Chapter 2

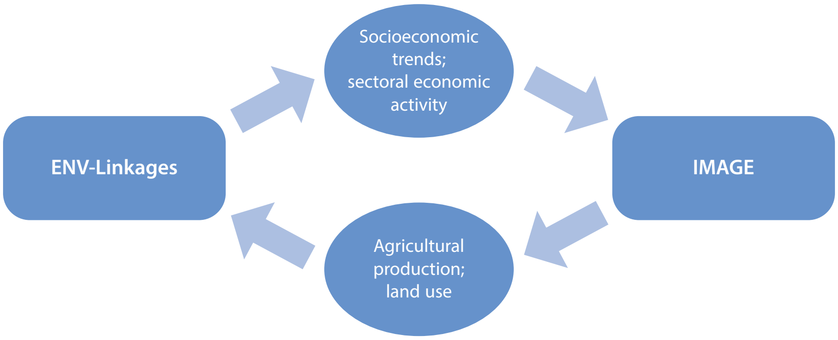
A framework for assessing the land-water-energy nexus

This chapter presents the methodology used in this report to calculate the biophysical and economic consequences of the nexus bottlenecks. This methodology is based on soft-linking the IMAGE model with its detailed, grid-level projections of the global biophysical system with the ENV-Linkages model, which describes the sectoral and regional economic system. The chapter describes how both models are linked. The chapter ends with a description of the scenarios used in the modelling analysis in subsequent chapters.

2.1. A multi-model framework

Quantifying the costs of inaction is achieved through linking a comprehensive model that represents the global biophysical system (IMAGE) with a comprehensive model of the economic system (ENV-Linkages), see Figure 2.1. The economic model provides baseline projections for sectoral and regional economic activity (based on exogenous projections of the socioeconomic drivers), and the biophysical model translates this into grid-cell projections for the use of land, water and energy resources.

Figure 2.1. **Modelling framework**



Making use of endogenously modelled processes, the biophysical model can identify how the different elements in the nexus (land, water, energy) affect each other and what impact a bottleneck for a nexus resource has on the availability and quality of the other nexus resources, and on the productivity of the land system. These changes in resource availability and land productivity (i.e. crop yields) can then be used an input for the economic model to assess the economic impacts of the LWE nexus resource bottlenecks.

More precisely, this multi-model framework is applied in two steps to provide insights into the costs of inaction. In a first step, the linked modelling framework is used to run a baseline. In a second step, counterfactual scenarios are run with the biophysical model in which a specific bottleneck (or a set of bottlenecks) is imposed or released. The IMAGE model provides detailed information on the availability of the nexus resources (e.g. water supply) and their efficiency (e.g. in sustaining crop yields) under a consistent set of assumptions on future developments. These are fed back into the ENV-Linkages model as revised assumptions on exogenous trends (e.g. land productivity by crop sector) to calculate the consequences for economic activities. Together, the baseline and counterfactual scenarios provide insights into the consequences of the nexus.[1]

The ENV-Linkages model developed by the OECD Environment Directorate is a global dynamic computable general equilibrium (CGE) model that describes how economic activities are linked to each other across sectors and regions; the model is described in more detail in Chateau et al. (2014). The model has considerable detail regarding the structure of production and the flows of factors and produced goods and services across the economy and international trade flows between economies. Sectoral production is represented through a production function, which allows for a detailed representation of environmental feedbacks on the different drivers of economic growth. Land as an input to agriculture is explicitly modelled as a primary factor for agricultural production, and, like other production factors, is in limited supply. The energy system is also represented in detail. However, the model in its current form does not explicitly capture water use; rather, it relies on implicit assumptions on future water use in agriculture through the specification of crop yields as provided by IMAGE.

IMAGE is a comprehensive integrated modelling framework of interacting human and natural systems; Stehfest et al. (2014) provides a comprehensive overview of the model. The IMAGE model is suited to large scale (global and regional) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems and indicators. IMAGE contains detailed representations of processes governing water and land use as well as a detailed description of the energy sector. It does not only model the relevant processes for each separate sector but also their interactions. IMAGE is characterised by relatively detailed biophysical processes, a wide range of environmental indicators (including water, energy and land), and spatial explicitness where many calculations are performed at the grid level. Each grid cell is characterised by its climate (e.g. temperature, precipitation), soil, topography, and land cover (natural or anthropogenic). Because of this spatial explicitness, IMAGE can account for variability within and between regions and provide regional inputs for the economic analysis with ENV-Linkages (i.e. region-specific estimates of land supply and yields).

The regional aggregation of both models have been harmonised to 23 regions encompassing the world. For presentational purposes, these 23 regions are sometimes further aggregated into eight macro regions, as shown in Table 2.1.

Table 2.1. **Overview of the regional aggregation of the modelling analysis**

Macro region	Model countries and regions	Most important comprising countries and territories
OECD America	Canada	Canada
	Mexico	Mexico
	United States	United States
OECD Europe	OECD EU	France, Germany, United Kingdom, Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, Greece, Hungary, Ireland, Luxembourg, Netherlands, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden
	Other OECD	Israel,[1] Switzerland, Norway, Turkey, Iceland, Liechtenstein
OECD Pacific	Australia & New Zealand	Australia, New Zealand
	Japan	Japan
	Korea	Korea
Rest of Europe & Asia	China (People's Republic of)	China (People's Republic of) and Hong Kong (China)
	Non-OECD EU	Cyprus,[2] Latvia, Lithuania, Malta, Bulgaria, Croatia, Romania
	Russian Federation (hereafter "Russia")	Russia
	Caspian region	Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, Uzbekistan
	Other Europe	Albania, Belarus, Ukraine, Republic of Moldova, Andorra, Bosnia and Herzegovina, Gibraltar, Former Yugoslav Republic of Macedonia, Montenegro, San Marino, Serbia

Table 2.1. **Overview of the regional aggregation of the modelling analysis** *(continued)*

Macro region	Model countries and regions	Most important comprising countries and territories
Latin America	Brazil	Brazil
	Other Latin America	Argentina, Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Guyana, Suriname, Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Belize, Antigua and Barbuda, Bahamas, Barbados, Cayman Islands, Cuba, Dominica, Grenada, Haiti, Montserrat, Saint Kitts and Nevis, Saint Lucia, Saint Vincent and the Grenadines, Turks and Caicos Islands
Middle East & North Africa	Middle East	Oman, Bahrain, Islamic Republic of Iran, Kuwait, Qatar, Saudi Arabia, United Arab Emirates, Iraq, Lebanon, Syrian Arab Republic, Yemen
	North Africa	Egypt, Morocco, Tunisia, Algeria, Libya, Western Sahara
South & South-East Asia	ASEAN 9 (excl. Indonesia)	Cambodia, Lao People's Democratic Republic, Malaysia, Philippines, Singapore, Thailand, Viet Nam, Brunei Darussalam, Myanmar, Timor-Leste
	Indonesia	Indonesia
	India	India
	Other Asia	American Samoa, Cook Islands, Fiji, Guam, Kiribati, Marshall Islands, Federated States of Micronesia, Nauru, New Caledonia, Niue, Northern Mariana Islands, Palau, Papua New Guinea, Pitcairn, Samoa, Solomon Islands, Tokelau, Tonga, Tuvalu, Vanuatu, Wallis and Futuna Islands, Mongolia, Democratic People's Republic of Korea, Bangladesh, Nepal, Pakistan, Sri Lanka, Afghanistan, Bhutan, Maldives
Sub-Saharan Africa	South Africa	South Africa
	Other Africa	Cameroon, Côte d'Ivoire, Ghana, Nigeria, Senegal, Benin, Burkina Faso, Guinea, Togo, Cabo Verde, Gambia, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Saint Helena, Ascension, and Tristan da Cunha, Sierra Leone, Central African Republic, Chad, Republic of the Congo, Equatorial Guinea, Gabon, Sao Tome and Principe, Angola, Democratic Republic of the Congo, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, United Republic of Tanzania, Uganda, Zambia, Zimbabwe, Rwanda, Burundi, Comoros, Djibouti, Eritrea, Mayotte, Seychelles, Somalia, Sudan, Botswana, Namibia, Lesotho, Swaziland

Notes: 1. The statistical data for Israel are supplied by and under the responsibility of the relevant Israeli authorities. The use of such data by the OECD is without prejudice to the status of the Golan Heights, East Jerusalem and Israeli settlements in the West Bank under the terms of international law.

2. Note by Turkey: The information in this document with reference to "Cyprus" relates to the southern part of the Island. There is no single authority representing both Turkish and Greek Cypriot people on the Island. Turkey recognises the Turkish Republic of Northern Cyprus (TRNC). Until a lasting and equitable solution is found within the context of the United Nations, Turkey shall preserve its position concerning the "Cyprus issue".

Note by all the European Union Member States of the OECD and the European Union: The Republic of Cyprus is recognised by all members of the United Nations with the exception of Turkey. The information in this document relates to the area under the effective control of the Government of the Republic of Cyprus.

The complementarity between ENV-Linkages (with its detailed production structure for economic activities) and IMAGE (with its detailed biophysical modelling framework) makes these combined models an appropriate toolkit for studying the land-water-energy nexus. Nonetheless, not all of the linkages relevant for the nexus analysis can be captured in IMAGE or ENV-linkages. In soft-linking IMAGE and ENV-Linkages, there is no perfect match. The level of sophistication with which nexus issues can be included depends on model features and data availability. Table 2.2 gives an overview, and highlights which elements are captured in the models, which can only be assessed outside the modelling frameworks through anecdotal evidence, and which are entirely absent from the analysis in this report.

Table 2.2. **Overview of the nexus linkages and how they are captured in the analysis**

Nexus linkages	Type of impact	Treatment in this report
Land bottlenecks	Impact on water resource	Modelled in IMAGE through effect of agriculture on water quantity and quality
	Direct impact on agricultural and forestry sectors	Modelled in IMAGE and ENV-Linkages
	Impact on energy resource	Modelled in IMAGE and ENV-Linkages through endogenous bio-energy production
	Indirect impact on rest of the economy	Modelled in ENV-Linkages
Water bottlenecks	Direct impact on water sector	Not modelled
	Impact on land resource	Modelled in IMAGE through effect on agricultural yields
	Impact on energy resource	Anecdotal evidence on water for electricity
	Indirect impact on rest of the economy	Only indirect consequences of changes in crop yields
Energy bottlenecks	Impact on water resource	Anecdotal evidence on desalination
	Impact on land resource	Indirectly modelled in ENV-Linkages through agricultural energy use
	Direct impact on energy sectors	Modelled in ENV-Linkages
	Indirect impact on rest of the economy	Modelled in ENV-Linkages
Cross-cutting trends	Climate change	Modelled in IMAGE (water availability and use; yields) and in ENV-Linkages (effects through land availability and energy demand)

2.2. Assessing the biophysical impacts with IMAGE

Modelling water resources

The water bottleneck has been incorporated by looking at regional water scarcity. To assess this, IMAGE includes the hydrology model LPJml that calculates water demand and water availability at high spatial and temporal resolutions. Water quality as a bottleneck is yet not modelled in IMAGE.

Total water demand is the sum of the demand for agriculture/irrigation, livestock, electricity production, manufacturing and domestic demand. The demand in each grid cell is calculated as the product of crop irrigation demand and a country-specific irrigation efficiency factor that reflects the type and efficiency of prevailing irrigation systems

(Rost et al., 2008). Irrigation water is extracted from rivers and lakes in the grid cell or a neighbouring grid cell. If these local surface water sources cannot meet total demand, water is extracted from nearby (large) reservoirs – if available – or from groundwater reservoirs. The latter can be a limited or an unlimited source of water, which can be interpreted as non-sustainable groundwater.

The water demand for other sectors is calculated separately from LPJml:

- For the electricity sector, the type of power plant (e.g. standard steam cycle, combined steam cycle) determines the demand for cooling capacity (Davies et al., 2013; Bijl et al., 2016). In addition, the type of cooling facility determines the quantity of water required. Once through cooling systems use large volumes of surface water that are returned almost entirely to the water body from which they were extracted, albeit at an elevated temperature. Wet cooling towers exploit the evaporation heat capacity of water and thus require lower water volumes. However, a significant part of the cooling water evaporates during the process and does not return to the original water body. Estimates are based on Bijl et al. (2016).
- Livestock water demand is not included in the CIRCLE scenario projections.
- For household and manufacturing sectors, data and algorithms are derived through the methodology of Bijl et al. (2016). Both household and manufacturing water demand is a function of population size, corrected for structural and efficiency changes that relate to increases in regional income (GDP).
- The current version of IMAGE does not take into account the water needs of natural ecosystems, or of other uses such as shipping and recreation.

Largely reflecting existing water allocation rules (OECD, 2015b) and given the often observed difference in bargaining power and the economic losses incurred from interrupted water supply, meeting the demand from the electricity, household and manufacturing sectors receives priority in IMAGE over water withdrawal for irrigation.

Water stress has different impacts on the different sectors in IMAGE. For agriculture, the IMAGE model simulates lower production levels – especially in irrigated areas – due to limited water availability (Biemans, 2012). Under such conditions, the distribution of crops over the available land may change, new areas could come into production to meet regional crop demand (expansion) and management practices might need to intensify (intensification).

Water availability results in IMAGE from changes in various endogenous water flows. Firstly, there is surface water. This is in each grid cell the result of the net precipitation in a grid cell (i.e. gross precipitation minus interception of the land cover and evapotranspiration from soil and land cover), the net change in water storage in a grid cell (e.g. through snow melt), the inflow from surrounding grid cells using a routing algorithm (Rost et al., 2008), and a runoff into surface water storage in the cell, and subsequently flows downstream. Secondly, the IMAGE model includes three types of large reservoirs that could supply water in case local surface water sources are insufficient to cover the demand in a grid cell. The three types differ in the level that the water is used for irrigation or for other purposes, varying from primarily use for irrigation to not used for irrigation at all (Biemans et al., 2011). These reservoirs are included because about 50% of the river systems are regulated (Nilsson et al., 2005). Finally, groundwater formations can supply water to cover the demand (e.g. three out of the five water basins on the Indian subcontinent strongly rely on groundwater resources to meet irrigation water demand). Some of these formations are very large and use can be seen as sustainable, for others this is not the case.

Thus, IMAGE assumes groundwater withdrawals to be sustainable as long as they do not exceed the annual groundwater recharge. If the withdrawal demands exceed the annual groundwater recharge, it assumes that water is not available and demand is not met, unless the demand is at a location where there is an aquifer according to the WHYMAP dataset (BGR/UNESCO, 2015). At those locations the remaining demand is fulfilled from that aquifer. Groundwater recharge is contributing to river baseflow. The relation between groundwater recharge and river baseflow is implemented as a linear reservoir with a uniform release coefficient of 1/100, meaning that the average residence time of groundwater is around 100 days. Therefore there is a direct link between groundwater and surface water, and a direct link between upstream water use and downstream availability. If water is withdrawn from groundwater, it decreases the downstream baseflow and therefore surface water availability.

Modelling land resources

One of the important features of the IMAGE model is the explicit consideration of different types of land use and cover. The land-use categories are:

- Agricultural (irrigated and non-irrigation) and grassland areas to meet the demand for food and fodder.
- Other crop area to cover the demand for cash crops, such as fruits and fibres.
- Bioenergy area to meet the demand for biofuels.
- Built-up areas, which are assumed to be excluded from other biophysical applications in IMAGE
- Forest areas – including plantations established by humans – to cover the demand for timber (i.e. paper/pulp, sawlogs and traditional biomass for energy); and newly established forests for carbon storage (afforestation/reforestation under the climate convention).
- Other areas covered by natural vegetation to include areas that are not (strongly) affected by humans. These areas could be taken into human production in future, with the exception of protected areas and unsuitable areas such as deserts and ice.

Human activities affect many of these land-use categories, transforming natural areas to human dominated landscapes, changing ecosystem structure and species distribution, and water, nutrient and carbon cycles. Natural landscape characteristics and land cover also affect humans, determining suitable areas for settlement and agriculture, and delivering a wide range of ecosystem services. As such, land cover and land use in IMAGE results also from the interplay of natural and human processes, such as crop cultivation, fertiliser input, livestock density, type of natural vegetation, forest management history, and built-up areas.

Changes in different land-use purposes drive, among others, the land demand and supply in IMAGE for food, fodder, grassland, biofuels and timber. The demand is derived from economic activities and demographic information, like changes in income, income elasticities, commodity prices, etc.as provided by the ENV-Linkages baseline projection.

Land cover and land use are also the basis for the land availability assessment in IMAGE. In principle, the different land-use categories are allocated to grid cells in an iterative process until the regional demand is met. First, it is determined whether the supply from land-cover and land-use maps of the previous time step can meet the different demands. Yield changes over time are possible due to climatic and technological changes. If the production is lower than the demand, the area for the particular land-use form needs to become expanded, most often at the cost of natural vegetation. In contrary, when production exceeds the demand, land can become abandoned.

In determining the location of land expansion in a region, all grid cells are assessed and ranked by suitability, based on an empirical regression analysis. Suitability, in turn is determined by climate, atmospheric conditions like ozone, terrain characteristics (soil, slope) and two socio-economic variables (i.e. population density and accessibility). Additionally, a few other rules are applied in determining the suitability of a grid cell. For instance, agricultural expansion is not permitted in protected areas, and in areas otherwise protected, such as in assumed REDD (reducing emissions from deforestation and degradation) schemes. Finally, optionally a small random factor can be included to account for inherent uncertainty and non-deterministic behaviour of land-use change processes, allowing the emergence of new patches.

In IMAGE the specification of land competition, i.e. the allocation of the different land-use forms in the regions is done through a hierarchical land allocation mechanism. First, urban built-up areas and infrastructure is allocated. Second, the area for food/fodder (including other crops) is allocated, followed by the area for biofuels. Fourth, forests become productive and/or forest plantations are established to meet the regional demand for timber, and fuelwood, using different forest management systems. Finally, when a grid cell is not used to meet one of the demands, it is assumed to be covered by natural vegetation. These areas are very relevant as they play an important role in the global carbon cycle and as such in future climate change. Such a hierarchy can lead to simulations where, for example, built-up areas expand into very productive agricultural areas, resulting in additional demand for agricultural land elsewhere. Note that this effect is small compared to other drivers of agricultural land-use change.

In IMAGE, land use and land competition directly affect the other nexus resources:

- Different land uses have different water demands and thereby affect hydrology.
- Land suitability, degradation and competition affects the potential for biofuel production in a region and as such the energy supply.
- Climate change and atmospheric conditions (including ozone concentrations) affect land uses differently, and as such the land competition.

Modelling energy resources

Energy (demand and supply) is a central component of the IMAGE model and covers all major relevant aspects of the energy system; the focus in this section is on parts that are relevant for the land, water and energy nexus.

Energy interacts in multiple ways with water and land in IMAGE:

- Energy production is an important source of greenhouse and other gasses. Resulting changes in climate and atmospheric composition affects productivity of the different land-use types and as such in land demand.
- Different ways to produce energy have different demand for water. This can be cooling water in thermal power plants, or the water availability for hydro power and biofuels.
- Biofuels also compete with other demand for land, an interaction where water availability is included.

The IMAGE specification of the energy system is not used for the analysis, as this sector is sufficiently covered in the ENV-Linkages model.

Modelling feedbacks in IMAGE

These biophysical relationships in IMAGE have multiple dimensions that have an effect on the socio-economic dimensions as used in ENV-Linkages. Land productivity, for example, can change over time (e.g. due to climate and atmospheric changes, land degradation/overexploitation, agricultural intensification), affecting the land demand in a region. Likewise, land competition can result in changes in land demands (e.g. the expansion of built-up areas at the cost of high productive agricultural land). These feedbacks are relevant because of the assumption in IMAGE that most productive areas are used first, implying that expansion and relocation lead to the use of less productive regions with increasing operational costs. At the same time, information from ENV-Linkages (e.g. on agricultural management) is relevant for determining land production and land competition.

IMAGE represents a unified biophysical representation of linked land/water/atmosphere processes, including feedback such as changes in agricultural productivity due to climate change, or impacts of land-use change on the hydrological cycle, subject to human activities. Also interactions between the energy sector and land-use are accounted for, e.g. in the case of bio-energy production and use. Some feedbacks are not included in the current IMAGE model, such as additional energy use to sustain agricultural intensification (e.g. for fertiliser production and mechanisation).

2.3. Linking biophysical impacts to economic damages with ENV-Linkages

Modelling economic activity in ENV-Linkages

The detailed representation of economic activity in ENV-Linkages makes it especially suited for studying how environmental feedbacks affect the economy (as OECD, 2015a, shows for the feedbacks from climate change).

ENV-Linkages is a global dynamic computable general equilibrium (CGE) model that describes how economic activities are linked to each other between sectors and across regions. The version used for the current analysis contains 35 economic sectors and 25 regions, bilateral trade flows and has a sophisticated description of capital accumulation using capital vintages, in which technological advances only trickle down slowly over time to affect existing capital stocks.[2] It also links economic activity to the use of natural resources and to environmental pressure, specifically to GHG emissions, and contains feedbacks from climate change impacts on the economy.

Production in ENV-Linkages is assumed to operate under cost minimisation with perfect markets and constant return to scale technology. The production technology is specified as nested Constant Elasticity of Substitution (CES) production functions in a branching hierarchy. This structure is replicated for each output, while the parameterisation of the CES functions may differ across sectors. The nesting of the production function for the agricultural sectors is further re-arranged to reflect substitution between intensification (e.g. more fertiliser use) and extensification (more land use) of activities; or between intensive and extensive livestock production. The structure of electricity production assumes that a representative electricity producer maximises its profit by using the different available technologies to generate electricity using a CES specification with a large degree of substitution. Non-fossil electricity technologies have a structure similar to the other sectors, except for a top nesting combining a sector-specific natural resource with all other inputs. This specification acts as a capacity constraint on the supply of these electricity technologies. The model adopts a putty/semi-putty technology specification, where substitution possibilities among factors are assumed to be higher with new vintage capital than with old vintage capital. This implies relatively smooth adjustment of quantities to price changes. Capital accumulation is modelled as in the traditional Solow/Swan neo-classical growth model.

The energy bundle is of particular interest for analysis of nexus issues. Energy is a composite of fossil fuels and electricity. In turn, fossil fuel is a composite of coal and a bundle of "other fossil fuels". At the lowest nest, the composite "other fossil fuels" commodity consists of crude oil, refined oil products and natural gas. The value of the substitution elasticities are chosen as to imply a higher degree of substitution among the other fuels than with electricity and coal.

Household consumption demand is the result of static maximisation behaviour which is formally implemented as an "Extended Linear Expenditure System". A representative consumer in each region – who takes prices as given – optimally allocates disposal income among the full set of consumption commodities and savings. Saving is considered as a standard good in the utility function and does not rely on forward-looking behaviour by the consumer. The government in each region collects various kinds of taxes in order to finance government expenditures. Assuming fixed public savings (or deficits), the government budget is balanced through the adjustment of the income tax on consumer income. In each period, investment net-of-economic depreciation is equal to the sum of government savings, consumer savings and net capital flows from abroad.

International trade is based on a set of regional bilateral flows. The model adopts the Armington specification, assuming that domestic and imported products are not perfectly substitutable. Moreover, total imports are also imperfectly substitutable between regions of origin. Allocation of trade between partners then responds to relative prices at the equilibrium. Market goods equilibria imply that, on the one side, the total production of any good or service is equal to the demand addressed to domestic producers plus exports; and, on the other side, the total demand is allocated between the demands (both final and intermediary) addressed to domestic producers and the import demand.

Modelling environmental feedbacks in ENV-Linkages

The sectoral and international trade representation in computable general equilibrium (CGE) models is particularly suited to modelling the economic consequences of the modelled biophysical shocks. The biophysical shocks lead to changes in the equilibrium prices and supply of primary factors, which are unevenly spread across sectors and regions. The specification of international commodity markets in the CGE model allows projection of how demand, supply and trade patterns in all sectors and all regions adjust to minimise economic damages and maximise opportunities. These adjustments that take place in the model can be considered as market-driven adaptation, which already diminishes the level of damages imposed. For instance, a change in land productivity in a region will trigger substitution responses by agricultural producers that alter not only their use of land but also uses of other inputs, and substitution responses by consumers that may shift away to foreign producers of the commodity and to other commodities.

The production function approach that was used for studying the costs of inaction on climate change (OECD, 2015a) is also adopted to investigate the economic consequences of the nexus bottlenecks. In general terms, the production function approach specifies how nexus bottlenecks affect key elements in the sectoral production functions. Parameters capturing the level of productivity, biased technical change and changes in use of primary factors can be modified to reflect these bottlenecks. Similarly, changes in the households' demand system can be used to reflect consumption-related impacts. Finally, impacts on the supply of primary factors are important because they affect producers' input demands and output supplies as well as consumers' income and expenditures, which in turn lead to shifts in the equilibria in markets for factors and commodities.

In the illustrative set of scenarios analysed for this report, the impacts of the bottlenecks on the agricultural and land systems are passed from IMAGE to ENV-Linkages.[3] Specifically, IMAGE outputs for changes in crop yields and agricultural land use are used as input shocks in ENV-Linkages. Thus, the parameters that are affected in ENV-Linkages are agricultural productivity and land supply. Furthermore, the impacts of the energy bottleneck on the energy system are reproduced in ENV-Linkages through increased biofuel supply.

While other links between the environmental and economic systems can easily be imagined and quantitatively described, no other shocks are implemented in the scenarios in this report. The main reason for this is that insufficient data is available to provide robust quantitative assessments of these additional shocks, and the difficulty in teasing out such additional impacts from the ones that are quantified via the link with IMAGE.

2.4. Overview of the modelling scenarios

The combination of the IMAGE and ENV-Linkages modelling tools can illustrate the systemic effects of bottlenecks in the nexus: they provide a wide representation of global economic activity and their links to the biophysical system. However, there are significant data gaps that prevent a full inclusion of existing and potential nexus bottlenecks in the baseline projection provided by the models. More fundamentally, many of the consequences of the bottlenecks in the nexus operate on very specific local scales, both in terms of time and space. For instance, a drought will have serious short-term consequences within that particular area, but if the disruption is limited in time and geographical scale, it may not affect annual GDP much. But for wider scale bottlenecks, there are systemic effects that transcend the local community. The purpose of the modelling analysis is to shed light on these systemic effects, and illuminate the key mechanisms at play that are fundamental to the nexus. In order to do so, the modelling scenarios are constructed in a consistent, but stylised manner. Regarding the timing of the different bottlenecks, much is uncertain. Therefore, this report focuses on results by 2060, assuming the bottlenecks will have reached their full impact before then. This long-term horizon helps to shed light on the major permanent consequences of the nexus, but the analysis inherently remains more limited in describing the adjustment process.

A dynamic, disaggregated, integrated systems analysis of the combined costs of all the bottlenecks outlined in Chapter 1 can be considered to reveal the costs of inaction on the nexus. This refers to a scenario of inaction, in which policies remain absent for reconciling economic growth with resource preservation. A complexity in quantifying the consequences of the nexus lies in the interdependencies between land, water and energy resources. These resources are intricately linked, and many economic activities can substitute one of these resources with the others. A bottleneck in the availability of one resource can hence result in a higher demand for the other resources. Identifying how the different elements in the nexus (land, water, energy) affect each other and what impact the demand for one nexus resource has on the availability and quality of the other nexus resources is therefore important when quantifying the biophysical and economic consequences. The general concept behind CIRCLE's analysis is therefore to compare the system-wide performance of scenarios with selected nexus bottlenecks to a baseline projection without bottlenecks. A systems approach also allows illuminating how the consequences of combined bottlenecks are determined by specific interactions, and to what extent the various bottlenecks amplify or dampen each other.

A major complexity is that the costs of the various bottlenecks cannot be simply added up to determine an overall nexus-wide impact, given the strong internal linkages in the nexus. Therefore, the consequences of the nexus are first assessed for each individual counterfactual ("bottleneck") scenario. An illustrative scenario is designed for each of the three domains, based on an assessment of their significance and suitability for combination. A second step then consists of investigating an integrated scenario where multiple bottlenecks are addressed simultaneously, to provide deeper insights into the interaction effects between the different bottlenecks. A final third step is then to overlay this integrated scenario with changes in the climate system, to illustrate the role of the underlying megatrends that affect baseline projections between now and 2060.

Baseline projection: No bottlenecks

The baseline projection reflects the "business as usual" developments that are projected by the modelling tools in the absence of feedbacks from the nexus bottlenecks. The modelled baseline reflects a continuation of current socio-economic developments, including demographic trends, urbanisation and globalisation trends. The baseline reflects a continuation of current policies; it excludes new policies and feedbacks from air pollution and climate change impacts on the economy. This corresponds to the "no-damage baseline projection" in the CIRCLE analysis of the consequences of climate change (OECD, 2015a) and "no-feedback baseline projection" in the analysis of the consequences of outdoor air pollution.

Thus, the baseline projection resembles a hypothetical projection that ignores feedbacks from land, water and energy scarcity on the biophysical and economic system. The logic of this approach is not to deny that the nexus is already affecting these systems, but rather to be able to measure the consequences of the bottlenecks. The baseline projection describes the pressures that economic activity puts on the environment, by linking economic activity to the biophysical system. The bottleneck scenarios take this baseline projection to calculate the biophysical impacts of the bottleneck, describe how these feed back to the economy and project the resulting changes in economic activity, and calculate a range of specific indicators. The difference in indicators between the two projections reflects the consequences of the bottleneck.

Water bottleneck scenario: Limiting groundwater extraction

This scenario explores the effect of reductions in the availability of groundwater for agricultural production, used in many world regions to supplement inadequate supplies of surface water to sustain crop growth (see Box 2.1). In several cases, however, the continued supply of sufficient groundwater is not guaranteed. In the baseline, by assumption any differences between water demand for irrigation and surface water supply is always met by extraction of groundwater, i.e. ENV-Linkages and IMAGE assume no limits on the continued supply of groundwater available for irrigated land, ignoring potential groundwater scarcity issues in their calculations. The counterfactual analysis in this scenario explores what the impact would be of an emerging depletion of groundwater in specific reserves. In some regions, groundwater reserves and recharge rates are quite large and their depletion is by no means imminent, but groundwater extractions in other regions exceed recharge rates and depletion of these groundwater resources is a real possibility. Note that only withdrawal demands exceeding the annual groundwater recharge is restricted in the counterfactual scenario (see Box 2.1).

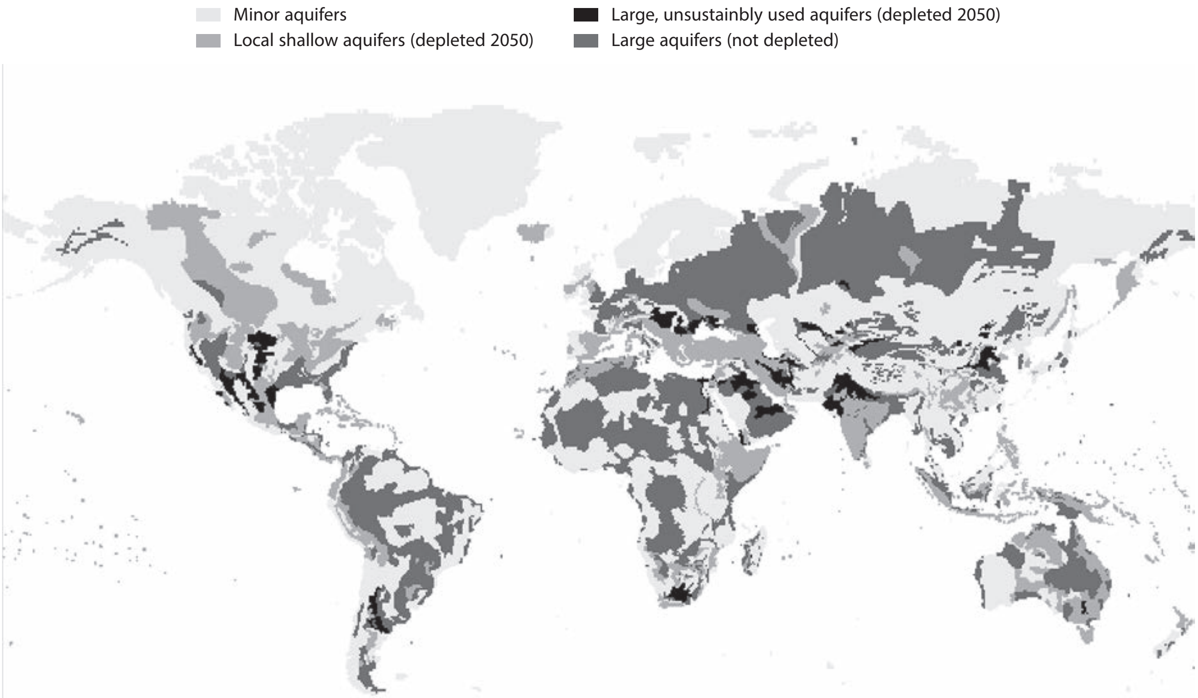
Box 2.1. **Sources of agricultural water supply**

Water use in agriculture draws from both surface water and groundwater. The modelling framework models the annual hydrological cycle including groundwater recharge; i.e. annual groundwater recharge flows are explicitly modelled and groundwater withdrawals reduce these recharge flows, which in turn reduces base flow downstream. These groundwater recharge flows are referred to as "renewable" groundwater in this report.

Some aquifers have lower recharge rates and are more vulnerable for unsustainable groundwater use, with groundwater withdrawals becoming higher than recharge rates (Figure 2.2). Such unsustainable groundwater use is captured in the modelling framework through a different "non-renewable" groundwater fraction. The modelling framework can restrict the use of this additional "non-renewable" groundwater fraction when an aquifer is "depleted" in the groundwater limitation scenario.

Although the labelling of renewable and non-renewable groundwater is technically not entirely correct, this terminology is shorthand for the more complex representation of water flows in the modelling framework.

Figure 2.2. **Overview of affected aquifers**



Source: IMAGE model based on WHYMAP (BGR/UNESCO, 2015) and Gleeson et al. (2012).

The specification of the depletion rates of aquifers in the model suite is based on the approach in a global analysis by Gleeson et al. (2012) to identify which groundwater aquifers are possibly used unsustainably. In the analysis, unsustainable use is associated with the groundwater "footprint", i.e. the area required to receive sufficient precipitation, given the local intensity, to sustain groundwater use and groundwater-associated ecosystem services. The larger the ratio between the water-collecting surface area and the area covered by the aquifer, the bigger the risk that extraction will exceed influx and thereby gradually exhaust the reservoir.

Unfortunately, insufficient and incomplete information exists to date that would make it possible to realistically assign depletion risks to all aquifers (although a number of ongoing research projects use Grace satellite data to improve on this). Therefore, the ad-hoc assumption is made that aquifers for which the water-collecting surface area exceeds five times their geographic area are depleted by 2055 and will become unavailable for irrigated agriculture from that year onwards. Hence, no attempt is made to model a smooth adjustment of groundwater extraction over time to minimise the impacts, but one source of water for irrigation is discontinued. Obviously, groundwater from aquifers that are not considered at risk of depletion remains available for irrigation. Additionally, groundwater from local aquifers is also assumed to become depleted by 2055. This does not mean that the entire aquifer is depleted, but that withdrawals from the non-renewable part are no longer available. In conformity with Wada et al. (2012), groundwater irrigation is assumed to be absent in all locations with very limited groundwater resources – both in the baseline and in the counterfactual scenario. The consequences of this bottleneck on water availability for water use by region is shown in Section 4.1, but Figure 2.2 shows the substantial regional differences in how aquifers around the world are affected.

Land bottleneck scenario: Urban sprawl and protection of natural areas

This scenario explores the effect of increased land competition and reduced potential agricultural land supply. Agricultural land supply (covering food and fodder crops, intensive and extensive grazing) can in most regions be further expanded beyond current levels, and in many cases also beyond the projection made in the baseline. But agricultural land supply is limited by the amount of currently unused land that can potentially be converted for use as agricultural land. In the modelling framework, this potential land is calculated by determining the total land area of each world region and subtracting the area unsuitable for agriculture due to biophysical or other restrictions and includes e.g. managed forests and unmanaged land that is not too steep. The closer agricultural land use gets to this potential supply, the more difficult it becomes to increase land use.[4] The rationale behind this is that a large supply of suitable land results in low land rental rates and a high price elasticity, and vice versa. In the baseline, best-guess default assumptions are used to project land that is unsuitable for agricultural production and thereby directly limit regional land supply. In this counterfactual scenario, the effects of the agricultural land supply bottleneck will be explored, by adding two further land conversion restrictions: *(i)* increased urban sprawl, and *(ii)* increased nature conservation.

Urban sprawl, i.e. the rapid expansion of low-density and non-contiguous development, or in IMAGE modelling terms the increase in urban land area, has been a significant cause of reduction of highly productive agricultural land in the past (OECD, 2017). Although the relationship between urban areas and agriculture is complex and extends both ways, urban sprawl generally reduces the availability of fertile land and thus reduces agricultural productivity.[5] Cities are historically mostly built on very fertile land and thus urbanisation takes away highly productive agricultural land; furthermore, cities compete with surrounding agriculture for water and other resources, which further limits agricultural production near urban areas.[6] In many regions, urbanisation is projected to continue in the coming decades (Jiang and O’Neill, 2017). The baseline projection uses the database of Klein-Goldewijk and Van Drecht (2006) to project urban land (see also Section 3.3). However, it is not straightforward to accurately measure which partially built-up land is still available for agriculture and which should be accounted for as urban land. Therefore, the influence of urban land expansion on the amount of land available for agriculture is unclear and alternative projections of urban land as discussed in Potere and Schneider (2007) suggest much larger areas than assumed in the baseline.

In the bottleneck scenario, the assumption is made that urban sprawl leads to a significant increase in urban land compared to the baseline. Due to regional differences in driving forces as well as in model parameters, the increase in urban area by region ranges from 2.6 to 6.7 times the baseline. For the world as a whole, the built-up area is relatively small in the baseline: 0.6% of the terrestrial surface, but for regions the percentage varies widely between 0.1% for vast sparsely populated countries (Canada and Russia), and around 4% for densely populated countries. With the land constraint in place, the percentage built-up area is around 3.7 times bigger, ending up at 2.3% for the world with a range of 0.3% to 15% between the regions.

The urban sprawl assumption is complemented with a projected increase in nature conservation. Based on the Aichi biodiversity targets as laid out in the Convention on Biological Diversity (UNCBD, 2012), specifically target #11, the assumption is made that 17% of all major natural ecosystems or biomes are protected from 2020 onwards, and are deemed unavailable for conversion to agricultural land from that year The additional protected areas are made geographically explicit, similar to existing nature reserves (percentages) of grid cells are excluded from conversion to agricultural land.

Together, these two assumptions constrain the possibilities for land use change in agriculture, with consequences for productivity and agricultural land expansion compared to the baseline.

Energy bottleneck scenario: Ambitious global biofuel targets

In the energy bottleneck scenario, the policy ambition to increase energy security and reduce reliance on fossil fuels is being pursued by an ambitious increase in biofuel production around the world.[7] This will relieve the pressure on fossil energy resource scarcity, but may have significant consequences for the other nexus resources land and water. Thus, there can be important trade-offs between policy objectives in this scenario. Increasing bioenergy supply is one of the very few options available in the short run to substitute away from fossil fuels, without requiring massive changes in the fuel delivery infrastructure, such as engine design. Especially in transport there are relatively few alternatives.

The scenario implementation assumes that global production of (second generation) biofuels, measured as input for conversion, will gradually increase to 220 EJ (5250 Mtoe) per year by 2060. This reflects an ambitious but technically feasible target (EMF, 2017). Production is spread across countries and regions based on the availability of land. To reduce conflicts between biofuels, nature conservation and agricultural production, regional production volumes are projected by looking at how much non-forest and non-agricultural land is available. However, there is no hard constraint on land allocation, and the increased land prices from the additional activity may endogenously lead to some competition with nature conservation and food production. Together, these assumptions reflect an ambitious policy that is not completely ignorant of other policy objectives.

As implemented in the IMAGE model, production of (second generation) feedstock for biofuel production is restricted to rainfed areas, hence there is no impact on water withdrawals. However, conversion of natural land to bio-energy crop land may alter the local water supply due to changes in water holding capacity, evapo-transpiration and run-off.

The increased biofuel production is assumed to enter the economy as substitutes for refined oil, and may lead to crowding out effects on oil markets, given that overall fuel demand is not exogenously adjusted.

Combined bottlenecks scenario

In this scenario, the individual water, land and energy bottleneck scenarios of limiting groundwater availability, urban sprawl and protection of natural areas, and ambitious biofuel targets are combined, to investigate whether there are significant interaction effects between these various bottlenecks. If there are, then indeed the LWE nexus is not just a combination of land, water and energy bottlenecks, but a true nexus.

Climate change scenario

The impact of climate change on the biophysical system, including water availability and regional temperature change are captured in the IMAGE model and translated into shocks on crop yields. The impact of elevated levels of CO_2 concentration in the atmosphere, referred to as the CO_2 fertilisation effect, is not included as its magnitude is very uncertain (see Box 2.2). These crop yield shocks are mimicked in ENV-Linkages. To ensure consistency, these climate change impacts have been scaled to the emission projection of the CIRCLE baseline, which leads to levels of radiative forcing that are between RCP6.0 and RCP8.5 (see Van Vuuren et al., 2012, for more details on these representative concentration pathways), albeit closer to the latter.

Box 2.2. **Influence of the CO_2 fertilisation effect on climate change damages in agriculture**

The projections in this report exclude an effect of higher carbon concentrations in the atmosphere on crop growth (the CO2 fertilisation effect, for which the basic idea is that increased concentrations of CO_2 can boost photosynthesis and dry weight of harvested crops). The CIRCLE report on the economic consequences of climate change (OECD, 2015a) presents a detailed analysis of the sensitivity of the economic analysis to this effect. That analysis provides at least tentative insights into the influence of the assumptions on CO_2 fertilisation for the bottlenecks in the nexus. The magnitude of the CO_2 fertilisation effect in agricultural practice is very uncertain, as plants require a range of other conditions to support enhanced growth and CO_2 is often not the primary constraining factor. Therefore crop models show diverging responses to CO_2 concentration.

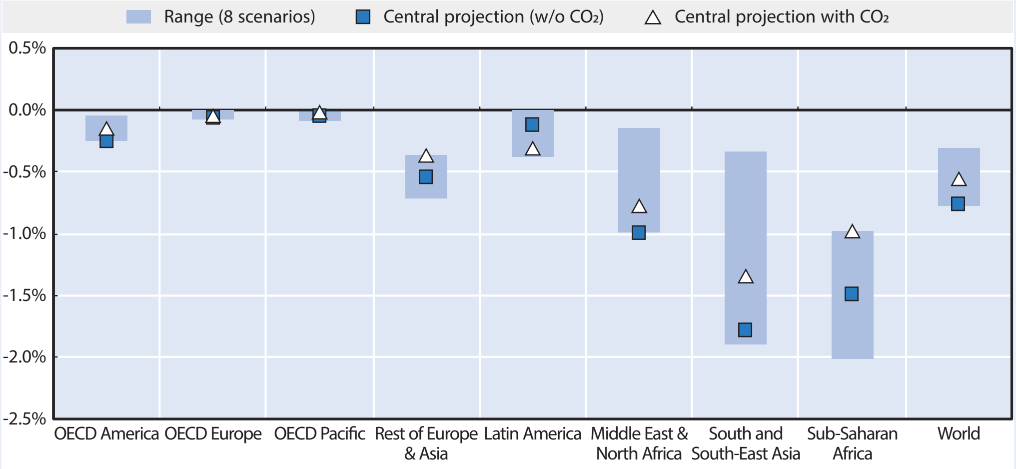
The analysis in OECD (2015a) clearly shows that the impacts of climate change on crop yields varies widely between crops. Generally, the effect of CO_2 fertilisation on yields is quite strong and positive and can limit some of the major negative consequences in agriculture. The effects of CO_2 fertilisation on the economy is more limited. According to the simulations in OECD (2015a), the CO_2 fertilisation effect amounts to 0.2 percent-points of GDP by 2060, i.e. agricultural damages are a little less than 0.6% of GDP rather than a little less than 0.8%.

Figure 2.3, also reproduced from OECD (2015a), puts this result into perspective, by also varying the underlying crop model (LPJmL instead of DSSAT) and the underlying climate model (IPSL instead of HadGEM). The figure highlights the regional differences: for some regions, especially OECD Europe and OECD Pacific, the range of the projections of the four model combinations under scenarios of CO_2 fertilisation and no CO_2 fertilisation is very small, with minor impacts projected in all scenarios. For other regions, the range is much wider. The simulations with alternative crop and climate models all provide similar global gains from CO_2 fertilisation, between 0.2 and 0.3 percent-points, respectively. For a more detailed analysis of these results see OECD (2015a).

Box 2.2. Influence of the CO_2 fertilisation effect on climate change damages in agriculture *(continued)*

Figure 2.3. **Range of regional agricultural damages from climate change for alternative scenarios (including CO_2 fertilisation)**

(Percentage change in GDP in 2060 from baseline)



StatLink http://dx.doi.org/10.1787/888933554620

Source: OECD (2015a).

This scenario is not intended to by itself shed light on the LWE nexus. Rather, it allows a comparison of the feedbacks from the nexus with those from climate change, and provides the relevant starting point for the comprehensive combined bottlenecks with climate change scenario.

Combined bottlenecks with climate change scenario

The combined bottlenecks scenario is coupled with the climate change scenario, to explore how climate change affects nexus scarcity projections, and the associated economic consequences. This scenario provides the most comprehensive assessment of the biophysical and economic consequences of the nexus.

Notes

1. In principle, the changes in economic activity as calculated by ENV-Linkages should feed back into the IMAGE model through a change in e.g. food demand. This iterative procedure is, however, very computationally expensive, and only relevant when the second-order effects of such a feedback are significant. Given the price-inelasticity of food demand, this is unlikely, and these feedbacks are ignored.

2. As the IMAGE model has a different regional aggregation, the ENV-Linkages results for both OECD EU regions are aggregated together in the presentation of the results; similarly, results for Chile are aggregated with Other Latin America. This re-aggregation prevents false insights coming from the fact that these regions are aggregated in IMAGE.
3. As IMAGE and ENV-Linkages do not have matching aggregations of the different crop sectors, some ad-hoc assumptions are made to translate the IMAGE outputs into inputs for ENV-Linkages. These assumptions aim to provide the best fit for representing the changes in yields for the crop sectors in ENV-Linkages and use FAO data on land use and production quantities for individual crops to disaggregate the IMAGE results and then re-aggregate for ENV-Linkages input.
4. Technically, the land supply elasticity, which describes the change in land supply as a function of changes in the rental price of land, falls with increasing land use. The more scarce land is, the more difficult it becomes to convert new land to agricultural land and the higher the land rental price.
5. Another issue with urban sprawl is that it reduces amenities and quality of life in both urban and rural communities (OECD, 2017).
6. However, cities are also a source of agricultural growth, not least because cities provide easy access to markets.
7. This scenario does not suggest that a massive biofuel penetration is optimal in any sense; for instance, energy efficiency improvements will likely be much more important in decarbonising the energy system.

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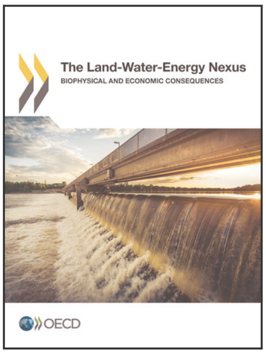

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