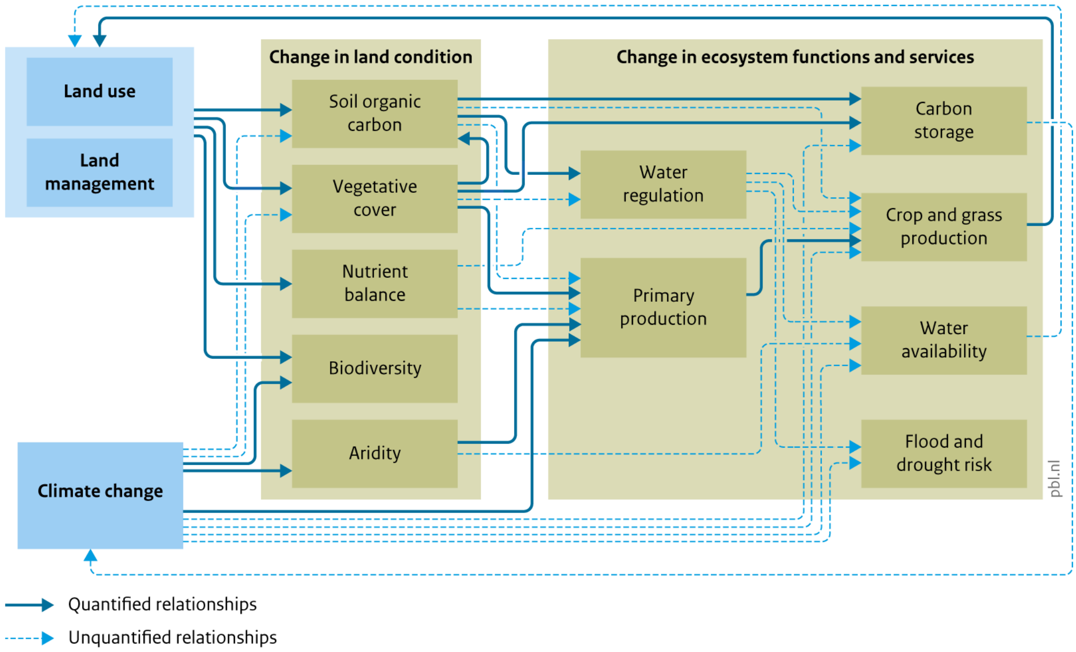
Indicators	Indicators	Explanation
Land degradation neutrality - UNCCD Strategic Plan, Land Degradation Neutrality, SDG 15.3	• Land use/land cover • Net primary production • Soil organic carbon	These three indicators are the basis for assessing the extent of land degradation under UNCCD and SDG 15.
Halt biodiversity loss - CBD Aichi Targets, SDG 15	• Mean species abundance • Remaining natural area	Mean species abundance is a measure of the intactness of an area compared to its natural state; it is an established indicator in biodiversity assessments (Alkemade et al., 2009; Schipper et al., 2020). Remaining natural area is a direct indicator of how much land remains unused for agriculture, urban, infrastructure or forestry.

Avoid dangerous climate change - UNFCCC	• Carbon sequestration in soils (soil organic carbon) • Carbon sequestration in vegetation	Restoring or enhancing the ability to store carbon by ecosystems can help mitigate climate change.
Food security - SDG 2 on zero hunger and food security; sustainable production	• Crop yields • Grass production • Food prices	Processes of land degradation pose a threat to maintaining or increasing agricultural productivity (UNCCD, 2017a,b). Cropland and grassland can both be affected by degradation processes, affecting productivity and, potentially, food availability and prices.
Water security - SDG 6 (6.4 on water-use efficiency and 6.6 on restoring water-related ecosystems)	Water-holding capacity by soils	Changes to land affect hydrological cycles through use for agriculture or changing vegetation. This can result in changes to water availability and/or changing discharge patterns, and potentially more exacerbated wet and dry spells. The capacity of soils to hold water can mitigate the impact of droughts on agriculture.

The indicators are linked to the conceptual approach as discussed in Box 2.1 in Section 2.1. Land condition includes soils, vegetation and biodiversity, as well as its local climate and hydrology. Land condition can change as a consequence of land-use change (conversion from one use to another), land management (e.g. more intensive or extensive land management systems) and climate change (Figure 2.5). Climate change can affect an area's temperature and precipitation levels, and is a driver of land degradation. Not shown are processes such as pests, diseases and fires, which can also affect land condition, but it is unclear to what extent the impacts of these are permanent; persistence being a key factor in the definition of land degradation and also important for long-term scenarios. Also not shown are specific degradation processes, which would fall between land use and land management, and change in land condition. Degradation processes include for instance wind and water erosion, salinisation and compaction of soils (also see Chapter 3).

Changes in the condition of land affect its ability to provide ecosystem functions and services (Figure 2.5). There are more functions and services than presented here, but these were chosen for relevance and due to the scope of the study and model and scale constraints. Also, this study does not quantify all of the existing relationships between the components shown in Figure 2.5, mostly for reasons of model limitations.

Figure 2.5
Effects of changes in land use, land management and climate on land condition and ecosystem services



Source: PBL

One baseline and two restoration scenarios

This study employs three different scenarios: one baseline scenario and two restoration scenarios. Figure 2.6 presents a stylised illustration of these scenarios. Historical change has taken place before 2015, and this is estimated and presented in the following chapters for a number of indicators as it can help to estimate a restoration potential. After 2015, the three scenarios differ in their outcomes for the indicators used.

The *Baseline* scenario (Chapter 3) has three purposes: (1) to explore the order of magnitude of future changes to land between 2015 and 2050 under relatively standard assumptions (a *business-as-usual* future), (2) to assess the relative impact of future land degradation, and (3) to help assess the potential benefits of land restoration by estimating which potential future losses could be prevented by restoration measures.

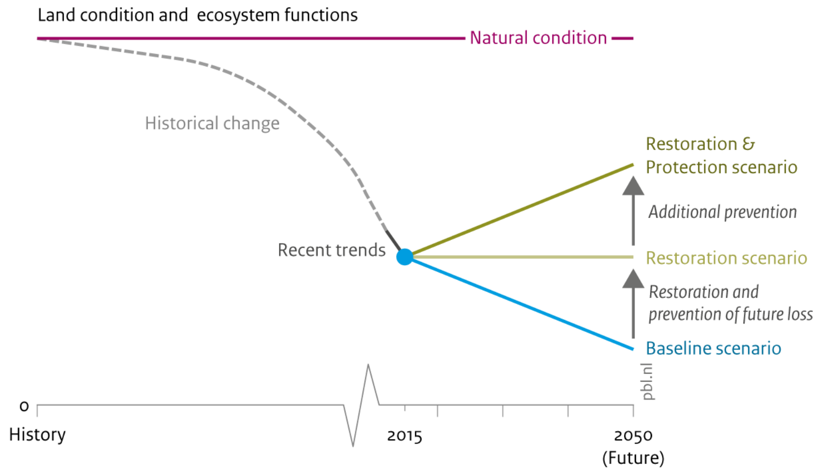
The purpose of the two restoration scenarios (Chapter 4) is to estimate the potential future impacts of ambitious restoration and prevention of further future land degradation. They are composed of a scenario that focuses only on restoration measures (the *Restoration* scenario) and a scenario that, in addition to the restoration measures of the first *Restoration* scenario, also applies extensive protection of areas to safeguard key ecosystem functions or biodiversity (the *Restoration & Protection* scenario).

The *Restoration* scenario assumes ambitious restoration up to 2050 in both managed and natural lands where restoration of soils is estimated to be possible, through a set of eight restoration and land management measures. The *Restoration & Protection* scenario builds on the *Restoration* scenario by expanding protection of land to safeguard key biodiversity areas and areas that are important for different ecosystem functions, such as water regulation, erosion prevention and carbon sequestration. This second scenario highlights the potential importance of safeguarding areas that provide important ecosystem functions, and the idea that prevention of degradation is just as important as restoration. Assessing both restoration and prevention of future degradation ties in with the definitions of land degradation as discussed in Section 2.1.

The scenarios do not include changes in demand/consumption, changes to the energy system, or changes to production chains. It is by now well established that changes in these areas are necessary to limit pressure on natural systems and mitigate climate change, and several studies have estimated the order of magnitude of the effect that measures in these areas may have on global land use (Ten Brink et al., 2010; IPBES, 2018; Kok et al., in prep.). Such measures were not included here as their effects are now well established and the analysis would become very complex to combine with the effects of restoration, which is the focus of this study.

Figure 2.6

Illustration of scenarios to assess potential benefits of land restoration



Source: PBL

3 Future developments under the baseline scenario

This chapter describes the baseline scenario. Section 3.1 introduces the purpose of the baseline scenario, its storyline and the background to the projection of a number of key parameters, such as socio-economic changes, demand for land-based products and land availability for agriculture. Section 3.2 outlines the changes in land condition between 2015 and 2050 as a consequence of changes in land use and land management and climate change. Section 3.3 describes the impacts on ecosystem functions, specifically for agricultural productivity, water regulation and carbon sequestration. Section 3.4 then pulls all of these projections together in a reflection on what they mean for current land restoration ambitions.

3.1 Purpose and background of the baseline scenario

3.1.1 Purpose of the baseline scenario

The baseline scenario serves three purposes in this study. Firstly, it provides an idea of the order of magnitude of future changes related to land, expressed in the indicators outlined in Section 2.4. Secondly, it shows the relative importance of the main drivers of these changes, which are demand for land-based products, climate change and land degradation. Thirdly, it serves as a benchmark for the restoration scenario, as it enables a comparison to be made of the outcomes of the restoration scenario not against the current situation but against an alternative future scenario in which no restoration action is taken. This makes it possible to estimate the potential of restoration measures to prevent future land degradation.

3.1.2 Background and socio-economic projections

Storyline behind the baseline scenario

A set of five scenarios, known as the *shared socio-economic pathways*, was developed by the scientific community; initially, to serve climate research, their broad coverage of global trends and aspects of land use make them suitable for assessing the global land system. The storyline underpinning the baseline scenario is the shared socio-economic pathway (SSP) representing a *business-as-usual* future (SSP2). In this SSP2 scenario, future trends do not shift markedly from historical patterns (O'Neill et al., 2017). This implies continued uneven economic growth, with some countries experiencing substantial growth while others fall behind. Population growth remains high in developing regions, and technological development continues, but no major breakthroughs take place. Pressure on the natural system increases due to growing demand for food and other resources, and due to climate change. In addition, it is assumed that declines in land condition continue. However, some moderate improvements take place with the successful protection of currently defined protected areas. Also, overall agricultural productivity continues to increase, which limits the amount of additional land required to meet demand. This does however imply more intensive agriculture with increased fertiliser, pesticide and water use, although part of the productivity increase results from improved crop varieties and agronomic practices.

Table 3.4
Projections for main drivers in the baseline scenario

	2015	2050
Population	7.4 billion people	9.3 billion people
Income	USD 12,200 per capita (PPP)	USD 27,600 per capita (PPP)
Crop production	4,570 million tonnes	6,620 million tonnes
Livestock production	300 million tonnes	430 million tonnes
Agricultural productivity (cereal yields)	3.5 tonnes per hectare	4.1 tonnes per hectare
Land protection	13% of terrestrial area	13% of terrestrial area

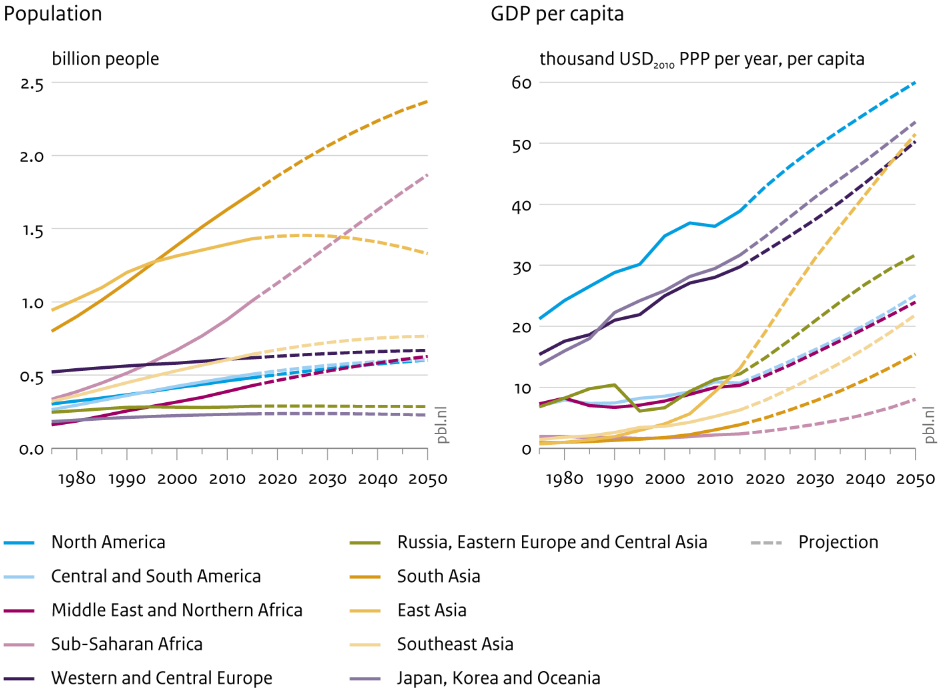
Socio-economic trends in the baseline scenario

The basic demographic and economic drivers of the baseline are shown in Figure 3.1. The global population is projected to grow to 9.3 billion up to 2050. The strongest growth takes place in sub-Saharan Africa and South Asia, by some 850 million and 600 million people, respectively, between 2015 and 2050, due to high fertility rates. Only East Asia (mainly China) sees a substantial decrease, of about 100 million people from 2015 to 2050 due to the effect of previous population control policies. These projections are slightly lower than those of the UN World Population Prospects 2019, which estimates a population of 9.7 billion people in 2050 (UN, 2019).

Economic growth is assumed to continue in all regions, with strong increases in GDP per capita. The highest relative increases take place in developing regions such as sub-Saharan Africa and South Asia; however, because of the relatively low levels of current GDP in these regions, they do not converge with developed regions such as North America and Europe.

Demographic and economic developments are uncertain. Optimistic and pessimistic assumptions in fertility rates in other SSP scenarios show a range in population growth, from 8.5 billion people in 2050 in SSP1, to 10 billion people in SSP3 (KC and Lutz, 2017). Per capita income in 2050 in the same analysis ranged from USD 18,000 (PPP)/capita on average in SSP3 to USD 34,000 (PPP)/capita on average in SSP1 (Dellink et al., 2017). Figure 3.1 shows the regional baseline trends in population and GDP per capita based on the SSP2 scenario (KC and Lutz, 2017; Dellink et al., 2017).

Figure 3.1
Socio-economic drivers under the baseline scenario



Source: PBL/IMAGE

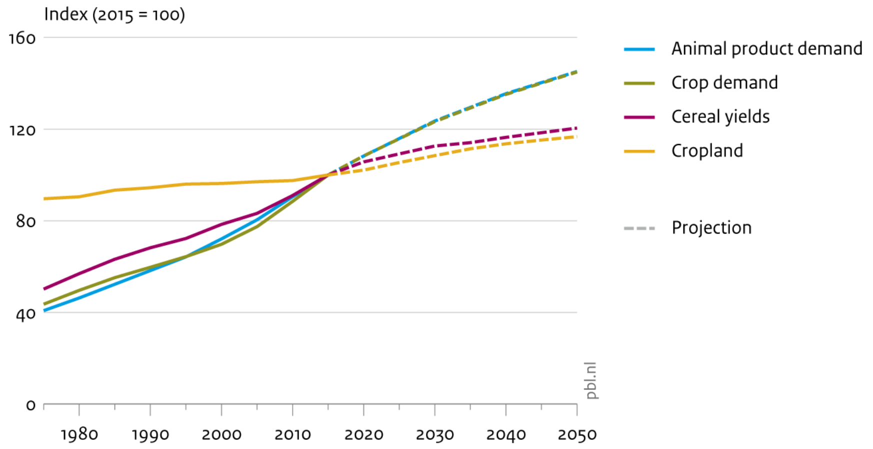
Demand for food and trends in production efficiency are key drivers of future land use

Developments in food demand and agricultural productivity are at the core of future land system dynamics. In the baseline scenario, demand for crops and animal products at the global level continues to increase up to 2050 (Figure 3.2). The largest increases take place in developing regions, where the growing population and higher incomes lead to major increases in food demand. Only a small share of total crop demand is related to the production of biofuels, as no large-scale climate change mitigation policies are taken into account.

Agricultural productivity also continues to increase, as shown by the cereal yield indicator (Figure 3.2). The potential for increases in crop yield varies greatly between regions: in developing regions, there is high potential for yield gap closures through improved management and increased nutrient input; in many developed regions, yields are already near maximum attainable levels, implying that productivity improvement needs to come from technological improvements such as new genetic crop varieties. At a global level, the baseline scenario shows a slight levelling off of average yield improvements up to 2050. In combination with continued growth in demand for crop production, this results in continued increases in cropland area (Section 3.2.1).

Comparing the projections presented in this report to observed data on attainable and potential yields shows that yields are close to the maximum attainable yields in North America, Europe, Japan and Oceania by 2050 (Van Zeist et al., 2020). However, there is still large potential for yield improvement in sub-Saharan Africa. This variation implies that the yield projections presented here are not overly optimistic at the global level; however, it is uncertain whether historical trends will continue into the future, in particular in developed regions.

Figure 3.2
Global agriculture and food indicators under the baseline scenario



Source: PBL/IMAGE

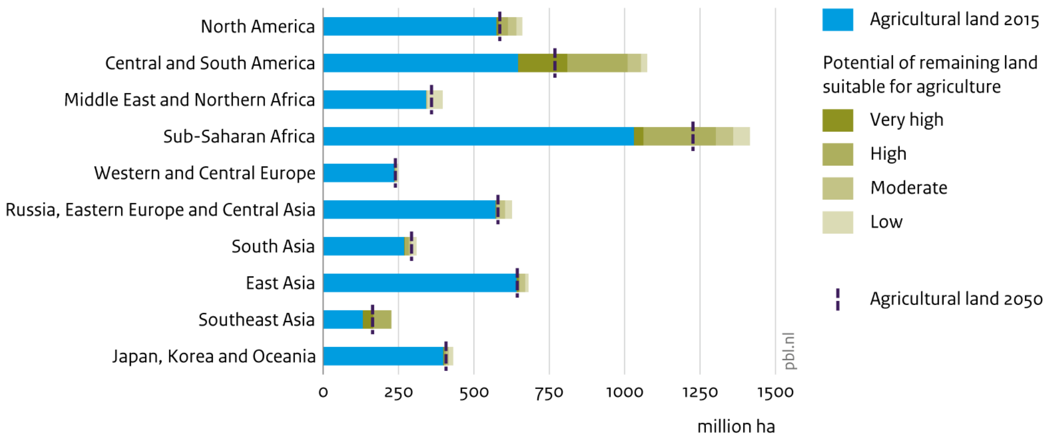
Availability and suitability of land for agriculture is an increasing constraint, with most of the highly productive soils already in use

An important starting point for the baseline and the restoration scenarios is the amount of land that is suitable and available for agricultural expansion (Figure 3.3), in addition to the 1.6 billion hectares of cropland and 3.2 billion hectares of pasture currently in use. The remaining land available for agriculture — crops and intensive pasture — is based on biophysical and anthropogenic factors (Appendix A4). Biophysically, land is considered unsuitable if yields are too low to sustain crop production, if slopes are too steep, if there is no soil or if there is permafrost. Anthropogenically, land is considered unavailable if it is already in use for crop or livestock production, if it is used for forestry, if there is infrastructure (built-up area or roads) or if the land is in use for other human activities (e.g. recreation). Lastly, protected areas according to the World Database on Protected Areas are also taken into account: all land that is currently in any way protected is considered unavailable.

About two thirds of all remaining available land is located in sub-Saharan Africa and Central and South America. Most of this land is suitable for agriculture as the potential crop productivity is relatively high in these tropical regions, although this does not consider the quality of soils. Southeast Asia also has a substantial area of available land with high productivity, though much of the available land in these tropical regions is located on vulnerable soils. Remaining available land in other regions is of moderate to low quality, indicating that most of the suitable land is already being used (Figure 3.3).

These results are highly dependent on the assumptions made in the scenarios. A crucial assumption is that land currently in use for forestry is not available, even though conversion could take place if there is a high demand for agricultural land. Also, the crop productivity at which land is considered suitable is uncertain and depends on the potential crop yield data set used, as well as the threshold assumed. Estimates of remaining available agricultural land in the literature vary widely depending on the assumptions made. The estimate used in this report is a total of 1.2 billion hectares of remaining available agricultural land. A meta-study of different estimates by Eitelberg et al. (2015) reports a range of 40 million hectares to 2.6 billion hectares remaining available agricultural land.

Figure 3.3
Agricultural land use and remaining suitable land under the baseline scenario



Source: PBL/IMAGE

3.2 Projected changes in land use and land condition

3.2.1 Land-use change

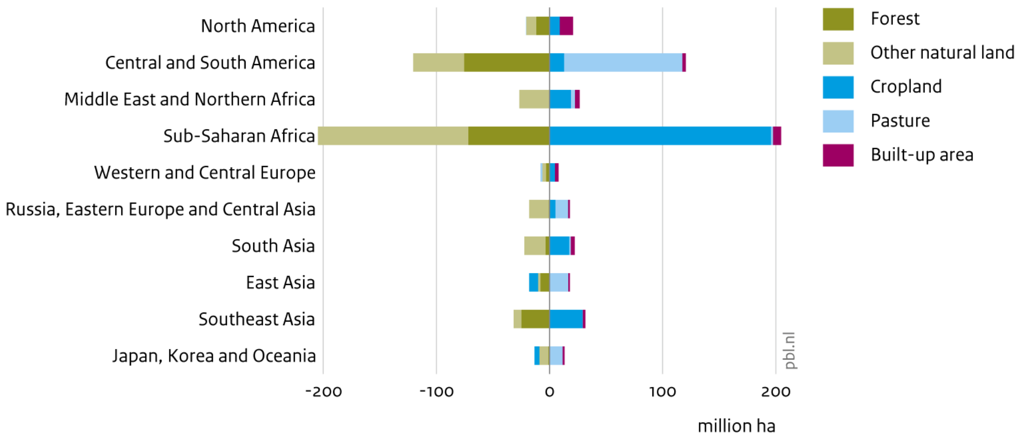
Agricultural land use is projected to further increase, predominantly in tropical regions

The land-use projections in the baseline scenario show continued land-use change up to the year 2050: cropland expands by 280 Mha and pasture by 150 Mha globally. The main drivers are continued population growth and increases in average income leading to higher food consumption per person, both of which result in increased demand for agricultural production. The largest increases in agricultural area occur in Central and South America and in sub-Saharan Africa (Figure 3.4). These regions see the highest relative increases in population and demand for land-based products and have large areas of land suitable for agriculture. The increase in agricultural area takes place at the expense of forests, notably tropical rainforests, for example in the Amazon, the Congo Basin, Indonesia and Cambodia (Figure 3.5). Other natural land is also converted to agriculture, such as the dry forests of the Gran Chaco in Bolivia and northern Argentina, and the savannahs of eastern and southern Africa. Although relatively small, built-up area also increases considerably, by 55% in the 2015–2050 period, due to continued urbanisation, which can have a disproportionately negative effect on agriculture as urbanisation typically takes place on highly productive agricultural lands (Van Vliet, 2019).

The baseline scenario includes the impacts of climate change and land degradation on agricultural productivity and consequently on land use. Long-term negative trends in primary productivity based on NDVI (Normalised Difference Vegetation Index) satellite data are used to estimate human-induced degradation effects on crop productivity (for more detail, see Section 3.2.2) and are assumed to be degressive throughout the scenario period. As all drivers are included in the scenario, this makes it possible to distinguish the order of magnitude of land degradation effects, climate change impacts and socio-economic developments on crop yields (Figure 3.5) and agricultural land use (Figure 3.6). This shows that yield loss from land degradation contributes considerably to future land expansion, as the negative impact of degradation on crop yields increases the required area to fulfil the demand for crop production. It is estimated that, at the global level, an additional 68 million hectares of agricultural land are required because of this effect. In addition, negative impacts of climate change lead to additional land requirements in some regions: in the Middle East and Northern Africa, this amounts to 9 million hectares. In Russia, Eastern Europe and Central Asia, on the other hand, climate change improves crop yields, leading to a reduction in agricultural land of 24 million hectares.

Projections of future agricultural expansion are most uncertain for pasture areas
The extent of agricultural area expansion depends on many drivers and scenario assumptions as well as model characteristics. A model comparison for the SSP2 scenario where demographic and economic trends as well as the storyline are harmonised shows a range in cropland expansion of 194 million hectares to 274 million hectares for the 2010–2050 period (Popp et al., 2017). Pasture trends show a wider uncertainty range than cropland, ranging from a decrease of 122 Mha (1.2 million km²) to an increase of 113 Mha (1.1 million km²). A decomposition analysis showed that the effects of different drivers on cropland expansion varied substantially between models (Stehfest et al., 2014). The effects of population, GDP and productivity are roughly equal in size for the IMAGE model that is used in this study and, other than in other models, land-use change regulation also plays an important role. Changes in trade regimes (which are assumed not to change in SSP2) do not have a large effect.

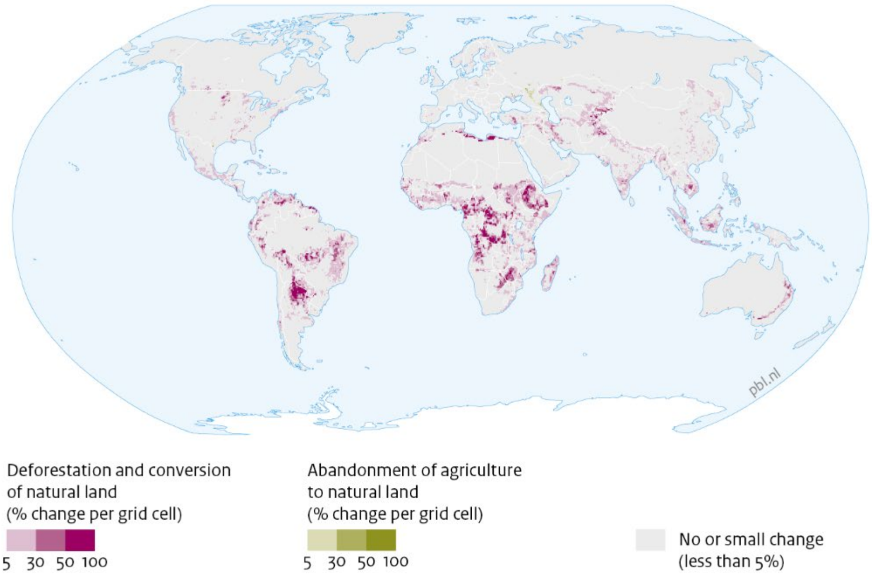
Figure 3.4
Land-use change under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

Figure 3.5

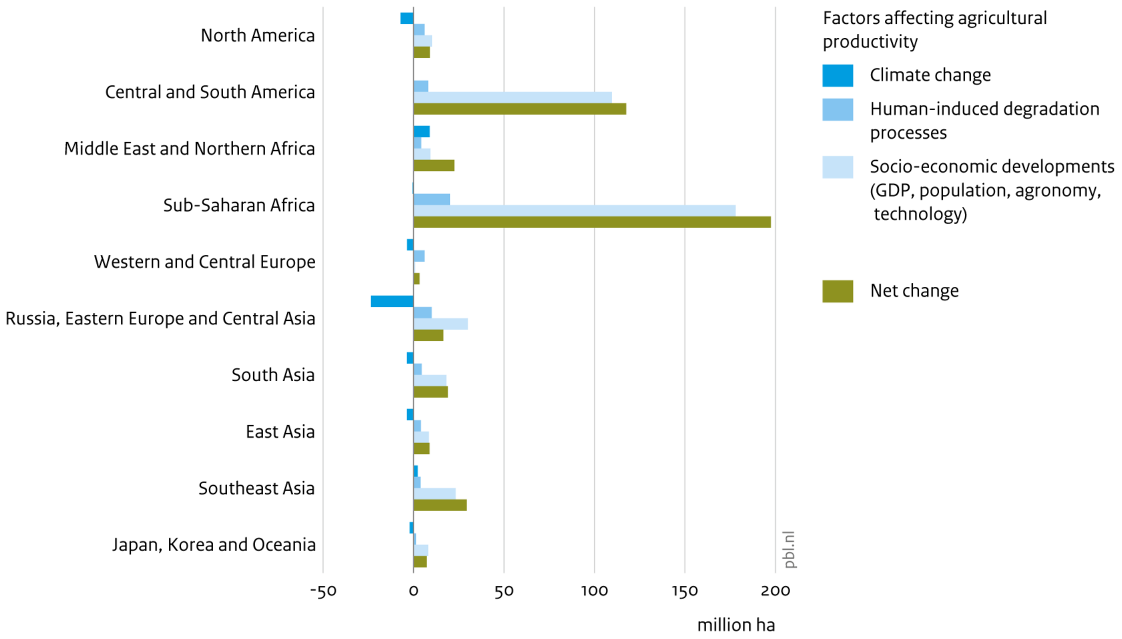
Land-use change under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

Figure 3.6

Change in agricultural land due to changes in agricultural productivity under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

3.2.2 Land management and productivity

There is very little consistent information at the global level indicating where which type of land management is applied. What is consistently available at the global level is the satellite observations of trends in the NDVI. These observations go back decades, making a trend analysis possible over time that can be used as an indicator of the effects of land management on productivity. NDVI relates to biomass productivity, though the relationship is not as strong for each biome, and is for instance less reliable in colder regions. Productivity, or net primary production (NPP), represents the ability of an ecosystem to produce biomass from water, carbon dioxide, nutrients and solar energy. Terrestrial NPP is the annual production of vegetation biomass on land. As discussed in Section 2.1, productivity is a key indicator for the UNCCD and the SDG 15.3 on land degradation and restoration. This study uses NDVI as a proxy for photosynthetic activity and biomass productivity.

Many factors can influence biomass productivity, including land management

Changes in productivity can be caused by a variety of factors, key among which are changes in land use and land management, climatic fluctuations and climate change. Other potential factors are fires, changes in species compositions, or pests and diseases. Through land use and land management, impacts on soils such as erosion, nutrient mining, compaction, pollution and salinisation can negatively affect the long-term productivity of land. On the other hand, agricultural technology and the application of fertiliser may have a positive effect.

Given the numerous factors, it is difficult to assign the trends in satellite data to a specific cause. One factor that could be isolated with the currently available data at the global level is climate. This is also suggested in the Trends.Earth approach[4], which is the method suggested by UNCCD for countries to identify land degradation of their land area and make their Land Degradation Neutrality plans. The purpose of this approach is to distinguish what part of the trend in land productivity is driven by changes in human use and management of land, and what part is driven by short-term or longer term fluctuations in climate. Productivity can be affected by climate change in both positive and negative ways. In cooler regions such as the northern latitudes, warming reduces constraints on photosynthetic activity and the higher atmospheric CO_2 concentration increases the CO_2 fertilisation effect. On the other hand, reductions in water availability due to changes in precipitation or extreme heat events may negatively affect productivity.

NDVI is measured by satellites and can therefore provide a globally consistent indicator. The NDVI (Didan et al., 2015) for the current situation was compared to an estimate of what it would be in a natural situation (i.e. without human land use) to assess historical change up to the present day (2018). To add the impacts of decline in primary productivity to the baseline scenario as a proxy for land degradation processes, the long-term trends in NDVI were analysed. These long-term observed trends were then corrected for climate change effects using a vegetation model (Schut et al., 2017) and extrapolated to 2050. The climate-corrected negative trends were included in the baseline scenario, affecting crop yields and land-use extent. The observed trends were then applied to estimate the state and trends in soil conditions globally. Appendix A6 provides more details on the methodology. The positive trends were omitted, as many of these effects are already included in the model framework (Figure 3.7).

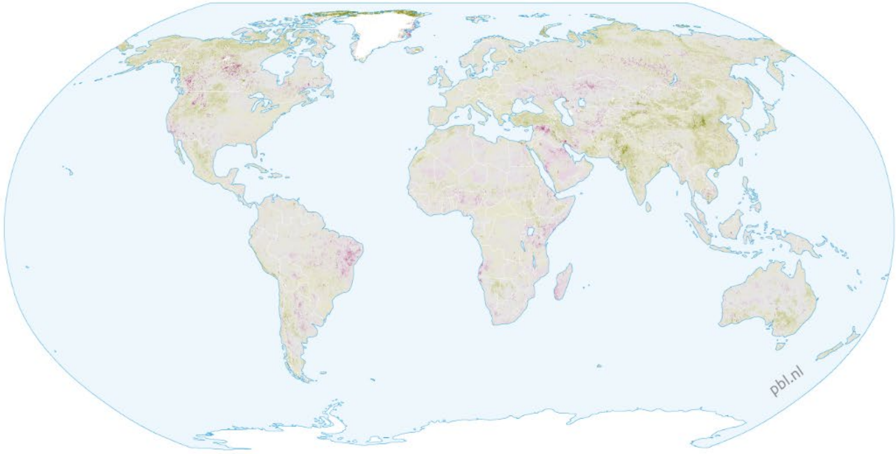
[4] See Trends.Earth — Trends.Earth 1.0.2 documentation

NDVI is difficult to interpret as a measure for primary productivity, and there is discussion in the scientific literature on its use, applicability and adequacy (Schut et al., 2015). Correcting trends in NDVI for climate change creates uncertainty due to the combination of methods and data necessary, as well as factors unaccounted for in the vegetation model used, such as atmospheric fertilisation.

Figure 3.7

Trends in primary production estimated by NDVI, 2000 – 2018

Satellite-observed trend



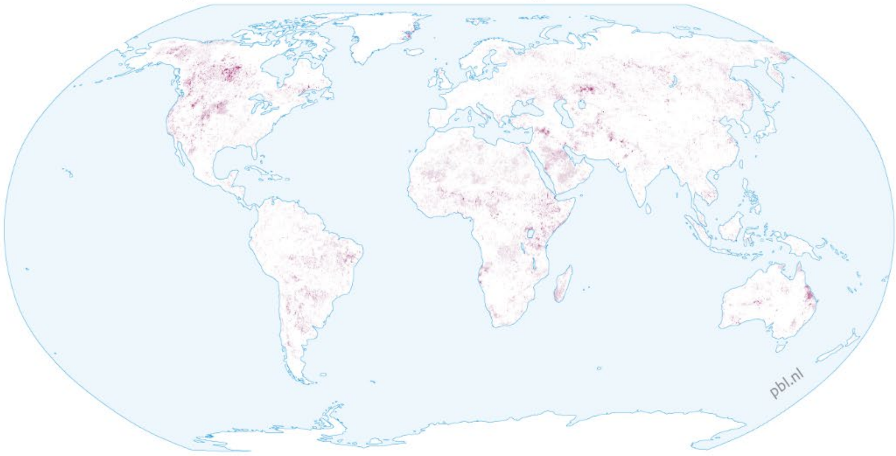
Decrease NDVI (% per year): 0.1 1 2 3

Increase NDVI (% per year): 0.1 1 2 3

No or small change (less than 0.1% per year)

No data

Satellite-observed negative trend corrected for climate change



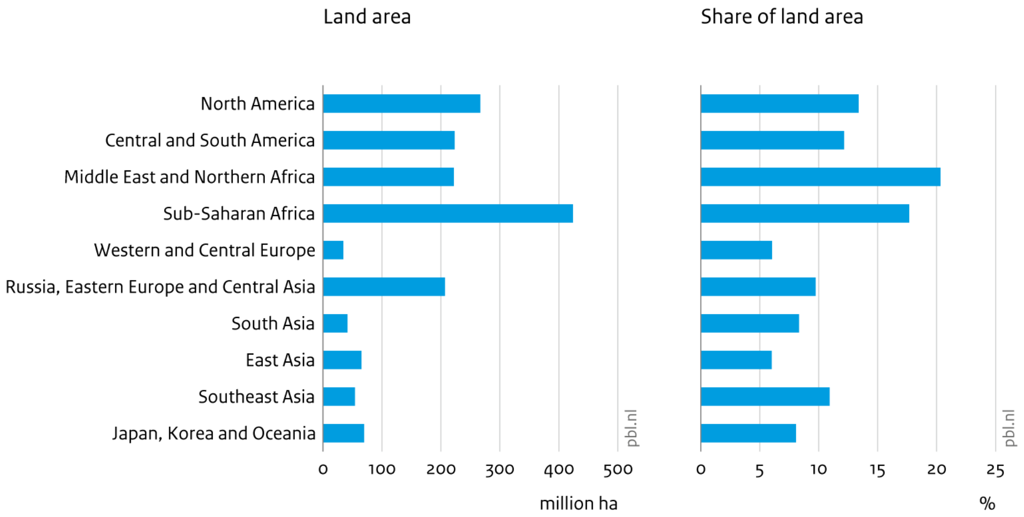
Decrease NDVI (% per year): 0.1 1 2 3

Small decrease (less than 0.1% per year)

No change, increase or no data

Source: PBL, NASA/MODIS

Figure 3.8
Areas with a negative productivity trend, corrected for climate change, 2001 – 2018



Source: PBL, NASA/MODIS

Table 3.2
Percentage of area showing declining trends in productivity, climate-corrected over the 2001–2018 period, per region

Region	Cropland area	Grassland area	Natural area
North America	11%	13%	14%
Central and South America	16%	13%	11%
Middle East and Northern Africa	10%	26%	19%
Sub-Saharan Africa	28%	17%	16%
Western and Central Europe	6%	5%	6%
Russia, Eastern Europe and Central Asia	13%	14%	8%
South Asia	8%	13%	8%
East Asia	12%	5%	5%
Southeast Asia	12%	19%	10%
Japan, Korea and Oceania	10%	6%	10%
World	14%	13%	12%

Correcting for climate change results in a larger area with negative trends in productivity

Without correcting for climate change, some 1.25 billion hectares globally show a declining trend in productivity as measured by NDVI over the 2001–2018 period. This is close to 10% of the global area, excluding Greenland and Antarctica. With the climate correction, this figure rises to some 1.6 billion hectares, or 12% of the global area. This implies that, on balance, climate change masks negative pressure on productivity from human land use or management or from other causes such as pests and fire. This is not unexpected. A larger share of the world's land area shows positive trends in productivity than negative trends (Figure 3.7), due to climate change (including CO_2 fertilisation) but also positive effects from human management with increased nutrient inputs or irrigation.

All regions see declining trends associated with land management on 5% of their land area or more, with some over 10%

The top three regions with negative trends in productivity on more than 10% of their land area are sub-Saharan Africa, the Middle East and Northern Africa, and North America (Figure 3.8). These regions also show the largest area in absolute terms, with about 200 million hectares, 200 million hectares and close to 350 million hectares, respectively. Least affected in terms of share of land area appear to be the East Asia region and Western and Central Europe. Still, all regions see at least 5% of their land area with negative trends and often this figure is higher.

Some 13% of agricultural land and 12% of natural land show declining trends when corrected for the effect of climate change

In terms of what type of land is affected, some 14% of cropland and 13% of grassland show negative trends, as well as 12% of natural land (Table 3.2). Regional differences are large, with cropland and grassland especially affected in Central and South America, Middle East and Northern Africa and sub-Saharan Africa, while South Asia, East Asia, Japan, Korea and Oceania and Western and Central Europe see relatively little impact on their agricultural land. As stated above, this may be because negative effects are masked by the widespread use of fertiliser. Another recent study estimates that some 10% of terrestrial areas are seeing a declining trend in land productivity, and another 10% is stressed, with roughly the same percentages for cropland and grasslands (JRC, 2018).

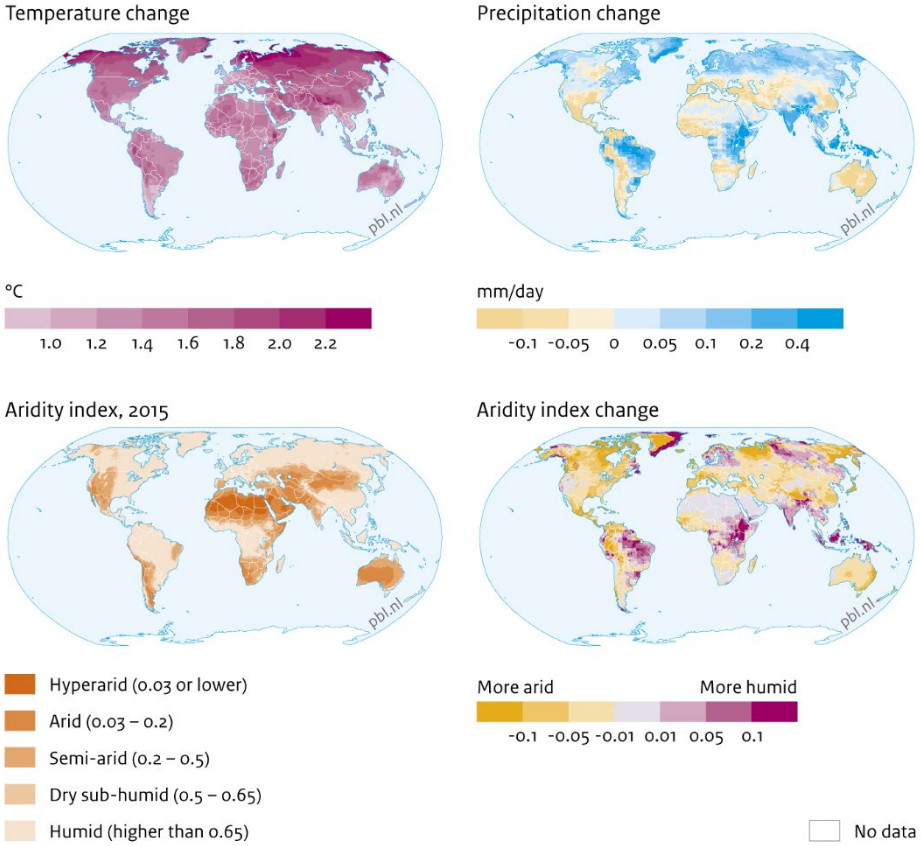
3.2.3 Climate change

Further changes in climate will increasingly affect the land system

Climate change is an integral part of the baseline scenario: changing patterns of temperature and precipitation affect crop yields, carbon storage in natural ecosystems, the hydrological cycle and biodiversity. Climate change in the baseline scenario is in line with the RCP 6.0 scenario (Van Vuuren et al., 2011), which results in an average global temperature change of approximately 1.4–2.5 °C by the year 2050 (IPCC, 2014). Patterns of climate change (temperature and precipitation) are highly uncertain. As a default, we use patterns from the IPSL climate model as proposed by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP), which is specialised in climate change impact studies (Frieler et al., 2017). In addition, we explore the sensitivity of agricultural production to different climate models (Box 3.1).

Changes in climate and aridity in the 2015–2050 period as included in the baseline scenario are shown in Figure 3.9. Temperature increases everywhere, but the arctic and boreal regions warm substantially faster than other world regions. Changes in precipitation are highly variable, with increases projected in the northern latitudes, South and Southeast Asia, most of Brazil and eastern Africa. Conversely, much drier circumstances are projected in the Mediterranean, Central America, Central Asia and Australia. The aridity index in 2015 shows similar patterns, with arid conditions in the deserts of the world. Changes in the aridity index are mostly in line with the changes in precipitation; however, relatively drier conditions are also projected in northern latitudes due to higher temperatures and increased evapotranspiration.

Figure 3.9
Change in climate and aridity under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

Box 3.1 Uncertainties in climate projections and their impacts

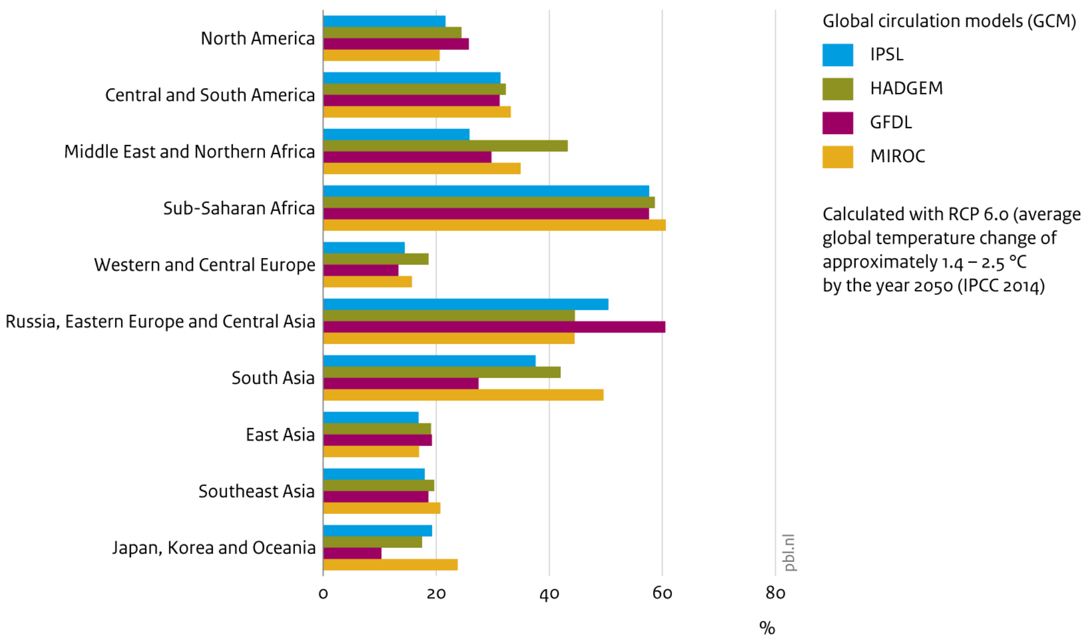
Climate change projections from specialised biophysical climate models known as global circulation models (GCMs) form a crucial input to this study. Projections from different GCMs differ markedly from one another, for example in their sensitivity to greenhouse gas emissions or their spatial patterns of temperature or precipitation change (IPCC AR5 Summary for Policymakers, Figure 7) (IPCC, 2014). Throughout this report, temperature and precipitation data from one specific model are chosen (IPSL-CM5A-LR), as climate change impact variation is not the main focus of this study.

To test and illustrate the sensitivity of the results discussed in this study to different climate change projections, we implemented three different climate change patterns based on the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP). The three GCMs tested were GFDL-ESM2M, MIROC5 and HadGEM2-ES. Figure 3.10 shows the impacts of these different projections on cereal yields.

At the global level, the variation is moderate, with a 3% difference between the highest and lowest cereal yield projections and 38 million hectares difference between the highest and lowest cropland area projections. However, the relative differences are much larger at the regional scale, due to the large variation in spatial patterns of temperature and precipitation change between GCMs. For example, in the Middle East and Northern Africa and in South Asia, the difference in cereal yield changes between the highest and lowest impacts is 22% and 17%, respectively. This translates into differences in required cropland expansion of 80 million hectares and 240 million hectares, respectively, which is 11% and 18% of the cropland area projected in 2050.

Figure 3.10

Sensitivity of cereal yield change under the baseline scenario, 2015 – 2050



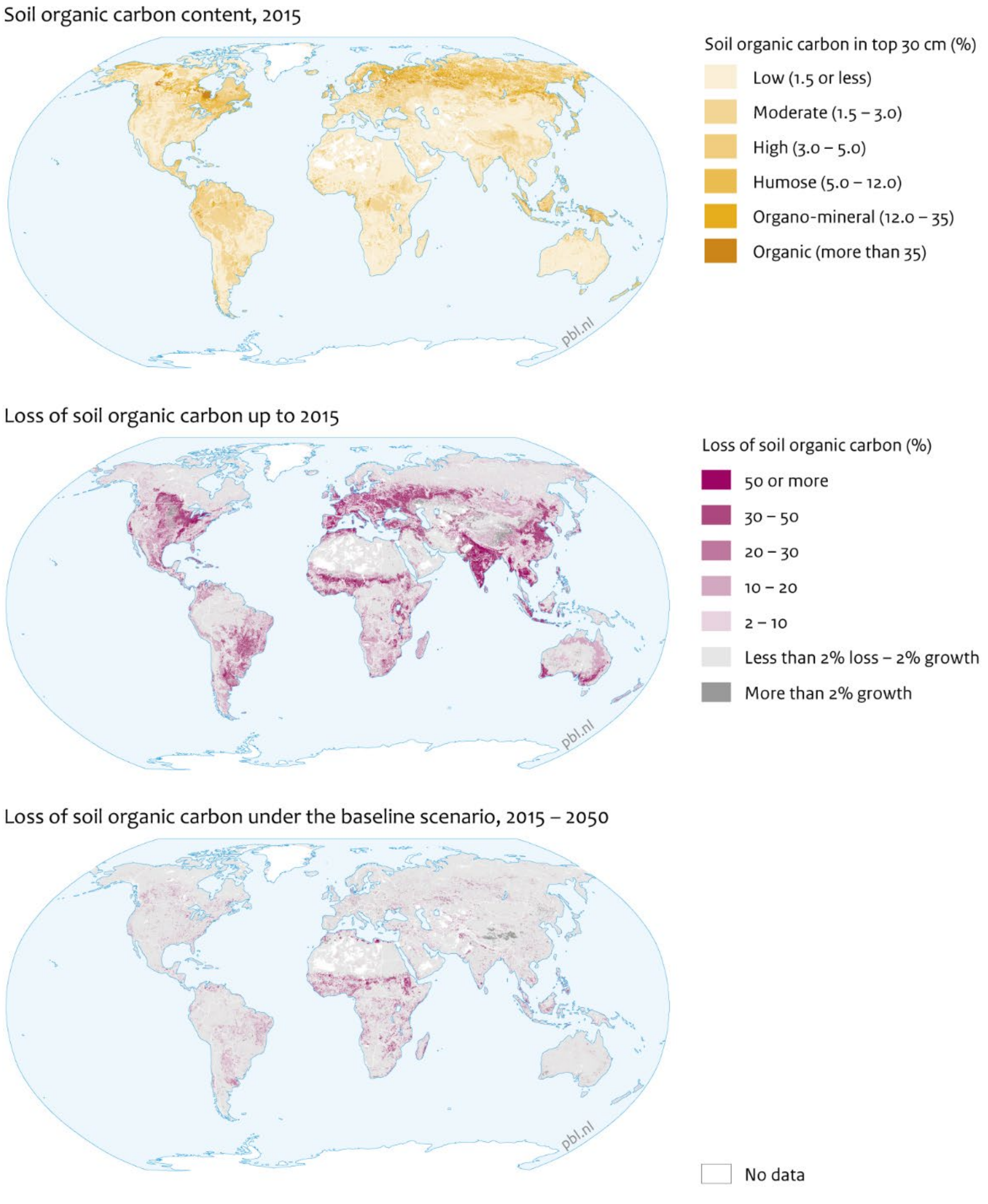
Source: PBL/IMAGE

3.2.4 Soil health

Soil organic carbon affects ecosystem functions and is used as a key indicator to assess land degradation

The state of and change in soil organic carbon (SOC) is one of the three indicators used by the UNCCD and in the SDGs to assess the extent of degraded area and soil health. Soil organic carbon is the carbon component of soil organic matter. Soil organic matter affects the maintenance and provision of ecosystem functions and services. A loss in organic matter translates into lower nutrient cycling and fertility levels of the soil and a decline in water-holding capacity and soil stability, in turn affecting agriculture, water regulation and carbon storage. As SOC is easier to measure than soil organic matter, it is generally used as an indicator of soil health. The stock of carbon in the soil is a balance of biomass input and loss through decomposition through decay, dissolution and erosion. Climate affects both the build-up — with faster biomass growth in warmer and wetter regions — and loss of SOC, with lower temperatures preventing quick decay. Therefore, colder regions have larger stocks of SOC that has taken a long time to accumulate, whereas in warmer regions lower carbon contents are generally found as the decay rate is faster, even though the biomass growth is faster as well (Figure 3.11). Human land use influences these balances, by reducing biomass build-up and taking biomass out of the system by agriculture or erosion from land clearing, and through climate change, which affects both the growth of biomass and the decay rate.

Figure 3.11
Soil organic carbon



Source: Stoorvogel et al. 2017, PBL

Past and future losses of soil organic carbon

Compared to the natural situation, some 7% of soil organic carbon has been lost, which is equivalent to about 140 Gt of carbon (Appendix A6). This is mainly due to the conversion of natural land to agriculture. The largest losses have taken place in agricultural regions in the northern hemisphere, where originally high soil carbon stocks were found (Figure 3.11).

Future losses of soil organic carbon are estimated under the baseline scenario. Only the losses are discussed here, as this is relevant for informing the extent and severity of human-induced land degradation. Two processes affect future soil organic carbon in the scenario. Firstly, soil organic carbon losses that result from the projected future conversion of natural land into agriculture, which amounts to some 17 Gt between 2015 and 2050. Secondly, continuing losses (Section 3.2.2) as a consequence of land management practices, climate change or factors such as pests and fires, which amount to some 15 Gt (Section 3.3.3). Part of the loss may be countered by increases elsewhere from biomass productivity increases as a result of climate change.

Reduced soil health in terms of depth, topsoil loss, nutrient mining and loss of organic matter can have different consequences of varying importance, depending on the location and land use. For instance, in areas with relatively deep soils, loss of topsoil can go on for a while before any consequences become apparent. In other regions, where soils for instance have by nature a relatively low percentage of soil organic matter or are low in nutrients, consequences can become apparent much faster. In such soils, even though organic carbon levels may be low, soil management is very important, as that small organic matter percentage may be crucial for holding water long enough to cover dry spells and the nutrients may sustain at least some agriculture.

Soil nutrient budgets are increasing in some regions and depleted in others

The productivity of soils depends strongly on the availability of nutrients, and phosphorus and nitrogen in particular for agriculture. Therefore, a decline in nutrients in soils may indicate overexploitation and a future decline in the production of crops and grass, and could therefore be a measure of land degradation.

A nutrient budget is the balance of inputs (fertiliser, animal manure, compost, atmospheric deposition) and outputs (nutrients in the harvested parts of crops and losses). If there is a surplus, excessive nutrients are input to the environment mainly through nutrient run-off, leaching or wind erosion. Additional inputs for nitrogen include biological nitrogen fixation (mainly by leguminous crops such as beans and clovers). Losses can occur in the form of ammonia, nitrous oxide (one of the major greenhouse gases), nitrogen oxides or nitrogen gas (N_2, inert). Depending on the budget of inputs and outputs, soils can either be stable in nutrient availability, enriched with nutrients (due to positive budgets) or depleted (due to negative budgets). The use of mineral fertilisers, which are often artificial, has greatly enhanced crop yields all over the world.

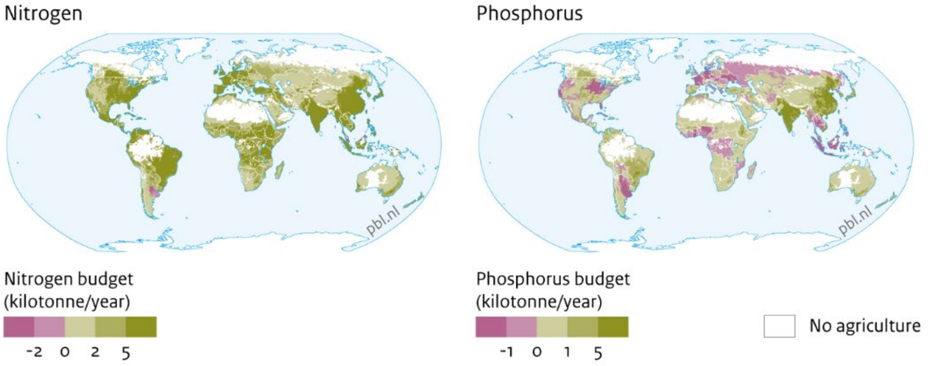
Excessive nitrogen and phosphorus use have negative environmental effects

At present, almost all soils have a positive nitrogen budget and some have a positive phosphorus budget (Figure 3.12). The surpluses of nitrogen and phosphorus, mostly from fertiliser use, are emitted to air and leach into surface water and groundwater, with consequential impacts on plant species in natural areas and on water quality for decades to come. Countries that have not yet seen this build-up still have the chance to avoid this environmental damage.

Phosphorous depletion implies a risk of decreased soil productivity in some regions

Other than nitrogen, there are large areas in the world that have a negative phosphorus balance. Partly, this is in areas that have had a positive budget for decades which means that, with phosphorus stored in the soils over time, negative budgets in these areas will not translate into lower production for some time to come. This is for example the case in Europe and parts of the United States. In some tropical regions, despite positive budgets, phosphorus is severely limiting crop production because phosphorus is chemically absorbed by strongly weathered soils. In 2015, phosphorus was strongly limiting crop productivity in regions such as sub-Saharan Africa, Southeast Asia, the Mediterranean and parts of South and Central America. In these areas, agricultural productivity depends on the available nutrients in the soil, in the absence of sufficient addition.

Figure 3.12
Nutrient budgets, 2015



Source: PBL, JRC, PIK

3.2.5 Biodiversity

Biodiversity has declined by about one third due to human development

As discussed in Sections 2.1 and 2.4, the state of biodiversity can help to inform discussions on the extent and severity of land degradation and is part of the definition of land degradation. Biodiversity is declining due to a number of drivers and pressures (Figure 3.13). Prior to 2015, biodiversity declined to an estimated 55% of its original, undisturbed state measured in mean species abundance (MSA)[5]. Also, as described in Section 3.2.2, the extent of natural areas estimated to have a decline in primary productivity over the past decades is some 12% of the total natural area in 2015, without the effect of climate change. The largest losses up to 2015 took place in regions that have seen extensive development over centuries and where agriculture benefited from the most suitable soils and climate.

Biodiversity decline continues with climate change becoming the largest pressure

The baseline scenario projects an additional 6% of loss up to 2050 (3 percentage points down from 55%) compared to 2015. While loss from land-use expansion and fragmentation is projected to taper off towards the middle of the century if increases in agricultural productivity and demand are evenly balanced, impacts from climate change are likely to increase and will continue after 2050.

3.3 Projected impacts on ecosystem functions

3.3.1 Exploring the impact of changes in land condition on agricultural production, water regulation, and carbon storage

This section shows the projected impacts of changes in land condition on agricultural production in crop and livestock systems and on food prices. To improve the understanding of underlying soil processes, we present a literature-based evaluation of degradation processes and risks.

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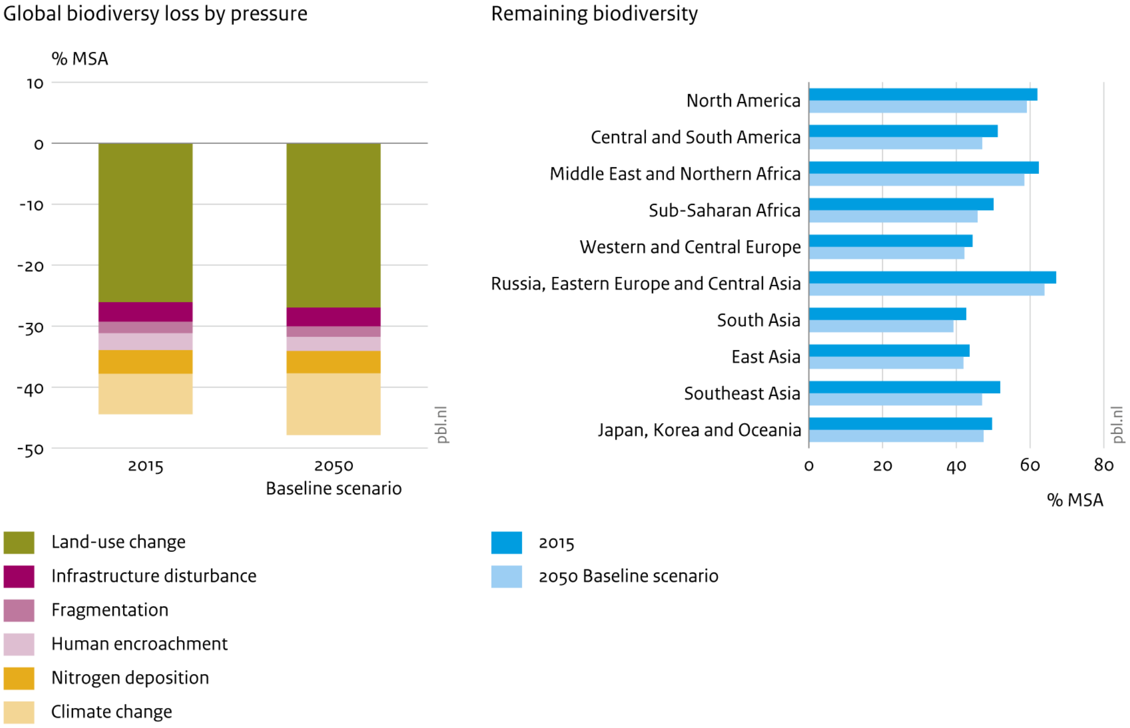
[5] The indicator used here for biodiversity is mean species abundance. MSA measures or estimates the number and composition of species in the current or future projected state and compares this to the number and composition under natural conditions. See also Alkemade et al. (2009) and Schipper et al. (2019).

Figure 3.13
Change in biodiversity, compared to natural condition



Source: PBL/IMAGE/GLOBIO

This can be used to identify locations where managed lands are at risk of a reduction in their agricultural productivity and where improvements to land management are most urgent.

Agricultural degradation processes and risks

Processes and impacts of degradation are highly location-dependent

Land degradation can affect agricultural production through different processes (Table 3.3a and 3.3b). The risk that such a process will occur depends on local biophysical conditions, the land use and land management. Some types of land management systems reduce or avoid the risk of specific processes. For more details on the degradation risk framework, see Appendix A5.

The mechanisms of degradation processes are relatively well known, but studies are mostly conducted at local or regional levels, due to the shortage of relevant data globally. Some studies have however directly quantified degradation process magnitudes or risk indices at a global level (e.g. Schofield and Kirkby, 2003; Montgomery, 2007; Borrelli et al., 2017). More studies have focused on *aspects* of degradation processes such as global nutrient budgets or carbon loss (e.g. Bondeau et al., 2007; Bouwman et al., 2017; Stoorvogel et al., 2017b). There are no studies on global crusting or overgrazing risk, and no study has combined degradation risks globally.

The uncertainty at the global level is partly due to the fact that crop yields (and pasture productivity in some regions) are still increasing in most regions through the increased use of fertilisers, irrigation or improved crop varieties, which masks any negative effects of degradation processes. In such cases, degradation effects go unnoticed until they become larger than the positive effects. This suggests that mitigating degradation processes in areas where yields are still increasing might be a way to contribute to faster yield gains. This is important in regions requiring fast increases in yields over the coming decades to feed fast-growing populations, such as sub-Saharan Africa and South Asia.

Knowledge of degradation risks can help to inform management responses. At the global level, such knowledge provides insight into potential causes of observed declines in land productivity or smaller than expected yield increases. In time, it can also contribute to the more advanced inclusion of land degradation impacts in global models. Each degradation process has a different pathway through which it impacts crop yields and, while the mechanisms are generally known, models and data are unable to calculate specific impacts globally.

Biophysical land degradation risk maps, which were developed for this study, show which areas are prone to specific degradation processes on arable land at a global scale (Figure 3.14). Indicators and impact thresholds are used rather than absolute yield reductions. The presented five degradation risks all have significant global impacts on crop productivity, as detailed in Table 3.3a and 3.3b and Appendix A6. Note that this approach does not provide estimates on the percentage of crop yield impacted. The method is therefore separate and additional to the approach used in the baseline scenario.

Table 3.3a
Degradation processes, their causes and their impacts on plant productivity covered in this report

Process	Description	Cause / aggravated by	Impacts on productivity
Water erosion	Removal of topsoil by surface run-off	Poor vegetation cover (e.g. after ploughing) Unstable surface soil structure (e.g. due to loss of soil organic matter) Steep or long slopes Slow infiltration of surface water into the soil (e.g. due to dense surface soil)	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 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	Poor vegetation cover Unstable surface soil structure (e.g. due to ploughing, 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
Salinisation	Accumulation of salts in rooted part of the soil	Arid or semi-arid climate Irrigation with poor-quality water	Physiological drought Nutrient imbalances Toxicity of salts to crops

		Shallow groundwater level with high salt content	
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 the nutrients 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
Overgrazing	Grassland degradation through inadequate grazing management	Grazing and fire management that do not allow sufficient regeneration of the most productive grass species, either through too high stocking densities, neglect of sufficient rest periods or too much or too little fire	Less productive ephemeral grass, shrubs or woody vegetation become dominant, larger fractions of bare soil
Land clearing	Removal of trees, stumps, brush, stones and other obstacles from an area to increase the size of cropland	Increased demand for agriculture or forestry products Loss and reduced productivity of existing agricultural land	Essential to provide space for agricultural production Loss of supporting ecosystem services associated with 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
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 soil structure and stability, making the soil more vulnerable to erosion and compaction

Source: Adapted from Van der Esch et al., 2017.

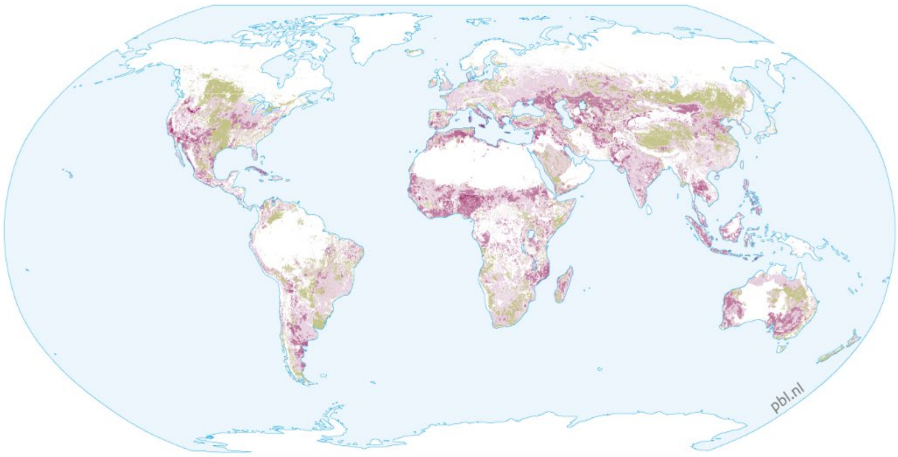
Table 3.3b
Degradation processes, their causes and their impacts on plant productivity not covered in this report

Process	Description	Cause / aggravated by	Impacts on productivity

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
Wind erosion	Removal of topsoil by wind	Poor vegetation cover (e.g. after ploughing) Unstable surface soil structure (e.g. due to loss of soil organic matter) 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 Direct damage of plants by airborne soil particles
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 biota)	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, 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
Soil contamination	Contamination of soils with toxic materials (heavy metals, persistent organic compounds)	Use of certain agrochemicals (pesticides, polluted fertilisers) By water or air pollution from other sources	Lower crop yields Contaminated crops or livestock products
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 Restriction to root growth
Aluminium toxicity	Increase in soluble aluminium through acidification	Acidification, for example through ammonium fertiliser	Disturbed nutrient balances, toxicity to plants

Source: Adapted from Van der Esch et al., 2017.

Figure 3.14
Number of degradation risks potentially impacting yields, 2015



Number of overlapping risks

1
2
3
4
5
0

No agriculture

Degradation risks shown on map include: overgrazing, nutrient depletion, salinisation, crusting and erosion

Source: PBL/IMAGE

Three geographical clusters of agricultural degradation risk combinations can be identified

Each degradation process has a unique global distribution (see Appendix A5 for individual degradation process maps), but some processes form regional clusters of two or more processes. While numerous local clusters can be identified, three major clusters span the globe:

- Cluster of the humid and subhumid tropics. **Erosion and nutrient depletion**. The humid and subhumid tropical parts of sub-Saharan Africa and Southeast Asia are dominated by negative nutrient budgets and high erosion rates. Locally, such as in Thailand, salinisation or crusting can also occur. With some notable exceptions, such as Bolivia and Cuba, the humid and subhumid tropics in South and Central America have positive nutrient budgets but high erosion rates with local risks of overgrazing and crusting.

- Cluster of the extensively used drylands. **Crusting and salinisation**. The relatively thinly populated dryland areas of Australia, southern Africa, southern Russia and parts of Central Asia, Argentina and the Andes and the western United States all have some degree of crusting and salinisation risk. Generally, however, population and livestock densities are too low to create a high overgrazing risk.

- Cluster of the intensively used drylands. **Crusting, salinisation, overgrazing and more**. Parts of the Sahel, the Mediterranean, the Middle East, Central Asia and South Asia are more intensively used and are at risk of three or more degradation processes. In addition to crusting and salinisation, there is a local risk of overgrazing, erosion or nutrient depletion.

These clusters are dependent on the choice of analysed degradation processes and are not exhaustive. For example, compaction and the use of agrochemicals are degradation problems in the intensive agriculture areas, including North America and Europe (e.g. Lamandé et al., 2018; Sun et al., 2018). Another aspect not highlighted by this analysis is that even a single degradation process can, if strong enough, seriously impact productivity. For example, erosion in areas outside the first cluster (the tropics and subtropics) can seriously affect yields (see next section). Adding other processes to the map may increase the number of risks in areas that currently see fewer risks.

Impacts on crop productivity

Water erosion is the degradation process for which most information on crop yield impact is available. Water erosion field trials in Africa showed a decline in yields of 0.1% to 20% per cm of topsoil erosion (Lal, 1995), and a worldwide review of erosion effects on crop productivity found an average annual decline of 0.3% (Den Biggelaar et al., 2003). Yields can also be affected by erosion in well-fertilised soils (Frye, 1980; Mokma and Sietz, 1992; Fenton et al., 2005). These yield reductions can be even higher where subsoil conditions are unfavourable (Olson and Nizeyimana, 1988) or during drought (Mokma and Sietz, 1992). Most of the yield reduction can be attributed to loss of soil water due to run-off, followed by loss of nutrients, soil organic matter, soil depth, water-holding capacity and soil biota (Pimentel, 1997).

Salinisation can have measurable effects on crop productivity at a regional scale (Ali, 2000), and experiments show clearly that the impact of salt on plant growth can be severe (Nachshon, 2018). However, it is difficult to apply these functions to assess the impacts on crops, because data on actual electrical conductivity in soils depend very much on agricultural and irrigation management, which is not well mapped globally.

Much less is known about the impact of crusting on crop yields. Some researchers have presented soil crusting as the starting point of soil degradation, ultimately leading to long-term reduced crop yields (Sumner and Miller, 1992; Watt and Valentin, 1992). For example, Watt and Valentin (1992) write (for Africa): “Too often the processes beginning with soil crust formation proceed to water and soil loss through erosion, followed by reduced plant cover and, in the case of cultivated land, reduced yields.” However, due to the complexity of the process, there are no estimates of its impact on crop productivity.

For nutrient depletion, maps of the nitrogen and phosphorus budgets give a snapshot of the current trends. For the effect on plant productivity, however, it is better to look at phosphorus limitation to plant growth, which has a substantial negative effect on crop production (often 30% to 80%). However, an important assumption is that all other conditions, including nutrient ratios, are held equal. In effect, it is likely that other limitations become relatively more important as phosphorus limitation is reduced. Despite this, it is safe to say that nutrient limitation is a major problem for productivity, particularly in the subhumid tropics as discussed above.

In the short term, other factors than land degradation processes usually dominate crop yields (Section 3.3.1.2). However, once a land degradation process passes certain thresholds, it is very costly to restore land to its former productivity and land must be abandoned. Moreover, in marginal erosion-prone lands, often farmed by poor farmers who cannot invest in soil conservation measures, the effect of land degradation can be devastating, as has been illustrated for example in Haiti (Kaiser, 2004).

Projected impacts on agriculture and food

In the baseline scenario, decline in crop yields due to land management is the same order of magnitude as decline due to climate change. Both depress future increases in agricultural production.

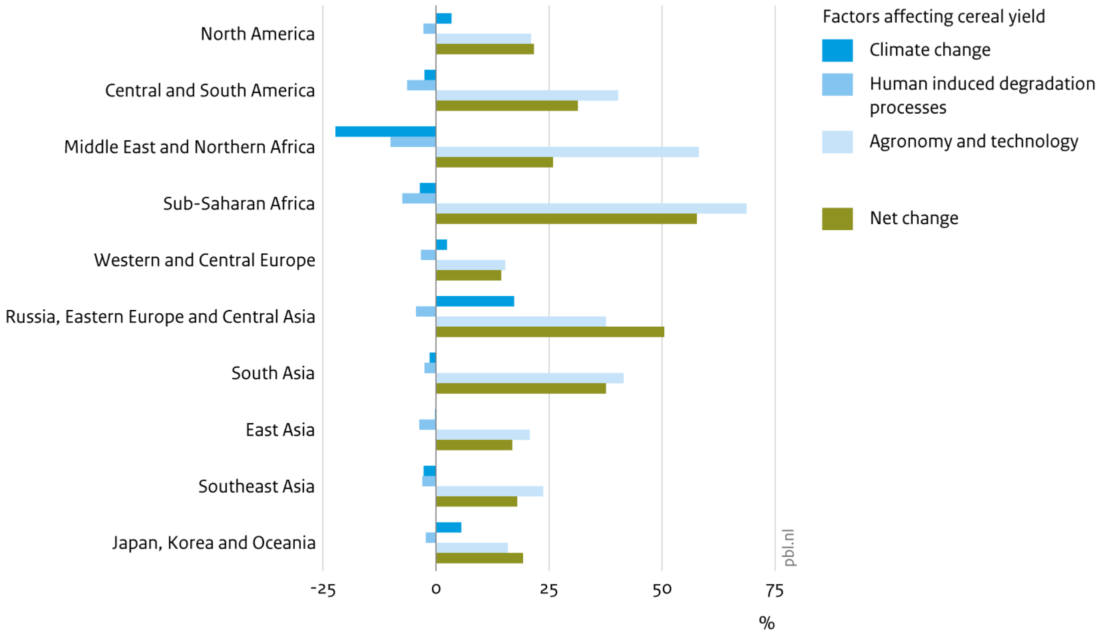
Under the baseline scenario, crop yields are affected by many different drivers, such as technological developments, agronomy, changes in production location, climate change and soil degradation. Other threats, such as diseases, pests, drought and flooding, could not be taken into account in this analysis due to limitations in the scope of the implemented models. The scenarios do account for technological developments and agronomy, location effects, climate change and soil degradation. The impact of soil degradation processes is approximated by extrapolating at a regressive rate the negative, climate-corrected NDVI trends for cropland and grasslands (Appendix A6). Figure 3.15 breaks down the projected change in average crop productivity per region to individual factors.

Changes in regionally averaged cereal yields (including wheat, maize, rice, barley and sorghum) from 2015 to 2050 in tonnes per hectare, per year, are used as an indicator (Figure 3.15). Overall, the developments in agronomy and crop technology are projected to dominate, ranging from an increase of 15% in Europe to 69% in sub-Saharan Africa. Even though sub-Saharan Africa shows a large increase, the absolute yield levels remain the lowest of all regions in the year 2050. Climate impacts on yields vary greatly between regions, with positive impacts in the temperate regions due to higher temperatures and CO_2 fertilisation. The Russia, Eastern Europe and Central Asia region is most notable, with a 15% increase in cereal yields. Climate has negative impacts in tropical regions due to reduced rainfall and higher average temperatures, which negatively affect yields with up to a 4% reduction in yields in sub-Saharan Africa. The effect of human-induced degradation processes is of a similar magnitude in our analysis, with a negative effect of up to 6% to 10% in the Middle East and Northern Africa, sub-Saharan Africa, and Central and South America.

Livestock production is increasingly concentrated in areas with overgrazing risk

Of the global land area, 23% or about 3.2 billion hectares are covered by grassland used predominantly for livestock production, and mostly managed extensively (Asner et al., 2004; Steinfeld et al., 2006; FAO, 2017). From a global food production perspective, the productivity of these grasslands matters greatly. As a response to increasing meat and dairy demand, in conjunction with competition for land, ruminants are increasingly raised in intensive or even landless systems (Bouwman et al., 2005; Lambin and Meyfroidt, 2011; Robinson et al., 2011). Intensification relies on the partial substitution of grass with feed concentrates such as grains which reduces the overall land footprint per unit protein output but is in direct competition with human consumption (Herrero et al., 2015). Intensification also results in a wide range of adverse effects on the environment (Steinfeld et al., 2006). In particular, the exceedance of the 'planetary boundary' of the nitrogen and phosphorus cycles, largely due to intensive livestock production, calls attention to the environmental limits of intensification (Bouwman et al., 2013; Steffen et al., 2015).

Figure 3.15
Change in cereal yields in baseline scenario, 2015 – 2050



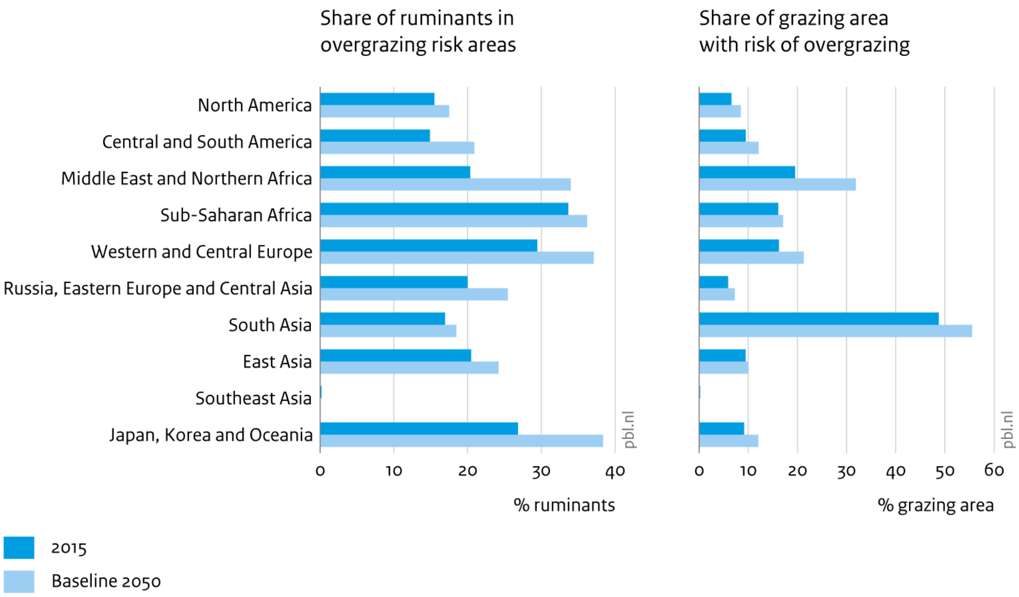
Source: PBL/IMAGE

Finally, as ruminants require grass, there are also metabolic limits to substituting grass with feed concentrate. There will therefore still be a growing demand for grassland (Lambin and Meyfroidt, 2011). As a consequence, managed grasslands continue to expand at the expense of forests and other natural vegetation, while at the same time grassland is encroached upon by cropland, mainly at the margins of agricultural heartlands (FAO, 2006; Andela and Van der Werf, 2014; Emili and Greene, 2014; Graesser et al., 2015; Curtis et al., 2018).

Since modern livestock management systems started spreading, fragmentation and the fencing of grassland have increasingly resulted in reduced mobility for livestock and the retraction of pastoralism. Together with widespread fire suppression and increasing livestock numbers, this has had profound impacts on plant communities and grassland productivity (Bahre, 1997; Hoffman, 2003; Asner et al., 2004; Krätli et al., 2013; Twidwell et al., 2013). Most importantly, the large increases in livestock numbers have cause grassland degradation through overgrazing. Grassland degradation has been conceptualised as a series of transitions between vegetation states, some of which are difficult to reverse (Westoby et al., 1989; Milton et al., 1994). In arid and semi-arid grasslands and savannah, degradation through overgrazing is manifested in the reduction of grass reserve biomass (Gao et al., 2008), less productive smaller grass plants (Li et al., 2015), the replacement of palatable species with less palatable species (Friedel et al., 2003), the replacement of perennial with ephemeral species (O'Connor, 1991), an increase in woody vegetation and shrubs (Asner et al., 2004), and an increase in the bare and eroded soil fraction (Milton et al., 1994).

While there is no simple equilibrium between stocking rates (the number of livestock per area) and grassland productivity (Westoby et al., 1989; Müller et al., 2007), overgrazing occurs when grazing management causes grassland degradation that, in turn, means that the potential *long-term* stocking rate under optimal management cannot be achieved. In the absence of models that can explicitly predict grassland degradation due to overgrazing involving transitions between vegetation states, we calculate grazing intensity (GI), which is the ratio of grass demand to grass supply, and disregard areas where overgrazing is less relevant due to intensive pasture management (see Appendix A5 for technical background report for methods and a map of the overgrazing risk).

Figure 3.16
Areas with risk of overgrazing



Source: PBL/IMAGE, PIK

Overgrazing is mainly a risk in drylands with high livestock densities. In Africa, relatively large at-risk areas are found in countries of the Western Sahel, in Sudan, in northern Ethiopia and in somewhat smaller pockets in East African countries (see Appendix A5.3 for a map). The largest hotspot in Asia is in Pakistan and north-west India. Smaller hotspots are found in the Middle East, Turkey, Central Asia and western and northern China. Australia is sensitive to overgrazing just west of the Great Dividing Range. In the Americas, a high overgrazing risk is limited to relatively small pockets, but large parts of Brazil still have a moderate overgrazing risk. In Europe, parts of Spain are at risk of overgrazing.

In general, sheep and goats are more likely to be in overgrazing risk areas than cattle. This is not surprising, since small ruminants can make do with sparser vegetation than cattle. Most world regions have sizeable portions of their livestock in at-risk areas. Southeast Asia has very little grazing land, most of which is not susceptible to overgrazing. South Asia stands out in terms of percentage area affected in 2015 (Figure 3.16). The largest increases towards 2050 in both livestock and area at risk are projected for the Middle East and Northern Africa region. All other regions show a moderate increase in risk. Sub-Saharan Africa is not likely to have a strong increase in overgrazing risk, mainly because much grazing land will become intensively managed or converted to cropland and therefore falls outside the overgrazing relevance mask used in this report.

Previous studies using grazing intensity were based on livestock statistics in conjunction with some harvestable fraction of NPP (Haberl et al., 2007; Petz et al., 2014; Fetzel et al., 2017). Rolinski et al. (2018) introduced several explicit harvesting and grazing routines for managed grassland in LPJmL, the global dynamic vegetation model (Bondeau et al., 2007), which is used in this report. While not reporting a grazing intensity directly, they contrasted actual livestock densities with livestock densities supported by a given harvest or grazing management system. The above results differ from earlier studies mainly in the projection of overgrazing risk into the future. As parts of the underlying data are shared by other studies, it is unsurprising that similar patterns emerge. For example, hotspots in most studies, including ours, are Pakistan and north-west India, the northern Sahel, northern China, and parts of Central Asia and the Middle East (Petz et al., 2014; Fetzel et al., 2017; Rolinski et al., 2018).

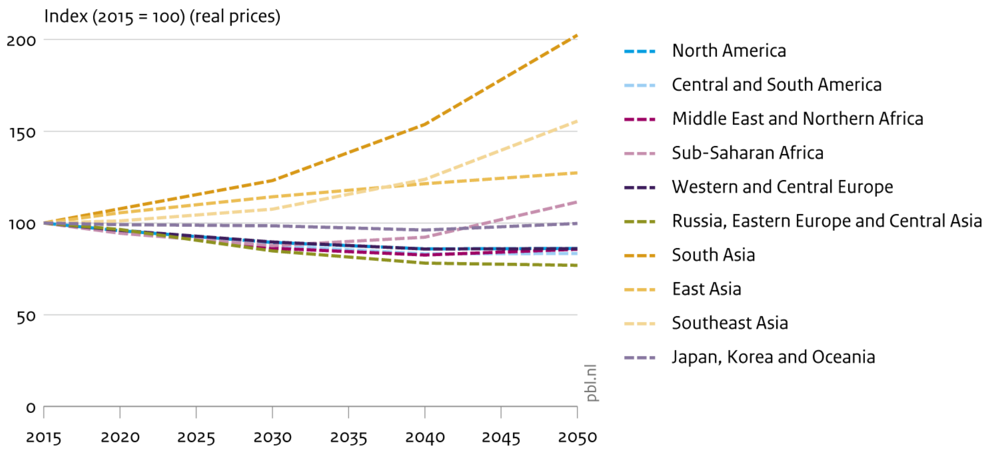
Food prices increase in hotspot regions in baseline scenario

A commonly used definition of food security is that food security exists “when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life” (FAO, 1996). This implies a physical aspect to food security (sufficient food needs to be produced that is both nutritious and safe), as well as an economic aspect (people need to be able to afford food and it needs to be available at the right place and time). In this section, we investigate both the physical and the economic aspects of food security in relation to changes in future economic and demographic developments, land degradation and climate change.

Average developments in food prices are an indicator for the economic accessibility to food (Figure 3.17). Here, food prices are calculated for the baseline scenario using the agro-economic model MAGNET (part of IMAGE), taking into account economic developments, demographic changes, limits to land expansion and impacts of land degradation and climate change (Van Meijl et al., 2020). The strongest increases are projected for South and Southeast Asia. In these regions, strong increases in population are projected as well as continued economic growth. Moreover, most notably in India, little additional land is available for agricultural expansion, which increases the pressure on the agricultural market. In sub-Saharan Africa, increases in food prices are projected from 2030 onwards. Here too, strong increases in population and GDP are underlying drivers. However, as there are more possibilities to increase the amount of agricultural land, food prices rise less strongly. In developed regions such as North America, Europe, Japan and Oceania, food prices are stable or decrease slightly as the population remains stable or even decreases, and as high levels of agricultural productivity are projected to be maintained.

Figure 3.17

Food prices under the baseline scenario



Source: PBL/IMAGE

3.3.2 Exploring the impact of changes in land condition on water regulation

The water-holding capacity of soils is especially important for dryland agriculture

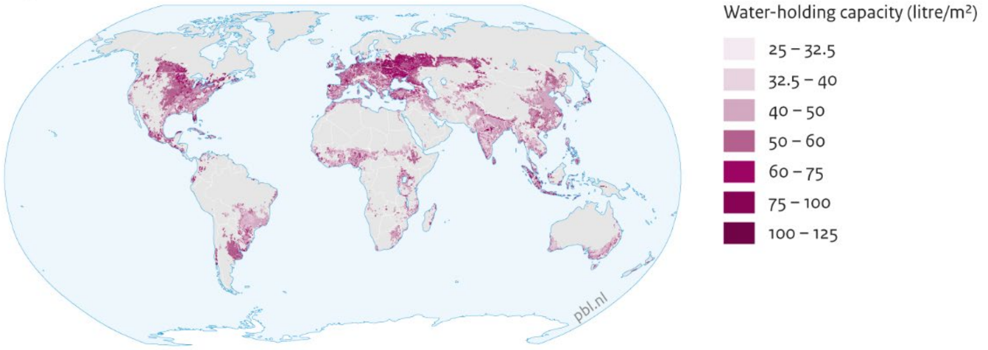
The ability of soil to hold water against the force of gravity in the root zone (where it is available for plants) is an important factor for plant growth in general, and agricultural production in particular. The water-holding capacity defines the upper limit of the amount of water that can be stored in the soil. Though the actual water availability over time does not only depend on soil characteristics — it also depends, among other things, on climatic variability and plant characteristics — the water-holding capacity is particularly important for the cultivation of rain-fed crops and pasture in dryland areas.

There are strong regional differences in water-holding capacity in rain-fed cropland areas (Figure 3.18), with high values prevailing in areas with soils rich in organic material such as the boreal zones of North America and Eurasia and in tropical and sub-tropical areas, and low values in the more arid regions such as parts of India, East and West Africa and around the Mediterranean. In the baseline scenario, the projected changes to soils lead to a reduction in the water-holding capacity in agricultural areas. Areas that are already significantly limited by water availability for their crop production are projected to be particularly affected, such as East and West Africa and parts of South America. Overall, sub-Saharan Africa is projected to be worst affected, followed by Southeast Asia (Figure 3.19). A 3% loss in the average water-holding capacity for rain-fed agriculture in sub-Saharan Africa implies a comparable reduction in the maximum available water for plants in the soil and thus a reduction in the ability to cover dry spells. These are averages for all rain-fed cropland per region, some specific areas are much more affected.

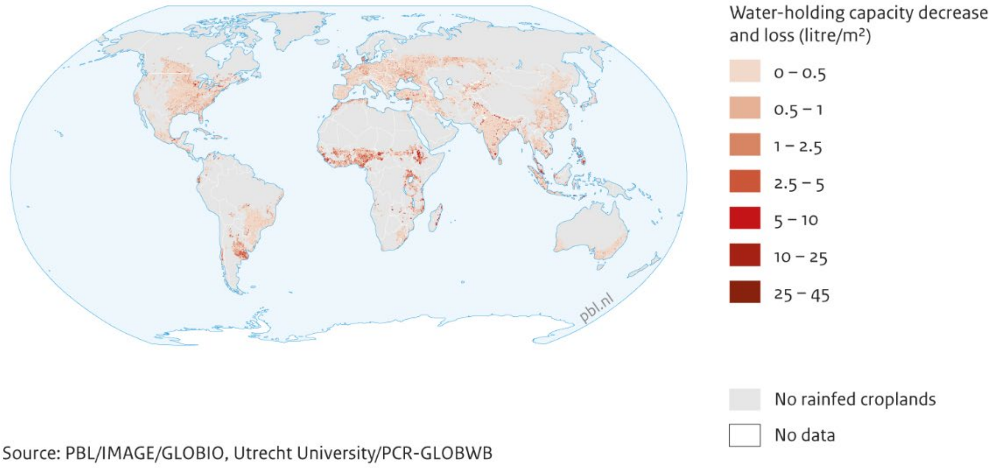
Figure 3.18

Water-holding capacity of rainfed croplands

2015



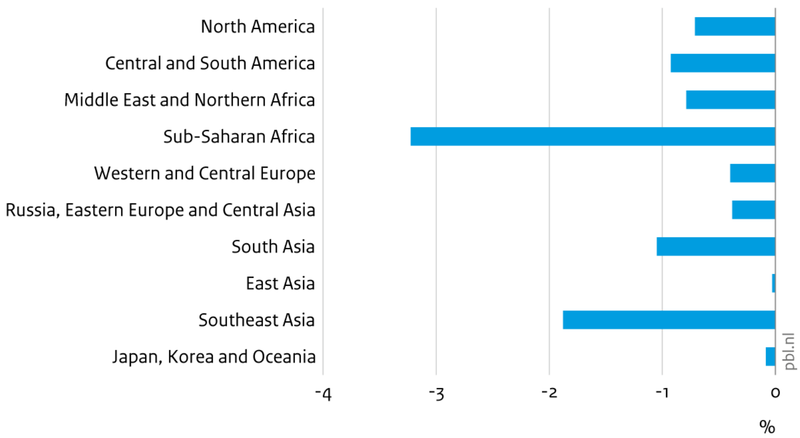
Change under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE/GLOBIO, Utrecht University/PCR-GLOBWB

Figure 3.19

Water-holding capacity for rainfed croplands undert the baseline scenario, 2015 – 2050



Source: PBL/IMAGE/GLOBIO, Utrecht University/PCR-GLOBWB

3.3.3 Exploring the impact of changes in land condition on carbon emissions and sequestration

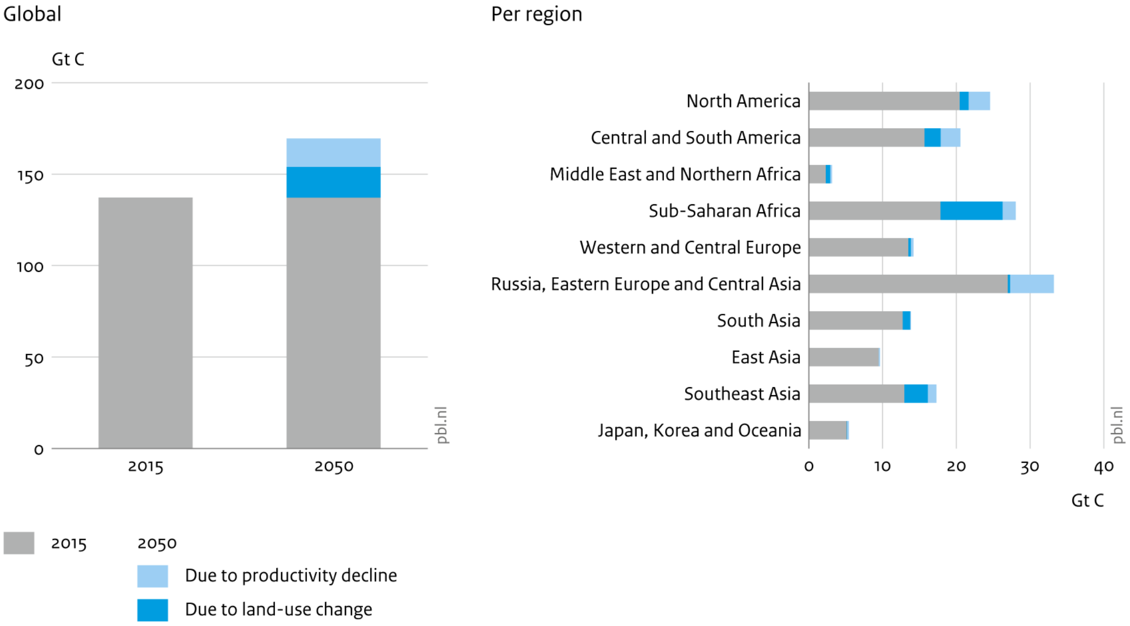
The total current carbon stocks in soils amount to about 2,000 Gt, while those in vegetation come to about 450 Gt. Changes in carbon stocks in soils and in vegetation are crucial for carbon dioxide concentrations in the atmosphere. Reductions in vegetation and soil carbon stocks due to land-use change, land management, natural factors and climate change lead to increased emissions of CO_2 to the atmosphere (or reduced uptake), which further exacerbates climate change. On the other hand, if carbon stocks can be increased through changes in land use or management, this could help to mitigate climate change (Griscom et al., 2017).

Carbon emissions from soils

We estimate that about 140 Gt of carbon have been lost from soils historically (Figure 3.20). Future emissions from SOC associated with land-use change and declining trends in primary productivity are estimated at 32 GtC in the 2015–2050 period, of which 44% is due to land-use change and 56% due to negative trends in primary productivity (Appendix A6). This is substantial as it amounts to an emission of about 0.9 GtC/yr, which is equal to 9% of today's carbon emissions from energy and industry. The productivity trends entail a combination of land management, natural factors and climate change but cannot be further attributed. A number of regions are responsible for the bulk of changes in SOC due to anthropogenic activities. In sub-Saharan Africa and Southeast Asia, losses of 10 and 4 GtC respectively, are projected to take place, mainly due to land-use change. North America, Central and South America and Russia, Eastern Europe and Central Asia see changes of 4, 5 and 6 GtC respectively, predominantly due to land management. Although not considered in this analysis, it is likely that there will be some increases in soil carbon, especially in natural areas with an increase in primary productivity.

Figure 3.20

Loss of soil organic carbon, compared to natural condition



Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017

Peatlands are estimated to store about 640 GtC, while they only cover 3% of the global land area (Leifeld, 2018). Degradation of peatlands due to agricultural practices on peat soils (most notably in Europe and Russia) and the recent expansion of agriculture on peat soils (most notably in Indonesia) makes peatland a substantial source of carbon emissions. In the baseline scenario, ongoing emissions from degraded peatlands and conversion of pristine peatlands amounts to an additional emission source of 10 GtC in the 2015–2050 period.

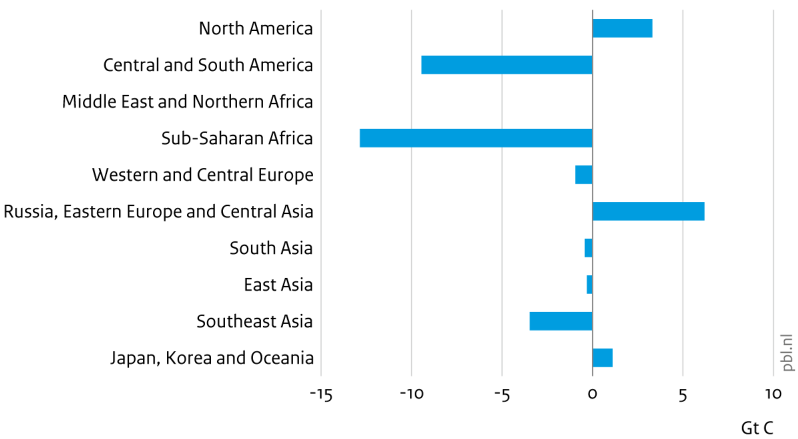
Carbon emissions from vegetation

A substantial expansion of agricultural area takes place in the baseline scenario (Section 3.2.1), most notably in the tropical regions Central and South America, sub-Saharan Africa and Southeast Asia. These are consequently also the regions where the largest loss of carbon in vegetation takes place, with cumulative losses of 13, 9 and 3 GtC respectively, in the 2015–2050 period. This translates into emissions of 0.7 GtC/yr, which is equal to 7% of current annual CO_2 emissions from energy and industry. Conversely, there are also regions with an increase in carbon stocks, such as North America and Russia and Central Asia. This increase is predominantly the result of higher temperatures and CO_2 fertilisation due to climate change, which leads to the expansion of forest in the northern latitudes.

In the regions with a net loss in living carbon stocks, a total of 27 GtC will be lost in the 2015–2050 period. A model comparison of SSP2 scenarios showed a range of land-use-change emissions of 10 to 55 GtC in the 2010–2050 period (Popp et al., 2017). Compared to these results, the estimate presented here is in the middle of the range. Uptake of carbon due to climate change combined with CO_2 fertilisation is projected by multi-model experiments performed with Earth system models for the IPCC Fifth Assessment Report (IPCC, 2013). These experiments found a consistent sink in natural vegetation, most notably in the northern latitudes where both CO_2 fertilisation and higher temperatures have a positive impact on the amount of carbon stored in the vegetation. Increased tree cover in northern latitudes is also confirmed by satellite observations. However, it is uncertain whether this sink will persist in the near future, as the impacts of CO_2 fertilisation and other factors that explain the historic land carbon sink are poorly understood (IPCC, 2019).

Figure 3.21

Change in vegetation carbon stocks under the baseline scenario, 2015 – 2050



Source: PBL/IMAGE

Annual carbon emissions from land-use change and land management over the baseline period amount to about 17% of current annual emissions

The estimate presented in this study, which includes changes in vegetation, SOC and peatland degradation, amounts to cumulative emissions of 69 GtC in the 2015–2050 period. This translates into an annual emission of 2.0 GtC/yr. Net emissions from land are estimated by the Global Carbon Project at 1.5 GtC/yr with a large uncertainty range of 0.8 to 2.2 GtC/yr (Friedlingstein et al., 2019), showing that the estimate presented here is at the higher end but within the range of estimates in the literature.

Total current global emissions according to the Global Carbon Budget study amount to 11.5 GtC/yr. The bulk of anthropogenic carbon emissions is produced by the energy and industry sectors (about 10 GtC/yr in 2018). Most of this results from energy generation through the combustion of coal, oil and gas; however, the production of cement and fossil fuel use in industrial processes (e.g. steel, chemical and paper production) also contribute substantially. This implies that the carbon emissions from land estimated in this study are equal to about 17% of today's total carbon dioxide emissions. This underlines the importance of carbon emissions from land-use change and land management in the global climate change discussion.

3.4 What the baseline scenario means for ambitions to counter land degradation

The results presented in this chapter show that, under baseline conditions, pressure on land is projected to further increase up to the year 2050. Continued growth in demand for agricultural production leads to further intensification of agriculture and expansion of agricultural land, most notably in sub-Saharan Africa and in Central and South America (Section 3.2.1). Satellite-based analyses find negative trends in productivity in nearly all regions, and these are expected to continue in the near future, causing additional pressure on the land system (Section 3.2.2). Climate change further exacerbates the challenge, although in the boreal regions such as North America and Russia higher temperatures and CO_2 fertilisation have a positive impact on agricultural productivity (Section 3.2.3). The projected changes also negatively affect soil health and biodiversity. In turn, the baseline developments have substantial impacts on ecosystem functions such as agriculture, water and food security, water regulation and carbon sequestration.

In Chapter 2, the current restoration commitments were presented that have been made by countries to limit degradation by protecting land from conversion, to restore land through processes such as reforestation, and to improve the management or rehabilitation of land. In this section, a comparison is made between the baseline trends and the restoration commitments to see how and to what extent these align. In Chapter 4, the challenges arising from unabated developments in the baseline scenario are addressed by discussing the potential of restoration and protection measures.

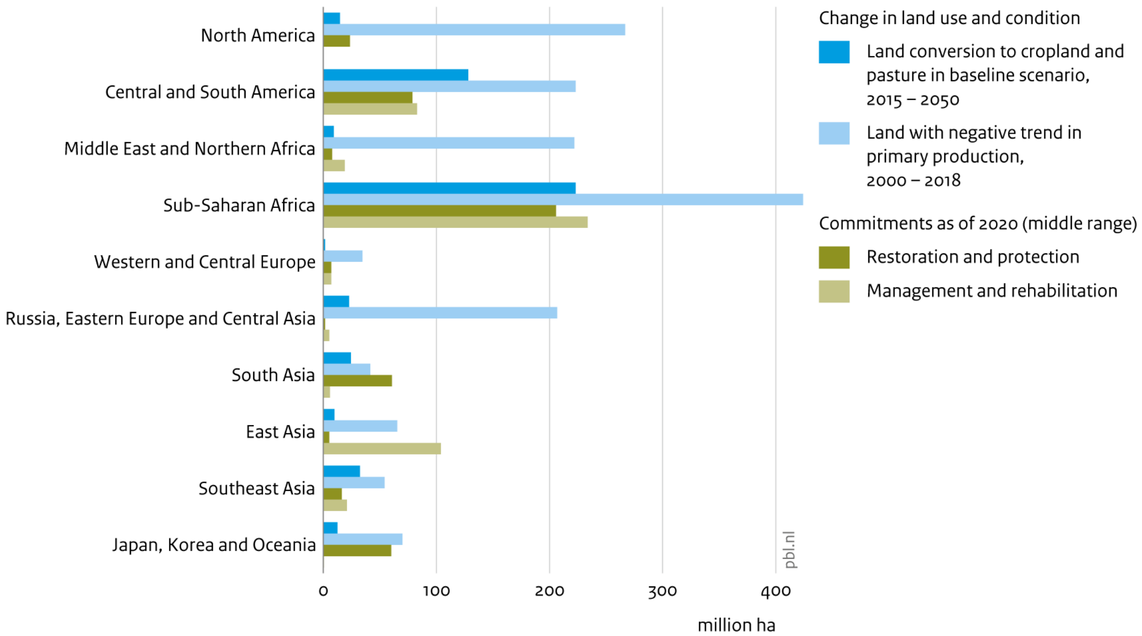
Restoration and protection commitments are in the same order of magnitude as projected land-use changes

The regions with the largest relative projected land-use changes up to 2030 are sub-Saharan Africa, Central and South America and Southeast Asia, with 90 million hectares, 60 million hectares and 16 million hectares of loss of forest and other natural land, respectively (Figure 3.22). Commitments categorised as restoration and protection in these regions amount to 206 million hectares, 79 million hectares and 16 million hectares, respectively. The order of magnitude of the commitments in these regions is similar to the projected land-use change, indicating that the commitments in these regions to restore and protect natural areas are comparable in size to the projected conversion of natural land. However, restoring existing natural areas may not counterbalance the loss of other natural areas to urbanisation or agriculture.

The analysis in this report is made at an aggregated scale of world regions. Moreover, the commitment activities are simplified in two broad categories. It might be that land-use change is projected to occur in one country while the commitment is made for a different country, or that a restoration activity that is intended as reforestation on current agricultural land might not prevent conversion of natural land in other locations. This calls for a more detailed analysis as well as better-specified and more geographically specific restoration commitments.

Figure 3.22

Change in land use and condition and restoration commitments



Source: PBL/IMAGE, NASA/MODIS, UNCCD, UNFCCC, CBD, Bonn Challenge; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

Land areas with negative productivity trends are larger than area commitments for management and rehabilitation

Large areas with negative productivity trends are situated in sub-Saharan Africa (332 million hectares) and Central and South America (156 million hectares), similar to the large areas of projected land-use change in these regions. There are also large areas with negative productivity trends in North America (219 million hectares), the Middle East and Northern Africa (184 million hectares) and Russia, Eastern Europe and Central Asia (161 million hectares), though here the projected land-use changes are small. Restoration commitments for the management and rehabilitation of soils are also small in these regions, with fewer than one million, 19 million and 5 million hectares, respectively, though this may be due to categorisation of the Bonn Challenge commitments (Sewell et al., 2020). Sub-Saharan Africa and Central and South America do have substantial restoration commitment areas (234 million and 83 million hectares, respectively), but these are substantially smaller than the total area projected to have a negative productivity trend. This implies that commitments related improved land management are not aligned with the magnitudes nor the regions where the productivity declines are observed. A caveat is that negative trends are observed on both agricultural and natural lands (Section 3.2.2).

4 Potential benefits of land restoration and improved land management

4.1 Purpose and overview of the two restoration scenarios

4.1.1 Purpose of the two restoration scenarios

The two restoration scenarios aim to quantify the potential of land restoration globally and for the 10 regions distinguished in this report, in light of future developments in land and land use, and for multiple goals and benefits that can result from restoration. This is done in accordance with the conceptual approach highlighted in Chapter 2. The potential benefits of restoration are estimated and compared to the baseline scenario of projected future changes towards 2050 as described in Chapter 3.

As described in Chapters 1 and 2, increased attention is being paid to restoration, from various disciplines and sustainable development perspectives, and a few scenario studies have assessed the potential for land restoration at the global level (Strassburg et al., 2020; Wolff et al., 2018). This study adds to these earlier studies by accounting for future dynamics, by assessing land restoration in conjunction with agricultural production as well as restoring natural lands, and by including indicators relevant to UNCCD as either an input (primary productivity) or output (soil organic carbon) of the analysis. Crucially, the restoration scenarios do not compete with current agricultural production. Rather, they estimate to what extent restoration is possible in conjunction with the current agricultural area.

The estimates presented in this chapter represent the technical potential of land restoration, based on the measures described in Section 4.2. They do not account for barriers to the large-scale implementation of restoration measures that may arise, for instance due to regulations, financing and technical capacity.

4.1.2 Overview of the two restoration scenarios

We distinguish two restoration scenarios. The first of these (*Restoration*) focuses on purely restorative land management to halt land degradation and to improve soil conditions and ecosystem functions while not changing the major land-use type. The *Restoration* scenario employs eight different measures in the area where the measures are suitable (e.g. conservation agriculture, cross-slope barriers; see Section 4.2.2). In most locations, multiple measures are identified as options for land restoration. The second scenario (*Restoration & Protection*) has the same restorative land management, but adds protection measures (conservation areas, see Section 4.2.3), thus preventing the future conversion of natural areas in specific locations. These protection areas are selected based on their importance for biodiversity and key ecosystem functions. The reason for adding protection is to further address the potential of preventing land degradation and loss of ecosystem functions. This is in line with the response hierarchy to first avoid, then reduce and then reverse land degradation (UNCCD, 2017a,b). The results are compared to the baseline, which does not include restoration measures or additional area protection ambitions. Both restoration scenarios assume the same future changes to demographics, economics, trade and consumption as in the baseline and the additional demands on land and land use resulting from this. Most of the areas that have restoration potential are assumed to be restored by the various measures in the scenario.

Not included in the restoration scenarios are measures on the consumption side (e.g. dietary transitions) or the production side (e.g. through supply chain efficiencies), though both are required to develop a transition that comes close to the goals set for biodiversity and climate change. Similarly, agricultural land is not taken out of production for restoration or reforestation.

As land restoration aims to provide multiple benefits at the same time (Chapter 2), appreciating the potential of restoration requires a set of indicators of land condition and ecosystem functions. This chapter applies the same set of indicators as introduced in Chapter 2 and quantified in Chapter 3 to estimate the potential benefits and trade-offs arising from restoration and protection measures.

4.2 Land restoration measures used in the projections

This section outlines the different measures applied in the *Restoration* and the *Restoration & Protection* scenarios. An overview of all measures in the scenarios and where they are applied is given in Section 4.2.1. A detailed description of the measures is provided in Sections 4.2.2 and 4.2.3.

4.2.1 The potential area for land restoration

All areas identified as having less soil organic carbon than under natural conditions or declining trends in primary productivity can potentially be restored (Section 3.2.4). This includes: (i) all land used for agriculture and livestock, (ii) areas with a persistent negative trend in NDVI for the past 20 years, and (iii) areas where the current NDVI is lower than the estimated natural NDVI (Section 3.2.2) (Stoorvogel et al., 2017b). Though urban areas might be regarded as degraded and theoretically restorable to some extent, they are not included in this analysis as the restoration measures employed do not work in urban areas.

The total area in which at least one of the restoration measures is applied in the restoration scenarios is about 5.2 billion hectares. In the restoration scenarios, future agriculture expansion is assumed to be carried out under the type of land management measure that scores best for restoring soil organic carbon at a specific location. This implies a minimised loss from future land conversion, though this will still result in a loss compared to the previous natural state in many cases.

4.2.2 Restoration and improved land management

Land restoration measures included in the scenarios

As described in Chapter 2, restoration includes ecological restoration and improved land management (Lal, 2006; WOCAT, 2007; 2012). Eight measures are included in the restoration scenarios, based on a detailed inventory and classification (WOCAT, 2007; 2012) (Figure 4.1)[6]. These measures cover agronomic, vegetative, structural and management approaches, and are:

1. Agroforestry
2. Conservation agriculture
3. Cross-slope barriers
4. Grazing management
5. Grassland agroforestry (silvopasture)
6. Grassland improvement
7. Assisted natural regeneration
8. Forest plantation (on degraded land)

This is not an exhaustive list of potential restoration measures. Not included here are, for instance, wetland, riparian or peatland restoration (e.g. rewetting of peatlands and replanting of vegetation along riverbanks), and improvement of irrigation systems.

In the scenarios, the area suitable for restoration depends, firstly, on there being potential for soil restoration (Section 4.2.1), and secondly on a combination of land use/land cover, population density, rainfall, soil texture and depth, slope, and distance to infrastructure (Box 4.1).

There is a lack of globally consistent information on current land management systems. Therefore, we assume that the restoration measures can be applied everywhere to improve soil conditions, even though they may already be implemented in some locations. This means that the estimate of the potential of restoration still holds, but that in reality part of this may already be implemented. This especially influences the assumption that all cropland and pasture areas are currently not under sustainable management or restoration.

Agroforestry

Agroforestry integrates the use of trees (and shrubs) with agricultural crops and/or pasture (see grassland agroforestry) for a variety of benefits and services such as improved use of soil and water resources, multiple fuel, fodder and food products, and habitats for associated species (ICRAF, 2020; FAO, 2017). There are five main forms of agroforestry: alley cropping, forest farming, silvopastoralism (see grassland agroforestry), riparian forest buffers and windbreaks. These examples cover a wide range of restoration approaches used for restoring degraded forests and agricultural lands and integrating technologies, such as contour farming, multistorey cropping, intercropping, multiple cropping, bush and tree fallows, parkland or home gardens (FAO, 2011).

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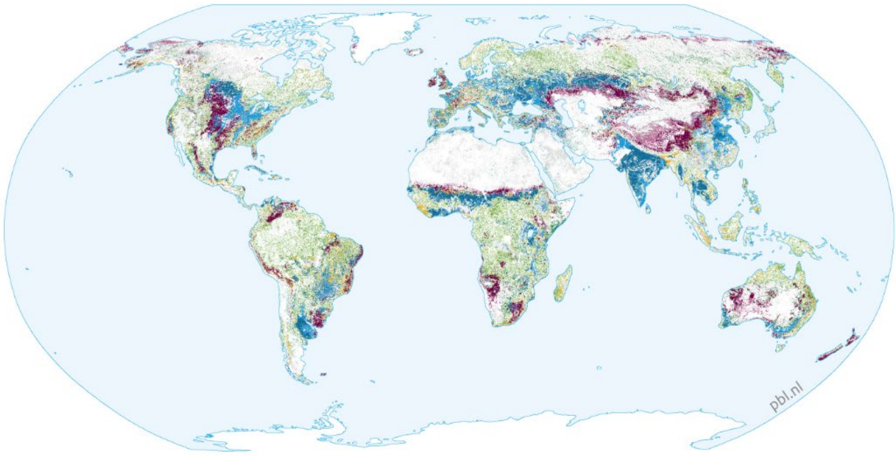
[6] Note that these restoration measures do not correspond to the classification used in Figure 2.4 in Chapter 2. The classification in Figure 2.4 is based on the specific texts used by countries. The classification in eight categories used in the scenarios is based on WOCAT and refers to more specific restoration approaches.

Figure 4.1

Locations of improved land management and restoration measures, as applied in the Restoration scenarios



Measures and combinations of measures

- Agroforestry; Conservation agriculture
- Conservation agriculture
- Cross-slope barriers; Agroforestry; Conservation agriculture
- Cross-slope barriers
- Grazing management; Silvopasture
- Grazing management; Grassland improvement
- Grassland improvement
- Assisted natural regeneration
- Forest plantation
- Assisted natural regeneration; Forest plantation
- Other combinations
- Restoration potential, but no measure possible
- No restoration potential

Source: PBL/WUR

Box 4.1 Methodology: How restoration measures and protection work through to land condition and ecosystem functions in the modelling

The effects of both restoration scenarios are quantified using the integrated model framework and a set of coupled models for various impacts. Appendix A6 describes the modelling set-up and methodologies in more detail. The two core aspects of restoration in this study are the effects on soils and on agricultural productivity, as summarised below.

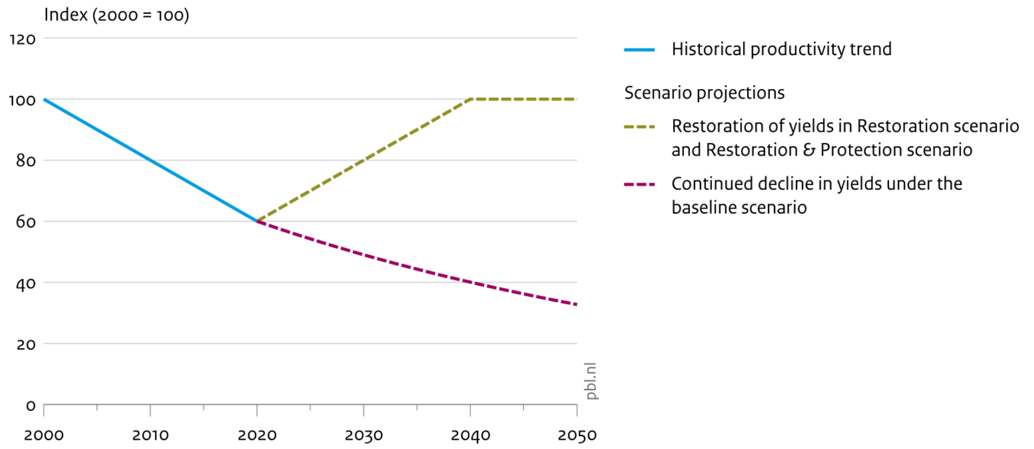
Effects of restoration measures on soil and vegetation carbon
An extensive literature review was conducted of the potential of the eight restoration measures in the scenarios to restore soil organic carbon (SOC), differentiated by climate zone (Fleskens et al., in prep.). The reporting of the effect of restoration on soil carbon varies greatly across studies. Based on the literature review, in the scenarios, a percentage increase on the estimated 2015 SOC state is applied to calculate the potential of the measures to restore soil organic carbon. As we apply this increase, no explicit assumption has to be made on how long the restoration process takes; restoration of soil carbon in severely degraded lands may take a very long time — longer than the scenario period. The soil carbon levels of undisturbed soils were applied as upper bounds for increases in soil carbon, based on the S-World model (Stoorvogel et al., 2017). For vegetation carbon, the IMAGE model framework with the dynamically coupled LPJmL vegetation model was used (Müller et al., 2016). As it was not possible to link the literature-based soil carbon effects to IMAGE, the effects of restoration measures on soil carbon were performed separately and later combined with the IMAGE-LPJmL results on vegetation carbon.

Effects of restoration measures on agricultural yields
It is assumed that improved management prevents further degradation and agricultural yield decline (as applied in the baseline, Chapter 3), and that historic degradation is reversed, resulting in restored yield levels (Figure 4.2). Temporal dynamics and final levels of restored yields vary a lot. It is assumed that the degradation that has occurred over the past two decades (2001–2018, Chapter 3) can be restored to the yield level at the beginning of this observation, within the same period of 20 years. This approach is rather conservative for various reasons. Firstly, only the yield loss of the last 20 years is restored and not the potential loss before that time. Secondly, areas with currently stable productivity may be in a degraded state and yields would benefit from restoration measures, but these potential yield gains are not included here. Thirdly, in terms of time frame, restoring yield levels within 20 years is a rather conservative estimate, also accounting for implementation lags.

Both scenarios assume the same restoration of agricultural productivity; the scenarios only differ in the more extensive protection of areas in the *Restoration & Protection* scenario. The restoration measures are assumed not to further change potential yields.

Figure 4.2

Schematic showing restoration of agricultural productivity in restoration scenarios



Source: PBL, NASA/MODIS

Agroforestry is generally described as a promising measure throughout the tropics that is beneficial for various ecosystem functions. Establishing and managing trees on active agricultural land, either through planting or regeneration, can help to improve crop productivity, provides dry season fodder, increases soil fertility and carbon stocks and enhances water retention (Cardinael et al., 2018; Feliciano et al., 2018; IUCN and WRI, 2014). Agroforestry is most common in sub-tropical and tropical zones (Torquebiau, 2000; Nair, 1985), and agroforestry systems are predominantly practised by smallholder farmers in the tropics (Lorenz and Lal, 2014).

In the restoration scenarios, agroforestry is deemed suitable on cropland with yields equal to or below 70% of the maximum potential yield, and where precipitation levels can sustain the trees. The scenarios do not account for a possible yield decline related to effective lower cropping area (Blaauw et al., 2019), and they assume that in these croplands the beneficial effects of agroforestry on harvested yields at least counterbalance a possible negative effect on yields. A switch to agroforestry on current high-yielding croplands would possibly lead to a trade-off with crop yields and thereby spillover effects across regions, which are beyond the scope of this study (Kok et al., in prep.). In addition, agroforestry and reforestation type measures could have adverse impacts on water availability downstream. This effect is not accounted for in the scenarios.

Conservation agriculture

Conservation agriculture is a system of managing agricultural lands based on farming practices that aim to achieve sustainable agricultural production through the preservation of soil quality and improvement of soil biodiversity. This approach is characterised by three main techniques: minimal or reduced tillage of soil, permanent organic soil cover (using previous crop residues or cover crops), and species diversification and rotation (FAO, 2016).

Conservation agriculture techniques work well with vulnerable or degraded agroecosystems by assisting in the conservation and restoration of land while at the same time increasing the environmental resilience and agricultural sustainability. For example, reduced tillage of soil allows new crops to be grown over previous crops, thereby aiding improvement of the soil structure and fertility (Haddaway et al., 2017). In addition, reduced tillage can be practised with minimal soil disturbance and can therefore play an important role in preventing soil erosion, especially in hilly and mountainous areas. When practised over large areas, conservation agriculture can also contribute to ecosystem services delivery, such as water regulation, erosion prevention, carbon sequestration and maintenance of soil fertility (Powlson et al., 2016; Haddaway et al., 2017; González-Sánchez et al., 2016; Kassam et al., 2010).

Conservation agriculture is compatible with other restoration measures, such as cross-slope barriers and agroforestry. This measure is therefore applied to all cropland in the restoration scenarios. Current conservation agriculture is not included, as no consistent global data on locations with full implementation of all aspects of conservation agriculture were available at the time of this study. Therefore, it is assumed that there is zero conservation agriculture at the start of the scenarios in 2015, leading to a possible overestimation of its effects.

Cross-slope barriers

Cross-slope barriers are soil and water conservation measures that are created on sloping lands in the form of terraces, earth or soil bunds, stone lines, and/or vegetative strips or barriers (Liniger et al., 2011). By reducing the steepness and/or the length of the slope, these techniques contribute to soil, water and nutrient conservation and can help the land to cope with extreme rainfall events. The implementation of cross-slope barrier techniques, suitable for a wide range of arid to humid areas, has the potential to reduce both surface run-off and soil erosion as well as improve infiltration, soil organic matter and soil fertility, which can help to increase crop yields and food security (Liniger et al., 2017; Saiz et al., 2016; Sudhishri et al., 2008; Vancempenhout et al., 2006). In the restoration scenarios, cross-slope barriers are implemented on sloping land that is cropland, pasture, rangeland or forested land.

Grazing management

Grazing management involves planning, implementing and monitoring grazing. By reducing overgrazing and improving forage production, this restoration technique aims to maintain healthy and productive pastures so that cattle can use the land for as long as possible during the year, while staying within the limits of the ecosystem. Measures include simple rotational grazing or intensive rotational grazing, both of which allow time for the grass to recover between grazes and maximise forage regrowth (FAO, 2020). Managing where and when livestock graze can improve land and pasture conditions, enhance livestock production, and encourage an increase in forage utilisation. Improved grazing management can also help to improve soil carbon stocks (Conant et al., 2017; Garnett, 2017), with the greatest effect found in the tropics (Eze et al., 2018).

Grassland agroforestry (silvopasture)

Grassland agroforestry, or silvopasture, is a method that combines trees, forage and livestock in the same plot or system (IUCN and WRI, 2014), and is applied both in tropical and temperate regions (Orefice et al., 2016). It provides a wide range of benefits, including livestock, timber and other forest products such as nuts and fruit (Chara et al., 2019). The livestock also functions as weed control, reducing trees' competition for water, light and nutrients, while also providing natural fertiliser that enhances soil fertility and moisture (ICRAF, 2015; Jose, 2009; Orefice et al., 2016). Silvopastoral systems are especially effective for soil carbon sequestration (Feliciano et al., 2018). The applicability of silvopasture is constrained in this analysis to regions where the natural vegetation is forest or savannah/woodland as this measure requires trees.

Grassland improvement

Grassland improvement is a restoration technique that introduces a selection of local or exotic grasses and legumes (FAO, 2020). Along with sown pasture, it is common in commercial mixed farming and more intensively managed grasslands. Techniques usually involve the at least temporary suppression of the existing vegetation by fire, hard grazing, herbicides or mechanical removal, before other species are introduced (Suttie, Reynolds and Batello, 2005; FAO, 2020). As such, grassland improvement can also be regarded as involving a loss in certain ecosystem functions. Nutrient levels and acidity can be improved by fertilisation and liming (to raise soil pH), which are typically the most common management activities for improving or maintaining grassland productivity. Grassland improvement can lead to improved soil fertility and an overall increase in soil health (Conant et al., 2001; 2017).
In the scenarios, grassland improvement is applied on pasture areas and requires a minimum precipitation level and soil depth.

Assisted natural regeneration

Assisted natural regeneration (ANR) is a low-cost forest restoration method that can effectively restore forests on degraded lands and convert degraded vegetation into more productive forests by accelerating natural successional processes (FAO, 2011; Shono, Cadaweng and Durst, 2007). ANR techniques such as marking/tending areas of woody generation, suppressing weeds, and protecting land from disturbance, help to enhance the growth of secondary/semi-natural forest on deforested land, degraded grassland and shrub vegetation (FAO, 2019). In addition to protection efforts, new trees are planted when needed or wanted (e.g. enrichment planting). These techniques allow for the integration of various benefits such as timber production, biodiversity recovery, carbon sequestration and the cultivation of crops, fruit trees and non-timber forest products (Shono, Cadaweng and Durst, 2007).
In the scenarios, ANR is applied to a variety of land covers, excluding croplands, and is mostly limited in its potential area by precipitation levels.

Forest plantations (on degraded land)

Plantation forests are one form of planted forests — typically monocultures that are composed of trees established through planting and/or deliberate seeding (Freer-Smith et al., 2019). Plantation forests are established primarily for wood and fibre production, as well as to stabilise slopes and watersheds, and are usually intensively managed, with relatively high growth rates and productivity

(WOCAT, 2017). The establishment of forests on land with previously no forest is called afforestation, and the replanting of trees in an area where there was once a forest that has since been destroyed or damaged is known as reforestation.

Like natural forests, plantation forests can contribute to climate change mitigation and can act as a source of fuel and materials, and they currently provide about 33% of the world's roundwood (Freer-Smith et al., 2019). Important to note is the controversy that exists concerning the use of forest plantations. For example, some see plantations as part of the answer to the growing demand for timber and wood fibre (Brockerhoff et al., 2008; Buongiorno and Zhu, 2014). At the same time, plantations lessen the need to log natural forests, and can therefore inadvertently contribute to the conservation of forest biodiversity in natural forests (Pawson et al., 2013). However, forest plantations are also seen by some as homogenous ecosystems/monocultures that use a lot of water and likely support lower levels of biological diversity (Albert et al., 2021).

Plantation forests do not need to be problematic if planted and managed in ways that take into account environmental impacts, the balance of different ecosystem services and the full range of stakeholder views. If managed well, forest plantations have the potential to sustainably supply a substantial proportion of the goods and services required by society, and therefore allow other forest areas to be managed for conservation and protection objectives (Freer-Smith et al., 2019).

In the restoration scenarios, this measure is applied only to degraded areas not used for agriculture, therefore technically functioning as a restoration measure. Also, it is only applied in naturally occurring forest areas, and therefore not as afforestation. This is in line with the Bonn Challenge forest and landscape restoration approach and the Land Degradation Neutrality approach.

4.2.3 Safeguarding key ecosystems and their functions

In addition to restoration by specific measures and adapting land management practices, the longer term perspective of the baseline scenario reveals that safeguarding important functions of ecosystems and preventing their decline or degradation may be just as important. Protecting land from future conversion and degradation should focus on the areas that are most relevant to land condition and ecosystem functions. For the *Restoration & Protection* scenario, we identify the following key areas to be protected from conversion, based on the key ecosystem services of carbon storage, biodiversity, crop yields, livestock production, water availability and water regulation:

1. Important biodiversity areas: locations which are most critical for species and their habitats (Birdlife international 2019).
2. High-carbon forests: forest areas important for carbon storage and climate regulation
3. Peatlands: high-carbon wetlands important for carbon storage and water regulation
4. Water regulation: areas considered important for maintaining water availability and regulation in watersheds, functioning as 'sponges'
5. Riparian zones: important for preventing soil erosion and improving water regulation and purification
6. Slopes: areas vulnerable to erosion, also important for carbon storage and water regulation

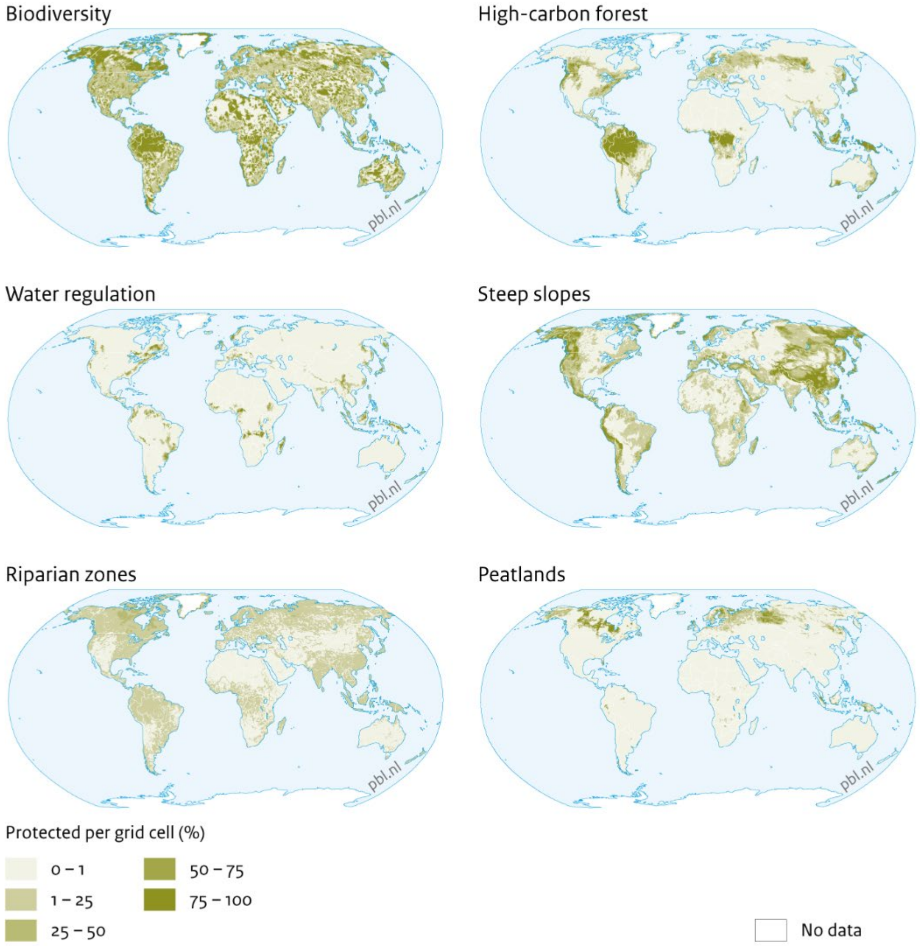
For each of these (also see Table 4.1), we defined locations and protection levels as shown in Figure 4.3.

Table 4.1
Overview of protection measures and their implementation levels as applied in the *Restoration & Protection* scenario

Type of protection	Implementation level
Biodiversity	30% of the land area, by ecoregion type, is assumed to be protected effectively
High-carbon forests	No conversion of forests with a vegetation carbon stock of 100 t/ha or more
Peatlands	No conversion of peatlands. Emissions continue from peatlands already converted or drained
Water regulation	Protection of areas with a relatively high contribution to water regulation (per water basin)
Riparian zones	Protection from future conversion of 300 metres around rivers and streams
Slopes	No expansion of agriculture on slopes steeper than 15° to avoid erosion

Figure 4.3

Safeguarding areas for biodiversity and key ecosystem functions, Restoration & Protection scenario



Source: PBL, Utrecht University

Important biodiversity areas
Conserving biological diversity is regarded as key to safeguarding the provision of ecosystem services. Current proposals for new targets under the CBD propose that the current conservation areas are expanded to 30% (Waldron et al., 2020). The biodiversity areas protected in the *Restoration & Protection* scenario cover 30% of terrestrial ecosystems (Kok et al., in prep.), including key biodiversity areas. These areas are excluded from future agricultural expansion. Protecting certain areas may redirect agricultural expansion to other locations, but is also considered to limit the net increase in agricultural area (Leclere et al., 2020). The combination with the other five categories of protected areas brings the total area protected above the 30% as the areas do not fully overlap.

High-carbon forests
Forests do not only store large amounts of carbon (46% of the terrestrial carbon stock; IPCC, 2000), but they also absorb almost 30% of anthropogenic CO_2 emissions (IPCC AR5) and play a vital role in climate regulation and water regulation). Furthermore, reducing emissions from deforestation and forest degradation is most effective in high-carbon forests. To reflect an ambitious level of forest protection, we use a recent detailed map of forest biomass (Avitabile et al., 2014) and a threshold of 100 Mg/ha carbon (Doelman et al., 2019), above which forest biomes are protected.

Peatlands
Peatlands are estimated to store about 640 GtC, which is 21% of the total soil organic carbon, while they cover just 3% of the global land area (Leifeld, 2018). Their conversion therefore makes a substantial contribution to anthropogenic greenhouse gas emissions (Leifeld and Menichetti, 2018). Considerable uncertainty exists in identifying global peatlands (Krankina et al., 2008), and the peatland area as applied here is based on Stoorvogel et al. (2017). This is in the upper range of peatland estimates and has a detailed representation of tropical peatlands (all historols are reclassified as peatlands) but does not include more recently discovered peatlands such as in the Congo Basin. In the *Restoration & Protection* scenario, it is assumed that all peatlands currently not converted are protected from conversion to agriculture. However, emissions from the deterioration of peatlands that were already under human use in 2015 continue, as no measures are included in the scenario that can halt these.

Water regulation
In all watersheds, upstream areas regulate water availability and influence extremes and the inter-annual variability of run-off in downstream areas. There is a specific role for these ‘water towers’, which are forested upland areas that contribute disproportionally to streamflow generation (UNEP, 2010), or mountainous regions identified as ‘mountain water towers’ (Immerzeel, 2019), though this follows a different definition. We apply the UNEP’s definition (UNEP, 2010) to identify water towers globally, which we exclude from future agricultural expansion.

Riparian zones
Although small in area, riparian zones are very important for water regulation and are excluded from further conversion. Based on rivers as represented in the HydroSheds GloRiC database (Dallaire et al., 2018), we applied a protection buffer of 300 metres around large/medium rivers and 150 metres around smaller rivers.

Slopes

Slopes are especially vulnerable to soil erosion. The *Restoration* scenario applies cross-slope barriers as a possible management measure to restore and prevent further degradation. As the suitability of steep slopes for agriculture is limited anyway, slopes above 15% in high income countries, and above 20% in all other countries, are excluded from agricultural use in the *Baseline* scenario. To take into account the vulnerability of moderate slopes, the *Restoration & Protection* scenario assumes that slopes above 15% are excluded from agricultural expansion globally. Sensitivity to erosion further depends on precipitation — especially precipitation intensity — and soil type, but these factors are not used to further specify where slopes are protected.

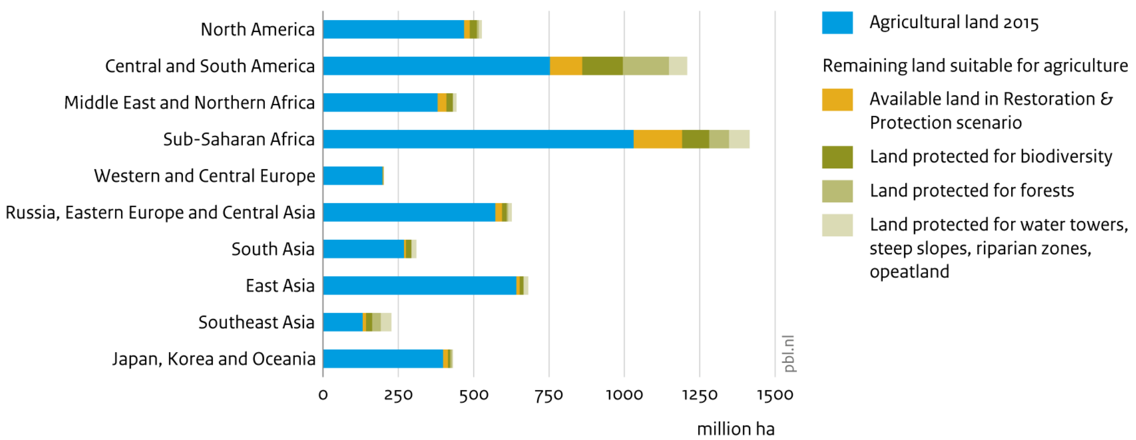
Overlap between areas protected from conversion

There is some overlap between the various protection measures. At the global scale, locations with one, two, three or four protection measures made up 64%, 28%, 6% and 4%, respectively, of the protected locations. About one third of the areas therefore shows some overlap.

The six categories of protected areas that are applied in the *Restoration & Protection* scenario severely limit where agriculture can expand in this scenario. However, demand for land-based products grows just as much as in the *Baseline* scenario, and the scenarios do not assume any changes in consumption patterns or improvements in production efficiencies. The consequence of the limited land availability in the *Restoration & Protection* scenario results in the expansion of agriculture into other areas than in the *Baseline* scenario, and in general lower agricultural expansion through increased land scarcity and higher land prices. The largest absolute reductions in land available for agricultural expansion occur though protecting biodiversity and high-carbon forests, in sub-Saharan Africa and Central and South America (Figure 4.4). The relative reduction is largest in Southeast Asia, South Asia and East Asia and leaves little remaining land, which was already very limited.

Figure 4.4

Agricultural land use and remaining suitable land in Restoration & Protection scenario



Source: PBL/IMAGE

4.3 Benefits of restoration and protection to land condition and ecosystem functions

This section presents the outcomes of the *Restoration* and the *Restoration & Protection* scenarios for land condition and ecosystem functions. The same indicators are used as in Chapter 3 for the *Baseline* scenario. This allows for a comparison of potential benefits of land restoration with the alternative in the absence of land restoration. The land condition indicators are land cover and land use (Section 4.3.1), soil organic carbon (Section 4.3.2) and biodiversity (Section 4.3.3). The ecosystem function indicators are agriculture and food (Section 4.3.4), water (Section 4.3.5) and carbon storage (Section 4.3.6).

4.3.1 Land-use change under the restoration scenarios

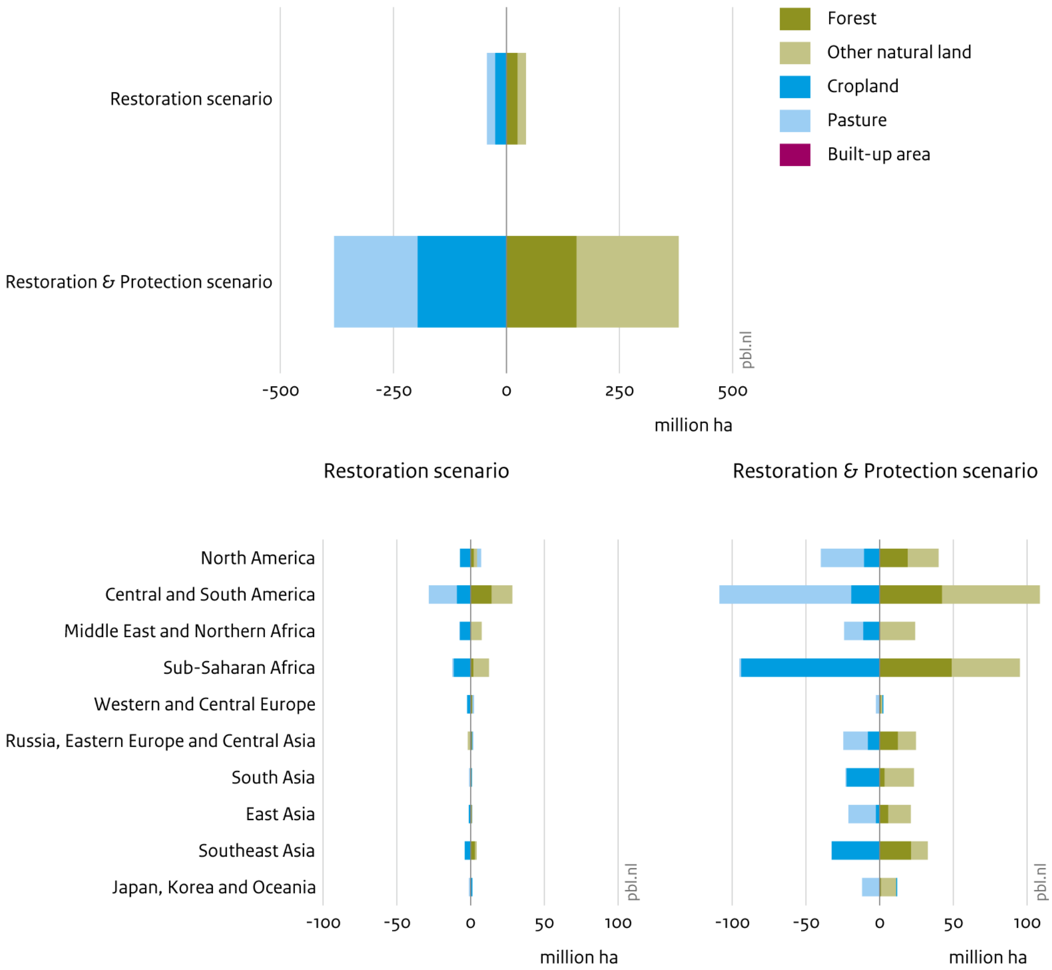
As a result of the restoration measures, agricultural yields are partly restored in the scenarios (Box 4.1). As a consequence, less land is needed for crops and livestock, and agricultural expansion in many regions is reduced compared to the baseline (Figure 4.5). This is most notable in sub-Saharan Africa and Central and South America. The initial benefit of yield increases as described in Box 4.1 might be expected to work through to a substantial benefit in reduced area demand (first-order effect). However, the agroeconomic model applied here makes it possible to include dynamic feedback in the system, and shows that the yield increase also leads to higher demand (second-order effect). In other words, the yield increase does not fully work through to a reduction in agricultural area, but also results in higher consumption (also see Stehfest et al., 2019).

In the *Restoration & Protection* scenario, a further reduction in land-use change takes place due to the protection of key conservation areas (Section 4.2.3). As a result, the global agricultural area in 2050 is almost 400 Mha less than in the baseline scenario (Figure 4.5). Compared to 2015 levels, the global agricultural area hardly increases in the *Restoration & Protection* scenario, avoiding much of the loss in natural land (Section 4.2, Figure 4.4). Prevention of land conversion occurs most notably in Central and South America and sub-Saharan Africa, but also in other regions. A small part of the protection does not just reduce future conversion, but also affects the location where the remaining expansion takes place. In sub-Saharan Africa, the region with the largest pressure on land systems, land conversion is reduced but agricultural land use increases after 2015 in both restoration scenarios. While the decrease in land conversion compared to the baseline is expected for most locations, some locations might also see an increase in conversion due to the large reduction in land availability elsewhere (Figure 4.5).

Figure 4.5

Land use compared to baseline scenario, 2050

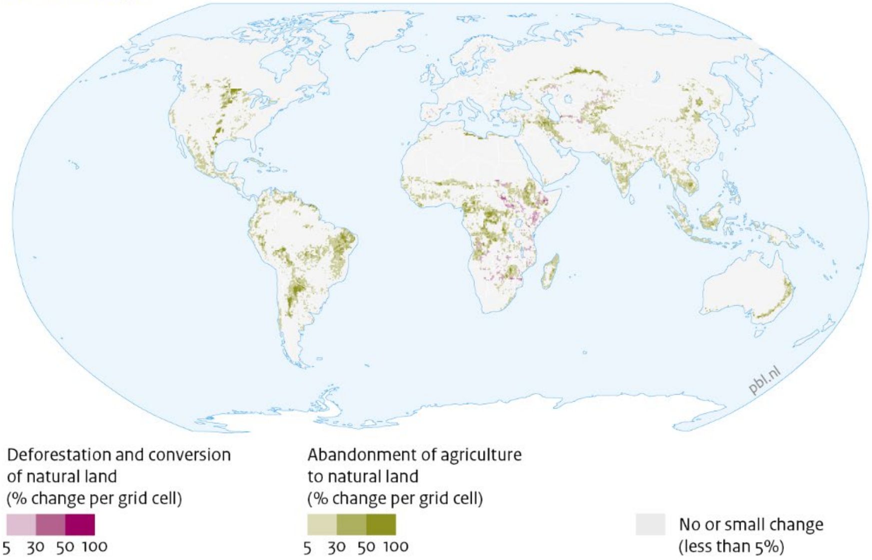
Global



Source: PBL/IMAGE

Figure 4.6

Land conversion under the Restoration & Protection scenario compared to the baseline scenario, 2050



Source: PBL

4.3.2 Soil organic carbon

Sufficient levels of soil organic carbon are key to both nutrient and water cycling, and can also be regarded as indicative of soil health in general. Soil organic carbon is one of the three indicators used to assess the extent of land degradation in SDG 15 and under the Land Degradation Neutrality goal of the UNCCD.

The effects on soil organic carbon under the restoration scenarios are, as with the baseline scenario, due to a combination of changes in land management and changes in land use. The effects of future climate change on soil organic carbon are not included here. The effect of changes in management is based on the restoration measures and their potential to increase soil organic carbon (Box 4.1 and Appendix A6). In areas where combinations of measures were possible, the measure was chosen with the highest effect on soil organic carbon restoration. A combination of measures (e.g. conservation agriculture and cross-slope barriers) is certainly possible in reality and might lead to a larger effect on soil restoration. The effect of land-use change is based on the conversion of natural areas to cropland or pasture, which reduces soil organic carbon. In such newly converted areas, the assumption is that the restoration measure with the most effect on soil organic carbon is used, as with land management, but in general this does not fully compensate for the loss due to land conversion.

Change in soil organic carbon can be expressed in the percentage increase in soil organic carbon, and in tonnes of carbon. For a global analysis, the percentage change is better suited to show how the change can affect the locally and regionally relevant ecosystem functions. For instance, in dry areas, the contribution to improved resilience to droughts and water regulation (e.g. through the higher water-holding capacity of soils) can be highly relevant, even when the carbon gains in tonnes are relatively modest. The change in tonnes of carbon shows larger changes in carbon-rich soils and lower changes in carbon-poor soils.

In percentage change, the largest gains in soil organic carbon under both restoration scenarios are projected in parts of South America, in West Africa and East Africa, and in various areas in Asia (Figure 4.8). In these areas, the restoration measures as applied in the scenarios can result in increases of 20% or more soil organic carbon than would be the case under the baseline scenario. Percentually smaller gains are projected in Europe and North America.

Compared to the *Baseline*, the *Restoration* and *Restoration & Protection* scenarios show an increase in soil organic carbon of 55 Gt and 56 Gt, respectively, by 2050 (Figure 4.7). This is a balance of positive and negative effects. Positive effects are the restoration measures restoring soils, preventing future loss in areas where measures are applied, and limiting future land-use change. Negative effects are continued loss of soil organic carbon in areas that are degrading but where no restoration measures are applied, and in areas where natural land is converted into cropland or pasture. In both restoration scenarios, the largest gains are projected in the regions of Russia, Eastern Europe and Central Asia and in Central and South America, while the highest prevented loss of soil organic carbon is in sub-Saharan Africa.

The share of prevented loss of soil organic carbon (Figure 4.7) underscores the importance of estimating the potential effect of land restoration compared to the situation in which no measures are taken, rather than with the current situation. When no restoration measures are implemented and land management systems remain the same, loss of soil organic carbon is expected to continue. The prevention of future losses should be taken into account when evaluating whether or not to implement land restoration measures.

The effects on soil organic carbon presented here have uncertainties, especially regarding the effects of restoration measures and the time needed for restoration. At least three factors could lead to an underestimate: (1) the soil organic carbon levels of undisturbed soils were applied as upper bounds to the increases, although increases beyond that level are physically possible with external inputs; (2) not all losses are included in the baseline (masked for instance by anthropogenic fertiliser use and specific processes like subsidence of peatlands; (3) multiple restoration measures may be applied in practice and lead to higher levels of soil organic carbon. The results may also be overestimated, for at least three reasons: (1) the assumption is made that there are no restoration measures in place at the start of the restoration scenarios, where in reality this is possible; for instance, there are long-existing areas of terracing in the world; (2) restoring soil organic carbon requires organic matter and this is in many areas also used for fuel or fodder; (3) to produce organic matter at high enough levels for restoration, it is likely that additions of nutrients are in many cases necessary, and this can be achieved through certain crops or fertiliser. An overall limitation to the estimate of current soil organic carbon levels is the very limited global data on land management.

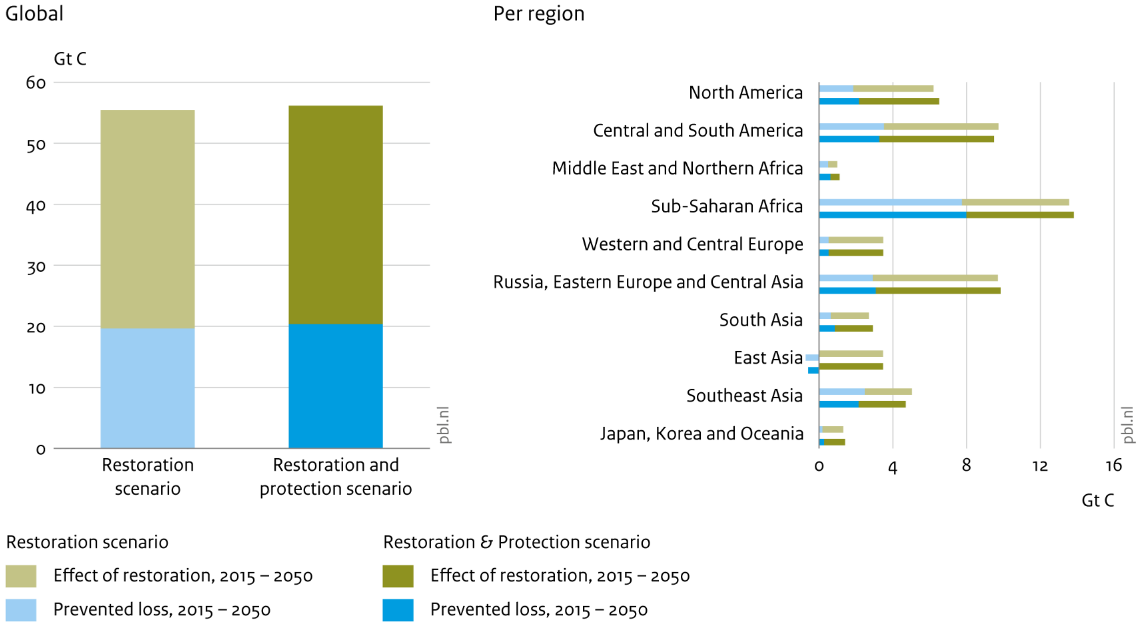
4.3.3 Biodiversity

Land restoration has the potential to improve biodiversity and prevent future loss. Chapter 2 highlighted the relevance of land restoration to the global goals and targets for biodiversity. Chapter 3 described the main pressures and driving factors causing biodiversity loss in the past, and under the baseline scenario projections.

Restoration can improve biodiversity in some locations and limit its loss in others, through a variety of effects. Habitats can be restored and supported by restoring degraded land or abandoned agricultural land and by adding trees and vegetation.

Figure 4.7

Change in soil organic carbon, compared to the baseline scenario

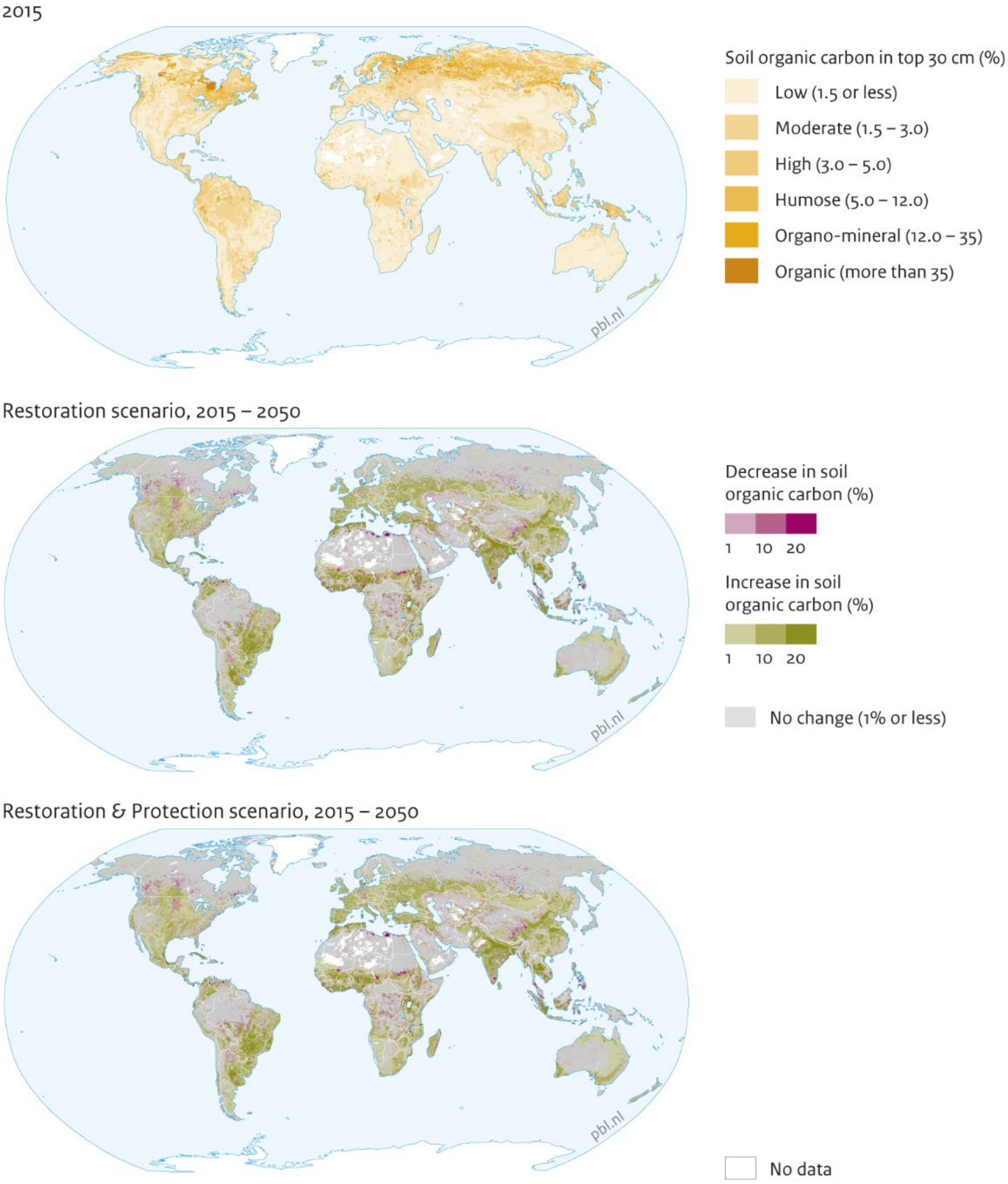


Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017

An indirect effect is that restoring the productivity of degraded agricultural lands reduces the need to convert additional natural areas to agriculture. Biodiversity in this report is assessed by the remaining natural area, and by the mean species abundance (MSA) indicator, the latter being a measure of the average population sizes of species relative to an undisturbed, natural state (Schipper et al., 2018; Alkemade et al., 2009).

The *Restoration* scenario and the *Restoration & Protection* scenario see an increase in natural area of 40 million hectares and 400 million hectares, respectively, compared to the *Baseline* in 2050 (Section 4.3.1 and Figure 4.5). This results in a natural area that is about 1% higher under the *Restoration* scenario and 5% higher under the *Restoration & Protection* scenario compared to the baseline in 2050. This is the result of a smaller agricultural area. Agricultural expansion is reduced because of the restoration of agricultural areas (in both restoration scenarios) and because of the limited room for agriculture to expand under the *Restoration & Protection* scenario. In addition, the use of agroforesty on large areas can contribute to gains in biodiversity (Jezeer et al., 2019), and some 1.4 billion hectares of natural areas are restored under both restoration scenarios through assisted natural regeneration and other measures. The *Restoration & Protection* scenario prevents key biodiversity areas from being converted for human use (Section 4.2). The largest effects can be seen in Southeast Asia and in Central and South America, both having over 10% more natural area under the *Restoration & Protection* scenario than under the *Baseline* scenario (Figure 4.5).

Figure 4.8
Change in soil organic carbon after restoration and protection, compared to 2015

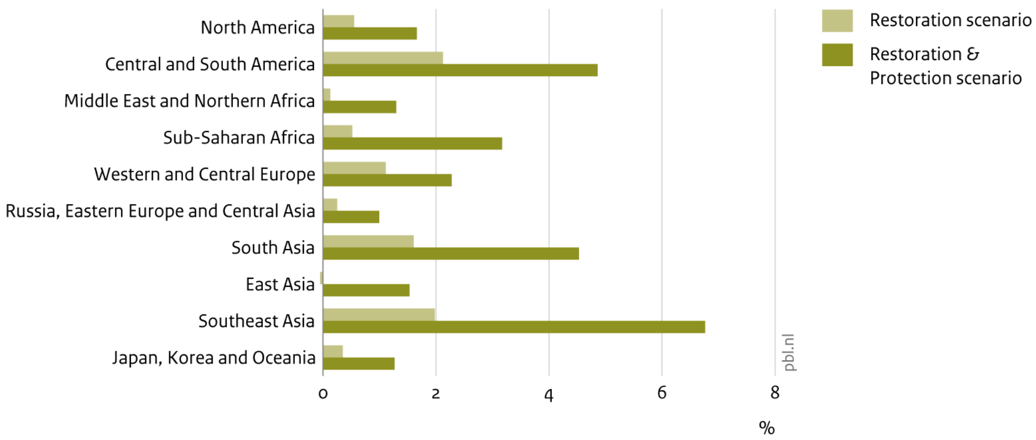


Source: PBL, Stoorvogel et al. 2017, WUR

In terms of mean species abundance, the scenarios lead to reduced losses, resulting in higher biodiversity by an improvement of 0.7% under the *Restoration* scenario and 2.4% under the *Restoration & Protection* scenario at the global level, compared to the baseline in 2050. This means that the measures in the scenarios prevent 11% and 37% of the loss in the baseline. The biggest gains are found in Southeast Asia and Central and South America (Figure 4.9). Small losses in some regions are the result of reduced pressure on land being counteracted by increases in other pressures, for instance more intensive production on rehabilitated croplands. The estimates for MSA include the effect of land-use change and agroforestry, but not the effect of the restoration of 1.4 billion hectares of natural areas.

The measures included in the *Restoration* scenario are limited in reducing the key pressures on biodiversity. Further gains for biodiversity could be achieved through a much more aggressive limitation of land use, for instance through production and consumption changes, as well as by limiting climate change and fertiliser use. On the other hand, measures to restore land, restore biomass and agricultural productivity and build up soils are likely to require additional inputs of fertiliser, at least in some areas, with the risk of additional pressures on biodiversity. This shows the importance of integrated solutions, where restoration is carried out in conjunction with protection, as well as measures in production and consumption chains (Ten Brink et al., 2010; Kok et al., in prep.).

Figure 4.9
Change in biodiversity, compared to the baseline scenario, 2050



Source: PBL/IMAGE/GLOBIO

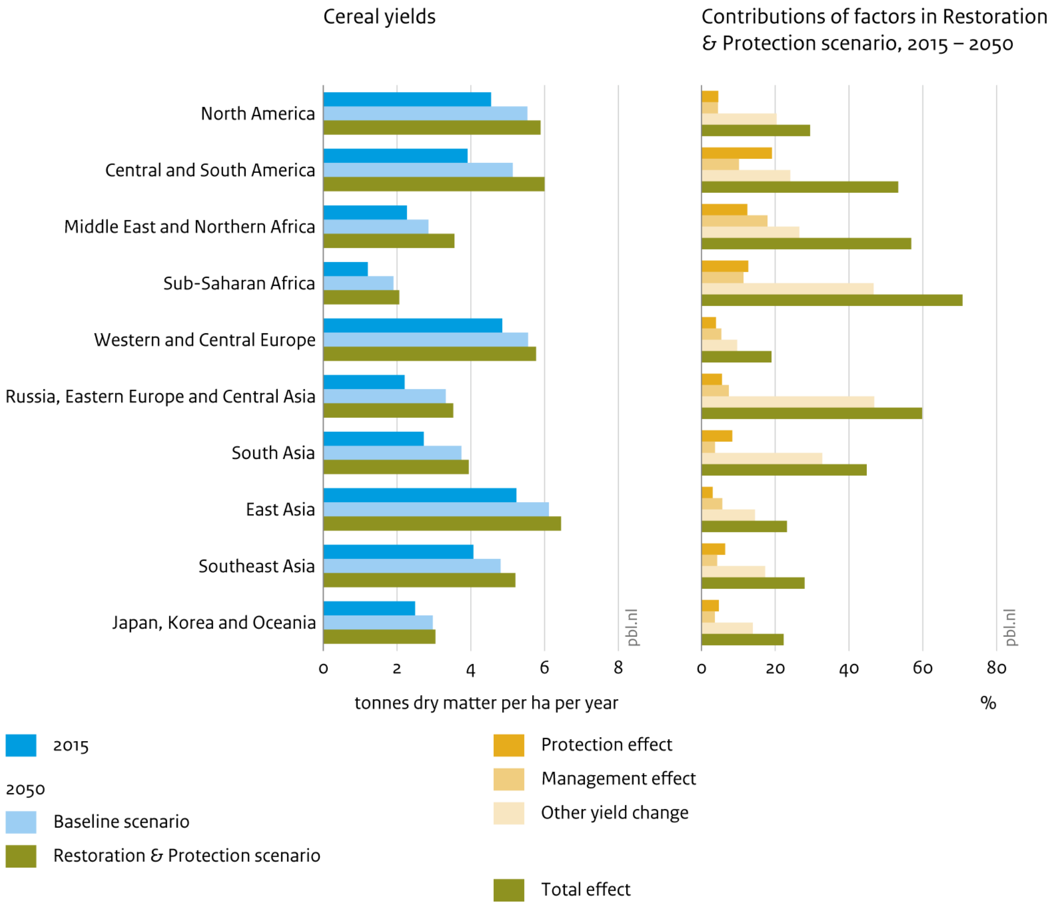
4.3.4 Agricultural yields and food security under the restoration scenarios

Crop yields

As described above, crop yields are restored and the negative effects of soil degradation on productivity are reversed through the restoration management in both restoration scenarios (Box 4.1 and Figure 4.2). Under the *Restoration & Protection* scenario, the protection of key areas and the resulting limited land supply and higher land prices also lead to higher yields, though through very different mechanisms. The restoration measures are applied in specific areas, come at zero cost in the scenarios, and thus lead to some price decreases and increased consumption (see below). The limited land availability, on the other hand, leads to an increase in prices and price-driven intensification. Yields under the *Restoration & Protection* scenario are above baseline levels in all regions (Figure 4.10, left). When trying to attribute yield changes under the *Restoration & Protection* scenario to the various underlying contributions (through partial scenarios, excluding one effect at a time), the technological progress of the baseline dominates. The yield increase due to restoration measures tends to be slightly smaller than the yield increase due to the protection of key areas; only in sub-Saharan Africa is the effect of the management measures larger (Figure 4.10, right).

Figure 4.10

Cereal yields and contribution of factors in Restoration & Protection scenario



Source: PBL/IMAGE

Figure 4.11

Meat produced per area of grassland, 2050

Source: PBL/IMAGE

Livestock

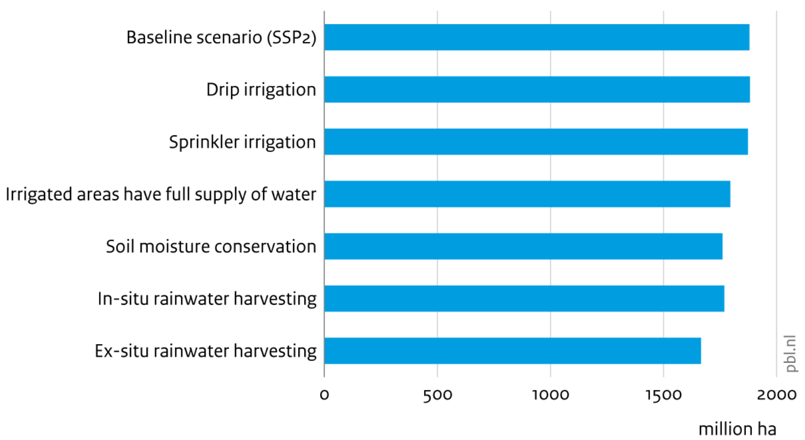
As described in Chapter 3 (Table 3.2), there are various degradation risks related to grazing livestock. Livestock husbandry can therefore play a central role in restoration, through the improved management of nutrients, livestock densities and grazing regimes. Under the restoration scenarios, grassland productivity, like crop productivity, is restored to initial levels as a result of the management measures (improved grazing, grassland management and silvopasture; see Section 4.2.2). Higher grass productivity allows the ruminant efficiency index — measured as the weight of produced meat per area of grassland (Figure 4.11) — to increase, and prevents the further degradation of soil functions.

Box 4.2 Potential of improved water management in rain-fed cropland areas

The improved management of rainwater and irrigation water can have a substantial impact on soil condition, water-holding capacity, soil organic carbon and crop yields. For rain-fed croplands, the measures to achieve this are broadly consistent with the conservation agriculture category as applied in the scenarios. We assessed a range of water-saving measures, presented by Jägermeyer et al. (2016), in terms of their potential to limit the area needed for agricultural production (Figure 4.12). As irrigation areas regularly face shortages in available water, higher yields and thus a reduced demand for cropland can be achieved by the hypothetical option of a full supply of irrigation water and by managing irrigation water more efficiently by implementing drip or sprinkler irrigation. With the improved management of rainwater, yield increases could save about 7% of cropland area through soil moisture conservation and in-situ rainwater harvesting, and 14% through ex-situ rainwater harvesting (as a first-order effect, excluding feedback on prices and consumption levels).

Figure 4.12

Reduction in cropland area due to yield increase from water management measures, 2050

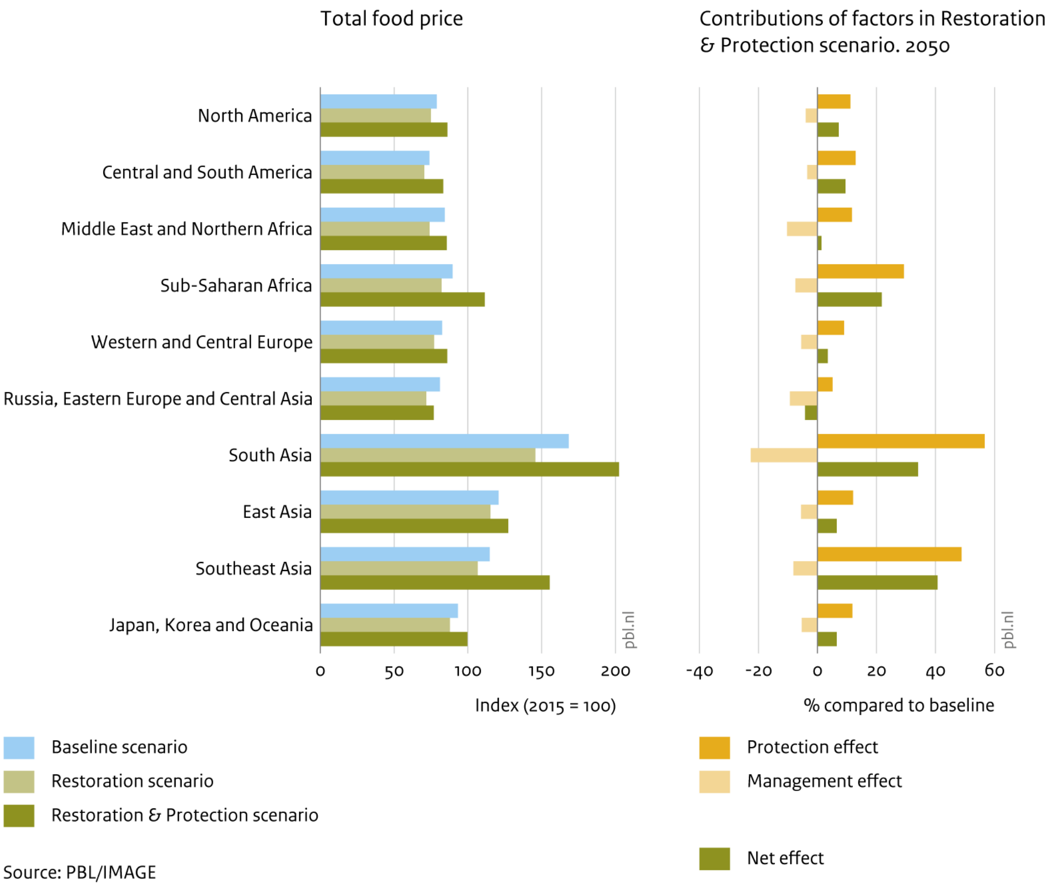


Source: PBL/IMAGE/LPJml

Food security

To evaluate how food consumption and food security may change under the restoration scenarios, we concentrate here on food prices. Under the baseline, the modelled food prices show a continued decline, as also observed historically. However, projecting food prices over long time horizons is very uncertain. To account for this uncertainty, the effects compared to the baseline can be explored (irrespective of whether the baseline shows an increase or decrease). The restoration measures and restored yields lead to higher productivity and a decline in food prices, and somewhat higher food consumption. While this effect is not described in literature for restoration, the general link between higher crop yields, declining prices and increasing consumption has been documented for various models (Stehfest et al., 2019), while empirical research shows that the land-sparing effect of intensification is complex (Rudel et al., 2009, Byerlee et al., 2014). In the *Restoration&Protection scenario*, on the other hand reduced land availability increases land scarcity and land prices, and therefore food prices, relative to the baseline (Figure 4.13). This relationship between reduced land availability and increasing food price is consistent with other modelling work (Kok et al., in prep.; Leclere et al., 2020). However, food security is a complex issue and goes beyond food prices. It is strongly context-specific, and various groups (farmers, smallholders, urban populations) will face different impacts through restoration and food prices. For example, the farm income of smallholders may actually benefit from rising food prices. Furthermore, all of this takes place in a situation of continuously declining food prices under the baseline in most regions (Figure 4.13).

Figure 4.13
Food prices and food price effects, 2050



Source: PBL/IMAGE

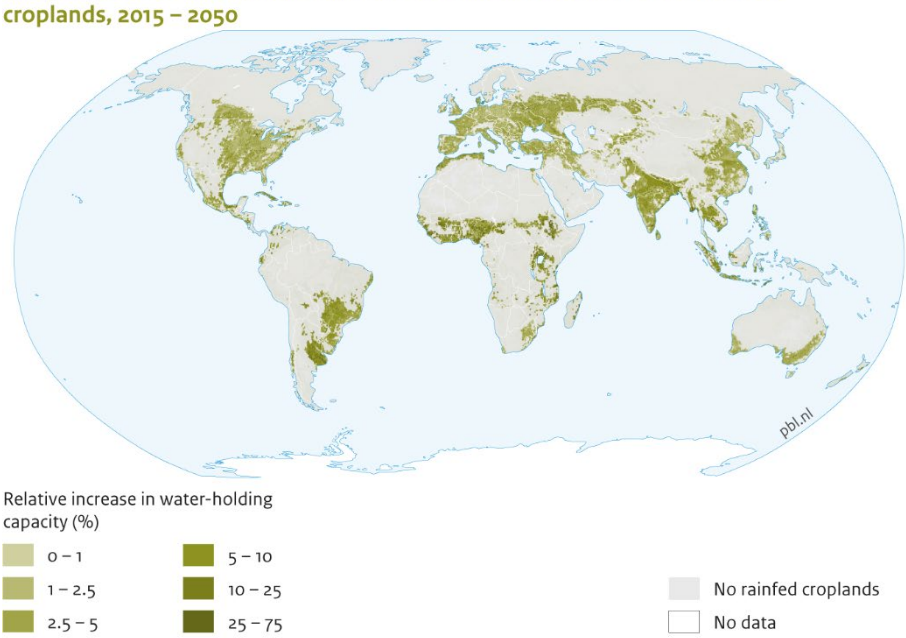
4.3.5 Water regulation

As discussed in Chapter 3, the water-holding capacity of soils is especially relevant to rain-fed agricultural production in arid areas, where the buffering capacity of soils can help plants to bridge dry spells. Low yields in semi-arid systems are often ascribed to excessive water evaporation from soils. In this case, higher levels of soil organic matter and the use of soil cover can improve productivity (Jägermeyer et al., 2016).

The restoration measures lead to improvements in the water-holding capacity of soils. Figure 4.14 shows the projected change in water-holding capacity as a consequence of the restoration measures when they are applied to the area of rain-fed croplands in 2015. The effect on the water-holding capacity of the additional land-use change projected in the scenarios is not included in this map. Under the restoration scenarios, the water-holding capacity improves most in parts of East and West Africa and in parts of South America, as well as in parts of South and Southeast Asia. This is also shown in Figure 4.15, where these regions show an average increase in water-holding capacity of 6% or more. This would allow plants and crops to cover longer dry spells, provided there has been precipitation to be held in the soils.

Figure 4.14

Change in water holding capacity under the Restoration scenario in rainfed croplands, 2015 – 2050

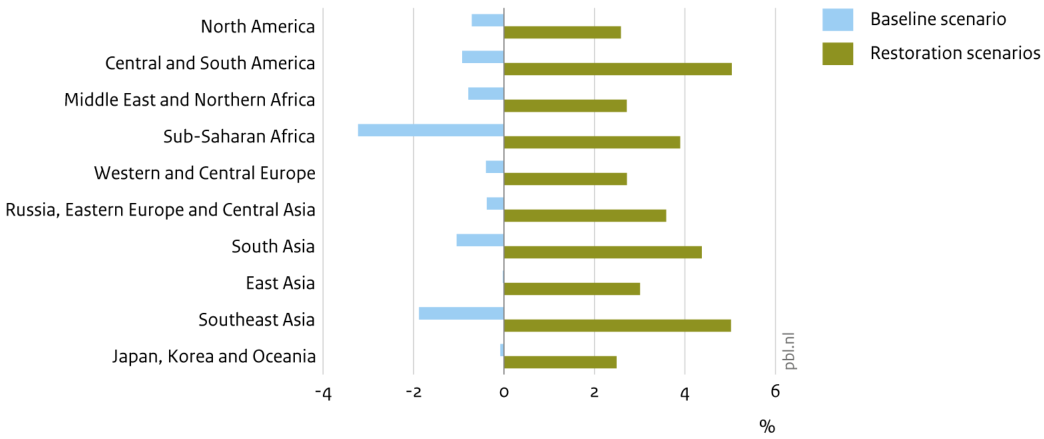


Source: PBL/IMAGE/GLOBIO, Utrecht University/PCR-GLOBWB

4.3.6 Carbon sinks and emissions

Land-use change, land degradation and climate change all affect the ability of soils and vegetation to store and sequester carbon. Soil organic carbon (SOC) increases under both restoration scenarios through restoration measures that increase soil carbon stocks and prevent loss in degrading areas, and through prevented loss from reduced agricultural expansion (Section 4.3.2). Vegetation carbon also benefits from reduced agricultural expansion and from increases in vegetation due to restoration measures such as agroforestry and assisted natural regeneration.

Figure 4.15
Change in water-holding capacity for rainfed croplands, 2015 – 2050



Source: PBL/IMAGE/GLOBIO, Utrecht University/PCR-GLOBWB

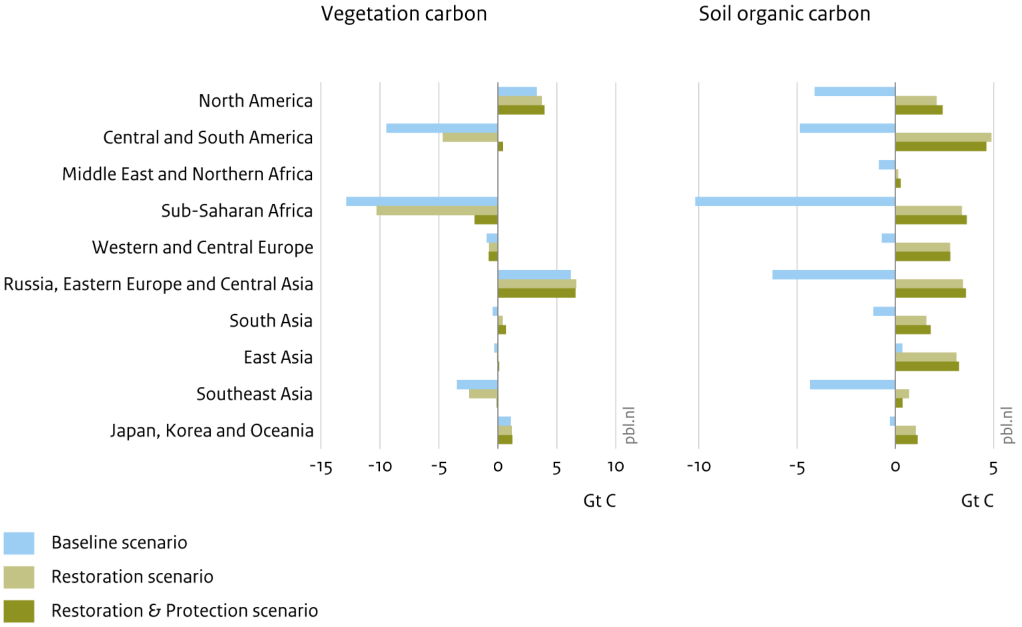
Vegetation carbon is projected to decline under the *Baseline* by about 17 GtC between 2015 and 2050, but to increase by about 3 GtC under the *Restoration & Protection* scenario (Figure 4.16). Part of this gain comes from restoration measures (4 GtC), and there is a benefit of 16 GtC through the protection of key ecosystems in the *Restoration & Protection* scenario. This benefit is highly heterogenous across regions, following the differences in land use in the various scenarios (Section 4.3.1).

The gain in SOC under the *Restoration & Protection* scenario is about 56 GtC compared to the *Baseline* in 2050 (Figures 4.16 and 4.7). Under the *Restoration* scenario, SOC is 55 GtC higher compared to the baseline. The main contributor to this difference between the baseline and the restoration scenarios is the restoration measures, as these operate over extensive areas (Section 4.2.2).

The areas in which agroforestry can be applied and where the yield gap is large enough not to hamper agricultural production (Section 4.2.2) amount to about 450 Mha of cropland globally, and about 220 Mha of silvopasture. This will result in a potential carbon storage in agroforestry systems of 7 GtC by 2050. The recent literature shows that the global potential for prevention of soil carbon loss and carbon sequestration in soils is uncertain, with a range of 0.1 to 1.8 GtC/yr for cropland, and 0.1 to 0.7 GtC/yr for pasture (Roe et al., 2019). Our estimate, annualised over 35 years to 1.6 GtC/yr for cropland and pasture together, is in line with the upper end of the range in the literature. For agroforestry, our value (0.2 GtC/yr) is at the lower end of the wide range in the literature of 0.1 to 1.5 GtC/yr (Roe et al., 2019).

The potential contribution of land to climate mitigation has been discussed extensively (Roe et al., 2019), also with the notion that these benefits are temporary and should not distract from the need to decarbonise the economy (Friedlingstein et al., 2019). We show here that a focus on restoration could create a carbon sink of 64 GtC up to 2050 compared to 2015, in vegetation (including agroforestry) and soils. With current global emissions at 11 GtC/yr (IPCC SR1p5), this can make a substantial contribution to meeting climate ambitions and buying time for the energy system transformation.

Figure 4.16
Changes in carbon stocks in vegetation and soil, 2015 – 2050



Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017

4.4 Multiple benefits and regional relevance of restoration and protection

4.4.1 Global overview of the multiple benefits of land restoration

Restoration and protection provide multiple benefits globally

When compared to the *Baseline* scenario, both the *Restoration* scenario and the *Restoration & Protection* scenario show benefits across all indicators in 2050. Figure 4.17 shows the results for six indicators at the global level. These indicators were discussed in detail in Section 4.3 and their results are summarised in an overview here. Figure 4.17 presents, first, the changes under the baseline scenario and the two restoration scenarios compared to 2015, as a percentage for each indicator, and, secondly, the change under the two restoration scenarios compared to the baseline situation in 2050.

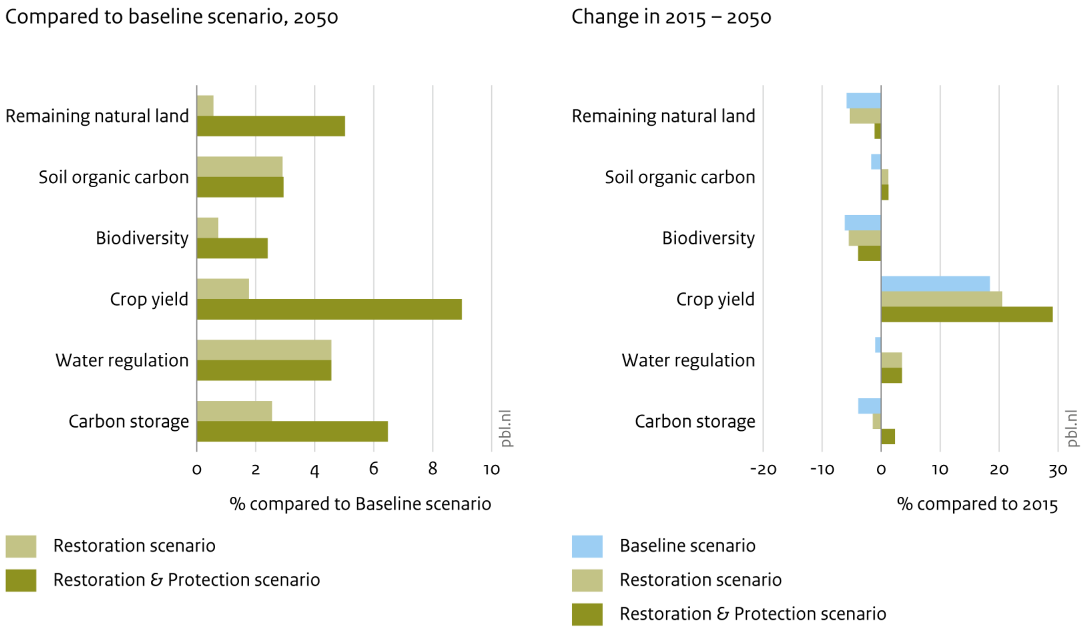
Remaining natural land and soil organic carbon are key indicators for Land Degradation Neutrality, including SDG 15, and for biodiversity. In all scenarios, the area of remaining natural land declines up to 2050, but the loss is very small under the *Restoration & Protection* scenario, where there is 5% more natural land in 2050 than under the *Baseline* scenario. Soil organic carbon, measured in Gt, declines under the baseline scenario but increases under both restoration scenarios. There is some 3% more soil organic carbon by 2050 under both restoration scenarios than there is under the baseline in 2050. Biodiversity as expressed in MSA (Section 4.3) is projected to decline under the baseline and under both restoration scenarios. The restoration scenarios however limit this loss, by 11% under the *Restoration* scenario and by 37% under the *Restoration & Protection* scenario (Section 4.3). Biodiversity (in MSA) is therefore 0.7% and 2.4% higher in 2050 under the two restoration scenarios compared to the baseline.

Crop yields are projected to increase, as croplands that saw long-term declining trends in primary productivity under the baseline scenario are restored. This cropland restoration leads to a small increase in average global crop yields of close to 2% compared to the average yields in 2050 under both restoration scenarios. The additional increase in yields to 9% under the *Restoration & Protection* scenario is not a benefit of restoration but a consequence of limited land availability due to the large areas protected, and would present an additional challenge to achieve. Water regulation, as measured in change in the water-holding capacity for rain-fed cropland, increases globally by some 4% compared to the baseline situation in 2050, due to the restoration measures. This measure is the same for both restoration scenarios as it is only calculated for cropland in 2015 and not for the cropland expansion in the baseline and restoration scenarios.

Carbon storage in soils and vegetation combined increases by 1% under the *Restoration* scenario and by 5% under the *Restoration & Protection* scenario compared to the *Baseline* in 2050. Overall, carbon storage still declines under the *Restoration* scenario, as the effect of restoration on soil carbon and vegetation does not compensate for the loss due to land-use change for agriculture. As agriculture expansion is much more limited under the *Restoration & Protection* scenario, global carbon storage increases compared to 2015.

Figure 4.17

Global effect of Restoration scenarios on land condition and ecosystem functions



Crop yield increases under the Restoration & Protection scenario beyond the impact of the Restoration scenario are caused by the additional protection of areas constraining agricultural expansion. Therefore, this additional increase in yields is a requirement in this scenario, not a benefit of restoration.

Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017, Utrecht University

4.4.2 Overview of regional benefits of land restoration and protection

The global averages provided in the previous section mask significant regional differences in the benefits of restoration and protection measures. Central and South America, sub-Saharan Africa, South Asia and Southeast Asia see, overall, larger potential benefits of land restoration than the other regions (Figure 4.18). These benefits are shown as a percentage increase in the indicators under the restoration scenarios by 2050 compared to the situation for that region under the baseline scenario in 2050. They therefore show the relative contribution that land restoration can make to improving these indicators compared to the situation where no restoration measures are implemented in the regions.

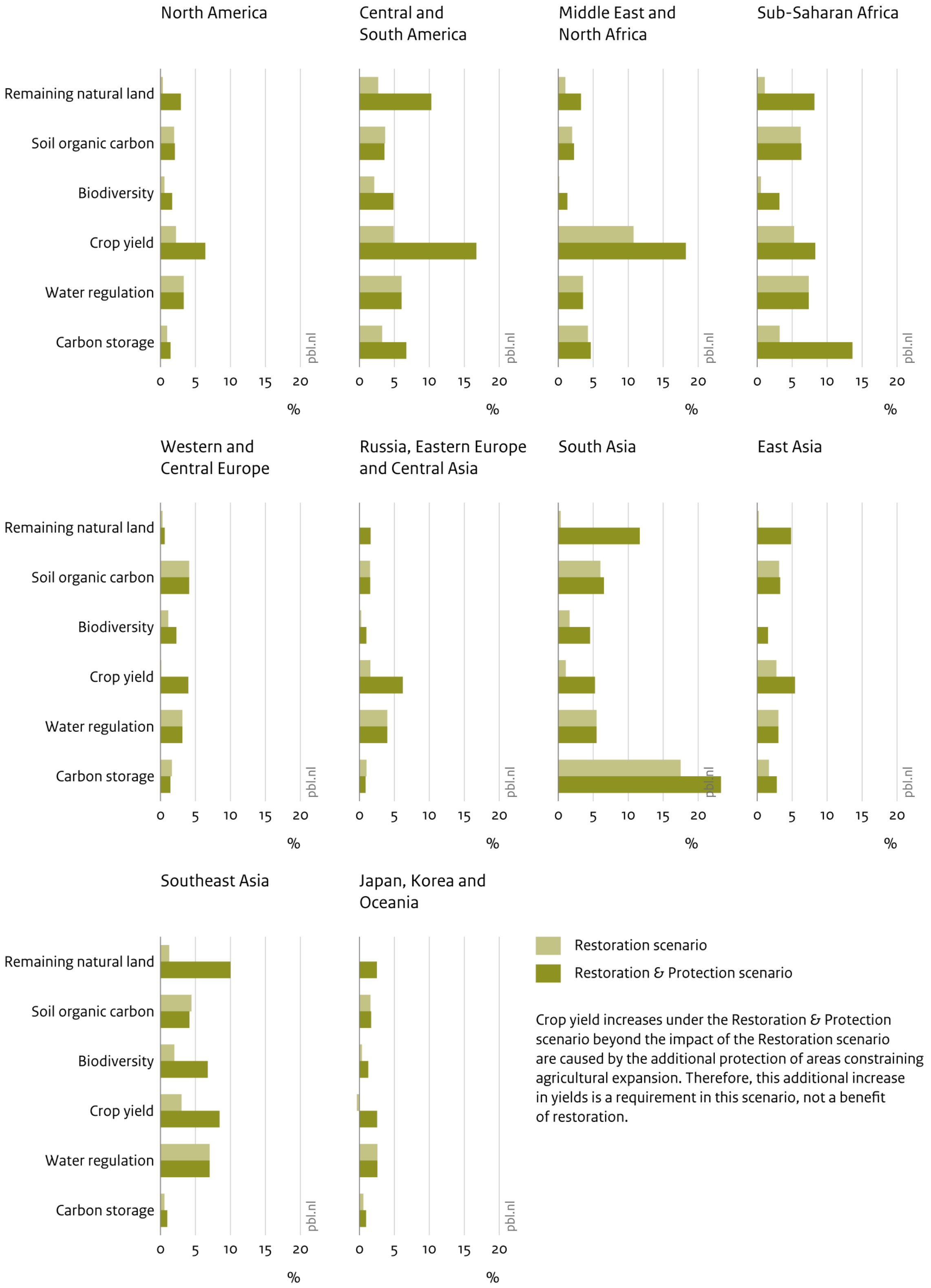
4.4.3 What part of the land restoration potential is covered by the current national commitments?

Chapter 2 described the current commitments made by countries in various national plans under the UNCCD, CBD and UNFCCC and in the Bonn Challenge. Figure 4.19 compares these commitments to the area that is assumed to be restored under the restoration scenarios. Most of the current national commitments have the objective to be implemented by 2030, meaning that restoration should be in progress by then. The area that is restored under the restoration scenarios is assumed to be restored over a longer period, between 2015 and 2050. The area restored under the restoration scenarios is also an estimate of the potential area for land restoration. Comparing the commitments to this potential area provides an estimate of the share of the potential restoration area that is covered by current commitments.

Globally, the national commitments cover about one billion hectares, while the estimated potential in the restoration scenarios is 5.2 billion hectares (Section 4.2 and the sum of the regional areas in Figure 4.19). About one fifth of the global potential is therefore covered by current national commitments. The restoration commitments in sub-Saharan Africa cover almost half of the potential in the region. As shown in the baseline scenario (Chapter 3), sub-Saharan Africa is one of the regions with the largest share of land showing negative trends in primary productivity trends caused by land management, and it is the region that is projected to have the highest land-use change up to 2050 (Figure 3.4). These commitments therefore appear to be focused on the right place. The other regions show much lower coverage of the current commitments relative to the potential restoration area, indicating that significant increases in restoration plans are required to achieve the projected benefits under the restoration scenarios.

Figure 4.18

Effect of Restoration scenarios on land condition and ecosystem functions, compared to the baseline scenario, 2050

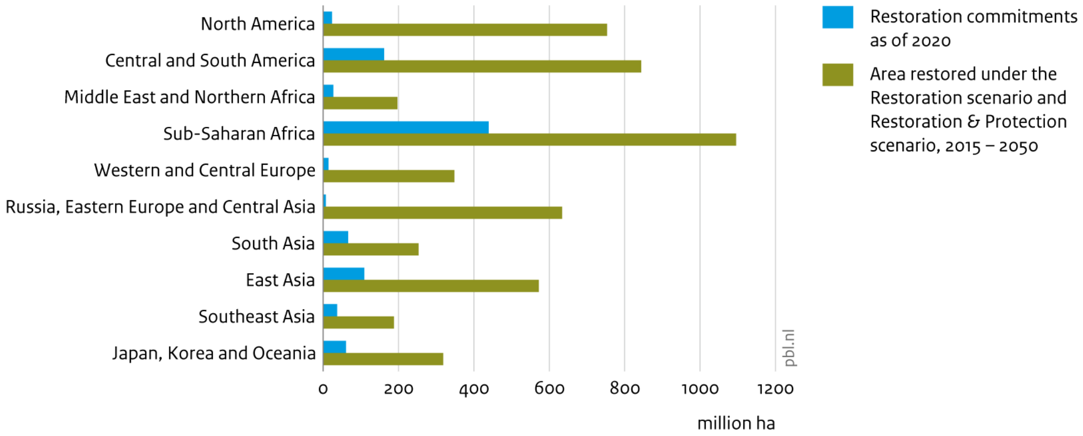


Crop yield increases under the Restoration & Protection scenario beyond the impact of the Restoration scenario are caused by the additional protection of areas constraining agricultural expansion. Therefore, this additional increase in yields is a requirement in this scenario, not a benefit of restoration.

Source: PBL/IMAGE/GLOBIO, Stoorvogel et al. 2017, Utrecht University

Figure 4.19

Restoration commitments compared to areas restored under the Restoration scenarios



Source: UNCCD, UNFCCC, CBD, Bonn Challenge; collected and adapted by PBL for the Global Restoration Commitments database, August 2020

4.4.4 An integrated set of measures is needed to achieve global sustainability goals

While substantial benefits can be achieved through the restoration and protection measures analysed here, the contributions to goals such as biodiversity conservation are relatively modest at the global level but become larger at the level of some regions (Section 4.4.2). At the local level, restoration can make a substantial impact. The reason for this scale effect is that restoration is site-specific and cannot be carried out everywhere, leading to a dilution of the effect when measured at the global and regional scales. At the same time, the fact that restoration has the capacity to deliver improvements across a range of indicators makes the combined potential benefits of land restoration significant.

Land restoration and the protection of areas that are of key importance to certain ecosystem functions can contribute to global sustainability goals. In the case of the *Restoration & Protection* scenario, the upward pressure on food prices, and possibly food security, indicate that additional changes in consumption patterns and supply chains are essential to reduce pressure on land, ecosystem functions and biodiversity. These demand-side measures are not included in these scenarios, as the scenarios were designed to focus on direct restoration measures. However, they have been analysed in detail in other publications (Ten Brink, 2010; Van Vuuren et al., 2015; Leclere et al., 2020; Kok et al., 2020).

5 From commitments to implementation of restoration and improved land management

The wide-scale implementation of land restoration and sustainable land management (SLM) techniques depends to a large degree on the benefits that these techniques provide to land users and landowners. This chapter therefore considers the benefits and costs of these techniques in closer detail and discusses key policies that could provide a further incentive to adopt restoration and improved land management.

5.1 From goals and commitments to implementation

Too few insights exist on translating national policy goal-setting into effective policies and projects.

As outlined by the Assessment Report on Land Degradation and Restoration by IPBES (2018), restoration activities can deliver multiple benefits, including improved food security and reduced poverty. However, promising interventions such as agroforestry often fail to deliver at scale, and other interventions such as conservation agriculture are still subject to dispute on whether income gains are possible under farmer-managed conditions. More importantly, the state of knowledge on the impact of land restoration is predominantly based on case studies. Many questions on the precise costs and benefits, for landowners and land users in particular, therefore remain unanswered. At the onset of the Decade on Ecosystem Restoration, such knowledge is imperative, and will be the focus of this chapter. How can we move from goal articulation to measures that actually make an impact? What is needed to move swiftly from goal setting to sustainably managed land? What techniques work under which conditions and where, and how can project results be sustained or scaled up?

Changes in land management practices are governed by incentives and shaped by costs, benefits and institutional arrangements.

Land restoration and sustainable land management techniques are adopted if the landowner or land user perceives their net benefits to be superior to alternative current practices. There are two elements that dictate the adoption decision. The first is the direct costs and benefits: do the gains in benefits, or the reductions in costs, result in net benefits? The second element is the institutional and policy framework that shapes the incentives, including arrangements of tenure as well as culture and traditions. Existing or new policies and governance structures may influence the decision to adopt alternative practices or to stick with existing ones.

In Section 5.2, the benefits of restoration and sustainable land management measures to land users are assessed, with a focus on agricultural measures. This section discusses the evidence of where and when projects that promote sustainable land management measures deliver notable changes in household income, consumption or food security.

Section 5.3 presents estimates of the costs of implementing restoration and sustainable land management measures. This section shows how the costs of such projects vary across types of restoration and countries, and presents cost estimates of the current restoration commitments by countries.

Section 5.4 considers the complementary policies and governance strategies that are most conducive to achieving land restoration and sustainable land management. It describes ways in which the current sectoral policies (agriculture, forestry, environment) can incentivise land restoration measures, including price support and organisation of knowledge exchange; it highlights key elements in national policies and governance structures that may alter incentives, notably the way in which land tenure is organised; and it briefly considers other sectors that may impact incentives, including the infrastructure and energy sectors.

5.2 Socio-economic impacts and benefits of improved land management

5.2.1 Building a better understanding of the benefits

Many governments and NGOs seek to promote improvements in cropping practices and land conservation interventions[7], with the aim to improve the productive capacity of land, or at least to prevent its further deterioration, as well as to boost production and income.

An array of practices is promoted, including agroforestry, conservation agriculture, physical soil and water conservation and integrated nutrient management, including the uptake of different types of fertiliser. Often, these agricultural practices are called sustainable land management (SLM) techniques. Some of these practices have a long history, and were promoted as early as colonial times (Wolmer and Scoones, 2000).

Many of these interventions are based on a clear and plausible theory of change, but the empirical base for such claims is often less clear.

Improved land management is viewed as the key for unlocking multiple benefits to land users, including better soil quality, higher agricultural productivity and higher incomes. In practice, however, SLM techniques may or may not improve labour productivity, depending on labour requirements, wages, market prices and the institutional setting in which interventions take place (Boserup, 1965).

Many of the studies that document positive impacts of land restoration or SLM are based on case studies, and it remains unclear when and where impacts, for example on household incomes, can be generalised.

[7] The terms 'land restoration' and 'sustainable land management' (SLM) are partially overlapping categories that are sometimes used interchangeably. SLM is more often used to describe a set of agricultural practices that aims to improve on-farm soil conditions. These practices, the focus of Section 5.2, include agroforestry, conservation agriculture and integrated soil fertility and nutrient management.

The large commitments by countries make it necessary for policymakers to understand the pathways and size of effects of land restoration measures.

This section provides an overview of the evidence from impact assessments on SLM-related interventions in agriculture. The results are based on a systematic review that collates an evidence base of SLM-related interventions, the impact of which is assessed using statistical methods. Studies are screened for the correct use of such methods, to distinguish causal effects from correlations. This prevents, for instance, the erroneous interpretation of the large income of a wealthy smallholder who has adopted SLM techniques as a causal outcome of the adoption decision. The studies selected assessed the impact of adopting land restoration or SLM techniques compared to the situation in which these techniques were not adopted. In addition, studies were sought that documented the impact on a range of indicators beyond crop productivity, including livelihood indicators such as change in income, food security or poverty. The full details are provided in Malan et al. (in prep.), while the next section briefly considers the methodology before highlighting the key findings and conclusions.

At present, there is no firm evidence to support the claim that restoration and sustainable land-use interventions have a net positive impact on households.

This conclusion draws on four specific arguments outlined in the sections below: (1) the evidence base is very small with considerable diversity in findings, including many null results; (2) methodological problems remain for many studies in the evidence base; (3) only a few studies have indicators for household income, food security or poverty; and (4) it was not possible to correct for publication bias.

The small evidence base in this study is similar to that of other reviews of agriculture-based interventions (Lawry, 2016; Higgins, 2018; Waddington, 2014), but in sharp contrast to some other development policy interventions, such as interventions to improve nutrition (e.g. Das et al., 2013).

Absence of evidence of impact does not mean that there is no impact.

There is simply too little information available to make generalised statements on a possible impact and its magnitude across various environments and institutional settings. A much greater effort is required to produce good quality impact assessments of land restoration programmes that focus, beyond the adoption of a technology, on the resulting impact on households. Addressing this knowledge gap is essential at the onset of the Decade on Ecosystem Restoration, and is a prerequisite for increasing the effectiveness of decision-making and policymaking in the coming years.

5.2.2 The evidence base

The systematic review underlying the results presented in this section is based on an extensive literature search in eight major bibliographic databases, which yielded an initial 3,785 publications (Malan et al., in prep.). The search focused on four specific types of SLM techniques: (1) conservation agriculture, (2) agroforestry, (3) integrated soil fertility management (ISFM), and (4) soil and water conservation structures. This set of publications was then screened, leaving 29 relevant studies of sound methodological quality. See Malan et al. (in prep.) for the methodology, the evidence gap map and the geographical spread of the studies.

A detailed meta-analysis proved impossible due to methodological limitations and unclear reporting in various studies in the database.
Therefore, instead of estimating scores for the impact of the measures on households, the key quantitative evidence in each study was described and, where available, evidence of the extension methods used was presented.

The evidence base provides a set of key observations:

- Most studies concerned integrated soil fertility management (ISFM), and more specifically the promotion of inorganic fertiliser. Notably fewer studies focused on conservation agriculture or soil and water conservation, and very few on agroforestry. This finding is surprising, especially since the promotion of these practices has been common in recent decades.
- Very few studies assessed the impact on total household income, food security or poverty, despite the dominant narrative that SLM techniques impact such household indicators. Most outcome indicators in the studies were for crop yields, income from a selected crop or an aggregate measure of farm income. This ignores potential trade-off effects on other components of household income.
- There is a lack of good quality studies, despite the emphasis on searching for and selecting studies that use sound statistical methods. Many of the selected publications still had clear methodological problems. These cast doubt on the findings of several of the studies, making it impossible to establish whether the impacts found were truly attributable to the restoration programmes or whether they merely captured correlations between pre-existing variables.
- Language and publication bias may have influenced the outcomes. Nearly all of the studies selected described interventions in English-speaking countries in sub-Saharan Africa. This probably reflects a selection bias due to searching databases that list publications in English-language journals, and due to English-speaking researchers favouring those countries. Publication bias can result from neutral or negative outcomes not being published; however, several studies in the selection did show neutral or negative results.

5.2.3 What does the evidence base tell us about the impact of SLM practices on household incomes?

Far too few studies exist to firmly assess the impact of land restoration on household incomes. This is a key knowledge gap to be addressed, particularly at the onset of an expected increase in restoration and SLM projects.
The key purpose of this review was to study the impact of land restoration on household indicators for income, consumption or poverty. The rationale was to move away from purely farm-level indicators (e.g. crop yield or production), as household-level indicators are likely to present a more accurate picture of the overall equilibrium effects in households; for instance, after adjusting labour input across on-farm and off-farm activities. It is sobering that only four studies did this, assessing six intervention–outcome combinations for full income, poverty or food security, while the vast majority of studies selected a focus on the impact on crop yields or total crop production. Though this is still informative — as long as the impact assessment is unbiased — it is clearly less informative than anticipated. It is clear that a greater understanding of the impact of land restoration practices on households is imperative (does it increase incomes or reduce poverty, and by how much?).

The 29 relevant studies assessed the impact of 35 intervention–outcome combinations. A positive effect was found for 23 of these combinations.

The studies present a broad range of impact findings for various restoration approaches, making it difficult to compare outcomes. This is further compounded by the small size of the evidence base and the limitation of computing a normalised impact score. The studies display a broad range of impacts found, from very high effects, to moderate effects, to no effects. Table 5.1 provides an overview of the frequency with which studies find null results or positive results. For instance, Arslan et al. (2017) found increases of 22% to 42% in crop yields (from a mean of 1,593 kg/ha) for soil and water conservation combined with inorganic fertiliser promotion in Tanzania. On the other hand, Abdulai and Huffman (2014) found an increase of 16% in net farm returns in Ghana due to soil and water conservation adoption (without fertiliser promotion), from a mean of GHS 205 (i.e. USD 35) per hectare. As discussed below, a considerable number of the studies found no impact whatsoever.

The diversity in findings makes it difficult to make comparisons. First of all, the findings represent insights from a wide range of practices in diverse settings. The diversity in impact found strongly suggests that practices do not raise incomes universally, but that they may need careful targeting. Secondly, absolute numbers cannot be compared easily. The findings by Arslan et al. (2017) and by Abdulai and Huffman (2014) are a case in point. The data from Arslan et al. (2017) suggest potentially large increases in mean crop yield. Indeed, these are statistically significant, meaning that they deviate from the normal variation (standard deviation) significantly. However, whether the deviation is relatively larger than for instance the effect observed by Abdulai and Hofman (2014) is unclear (after all, variation in crop yields in the former study from Tanzania could have been larger to begin with). Either way, it is not possible to investigate such issues in closer detail.

No impact of the restoration intervention was observed for 11 indicators assessed in the studies.

Many of the studies found no significant impact of the restoration intervention on the selected indicators. This applies in particular to the studies that investigated the impact on household (not farm-level) indicators. For instance, Wainaina et al. (2018) found no significant impact of soil conservation on household income in Kenya, and Faltermeier and Abdulai (2009) found no significant impact of water conservation on net farm income in Ghana. Wainaina et al. (2018) did, however, find a positive effect of the use of manure (ISFM). Ragasa and Mazunda (2018) considered a range of ISFM activities, but found no impact on food security. One exception is the study by Abdulai (2016), which observed a reduction in poverty due to the adoption of conservation agriculture. Conversely, more studies reported positive impacts when considering on-farm impacts (e.g. Biggeri et al., 2018; deGraft-Johnson et al., 2014).

One hypothesis to explain this finding is that, while restoration practices may increase on-farm productivity, the overall effect on households (when corrected for effects such as changes in labour allocation) may be negligible. Adopting an SLM technique may increase labour demands and therefore induce farmers to shift labour away from other income-generating practices, either on-farm or off-farm. This could lead to a negligible net change in income or even a negative change, at least in the short term. A similar effect (of no discernible change in net income) was seen for other agricultural technologies (e.g. Takahashi and Barrett, 2013), despite increases in crop yields.

Table 5.1
Frequency of studies showing negative impact, no impact or positive impact

	Outcome	Negative impact	No impact	Positive impact
Soil and water conservation	Partial farm			3
Soil and water conservation	Full farm	1	2	3
Soil and water conservation	Full household		1	
Soil and water conservation	Food security			
Soil and water conservation	Poverty			
Integrated soil fertility management	Partial farm		4	10
Integrated soil fertility management	Full farm		1	1
Integrated soil fertility management	Full household			1
Integrated soil fertility management	Food security		1	
Integrated soil fertility management	Poverty			
Conservation agriculture	Partial farm			4
Conservation agriculture	Full farm			
Conservation agriculture	Full household		2	
Conservation agriculture	Food security			
Conservation agriculture	Poverty			1
Agroforestry				

Since studies often assess the impact on multiple indicators, the frequencies in this table exceed the total number of selected publications.

The evidence base provides no information on the impact of agroforestry, while the impact of inorganic fertiliser use is overrepresented.

No studies on agroforestry were selected, meaning there was no evidence in this selection of studies of any potential impact of agroforestry on households. On the other hand, 7 studies on conservation agriculture and 10 studies on soil and water conservation (SWC) were identified, providing relatively more insight into these practices. There were also 15 studies on ISFM. However, the true impact of the components of ISFM remains obscure. Most studies categorised under ISFM assessed the impact of modern input packages, of which inorganic fertiliser is a key component. Improved seeds and pesticides are additional components that are often promoted, as well as (though more rarely) advice on organic fertilisers (compost/manure) or cropping practices. The combined technical advice that farmers receive in such projects makes it nearly impossible to disentangle the impacts of the separate components, particularly those of manuring, composting, rotations or intercropping. Key exceptions that do provide insights are Kassie et al. (2015a,b) and Wainaina (2018).

SLM practices may mitigate production risks in specific agroecological zones.

While most of the studies only assessed the mean impact, three studies that investigated soil and water conservation provide interesting exceptions. Arslan et al. (2017) pointed to the relatively larger impact of these restoration practices in regions that display temperature shocks, and Kato et al. (2011) did the same for regions with lower than average rainfall. Furthermore, Kassie et al. (2008) found that, in high rainfall areas, soil and water conservation measures have no significant impact on the value of production. Such findings are plausible and aligned with expectations since increases in water-holding capacity should allow crops to cope more easily with higher temperatures or droughts. Hence, the benefits of the various practices are potentially broader than simple mean changes in farm or household income. In fact, key benefits in relation to mitigating production and income risks, as pointed out in much of the biophysical literature (Brouder and Gomez-Macpherson, 2014), could be relatively more important than increases in mean income. Except for the three studies above, none of the studies selected investigated such effects in closer detail.

Potential synergies between SLM practices need further investigation

Synergies may arise between the four types of SLM practices considered or between components of them.. Wainaina et al. (2018) studied this proposition in closer detail, suggesting that synergetic effects may exist in a combination of zero tillage (CA) and the use of manure (ISFM). Kassie et al. (2015a,b) explored possible synergetic effects between crop diversification and minimum tillage.

The studies provide little information on the long-term impacts or the institutional and governance environment in which they were implemented

All of the studies assessed impact over a relatively short period of time, typically one to two years after the intervention. Only three studies assessed the impact over a longer period (four to seven years) (Schmidt and Tadesse, 2013; El-Shater et al., 2016; Schmidt and Tadesse, 2017), and they found ambiguous results. None of the studies reviewed provided any insights into the role of and differences in extension services or local governance arrangements. As discussed in greater detail in Section 5.4.2, these play a crucial role in shaping the process by which land users exchange information on new practices and adapt these to local circumstances. Clearly, differences in the extension approach may well yield significant differences in either the speed or scale of adaptation and take-up.

5.3 The estimated financial costs of land restoration measures and ambitions

Moving from commitments to implementation requires adequate regard for restoration costs

Current estimates of global restoration commitments under the three Rio Conventions and the Bonn Challenge range from 765 million hectares to close to 1 billion hectares (Section 2.3 and Sewell et al., 2020). To achieve these commitments, large investments will be necessary on a global scale. Given that restoration delivers both public and private benefits, securing public and private investment is important for the long-term success of ecosystem restoration projects (Sewell, Bouma and Van der Esch, 2016). Just as a better understanding of the biophysical and social benefits of restoration is needed, restoration costs also need to be better understood, as there is a wide range of estimates of costs per hectare and uncertainty on what drives differences in costs (Blignaut et al., 2014). More information on the costs at the global, national and project levels can help policymakers and investors to make decisions to prioritise and balance costs against potential benefits.

Uncertainties in restoration costs increase perceived risk and limit investment

The lack of sufficient and reliable cost estimates for restoration (Table 5.2) has resulted in a high perceived risk of restoration investments. This is in part due to the context-specific nature of restoration projects, but also due to the lack of a standardised methodology for reporting restoration costs (Blignaut, Aronson and Wit, 2014). There is also a lack of understanding of what causes the high variation in costs between different types of restoration and different countries and regions (Verdone and Seidl, 2017). Additionally, there is a lack of comparability of costs between restoration projects, as the types of costs reported vary per assessment (Blignaut et al., 2014). These uncertainties mean that restoration costs are often perceived as high, which inhibits action (Nkonya et al., 2016).

Table 5.2
Overview of estimates of restoration costs

Source	Cost estimates	Method
De Groot et al. (2013)	Tropical forests: USD 8–9,000/ha Grasslands: USD 200–2,000/ha Coastal wetlands: USD 10,000–800,000/ha	94 case studies
ELD and UNEP (2015)	Establishment cost: USD 344/ha (median, range is USD 0.5–86,992/ha) Maintenance cost: USD 63/ha (median, range is USD 0.03–21,748/ha)	90 case studies in Africa
FAO and UNCCD (2015)	Achieving the Bonn Challenge would require an annual investment of USD 36–49 billion up to 2030, while achieving land degradation neutrality would cost USD 318 billion per year, over a period of 15 years	Estimate based on average restoration costs from De Groot et al. (2013), but does not take into account type and location of restoration
Verdone and Seidl (2017)	Average restoration cost: USD 1,276/ha	Cost-benefit analysis (CBA) based on 16 cost observations
Giger et al. (2018)	Establishment cost: USD 500/ha (median) Maintenance cost: USD 100/ha/yr (median)	Data-set analysis of 258 restoration practices
Brancalion et al. (2019)	Costs for different types of forest restoration: Planting/reforestation: USD 2,041/ha (mean) Enrichment planting: USD 789/ha (mean) Natural regeneration, fences: USD 344/ha (mean) Natural regeneration, no fences: USD 49/ha (mean)	Survey among restoration practitioners in Brazil, includes 40 forest restoration projects
Verhoeven et al. (in prep.)	Median restoration cost of USD 1,464/ha overall, ranging from USD 152/ha (median) for forest management to USD 2,365/ha for irrigation measures Estimated cost of current global restoration commitments (812 million ha): USD 305–1,672 billion in total, or USD 403–2,058/ha	Data-set analysis of 232 restoration projects worldwide Econometric analysis based on this data set

New research developed for this report by Verhoeven et al. (in prep.) improves on past estimates by looking at restoration cost data from 232 restoration projects from three sources (WOCAT, World

Bank and academic journals), and categorising these into 12 restoration types and 10 geographical regions, while including both establishment and maintenance costs. These cost data were developed into a model to estimate the costs of implementing current global commitments for landscape restoration, using the recently developed Global Restoration Commitments (GRC) database (Sewell et al., 2020; Section 2.3). Commitments that focus on conservation and protected areas were excluded.[8]

Restoration costs vary from USD 152/ha to USD 2,365/ha, depending on the restoration measure

These figures for restoration costs include initial implementation costs and five years of maintenance costs. The latter is in line with budgeting for such projects at organisations such as the World Bank. Given the high discount rates of the farmers involved, the inclusion of a longer time period is unlikely to alter the findings by very much.

The median restoration cost for all restoration measures comes to USD 1,464/ha (mean USD 2,423/ha). The highest median restoration costs are found in agroforestry (USD 1,959/ha), silvopasture (USD 2,309/ha), cross-slope barriers (USD 2,100/ha) and irrigation (USD 2,365/ha). The lowest median costs are recorded for forest management (USD 152/ha), grazing management (USD 517/ha) and passive regeneration (USD 584/ha) (Figure 5.1). Econometric analysis also shows, as expected, that countries with a higher GDP, and thus higher costs for labour and materials, have higher restoration costs for the same measure (Verhoeven et al., in prep.). Furthermore, the cost estimates differ significantly across the data sources utilised, pointing to differences in cost reporting. Overall, the per hectare restoration costs found in this study for different restoration types are similar to earlier studies (Giger et al., 2018; Verdone and Seidl, 2017; ELD and UNEP, 2015; Sukhdev, 2008).

The cost to implement the current global restoration commitments is 0.38%–2.06% of global annual GDP

When the cost model is combined with the global restoration commitment data, the total cost for restoration commitments (812 Mha[9]) ranges from USD 305 billion to USD 1,672 billion, depending on the cost accounting and commitment accounting methods, the type of restoration implemented and the country's GDP (Verhoeven et al., in prep.). These costs are modest compared to global GDP, reflecting 0.38%–2.06% of the annual global GDP, or 0.04%–0.21% of annual global GDP if implementation is spread out over 10 years. An earlier estimate of global restoration costs by FAO and UNCCD (2015)[10] used the rough assumption that restoration costs total USD 2,390 per hectare, irrespective of location and restoration type. The estimate by Verhoeven et al. (in prep.)[11], which does consider location and restoration type, translates into a considerably lower average restoration cost of USD 403 to USD 2,058 per hectare. Note that potential improvements in terms of economies of scale and learning curves in implementation are not yet accounted for. On the other hand, transaction and coordination costs may exist when projects are funded internationally and smaller projects are bundled for larger investors. Neither learning costs nor transaction costs are represented in the data presented in this section.

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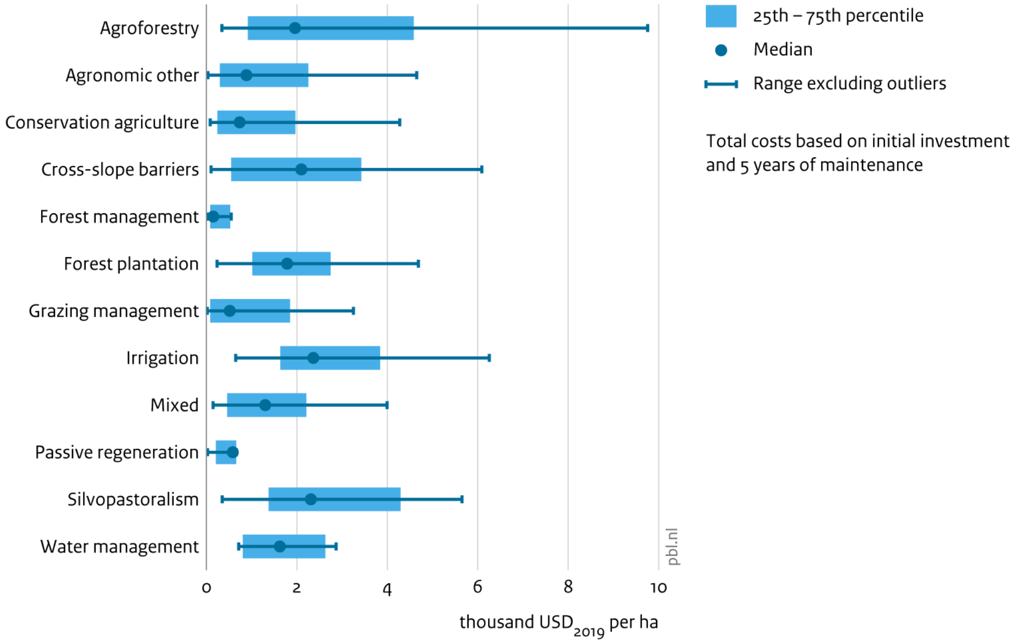
[8] Excluding the commitments for conservation and protected areas brings the total global commitments to 626–812 million ha globally.
[9] Differs from total commitments in Chapter 2 as Verhoeven et al. (in prep.) exclude the commitments for conservation and protected areas.
[10] USD 318 billion per year for 15 years to restore 2 billion hectares.
[11] USD 240–1,608 billion for 625–812 million hectares.

Figure 5.1
Costs per type of restoration

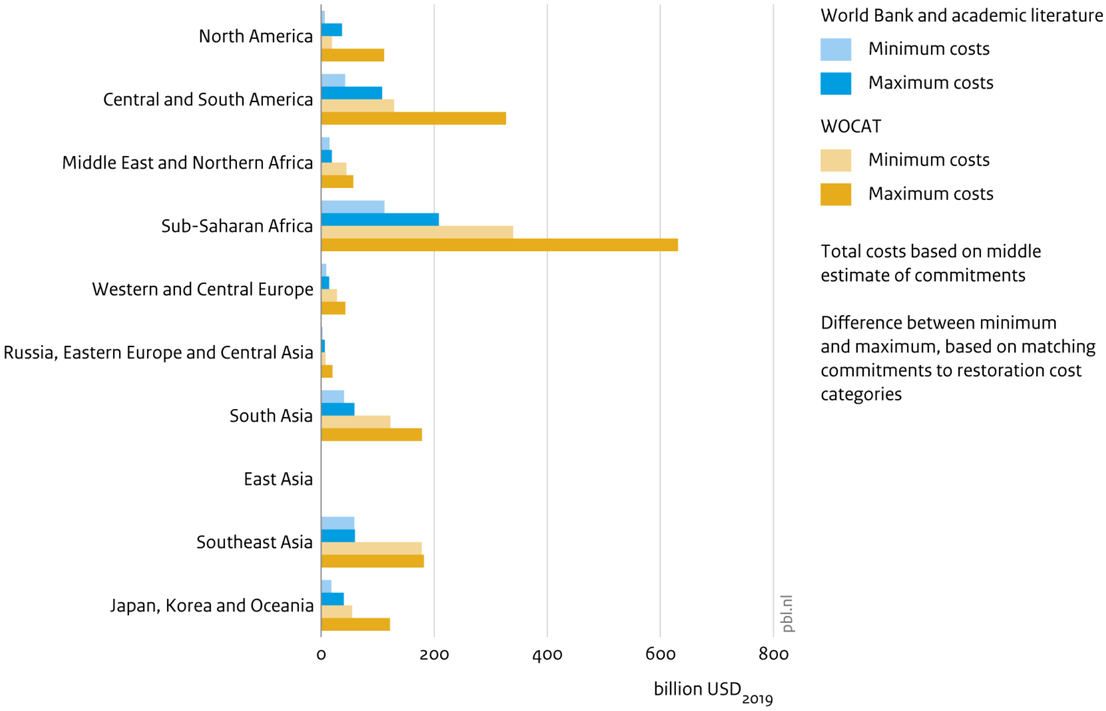


Source: PBL, Verhoeven et al. in prep.

A large proportion of the commitments and costs are in developing countries

The largest shares of the restoration costs are in sub-Saharan Africa (USD 112–631 billion) and Central and South America (USD 43–327 billion) (Figure 5.2). In part, this is due to more restoration commitments being made in the global south than in the global north (Section 2.3). If restoration were to be taken up as a tool to achieve sustainability goals by more developed countries, which currently have very small commitments in general, the GDP effect on costs per hectare would mean that these additional commitments would probably come at a higher cost in these countries. The uneven geographical spread of commitments also leads to distributional issues. The costs of implementing the restoration commitments for sub-Saharan Africa total 837% of the GDP (0.8%–3.7%, annually, up to 2030), and are therefore very likely to be prohibitive for these countries. Unless international cost-sharing mechanisms for restoration are agreed upon, it seems likely that a significant part of the commitments will lack the resources for implementation, even without considering opportunity costs.

Figure 5.2
Total costs of restoration commitments as of 2020



Source: PBL, Verhoeven et al. in prep.

Opportunity costs and additionality of costs not included

While the above estimates represent a step forward in identifying the bandwidth of costs for different restoration measures and commitments in different regions, it is impossible to establish a full picture of the restoration costs. This is likely to continue to be the case, given the diverse local contexts and the lack of standardised cost reporting. Furthermore, opportunity costs, which are the value of the tangible goods and services that were foregone to make restoration possible (Verdone, 2015), are always excluded. Opportunity costs, combined with insights on cost-sharing between actors, provide a better understanding of whether a proposed restoration measure reflects the most diligent use of resources, for land users, private investors and donors alike (Ding et al., 2017). Similarly, the additionality of costs is rarely discussed; in other words, the extent to which the costs only cover the additional management costs incurred by the intervention, rather than also including costs that arise irrespective of the restoration measure.

Coordination required between public and private investors

Opportunities may also lie in mobilising large private investors or impact investors. This relies on the bundling of restoration opportunities for private investors to attain size and reduce risk, but also requires contracts for loan repayments, safeguards and legal certainty (Reyhanloo et al., 2018). However, this may prove to be complicated, as the benefits of restoration are often not directly transferable into monetary terms. Innovative mechanisms for financing restoration are necessary, both at the level of projects as well as for international burden-sharing, which can be supported by initiatives, platforms or organisations that can coordinate between public and private investors and between projects (Sewell, Bouma and Van der Esch, 2016). Furthermore, it is essential to obtain more insight into who bears the cost of landscape restoration. A better assessment of the costs and benefits from different actor perspectives (farmers, governments, private investors), at different levels, and including opportunity costs, is key in the design of new financing mechanisms to ensure the participation of these actors in landscape restoration practices.

Importance of enabling environment, governance and policy instruments
Making restoration cost data visible can aid cost-sharing negotiations within and between countries, while also providing valuable information for engaging and motivating the private sector. As a next step, information on costs should be accompanied with a better assessment of the benefits and their distribution over actors. For example, a closer investigation is required of how much of the restoration benefits accrues to landowners and private investors, and how much is supplied in the form of public goods, and at which scale. Such information is essential to answer the key question of which policy instruments are the most effective in supporting and enabling investments and action. Various types of governance arrangements or policy instruments can be considered, including variations of Payment for Ecosystem Services (PES) and conditional and unconditional subsidies. Research is ongoing into which type of governance arrangement works best in which circumstances, also to mobilise private sector participation.

5.4 The effectiveness of policy instruments and institutional changes in stimulating land restoration

5.4.1 Introduction

Restoration and sustainable land management practices are more likely to be adopted within a secure or enabling environment
Land users are more likely to adopt restoration and sustainable land management practices if the benefits of doing so are perceived to be sufficiently favourable (Section 5.2). This implies that either the benefits are sufficiently high (increase in productivity, production or income, improved resilience or reduced risk), or the costs are sufficiently low or reduced, making these practices the superior alternative. However, the costs and benefits can be shaped through various complementary policies, for instance by increasing the benefits (e.g. in the form of price support) or by reducing costs (through subsidies or income transfer). In addition, complementary policies exist that create a more secure or enabling environment for land users to invest in land restoration practices, such as building rural infrastructure, strengthening local institutions, and stimulating farmer-to-farmer learning and experimentation. Regulations can also play an important role, though their requirements still need to be affordable for the land user. While many of these policies are hypothesised to stimulate land restoration, questions remain on their effectiveness. This section reviews the evidence for such policies incentivising the adoption of land restoration practices.

Three groups of policies are thought to play an important role in incentivising land restoration: agricultural and land-related policies, nationwide economic policies, and policies in other sectors with a notable impact on land management
Sections 5.4.2, 5.4.3 and 5.4.4 summarise the policies that are assumed to support the adoption of land restoration and SLM practices, the way in which these policies potentially shape the economic feasibility of SLM, and the empirical evidence. Three broad groups of policies are distinguished: (1)

agricultural and land management policies, (2) national institutional and macroeconomic policies, and (3) policies in sectors other than agriculture with second-order effects on agriculture and land management (Table 5.3). The order does not reflect an underlying order of importance, but highlights the decreasing availability of knowledge of the impact on agriculture, and on land restoration adoption in particular. Note that the groups are not mutually exclusive but overlap in some instances.

Though the impact on agriculture is known to some degree for many policies, the impact on land restoration often remains undocumented.

As the remainder of this chapter illustrates, many of the policy instruments considered change the relative input and output prices on which land users base decisions. However, to give an example, do higher output prices stimulate sustainable intensification, or simply speed up soil fertility mining? To complicate matters, both outcomes are possible, depending on various other sets of prices and the institutional environment. The remainder of this section considers these groups of policies in closer detail and reviews the scientific literature to document how and when these policies do indeed contribute to incentivising land restoration, and by how much.

Table 5.3
Three broad groups of policies assumed to support the adoption of land restoration and SLM practices

Category	Type of policy instrument	Section	Theory of change with respect to uptake of SLM
Rural development and agricultural sectoral policies	Support of local institutions and governance	5.4.2	• Improve local governance for improved SLM project targeting • Organisation of producers (cooperatives) for linkage to markets • Responsive agricultural extension and enhancing local knowledge exchange on novel SLM practices
Rural development and agricultural sectoral policies	National agricultural sector policies aimed at altering agricultural prices, including input subsidies, taxes and trade policies	5.4.2	• Temporary subsidies as a means to cover cost (incl. learning cost) of new SLM practices • Removal of taxes or subsidies that unfavourably affect agriculture and take-up of SLM practices
National level governance	Land policy frameworks	5.4.3	• Government supply of complementary public goods, including land tenure or land market mechanisms, to support investment in SLM practices
Key relevant sectoral/non-agricultural policies	Infrastructure development	5.4.4	• Better infrastructure reduces transport costs, providing farmers with a price advantage and affecting take-up of SLM practices
Key relevant sectoral/non-agricultural policies	Decentralisation policies	5.4.4	• Decentralisation of policymaking shifts policies towards local priorities, affecting policies related to SLM take-up

Key relevant sectoral/non-agricultural policies	Energy policies	5.4.4	• The significant use of agricultural and forest biomass to meet energy demands implies that any sectoral energy policy has implications for demand for biomass from agriculture and forestry

5.4.2 Rural development and agricultural sector policies

To effectively implement goals and policies to support restoration, they should be integrated and mainstreamed into existing agricultural and rural development projects and policies.
Many of the policies highlighted in this section are standard elements of agricultural and rural development. Also, as explained above, many have important implications for the decision to adopt or adapt restoration and sustainable land management practices. However, the effectiveness of these policies in terms of stimulating the uptake of such measures often remains poorly understood.

Facilitating local development through local institutional arrangements

Local institutions play a critical role in supporting development processes
Successful interventions to stimulate rural development start from the right combination of technological change, market incentives (or removal of market barriers) and local institutional change (e.g. Ruben and Pender, 2004; Pingali, 2012; Kassie et al., 2015a,b). Local institutions prescribe the formal and informal set of rules that govern interactions between farmers, land users, traders and government agents (North, 1991). Institutions also have a role in governing whether and how information on novel land-use practices flows from one farmer to another, whether a sustainable development project serves the interest of only a few (elite capture) or the wider community, whether farmers are willing to cooperate to protect the commons, and whether farmers deem traders sufficiently trustworthy to engage in longer term value chain commitments.

The importance of institutions in explaining why or where sustainable development occurs, and why or where not, has been established unequivocally (e.g. Ostrom, 1990; Platteau, 2000; Acemoglu et al., 2005). Following Ostrom (1990), many of these studies document how communities self-organise with the aim to manage public, or 'common resource', goods, including forests, water bodies and, in some instances, soil resources. These studies also suggest that whether or not effective resource management occurs depends on whether communities develop mechanisms to collectively choose rules, to co-enforce these rules and to arbitrate when conflicts arise, and whether regional or national governments respect, facilitate and incorporate such locally designed strategies.

Governments and NGOs often actively seek to alter rural local institutions to facilitate or scale up sustainable development projects.
This is often done through projects that aim to influence local institutions, and many do indeed alter local institutional architectures, sometimes leading to improvements in development indicators (Berkhout et al., 2017). Though none of the studies reviewed by Berkhout et al. (2017) assessed the impact on sustainable land management uptake, many of the interventions described in the studies can have such an impact.

For example, development projects that are conducted in a participatory manner, rather than being designed and implemented top-down, have become the norm in development practice. A prime argument for doing this is to minimise processes of elite capture. Elite capture describes the state whereby existing village governance arrangements lead to the formulation of project activities that serve the interest of a few. Participatory methods, on the other hand, lead to the formulation of project activities that benefit wider subsections of local communities and, in some instances, encourage more sustainable land use (e.g. Casey et al., 2012; Mazunda and Shively, 2015). This secures wider commitment to project activities, increases the scale of implementation, and makes it more likely that impact of projects will extend beyond the project lifespan.

Furthermore, more land users experimenting with the same technology may lead to the swifter identification of its best local adaptation, a process called social learning (Conley and Christopher, 2001; Hogset and Barrett, 2010; Maertens, 2017). Moreover, conducive social structures such as strong intercommunal ties can encourage the diffusion of innovations (Van Rijn et al., 2012). Several projects have yielded positive results by smartly targeting existing social networks, with the aim to stimulate knowledge exchange and social learning (Beaman et al., 2015; BenYishay and Mobarak, 2019). That being said, too strong communal ties are also known to foster conservatism and may actually impede experimentation with agricultural technologies (Moser and Barrett, 2006; Van Rijn et al., 2012).

Various policies strive to directly influence the processes by which knowledge is exchanged.
One approach is the use of Farmer Field Schools (FFS), in which a small group of farmers experiments with a novel technology. The assumption is that these farmers quickly master the technology and their best local adaptations, and that they can educate others in their locality. Waddington et al. (2012) reviewed the impact of FFS, and while none of the reviewed studies had an explicit focus on restoration or sustainable land management, they concluded that FFS improves intermediate outcomes in relation to knowledge of new practices as well as final outcomes related to agricultural production and income. None of the studies, however, found evidence of the adoption of novel practices beyond the participants. More broadly, Stewart et al. (2016) reviewed the impact of input and training programmes in agriculture (again with no specific focus on land restoration), and found that training programmes raised incomes but rarely improved nutritional status.

Many development projects aim to stimulate the formation of cooperatives
Examples are described by e.g. Fischer and Qaim, 2012; Matchaya and Perotin, 2013, and many others. Cooperatives can deliver benefits related to social learning, but offer other benefits too. For example, they can make it easier to promote the collective action of some sustainable land management techniques, such as communal soil and water conservation structures. In some countries, the formation of rural cooperatives is almost mandatory and such cooperatives are used for land rehabilitation initiatives. Food-for-work schemes, which are for instance often used in Ethiopia, help provide public goods, including road infrastructure or slope terracing. Well-targeted projects may crowd in private agricultural investment in these initiatives (Holden et al., 2006; Bezu and Holden, 2008).

Cooperatives have the potential to integrate groups of farmers into value chains more easily.
The rationale is that farmers in such contract farming arrangements could reap rewards through increased trading and/or price advantages, both of which could make investments in land

restoration more lucrative. Nonetheless, considerable doubts exist as to whether, or when, such schemes live up to their expectations. While contract farming enhances welfare in some instances, questions remain as to whether such outcomes are generalisable (e.g. Ashraf et al., 2009; Barrett et al., 2012; Bellemare, 2012; Meemken and Bellemare, 2020).

The certification of sustainable land management practices is promoted but evidence of impacts remains slight.

A review of the impact of certification schemes (Oya et al., 2017) suggests that their impact on household income is often limited, while wage labourers in certification schemes often appear worse off. Insights into whether certification leads to more sustainable land management are slim. Only a few rigorous evaluations exist, and these do not support a ubiquitous positive impact on sustainable land management (Blackman and Rivera, 2011).

Alternative institutional arrangements such as PES can have a positive impact.

These arrangements are designed around the idea that the implementation of land restoration often has benefits that extend beyond the land user (be it downstream effects, or increased soil carbon storage). Rewarding land users for such benefits (i.e. internalising externalities) is the premise of PES. While PES has been tried in various instances, solid studies on its impact remain scarce, as pointed out by Samii et al. (2014) in their review of the impact of PES on reducing deforestation. Nonetheless, PES schemes were found to have a moderate, positive impact on deforestation. The few studies that have assessed impact on household incomes also found small positive gains. However, the evidence suggests strong distributional effects, with participation strongly skewed towards wealthier households, suggesting that PES does not automatically increase incomes for the poorest.

Not all options for altering rural institutional structures are likely to achieve impact on their own.

Moreover, none of these types of interventions are likely to be a panacea for restoration and sustainable land management. They may be necessary, but will rarely be sufficient to change practices. As discussed below, a wider range of policies and price incentives needs to be taken into account.

5.4.3 Sustaining innovation and technological change

Technologies developed by research institutes require adaptation to local conditions, which in turn requires responsive extension services.

There is widespread evidence of considerable returns on public investments in agricultural research and knowledge exchange (Alene and Coulibaly, 2009; Chang, 2009; Cunguara and Moder, 2011; Mogues et al., 2012). Moreover, regarding the most effective design of agricultural extension and innovation, there is now greater recognition that many of the technologies developed by research institutes require adaptation to local conditions. The goal of reducing the costs of social learning is a key element of many of the local interventions described above. In the process of technological change, land users incur costs of experimentation as they need to divert productive resources (land, labour, capital) from proven technologies to something new. In this process, cooperatives or Farmer Field Schools should be seen as the first, or the last, mile of knowledge exchange.

Indeed, thinking on on-farm technological change has moved from linear top-down views of technology transfer to co-learning and knowledge exchange (Leeuwis and Van den Ban, 2004). The promotion of Farmer Field Schools is but one example of this trend and part of a broader change from top-down technology transfer to the promotion of innovation systems (Kilelu et al., 2013; Klerkx et al., 2013). It is however noted that existing institutional arrangements are not always conducive to effective technological innovation (Struik et al., 2014).

Extension or innovation systems should respond to the specific questions and needs of land users, and be less supply-driven than has often been the case.

There is scope for public-private partnerships in designing effective and farmer-responsive modes of extension services (Anderson and Feder, 2004; Feder et al., 2011). Moreover, with the advent of mobile phone usage, also in the most remote areas of the developing world, there may no longer be a need for extension agents to travel widely and frequently. Experiments with telephone helpdesks (Cole and Fernando, 2012) may yield cost-efficient alternatives.

Each of the above interventions may serve to reduce the learning costs that land users incur. An alternative is to compensate land users for the costs of learning and experimentation that they incur, for which subsidies are a key policy instrument.

5.4.4 Agricultural taxes and subsidies

Subsidies, taxes and fixed exchange rates change local or domestic prices of inputs and outputs, altering the efficient rates of production in land-related sectors (agriculture, livestock and forestry) and efficient land management.

The reduction of taxes and subsidies was a key element of the structural adjustment programmes (SAPs) that were implemented in many developing countries in the 1980s and 1990s (Kherallah et al., 2002) and that aimed to provide smallholders with better financial incentives to invest in agriculture.

One reason for providing subsidies for agricultural inputs is to temporarily cover the learning costs associated with the use of new technologies. When, after some time, farmers have fully mastered the best adaptation of a new technology (e.g. they have identified the optimal fertiliser dose), the need for further subsidisation decreases. On the other hand, the taxation of crops (a negative subsidy) mostly or only occurs through the levying of border taxes, or through price controls by setting domestic farmgate prices below world market prices. Moreover, many developing countries set fixed exchange rates for local currencies. In countries with little or no industrialisation or services sector, taxing primary exports is often the only way to raise government revenues.

Many studies have investigated the link between the price changes resulting from such policies and agricultural production. Recent work includes that of Malan (2015), Haile et al. (2016) and Magrini et al. (2016). Generally speaking, farmers are found to raise output in response to output price increases, for instance by increasing the use of labour or fertiliser. Taxes, on the other hand, depress crop yields, but the effects of subsidies (negative taxes) on crop yields are ambiguous (Malan, 2015).

Fertiliser subsidy programmes may positively affect crop yields, but they are prone to inefficiency and corruption, with limited impact on poverty (Hemming, 2018; Holden, 2018).

Input subsidies, mostly on inorganic fertilisers, have moved away from blanket fertiliser provision to ‘smart’ systems, targeting the poorest farmers with vouchers redeemable with local traders, so as not to crowd out local private input suppliers. However, despite intentions by policymakers, programmes often fail to reach the intended groups (Jayne et al., 2018). Moreover, the subsidy of agricultural inputs is often governed by political economy considerations and plays an important role in influencing election outcomes (e.g. Banful, 2011). A contentious debate has emerged as to whether or not input subsidies are an effective and efficient means to stimulate food security (Dorward and Chirwa, 2011; Jayne et al., 2013; Jayne et al., 2015).

A key question in the adoption of sustainable land management technologies is whether organic soil fertility is a substitute for inorganic fertiliser, or whether organic and inorganic fertilisers complement one another.

A few detailed farm-level studies suggest that soil organic carbon content and inorganic fertilisers are indeed complementary (Marenya and Barrett, 2009a,b; Holden and Lunduka, 2012). In that case, a well-designed programme for the subsidy of inorganic fertiliser could improve the economic feasibility of costly land restoration investments (Holden, 2018).

Some studies suggest that higher net output prices increase the return on investments in sustainable land management, but others suggest it merely creates a greater incentive to mine soil fertility.

When subsidies raise output prices, they may make the adoption of land restoration practices more attractive. However, empirical studies that examine the link between output prices and the adoption of practices such as SLM provide mixed insights (as reviewed in Bluffstone and Gunnar, 2012; Chapter 2). In fact, specific local conditions are likely to determine which of these conditions holds (Pagiola et al., 2004).

5.4.5 National level governance

Effective national institutions and their quality shape effective land policymaking.

Among other things, institutional quality is responsible for the degree to which rule-of-law is upheld, or levels of nepotism and corruption are suppressed. What distinguishes countries with ‘good’ institutions (or better institutional quality) from countries with ‘bad’ institutions is that, in the former, key government actors more often use state systems to supply public goods to the broader society, instead of supplying private goods to a select elite (Robinson and Acemoglu, 2012). Starting with Acemoglu et al. (2001), a range of studies has investigated the role of institutional quality in explaining economic development, and a causal link between the two has now been established unambiguously (Acemoglu et al., 2005; Michalopoulos and Papaioannou, 2013).

Public goods are important drivers of private economic investments, including those in sustainable land management. Moreover, ‘better’ institutional quality may also signal a greater capacity of policymakers and civil servants to design fair and effective land-use policies. Indeed, capacity building among policymakers and civil servants is considered critical for stimulating sustainable land-use management (Willemen et al., 2018).

Land policy frameworks provide guidance for identifying and removing barriers to effective policymaking.

Effectuating a change towards more sustainable land management and reversing processes of land degradation therefore require the right institutional setting. Often, improving tenure security is a starting point, but this may need to be complemented with a number of additional changes. Two

frameworks, developed by key development donors (Deininger et al., 2011; GIZ, 2016), provide guidelines for policy reform to improve 'good' land governance. To this end, GIZ (2016) considers three principles — efficiency, equity and accountability — for stimulating efficient land management. Efficiency implies that land-use rights should be clarified and the process should be simple, affordable and sustainable. Equity requires that the process ensures equitable access to land, focusing explicitly on gender equity and the protection of vulnerable groups. Finally, the process should be accountable and transparent, with clear roles and responsibilities, public access to records, and the prevention of corruption. In accordance with these principles, policies need to ensure the establishment of land registries (cadastres) and effective mechanisms for dispute resolution, and publicly accessible information management needs to be developed alongside participatory spatial planning processes.
Following broadly similar principles, the World Bank has proposed the use of a diagnostic tool to assess countries' current land policies and whether they require change (Deininger et al., 2011). The tool, which has been applied to a number of countries, typically takes three to six months to implement and focuses on five thematic areas:

1. A legal, institutional framework that recognises existing rights, enforces them at low costs and allows users to exercise them in line with their aspirations.
2. Arrangements for land-use planning that avoid negative externalities and support effective decentralisation.
3. Clear identification of state land in a way that cost-effectively provides associated public goods.
4. Public provision of land information in a way that is broadly accessible.
5. Accessible mechanisms to authoritatively resolve disputes and manage conflict.

Improving land tenure could stimulate agricultural productivity...

As the frameworks above point out, a key objective of improved land governance is often to increase land tenure security. The reasoning is that the incentive for landowners to make durable investments in land, including costly ones in sustainable land management, is greater when they are faced with a smaller risk of losing the land. Various empirical studies and meta-reviews give credence to this argument (Lawry et al., 2016; Tseng et al., 2021). For instance, Deininger et al. (2019) find that tenure insecurity is high among farmers in Malawi and constrains investment in land quality, and that agricultural productivity is 9% lower for female farmers in Malawi who face tenure insecurity. Similar findings have been observed in other countries, for example in Ethiopia (Holden et al., 2011). What is more, insight into the magnitude of losses in productivity makes it possible to conduct a cost-benefit analysis of public programmes that improve tenure security. Deininger et al. (2019) argue that, for the Malawian case, the benefits outweigh the costs sufficiently to warrant such public investments.

That being said, positive findings from a number of case studies do not make a general argument for formalising land tenure everywhere. After all, the available evidence is clustered in countries; for instance, the case of formalising tenure in Africa is well-studied in Ethiopia. In fact, the prominence of such a policy focus could suggest that tenure insecurity is particularly problematic in Ethiopia. A synthesis of findings from multiple studies across a variety of countries is therefore required. Lawry et al. (2016) provide such a systematic review and observe that, across a wide range of studies, formalising tenure leads to an increase in agricultural productivity, income or consumption.

... but lack of secure tenure may not always be a binding constraint.

That tenure insecurity is not always a key impediment to raising agricultural productivity is also observed in other studies (Place and Hazell, 1993; Bluffstone and Gunnar, 2012). In a large cross-country study (Scoones and Toulmin, 1999) that reviewed 15 case studies on soil fertility management in a wide variety of settings in Africa, tenure insecurity was not cited by farmers as a key impediment to their adoption of land restoration practices. Rather, the main impediments to investing in soil fertility were found to be insufficient market access, the inability of farmers to market produce easily, and insufficient labour per hectare.

The diverse findings on the role of tenure in spurring land-related investments would seem to suggest that tenure insecurity is not a ubiquitous binding constraint. As Holden and Ghebru (2016) point out, enhanced tenure security could be an endogenous demand response in the wake of either increasing population pressure or outside demand for land. If neither is an issue, then programmes to improve tenure security are not likely to make much difference. Either way, this provides a further argument for the diligent use of diagnostic approaches such as that used by the World Bank, to assess whether tenure policies and regulations need tweaking in the face of large-scale investments in restoration and support for sustainable land management.

Checks and balances need to ensure that improved tenure leads to pro-poor development and land restoration uptake.

Despite the reported positive impacts of tenure regulation, it is worth recognising that there are also a number of potential downsides or trade-offs. Discussion is ongoing as to whether titling or tenure regulation is a pro-poor (or pro-inequality) policy or not. In fact, titling could be a divisive and controversial process (e.g. Boone, 2019) as it could foster elite capture, whereby access to land by vulnerable groups (e.g. women farmers or minority groups) that is guaranteed in customary tenure arrangements is denied.

Indeed, examples exist of powerful, well-connected and well-informed elites influencing processes of tenure securitisation and capturing such resources to their own benefit, worsening the rights of women, migrants or pastoralists (Meinzen-Dick and Mwangi, 2009). Overall, the impact of land tenure improvement on women’s rights remains mixed (e.g. Higgins, 2018, pp. 439; Andersson Djurfeldt, 2019). At the same time, the potential of formalising land tenure to address both inequality and environmental problems such as land degradation is limited. As the review by Tseng et al. (2021) points out, few studies (24) have investigated the impact of improved tenure on both human well-being and environmental objectives, but half of those that do suggest the existence of trade-offs between the two. Diligent use of the frameworks outlined above and a focus on equitable processes could mitigate such downside effects.

Finally, increased tenure security is expected to increase trade in land assets, as clarity in titling (and a corresponding land registry) should reduce competing claims over similar tracts of land. However, increased trade may quickly concentrate land in the hands of the most able (Amanor, 2017), as poor, cash-strapped farmers, lacking access to financial markets, may be tempted to sell their titles. This would lead to the emergence of a new landless class. In some cases, sellers may enter into sell-and-lease-back arrangements; in other words, the widespread sharecropping arrangements that continue to exist in many countries, also developed ones. It is not clear a priori how concentration or lease arrangements affect investments in sustainable management, as this critically depends on both the length of the rental arrangements and the rental price. Clearly, short-term rental arrangements provide few incentives to invest in soil quality. Problematically, but understandably, some countries cap the length of rental agreements in order to prevent the exploitation of tenants. High rental prices, either through high fractions in sharecropping or high fixed rents, are therefore also a disincentive to make costly investments in soil fertility. Few insights exist to guide policy on the effect of land rental on land restoration uptake.

Box 5.1 Land-related conflict risks

Land restoration can provide a range of benefits for land users and the wider public and can have positive effects on ecological functions or incomes. On the other hand, land-use change, land degradation and limited access to land can result in social and ultimately even violent conflict. Access to and power over land have played, and still play, an important but also contested role in numerous conflicts. Land use or land degradation are however seldom the main reason for conflict: issues regarding institutional capacity, social and economic inequality, historical grievances and livelihood insecurity often collide with land issues. A historically unprecedented example is found in the Rwandan genocide, where the declining availability of land is believed to have been an underlying factor of importance. In this case, land disputes, in the context of colonial grievances and economic inequalities, intensified ethnic tensions (Musahara, 2005). However, other land-related factors can also induce conflict. For example, rising land-related economic interests, insecure land rights and power inequalities were and still are major aspects in conflicts over land in de Brazilian Amazon, where land is abundant (Puppim de Oliveira, 2008).

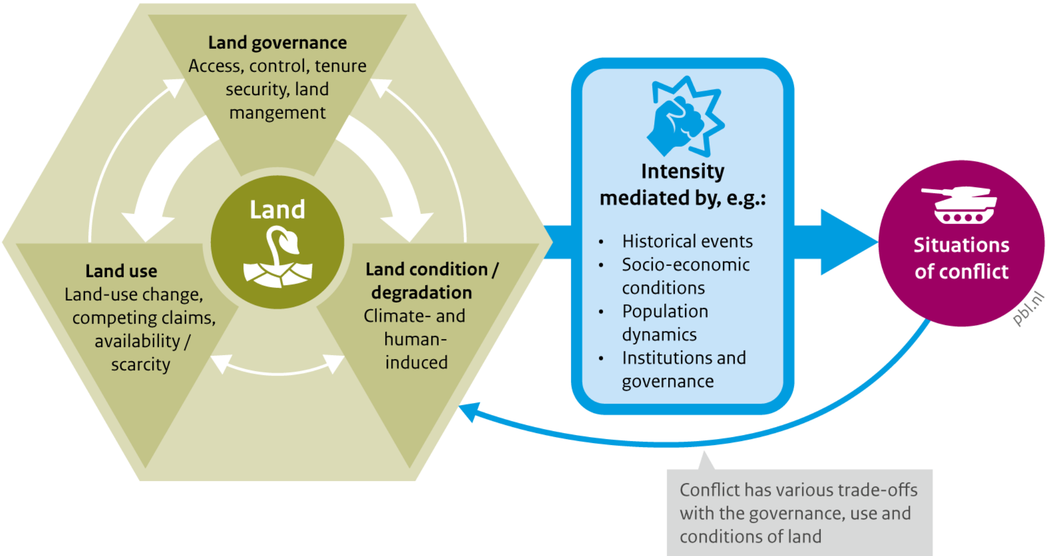
Figure 5.3 conceptualises the interaction between land and conflict. How access to and control over land is arranged can contribute to conflict when mechanisms are perceived as unfair. The existence of historical grievances between different communities over land tenure can exacerbate such perceived feelings of injustice (Kameri-Mbote and Kindiki, 2008), for example in post-colonial settings (Banerjee and Iyer, 2005) or between farmers and pastoralists (Benjaminsen, 2009). Formalising land rights can be a way to deal with land tenure issues. This process has however occasionally contributed to the marginalisation of certain, often underrepresented, communities or ethnic groups. For example, new land policies in Malawi at the beginning of this century increased power asymmetries and intensified competition over land (Peters, 2007).

Land-use change conflict

Conflict over access to or the use or ownership of land can be a direct and concrete form of conflict. These conflicts are essentially a fight over control of land and its use, in which real or perceived inequities play a major role (Ray, 2017). Most of the literature on this issue consists of in-depth, qualitative case studies of situations in which changes in land use have been identified as a reason for conflict (Carl LeVan and Olubowale, 2014; Sulieman, 2015; Valera et al., 2016). However, these case studies say little about the structural nature of the relationship between land-use change and conflict. A study by De Jong et al. (in prep.), performed for this report, analysed 62 case studies that discussed conflict related to land-use change. In general, different types of land-use change (e.g. deforestation, agricultural intensification and urbanisation) relate to different levels of conflict intensity and different indicators. However, population growth (both natural and due to immigration), overlapping land rights, ethnic fragmentation, inequality and corruption are often found to be important contextual factors (De Jong, 2021).

Figure 5.3

Links between land and conflict



Source: PBL

Land degradation and conflict
Land-use change often results in land degradation, but land degradation due to human-induced climatic changes can in some cases also be related to situations of conflict. This link is however not well understood, since different contextual factors influence these cases, including land governance mechanisms. Different studies make use of different indicators for land degradation, due to earlier confusion regarding the definition of land degradation. Some studies have found a small impact of land degradation on conflict (Theisen, 2008; Hauge, 1998; Raleigh and Urdal, 2007), while other studies found no relation (Hendrix and Glaser, 2007). According to the IPCC Special Report on Land, there is medium evidence of and limited agreement in the literature on a link between land degradation and conflict, and a major knowledge gap regarding this link (Olsson, 2019). The land-conflict literature brought together in this IPCC sub-chapter is however very limited. From the 20 studies referred to, 8 discuss land degradation and migration, 2 are other IPCC reports, 2 focus on livelihoods in general, 1 focuses on water and conflict, 2 are non-academic comments, 2 are studies from the 1990s referring to land degradation and conflict, and 3 do link land to conflict, but not land degradation specifically.

5.4.6 Key relevant sectoral non-agricultural policies

It is important to observe that improved institutional quality could imply a considerable growth in the non-agricultural sectors, spurring rural-urban migration and agricultural concentration, increasing wage rates and, therefore, making some labour-intensive restoration options less attractive. In other words, the relationships between land-related and other economic sectors need to be considered.

Infrastructure policies

Better infrastructure could stimulate agricultural productivity but better roads also lure labour away to urban areas, at least seasonally, and the overall impact on sustainable land management is unclear. Improved roads and railways reduce travel times and costs between urban and rural areas. Better infrastructure therefore reduces the costs of inputs for producers in rural areas and allows them to market agricultural produce in urban markets at more favourable prices.

Overall improved infrastructure has been found to have a positive effect on agricultural productivity (Fan and Zhang, 2004; Moser et al., 2009; Barrett, 2008; Hussein and Suttie, 2016), and better infrastructure has been quoted as one of the drivers of the advent of the Green Revolution in south Asia (e.g. Pingali, 2012; Dorosh et al., 2012; Berg et al., 2018; Storeygard, 2016). However, these studies focused on agricultural productivity, not the impact on land restoration adoption/adaptation, for which the picture is less clear. And, as with the subsidy of output prices (Section 5.4.1), the resulting increase in output prices could spur processes of soil fertility mining.

Changes in the labour market resulting from improved infrastructure could have a considerable influence on the adoption of land restoration practices. As rural wages and opportunity costs of labour rise, labour-intensive land restoration options may become less attractive. Indeed, such a potential chain of effects was theorised by Boserup (1965) and has been observed in various empirical studies (Bluffstone and Gunnar, 2012; Chapter 2). Hence, while better infrastructure could benefit agricultural productivity, it may not necessarily lead to better land management in the long run. Additional support may therefore be required to cover high initial labour costs.

Decentralisation of government policies

There is little information to guide policymakers on whether decentralisation is a desirable strategy from the perspective of sustainable land management. Often, local and regional governments are thought to be more responsive to the needs of the local population and therefore to place a stronger focus on reverting processes of land degradation than national governments. However, whether or not regional or local governments can respond in this way depends, of course, on their autonomy and representation. These may be high, as evidenced by Nigerian states implementing fertiliser subsidies (Liverpool-Tasie et al., 2010). Still, all the disclaimers of institutional quality and their impact on effective policymaking still apply and in general these may be even more prominent for regional or local governments that may be less equipped in terms of staff and capacity than national governments to begin with. Moreover, agricultural development often has a lower priority for regional policymakers than health or education (Birner and Resnick, 2010). The impact of decentralisation policies on deforestation and poverty was reviewed systematically by Samii (2014). The few studies reviewed suggest a modest reduction in deforestation due to decentralisation and increases in mean income.

Energy policies

Energy policies directly impact land-related policies. Agriculture (crop residues, biofuels) and forests (charcoal) are prime sources of energy for many households in the developing world (Zulu and Richardson, 2013). While widespread concerns exist over overexploitation, particularly of forest resources, current evidence seems to suggest that charcoal and fuelwood demand are, in general, minor causes of forest degradation (Chidumayo and Gumbo, 2013). However, fuelwood and charcoal production as drivers of deforestation are more pronounced in some regions and around large urban areas. Concerns over deforestation led Senegal, for instance, to subsidise LPG as a substitute for the household consumption of charcoal (Prasad, 2008). While the programme has been successful in increasing LPG consumption compared to charcoal use, there are concerns over leakages due to the illegal trading of subsidised LPG (The Global Subsidies Initiative, 2010).

5.5 Taking stock: how to incentivise land restoration

This chapter considered the financial incentives for adopting land restoration practices. We considered the benefits to land users of adopting a range of land restoration practices, the costs of promoting these practices, and a range of policies that further shape the incentive for land users to adopt land restoration practices. While a number of novel insights emerged from this chapter, key knowledge gaps and a corresponding research agenda were also identified.

Firstly, the evidence base documenting private benefits of land restoration (SLM practices) at the smallholder farm level is remarkably small. Only a few rigorous impact assessments exist, and these are clustered with respect to both SLM techniques and geographical location. The studies that were used paint a mixed picture. While some suggest modest benefits to land users, several others conclude that there is no net income effect. Indeed, heterogeneity with respect to benefits is likely to exist, but either way much greater emphasis should be placed on conducting more, and more rigorous, impact assessments. Such assessments should reveal in closer detail when and where SLM techniques deliver benefits to land users, and where and when they do not.

Secondly, there are significant differences in the costs of land restoration, across types of restoration measures and across countries. The total costs of cumulative global restoration commitments are high but, when divided over multiple years, they are small compared to global annual GDP. The highest total costs and largest size of restoration commitments are mostly in developing countries and, unless international cost-sharing mechanisms for restoration are agreed upon, it seems likely that a significant part of the commitments will lack the resources for implementation, even without considering opportunity costs.

Thirdly, private costs and public benefits may not align well. The cost ranges documented in Section 5.3 are often higher than the benefits documented in Section 5.2. In part, this is due to the set-up of the research in this report. For example, costs often include project overheads that land users are unlikely to pay. In addition, Section 5.3 estimates total costs over a longer time frame, while the benefits in Section 5.2 document annual changes. That being said, many of the cost data included, particularly from the WOCAT database, should accurately capture actual costs faced by land users. Moreover, some of the studies discussed in Section 5.2 reported very small or null changes in income, and a discrepancy between costs and benefits is likely to arise in many instances. Again, this should not come as a surprise, as many of the quoted benefits of SLM are public in nature, as further illustrated in Chapter 4. It does, however, raise the question of how to stimulate the adoption of SLM in the long term.

5.5.1 Key factors of land restoration

Land restoration helps to address multiple sustainability ambitions at the same time. As outlined in Chapter 4, land restoration can provide important contributions to supporting food and water security, biodiversity conservation and sustainable use, and climate change mitigation and adaptation. While land restoration is not a silver bullet for any of these goals, its defining characteristic is that, by adding up all of its potential contributions to these goals, it becomes a highly attractive solution. However, the degree to which private actors, including smallholders, reap the public benefits in the short or long term remains unclear. Further adding to the complexity is the number of actors involved, as restoration projects need to engage with millions of smallholders across many regions of the world.

Restoration and protection measures can prevent future land degradation, and this should be accounted for when assessing investment in restoration measures. The impacts avoided by preventing continued land degradation processes are a benefit of the implementation of restoration measures. This requires an estimate of the potential future impact in the absence of restoration measures. Not accounting for prevented impacts would underestimate the potential benefits of land restoration. Prevention is also crucial because, while deterioration of land condition can be fast (in the case of land conversion) or slow (in the case of slow but persistent degradation processes), land restoration is generally a long-term process.

The multiple benefits and required long-term perspective for restoration create fragmentation among actors and make public or private investment decisions complex. Because restoration can provide a range of benefits, rather than being a focused solution for a single goal, it can result in fragmented planning, funding and implementation. This is shown clearly in the analysis of current national commitments (Chapter 2). The onset of the UN Decade on Ecosystem Restoration and the inclusion of land restoration in the Rio Conventions, the SDGs and the national plans of a large and increasing number of countries may help to create more coherence. The question will be to what extent this carries over into the development of restoration projects. The mix of multiple public and private benefits makes for potentially complex projects.

5.5.2 The need for monitoring and involvement of non-state actors

Moving beyond commitments to implementation and impact requires feedback loops to assess performance against targets

The restoration playing field includes public actors such as national governments, who contribute to the formulation of multilateral agreements and goals such as the Paris Agreement. Effective implementation of these goals requires their endorsement, translation and incorporation into national plans, policies, strategies, spatial priorities and commitments, as well as incorporation into local management plans (Meli et al., 2019). Alongside their target setting and policymaking role, public actors also have the role of providing funding, support, capacity and economic incentives for actions at the local level (Meli et al., 2019). Governments are consequently reliant on bottom-up feedback loops from location realities to ensure policy relevance, to monitor progress and impact, and to update national-scale data to assess performance against targets, or to adjust targets (Meli et al., 2019; Roux et al., 2016). Monitoring, which is currently being developed by the Task Forces on Monitoring and Best Practices for the UN Restoration Decade, is not only relevant for restoration practices, but also for restoration costs (Section 5.3). However, governments cannot do all of these tasks alone.

Moving from single-issue to complex multi-issue governance requires new agents of change

There is a movement away from single-issue environmental governance (dominated by governments) towards complex, multi-issue governance, which involves wider networks of entwined governance institutions and actors connecting various issue areas such as climate change, biodiversity and health — as demonstrated by the SDGs (Biermann et al., 2009). Restoration is viewed as such a connecting issue (Section 2.1.2), reflected in the broad playing field (Section 2.2) of international and transboundary initiatives (i.e. the Bonn Challenge) that co-exist with traditional government policies. Focusing on a multitude of smaller efforts that jointly create a more effective solution is characterised as a 'distributed' or 'polycentric' global governance landscape (Ostrom, 2010). Here, non-state and subnational actors — 'new agents of change' — help to fulfil various governance functions, including goal setting, information sharing and networking, creating standards and guidelines for policy implementation, field operations, and providing or facilitating finance (Kok et al., 2019). Table 5.4 provides examples of supporting governance functions and international supporting initiatives for the restoration agenda.

Table 5.4
Examples of governance functions and international supporting initiatives

Type	Examples
Goal setting	Bonn Challenge, New York Declaration on Forests, Initiative 20x20
Information and networking	The Global Partnership on Forest and Landscape Restoration (GPFLR), Landscapes for People, Food and Nature (LPFN), Forest Ecosystem Restoration Initiative (FERI)
Operations	Commonland, reNature, Land Life Company, Grounded
Standards and guidelines	FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT), LandScale, IUCN Global Standard for Nature-based Solutions, SER restoration principles, FLR principles, Plan Vivo
Financing	FAO Forest and Farm Facility, WWF Landscape Finance Lab, WRI TerraMatch, Global Environment Facility (GEF), Green Climate Fund (GCF), World Bank, Global Mechanism, Land Degradation Neutrality Fund, African Development Bank, The Endangered Landscapes Programme

Including non-state and subnational actors in implementation strategies has many potential benefits, including raising ambition levels and coordinating finance
Efforts have been made in recent years to group existing yet siloed ambitions together — for example for climate and biodiversity — under hybrid, international initiatives such as the Bonn Challenge and the New York Declaration on Forests. These initiatives invite an array of public, private and civil society actors to make commitments at multiple levels. A wider governance landscape can help to build grassroots movements, engaging more diverse actors and building positive momentum and legitimacy on the policy agenda, while showcasing action and mainstreaming restoration across society (Kok et al., 2019). It can also help build confidence for governments to adopt more ambitious goals and commitments, foster innovative partnerships, and provide governance functions that complement public policies such as new standards, knowledge dissemination and action on the ground (Kok et al., 2019). Such initiatives often operate beyond the sponsorship of the established conventions (e.g. UNFCCC, CBD, UNCCD) and are often driven by smaller groups of like-minded countries, regional authorities, international institutions, private actors, academia and NGOs (e.g. Blok et al. 2012; UNEP, 2013). These partnerships are promoted as a solution to deadlocked international negotiations, ineffective development cooperation and overly bureaucratic international organisations (Pattberg et al., 2014).

Non-state actors and initiatives can also help to coordinate finance streams. Reducing risks for investors and coordinating funding sources and projects have long been identified as ways of removing obstacles to the mainstreaming of restoration (Sewell et al., 2016). Multiple organisations have stepped up to the task by creating platforms that help to broker these two areas, including WRI's TerraMatch and WWF's Landscape Finance Lab. Alongside these are a number of investment funds that aim to reduce the risk of long-term investments in restoration by blending public and private finance, such as the Land Degradation Neutrality Fund (LDN Fund).

5.5.3 Effective governance for land restoration requires policy interventions at the micro, meso and macro levels

Policy instruments to stimulate the adoption of land restoration practices are dependent on governance and institutional structures. While the stronger involvement of non-state and subnational actors could contribute to the implementation and governance of the restoration agenda, and could represent a feasible and impactful way forward to achieve global restoration commitments, a major task remains in creating a supportive policy environment at multiple levels. This question was examined in closer detail in Section 5.4, reflecting on key land-use-related policy instruments. For many of these instruments, the impact on agriculture is known to some degree, yet much less insight exists on the precise impact on the incentive to adopt land restoration practices. As a rule of thumb, many of the policy instruments considered change the relative input and output prices on which land users base decisions. However, do higher output prices stimulate sustainable intensification, or simply speed up soil fertility mining? To complicate matters, both outcomes could occur in different settings.

Incentivising land restoration requires a palette of instruments. No single policy instrument is sufficiently powerful to promote land restoration alone. Rather, incentivising land restoration requires a palette of instruments. Projects that aim to stimulate land restoration could lift to some extent on general, and necessary, rural development policies, including those that aim to organise participatory development processes or to remove or reduce adverse taxes and subsidies. In some instances, additional financial incentives in the form of subsidies or PES could be provided. Clearly, there are no silver bullets, and a tailor-made palette of policies needs to be considered on a country-by-country basis.

Combining land restoration and protection measures with changes to production, supply chains and consumption patterns can achieve larger benefits. The restoration scenarios account for changes in land restoration and management, and the protection of key ecosystem functions. Larger improvements to land condition, biodiversity and ecosystem functions could be achieved if restoration and protection were to be combined with consumption shifts, for example to less meat-intensive diets, reductions in food waste, and more sustainable supply chains. Increasing efficiencies in production chains, for instance through improved livestock efficiency or reduced losses of food in the supply chain, would also reduce pressure on land. If less land is needed for the production of land-based products and thus abandoned, this land could be restored.

5.5.4 There are no silver bullets for choosing the right mix of policies or projects to incentivise land restoration at scale

Key questions remain, most importantly on when and where the public benefits of land restoration can be internalised by private actors, including millions of smallholder land users. This should be a key focus of additional research. Are the public benefits that are associated with land restoration options sufficiently large to warrant long-term public support for land users? If so, which are the most efficient mechanisms to compensate land users? Should we consider conditional or unconditional subsidies, PES-like schemes, or other types of novel policy instruments? Could some policy instruments be more effective in specific contexts, or will the same instrument work sufficiently in all contexts? Can the large variability in costs and benefits be tackled, despite the dependence on local circumstances? These are clearly defined research questions that can be addressed in policy experiments. Given the ambition of the UN Decade on Ecosystem Restoration and the global commitments, these questions should be high on the agendas of researchers and policymakers if we are to make the decade a lasting success.

Appendices

A1. Land-related SDGs, targets and indicators

Table A1.1
Overview of SDGs, targets and indicators most closely related to land

Category	SDG	Target	Indicator
Conservation and restoration of land resources	Life on land	15.1 **Conserve and restore 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
Conservation and restoration of land resources	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. Degraded land as a proportion of total land area
Conservation and restoration of land resources	Life on land	15.5 **Halt biodiversity loss** *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
Conservation and restoration of land resources	Clean water and sanitation	6.6 **Restore water-related ecosystems** *By 2020, protect and restore water-related ecosystems, including mountains, forests, wetlands, rivers, aquifers and lakes.*	1. Percentage change in extent of water-related ecosystems over time
Sustainable and efficient management of land	Zero hunger	2.3 **Double agricultural productivity and improve 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*	1. Volume of production per labour unit by classes of farming/pastoral/forestry enterprise size

		productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment.	
Sustainable and efficient management of land	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
Sustainable and efficient management of land	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
Sustainable and efficient management of land	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 and legally recognised documentation, and who perceive their rights to land as secure, by gender and by type of tenure

Ownership and access to land	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 gender; 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
Sustainable production and consumption of natural resources	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
Sustainable production and consumption of natural resources	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
Sustainable production and consumption of natural resources	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

Sustainable production and consumption of natural resources	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 as percentage of available freshwater resources

A2. Assumptions behind range in commitment estimates

The assumptions behind the range of total estimates in Figure 2.2 are explained in Table A2.1. In an effort to address uncertainty in the overlap between the various commitments and sources, high middle and low estimates are expressed.

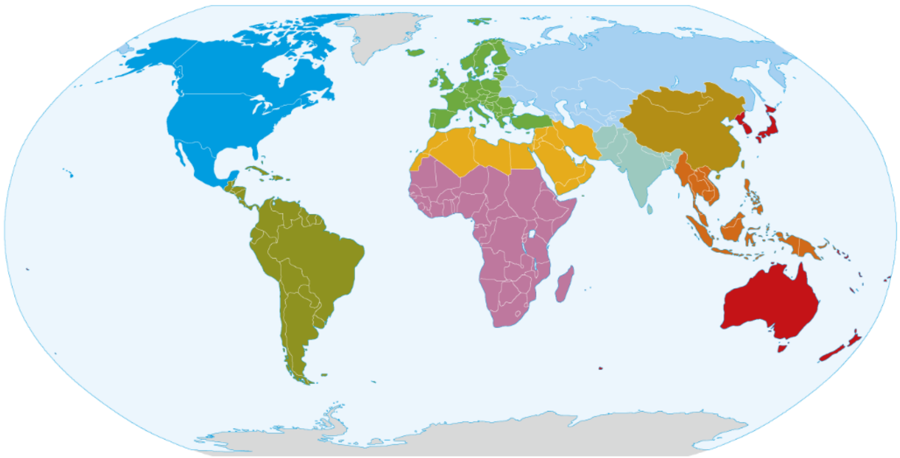
Table A2.1
Range of total restoration commitment estimates

Name	Description	Assumption	Total (ha)
High estimate	All targets added up and combined per country	Assumes no overlap: each target is additional to the others	1,002,118,074
Middle estimate	Only the highest target (between sources) per restoration measure category, per country	Assumes some overlap: that other sources with a smaller target for the same restoration measure are included in the highest estimate of another source	946,844,114
Low estimate	Only the single highest commitment between all sources, per country, regardless of measure	Assumes high overlap: all other smaller commitments from other sources are included	765,472,331

A3. Map of the 10 world regions in this report

Figure A3.1

The 10 regions in this report



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

Source: PBL

A4. Land suitability and availability assessment

The area of land that is potentially suitable and available for agricultural expansion is an uncertain but important input parameter for land-use projections. Estimates in the literature vary considerably, depending on the underlying assumptions (Eitelberg et al., 2015). The estimates presented in this report are used in the IMAGE integrated assessment model (Stehfest et al., 2014) and are an update of the methodology described in Mandryk et al. (2015).

The assessment focuses on the availability and suitability of land for rain-fed cropland and intensive grazing land (as opposed to rangelands with extensive grazing). The analysis is performed using gridded data with a spatial resolution of 5 arc minutes (~9 km at the equator). We take into account biophysical (environmental) and anthropogenic (human) exclusions factors, or reasons, why the land is unsuitable or unavailable for agricultural expansion.

The biophysical factors taken into account are marginal yields, steep slopes, non-soils and permafrost. Yields are derived from the LPJmL dynamic global vegetation model (Bondeau et al., 2007). Land is considered suitable if potential yields at a location are higher than 10% of the global maximum potential yield (Figure A4.1a). As not all crop types are representative in each region, we use maize for temperate and boreal regions, wheat for arid regions and both for tropical regions. Data on slopes, non-soils and permafrost are taken from the Harmonized World Soil Database (Nachtergaele et al., 2010). Furthermore, steep slopes are considered unsuitable for agriculture (Figure A4.1b). Taking into account the level of mechanisation in higher income regions, it is assumed that slopes steeper than 16° are unsuitable in these regions, that slopes steeper than 30° are unsuitable in middle income regions, and that slopes steeper than 45° are unsuitable in low-income regions. Locations without soil (i.e. non-soils) and with permafrost are also considered unsuitable (Figures A4.1c and A4.1d).

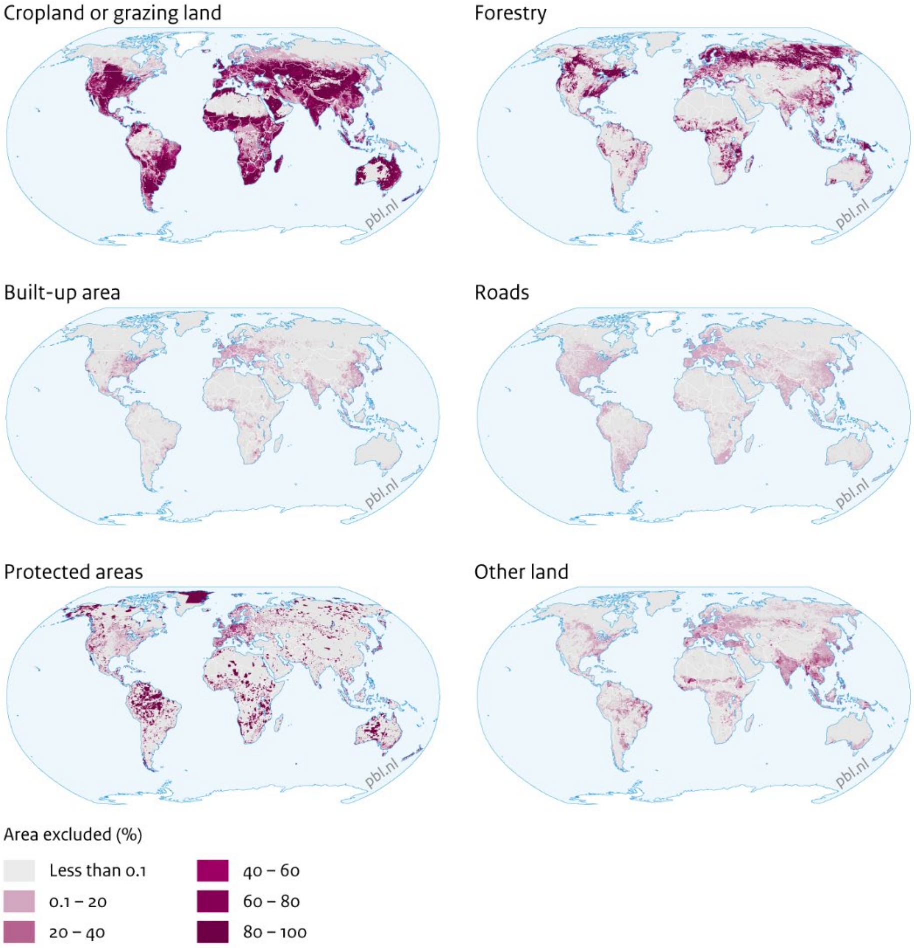
The anthropogenic factors taken into account are built-up areas, roads, current agriculture, forestry, protected areas and other anthropogenically used land. Current cropland and grazing land is based on the HYDE 3.2 database (Klein Goldewijk et al., 2017) (Figure A4.2a) and gridded forestry areas are taken from Schulze et al. (2019) (Figure A4.2b). Built-up area is taken from the urban area model 2UP (Van Huijstee et al., 2018) (Figure A4.2c) and area covered by roads is derived from the GRIP global roads database (Meijer et al., 2018) (Figure A4.2d). All areas classified as built-up, roads, cropland, grazing land or forestry are considered to be unavailable for agricultural expansion. Protected areas are taken from the World Database on Protected Areas (UNEP-WCMC, 2020), and all types of protected areas are assumed to be unavailable for agricultural expansion (Figure A4.2e), which is an important assumption regarding risks of encroachment or use of indigenous land. Other anthropogenically used land is derived from an analysis of the difference between agricultural land according to the HYDE database (consistent with FAO statistics) and agricultural land estimates according to the ESA-CCI satellite-based land-cover data (Hollmann et al., 2013).

This analysis shows that, in many locations, the estimate of agricultural land is higher using satellite-based land cover than using the HYDE database, which can to a large extent be explained by other land uses such as hedges, canals, bare areas and recreational areas (Figure A4.2f). Most of these areas are not classified as agriculture by the FAO because they are probably unsuitable or unavailable and, therefore, we assume that they are not available for agricultural expansion.

All of the factors described above were combined to derive a grid-based estimate of land available for agricultural expansion (Figures A4.3, A4.4 and A4.5). This shows that most of the suitable and available land is located in tropical regions.

Figure A4.1

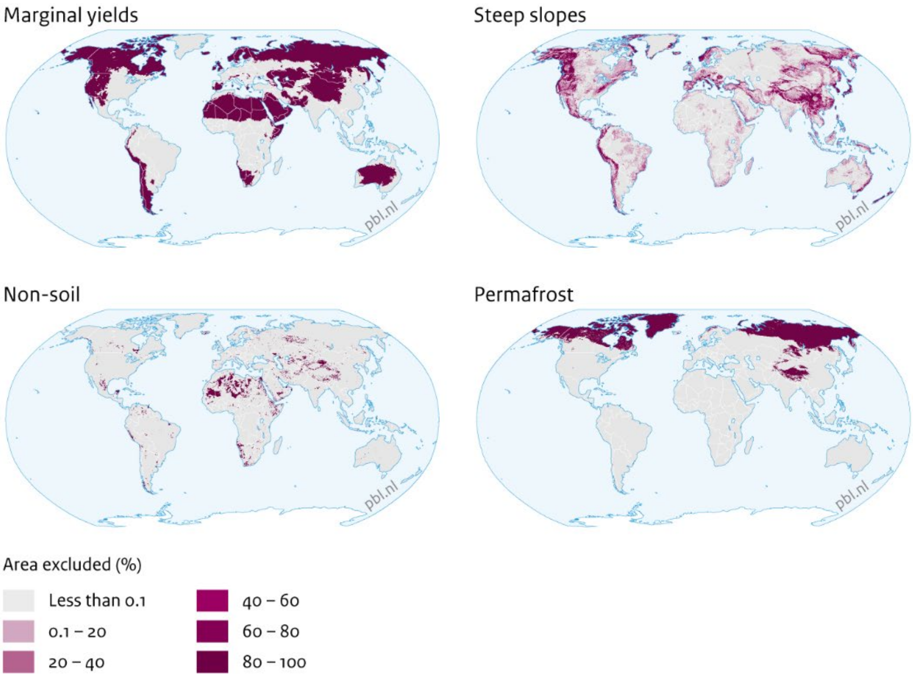
Anthropogenic reasons for excluding land from agricultural expansion under the baseline scenario



Source: PBL/IMAGE, 2UP, GRIP, Schulze et al. 2019, WDPA

Figure A4.2

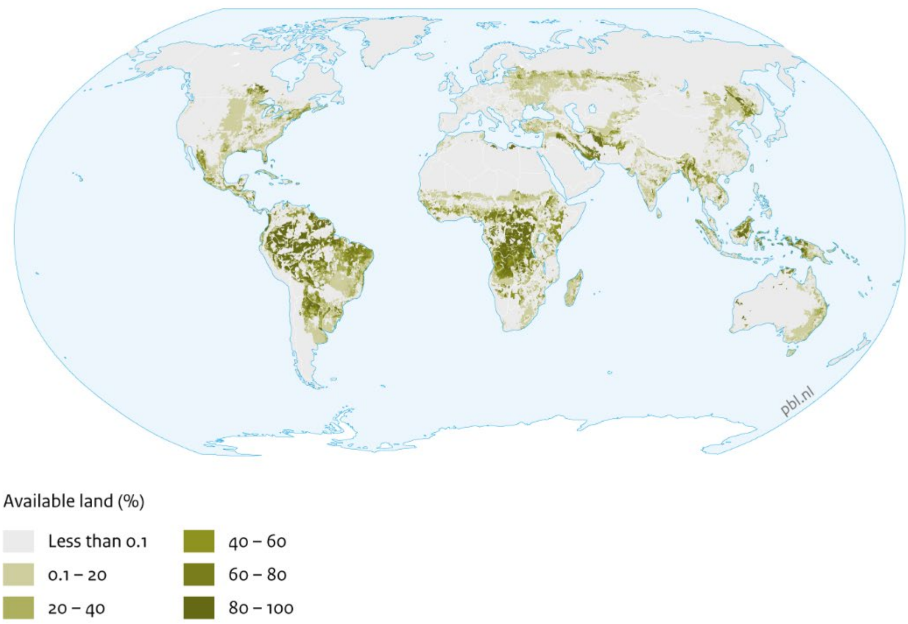
Biophysical reasons for excluding land from agricultural expansion under the baseline scenario and Restoration scenarios



Source: PBL/IMAGE, HWSD

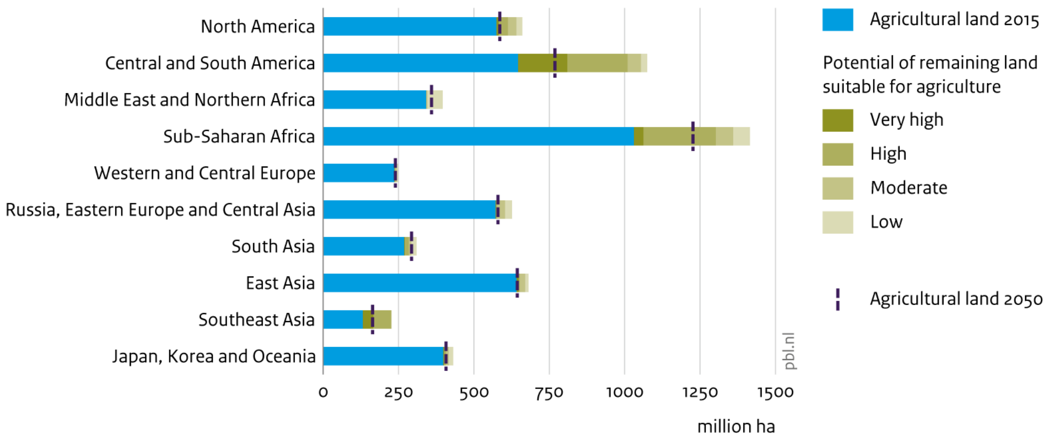
Figure A4.3

Available land for agricultural expansion, 2015



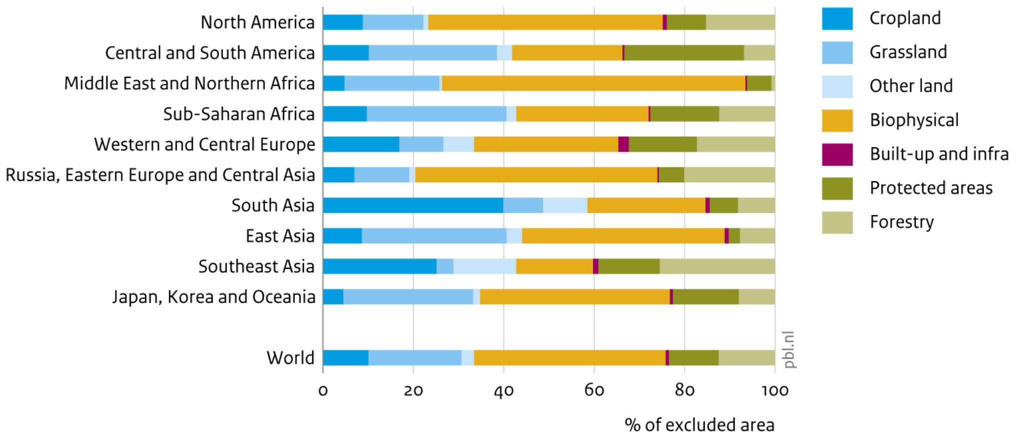
Source: PBL/IMAGE, 2UP, GRIP, Schulze et al. 2019, WDPA, HWSD

Figure A4.4
Agricultural land use and remaining suitable land under the baseline scenario



Source: PBL/IMAGE

Figure A4.5
Exclusion of land from agricultural expansion, 2050



Source: PPBL/IMAGE

A5. Maps of degradation risks

A5.1. Framework of degradation risks

The UNCCD defines land degradation as the human-induced reduction or loss of biological or economic productivity of land (Vogt et al., 2011). We are therefore interested in both, the human-induced state changes, and the impact on productivity. Land degradation is the result of one or more degradation processes in one location.

Rather than mapping *actual* land degradation, which is currently not possible because of the lack of appropriate models and data, we map land degradation *risk*, which conceptually includes both the probability and magnitude of degradation processes for an unknown current or future state and the severity of consequence. The degradation risk distribution in one location is unknown, but we can assume that it is conditional to the modelled degradation process magnitude or degradation index value. All unknown factors being equal, a higher modelled magnitude leads to a higher conditional distribution, which means that the distribution shifts to the right and the risk increases. Conversely, a lower modelled magnitude leads to a shift to the left in the conditional distribution and the risk decreases. This concept implies that risk needs to be understood in relative or indicative terms.

We call our maps '*biophysical* land degradation risk maps', to emphasise that management or human-related aspects of degradation risk are limited to relatively generic information on agriculture, such as crop or land-cover type, irrigation, livestock density and fertiliser application. There is even less information on the severity of consequence aspect, and we need to assume that the impact on productivity monotonically increases with the magnitude of the index used for each degradation process. This assumption is justified for each degradation process in the following section.

A5.2. Selection of processes, assumptions and impact thresholds

Degradation processes were selected for modelling if modelling approaches were available with only moderate modifications (water erosion, salinisation, nutrient depletion and grazing index) or if we perceived that modelling was possible and the processes significant, but no model already existed (e.g. crusting). Processes were not included if there were no relevant global data sets available (e.g. wind erosion) or if the state of research was not sufficiently well advanced to enable global modelling. This justification of process selection is not conclusive and there is certainly a subjective element to the choice. Still, we believe that the most important processes and impacts are covered by the maps, which we will justify in the following.

For the degradation process of water **erosion**, field trials have been conducted and evidence of impact on crops is well established (Den Biggelaar et al., 2003). As far as soil **crusting** is concerned, it is clear in theory that crusting greatly increases run-off, which has large effects on yield and suggests that the process has a large impact (Watt and Valentin, 1992). However, the effect of the process cannot be directly assessed: one reason being that it is very difficult to separate the multiple effects of mulching or tillage, of which reduced crusting is only one. Nevertheless, it is clear that aggregate stability is the dominant factor for crusting (Le Bissonnais, 1996). We therefore developed an index for aggregate stability in order to assess crusting risk This approach will underestimate crusting in high rainfall energy areas such as the wet tropics, because rainfall energy and dissipation by soil cover was not considered. There is as yet no model that can be applied globally to combine rainfall energy with aggregate stability.

The general effect of salt on plants is however well documented: between 2 dSm^{-1} and 10 dSm^{-1}, the relative yield plunges to 0.2 (Steppuhn et al., 2005). Even so, **salinisation**, and specifically electrical conductivity, the main indicator of soil salinity, is poorly mapped. Furthermore, the salt tolerance of plants varies strongly (Nachshon, 2018) and therefore the spatial overlap of crop type and salt level becomes very important. These data are not available, and thus we use a risk index of salinisation potential similar to Schofield and Kirkby (2003).

Macronutrients (N, P, K) are essential for plant growth, and plant growth reacts directly to limitations in any of these (Michaelis and Menten, 1913). Nutrient limitation is the pathway though which crop yields are impacted. Given that nitrogen and potassium limitations can be directly removed from soil through artificial fertiliser application in modern agriculture, it becomes difficult to view the risk of nutrient depletion as inherently soil-related, but rather as a management-related limitation. For **nutrient depletion**, maps of the nitrogen and phosphorus budgets give a snapshot of current trends, but a more complete picture of nutrient depletion only emerges together with the phosphorus limitation map (Chapter 3).

The risk of grassland degradation, and therefore decline in primary and secondary productivity, increases with increasing livestock densities (Steffens et al., 2013; Westoby et al., 1989). No models are available at the global level that enable the prediction of under which conditions state transitions of vegetation occur that lead to grassland degradation, nor are there any general estimates of the magnitude of productivity decline. Instead, we calculated grazing intensity (GI), which is the ratio of grass demand to grass supply, and a relevance mask, which reflects the relevance of the GI to **overgrazing**. Grass supply is calculated without degradation effects.

To allow overlay of the degradation process maps shown in Chapter 3, threshold values of crop impact were chosen in order to obtain binary maps of risk/no risk (**Table A5.1**).

Table A5.1
Threshold values for including a grid cell as risk of productivity impact in 'number of degradation process'

Degradation process	Threshold value for productivity impact
Erosiona	Above 10 t/ha/yr
Crustingb	Above 75th percentile
Salinisationb	Above 75th percentile
Nutrient depletion	Areas with either a negative N or P budget
Overgrazingc	Above GI of 0.5 and above relevance of the 33rd percentile

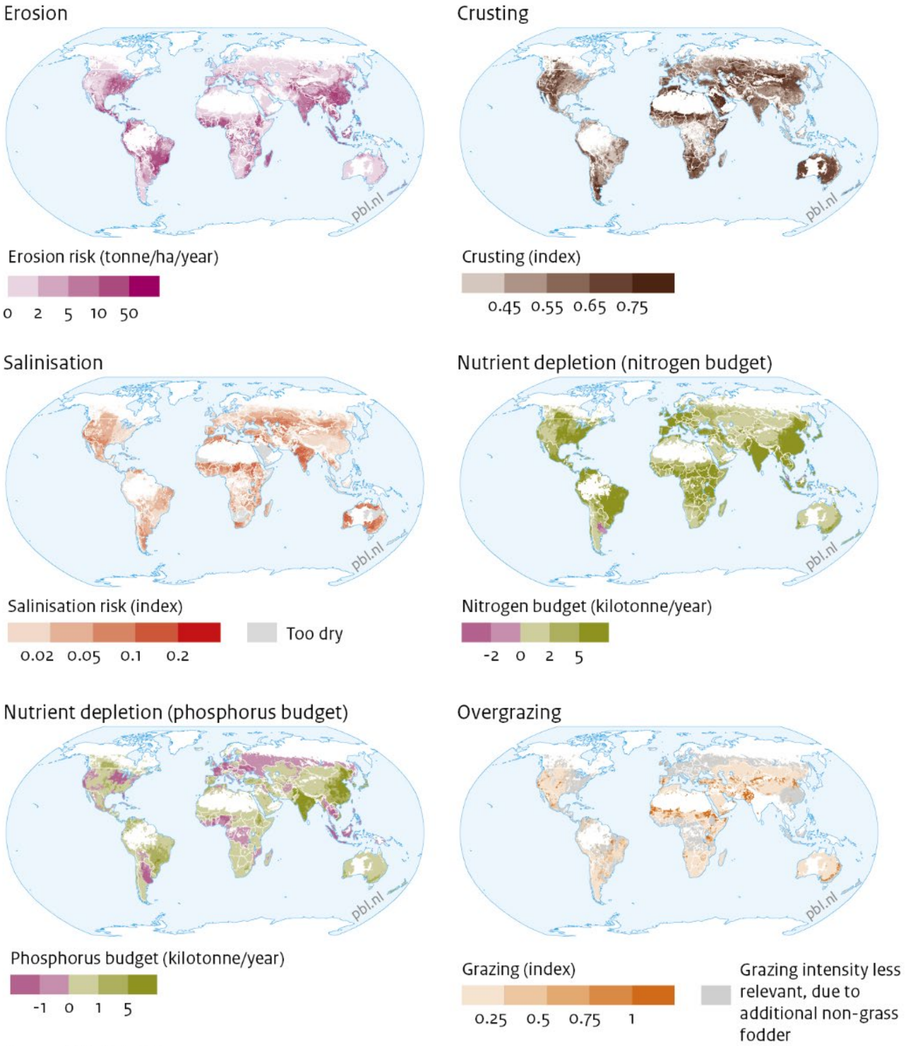
a) The value of 10t/ha/yr is within the range considered the threshold for acceptable erosion by the USDA, and can be considered rather high (Montgomery, 2007). The value is therefore conservative in the context of this study.
b) No biophysical reasons available. The threshold reflects the view that at least 25% of land suffers from land degradation
c) In many extensive grasslands, fire or deferred grazing need to be applied to maintain long-term productivity. We set a GI threshold of 0.5 to indicate areas where these measures cannot be applied because of overgrazing. In other words, the assumption is that half of the harvestable biomass production needs to be left unused in order to avoid overgrazing. Of all grassland area, one third

containing the lowest relevance values were excluded from the analysis (‘low relevance’ in overgrazing map).

A5.3. Maps of degradation risks

Figure A5.1

Risks of degradation processes on agricultural land, 2015



Source: PBL, JRC, PIK

A5.4. Methods for risk map calculation

5.5.5 *Water erosion*

Water erosion was calculated using the empirical Revised Universal Soil Loss Equation (RUSLE), which was developed from standardised plot measurements (Renard et al., 1997). Annual erosion estimates (A, in t ha^{-1} yr^{-1}) were calculated by multiplying the following factors:

$$A = R * K * L * S * C * P \quad \text{(Eq.1)}$$

where R is the rainfall erosivity factor (MJ mm h^{-1} ha^{-1} yr^{-1}), K is the soil erodibility factor (t ha MJ^{-1} mm^{-1}), L is the slope length factor (-), S is the slope gradient factor (-), C is the cover factor (-) and P is the management factor (-). R, K, L and S were obtained from Borelli et al. (2017) and P was assumed to be 1, which means that no conservation measures are taken. To obtain C for the years 2015 and 2050, we first assigned the cover factor for the corresponding crop type as reported in the Supplementary Table 2 in Borelli et al. (2017) for each IMAGE crop type. Where the crop types did not directly match, the phenotypically best matching crop type was chosen. The cover factor of three IMAGE classes (fruit and vegetables; other non-food, luxury, spices; plant-based fibres) was formed by the area-weighted averaging of cover factors of more specific crops (i.e. individual vegetables) reported in the table. The area weights were calculated based on FAOSTAT (faostat.org) average crop areas from 2014 to 2016. The cover factor per 5 arcmin grid cell was assigned based on the dominant crop type in IMAGE alone.

5.5.6 *Soil crusting*

Crusting has the largest impact on crop productivity in the period between tillage and crop emergence. Given that this occurs mostly at the start of the rainy season, and given that most sealing occurs during the first few 100 J m^{-2} of rainfall energy after tillage, it can be assumed that the impact of crusting on infiltration rates (and therefore productivity in water-limited systems) is, as a first approximation, sufficiently represented by the complement of aggregate stability. A range of factors influence aggregate stability, the most important of which are presented in Table A5.2.

Table A5.2
Properties that increase aggregate stability and estimate of effect

Property	Function	Studies	Effect type [range]
Soil organic carbon	Many forms of SOC form stable bonds between mineral grains. SOC can increase hydrophobicity of aggregates under dry conditions, reducing impact of wetting.	Algayer et al., 2014; Kemper and Koch, 1966; Le Bissonnais and Arrouays, 1997; Le Bissonnais et al., 2007	1-exp (-SOC%/2%)
Iron oxides	Sesquioxides cement aggregates. The evidence for this is greater for iron oxides than for aluminium oxides, so only the former is considered.	Kemper and Koch, 1966; Seta and Karathanasis, 1996	FeO% or Kaolinite%
Clay	Under most conditions, clay particles attract each other, stabilising the whole aggregate.	Dimoyiannis et al., 1998; Kemper and Koch, 1966; Le Bissonnais et al., 2007	Clay(-)0.5
Kaolinite index	Negative charge of clay mineral edges through the adsorption of anions. At high pH, this can cause clay dispersion. Kaolinite is the clay mineral least susceptible to dispersion.	Kitagawa et al., 2001; Nguyen et al., 2013	Kaolinite% / (pH – 5) pH[6, 9]
Sodium index	Sodium adsorption on clay particles increases repulsion with other clay particles, causing	Amezketa et al., 2003; Goldberg et al., 1988; Nagy	(2/3) * (EC) +1.5) / (ESP+1); [0, 1.5]

	dispersion. Salt counters the effect.	et al., 2016; Shainberg and Letey, 1984

SOC%: soil organic carbon percentage; FeO%: iron oxide percentage; EC: electrical conductivity in dS m^{-1}; ESP: exchangeable sodium percentage

Based on the studies mentioned in Table A5.2, we formed a function between 0 and 1 for each factor ('effect') that describes the approximate relationship between aggregate stability and the factor. While these factors are well known, there is no general model of aggregate stability that takes into account the interactions between the factors in relation to drivers such as wetting and drop impact. What becomes clear, however, is that soil organic matter seems to be by far the most important factor. In the absence of a general model, we assigned weights to each factor and summed them to produce an index between 0 and 1 for aggregate stability (AS):

$$AS = w_1 * SOC_{effect} + w_2 * FeO_{effect} + w_3 * Clay_{effect} + w_4 * \text{Kaolinite index}_{effect} + w_5 * \text{Sodium index}_{effect} \quad \text{(Eq.2)}$$

$$\text{Crusting potential} \approx 1 - AS \quad \text{(Eq.3)}$$

where the subscript 'effect' refers to the term in the last column in Table A5.2. SOC and Clay were derived from the S-World model (Stoorvogel et al., 2017a), Kaolinite% and FeO% were derived from a global model for clay-sized minerals (Ito and Wagai, 2017), and pH, EC and ESP were derived from the Harmonized World Soil Database (HWSD) data set (FAO et al., 2012).

5.5.7 Salinisation

For salinisation risk, we adapted a potential salinisation modelling approach by Schofield and Kirkby (2003). In this approach, salinisation potential ('salipot') was defined as the product of three factors, representing effects of local topography, aridity, and the potential vertical flux of water in the soil column. We adapted the approach by: (1) transforming the aridity index, (2) including a 'clay effect', and (3) applying cut-offs and normalisation for comparison of the value ranges. Salinisation risk was thus defined as:

$$\text{Salinisation risk} = \text{local topography} * \text{flow potential} * \text{aridity} * \text{clay} \quad \text{(Eq.4)}$$

Table A5.3
Equations and cut-off values used to calculate the factors in Equation 4

Factor	Equations	Cut-off value
Local topography	1 – (local topography/cut-off) If factor < 0 then factor = 0	500 m
Flow potential	If abs(min. monthly flow) > max. monthly flow then abs(min. monthly flow) = 0 fp = (max. monthly flow + 50 mm) – abs(min. monthly flow) factor = fp/cut-off	Max. fp value on grid
Aridity	AI = PET / P Factor = ln(AI+AI_min)/ln(AI_max+AI_min)	AI_min= 0.5 AI_max=15
Clay	Factor = clay fraction/cut-off	Max. clay fraction on grid

The **local topography** factor was calculated from the inverse of the standard deviation of elevation at 30 arcsec resolution within each 5 arcmin grid cell. A lower standard deviation indicates less run-off potential, which could remove accumulated salts from the surface. Values higher than 500 metres are assumed to have no salinisation potential.

For salinisation to occur, there needs to be an alternating flux of water downwards and upwards in the soil profile within a year. Where this alternating flux occurs, the difference between the maximum (positive) monthly flux potential and the minimum (negative) monthly flux potential is taken as the **flux potential**. Monthly flux is given by P + irrigation — PET, where P (mm month^{-1}) is the monthly total precipitation, PET (mm month^{-1}) is the monthly potential evapotranspiration, and irrigation is the irrigation flux (mm month^{-1}). These values were taken from the SSP2 scenario of IMAGE. A value of 50 mm was added to the maximum flux to account for the fact that salinisation can occur in arid areas even where there is no month with a positive flux, as water can easily redistribute during intense rainstorms.

The **aridity index** (AI) was calculated as the ratio of annual potential evapotranspiration (PET) to annual precipitation (P). The cut-off values of AI_min and AI_max limit the factor to a range in which climate is neither too wet nor too dry for salinisation to occur. Because it is a ratio, AI values quickly increase to very high values in very dry areas. In order to de-emphasise this effect, the natural logarithm was used to transform and normalise the values.

The **clay** factor was introduced in this method because texture affects the risk of salinisation through capillary action. The finer the texture, the greater the depth below the surface from which water can be drawn up by capillary action. This means that shallow groundwater can be more easily accessed by soil evaporation (Nachshon, 2018).

A5.5. Nutrient depletion

N and P budgets
Nitrogen and phosphorus budgets were calculated in IMAGE (Beusen et al., 2015; Stehfest et al., 2014a), and scenarios were updated with data up to 2015. Negative budgets indicate current depletion.

Phosphorus limitation

Phosphorus limitation was calculated in IMAGE-DPPS (Zhang et al., 2017) for the base years 2015 and 2050. In a scenario, phosphorus was applied at a rate of 50 kg ha^{-1} yr^{-1} during a 20-year period in all grid cells with cropland, and in which uptake was only limited by the size of the available phosphorus pool. In the year after the base year and the following 20-year period, no phosphorus was applied (zero inputs). P limitation is the ratio of P uptake in the base year (+1) to the P uptake after the 20 (+1) year quenching period. The ratio therefore represents the soil-mediated P limitation, and not the limitation stemming from the lack of direct fertiliser application in the years compared.

A5.6. Overgrazing

Overgrazing risk occurs where conditions are relevant to the overgrazing problem AND where the grazing intensity is high. For a binary overgrazing risk, threshold values for relevance (REL) and grazing intensity (GI) can be used:

Overgrazing risk (binary) = true IF ($REL>REL_{crit}$) AND IF ($GI>GI_{crit}$) (Eq.5a)

where REL_{crit} and GI_{crit} are critical values. Alternatively, for a continuous measure of overgrazing, only GI can be used directly, with a REL threshold as condition:

Overgrazing risk (continuous) = GI IF ($REL>REL_{crit}$) (Eq.5b)

Grazing intensity

Grazing intensity is the ratio of grass demand by ruminant livestock to grass supply in a grid cell. Given this definition, the grid resolution is relevant. A grid resolution of 30 arc minutes was chosen. At this scale, a spatial mismatch of grass production and consumption will be relatively small because herd movement and hay transport are mostly local. In the analysis of grazing intensity, goats and sheep were taken to form one class, and beef and dairy cattle the other. Both classes of ruminants can either be held in intensive or extensive systems.

Grass demand calculation

Grass demand per area of grassland per two classes of ruminant type (sheep and goats/cattle) (GD_{sys}, gC m^{-2}) is given by:

$$GD_{sys} = GD_{cell/sys} * conv / (area_{cell} * gfrac) \qquad \text{(Eq.6)}$$

where $GD_{cell/sys}$ is grass demand per grid cell (in 1,000 kg dry matter), $area_{cell}$ is the area (in km^2) of a grid cell, and conv is the conversion factor between dry matter and carbon content, set to 0.48. The suffix '…/sys' means that the data are per livestock system (intensive and extensive). The grassland fraction (gfrac) per grid cell is derived from IMAGE.

$$GD_{cell/sys} = NR_{cell/sys} * GD_{reg/sys} / NR_{reg/sys} \qquad \text{(Eq.7)}$$

where NR stands for number of ruminants and the suffix ‘reg’ stands for regional sum for all 26 IMAGE regions. Both $GD_{reg/sys}$ and $NR_{reg/sys}$ were taken from IMAGE output (Bouwman et al., 2005; Stehfest et al., 2014b).

$NR_{cell/sys}$ is derived from (undifferentiated) NR_{cell} and a binary (intensive and extensive) livestock system grid.

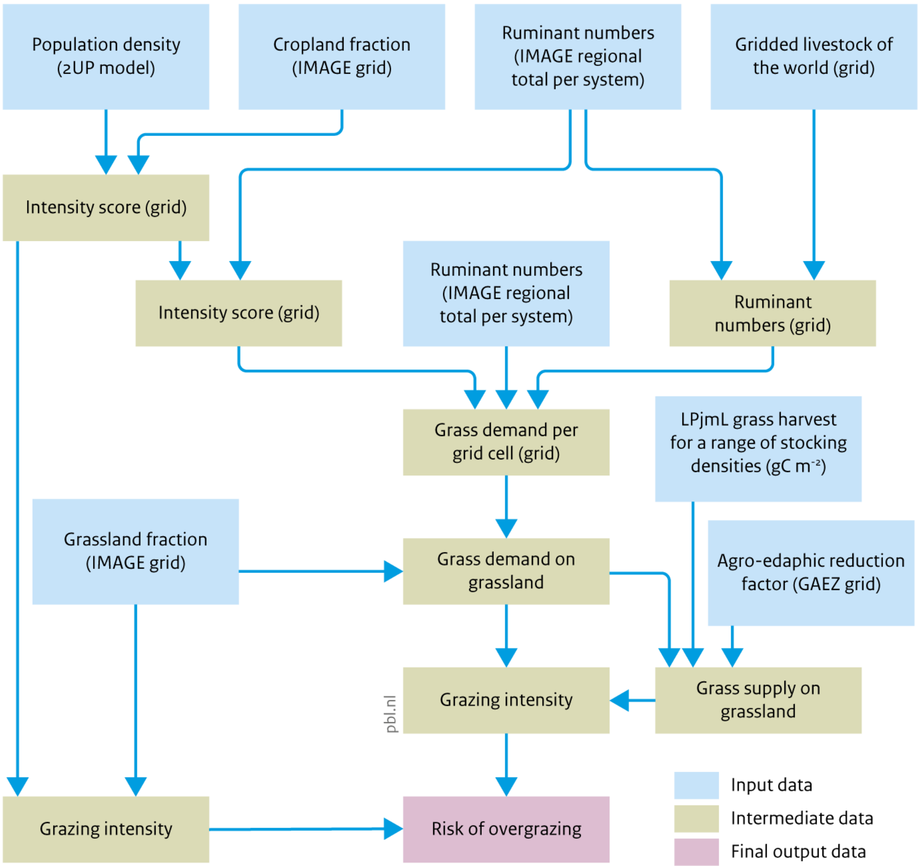
$$NR_{cell} = NR_{GLWcell} * NR_{reg} / NR_{GLWreg} \quad \text{(Eq.8)}$$

where the suffix ‘GLW…’ refers to the Gridded Livestock of the World data set (Gilbert et al., 2018), which gives the number of livestock by type. NR_{GLWreg} is the sum of ruminants from GLW in the IMAGE region.

The binary livestock system grid was obtained by summing NR per cell starting from the cell with the highest intensity score, until the sum equalled $NR_{reg/sys}$ for the intensive system. The intensity score was calculated by first ranking both a population density grid from 2UP (Huijstee et al., 2018) and the IMAGE cropland fraction grid, summing both ranks per grid cell, and then re-ranking to avoid same-number ranks. Cropland fraction is defined as the agricultural land fraction minus the grassland fraction. The use of population density and cropland fraction as predictors for livestock production system intensity was inspired by the livestock system classification scheme by Robinson et al. (2011).

Figure A5.2

Calculation of the risk of overgrazing



Source: PBL

Grass supply calculation

Grass supply (GS, in gC m^{-2}) is derived from a range of grass harvest simulations (GH, in gC m^{-2}) using the managed grassland module in LPJmL (Rolinski et al., 2018). Scenarios and settings are described in Table A5.4. In the model, grass harvest is dependent on grass demand.

$$GS = GH_{max} * f_{GAEZ} \qquad \text{(Eq.9)}$$

where GH_{max} is the maximum simulated grass harvest, and f_{GAEZ} is a reduction factor (agro-edaphic suitability) calculated with the global agroecological zones (GAEZ) model (IIASA/FAO, 2012). This factor is required as LPJmL does not consider soil suitability and assumes no yield reduction due to limited soil quality. Grass harvest increases linearly with increasing livestock unit (LSU) (i.e. grass demand) until grassland productivity starts to decline, at which point maximum productivity (GH_{max}) is reached. On the declining part of the curve, livestock cannot meet their daily grass demand, productivity declines, and overgrazing occurs. Two sets of grass harvest simulations were performed, one with 2 cm stubble length to simulate goat and sheep (which nibble grass much shorter than cattle), and one with 5 cm stubble length to simulate cattle. Scenario settings of LPJmL managed grass were chosen to match settings of the Global Land Outlook (GLO) baseline simulation of IMAGE-LPJmL (Table A5.4). The rotational grazing scheme is a variant of the 'daily grazing' routine in Rolinski et al. (2018), in which each grid cell is continuously grazed on a daily basis at average livestock density. This setting is more reflective not only of intensive grasslands that are rotationally grazed, but also of continuously grazed, extensive grasslands than evenly distribute ruminants, or daily rotations, which is the implicit assumption of the daily grazing routine.

Table A5.4
Description of scenarios and settings used for grass harvest simulations with LPJmL-managed grassland

Scenario settings	Description
RCP 6.0	Emissions scenario most compatible with the SSP2 socio-economic scenario used in the IMAGE baseline scenario
CO2 fertilisation	CO2 concentrations are expected to rise in the RPC 6.0 and, despite uncertainty, a positive effect on productivity can be expected
HadGEM / ISIMIP	Climate model (HadGEM) and data from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP)
Stubble height of 2 cm and 5 cm	Minimum thresholds at which grazing stops, in gC m-2, equivalent to the stubble height in cm. Stubble height of 2 cm is assumed for goat and sheep, and 5 cm for cattle
Rotational grazing	Grazing occurs on 3 days each month, at 10 times average livestock density, to simulate a herd moving through any location in a grid cell
LSU range: [0, 0.1, 0.2, 0.3, ... 4.0]	A range of livestock densities (LSU ha-1) were simulated. In LPJmL, LSU are assumed to consume 4,000 gC day-1, so LSU can be directly converted to grass demand

Overgrazing relevance

A high GI will not necessarily result in overgrazing. In areas with a stable, humid climate and sufficient management capacity, most or even all of the potential grass supply (GS) can be harvested without risk of overgrazing. Management capacity is difficult to model, and insufficient knowledge is available about which conditions result in management that avoids overgrazing.

Climate, however, can be approximated with the aridity index. The drier the area, the more likely it is that the water supply, and therefore the grass supply, will be erratic and prone to drought. In arid conditions, more grass needs to be left to mature for new seeds, or fire needs to be applied for range renewal (Müller et al., 2007; Steffens et al., 2013; Twidwell et al., 2013; Westoby et al., 1989). This means that, all being equal, a high GI becomes more relevant to overgrazing in arid areas. A second factor that makes a high GI more relevant to the overgrazing problem is the grassland fraction. The lower the grassland fraction, the less relevant grazing within the agricultural system is relative to alternative sources of agricultural activity. Conversely, in areas with a high grassland percentage, livelihoods are strongly coupled to the number of livestock, and opportunities to divert livestock from grazing land are fewer.

These two factors were combined to form a single relevance value. For aridity, the aridity factor in Table A5.3 was used, but with a different maximum value (AI_max= 10).

Relevance (REL) = 0.5 * aridity factor + 0.5 * gfrac (Eq.10)

Grid cells with less than 5% grassland were excluded because a low gfrac translates disproportionately into grass demand (Equation 5).

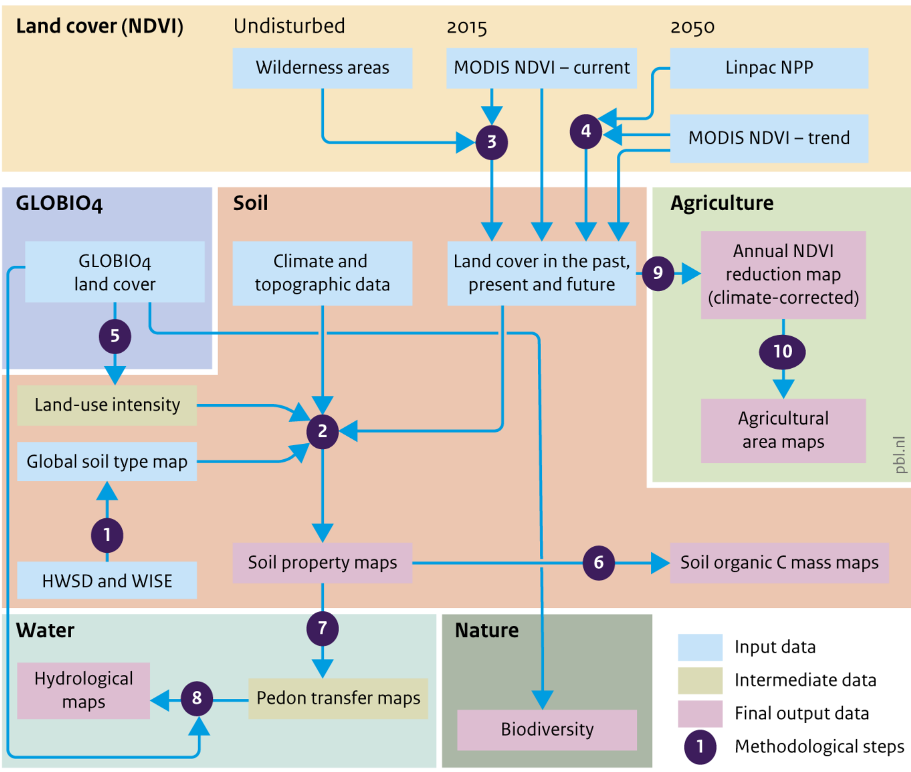
A6. Procedure to assess change in land condition and functions

A6.1. Introduction

This appendix presents the procedure for calculation of changes in land condition as described in Chapter 3 and Chapter 4 of this report. Section A6.2 of this appendix elaborates on changes in soil properties, in particular soil organic carbon. Section A6.3 discusses the impact of changes in soil properties and land cover on water scarcity and fluctuations in river discharges. Section A6.4 deals with the loss in productivity and the impact on the extent of cropland, and Section A6.5 with the loss of biodiversity resulting from land-cover loss in natural areas and productivity loss in cropland. **Figure A6.1** provides an overview of the calculation procedures in 10 steps, which will be referred to in the text below.

Figure A6.1

Procedure for the calculation of changes in land condition and functions



Source: PBL

A6.2. 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 A6.2.1 briefly describes how soil conditions are mapped. The second part, Section A6.2.2, describes the methodologies to map soil conditions in the undisturbed state and for the projected state in 2050. The adaptation of the S-World model to make it compatible with the IMAGE-GLOBIO model and to enable integrated scenario studies is also addressed. The result is a first estimate of soil properties at three points in time: a hypothetical original situation where soils are undisturbed, and therefore unaffected by anthropogenic land use and land-cover changes; the situation in 2015 ('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 different stages of socio-economic development (Kotiaho et al., 2016; UNEP, 2003).

A6.2.1. S-World, mapping of present soil properties

The S-World model (Stoorvogel et al., 2017a) was developed to produce global maps of soil properties, such as soil organic carbon (SOC), soil depth and soil texture. 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 property information with soil-forming factors such as climate and topography. The assessment of the impacts on ecosystem functions requires compatibility of the S-World model with other integrated assessment models such as IMAGE (Stehfest et al., 2014), GLOBIO (Schipper et al., 2020; Alkemade et al., 2009) and the water model PCR-GLOBWB (Sutanudjaja et al., 2014; Van Beek and Bierkens, 2009; Van Beek et al., 2011), as described in the following sections.

The S-World model consists of two components, elaborated in Step 1 and Step 2 (Figure A6.1). 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 Harmonized World Soil Database (HWSD) (FAO et al., 2012) provides a rough spatial representation of complex soil units that are present at the Earth's 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 current (2015) soil properties

In the S-World model (Figure A6.1), the local value of each soil property is a function of the following 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 the global soil profile database WoSIS (Batjes, 2017), which contains 118,400 soil profiles;

ii) **Climate**
the factors used are the mean annual temperature and precipitation from the WorldClim database (Fick and Hijmans, 2017);

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 the ESA land-cover maps (ESA, 2017);

v) Land cover
or vegetation cover protects the underlying soil from erosion and is a source of soil organic carbon. Land cover is derived from a five-year average of MODIS MOD13A3 NDVI image ('greenness') data over the 2010–2015 period (Didan, 2015).

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).

A6.2.2. 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 assessments of how much was lost in the past at different locations and, in the case of soil organic carbon, 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 second 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 or natural processes.

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 MODIS 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 2001–2018 period 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 GLOBIO4 model (Schipper et al., 2020; Alkemade et al., 2009) using input for the claims for cropland, pasture, rangeland and forestry from the IMAGE model. To ensure compatibility between maps of present and future land-use intensity, the 2015 map of S-World is replaced by the map derived from the GLOBIO4 model for the year 2015. The assessment procedure of land-use intensity is elaborated in Step 5.

The other 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 by assuming that climate conditions in the undisturbed state and future state are equal to those in the present (2015) situation. The resulting undisturbed-condition maps of soil organic carbon show a restoration potential under *current climate* conditions, instead of climate conditions of the past that no longer exist, 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 for SPOT NDVI data in Stoorvogel et al. (2017b); a similar approach has been applied to the MODIS MOD13A3 NDVI data (Didan, 2015). 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 served as a reference, using multiple regression kriging.

Step 4: Deriving land-cover maps for 2050 by trend extrapolation over the 2001–2018 period

To explore loss in soil properties up to 2050 due to land management, projections were made for land-use change and land-use intensity. For the land-cover map in 2050, current negative NDVI trends were extrapolated to 2050 (Step 4, Figure A6.1), assuming that these 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 different methods for the determination of 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 (two segments) as the most robust approaches. These methods are not dependent on the start and finish of growing seasons of crops, which are particularly difficult to estimate in areas with two cropping cycles. This approach is also followed in this assessment, with the exception that we did not use the segmented regression but a linear regression over the full period of 2001 to 2018. Also, instead of the NDVI data from the GIMMS3g data set, we used NDVI data from MODIS-MOD13A3 (Didan, 2015) over the 2001–2018 period at a resolution of 30 arc seconds.

The land-cover map as input for S-World is not climate-corrected; this is different from the approach in the first contribution to the Global Land Outlook (GLO1; Van der Esch et al., 2017). Only the non-climate trend is needed for the soil model because NDVI is used as a proxy for protection from erosion (bare or not bare) and as a source of biomass (carbon) into the soil. Therefore, instead of the anomaly with respect to climate, we used the observed trend for the soil.

For each grid cell, the annual trend was extrapolated to 2050. Only those grid cells (of a 30 arc-second resolution) were selected that had a negative trend with an r^2 above 0.1.

The NDVI trend per pixel was 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, $year_{start}$ is equal to 2010, and the % annual decline is derived from the NDVI change over the period 2001 to 2018. Applying a power function, the negative NDVI trends in the selected grid cells continue to 2050, though at a slowly declining rate. The resulting NDVI map for 2050 was 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 the conversion of the GLOBIO4 land-cover map (Step 5).

Climate-corrected NDVI trend

To assess the effect of the NDVI trend on yields, we need the climate-corrected NDVI trend; in this situation, we are interested in the difference with the expected climate trend because the IMAGE model already takes into account climate and we need to know the difference to model the loss in productivity.

Schut et al. (2015) compared the observed NDVI trends to 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, we used a slightly different approach in that we used the NDVI trend. We therefore converted the LINPAC TBW data into NDVI data and calculated the climate-related NDVI trends. These modelled climate-related trends in NDVI were used to correct the MODIS NDVI trends for the impact of structural climate change, which is described in the next two paragraphs.

The first step is to determine a relation between TBW and MODIS NDVI. LINPAC TBW and MODIS NDVI data differ in spatial resolution, therefore the average MODIS NDVI per 5 arc-minute resolution was calculated. Then, in RStudio, we determined the overall and biome-specific (from the WWF Terrestrial Ecoregions of the World (Olson et al., 2001)) relations using a polynomial regression model: NDVI ~ TBW + TBW^2.

Table A6.1

Regression parameters for converting LINPAC TBW into MODIS NDVI: NDVI ~ Intercept + factor1 * TBW + factor2 * TBW2

#	Biome	Intercept	factor1	factor2
1	Tropical and Subtropical Moist Broadleaf Forests	10042.49559	2.011990141	-0.000102287
2	Tropical and Subtropical Dry Broadleaf Forests	8870.260935	2.022433040	-0.000099219
3	Tropical and Subtropical Coniferous Forests	7769.622761	2.646601352	-0.000177475
4	Temperate Broadleaf and Mixed Forests	6675.260722	3.280383501	-0.000247940
5	Temperate Conifer Forests	5777.533741	3.998610964	-0.000378398
6	Boreal Forests/Taiga	4036.539049	3.221169300	-0.000110924
7	Tropical and Subtropical Grasslands, Savannahs and Shrublands	4311.311815	3.702958269	-0.000293497
8	Temperate Grasslands, Savannahs and Shrublands	4633.564711	3.141065849	-0.000173658
9	Flooded Grasslands and Savannahs	3293.710455	4.191824081	-0.000354382
10	Montane Grasslands and Shrublands	3291.383031	3.698495742	-0.000262072
11	Tundra	2460.895702	4.887566725	-0.001172875
12	Mediterranean Forests, Woodlands and Scrub	5414.191415	4.440900378	-0.000297310
13	Deserts and Xeric Shrublands	3605.151451	4.963662164	-0.000551942

14	Mangroves	9048.954392	1.372012489	-0.000030009
98	Water	2803.085868	4.627172730	-0.000401238
99	Ice	1854.256158	1.785044253	-0.000311513

For each year, this biome-specific relation was applied on the LINPAC TBW rasters, which resulted in $NDVI_{Linpac\_TBW}$ rasters for the years 2001 to 2016 (the end year of the LINPAC time series). For this period, the climate-expected NDVI trend was determined and subtracted from the MODIS NDVI trend to give the climate-corrected MODIS NDVI trend.

The following rules were used to apply the climate correction:

1. Check MODIS NDVI trend r^2 is above 0.1
    a. If false then climate-corrected trend is 0
    b. If true then check $NDVI_{Linpac\_TBW}$ r^2 is above 0.1
        i. If false then no climate correction, use MODIS NDVI trend
        ii. If true then do climate correction and subtract $NDVI_{Linpac\_TWB}$ slope from MODIS NDVI slope

Step 5: Replacing S-World data with GLOBIO4 data for land-use intensity in 2015 and 2050

Coupling the S-World soil model with IMAGE-GLOBIO4 is necessary to create projections of future change in soil properties. This was achieved by substituting the land-use intensity (LUI) map of S-World with a GLOBIO4-based map (Step 5 in Figure A6.1). The GLOBIO4 model uses output from the IMAGE model to calculate claims for specific land uses, such as urban, cropland, pasture, rangeland and forestry. Using the S-World methodology as a guide, we used the value from Table A6.2. Because output from GLOBIO is at a 10 arc-second resolution and data for S-World are at a 30 arc-second resolution, we averaged the weight factors from the converted GLOBIO4 land-use map. For this report, two LUI maps were created (Figure A6.1) to make it possible to track changes over time: one depicts the present state (2015) and one illustrates the projections for a future state.

Table A6.2
GLOBIO land-use type and weighting factors used for the generation of the land-use intensity maps that are used as input for S-World

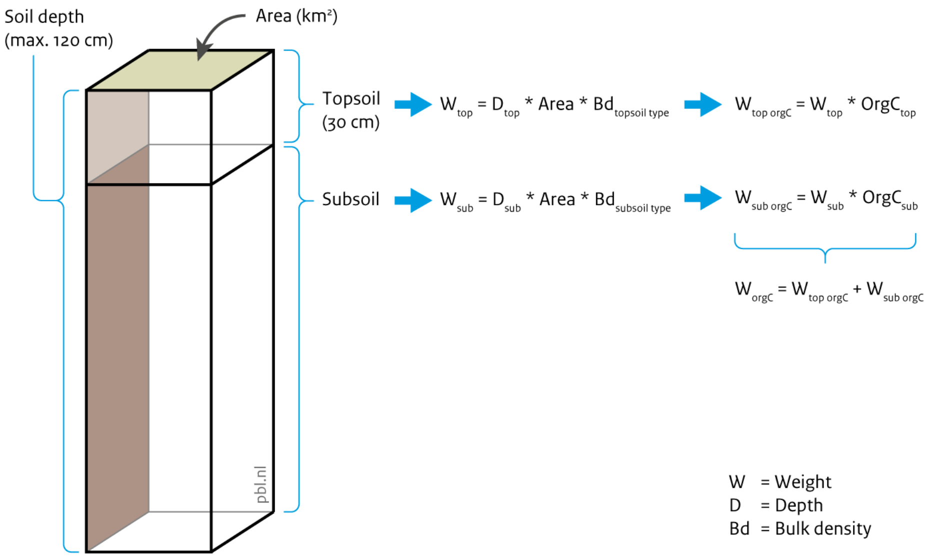
Land cover #	Description	Weight
1	Urban	75.0
2	Cropland	100.0
3	Pasture	20.0
	Other	0.0

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 at a 30 arc-second resolution (Step 6, Figure A6.1). 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 included in the equation (Figure A6.2). 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 Harmonized World Soil Database (HWSD; FAO et al., 2012), which provides data on the average bulk density for the top and sub-layers (FAO et al., 2012) per soil type (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 for the topsoil and subsoil were used. As a consequence, changes in the mineral composition of the soil (e.g. soil organic matter, clay or sand) therefore had no impact on the bulk density used to calculate the total mass of soil organic carbon. We chose not to calculate the bulk density from the S-World outcomes using, for example, formulas from Balland et al. (2008) because this would necessitate making assumptions about the particle density. The calculated total mass of soil organic carbon depends highly on the bulk density, see Figure A6.2. Consequently, variations in average bulk density estimates will lead 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 was calculated using that position, and assuming 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 was calculated as presented in Figure A6.2.

Figure A6.2
Calculation of the total mass of soil organic carbon



Source: PBL

The total stock of soil organic carbon changes over time (Step 6) and can be calculated by applying the S-World model according to Steps 1 to 4 in combination with the 2015 and 2050 land-use intensity maps in Step 5. For 2050, the figures were adjusted by first including changes in soil properties from the land-use change projected to take place between 2015 and 2050 under the baseline scenario ('Trend' column in Table A6.3).

Table A6.3
Soil organic carbon per region for different time points and scenarios

Region	Area (km2)	Natural (GtC)	Current (GtC)	Trend (GtC)
North America	19,974,189	342.9	322.4	318.3
Central and South America	18,292,022	285.1	269.4	264.5
Middle East and North Africa	10,877,247	52.8	50.5	49.7
Sub-Saharan Africa	23,937,930	246.4	228.6	218.4
Western and Central Europe	5,736,602	99.1	85.6	84.9

Russia and Central Asia	21,223,994	674.3	647.3	641.1
South Asia	5,018,825	58.6	45.9	44.8
China Region	10,839,432	96.7	87.2	87.6
Southeast Asia	4,869,244	131.2	118.2	113.9
Japan and Oceania	8,611,552	89.1	83.9	83.7
Greenland	2,112,774	2.3	2.3	2.3
Total	131,493,812	2,079[a]	1,941[a]	1,909[a]

a) Figures are rounded

A6.3. Water

The global hydrological model PCR-GLOBWB (Sutanudjaja et al., 2014; Van Beek and Bierkens, 2009; Van Beek et al., 2011) was applied to calculate water scarcity and changes in river discharge characteristics resulting from changes in land use, land cover, climate and soil properties. Section A6.3.1 briefly describes the technical features of the PCR-GLOBWB model. Section A6.3.2 describes the implementation of the soil property maps from S-World in the PCR-GLOBWB model, enabling the assessment of the impact of changes in land condition on water-holding capacity, water scarcity and river discharge. In this study, the impact of changes in soil properties was only determined for water-holding capacity, given the limitations of the modelling at this stage. However, the impact of climate change (precipitation and temperature) and land cover has been determined under the SSP2 scenario.

A6.3.1. 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 from 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 was further subdivided into different land-cover types. The seven land-cover types distinguished for this study are listed in Table A6.4.

Table A6.4
Land-cover types in PCR-GLOBWB

Nr.	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)

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 was compiled from different sources, and was in this case largely conditioned by land-cover and land-use information from the IMAGE model for the SSP scenarios. Of the land-cover types in Table

A6.4, 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 however be accurately linked to single land-cover units. Hence, the default PCR-GLOBWB does not distinguish between soil conditions for different land-cover types in a cell. By coupling S-World to PCR-GLOBWB, it is however possible to incorporate changes in soil properties.

A6.3.2. Incorporating S-World soil maps into PCR-GLOBWB

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 km^2) to be able to make a theoretical link between soil conditions and land cover, and to 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 on soil properties, by applying a land-use intensity map. However, this requires a means to transfer the soil information in S-World into the soil properties applied in PCR-GLOBWB and the use of a unified land-cover map.

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

The PCR-GLOBWB model cannot directly use the soil information in S-World, which has a finer spatial resolution and only specifies some general attributes. In Step 7, the soil attributes of S-World were transformed into the soil hydraulic properties such as water-holding capacity, field capacity and wilting point, which were then incorporated into PCR-GLOBWB using the pedotransfer functions of Balland et al. (2008). These functions were chosen because they are sound and compatible with the information supplied by S-World. Overall, these functions provide good results with high coefficients of determination and minimum 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) enable 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, all relevant properties were first calculated per 30 arc-second cell as originally provided by S-World for each scenario. This information was then scaled to the layer configuration of PCR-GLOBWB. In this study, the choice was 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 (100 cm), in which case a virtual, third layer was introduced that does not contain organic matter but has the same textural composition as the soil above. The soil properties of the three layers were then averaged proportionally by depth to provide an initial 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: Incorporating IMAGE land-use maps into PCR-GLOBWB and assigning soil properties from S-World

The large-scale hydrological model PCR-GLOBWB can be run at 5 and 30 arc minutes (0.0833333 and 0.5 decimal degrees) and requires information on land cover and soil properties. Land-cover information was assigned from IMAGE at 5 arc minutes with a focus on the agricultural crop types that are provided as a fraction of each cell. Soil properties were derived from the soil texture and SOC data of S-World that is available at 30 arc seconds (0.0083333). Consequently, information was processed to derive the PCR-GLOBWB parameterisation and often downgraded to match the coarser resolution, with one complete PCR-GLOBWB cell containing 100 30 arc-second cells at 5 arc minutes or 3,600 30 arc-second cells at 30 arc minutes.

For the soil parameterisation, the soil texture and SOC data from S-World were used to derive soil properties at 30 arc seconds and then averaged to the coarser PCR-GLOBWB cell where a distinction was made between cells that are in a near-pristine state and those strongly modified by man on the basis of the land-use intensity that was derived at 30 arc seconds using the GLOBIO land-use data set. 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. PCR-GLOBWB uses fewer and different types of land cover than IMAGE and assigns them to fractions of cells to simulate more accurately the hydrological response. Consequently, the cell-averaged values of the soil properties were linked directly to the IMAGE-derived land-cover parameterisation as cell-averaged values for two broad categories: (1) natural, in the case of near-pristine land-cover conditions, and (2) human land use, if the land cover is strongly modified by humans. This parameterisation therefore combines the available data, specifying at the cell level in PCR-GLOBWB the land cover and soil properties, but overlooks the fact that the data of the underlying sources do not necessarily reflect similar conditions at a finer level.

For the SSP2 scenario, without changes in soil properties, all S-World-derived soil properties at 30 arc seconds were averaged jointly, giving a single, homogeneous soil parameterisation that was applied to all land-cover types in a PCR-GLOBWB cell and that does not vary over time. 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.

A6.4. Food

A change in net primary productivity is likely to affect crop and grass production. In cases of locally declining yields, agricultural area will need to increase to compensate for the loss in productivity. In Step 9 (Figure A6.1), the change in productivity was derived from the change in climate-corrected NDVI. In Step 10, the additional expansion of agriculture was derived from the decline in productivity.

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 was 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 that additional cropland will be needed to compensate for the losses. The projected reduction in climate-corrected NDVI up to 2050, as elaborated in Step 4, was used as a first proxy for crop yield losses.

Step 9: Deriving agricultural productivity from NDVI

An annual climate-corrected NDVI reduction map was calculated using the climate-corrected NDVI maps cells with agriculture from Step 4. This map was used within the IMAGE model to assess the effects of changes in NPP, as a proxy for yield reduction on cropland. The 30 arc-second climate-corrected NDVI map, about 1 km² on the equator, was averaged to a 5 arc-minute resolution map for use within the IMAGE model. This aggregated NDVI map was converted into an annual NDVI reduction map using the following equation:

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

where $NDVI_{Agr\text{-}Sc}$ is the averaged aggregated NDVI map for the year 2050 and $NDVI_{Agr\text{-}current}$ is the averaged aggregated NDVI map for the present situation: the year 2010.

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, as established by the following formula:

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

After the soil-degradation effect on crop yields and grassland productivity was taken into account, the IMAGE land-use model was used to assess the losses in crops or livestock production. If demand for crops or livestock products is not met due to production losses, cropland or grassland expansion takes place (Step 10).

A6.5. Nature

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[12] of original species relative to their abundance in undisturbed ecosystems (Alkemade et al., 2009; Schipper et al., 2020). The IMAGE-GLOBIO model combination, applied to integrated global environmental assessments, calculates impacts on the MSA 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).

Biodiversity loss from agricultural expansion as compensation for productivity loss

There is an indirect effect from productivity decline, leading to losses in agricultural yields over the 2015–2050 period. The indirect impact on biodiversity is related to the additional expansion of

[12] 'Abundance' means 'population size'.

agriculture in natural areas to compensate for production loss in existing agriculture. This indirect effect of land-use change was determined according to the regular GLOBIO procedures, which deals with the expansion of cropland area.

A6.6. Method to assess restoration of soil functions in the Restoration scenario

An inventory was made of meta-analyses of the effect of different categories of soil restoration measures on soil organic carbon (SOC) sequestration, expressed as response ratio as well as absolute SOC stock change per year. Eight categories of soil restoration measures were defined and included, whereby the most encompassing measure was selected in the case of similar types of measures (e.g. conservation agriculture was selected as a category rather than cover crops or no tillage). Where multiple meta-analyses were available, a subset of the largest studies with the largest global spread of data points was selected for which georeferenced data points and effect size information were available.

Data points were geographically aligned with the climate zone map of Beck et al. (2018). Data points were only included if at least five years of post-restoration effect data were available. Effects were calculated for 30 cm soil depth by re-analysing data of SOC effects reported for soil depths within the range of 5 cm to 60 cm, and omitting studies reporting on shallower or deeper depths. Data on response ratios (RR) and SOC stock change rates were treated for extreme outliers, first globally and thereafter (number of data points allowing per climate zone). Overall effects for a restoration category were compiled over various data sets by attributing weights according to the number of data points. A climate zone-specific effect was given if there were at least five data points; otherwise, the overall effect (all climate zones) was used. For the spatial allocation, applicability limitations were considered for all restoration categories based on land cover, rainfall, slope, soil depth, soil texture, population density and distance to towns, ports and main roads. For each location (pixels of ca. 1 km^2), the most effective applicable type of restoration measure was implemented where the current SOC stock in the top 30 cm of soil is below the ceiling according to S-World (Stoorvogel et al., 2017).

1. Category-specific applicability limitations were considered.
2. Current SOC stock in top 30 cm soil (S-World) was taken as baseline.
3. Restoration effect was calculated based on response ratio (RR) multiplied by current SOC stock.
4. The estimated natural SOC ceiling was taken as maximum. If restoration effect hits this ceiling, no further improvement is possible.
5. Restoration effect was also limited by checking the p90 absolute annual SOC increase multiplied by the number of years.
6. The most limiting factor determined the restoration in each location.

A7. Restoration cost estimates

Table A7.1
Assumptions for range in commitments

Name	Description	Assumption	Total (ha)
Lower estimate	Calculation includes only the single highest commitment between all sources, per country	Assumes high overlap: all other (smaller) commitments for other sources are included in this	625,903,102
Middle estimate	Calculation includes only the highest target (between sources) per sub-category, per country	Assumes some overlap: that other sources with a smaller target in the same sub-category are included in the highest estimate of another source	812,193,938
Total estimate (not included)	All targets added up and combined per country	Assumes no overlap: each target is additional to the others, no overlap assumed	858,013,132

Table A7.2
Total range of commitments per primary and secondary category – middle estimate

	Primary aligned cost category	Secondary aligned cost category
Forest management	47,130,502	47,130,502
Passive regeneration	252,705,291	397,051
Forest plantations	116,095,789	368,404,029
Agronomic other	-	87,688,910
Irrigation	6,773,179	6,773,179
Grazing management	77,184,887	53,957,410
Agroforestry	377,400	377,400
Mixed	-	101,805,838
Conservation agriculture	98,768,960	11,080,050
Cross-slope barriers	97,112,995	97,112,995
Silvopasture	1,399,360	24,626,837
General/average	114,645,576	12,839,737
Total	812,193,938	812,193,938

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