**For Official Use** **ENV/EPOC(2015)25**

Organisation de Coopération et de Développement Économiques
Organisation for Economic Co-operation and Development **16-Oct-2015**

**English - Or. English**

**ENVIRONMENT DIRECTORATE**
**ENVIRONMENT POLICY COMMITTEE**

**Economic Impacts of the Land-Water-Energy Nexus:**

**A joint OECD/PBL report on exploring the feedbacks of bottlenecks in the nexus on the global economy**

**Meeting of the JWPAE:**
**9-10 November 2015**
**OECD Conference Centre, Paris, France**

*This report is a draft output of the CIRCLE project. It contains a draft of the first part of the assessment of the major consequences of bottlenecks in the land-water-energy nexus. Further scenario work will be carried out for the final report.*
*An advanced draft of the report is discussed at the 3rd ad-hoc technical workshop on CIRCLE of 20 October 2015.*

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*Action required: For comments and discussion.*

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**JT03384231**

# EXECUTIVE SUMMARY

1. This interim report contributes to the discussion of interconnections between scarce resources by highlighting the nexus between land, water and energy. The focus of the report is on a dynamic, integrated, and disaggregated analysis of how land, water and energy interact in the biophysical system and the economic system. This approach allows to capture additional mutual influences compared to an assessment which looks at resources individually. This is especially important as megatrends like strong population growth and climate change increase the pressure on scarce resources like water, energy and land, and shifts the pressure from bottlenecks that are currently most important to new ones.

2. Different scenarios with a time horizon until 2060 are simulated to analyse the interconnections of bottlenecks related to the land-water-energy (LWE) nexus. Furthermore, the effects resulting from limited quantity and quality are also highlighted on different economic dimensions. The most direct linkages in the nexus are at the resources level. Analysis of the biophysical impacts of the bottlenecks answers questions about the nexus at that level. But the indirect linkages between the resources are much stronger: these different resources are combined in different proportions in various economic sectors, with consequences for their productivity. Hence, it is vital to also look at the consequences of the bottlenecks on different economic activities and on different policy objectives (such as welfare, environmental quality, food, water and energy security). By encapsulating the key dimensions of impacts, the most important consequences can be clearly identified and allow a better understanding of linkages that occur between water, land and energy.

3. In the first round of modelling analysis reported here, only specific bottlenecks in groundwater availability, land supply and hydropower capacity could be considered, thereby limiting the ability to draw general conclusions on the LWE nexus. in a second stage, the analysis in this report will be further expanded by looking at more elaborate (integrated) scenarios and by studying the benefits of policy action. After completion of the second round of analysis, the main messages will be determined, that build on the preliminary findings in this report. Nonetheless, a number of important insights already emerge:

1. **A full numerical appraisal of the global economic consequences of the land-water-energy nexus is beyond reach**. Top-down assessments of how the nexus affects biophysical and economic systems such as the one carried out in this report are hampered by the fact that many consequences are very local in time and space. Furthermore, there are significant gaps and modelling tools that prevent an adequate representation of the nexus issues in the modelling frameworks. Nonetheless, the modelling analysis and anecdotal evidence together can shed light on the key elements in the nexus and how they affect the economy.

2. **There is no clear evidence of an absolute scarcity of nexus resources**. The preliminary results of the model analysis indicate that the impacts from LWE-bottlenecks vary by a great extent across regions and time periods. Despite a rapid increase in demand for food, water and energy in the last decades, and the projected substantial further increase in the coming decades, the main problems are not the global availability of resources, but having them available at the right time in the right place. Absolute scarcity at the global level may present itself in the long run, but for the coming decades it may be most useful to look at specific bottlenecks in specific regions, and how these spread to other sectors and regions beyond the local level.

3. **Availability of (clean) freshwater regionally seems to be the main bottleneck in the nexus**. Unlike energy security and food security, regional bottlenecks in water security are difficult to manage through international trade and transportation. The central role of water is likely to be further enhanced in the future, as demographic and economic megatrends imply a strong increase in water demand from agriculture, industry, the energy sector and households. This is aggravated by climate change, which influences precipitation patterns and is projected to worsen water stress in certain regions that are already water scarce.

4. The preliminary analysis suggests that **specific bottlenecks**, not least those related to water stress, **can have significant economic impacts in specific regions** that already have a high vulnerability in food, water and energy security, **but the effects on the global economy are minor**. Effectively, the influence of modest increases in the pressure on food, water and energy markets are dampened by their relatively small share in total value added generated in a country, and the possibilities of producers and consumers to adapt to changing circumstances by adjusting their behaviour. This does not mean that the nexus bottlenecks are without economic consequences: besides changes in the structure of the economy induced by the bottlenecks described above, the strong linkages between various economic activities imply that a shock in one specific sector in one specific region tend to cause a ripple effect throughout the economy and on other economies. For instance, a yield shock in Southern Europe will change the competitive position of the agricultural sector in these countries vis-a-vis their main competitors, change production costs in the food processing and other industries, and eventually lead to a re-allocation of labour and capital to adjust to the changes in relative prices induced by the shock.

5. There are (limited) **possibilities to substitute away from one particularly scarce resource to the other resources**. Water scarcity tends to lead to increased energy use in water supply, with desalinisation as an extreme example, or to increased land use for non-agricultural purposes, e.g. when building dams for hydropower. Similarly, energy bottlenecks can, to some extent, be compensated by using land and water resources for cultivation of bioenergy crops. But markets for land, water and energy are not perfect, and price signals are often distorted. Therefore, the relative scarcity of the different resources is not adequately projected through their prices, and private actions do not minimise social costs.

6. **The nexus resources are significantly affected by climate change**. Substitution patterns between resources can re-inforce the links with climate change, especially when fossil fuel based energy is used for water supply, or when land extensions for agriculture involves deforestation. But these linkages also represent indirect costs and benefits for climate change policies. The energy conservation part of climate change policies induce obvious benefits due to less stress on fossil fuel resources, water withdrawal and water pollution from the energy sector. In addition, reduced electricity demand diminishes the vulnerability of the power sector to water stress. Coal to gas switching in the power sector reduces $CO_2$ emissions, but it can also boosts shale gas development and the associated impacts on water scarcity. However, oil to gas switching in transportation, even if based on shale gas, may reduce negative impacts on water. Biofuels have to be considered with their associated effects on land and water use. Supporting renewables, such as wind and solar photovoltaic technologies, often contributes to increasing water security, but may lead to new bottlenecks due to the reliance on specific scarce materials. For hydropower, the links with land and water use are mixed. In case of a very ambitious climate target, large deployment of water-intensive carbon-free technologies such as concentrating solar power (CSP) and carbon sequestration and storage (CCS) would increase water stress.

7. There are also **possibilities to reduce economic consequences by shifting production between regions**, including shifting the patterns of international trade. Changes in the demand for

commodities that rely extensively on the nexus resource can in principle also alleviate the bottlenecks, but demand for food, water and energy tends to be relatively price inelastic. The ability of international trade to smoothen regional differences in demand and supply is a powerful tool to mitigate the consequences of local bottlenecks, e.g. increased production costs from reduced crop yields. The tradability of goods is therefore one of the most important factors to consider when assessing the impacts of bottlenecks.

8. **Uncertainty of supply can lead to significant costs to the system**, and the macroeconomic costs of the nexus bottlenecks will only be low if they are well-managed. The literature review showed that the cost related to the nexus in the energy sector is difficult to assess. For example, if overall energy supply is adapting adequately to both acute shortages and long-term scarcity of specific resources, the costs can be very low; it will mostly translate into slightly higher consumer prices. If disruptions of supply occur, the cost can be very high, but very difficult to assess. Therefore the challenge for the electric sector is improving resilience, for instance by using more water-efficient production techniques or increasing buffers in supply, which can be potentially very costly. This example shows that uncertainty in the availability of the nexus resources at the right time in the right place has to be seen as one of the main contributor to the cost of the nexus.

4. The bottom line is therefore that **negative economic consequences of the nexus bottlenecks tend to be concentrated in those countries that show strong bottlenecks in those economic activities that cannot be substituted or imported**. Specifically, regions with strong decreases in yields for crops and higher production costs and that are neither able to trade the most affected crops nor substitute them with other goods within their region are particularly affected. In addition, a higher share of food in the overall budget for households exacerbates the economic impacts resulting from bottlenecks. Therefore especially North Africa, the Middle East and parts of Asia, not least India, are projected to suffer the most from bottlenecks in the land-water-energy nexus.

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# 1 INTRODUCTION

5. Almost all economic activities are supported by the use of scarce water, land or energy, either directly or indirectly. We need water to grow food and for energy production, we need energy to grow food and to pump and treat water, and we need land to produce bioenergy. Unsustainable use of these resources raises serious concerns about their looming scarcity. There may be constraints or bottlenecks regarding the quantity and quality of supply of each of these resources, including pollution and degradation, and regarding increased demand for them in a growing global economy.

6. There are strong linkages between land, water and energy in biophysical and in economic terms. Nexus is a handy label for the fact that these resources are bound together and that the bottlenecks in one area are critically linked to the other resources. Policies neglecting these interlinkages may be sub-optimal and can actually create problems instead of solving them; i.e. they might resolve a specific problem with one of these resources but at the same time impact the others and create additional (and unforeseen) problems. Therefore some activities can impact indirectly other activities by increasing the scarcity or changing the quality of the resource they use in common. In terms of policy analysis, it implies that efficient management of the nexus resources needs to take into account the direct and indirect effects of changes in the demand and supply of the various resources on the whole biophysical and economic systems, as this is the only means to avoid negative side effects and to create synergies. For example, implementation of hydropower for electricity production can conflict with irrigation requirements where hydropower release schedules do not match the timing of irrigation needs. Under more favourable conditions and adequate operational management, a dam and reservoir can provide a win-win situation with both hydropower and agricultural benefits (Hellegers et al., 2008). This shows that a careful, simultaneous consideration of the land-water-energy resources is needed when designing policies, as ignoring their interactions can present negative side-effects. Therefore an integrated approach is needed to assess whether policies adequately resolves bottlenecks in the whole nexus, or effectively shift stress from one resource to another.

7. As part of the CIRCLE project[1], the scope of this report is to provide a broad assessment of the global and regional implication of some of the main bottlenecks in the land-water-energy (LWE) nexus, and project how the consequences of these nexus bottlenecks evolve in the coming decades.

8. More precisely, the aim of this report is threefold. Firstly it aims to shed light on the main trade-offs and synergies between the different bottlenecks in the LWE nexus, and their interactions with the global economy. Secondly, the report will also examine the sensitivity of these indicators to the changes in biophysical conditions stemming from alternative assumptions on the evolution of the underlying megatrends, not least climate change. Lastly, the report will assess how policy actions influence the land–water-energy nexus, with a focus on identifying how integrated policies can generate benefits for the whole system, and avoid trading-off reduced pressures in one part of the nexus with increased bottlenecks elsewhere. In other words, it addresses the following questions: **What would be the global and regional cost of policy inaction to account for the limited availability of land, water and energy, given all the complex relations between these resources? Furthermore, what are the benefits of policy actions that tackle the entire nexus in a systematic manner, compared to a set of policies that aim at reducing specific bottlenecks?**

9. A full quantitative assessment of the global costs of inaction (and benefits of action) for the LWE nexus would require detailed modelling tools that can represent the key linkages in resource use and

[1] CIRCLE stands for Costs of Inaction and Resource scarcity: Consequences for Long-term Economic growth.

economic activity at the local level. Many of the nexus bottlenecks will occur within specific water basins (see Box 1), and have widely varying effects in different geographical locations, depending on the availability of all three key resources, and distances to economic markets. For instance, the IEA (2015) shows that the cost of water shortages for coal power generation can be higher (albeit not very much) in water-stressed areas far from economic hubs such as in western China, than in regions that benefit from a local mix of abundant coal resources, water availability and nearby cities, such as northern India. But such a detailed bottom-up analysis is necessarily partial in scope. Therefore, specific insights can be drawn from a more top-down analysis of key interlinkages between land, water and energy in the global biophysical and economic systems. The current report hence does not aim to provide an exhaustive answer on the costs of inaction in all regions in the world. Rather, it limits itself to a top-down approach, by using large-scale global systems models to explore how major resource bottlenecks can affect the economies of the major regions in the world.

**Box 1. OECD project on water hotspots**

The OECD Joint Working Party on Agriculture and Environment (JWPAE) is conducting a project on "future water risk hotspots for agriculture" (COM/TAD/CA/ENV/EPOC(2015)7). The objectives of the project are to (a) identify the most pressing geographic and commodity-specific water risk hotspots for agriculture, (b) assess their expected implications on agriculture, trade and broader food security and (c) envisage possible policy responses. This includes assessing direct future risks to agriculture production in water stressed countries (shortage, excess, and quality), but also indirect risks via market effects driven by deteriorating water conditions in other countries, to ultimately define a set of likely future water constraints by major commodity and envisage corresponding policy responses.

A first report (COM/TAD/CA/ENV/EPOC(2015)40) has been drafted to cover objective (a). It defines and identifies future agricultural risk hotspots based on available data and the literature. Results of a country level global assessment point towards China, India and the United States as the countries with the most risk and agriculture importance in the future. More specifically, North-East and North West China, North India and Southwest US appear to be the agricultural regions most frequently considered under water risks. It is envisaged in the next step to look specifically at the possible impacts of water risks on agriculture in these regions, and their indirect possible consequences nationally and internationally, via the use of modelling and regional case studies.

10. The core of the analysis of the consequences of the nexus for the costs of inaction is carried out by soft-linking two global dynamic systems models: a general equilibrium economic model with a detailed specification of sectoral and regional economic activity and their interlinkages (OECD's ENV-Linkages model; Chateau et al., 2013) and a spatially explicit biophysical model with detailed representation of resource use (PBL's IMAGE model; Stehfest et al., 2014). This systems modelling assessment is complemented by more generic anecdotal evidence of specific bottlenecks that can have significant impacts on local economies and on specific sectors, but that will likely not lead to significant changes in the macro economy.

11. The nexus bottlenecks are described in this report from the perspective of the natural resources that are needed to sustain economic activity. But these are clearly linked to the services they provide: land use allows agriculture to provide food, energy use provides heat, power and fuel, and water use provides water for irrigation, cooling, drinking, et cetera. Therefore the LWE nexus is effectively roughly the same as the food-water-energy nexus as discussed in the literature, with a different label and with a more explicit acknowledgement that other sectors than agriculture, not least energy production, also rely on scarce land resources. These links also make it clear that there are three specific economic sectors that are central to

the analysis: agriculture, water production and energy production. But an essential part of the assessment in this report is to go beyond a partial investigation of direct impacts on these sectors. The report aims to highlight the sectoral linkages and indirect effects that the nexus bottlenecks have on the rest of the economy, and how bottlenecks in a certain region affect other regions.

12. Agriculture will be central to the nexus analysis, as it relies heavily on water, land and energy as inputs, in fact agriculture is by far the most important driver of land-cover and land-use changes and irrigation is the biggest water consuming activity at the global scale and in many regions and countries. In terms of economic impacts, challenges posed by restricted availability of LWE resources on agriculture come primarily in the form of yield reductions and/or limited availability of suitable land. Such impacts can be assessed with the IMAGE model. These impacts tend to increase production prices of agricultural commodities, compared to a situation without LWE bottlenecks. In the CGE framework of ENV-Linkages these sectoral impacts are introduced as exogenous shocks, which in turn induces economic impacts throughout the economy, and on other economies, not least due to shifts in competitiveness between regions.

13. The challenge is to move beyond the nexus as a "slogan" and developing a methodology to assess quantitatively the costs of inaction and the benefits of policy action. Moreover, expressing these costs of inaction in the same terms as the usual indicator for economic growth, i.e. in terms of GDP losses, helps to communicate the importance of the nexus for economic policy making. But macroeconomic impacts as measured by changes in GDP are not a very good indicator of the consequences of the nexus bottlenecks on well-being. Therefore, the report also looks at other indicators, such as those related to food security, water security an energy security.

14. Despite the complexity of the modelling tools, and their suitability to explore future pathways of economic activity, environmental pressure and their interlinkages and feedbacks, this report contains only exploratory insights into the costs of inaction on the nexus. It is not a prediction of what will happen, nor a synthesis of the full literature on LWE nexus concerns. Nonetheless, the land-water-energy nexus analysis in CIRCLE has several innovative aspects. Few studies have analysed linkages between land-water-energy simultaneously in an integrated framework and then translated the biophysical indicators into economic impacts. Some studies have looked at linkages and trade-offs between individuals pairs of the land-water-energy sectors (Bartos and Chester, 2014; Monaghan et al., 2007; Dale et al., 2011). Some other studies have looked at individual links between bottlenecks for a single resource and the economy (Berrittella et al, 2007; Veldkamp and Verburg, 2004). However, none of the above studies have profoundly addressed all three aspects of the land-water-energy nexus together and their link with the economy. The analysis of the land-water-energy nexus in the CIRCLE project follows such an integrative approach, and is thus complementary to earlier and ongoing research efforts.

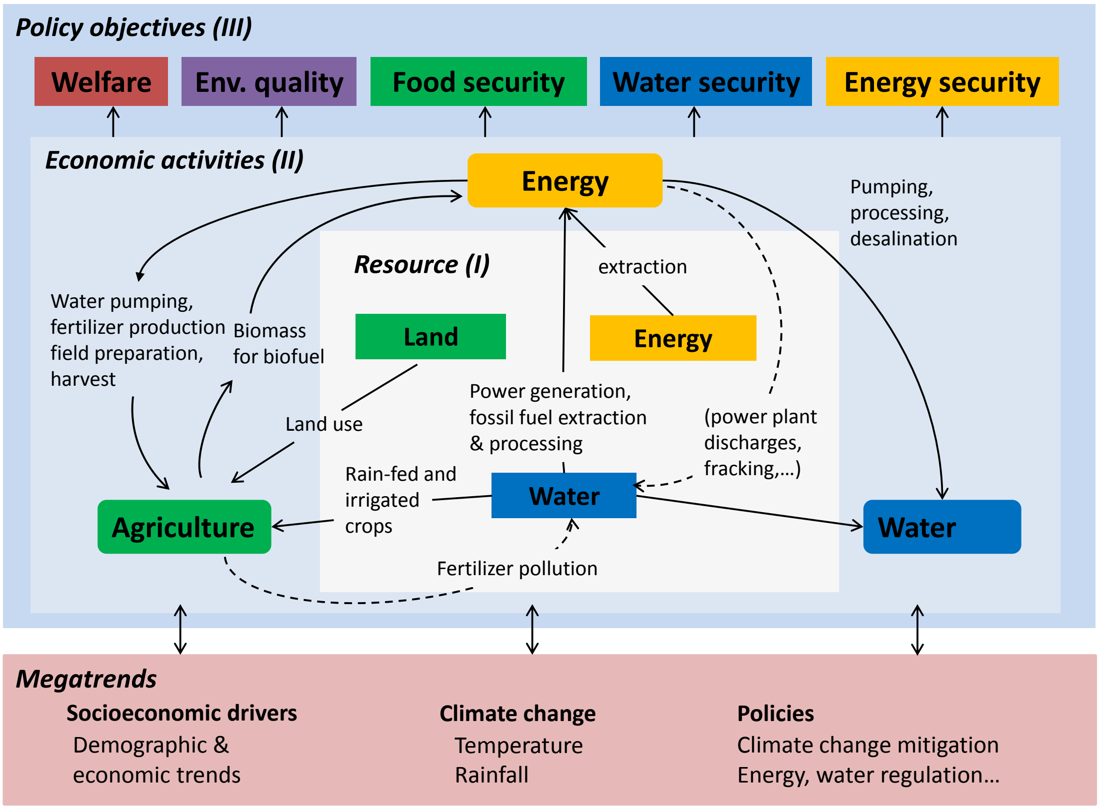
15. The paper is structured as follows. Section 2 introduces the LWE nexus in more detail and explains how the different aspects interact. Section 3 describes the methodology used for the quantitative analysis, with a brief description of the modelling tools, and an explanation of how the numerical analysis is used to assess the costs of inaction and benefits of policy action. Section 4 presents the main results from the modelling analysis, and complements that with anecdotal evidence of other major consequences of the various nexus bottlenecks. Section 5, on the benefits of policy action, will be elaborated in a later version of this report.

# 2 THE MAJOR LINKS IN THE LAND-WATER-ENERGY NEXUS

## 2.1 Overview of the LWE nexus and interlinkages

16. Key interactions within the LWE nexus are shown in Figure 1, which shows how the biophysical resources are linked to economic activities and – mostly indirectly – to a number of key policy objectives. In the first domain, the resources represent a biophysical system, characterized both in terms of quantity (for instance, surface of land, energy equivalent of in situ oil, volume of aquifer water and rainfall) and quality (for instance the type of land, the accessibility and temperature of water, the accessibility and property of the in situ oil). In the second domain, the resources are used as inputs for economic activities which provide various goods and services that meet the needs of the population, including nutrition, water and sanitation, and energy. The third domain transcends the sectoral domain and focuses on the wider context by highlighting how the resources in the nexus, and the economic services they provide, contribute to a range of policy objectives that drive the reforms in the nexus; obvious policy objectives include "security of supply" for food, water and energy, welfare and environmental quality.

**Figure 1. Main linkages within the land, water and energy nexus**




Source: Own presentation

17. In a narrow sense, security of supply is met only when there is no physical or economic scarcity, but definitions often go beyond pure access and include notions of satisfaction or preferences. Food security is defined in the 1996 Rome Declaration on World Food Security as "when all people, at all times, have physical and economic access to sufficient, safe and nutritious food to meet their dietary needs and

food preferences for an active and healthy life".[2] Similarly, the IEA defines energy security as "uninterrupted physical availability at a price which is affordable, while respecting environmental concerns" (Jewell, 2011). On water security, the UN (2015) write "The availability of an acceptable quantity and quality of water for health, livelihoods, ecosystems and production, coupled with an acceptable level of water-related risks to people, environment and economies (Grey and Sadoff, 2007)". However, the broader connotation, i.e. a movement in the direction towards security, is more relevant for this report, i.e. do the bottlenecks in the nexus, and the policies that aim to address these, bring the world closer to the objectives of security of supply.

18. The food, energy and water aspects are not independent of each other. Agriculture depends on land and water resources, and also on the energy sector. The energy sector needs energy resources and water. In the case of biofuel developments, it will also interact with the agriculture sector. Water services require indeed water resources, but also energy services. Unsustainable use of one resource can hence affect the other resources. Firstly because some sector use the same resource and will thus rival for access in particular when the resource is under stress. This is for instance the case for agriculture and energy which both use water. Hence, operations in the energy sector may affect the water availability for agriculture and therefore crop yields. Secondly, when the resource becomes scarcer and less accessible it may be overcome by using more of other resources (substitution). For instance, with depletion of conventional oil reserves, oil and gas resources require more water to be processed, which may put pressure on water resources. Lastly, resource scarcity may require distracting the output of a sector towards other sectors in order to ensure the security of supply. For instance, in the Middle East where water is scarce, a significant share of the regional energy production is used for pumping, transporting and desalinating water. This is beneficial to the water security objective, but it represents a cost for the society in the form of lower national revenues from energy exports.

19. The nexus interactions imply that a potentially large part of the cost of resource scarcity cannot be captured if not taking all the elements of the nexus together. It is also true for assessing the benefits of policy action. For instance, policies that favour biofuel, for climate policy of energy security (independence) reasons, can put pressure on land use and water resource and conflict with food security concerns.

20. The trade-offs and synergies within the land-water-energy-nexus and their impact on the economy are substantially influenced on the long run by a number of socio-economic and environmental "megatrends". The term "megatrends" which is further explained in Box 1, includes the consequences of demographic and economic growth, climate change and also climate change policies.

**Box 2. Megatrends and the LWE Nexus**

There are a number of important trends that underlie this baseline projection. Firstly, over the long run, there are important factors that influence the demand for goods and services, and therefore the demand for resources by the producing sectors. *Population growth* increases consumer demand for food, water and energy, thus increasing the pressure on the scarce resources, not least land, through agricultural production. It also exacerbates the competition for these scarce resources: more water is needed for final consumption, but also for agriculture. Similarly, *income growth* leads to stronger demand for high-quality commodities, often produced in ways that are more water and energy-intensive (a typical example is the shift in diet towards more meat-based food consumption). But the net influence of income growth is not a priori trivial. For example, it also means that people are more versatile in avoiding the negative consequences resulting from shortages or quality issues in the nexus. And it is often argued that people with higher income demand a higher quality of their environment, thereby increasing efforts to improve resource efficiency through re-use and recycling, and inducing

[2] See http://www.fao.org/docrep/003/w3613e/w3613e00.HTM

governments to do more to protect the essential resources. *Education* and *urbanisation* influence both population and income levels (and are affected by them), but also the composition of sectoral demand. Secondly, on the supply side, climate change is probably the most important megatrend. *Climate change* affects all aspects of the nexus directly and indirectly. IPCC (2013, 2014a,b) and others have shown that there are significant direct effects on land availability (not least due to land loss from sea level rise), water stress, and energy demand and supply. Not least, climate change influences the hydrological cycle, resulting in shifts in annual water availability in many regions, and also in more erratic precipitation patterns including extreme events such as droughts and excess rainfall. Reduced water availability can increase competition for water between sectors, as described above. Moreover, climate change is projected to have negative impacts on agricultural productivity in most regions, e.g. through loss of yields due to excess temperatures. Lower agricultural yields due to climate change means additional intensification and/or expansion of agriculture to meet the demand for agricultural products with implications for land and energy requirements. Finally, as all sectors are linked in the economic system, impacts on one sector in one region trickle through to other sectors and regions through changes in the allocation of production factors, changes in final demand and changes in trade patterns (OECD, 2015a).[3] Thirdly, there are a number of megatrends that affect both demand and supply, but in opposite ways for the different resources in the nexus. As a prime example, substitution of fossil fuels by *bio-energy* reduces energy stress, but exacerbates stress levels for land and water. Large-scale biofuel crop cultivation negatively interacts with the other elements in the land-water-energy nexus. Considerable land areas are required for biofuels to supply a substantial share of the global energy demand, which raises concerns over competition with food production and higher prices. Moreover, if and where additional land for biofuel production goes at the expense of naturally vegetated land, this will affect the hydrological cycle. Additional water stress can result on irrigated land, and this competition over water between food and fuel crops can affect agricultural production in drought-prone regions and potentially lead to yield reductions.

21. The next sections discuss in more detail how constraints in the quantity or the quality of these environmental resources can be a bottleneck for economic activities, and how economic competition for scarce resources affect the bottleneck. This discussion is grouped per bottleneck; i.e. each paragraph explains which factors and nexus linkages contribute to respectively land, water and energy bottlenecks, and highlights which economic activities are most affected by each bottleneck.

## 2.2 Land-related bottlenecks

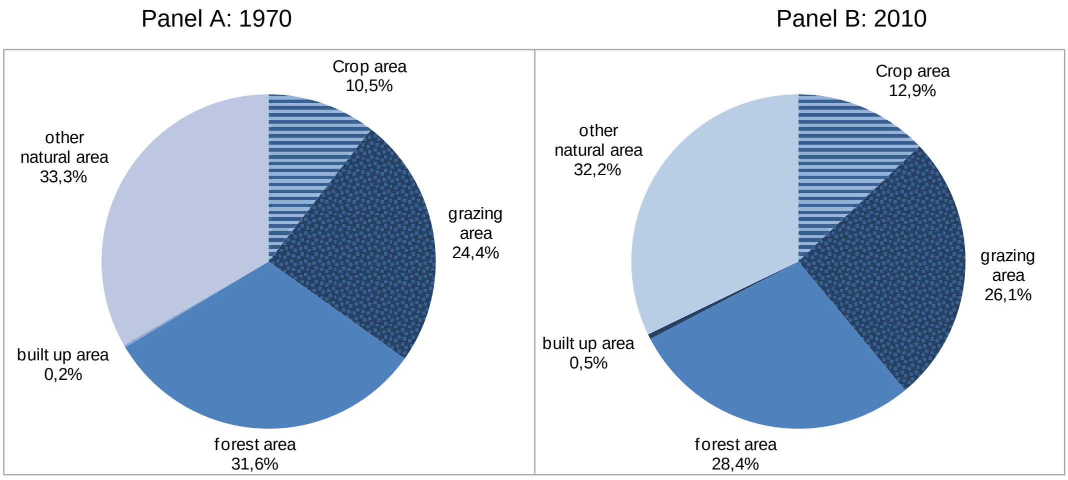
22. Agriculture is globally the most land-demanding human activity (see Box 2). Currently around 33% of the earth's surface (excluding Greenland and Antarctica) is used for crops and livestock farming (PBL, RIO+20). Projections indicate that agricultural land use is likely to increase even further in coming decades due to population and welfare growth. Meeting an increasing demand for food can be met either by increasing exploitation of the land resource (extensification), or by increasing the inputs of other resources per unit of land (intensification). Evidently, intensive agriculture also requires substantial water and energy inputs and has therefore a clear link with the nexus.

**Box 3. Agriculture as a key driver of global land and water use**

Agricultural production has increased strongly over recent decades to meet rising food demand driven by both population growth and changes in diets. About 80% of the production increase has been achieved through higher yields from existing land, and about 20% through expanding agricultural land (Bruinsma, 2003). Between 1970 and 2010, the share of agricultural land use (crop and grazing land), expanded by about 4 percentage points, largely at the expense of forest area (OECD, 2012: Figure 2.12). A somewhat lower pace of expansion has been observed over the last decade.

[3] By using a multi-sectoral, multi-regional general equilibrium model, the economic analysis in this report picks up such indirect effects in the same way.

**Figure 2. Global land use: *Baseline*, 1970 and 2010**




*Source*: *OECD Environmental Outlook Baseline;* output from IMAGE, calculations based on FAOStat data and additional data sources, including Klein Goldewijk, K. & van Drecht, G. (2006), "HYDE 3: Current and Historical Population and Land Cover", in: Bouwman, A.F., Kram, T., Klein Goldewijk, K (eds). Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4. Netherlands Environmental Assessment Agency, Bilthoven.

The *OECD Environmental Outlook Baseline* projects that competition between agricultural land use and other land uses will intensify in the coming decade under current policies. This is also the conclusion of the *OECD/FAO Agricultural Outlook to 2020* (OECD/FAO, 2011). A converging GDP per capita and a growing population will both increase the demand for food, especially animal products. Moreover, policies that stimulate the use of biofuels also increase the demand for agricultural production and land area (Chapter 4). Given the limited supply of land, this means that in the short run deforestation will continue, although at slower rates than in past decades.

Source: OECD Environmental Outlook to 2050 (OECD, 2012).

23. Various forms of renewable energy production require substantial land areas. Hydropower plants, biofuel plantations, solar and wind "farms", for example, require significant quantities of land, and sometimes even require relocation of existing activities and local communities (Bazilian et al., 2011). They often also interfere with existing hydrological flows and regimes. 'Regular' coal or gas fired power plants also require land for their site locations, but their land claim is relatively minor.

24. The combined land claims of economic activities can result in a regional competition for land, and such a land bottleneck can impact certain economic activities such as agriculture. Land competition reduces the available land supply for agriculture and increases land rental rates. In turn, this results in an agricultural expansion onto marginal lands if possible, or agricultural intensification (Van Meijl et al. 2006). Agricultural production on marginal lands often leads to lower overall yields unless more inputs are used. Likewise, agricultural intensification necessitates higher input requirements (Van Meijl et al., 2006; Smith et al., 2010; Bazilian et al., 2011; Lal, 2013; Ringler et al., 2013). This implies not only more capital/labour inputs (Van Meijl et al., 2006), but also more energy/water inputs. Overall, land competition seems to imply lower yields or a higher input use, and can thereby result in higher production costs and a shift in the pressure on other nexus resources (Bazilian et al., 2011; Lal, 2013; Ringler et al., 2013).

25. The pressure on land resources and the need to extend land use for agriculture has also led to other detrimental impacts, including deforestation, degradation of biodiversity and local water pollution,

and loss of recreational which all represent an additional cost involved by land scarcity and comprise of a trade-off between the nexus resources.

26. Climate change may influence the land resource. The change in temperature and precipitation will influence soil properties and may lead to decrease in yields, a loss of agricultural land due to sea level rise, etcetera (OECD, 2015a).

27. Climate policies reduce these impacts from climate change, but may also negatively affect the land bottlenecks, especially if they imply large scale development of biofuels in order to achieve climate change mitigation targets. The land claim of biofuels and biomass feedstock for energy production could be potentially very large, but will depend on the level of biofuel deployed and on the type of crop. There has been concerns over competition over land with current land uses (Anderson and Fergusson, 2006; Smith et al., 2010; Cai et al., 2005) and the consequences for food security (FAO, 2012). Moreover, a need for additional agricultural land for bioenergy production – at the expense of naturally vegetated land – will increase water demand and affect hydrological cycles (Berndes, 2002; Rowe et al., 2009). Similarly, climate policies aimed at reducing the use of fossil fuels provide an incentive to increase the amount of hydro, wind and solar power, which may lead to increased land use, e.g. from flooded areas behind dams. Thus, both ‘renewable’ power and large scale bioenergy production have substantial land claims and affect both water and energy, and thus interact within the land-water-energy nexus (Ringler et al., 2013).

28. An important final remark on this topic is that competition for land is currently mostly a regional phenomenon. At the global level, physical scarcity of land seems less of an issue; i.e. the world is not immediately running out of land as ‘only’ 33% of global land is used for agriculture. But agricultural commodities are heavily traded internationally, implying that a shock to the agricultural system in one region will have spill-over effects on other regions, the sign of which cannot be determined a priori. Furthermore, the lack of global scarcity may evaporate over time. Restrictions may be put on the use of land for agriculture, for instance because of biodiversity concerns. Under more stringent environmental restrictions, land competition may become increasingly important in the future. In combination with the socioeconomic developments (see the description of megatrends), this can put a significant strain on the available land resources, and may eventually lead to global scarcity, price increases and lower welfare.

### 2.3 Water-related bottlenecks

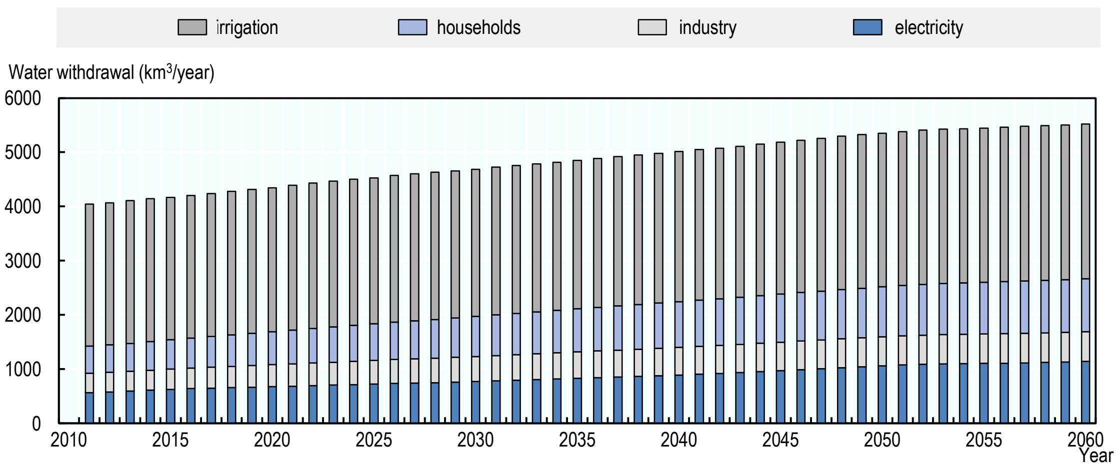
29. Many economic activities, including agriculture, require extensive water consumption, with impact on the quantity and the quality of water resources.[4] The energy industry requires water for power generation and also for fossil fuel extraction and processing, adding pressure to the resources. If trends in food consumption outpace increases in agricultural productivity, the bottlenecks and competition for access to water will increase, in particular between (irrigated) agriculture and energy. In addition, in regions with severe water stress, it may be necessary to use large amounts of energy for groundwater pumping and transporting water to consumption areas.

30. Agriculture is globally the most important water user; i.e. around 70% of all global water withdrawals are for irrigated agriculture, which provides 40% of the world’s food supply (Figure 3). Irrigated areas and subsequent water abstractions differ significantly between regions (Siebert et al., 2010). For irrigation water, some regions rely mainly on surface water abstractions, whereas others rely more

[4] N.B. Water consumption is not the same as water withdrawals. For instance in cooling of power plants, a large part of the water intake is given back to the system, leading to high withdrawals but relatively small consumption. However, non-consumptive withdrawals of water may affect the quality of the water resource (such as an increase of water temperature which may be detrimental to the functioning of aquatic ecosystems) and therefore still represent a water use.

heavily on groundwater abstractions. In some regions, concerns of groundwater overexploitation have risen due to large groundwater abstractions in combination with limited natural recharge (Wada et al., 2012). Projections by e.g. FAO and Wada et al. (2012) and confirmed by OECD (2012, 2015b), indicate that irrigated agriculture and groundwater abstractions will increase even further in coming decades, which means that irrigated agriculture will remain a great user of both surface and groundwater.

**Figure 3. Projected water withdrawals by sector**




Source: IMAGE model

31. While not the only sector responsible for water pollution, agriculture also has an impact on water quality through the release of excess nutrients and micro-pollutants into surface water and groundwater (OECD, 2012). Excess nutrient availability in surface and groundwater can lead to eutrophication problems, and make water unsuitable for human uses such as drinking and bathing. Such deterioration in water quality can thus also cause a water bottleneck by constraining the amount of water that is suitable for other uses. Municipal wastewater treatment at the intake can be used to manage water quality for most end users, but this requires energy.

32. These combined claims on the available water have the potential to constrain the quantity and/or quality of remaining water, and such a water scarcity can seriously impact certain economic activities. There is a clear reason why water scarcity particularly affects irrigated agriculture: irrigated agriculture is the largest global water user, while non-agricultural sectors often place a higher economic value per litre water than the agricultural sector. This makes it often the residual claimant in case of water scarcity (OECD, 2015b). Water scarcity can directly impact irrigated agriculture; i.e. less available irrigation water can lead to yield reductions during droughts and thus result in regional production losses (Berndes, 2002; De Fraiture et al., 2007; Havlik et al., 2011). But water scarcity and competition can also indirectly impact irrigated agriculture by compelling it to use alternative water sources (groundwater extraction, desalinization, etc.). Such alternative water resources necessitate a higher energy use (e.g. diesel for pumps), which ultimately translates into higher production end costs (Bazilian et al., 2011; Ringler et al., 2013). Furthermore, the investments needed for improving water quality or consumption efficiency link this to the rest of the capital market, and therefore to the entire economy.

33. In the context of the land-water-energy nexus, it is also important to note that lower agricultural yields due to water scarcity could induce agricultural intensification and/or expansion onto natural lands to compensate for production losses and to still meet the regional demand for agricultural products. In turn,

this requires more inputs and can increase land competition (Ramankutty et al., 2002; Godfray et al., 2010; Smith et al., 2010; Lal, 2013). This is discussed in more detail in Section 2.2.

34. Even though the energy sector uses less water than agriculture at the global level, (15% vs. 70% of withdrawal in 2010; IEA (2012), FAO (2012)), the energy sector's share in overall water use can nonetheless be significant in some countries. The share of water used for energy production is projected to increase in the next decades (IEA 2012, OECD 2008). Water needs are high for fossil fuel production, power generation and biofuel production.

35. Most power generation technologies need water (see Box 3). Hydropower needs water to activate the turbines. Although most of this water can be reused for other purposes such as agriculture, hydropower does interfere with existing hydrological flows and can alter hydrological regimes due to higher evaporation rates. Moreover, naïve hydropower implementation can conflict with other purposes as hydropower release schedules do not always match the timing of other water needs such as irrigation (Hellegers et al., 2008). Thermoelectric plants (nuclear, coal, oil gas fire) need large amounts of water for cooling and condensation the steam that passes through turbines. Globally, electric production depends strongly on this type of technology and therefore on cooling water availability. Water withdrawals for this technology are growing fast (Feeley et al., 2008; Roy et al., 2012; Ringler et al., 2013). Although this water use is largely non-consumptive, it can nonetheless have consequences for water quality (e.g. thermal pollution) and availability for other uses during droughts (Feeley et al., 2008; Bazilian et al., 2011; Ringler et al., 2013).

36. The energy sector might respond to sustained events of water scarcity and competition by switching to alternative cooling techniques for power plants such as wet-tower or dry-cooling (see Box 3). These cooling techniques require less water volume as input and their water withdrawal is therefore lower. A disadvantage is that their capital costs are higher, and that their water consumption is higher than regular cooling (i.e. although they withdraw less surface water, they actually evaporate a larger share of this water before returning it; IEA, 2012). Moreover, dry-cooling is less efficient and can affect power plant performance (IEAGHG, 2011). Another response of the energy sector to sustained water scarcity could be to locate new plants along the coast so they can use sea water for cooling, although land-locked countries do not have this option.

37. Fossil resource extraction, processing and transportation also require water. For instance, water is injected in oil wells for increasing the reservoirs' capacity, or used to remove dust from coal. The water intensity of fuel exploitation depends heavily on the type of resource used (IEA 2012). The exploitation of non-conventional fuel resources which are abundant in some regions can be very water-intensive compared with "conventional" resources (this will be discussed in section 2.4).

38. Biofuels and biomass also have water requirements, but their water use depends enormously on the type of bioenergy crop and whether these crops are irrigated or rainfed. In the latter case, additional water use is often modest. Nonetheless, biofuel/biomass production can exacerbate water stress in already drought-prone regions, including through the increased water pollution that this activity would also induce. Presently the share of biofuels/biomass in energy supply is modest, but this share could increase significantly to meet climate change mitigation targets (De Fraiture et al., 2008; Dominguez-Faus et al., 2009).

39. With climate change policies, energy efficiency and renewable deployment become more prominent, reducing thermodynamic power generation and the extraction of water-intensive fuel resources. There should be less need for cooling water. But on the other hand, there would be more need for more land-intensive renewables, incl. hydropower. Thus, climate change policies may influence the nexus in opposing ways, the net effect of which is difficult to determine. On the one hand the stress on water can be

decreased by less climate change and less use of water for energy. But on the other hand a decarbonisation with biofuel deployment mays create stress on land use and water requirements, displacing some of the water requirements from the energy to the agricultural sector.

40. Several industries, not least steel production and mining, use water for cooling or for processing purposes. In many cases water use by industry is non-consumptive, although it can have consequences for water quality (pollution) and can constrain the availability for other users during droughts (Feeley et al., 2008; Bazilian et al., 2011; Ringler et al., 2013). Households are also important water users. Globally, water demand for domestic uses is modest, but projections indicate a substantial increase due to factors including population growth, higher sewer connectivity levels (OECD, 2012).

41. Large quantities of energy are used for supplying clean water to the population and to industries. In the US, energy use in the residential, commercial, industrial sectors (including agriculture but excluding power) for direct water and steam services was in 2010 approximately 6.3%[5] of the primary energy consumption (Sanders and Webber, 2012). When surface water is abundant there is limited need for pumping and thus for energy use. But energy consumption will increase when water is scarce and needs to be pumped from deeper aquifers, or transported from other locations. In extreme cases, such as in parts of the Middle East, desalination and reuse of wastewater can be used, which in general has a high energy intensity compared with "conventional water" (Ghaffour et al 2013).

42. However it is very difficult to evaluate the energy consumption for water. Firstly, a large part comes from individual pumping in agriculture which is not well monitored. Secondly, the energy consumption for water supply largely depends not only on the volume of water consumption, in particular in the agricultural sector, but also on the availability of the water resources in the regions considered, and the distance from the place of consumption.

43. As with global land supply, water is not physically scarce at the global level. The global total quantity of freshwater is more than sufficient to meet current demand, but its uneven distribution makes water a scarce resource in some regions and watersheds. Moreover, part of the water reserves may be reserved for ecosystem functioning in order to maintain ecosystem services and biodiversity values. Under those environmental restrictions, water can already be considered a scarce resource in many regions and may become so in many more regions and watersheds as indicated by environmental outlooks (e.g. OECD, 2012).

**Box 4. Water use by type of power plant**

The water requirements for operating different types of power generation technologies differ markedly (Figure 4). Hydroelectric plants produce electricity from water that passes through turbines. The water is mostly discharged with no change of quality (the temperature is the same). But for hydropower with reservoir water storage (as opposed to run-of-the-river hydropower), water is consumed through evaporation. The consumption intensity, which depends on the weather condition and on the shape of the reservoir, can be higher than for the other power generation technologies (IEA, 2012; Mekonnen and Hoekstra 2012). Thermoelectric power plants, (i.e. plants where power is produces by steam that passes through a turbine) use large amounts of water for cooling. In these types of plants, that can be fuelled by coal, oil, gas biomass or nuclear energy, water cycles into a circuit where it is boiled to activate turbines, and then condensed. For this purpose, cooling water (mostly surface water) is passed through a steam condenser and where its temperature increases as it receives discharge of the heat of the steam. There are technologies that are much less water intensive. Open cycle power plants need less cooling, because the heat produced by the combustible is passed to the turbine directly and no steam condensation is needed. But the cost of such plants is high. Renewable technologies solar and wind consumed almost no water. Concentrating solar power, where solar energy created steam to activate a turbine can be more water intensive. The more efficient the plant is, the less waste heat per

[5] And 12.6% if including power which is 49% of the withdrawal.

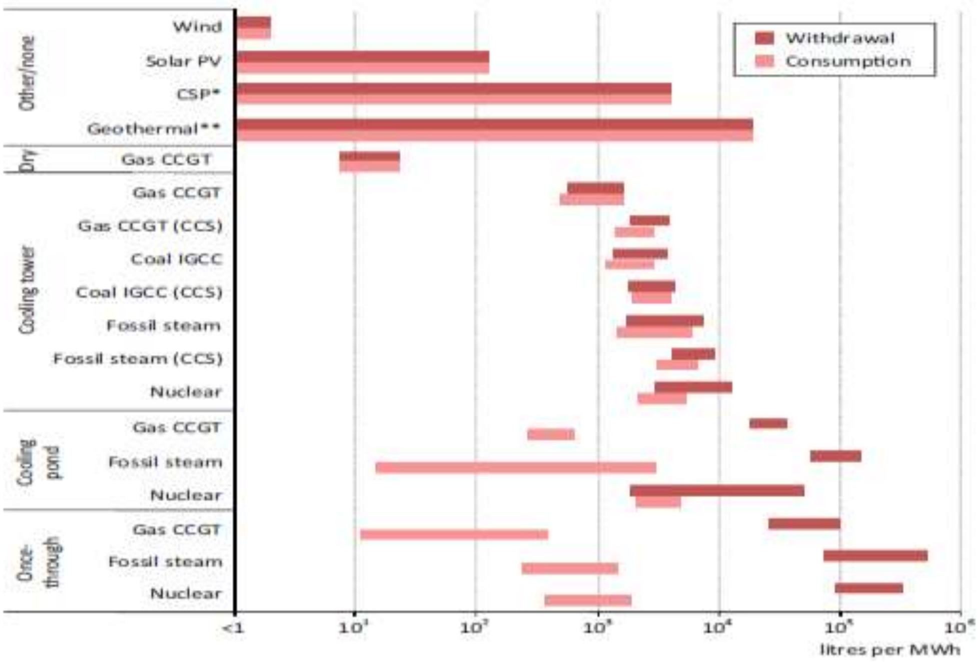
unit of electricity produced has to be cooled and thus the lower the water requirement. Because they are the less efficient, coal power plant have in general more water use. But water intensity also depends on the cooling techniques.

Once through systems: water passes through a steam condenser. The capital costs systems are low and the water consumption (evaporation) is small. But the withdrawal is high and the discharge is at a high temperature which detrimental to aquatic life and ecosystems. This is why permitting requirements for these systems have become more stringent, for instance in the United States, and they are being gradually phased out.

Wet re-circulating systems: the water passed through the steam condenser is water is cooled in a wet tower or a pond. Water not consumed by evaporation is returned to the steam condenser for reuse. This reduces the water withdrawals and exposure to risks posed by constrained on water resources and environmental impacts. But compared with once-through systems water consumption is higher and installation is more costly (40% higher than for once-through systems (US DOE/NETL, 2008)) and requires more land.

Dry cooling systems: instead of water this system uses air flow through a cooling tower to condense steam. Water requirements are very limited. Their cost is about 3-4 times higher than for re-circulating systems and they can reduce power plant efficiency. In addition, they may not suffice during warm periods.

**Figure 4. Water use for energy technologies**




*Source* : IEA (2012)

## 2.4 Energy-related bottlenecks

44. Energy is a key driver of economic activity. But energy resources are limited. For instance fossil fuel resources, including coal, oil and gas, decrease with extractions, and they become less and less accessible. The issue of depletion is not a matter of absolute depletion, but rather of the need to use a more diverse and more complex and thus more costly set of technologies to get them.

45. Over the last decade, instead of depletion there has been an increase in the use of costly technologies for exploration and productions. Most notably the booming shale oil and shale gas production has substantially increased the scope of fossil fuel resources. Shale gas and oil production require hydraulic fracturing (fracking) which consumes a lot of water and large quantities of water are needed for releasing and processing bitumen. At the global level, there is way less water used for fossil fuel extraction than for power generation (IEA 2012), but this part of the nexus can be crucial for many reasons.

46. Firstly because due to resource depletion, the share of non-conventional sources in fossil fuel supply is projected to increase steeply. Therefore, the water intensity will be pushed up and in the absence of water regulation it might significantly increase water withdrawals and consumption from the fossil fuel sector, although IEA (2012) argues that water consumption may not have to increase.

47. Secondly, in some regions, water intensive extraction activities and potentials are located in water stressed areas. When the resource is exploited, water stress becomes very high. For instance, if water for hydraulic fracturing is 1% of US water withdrawal, it is 20-30% in some counties of Texas that are semi-arid (WRI, 2014). The Monterey shale play in California, which is projected to contain the biggest shale oil reserve[6] in the US, is located is an area where water is scarce, and therefore, therefore if large-scale production starts, water stress will be high in these regions. In the case of China, the regions where shale resources are abundant are arid and therefore the competition for water is high according to IEA (2012).

48. Thirdly, there is not only an issue of water quantity but also of reduced quality (Kuyama et al 2013; Allen et al 2006). Even in regions where water is abundant, there can be problems because water effluents are polluted. The effluents need to be treated and stored by industrial and municipal facilities, which can have a high cost. In addition, there can be leakages and local pollution before and during clean-up. In areas where water regulation is not enforced, polluted water might be released and damage ecosystems. The water quality impacts are not well known for the moment, but can be significant.

49. Climate change policies may influence the energy resource bottleneck and thus the nexus. A reduction in $CO_2$ intensity would involve less fossil fuel consumption, and therefore less depletion and less need to develop very water intensive non-conventional resources. Therefore, one of their co-benefits would be to limit the energy and water bottlenecks. On the other hand, as outlined above, increased reliance on bioenergy may aggravate the competition for scarce land.

50. In the sense of the nexus, the energy resources bottlenecks are less stringent than the land and water bottlenecks, because the dependence of the services provided by energy on availability of local resources is less strong. Firstly, energy can be relatively easily transported and traded (compared with water and land). In addition, there are several options to produce energy from natural resources and various possibilities of substituting one fuel for another. Lastly, markets for energy products and services tend to be functioning better than those for land and water, thus helping to coordinate the supply and the demand and prioritize access for the most efficient uses. The notion of energy scarcity is therefore more one of increasing costs of supply rather than absolute scarcity, and its role in the nexus is primarily one of essential interlinkages with water and land resources.

## 2.5 The need for an integrated and dynamic analysis

51. The linkages in the nexus are complex. It is hard to say which link is most important or deserves most attention. Bottlenecks resulting from resource scarcity are time and place specific. The linkages with water deserve special attention. Projections show that over time limited supply and increasing demands

[6] http://www.eia.gov/analysis/studies/usshalegas/pdf/usshaleplays.pdf

will lead to increasing water stress. The OECD Environmental Outlook to 2050 projects that the number of people living in severe water stressed basins will threefold in the next decades to 4 billion in 2050 (OECD, 2012). Competition for this scarce resource will increase. Depending on how scarce water is allocated among different users, lack of water may lead to lower agricultural yields, high energy costs or both. The water-agriculture link may currently be the most relevant, with a majority of global water withdrawals for agricultural use. However, the water-energy link may become more relevant in the future with rapidly increasing water withdrawal by non-agricultural users (households, industry, electricity). Also the links between agriculture, land-use and energy may become increasingly important in the future. Biofuels only play a limited role in baseline scenarios. However, most climate mitigation pathways rely heavily on the input of biofuels. Whether biofuel production competes with food production for scarce water and land depends on the 'technology', i.e. whether it is rainfed or irrigated, on crop land or on abandoned lands. Population growth, income growth and climate change, all affect the demand and supply of the nexus resources in different ways, and has the potential to shift pressures from one side of the nexus to others. **This calls for a dynamic analysis that takes changing trends into account.**

52. This section showed that there are large interactions between the different resources in the land-water-energy nexus, and intricate connections to sectoral economic activity; increasingly strong links between economic sectors and between regions further spread the bottlenecks in the nexus to other parts of the global economic system. **This calls for integrated analysis**. An integrated systems approach is needed to shed light on how bottlenecks in the nexus affect the various aspects in the biophysical and economic systems.

53. In addition, physical scarcity may be less of an issue at the global level: the global economy is not running out of its most important resources any time soon. But the uneven distribution over space and time and often limited transferability make resources scarce in specific regions in specific periods. The global megatrends are also not manifesting themselves equally across the globe: population growth and income growth are projected to vary widely between OECD and non-OECD countries, climate change impacts primarily affect countries in Asia and Africa, etcetera. Therefore, tensions are more manifest on a disaggregated level. **This calls for an analysis at a disaggregated level.**

# 3 METHODOLOGY

54. A dynamic, disaggregated, integrated systems analysis of the combined costs of the bottlenecks outlined in Section 2 can be considered 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 costs of inaction for 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 costs of inaction. The general concept behind CIRCLE's analysis of the costs of inaction is therefore to compare the system-wide performance of a scenario with nexus bottlenecks to scenarios without bottlenecks. A systems approach also allows to illuminate how the overall costs of inaction are determined by specific interactions, and to what extent the various bottlenecks amplify or dampen each other.

### 3.1 Quantitatively assessing the costs of inaction on the nexus

55. 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. In the first round of analysis, costs of inaction will be assessed for each individual counterfactual scenario. A careful selection of scenarios from the three domains will need to be made, based on an assessment of their significance and suitability for combination. A second step then consists of investigated integrated scenarios where multiple bottlenecks are addressed, to provide deeper insights into the interaction effects between the different bottlenecks. A final third step is then to explore how policy action can reduce these costs of inaction, i.e. assess the benefits of policy action.

56. In some respects, land-water-energy bottlenecks already affect biophysical and economic systems and are therefore included in the baseline projection. For instance, the baseline projection of agricultural yields is based on an assessment of possible yields given a limited amount of available land and water for crop growth. When the bottleneck is accounted for in the baseline, the costs of inaction are determined by comparing the economic performance of the baseline with a counterfactual scenario where the bottleneck is relieved. The counterfactual scenario describes a hypothetical world where this bottleneck is not restrictive; i.e. any difference between the counterfactual and baseline then resembles the benefits of releasing the bottleneck. By approximation, the costs of inaction are then the negative of these benefits. However, technical constraints make it impossible to include certain bottlenecks in the baseline projection. One example is the default assumption of unlimited access to groundwater supply in agriculture, which underlies the baseline projection in the IMAGE model. In such cases, the baseline scenario ignores the bottleneck and it is imposed in the counterfactual scenario. The costs of inaction are then determined directly by taking the difference in economic performance between the counterfactual and baseline scenario.

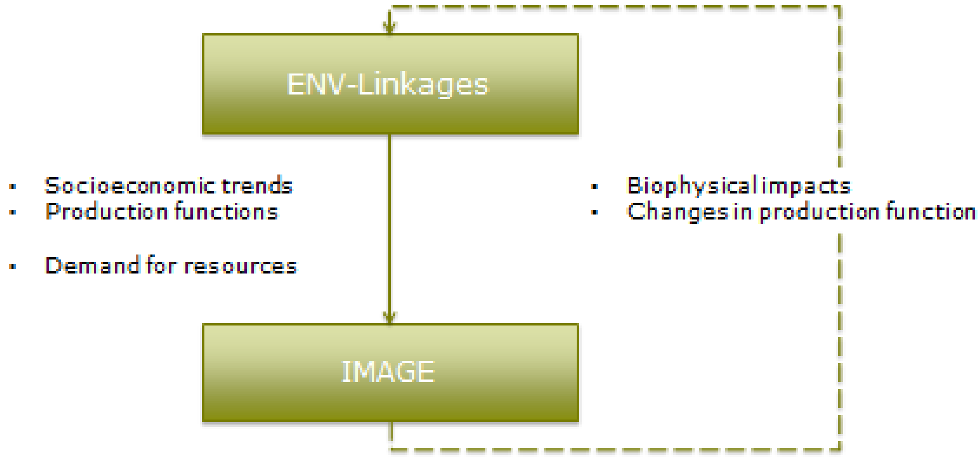
### 3.2 A multi-model framework

57. 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), cf. Figure 5. 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.

58. 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.

59. 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 costs of inaction.

**Figure 5. Modelling framework**




60. 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.

61. IMAGE is a comprehensive integrated modelling framework of interacting human and natural systems; PBL (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 characterized 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).

62. 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 tool 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 1 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 1. Overview of the nexus linkages and how they may be 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 |
| | Impact on energy resource | Modelled in IMAGE and ENV-Linkages through endogenous bio-energy production |
| | Direct impact on agricultural and forestry sectors | Modelled in IMAGE and ENV-Linkages |
| | Indirect impact on rest of the economy | Modelled in ENV-Linkages |
| **Water bottlenecks** | Impact on land resource | Modelled in IMAGE through effect on agricultural yields |
| | Impact on energy resource | Anecdotal evidence on water for electricity |
| | Direct impact on water sector | Not modelled |
| | Indirect impact on rest of the economy | Only indirect consequences of changes in crop yields |
| **Energy bottlenecks** | Impact on land resource | Indirectly modelled in ENV-Linkages through agricultural energy use |
| | Impact on water resource | Anecdotal evidence on desalinisation |
| | 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 partially in ENV-Linkages (effects through land availability and energy demand) |

63. The regional aggregation of both models have been harmonised to 25 regions encompassing the world. For presentational purposes, these 25 regions are sometimes further aggregated into 13 macroregions, as shown in Table 2.

**Table 2. Overview of the regional aggregation of the modelling analysis**

| Macro region | Countries and regions (short names in parentheses) |
|---|---|
| North America | Canada (CAN)<br>Mexico (MEX)<br>United States (USA) |
| Latin America | Brazil (BRA)<br>Chile (CHL)<br>Other Latin American countries (OLA) |
| European Union | EU largest 4 countries (France, Germany, Italy, United Kingdom) (EG4)<br>Other OECD EU countries (EU17)<br>Non-OECD EU countries (EU7) |
| Other OECD | Other OECD countries (Iceland, Israel, Norway, Switzerland, Turkey) (OE5) |
| North Africa & Middle East | North African countries (NAF)<br>Middle Eastern countries (MEA) |
| Sub-Saharan Africa | South Africa (ZAF)<br>Other African countries (OAF) |
| Transition Economies | Caspian region countries (TAN)<br>Russia (RUS)<br>Non-OECD, non-EU European countries (OEU) |
| OECD Asia | Japan (JPN)<br>Korea (KOR) |
| OECD Oceania | Australia & New Zealand (OCE) |
| China | China (CHN) |
| India | India (IND) |
| ASEAN | Indonesia (IDN)<br>Other ASEAN member countries (AS9) |
| Other Asia | Other Asian countries (ODA) |

### 3.3 Assessing the biophysical impacts with IMAGE

***Modelling water resources***

64. The water bottleneck has been incooperated by using 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.

65. 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.

66. 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 that 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 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.

67. Meeting the demand from the electricity, household and manufacturing sectors receives priority in IMAGE over water withdrawal for irrigation.

68. 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).

69. 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 (= 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 down 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.

70. Thus, IMAGE assumes groundwater withdrawals from 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 an 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 surfacewater availability.

***Modelling land resources***

71. 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 (e.g. cotton).
- Bioenergy area to meet the demand for biofuels
- Built-up areas, which are excluded from the biophysical modelling in IMAGE
- Forest areas - either strongly established by humans (=plantations) or a natural- to cover the demand for (i) timber (i.e. paper/pulp, sawlogs and wooded biomass); (ii) new forests for carbon storage (under the climate convention = af/reforestation).
- Other areas covered by natural vegetation to include areas that are not (strongly) affected by humans. These areas could potentially become used during a simulation with the exception of protected areas. This category also includes some degraded areas that have been (over)used in the past.

72. 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 results also in IMAGE 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.

73. 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.

74. 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.

75. In determining the location of land expansion in a region, all grid cells are assessed and ranked on 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.

76. A challenge in IMAGE has been the realistic specification of land competition, i.e. the allocation of the different land-use forms in the regions. For this a hierarchical land allocation has been introduced. First, urban built-up areas and infrastructure is allocated. Second, the area for food/fodder (incl. other crops) is allocated, followed by the area for biofuels. Fourth, forests become used and/or forest plantations are established to meet the regional demand for timber (sawlogs and paper), 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.

77. 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 & atmospheric conditions (incl. ozone concentrations) affect land uses differently, and as such the land competition.

***Modelling energy resources***

78. 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 & energy nexus.

79. Energy interacts in multiple ways with water and land in IMAGE.

- Energy production is 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.

80. In the first round of simulations, 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***

81. These biophysical relationships in IMAGE have multiple dimensions that have an effect/feedbacks 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 for particular land-use form. Likewise, land competition can result in changes land demands (e.g. the mentioned 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 movements lead to the use of less productive regions with increasing operational costs. At the same time, information from ENV-Linkages (e.g. on the agricultural management) is relevant for determining land production and land competition.

82. Some feedbacks are currently not included in the IMAGE model. One of these is the feedback from shortage of cooling water on energy production. IMAGE computes only the demand for cooling water, but assumes that this demand is fulfilled. Likewise, additional energy use when agriculture intensifies (e.g. for fertilizer, mechanization) is currently not calculated.

### 3.4 Linking biophysical impacts to economic damages

83. 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).

84. 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. 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.

85. 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 maximizes 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.

86. 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.

87. Household consumption demand is the result of static maximization 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.

88. 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.

89. 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.

90. In the current set of scenario analyses for the nexus, only the impacts on agricultural productivity (crop yields and land use or agriculture) are passed from IMAGE to ENV-Linkages.[7] Thus, the only parameters that are affected in ENV-Linkages are agricultural productivity and land supply. But the modelling framework is suited to also include other types of shocks if important effects on these other drivers are identified.

91. 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.

[7] 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.

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 minimize economic damages and maximize 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.

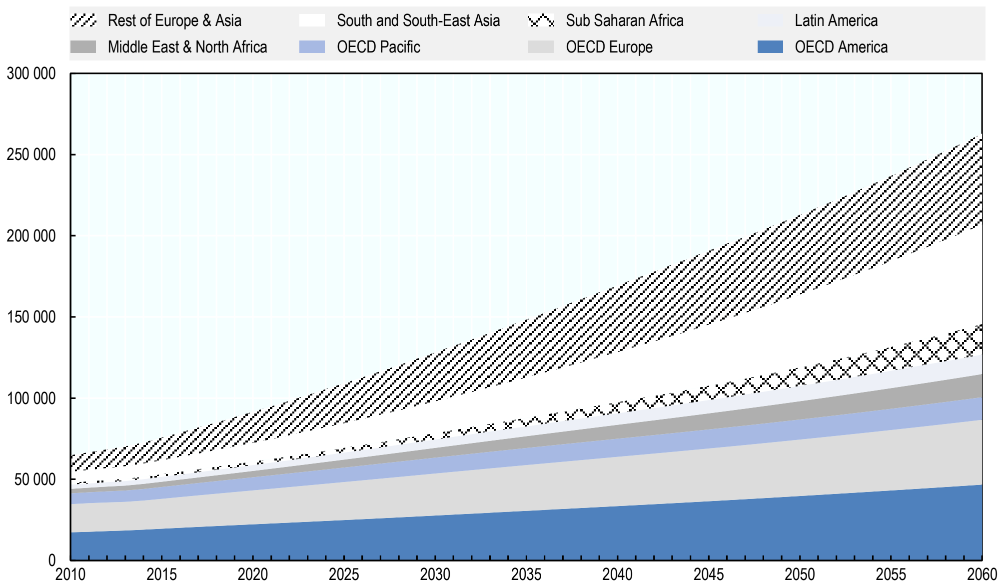
### 3.5 Brief description of the baseline projection

92. In ENV-Linkages, baseline developments of sectoral and regional economic activities are projected for the medium- and long-term future, up to 2060, based on socio-economic drivers such as demographic developments, macroeconomic growth and sector-specific trends (see also the discussion on megatrends in Chapter 2). The baseline projection for the most important elements in the ENV-Linkages model, and the associated land use and water use projections from IMAGE, are presented here; further baseline projections from ENV-Linkages are described in Annex I.

93. The regional projections of GDP indicate that the slowdown in population growth projected in the coming decades (see Annex I) does not imply a slowdown in economic activity. While long run economic growth rates are gradually declining, Figure 6 shows that GDP levels in the no-damage baseline are projected to increase more than linearly over time. The largest growth is observed outside the OECD, especially in Asia and Africa, where a huge economic growth potential exists. The share of the OECD in the world economy is projected to shrink from 64% in 2010 to 38% in 2060. These projections are fully aligned with the OECD Economic Outlook (OECD, 2014a) and includes the main effects of the recent financial crisis as they emerged until 2013 and is consistent with the central scenario of the OECD@100 report on long-term scenarios (Braconier *et al*., 2014).

**Figure 6. Trend in real GDP, baseline projection**

(Billions of USD, 2005 PPP exchange rates)




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

94. Baseline energy projections until 2035 are calibrated to be in line with the Current Policies scenario of the International Energy Agency's World Energy Outlook (IEA, 2013), and extrapolated to fit the macroeconomic baseline projections thereafter. In fast-growing economies such as China, India and Indonesia, the need to support economic growth with cheap energy drives an increased use of coal, which is abundant and cheap in the absence of carbon pricing. In OECD regions, however, energy use is projected to switch towards more gas, not least in the United States. Furthermore, in the OECD region, energy efficiency improvements dominate and imply a relative decoupling of energy use and economic growth. The resulting effects on energy production by fuel and region are given in Figure 7.

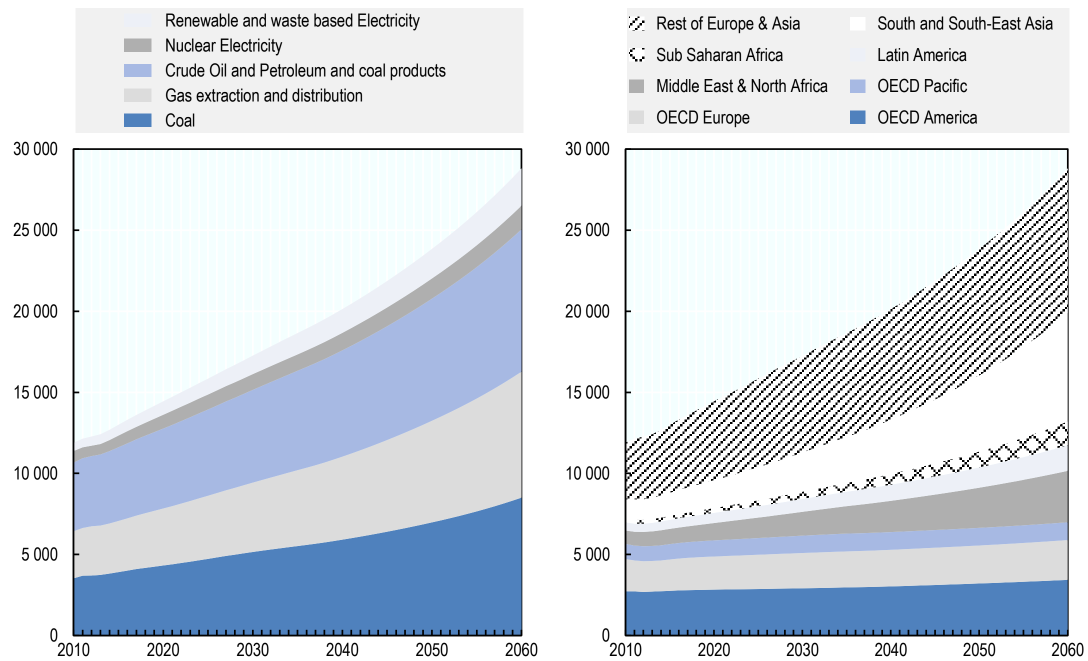
95. The examination of the projected energy trends helps to identify the second possible potential bottleneck of the LWE nexus. Figure 7 shows that, in line with the macroeconomic developments, the increase in future energy demands are projected to be strongest in rapidly developing economies (Sub-Saharan African countries and India, followed by other Asian countries, China excepted). Moreover, despite a growing share of renewables in electricity production, the increase in fossil-fuel energy demand is almost in line with the increase in total energy demand. Under current policies, both fossil-fuel extraction and fossil-fuel based power generation are projected to grow in the coming decades, and these activities are very water-consuming.

96. Liquid fossil energy resources are unevenly distributed across countries, with oil production projected to continue to be produced mostly in the regions that are now large exporters (Middle east, Former Soviet Union countries and Latin America), while gas extraction is projected to diversify to more regions. Countries with relatively small (or no) domestic sources of fossil fuels will generally meet the extra demand for energy through a substantial increase in electricity generation (this applies to all Asian countries as well as Sub-Saharan African countries).

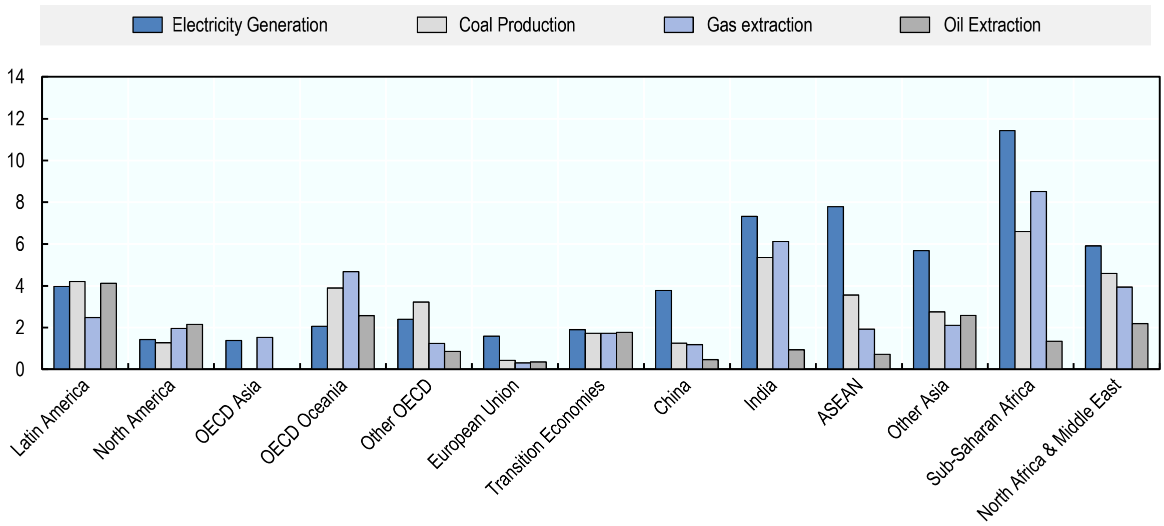
**Figure 7. Primary energy production, baseline projection**

(Million tonnes of oil equivalent)

Panel A. Evolution over time



Panel B. Fossil Fuel production and Electricity generation expressed as change from 2011 values

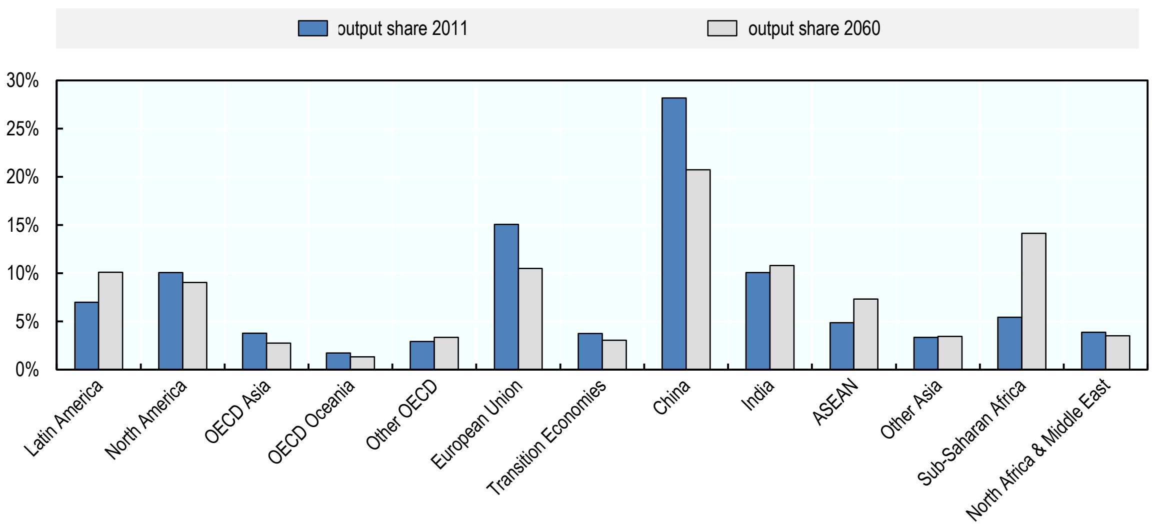



Source: ENV-Linkages model based on IEA (2013) projections.

97. The agricultural trends in the baseline scenario show that agriculture production (defined as the sum of real gross output over crops and livestock sectors) will increase in all regions between now and 2060. But while the increase will be moderate in countries with aging populations (around 13-25% increase in China, EU and OECD Asian and Pacific countries), while the increase in Latin America will be around 133% and even 320% in other African countries.

98. The agriculture production increase is closely related to the increase in food demand (Figure 8). As a consequence, from 2011 to 2060, world agricultural production shifts away from less rapidly growing countries, including mostly OECD countries and China whose share in world agricultural output declines (Figure 8), to less-developed but faster growing countries.

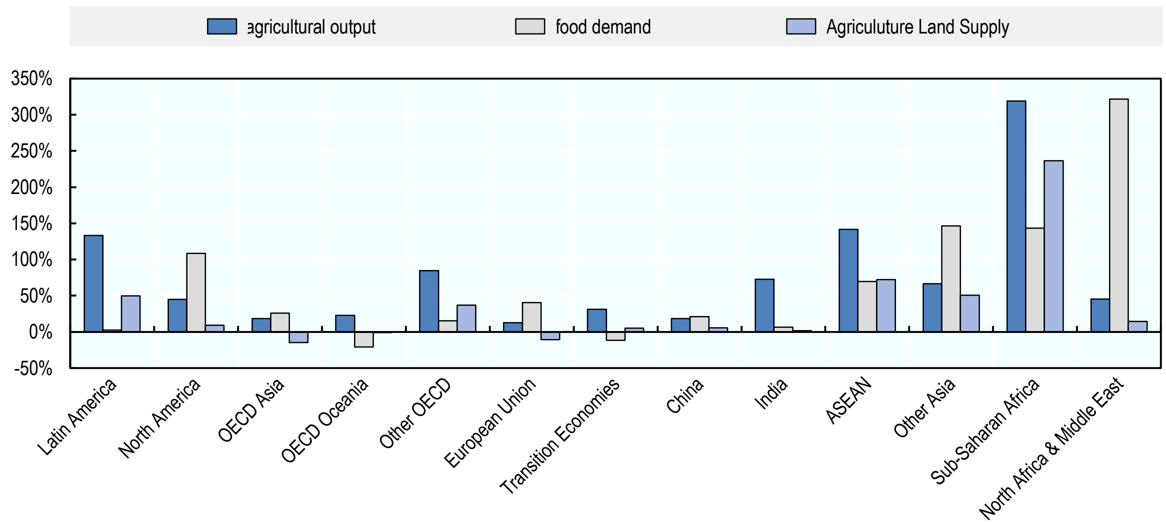
**Figure 8. Agriculture gross output by aggregate region (percentage of world total), baseline projection**




Source: ENV-Linkages model

99. The pressure on agricultural product demand will partly translate into increases in agricultural land use, as indicated in Figure 9, to cover the extra needs for food production. But agricultural production is still projected to increase much more than land use because of the lower-than-historical but continued increase in yields assumed in the baseline (driven by better land efficiency and better total factor productivity in the crop sectors). The baseline then assumes that both land use and water use could increase to satisfy future needs in human food and livestock feed production.

**Figure 9. Total agriculture output, total agricultural land supply and total food demand in 2060 by aggregate region, baseline projection (2060 level relative to 2011)**




Source: ENV-Linkages model

100. Based on the baseline projections of economic activity, the associated land use patterns and regional irrigation water use profiles are constructed. These are presented in Table 3 and Figure 10; see also Figure 3 in Section 2.3 for the baseline projection of total water use.

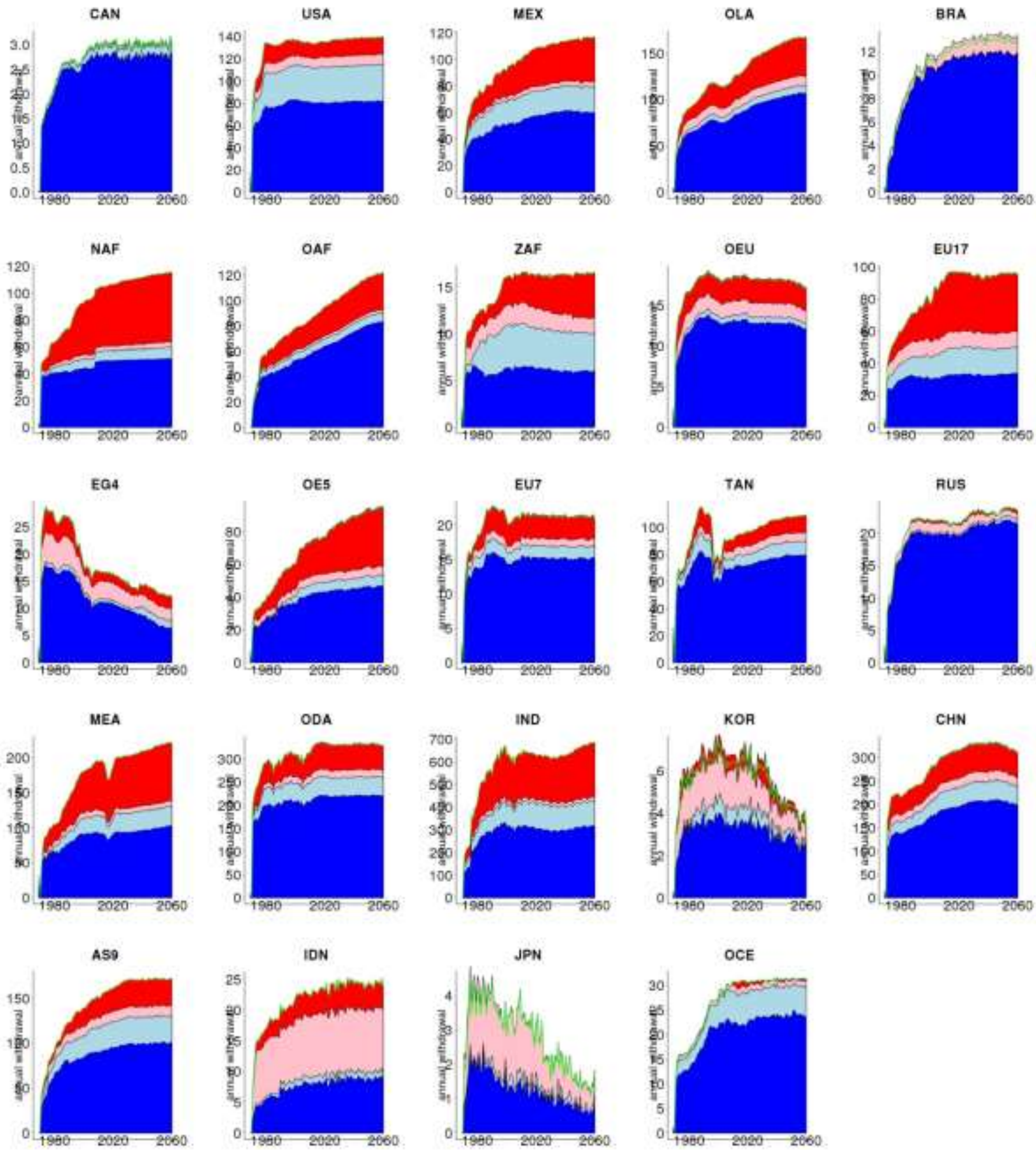
**Table 3. Land potentially available for agriculture in baseline**

| | Agricultural land (thousands km2) | Remaining potential land supply (thousands km2) | Total potential land supply for agriculture (thousands km2) | Current land use (% of total) |
|---|---|---|---|---|
| **Canada** | 675 | 491 | 1166 | 57,9% |
| **USA** | 4148 | 1319 | 5467 | 75,9% |
| **Mexico** | 1075 | 391 | 1466 | 73,3% |
| **Other Latin America** | 3491 | 2085 | 5576 | 62,6% |
| **Brasil** | 2636 | 1764 | 4400 | 59,9% |
| **North Africa** | 1008 | 37 | 1045 | 96,5% |
| **Other African countries** | 9272 | 5386 | 14658 | 63,3% |
| **South Africa** | 996 | 96 | 1092 | 91,2% |
| **Non-EU Eastern Europe** | 630 | 187 | 817 | 77,1% |
| **EU OECD 17 smaller countries** | 894 | 581 | 1475 | 60,6% |
| **EU OECD 4 Larger countries** | 783 | 298 | 1081 | 72,4% |
| **Other OECD Eurasia** | 465 | 302 | 767 | 60,6% |
| **EU non-OECD countries** | 272 | 126 | 398 | 68,4% |
| **Caspian countries** | 2927 | 137 | 3064 | 95,5% |
| **Russia** | 2155 | 1224 | 3379 | 63,8% |
| **Middle east** | 2164 | 151 | 2315 | 93,5% |
| **Other developing Asia** | 2185 | 406 | 2591 | 84,3% |
| **India** | 1802 | 419 | 2221 | 81,1% |
| **Korea** | 19 | 0 | 19 | 99,8% |
| **China** | 5563 | 752 | 6315 | 88,1% |
| **Other Asian countries** | 672 | 902 | 1574 | 42,7% |
| **Indonesia** | 478 | 722 | 1200 | 39,8% |
| **Japan** | 51 | 0 | 51 | 100,0% |
| **Oceania** | 4624 | 869 | 5494 | 84,2% |

*Note:* Current agricultural land in absolute terms (in $km^2$), and as a percentage of the land supply that was calculated for the baseline and the counterfactual scenario. Additionally, the land supply is shown (in $km^2$) for the baseline and the counterfactual scenario.

Source: Image model

**Figure 10. Absolute share of the different water sources in irrigation for the baseline**




*Note:* Dark blue: surface water; light blue: surface water in reservoirs; pink: 'renewable' groundwater; red: groundwater from non-renewable aquifers. Annual fluctuations stem from the variability in rainfall, as projected in the LPJmL model, and from changes in land use. Unit of X-axis: years. Unit of Y axis: km3.

Source: IMAGE model

### 3.6 Overview of the scenarios that can assess the costs of inaction

101. The combination of the IMAGE and ENV-Linkages modelling tools can illustrate the systemic effects of bottlenecks in the nexus: they provide a full 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 (see Section 3.2). 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.

102. The simulations in the final report will consist of the following categories:

1. *Bottleneck scenarios*: these investigate the consequences of bottlenecks posed by the quantity or quality of one of the three nexus resources: land supply, land degradation, water supply, etcetera.

2. *Integrated scenarios*: these investigate the consequences of the impact of several core bottlenecks simultaneously.

3. *Cross-cutting scenarios*: these investigate how alternative assumptions on the underlying megatrends (population, economic activity, use of biofuels, climate change) change – aggravate or alleviate – the consequences of the various bottlenecks.

4. *Policy scenarios*: these explore the benefits of policy action to reduce a specific bottleneck, capturing the trade-offs and synergies with other bottlenecks.

103. In the first round of analysis, the focus is on the first category: bottleneck scenarios, as these give insight in the severity of potential resource problems, and provide the reference point for the more advanced scenarios. Bottleneck scenarios investigate how behaviour of relevant natural and human systems changes in response to tighter or looser resource constraints. A key notion is that the potential of natural resources to deliver services to humans cannot be expanded by human actions: this is considered a given for historic, current and future economic activities, Still, the current and future severity of constraints is shaped by human interventions, for example current agricultural land occupies some forty percent of the total terrestrial surface, and the potential to expand in future is thereby limited to currently unused, suitable areas not reserved for other purposes such as nature conservation, human settlements including recreation, etc. In the baseline scenario, future resource use is estimated in the presence of a range of such constraints. To explore how important such constraints are, counterfactual cases are defined and analysed in which the constraint is relaxed.

***Scenarios covered in the first round of analysis***

*Water bottleneck scenario: Limiting groundwater extraction*

104. 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 4). 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 4).

105. 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. (2011) of which groundwater aquifers are used unsustainably. In the analysis, unsustainable use is associated with the ‘groundwater footprint’, i.e. the area required to receive sufficient precipitation to sustain groundwater use and groundwater-associated ecosystem services. The larger the water-collecting surface area, compared to the area covered by the aquifer, the bigger the risk that extraction will exceed influx and thereby gradually exhaust the reservoir.

106. Unfortunately, until now insufficient information exists to realistically link 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 groundwater footprints exceeds five times their geographic area are depleted by 2050 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 other aquifers that are not considered at risk of depletion remains available for irrigation. Additionally, groundwater from local aquifers is assumed to become depleted in 2040. This does not mean that the entire aquifer is depleted, but that abstractions 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 11 in Box 4 shows the substantial regional differences in how aquifers around the world are affected.

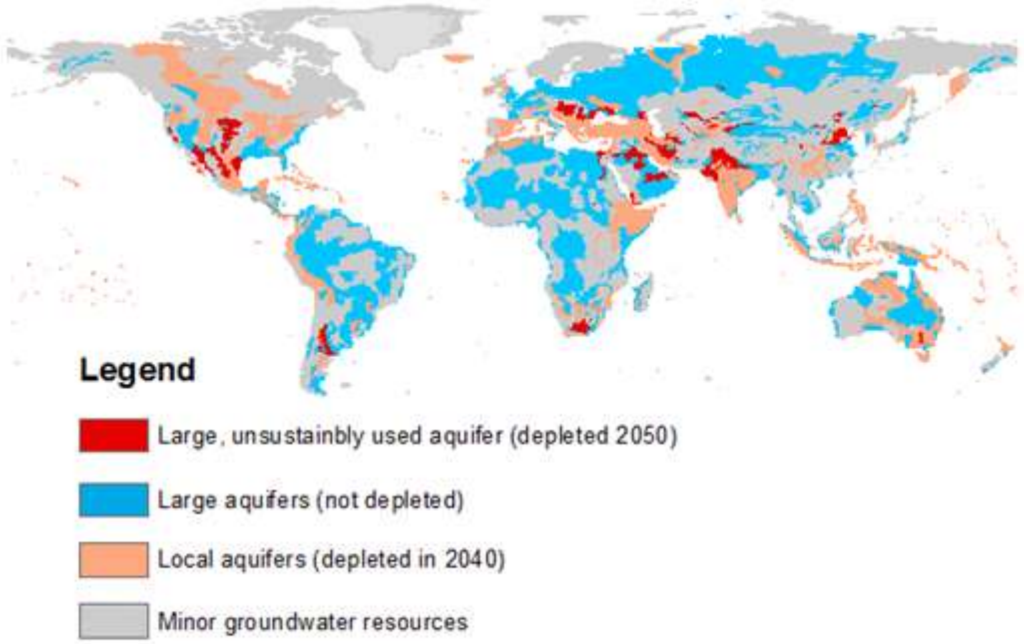
**Box 5. Sources of agricultural water supply**

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 abstractions 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 abstractions becoming higher than recharge rates. 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 11. Overview of affected aquifers**




Source: IMAGE model based on WHYMAP (BGR/UNESCO, 2015) and Gleeson et al. (2011).

*Land bottleneck scenario: Relaxing agricultural land supply*

107. This scenario explores the effect of changes in agricultural land supply. Agricultural land supply (covering food & fodder crops, intensive and extensive grazing) 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 (technically, the land supply elasticity falls with increasing land use). 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.[8] In the baseline, a number of restrictions, including urbanization, climate change, extreme land degradation and environmental protection, are considered that make land 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 relaxing these restrictions in each region. This is done by allowing conversion of wetlands and protected nature reserves, and by including low-productive land (with slopes of up to 30-45 degrees).

*Water-energy bottleneck scenario: Increasing hydropower capacity*

108. In this scenario, the limiting factors on hydropower are explored. To assess an "unlimited" but nonetheless plausible supply of hydropower, the practical assumption made is that technology improvements occur such that hydropower production is less reliant on the natural resource in production.

[8] See Annex II for a graphical exposition of this scenario.

This mimics the effect that the economic potential can more rapidly evolve to the technical potential. The upperbound on hydropower is still restricted by a technical potential for hydropower, loosely based on expert insights from IEA and Utrecht University. The increased capacity will make hydropower electricity cheaper relative to other electricity technologies than in the baseline: by 2060, the increase in hydropower generation is 40% higher in African countries, 25% higher in Asean countries and other developing Asia, 20% in OECD Pacific countries. For the other countries the increase remains limited, around 10% to 15%.

*Cross-cutting scenario: Limiting groundwater extraction under climate change*

109. In this scenario, the bottleneck scenario of limiting groundwater availability in agriculture is coupled with a projection of climate change, to explore how climate change affects water scarcity projections, and the associated economic consequences.

# 4 RESULTS FOR THE COSTS OF INACTION[9]

## 4.1 Results for the Limiting groundwater extraction scenario

***Biophysical consequences***

110. The IMAGE model is used to project the impacts of fossil groundwater depletion on agricultural yields, and thereby on land use, before endogenous adjustment process in the economic system take place. Impacts vary widely between regions and crop types (Table 4). There are two main reasons why impacts differ so much between regions. First, in many regions the precipitation volume and temporal pattern are such that agriculture is predominantly rain fed, so it does not depend on irrigation. In addition, where precipitation is insufficient to sustain plant growth over the growing season, ample supply of renewable water from surface waters (rivers, lakes and reservoirs) renders withdrawals from non-renewable groundwater bodies unnecessary. In both cases no, or only negligible impacts are bound to occur if water supply from groundwater is constrained. Finally, the estimated volumes stored in large groundwater reservoirs may be so large compared with annual withdrawals, that depletion is not a constraining factor.

[9] The presentation of results from IMAGE and ENV-Linkages, for example for different crops, will be further harmonised in the final report.

**Table 4. Percentage yield loss in the Limiting groundwater scenario w.r.t. baseline in 2060**

| | Temperate cereals | Rice | Maize | Tropical cereals | Pulses | Roots & tubers | Oil crops |
|---|---|---|---|---|---|---|---|
| Canada | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| USA | 0% | -3% | 0% | -1% | -1% | -1% | 0% |
| Mexico | -21% | -10% | -2% | -4% | -8% | 0% | -6% |
| Other Latin America | 0% | -1% | 0% | 0% | -1% | 0% | 0% |
| Brasil | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| North Africa | -2% | -27% | -32% | -19% | -10% | -22% | 0% |
| Other African countries | -4% | -1% | 0% | 0% | 0% | 0% | 0% |
| South Africa | -7% | | -2% | -8% | -3% | -1% | 0% |
| Non-EU Eastern Europe | 0% | 0% | -2% | 0% | -1% | 0% | 0% |
| EU OECD 17 smaller countries | -2% | 0% | -24% | 0% | -23% | -27% | -1% |
| EU OECD 4 Larger countries | 0% | 0% | 0% | 3% | -23% | -23% | 0% |
| Other OECD Eurasia | -5% | -35% | -34% | 0% | -40% | -26% | -5% |
| EU non-OECD countries | 0% | -100% | -1% | 0% | -3% | -3% | -1% |
| Caspian countries | -1% | -3% | -3% | -3% | -2% | -2% | -1% |
| Russia | 0% | 1% | 0% | 0% | 0% | 0% | 0% |
| Middle east | -12% | -45% | -42% | -30% | -18% | 32% | -3% |
| Other developing Asia | -1% | -1% | 2% | -2% | 1% | -2% | -4% |
| India | -16% | -20% | -17% | 0% | -6% | -1% | -1% |
| Korea | | 0% | 0% | 0% | 0% | 0% | 0% |
| China | 0% | -1% | 0% | -1% | -1% | 0% | 0% |
| Other Asian countries | 0% | 0% | 0% | 0% | 1% | 0% | 1% |
| Indonesia | | 0% | 0% | 1% | 0% | 0% | 0% |
| Japan | 0% | 0% | | | 0% | 0% | 0% |
| Oceania | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Source: IMAGE model
Note: Averaged irrigated and rainfed are shown. Temperate cereals comprise wheat, rye, oats and barley.

111. Canada, Brazil, other African countries, other Latin America countries, Oceania, and Russia are examples of countries and regions relying (almost) exclusively on rainfed agriculture and are thus not directly affected by groundwater limitations. The relatively small irrigated areas they have are amply supplied through surface water. As agricultural yields in these regions are hardly affected by the imposed water bottleneck, land use and agricultural production subsequently also differ little between baseline and counterfactual scenario. Figure 12 (which can be compared to Figure 10 in Section 3.5 which describes the baseline projection) confirms that these regions have sufficient water resources; i.e. they mainly use surface water for irrigation both in the baseline and counterfactual scenario. In these regions, groundwater availability does not seem to be a pressing aspect of the nexus.

112. In arid parts of Africa, agricultural output may well be constrained by water limitations, but irrigation is often not affordable, and the baseline assumption is that irrigation areas are not increasing over time. Hence the reliance on groundwater is very limited in the baseline and the impact of its depletion on crop yields is very little.

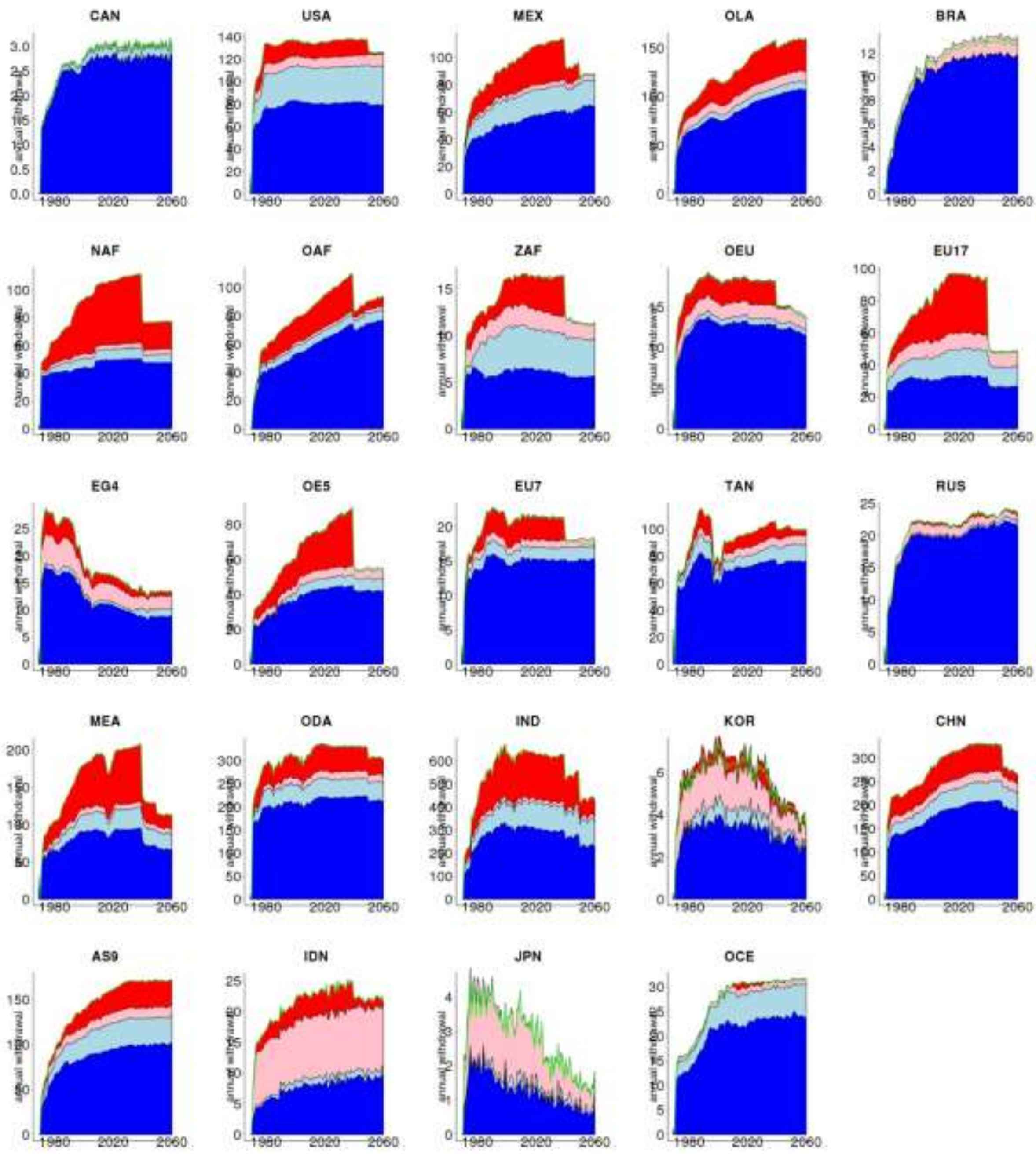
113. Countries such as Japan, Korea, and Indonesia do have substantial areas of agriculture under irrigation, in particular paddy rice fields, but availability of renewable water from surface sources and annually renewed groundwater is sufficient to sustain growth. These countries rely on surface water plus renewable groundwater (i.e. they use no or very little non-renewable groundwater). They do not rely much on non-renewable groundwater abstractions and therefore introducing this groundwater bottleneck hardly affects these regions. This is clearly shown by comparing Figure 12 to Figure 10: both in the baseline and the counterfactual scenario, surface water and renewable groundwater are the largest sources of irrigation water in these regions. These figures also confirm that these regions have few non-renewable groundwater abstractions. As agricultural yields are hardly affected by the imposed water bottleneck, agricultural production and land use are subsequently also little affected. Thus, groundwater depletion also plays only a minor role in the land-water-energy nexus in these regions.

114. The USA has some agricultural areas (California Central valley, High Plains aquifer) which rely heavily on non-renewable groundwater abstractions. Non-renewable groundwater abstractions account for 10% of all irrigation water abstractions in the baseline, but that this share is reduced to 1-2% in the counterfactual scenario due to the introduced bottleneck. Although the groundwater bottleneck is imposed upon certain agricultural areas, the impact of the bottleneck does not become apparent in the overall results for the US as local yield losses remain relatively minor and other regions are not affected, allowing the country to rebalance its land use system to minimise the disruption. Agricultural yields show only minor decreases, and subsequently agricultural production and land use is hardly affected. Figures 10 and 12 show that the US relies heavily on reservoirs for provision of irrigation water, and to a lesser extent on groundwater.

115. Other regions are affected more strongly by the imposed groundwater bottleneck. In Mexico and South Africa, the relative share of non-renewable groundwater in irrigation water is reduced substantially in the counterfactual scenario due to the imposed bottleneck as compared to the unlimited groundwater use in the baseline projection. This translates into some substantial yield losses in these regions. Mexico faces substantial decreases in yields of some of its major crops, i.e. maize and pulses. Figure 12 shows that substantially less water is subtracted from aquifers in the counterfactual scenario compared to the baseline –corresponding with the depletion of these aquifers. However, this water bottleneck has some knock-on effects; i.e. these yield changes induce an increase in agricultural land (Table 3) to compensate for these production losses in order to maintain the regional agricultural production. Similarly, South Africa faces yield decreases of some crops. Its main crop maize is cultivated mainly rainfed and therefore yield losses in maize are restricted. However, temperate cereals are more often irrigated and more substantial yield losses are therefore projected for this crop. Similar to Mexico, the imposed water bottleneck also impacts

land use; i.e. these yield changes necessitate an increase in agricultural land in order to maintain regional production.

**Figure 12. Absolute share of the different water sources in irrigation in the Limiting groundwater scenario**




*Note:* Dark blue: surface water; light blue: surface water in reservoirs; pink: 'renewable' groundwater; red: non-renewable groundwater from aquifers. Annual fluctuations stem from the variability in rainfall, as projected in the LPJmL model, and from changes in land use. Unit of X-axis: years. Unit of Y axis: km3.

Source: IMAGE model

116. North Africa and the Middle East are severely affected by the imposed bottleneck. Figure 12 shows a severe reduction in the projected share of non-renewable groundwater in overall irrigation water in the counterfactual scenario with the imposed bottleneck. The bottleneck hence results in important agricultural production losses in these regions. The dominant crop in both regions is temperate cereals, which is predominantly rainfed but there is also some irrigation of temperate cereals. Imposing the groundwater bottleneck affects the yield of temperate cereals in North Africa and the Middle East only a little, but it does heavily impact the other irrigated crops maize and rice. Moreover, land resources are so constrained in this area that no alternative suitable locations are available for these irrigated crops; i.e. the regional demand for these irrigated crops cannot be met without increasing imports (see also Section 4.2). Clearly, the groundwater bottleneck severely contributes to land competition in these regions.

117. China has a substantial irrigated agricultural area and partially relies on non-renewable groundwater abstractions for irrigation, which are reduced in the counterfactual scenario due to the imposed bottleneck. Nonetheless, agricultural yields in China are only modestly affected by the imposed bottleneck. A reason for this is that, following the scenario assumptions discussed in Section 3.6, relatively fewer aquifers are projected to be depleted than in most other Asian countries. Also, the aquifers that become depleted in China have a modest contribution to overall agricultural production and it is fairly easy to adjust the land use system to absorb the shocks posed by the depleted aquifers. The projected agricultural yield losses do induce an increase in agricultural land to compensate for the production losses, but this increase is also very modest.

118. Imposing the groundwater bottleneck results in much smaller shares of non-renewable groundwater in overall irrigation water abstractions in most European countries. This translates into yield losses in these regions. Projected yield losses for some crops in the various European (sub-) regions at first glance seem quite dramatic (Table 4). However, in some cases these yield losses concern crops that have very minor production volumes in these regions. An example is rice, which shows huge yield losses in EU non OECD countries but covers only 0.1% of the current cropland in this region. Moreover, most of the EU non OECD countries have aquifers that are depleted in the counterfactual scenario (or they are northerly countries), which means that very few alternative locations are available for irrigated rice. In EU non-OECD countries, the main crops (respective cropland shares: temperate cereals: 51%; maize: 20%; oil crops: 20%) show yield decreases but these are small compared to the yield losses of rice (i.e. yield losses ranging from -0.4 to -0.8%). As a result, the increase in agricultural land to compensate for production losses is also very small in this region, and impacts on land competition are thus negligible.

119. Very large yield losses (around -20%) are also found in pulses and roots & tubers in the EU OECD 4 Larger countries. But these crops occupy only a very small share of the cropland in these countries (currently < 1%). Temperate cereals and oil crops occupy by far most cropland in these countries. Yield losses are also projected for these latter crops (around -0.3%), but they are much smaller than the yield losses for pulses and roots & tubers. Overall, the combined yield losses of these crops do induce an increase (of around + 8%) in agricultural land to compensate for production losses. This bottleneck therefore does seem to exacerbate land competition in the EU OECD 4 Larger countries.

120. Yield losses of maize, pulses, roots & tubers in EU OECD 17 smaller countries are substantial and these crops do cover substantial land area. These yield losses mostly occur in the Mediterranean countries (Iberian peninsula, Greece) of this region. However, impacts on the 2 largest crops (temperate cereals, oil crops) are more modest in this region.

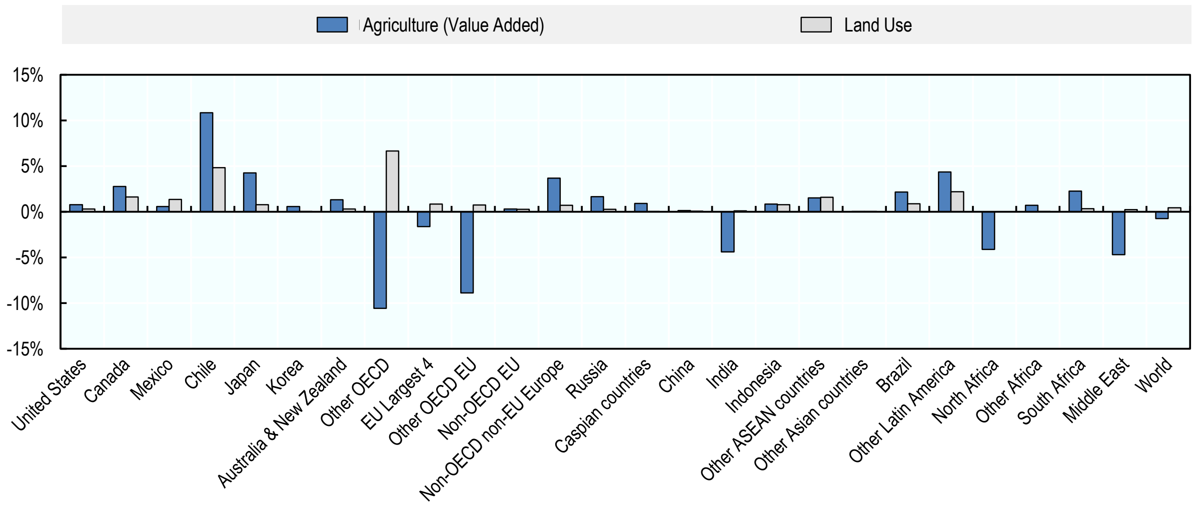
121. Also, yield losses in the region ‘other OECD Eurasian countries’ are quite substantial; temperate cereals, pulses and maize are affected and these crops have an important share in the overall agricultural production. In these countries, land use responds to these yield losses and the agricultural area in these

regions shows an increase as a result of this bottleneck. These results thus suggest that this groundwater bottleneck can potentially contribute to land competition in these countries.

***Economic consequences***

122. The regions that will suffer from the reduced land yields, caused by the limitation of groundwater extraction, will see their agricultural aggregate production negatively impacted, while the cost of production of some of their agricultural activities will increase substantially (although not all crops are symmetrically affected). In Other OECD Eurasian countries (incl. Turkey and Israel), it is the agricultural sector that is the most affected by the lack of water for irrigation (-11% of agricultural output in 2060). The EU countries, India and Middle East and North Africa all suffer from a substantial loss in agricultural output of around 5% by 2060.

**Figure 13. Agricultural value added and land supply in 2060 in the Limiting groundwater scenario (percentage change from baseline)**



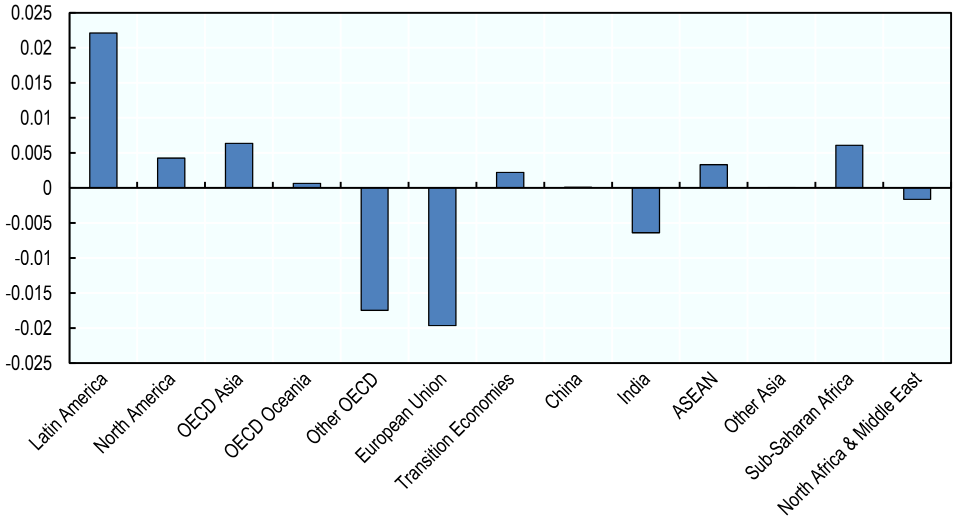

Source: ENV-Linkages model

123. At the world level, the re-allocation of agricultural production between countries will imply that the total agriculture value added loss is very moderate (around 0.7%).[10] Global production changes remain limited because food is a necessary good whose demand is relatively inelastic to changes in prices. The countries that are assumed to not be affected by the groundwater depletion will raise their crops production, as a response to the increase of world prices for agricultural commodities.

124. As indicated in Figure 14, the position of specific regions in the international market for crops depends on their *relative* competitive advantage: thus, regions that are not affected by the water bottleneck (Latin America) or regions that are less affected than their major trading partners (Other Africa), would have a chance to increase their market share, and thus benefit from the bottleneck, despite unchanged or even worsening domestic conditions. This in turn will partly offset the reduced production in regions facing yield decreases. For example, agriculture output in 2060 is projected to increase by 3.5% in Latin America and 1.7% in Transition economies (cf. Figure 13).

[10] Note that the model endogenously handles change in trade volumes, but does not allow the creation of trade from or to places where none exist currently.

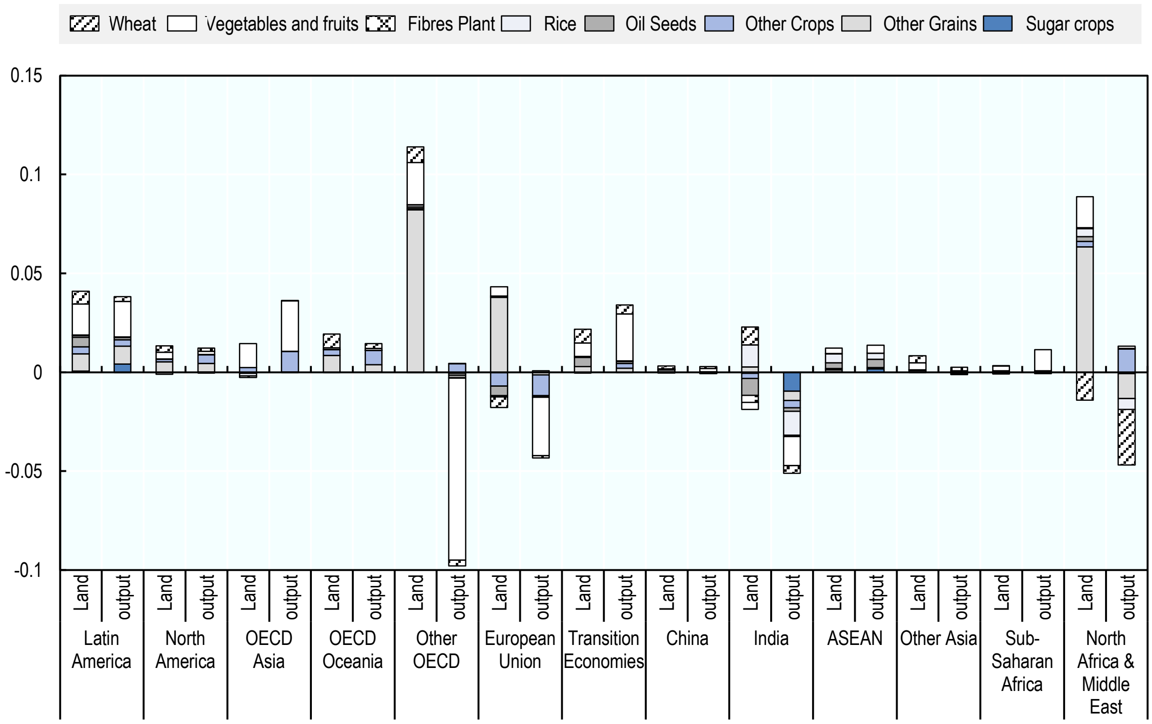
**Figure 14: Changes in geographical distribution of trade for crops in the Limiting groundwater scenario 2060 (regional exports as a share of world exports: difference to the baseline)**




Source: ENV-Linkages model

125. A non-negligible part of the reduction in yield will be offset by re-allocation of agricultural land and labour away from crops suffering from yields losses towards more profitable agricultural activities. Indeed as indicated in Figure 15 some crops see their production less impacted than the shock on their yields relative to other crops would suggest (for instance cereals in India or in North Africa relative to vegetables). Because some resources (e.g. land in Figure 13.) are reallocated across crops activities: some of the vegetable land in India is re-affected to cereals production. At the country level, the economic structures will also adapt to try to compensate for reduction of land yields due to groundwater limitation. Countries will increase the relative use of intermediate inputs and primary factors per unit of output (for example fertilizer utilization is projected to increase by 8% in North African countries compared to the baseline).

**Figure 15: Contribution of each crop to changes in total crop land use and output in the Limiting groundwater scenario, 2060, selected regions (percentage change from baseline)**

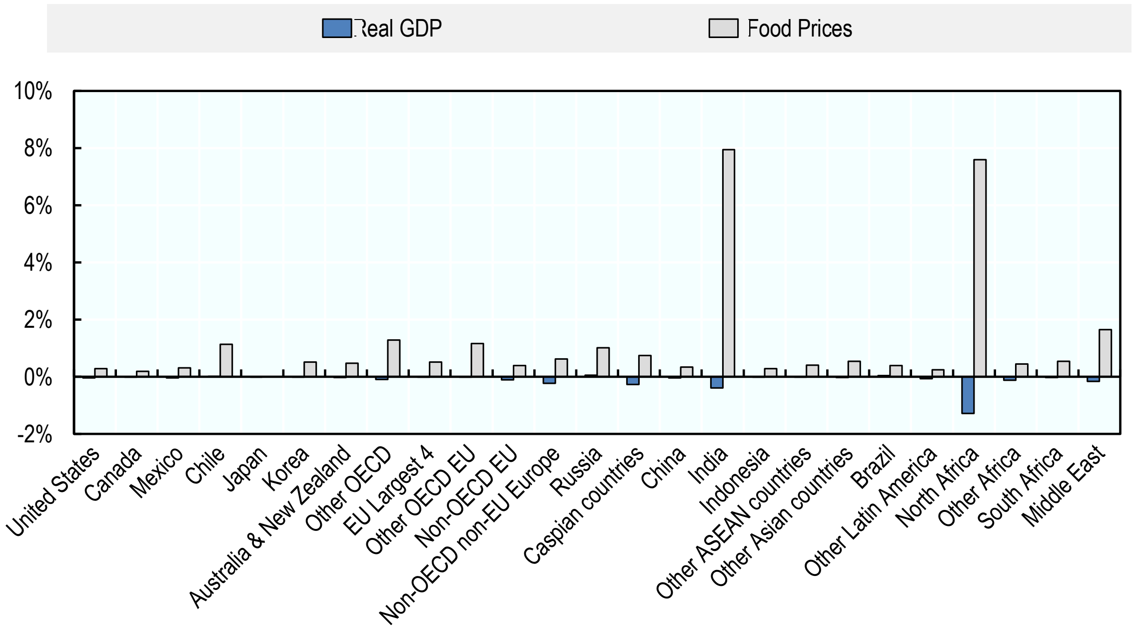



Source: ENV-Linkages model
Note: Other grains contains maize, rye, oats, barley.

126. In macroeconomic terms, for most regions the GDP impacts are quite small (Figure 16). Only North African countries will suffer from a substantial loss in GDP (around -1.2%), and the impacts in India are also non-negligible, but for the other regions it is much smaller, and the global GDP loss in 2060 compared to the baseline is less than -0.1%.

127. The effects on food security can be much more substantial, though. The reduction of crops yield due to reduced groundwater availability in specific aquifers gives way to an increase in food prices as shown in Figure 16. Although food is internationally traded, and the global food market price will adjust to all the regional changes, local prices deviate from the world market price. Consequently, the impacts in terms of food prices vary across countries, from almost zero to 8% in India and North African countries, reflecting the large regional variations in crop yield vulnerability to the lack of groundwater.

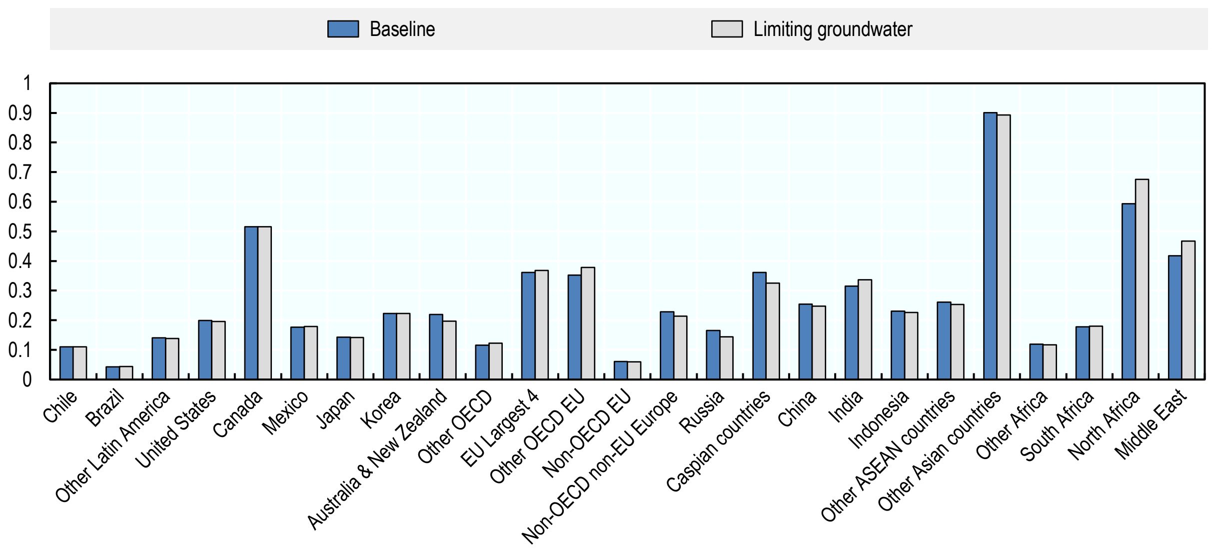
**Figure 16. Changes in real GDP and domestic food production prices in the Limiting groundwater scenario (percentage change from baseline)**




Source: ENV-Linkages model

128. International trade in food products limits the regional increase of food products price. But Figure 17 illustrates that regions that are projected to be most affected by the limiting groundwater could also face to some serious food security issues: the share of imports in total demand for crops could substantially rise relative to the baseline consumption This phenomenon is most important for North Africa and Middle-East.

**Figure 17. Ratio of crops imports to crops demands in 2060**



129. This scenario illustrates the close interactions between land and water resources. In these counterfactual simulations, agricultural land use will increase in all countries, as a result of the increases in crop prices that make agricultural land more profitable. This enlargement of land supply is, however, unevenly distributed among countries. In regions where land is abundant and relatively cheap, the increase in land is substantial (ASEAN countries, Latin America); for Mexico the use of extra land could even offset the negative impact of decrease in water access. Unfortunately, the potential to increase total land devoted to agricultural activities remains very limited in those countries that are most strongly affected by land yield losses: the North African and Middle Eastern countries where arable land is expensive, but also Western European countries where agricultural land is already close to its potential. For these later countries the land rental rate is projected to increase substantially when the water bottleneck limits yields. In Other OECD Eurasian countries (e.g. Turkey) land is relatively abundant, so the increase in land supply amounts to 6.5% and this will offset partly the reduction in groundwater access.

130. As a conclusion, the economic consequences are very unevenly distributed in this groundwater scenario, concentrated in Mediterranean countries and in India, implying up to 40% reduction in agricultural yields for some crops in some of these countries. Therefore an adaptation of the economic structure, international trade and the use of extra agricultural land is triggered that can in most cases smooth the impacts across countries, such that only North African countries (and to a lesser extent India) would suffer substantial macroeconomic losses.

## 4.2 Results for the Relaxing agricultural land supply scenario

### *Biophysical consequences*

131. The Relaxing land supply scenario aims to illuminate how bottlenecks related to a restricted use of land affects the agricultural sector, and the economy as a whole. The counterfactual scenario assumes that more land is potentially available for agricultural use, thereby partially lifting the bottleneck on scarce land in regions with limited land supply. With the IMAGE model, the effect of releasing restrictions on agricultural land supply was calculated. Table 5 shows the change in land supply (in $km^2$) for the baseline and counterfactual scenario.

132. Land supply differs between the baseline and the counterfactual scenario, but this difference varies considerably between regions. In some regions where agriculturally suitable land is already a scarce resource and where – to some degree – land competition is already a pressing issue, remaining land is small, and the counterfactual scenario can alleviate scarcity somewhat, but not a lot. Releasing land supply constraints (i.e. agriculture in wetlands, nature reserves, more marginal soils, limited road access or on steeper slopes) results in a somewhat larger land supply, as land competition has already forced agriculture to expand to these less suitable locations in these regions. This includes regions such as North Africa, Middle East, China, South Africa. Moreover, in some of these regions the land bottleneck is closely related to the water bottleneck; i.e. extreme water scarcity makes large areas unsuitable for agriculture, thereby contributing to land competition in these regions. Water bottlenecks are not released in this counterfactual scenario, and this limits the scope for reducing land scarcity in these regions.

**Table 5. Remaining land potentially available for agriculture in the Relaxing agricultural land supply scenario**

| | Current Agricultural land use in thousands km2 | Remaining potential agricultural land in the baseline projection | | Remaining potential agricultural land in the Relaxing agricultural land supply scenario | |
|---|---|---|---|---|---|
| | | **thousands km2** | **% of total** | **thousands km2** | **% of total** |
| Canada | 675 | 491 | 42% | 2727 | 80% |
| USA | 4148 | 1319 | 24% | 2395 | 37% |
| Mexico | 1075 | 391 | 27% | 490 | 31% |
| Other Latin American countries | 3491 | 2085 | 37% | 3942 | 53% |
| Brasil | 2636 | 1764 | 40% | 4744 | 64% |
| North Africa | 1008 | 37 | 4% | 63 | 6% |
| Other African countries | 9272 | 5386 | 37% | 7125 | 43% |
| South Africa | 996 | 96 | 9% | 102 | 9% |
| Non-EU Eastern Europe | 630 | 187 | 23% | 275 | 30% |
| EU OECD 17 smaller countries | 894 | 581 | 39% | 936 | 51% |
| EU OECD 4 Larger countries | 783 | 298 | 28% | 397 | 34% |
| Other OECD Eurasia | 465 | 302 | 39% | 371 | 44% |
| EU non OECD countries | 272 | 126 | 32% | 197 | 42% |
| Caspian countries | 2927 | 137 | 4% | 151 | 5% |
| Russia | 2155 | 1224 | 36% | 3584 | 62% |
| Middle East | 2164 | 151 | 7% | 222 | 9% |
| Other developing Asia | 2185 | 406 | 16% | 662 | 23% |
| India | 1802 | 419 | 19% | 740 | 29% |
| Korea | 19 | 0 | 0% | 66 | 78% |
| China | 5563 | 752 | 12% | 983 | 15% |
| Other Asian countries | 672 | 902 | 57% | 1442 | 68% |
| Indonesia | 478 | 722 | 60% | 1139 | 70% |
| Japan | 51 | 0 | 0% | 257 | 83% |
| Oceania | 4624 | 869 | 16% | 1214 | 21% |

*Note:* Current agricultural land in absolute terms (in $km^2$), and as a percentage of the land supply that was calculated for the baseline and the counterfactual scenario. Additionally, the land supply is shown (in $km^2$) for the baseline and the counterfactual scenario.

Source: IMAGE model

133. In other regions there are substantial differences between the baseline and the counterfactual scenario, and releasing land use constraints substantially increases the regional land supply. These regions (e.g. Canada, Russia, Brazil) have large land resources which are relatively isolated and located far from roads. In the baseline, their isolated location is one of the criteria that made them ‘unsuitable’. This somewhat subjective criterion was relieved in the counterfactual scenario, resulting in a larger regional land supply. Relaxing this land supply constraint does not really impact land competition in these regions as land scarcity is very limited in the baseline. Nonetheless, it can be potentially relevant for other world regions;

i.e. agricultural production could shift from regions with strong land competition and high land rental rates to the above regions with an abundant land supply. This also has consequences for water competition as relocation of agricultural production from world regions with limited water resources to world regions with ample water resources can reap a double benefit and alleviate both nexus constraints.

134. Two regions (Japan and Korea) stand out because their remaining land supply is very small in the baseline (i.e. nearly all suitable land is in agricultural use), whereas the remaining land supply is much higher in the counterfactual scenario. This is partly because the counterfactual scenario assumes agriculture is possible on steeper slopes. Another reason is that forest land is excluded from agricultural land supply in Japan and Korea in the baseline, due to strong cultural preferences which prevent the conversion of forest to agricultural land in these countries. This restriction is released in the counterfactual scenario, leading to a significant relaxation of the land supply bottleneck.[11]

135. Differences between the baseline and the counterfactual scenario remain limited for the majority of regions. Relaxing certain land supply constraints means that additional area is added to the regional land supply, which might lead to lower land rental rates. However, changes in land supply are relatively modest. Important effects on regional water use and water bottlenecks are therefore also not likely in these regions.

***Economic consequences***

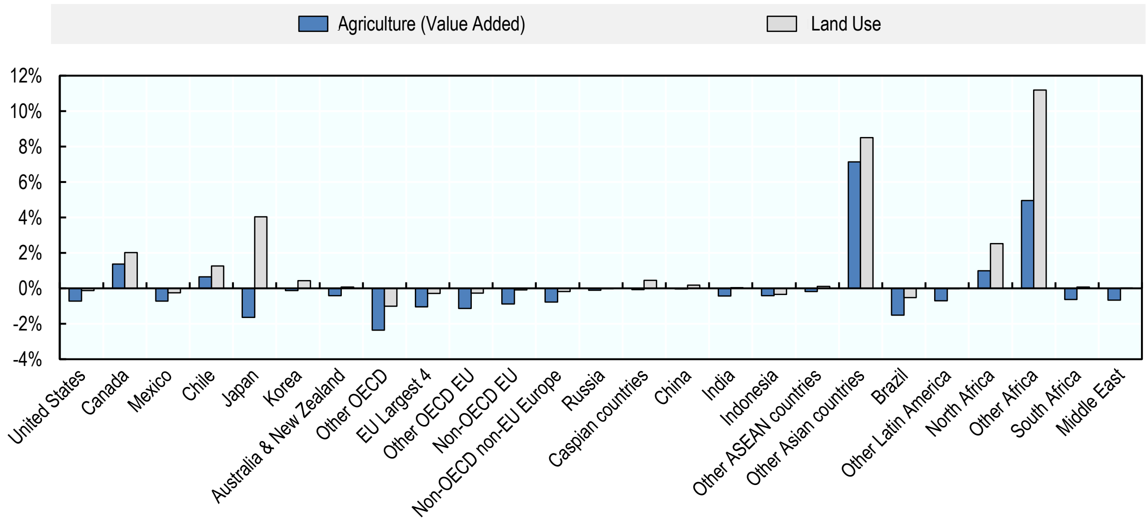
136. As indicated in Table 5, the expansion of the potential agricultural land is important in Brazil, Russia, Canada, Japan and Korea (more than 70%) but remain limited for the majority of regions (7%-30%) and is in certain countries even  marginal (less than 5%) for example in China, Oceania, South Africa, Middle East, Northern Africa.

137. But even if the potential expansion is important the increase in the effective agricultural land use (i.e. the value added generated by this land) will be moderate, and as a matter of fact only Sub-Saharan African countries as well as the ASEAN9 region can reap increases of more than 10% (Figure 18). This is because agricultural land use in most of the countries is rather insensitive to changes in the land rental price.

138. Some countries cannot take advantage of the possibility of access to new land. For example the USA and EU region will face substantial losses in their agricultural output. This is purely driven by competitiveness effects: increased competiveness in the African countries implies a reduction in the relative competitive position of the traditional OECD exporters, and as a result their land use will shrink even if potential land supply is higher.

[11] This specification of the counterfactual is in no way intended as a comment on these cultural preferences, but purely a hypothetical scenario which aims to provide a larger, but physically plausible upper bound on land supply in these regions.

**Figure 18. Agricultural value added and land use in 2060 in the Relaxing land supply scenario (percentage change from baseline)**



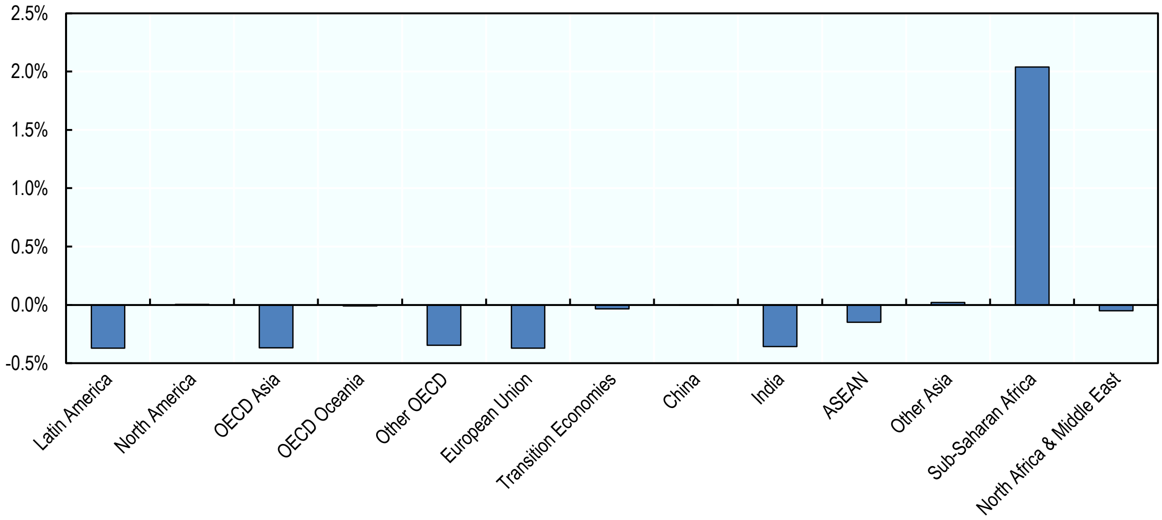

Source: ENV-Linkages model

139. The extra land supply will imply a reduction of the average land rental price and then farmers react by expanding the use of land for all agricultural activities. As a consequence, agricultural production will increase, but relatively less compared to land use, as there is a reduction in the pressure to intensive agricultural production. In countries where agricultural land expansion is costly or potentially limited, such as in EU countries, agriculture production will decrease.

140. Global food demand reacts only marginally to the relaxed land supply constraints, as it is relatively price inelastic. Thus, rather than a global expansion of agricultural production, the dominating effect is one of inter-regional substitution: countries and regions such as the USA and EU will just lose market share in favour of the countries where land expansion is economically and physically more attractive (Figure 16). This extra land supply will thus effectively imply agricultural production reallocations across countries, together to relative reduction of the use of non-land inputs in agricultural production. The latter may have significant environmental benefits in the form of reduced pollution, but also implies a cost for the sectors that provide inputs to agriculture, not least the fertiliser industry.

141. At the global level, in 2060, the increase of total agricultural production is about 0.5% for a 5% increase in total agricultural land supply. In summary, relaxing the constraints on potential agricultural land leads to an unevenly distributed reduction in land competition across regions. This induces a substitution of agricultural production across countries (Figure 19), while households' food demand will increase (slightly) in all countries regardless of whether domestic land supply increases a lot or not. This indicates that international trade helps to smoothen food consumption scarcity across countries by changing production patterns to accommodate changes in relative land scarcity.

**Figure 19. Changes in geographical distribution of trade for crops goods trade in land supply scenario (changes in gross exports as a share of world exports relative to the baseline)**




Source: ENV-Linkages model

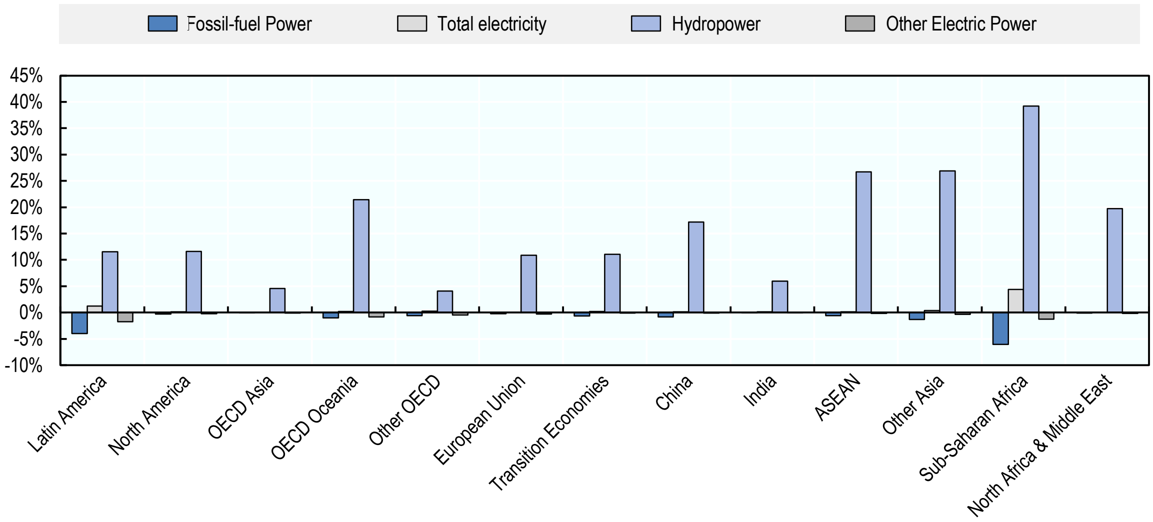
## 4.3 Results for the Increasing hydropower capacity scenario

***Economic consequences***

142. In this water-energy bottleneck scenario, the limiting factors to hydropower extensions are relaxed, using the ENV-Linkages model. As a consequence hydropower generation will increase relative to the Baseline (Figure 20).

143. The dominant effect of the increased hydropower capacity is a shift towards hydropower at the detriment of other sources of electricity. This reduces the reliance on scarce fuel resources and reduces greenhouse gas emissions. It thus contributes energy security and environmental objectives. Indirectly the power generation technology switch implies a small reduction in total demand for fossil fuels (around 1% at the global level) because of the reduction of their use in thermoelectric plants, and hence a minor reduction in water demand for cooling these same plants. In Sub-Saharan Africa, the improvements in the electricity generation mix are strong enough to lead to significantly lower electricity prices, thereby boosting total electricity production and demand. This has a positive effect on the economy, while at the same time reducing energy-sector emissions. The effects in other regions are smaller. The effect is still noticeable in Latin America, but virtually absent in the other regions.

**Figure 20. Change in Electricity generation in the Increasing hydropower capacity scenario (percentage from Baseline)**




Source: ENV-Linkages model

## 4.4 Results for the Limiting groundwater extraction under climate change scenario

***Biophysical consequences***

144. In this scenario, the bottleneck scenario of limiting groundwater availability in agriculture is coupled with a projection of climate change, to explore how climate change affects irrigation water availability and thereby agricultural production and land use.

145. Comparing Tables 4 and 6 shows that in most regions climate change does not really exacerbate the impact of the groundwater bottleneck, as the bottleneck has a very limited impact on agricultural production anyway (e.g. Canada, USA, other Latin American countries, Brasil, other African countries, non-EU eastern Europe countries, Caspian countries, Russia, other developing countries Asia, Korea, other Asian countries, Indonesia, Japan, Oceania, EU non OECD countries[12]). In comparison, the direct impact of climate change itself, i.e. not through the nexus bottleneck, on agricultural production (and yields) is much larger in these regions and overwhelms the impact of groundwater limitation. The resulting yield losses as depicted in Table 6 and land use change (not shown) should thus be attributed to climate change and not to the nexus bottleneck. Strikingly, the opposite occurs in the EU OECD 17 smaller countries and EU OECD 4 larger countries; i.e. climate change impacts are minor when compared to the impact of groundwater limitation. In China, both climate change and the groundwater limitation have little impact on agricultural yields. Thus, an important conclusion is that climate change and groundwater limitation show little interaction in these regions.

146. However, climate change does seem to exacerbate the impact of water shortage in some regions. Climate change almost doubles yield losses due to groundwater limitation in Mexico for important crops such as temperate & tropical cereals, rice, oil crops. It does not significantly reduce irrigation water withdrawals compared to the groundwater limitation scenario (not shown), indicating that water

[12] For the EU non-OECD countries, the exception is rice, which is a very minor crop in terms of land use in this region, so small changes in absolute terms translate into large relative changes.

availability for irrigated agriculture does not change very much due to climate change. Instead, climate change is projected to primarily to impact mainly rainfed agriculture (e.g. through changing local on-site rainfall and evaporation), and much less irrigated agriculture. Mexico's staple crop maize is not really affected by either climate change or groundwater limitation. The combined impact of climate change and limiting groundwater extraction has consequences for land competition, as the cropland area is respectively 16% larger than in the baseline (whereas it was 5% larger in the Limiting groundwater scenario). Such a larger cropland area can increase the pressure on biodiversity and ecosystems.

147. A similar pattern like in Mexico can be observed in South Africa; i.e. climate change exacerbates yield losses due to groundwater limitation for important crops. But the underlying mechanisms are different: climate change decreases irrigation water withdrawals in South Africa compared to the groundwater limitation scenario (not shown), indicating that water availability for irrigated agriculture is reduced under climate change conditions. Additionally, climate change also is projected to impact yields from rainfed agriculture. In turn, this has implications for land use and land competition as the cropland area is respectively 12% larger than in the baseline (whereas it was 2% larger in the groundwater limitation scenario).

148. In Northern Africa climate change exacerbates the impact of groundwater limitation for some crops (tropical cereals, pulses, roots & tubers, oil crops), but reduces the impact of groundwater limitation on other crops (rice, maize). Additionally, climate change also affects rainfed agriculture in this region. Temperate cereals are very important in this region in terms of land use. Although groundwater limitation alone has a limited impact on temperate cereals (Table 4), the impact is much larger when climate change is also taken into account. Land resources are already too constrained in this area to meet the regional demand for crops under groundwater limitation -without increasing imports. Adding the impact of climate change exacerbates this.

149. In the Middle East, climate change exacerbates the impact of groundwater limitation on all crops except pulses. But the relative impact of climate change is smaller than that of groundwater limitation. Similar to Northern Africa, land resources in the Middle East are already too constrained to meet the regional demand for crops under groundwater limitation without increasing imports. Adding the impact of climate change would worsen this.

150. Climate change exacerbates the impact of groundwater limitation in India. Comparing Tables 4 and 6 shows that climate change almost doubles the already substantial yield losses due to groundwater limitation for important crops such temperate cereals and rice. The groundwater limitation does not really affect some crops, such oil crops, but climate change also affects these. All in all, yield losses become even more substantial under the projected climate change conditions.

151. The impact of groundwater limitation on yields is dominant for most crops in other OECD Eurasian countries, but climate change does exacerbate this impact for most crops. Especially relevant in terms of land use is temperate cereals, which also shows additional yield losses when climate change is factored in. These yield losses have important implications for land use and land competition, as the cropland area is considerably larger than in the baseline and groundwater limitation scenario.

152. Overall, it can be concluded that climate change and groundwater limitation show little interaction in a large number of regions where climate change impact of on agricultural production (yield) is much larger and overrides the impact of groundwater limitation. However, climate change does exacerbate the impact of groundwater limitation in a number of world regions and substantially aggravates land competition in these regions. In two particular regions, Northern Africa and Middle East, land resources are already too constrained to meet regional demand for crops under groundwater limitation

without increasing imports. Climate change would worsen this in these regions. In a small number of regions, climate change reduces the impact of groundwater limitation, but only for some particular crops.

**Table 6. Percentage yield loss in the Limiting groundwater under climate change scenario w.r.t. baseline in 2060**

| | Temperate cereals | Rice | Maize | Tropical cereals | Pulses | Roots & tubers | Oil crops |
|---|---|---|---|---|---|---|---|
| Canada | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| USA | 0% | -3% | 0% | -1% | -1% | -1% | 0% |
| Mexico | -21% | -10% | -2% | -4% | -8% | 0% | -6% |
| Other Latin America | 0% | -1% | 0% | 0% | -1% | 0% | 0% |
| Brasil | 0% | 0% | 0% | 0% | 0% | 0% | 0% |
| North Africa | -2% | -27% | -32% | -19% | -10% | -22% | 0% |
| Other African countries | -4% | -1% | 0% | 0% | 0% | 0% | 0% |
| South Africa | -7% | | -2% | -8% | -3% | -1% | 0% |
| Non-EU Eastern Europe | 0% | 0% | -2% | 0% | -1% | 0% | 0% |
| EU OECD 17 smaller countries | -2% | 0% | -24% | 0% | -23% | -27% | -1% |
| EU OECD 4 Larger countries | 0% | 0% | 0% | 3% | -23% | -23% | 0% |
| Other OECD Eurasia | -5% | -35% | -34% | 0% | -40% | -26% | -5% |
| EU non-OECD countries | 0% | -100% | -1% | 0% | -3% | -3% | -1% |
| Caspian countries | -1% | -3% | -3% | -3% | -2% | -2% | -1% |
| Russia | 0% | 1% | 0% | 0% | 0% | 0% | 0% |
| Middle east | -12% | -45% | -42% | -30% | -18% | 32% | -3% |
| Other developing Asia | -1% | -1% | 2% | -2% | 1% | -2% | -4% |
| India | -16% | -20% | -17% | 0% | -6% | -1% | -1% |
| Korea | | 0% | 0% | 0% | 0% | 0% | 0% |
| China | 0% | -1% | 0% | -1% | -1% | 0% | 0% |
| Other Asian countries | 0% | 0% | 0% | 0% | 1% | 0% | 1% |
| Indonesia | | 0% | 0% | 1% | 0% | 0% | 0% |
| Japan | 0% | 0% | | | 0% | 0% | 0% |
| Oceania | 0% | 0% | 0% | 0% | 0% | 0% | 0% |

Source: IMAGE model

Note: Averaged irrigated and rainfed) are shown.

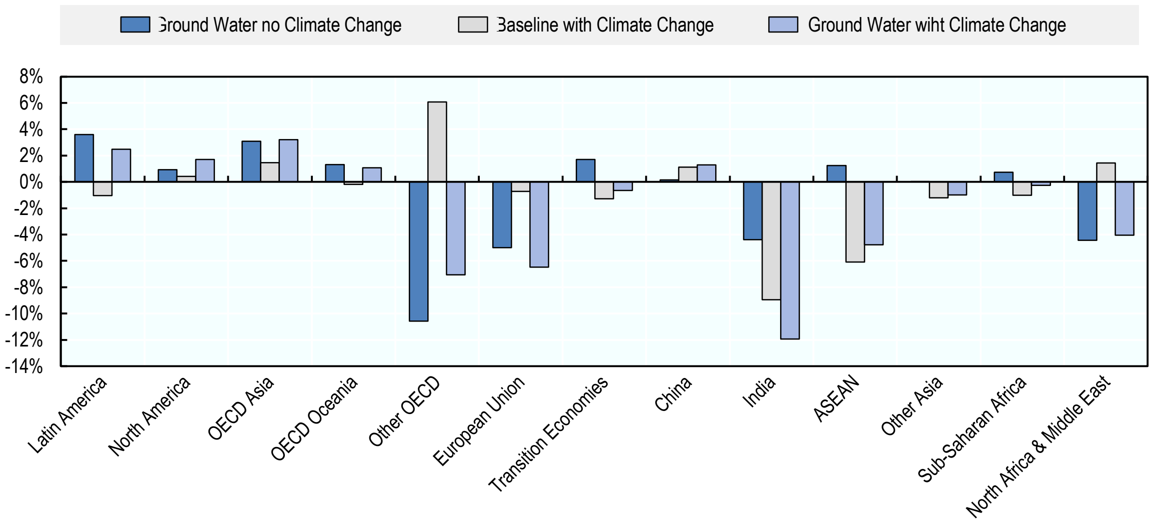
***Economic consequences***

153. The projections of climate change, as simulated with the IMAGE model, will strongly reduce yields for all crops in all regions of the world. The only exceptions are the upper northern regions (mainly Russia and Canada and to a lesser extent China) that will expect some increase in some crop yields (fruits and vegetables and oil crops) at lower temperature increases.

154. In light of the groundwater limitation with additional climate change damages the agricultural production of India and EU countries are even worse than in the no-climate change environment (Figure 21). In contrast, the impacts from climate change are less strong for the other Mediterranean countries. The reason is that climate change damages affect agricultural output across the world, and thus the changes in relative competitive position of all regions is less affected than when the groundwater limitations are considered under current climate conditions. Thus, the relative situation in term of competitive disadvantages for the crops sector in the Mediterranean countries is less bad than in the case of current climate conditions. The loss of competitiveness for EU countries can largely be explained by higher crops yields for their traditional trading partner (former Soviet Union countries).

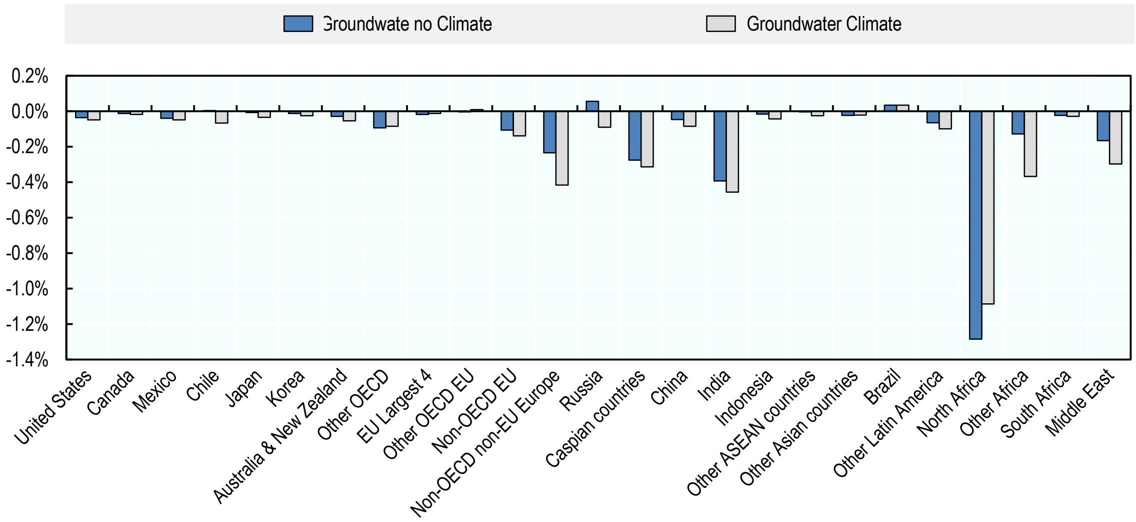
155. As indicated in Figure 22 the effects limiting groundwater on total GDP are generally reinforced when climate damages also affect crops yields, notably in Africa and Middle East. On the opposite the situation is slightly better in North Africa, which reflect the fact that this region is directly in competition with the two previous one on international trade markets for crops (they all three produce similar crops and they all of three facing similar trade partners, namely Europe).

**Figure 21. Agriculture Value Added in 2060 in the Limiting groundwater under climate change scenario (percentage change from baseline without climate change)**




Source: ENV-Linkages model

**Figure 22. Real GDP Impacts under the Limiting groundwater scenario with and without climate change (percentage difference of respective with and without climate change baseline)**




Source: ENV-Linkages model

## 4.5 Discussion of other major consequences

156. The first round of simulations for this interim report does not adequately cover the important linkages between water and energy. First, the modelling tools can only capture systemic effects that are noticeable in the top-down frameworks, and ignore important local bottlenecks with severe local consequences that may occur over short time spans. Secondly, there are significant data gaps (see e.g. OECD, 2010) that prevent a full representation of all the bottlenecks in the baseline and counterfactual projections of the modelling tools. Therefore, this section attempts to provide further insights into the consequences of this particular linkage. Where possible, numerical insights and relevant projections on costs available from the literature are provided. But given the large data gaps, some of the key consequences of the nexus bottlenecks can only be discussed in an anecdotal way. Nonetheless, the inclusion of these consequences in the evaluation of the bottlenecks is fundamental in providing an overview of the full costs of inaction on the nexus, and therefore in the assessment of the benefits of policy action.

***Water for energy***

*Water for electricity*

157. Water stress constrains electricity supply and thus affects the economy through three main channels. First, it can increase the cost of power generation and therefore the price paid by consumers for electricity. The macroeconomic impact of this channel is expected to be quite small given that the extra costs form a very limited share of the household's expenditures. A second possible channel is a disruption of the electric system, creating outages or blackouts with potentially very negative consequences. This is especially the case for advanced economies which are highly dependent on electrified infrastructures and information technologies. The last channel concerns regions with little access to electricity: water scarcity can be an additional obstacle to the delivery of access to electricity. This is particularly relevant for regions where the development of electricity is projected to be based to a large extent on hydropower technologies.

158. In general, the cost of water bottlenecks through constraining power supply for the economy is not easy to assess. On the one hand, if water constraints are well managed and the change of resource availability is well anticipated, all the options available to limit the effect of water scarcity will be implemented in a cost effective way. In that case, the cost of adjusting to the bottleneck is quite low for the electricity system. On the other hand, if disruptions in the electric sector cannot be avoided, they can be very costly. Therefore one needs to take into account the cost of investments to hedge against the risk of disruption, for instance by providing more back-up generation capacity. Lastly, a major policy problem is that currently a large part of the world population has no access to electricity. Nexus bottlenecks can make the deployment of energy infrastructure more difficult, and thus hamper energy security.

159. Table 7 summarises several quantitative assessments of water consumption for power generation in water-stressed areas. In general the studies provide projections for a cascade of trends. For instance economic growth drives power demand, climate change influences hydrology and exacerbates the water stress level. In turn, adaptation policies to climate change affect the choice of power generation technologies. The geographical scope is in general limited to certain countries as local circumstances matter (power generation mix, demand and hydrology). The only contributions with a global scope stem from Davie et al. (2013) and Kyle et al. (2012) but their analysis is just an assessment of future water demand from the power sector without assessing the resource constraints.

160. The nexus bottlenecks depend on the local circumstances. They will be aggravated by decreases in rainfall and increases in heat waves caused by climate change. The synergies with climate policies are strong. Mitigation policies can limit the stress on water resource by reducing the impact of climate change and they will also accelerate the transition from water intensive thermoelectric technologies to favour the deployment of wind and solar PV technologies which require far less water. The biophysical effects are: less, and more variable water patterns.

161. Even if they give good insights on the water energy part of the nexus, the studies do not provide a quantification of the cost of the nexus. Most of them just aim at identifying region of potential water deficit, i.e. hotspots for bottlenecks. They project water demand from the power sector and the water that can be supplied by the hydrological system are considered separately (Bhattacharya and Mitra; 2013; Roger et al, 2014; Smart and Aspinall, 2009; Sovacool and Sovacool, 2009). The projected water for power generation is not constrained by water resource, and the studies merely assess the water imbalances, pointing out bottleneck without assessing how and at what cost they can be managed. Other studies take into account the power sector adjustment to water imbalance: by adjusting operation of capacity addition including the choice technologies, cooling systems and plant location or interconnections (IEA, 2015; Van vliet et al 2012; Rübbelke and Vögele, 2011). Few studies assess, as Van vliet et al (2013) and IEA (2015) the costs involved by the adjustment of the power system and therefore the impact on power prices.

**Table 7. Main studies of the effect of water scarcity on power generation**

| Authors | Region | Scenario | Consequences |
|---|---|---|---|
| **Davie et al, (2013)** | World | No climate change | Adoption of better cooling technologies reduces water withdrawal of power sector by 60% at horizon 2095 wrt baseline. But more water consumption |
| **Kyle et al (2012)** | World | Climate mitigation, no climate change | Stable water withdrawal at horizon 2095 despite CCS deployment, CCS and concentrating solar cost effective even with dry cooling |
| **Bhattacharya and Mitra (2013)** | India | No mitigation, climate change causes draught and higher temperature | In 2050 20% of water withdrawal is for power generation |
| **Bhattacharya and Mitra (2013)** | Thailand | No mitigation, climate change causes draught and higher temperature | Water scarcity is a problem for operation during dry seasons |
| **Roger et al (2014)** | USA | No mitigation | Increased water withdrawal |
| **IEA (2015)** | India | No mitigation, no climate change | Slight increase in coal plant power generation costs |
| **IEA (2015)** | China | No mitigation, no climate change | Slight increase in coal plant power generation costs |
| **Smart and Aspinall (2009)** | Australia | No mitigation, no climate change | Increase in generation capacity in water-stressed areas (Queensland, New South Wales and Victoria) |
| **Cervigni et al (2015)** | Part of Africa[13] | Hydro development, climate change: more or less runoff | In dry (wet) scenarios, over- (under-) dimensioning of new hydro capacity |
| **Rübbelke, Stefan Vögele (2011)** | EU | Less rainfall | Less thermoecolectric production (focus on nuclear) |
| **Van vliet et al 2012** | EU,USA | Change in hydrology | Water constraints for some power plants |
| **Van vliet et al 2013** | EU | Change in hydrology, interconnections and capacities are fixed | Increase in power prices for 2030-2060 with strongest increases for Slovenia (12–15%), Bulgaria (21–23%) and Romania (31–32%). |
| **Sovacool and Sovacool (2009)** | USA | No mitigation, no climate change | "Summer water deficit" and qualitative assessment of the cost for non-electricity sectors. |
| **DOE (2012)** | South-west USA | Impacts of Long-term Drought on Power Systems | Ongoing study… |

Source: authors' compilation

162. One key determinant of the cost of the bottleneck which is missing in most of the studies is uncertainty. Water scarcity has to be managed by the electric sector such that there is very low risk of

[13] Congo, Niger, Nile, Orange, Senegal, Volta, and Zambezi river basins

disruption. It means that it is necessary to invest in solutions, making the supply system resilient to extreme and rather unlikely events affecting water availability. There is a need for “hedging” against water stress by developing capacities that can respond to these extreme events, but that will be mostly left idle. Given the very long lifetime of the power plants, there is a high uncertainty on possible water stress and the investments for hedging against the water stress are can be very costly.

163. If perfectly managed by the electricity sector, water scarcity challenges can be addressed by decreasing energy demand, adjusting operation and investment in the electric supply. The differences in impacts on final prices are due to local circumstances and also to the options given to limit the dependence to the water sector. In studies where the adjustment options are limited, for instance when they do not include investment in capacity or in transmission, as in van Vliet et al (2013) the impact may be relatively high reaching 30% at horizon 2060 in Eastern European countries. When more options can be used, as in the IEA (2015) study on the cost of water scarcity for the coal generation technologies in China, water scarcity can be managed at a very limited cost in the coal sector (+1%) which gives reason to expect a little cost for the entire power sector.

164. More costly energy supply represents a loss for the whole economy. From a pure “production function” perspective, a first proxy of the GDP cost can be given by the price effect multiplied by the share of electricity expenditure in GDP. In the case of Eastern Europe, where the electricity expenditure is less than 4% of GDP, the results of van Vliet et al (2013) would involve a loss of GDP of around of 1.2%. In China, where electricity expenditures are less than 6% of the GDP, the IEA (2015) assessment would involve a negative GDP impact of around 0.06%. We see that the very big differences in assessments of the GDP impacts come from very different assessment of the cost for the electric system.

165. However, the approach mentioned above can be misleading. It doesn’t take into account the additional cost required to secure against many sorts of extreme events. These costs have to reflect in higher power prices, with higher macroeconomic impacts. If the risk is not managed, disruption can happen with a very large cost for society. Finally the cost of the water constraints can be much higher than what the model of van Vliet et al (2013) and IEA (2015) which assume no disruption.

166. The economic cost of power disruption is a notion is central notion power supply regulation. It is measured as the Value of Lost Load (VOLL) which the average cost to consumers per unit of unserved electricity due to outages (Stoft 2002). For the regulator, it is the losses one wants to hedge against by investing in grid security. The VOLL is typically very high compared with power price, which reflects the importance of stable electric supply. The VOLLs, have very different values, depending largely on local circumstances, but also on the assessment method used, the time and the length of the outage. To our knowledge, there is no study of the VOLL with a coverage sufficient to allow for a global assessment of the cost of electricity shortage[14]. However, one can expect that GDP growth will increase our reliance on electronic equipment and contribute to higher VOLLs (RAE,2014). The estimation of VOLLs in the literature is discussed in Annex III.

167. The VOLLs is a notion that is at first sight more fit for regions that already have a reliable power supply system and where the overnight economics cost of disruption is high. But one need to assess the economic cost of repeated outages and black outs in regions with no access to stable power supply. In this case, the power interruptions can be seen as a lack of infrastructure which creates bottlenecks for economic growth. They also induce wasteful consumptions as individual or local-level utilities need to be deployed to face the shortages. For instances, communities may need to purchase and operate small scale diesel of

[14] However, there an online tool that calculates for most of the EU countries the costs of user defined blackout scenarios. The costs computation is based on a monograph about VOLLs (see http://www.blackout-simulator.com/)

gasoline power generators, with as a results a power cost much higher than what could be delivered by a conventional supply system of grid and power plants.

168. Increased water scarcity and uncertainty about water availability created by climate change may hinder the transition towards public supply systems, in particular because in many developing countries hydro with depends on water availability is regarded as the means to improve the security of supply. But there is an uncertainty on the potential for this type of generation. For instance in West Africa, uncertainty on hydrology increase the risk of under or over investment in hydro, thus increasing the cost of hydro generation compared with a situation with less uncertainty (Cervigni et al., 2015 ).

*Water for fossil fuel and biofuel*

169. Fossil fuel extraction also requires water. The water intensity of the technique varies a lot depending on the fuel and the process. The depletion of "conventional" reserves gave way to more and more water-intensive production and transformation processes. Clark et al. (2013) show that in the US unconventional gas produced by fracking has more water consumption than conventional. Even though unconventional gas is used as transportation fuel, their water intensity is less than for conventional oil. When fuel resources are located in water scarce areas, their exploitation represents an additional claim on water use. This is for instance the case in Texas. A similar problem occurs in China where large deposits of coal and shale gas are located in very water-stressed areas.

170. Unconventional resources are also a threat for water quality as underlined by IEA (2012). Fossil fuel production, transportation and processing generate effluents that pollute water bodies. Fracking techniques may increase the amount of toxic effluents per unit on energy produced although the consequences are still difficult to assess.

171. In a world where easily accessible fossil fuel resources get depleted and where GHG emissions constraints are tight, biofuels, such as biodiesel and bioethanol can be an option for energy security. However, biofuels are very water intensive (IEA, 2012). Therefore, if fossil fuel resources are deployed at a large scale, they may pressurise water resources. In addition, the competitiveness of water use will increase, in particular in regions where scarce water is also used for crops with a requirement of high amounts of water.

***Energy for water***

172. Water and end energy supply are also interlinked by the energy consumption for water extraction, processing and transportation. The energy intensity of water supplies depends on the structure of the water resource, the water demand as well as the need to rebalance regional demand and supply by transporting water over long distances (KAPSARC, 2015). Surface water typically requires little energy to be extracted. Also groundwater generally needs barely any intensive treatment before making it usable In contrast; extraction can be very energy intensive when deeper aquifers are used.

173. Water energy intensity also depends on the adequacy between zone of consumption and zone of extraction. When water resources are remote from the zones of consumption, water has to be transported over long distance which implies high energy costs. For instance, in California the State Water Project (SWP) with more than 662 miles of canals, tunnels and pipelines designed to move water from Northern California to users in the Central Valley and Southern California, is the single biggest power consumer of the state, with consumptions widely varying depending on precipitations (Trask, 2005). Note that the energy intensity of water transportation doesn't depend on the distance, but also on whether it is based on pumping or gravity.

174. Desalination is used in cases where water scarcity cannot be balanced by water availability in bone of the surrounding areas. This is typically the case in GCC countries. More generally, desalination increases due to urbanization, economic growth, and especially in water stressed areas. It also increased because of the decreasing cost of desalination (Ghaffour et al, 2013). There are various options available for desalination with different energy intensities. Desalination developed a lot in the Middle East, US. The increase in desalinated water capacity is also due to climate variability: in periods of drought, desalination facilities are built, but possibly not used when rain come back, which indeed has a cost for society as has been the case for the Australian desalination capacities, so there is a risk dimension[15].

175. The energy intensity of the desalination process is high (Siddiqui and Fletcher, 2015) and the energy demand can be a large share of the total energy consumption. For instance, in Saudi Arabia, Siddiqui and Diaz Anadon (2011) estimate that 9% of power consumption is for water pumping and desalination for desalination. With the increasing water needs, these activities can contribute to the increase in overall increase in energy demand.

176. Here, the policy question is primarily about pricing of water and pricing of energy. In countries where energy prices are very low, desalination is cheap, but it induces a wasteful energy use for desalination and wasteful energy consumption. In some regions like the gulf countries water treatment is compulsory in industries, but the water is not reused because desalinated water is relatively cheap. Another issue: give incentives to do desalination with renewable technologies. The desalination facilities could be operated when the intermittent supply is abundant (but anyway this also has a cost). So one can think about giving incentives to desalination and renewable or giving a part or the desalinated water bill to support renewable? The solution will depend on the region. In some regions, desalination may be too expensive.

177. The share of energy use for water related to irrigation in agriculture is important but still difficult to identify. Irrigation is important for agriculture: 16 % of the world’s cultivated cropland is irrigated. Most of the irrigated areas are in Asian Countries. Climate change may increase the use of irrigation because irrigation reduces the climate risk on water availability. But irrigation requires big amounts of energy. Energy consumption can be high e in many regions when energy (power, gasoil) is still subsidized for agriculture (e.g. in India) and there is no incentive in investing in efficient pumps or irrigation technique. In addition, the lower the groundwater, the deeper one needs to pump and the most on consume energy. Plus there are difficulties to control pumping as it is still a quite anarchic activity. Better pricing of energy for agriculture and support for energy efficiency methods could both improve the water conservation and decrease energy consumption.

### 4.6 An integrated look at the nexus in different world regions

178. The impacts from LWE bottlenecks vary by a great extent across regions depending on endowment, vulnerability to climate impacts, past and future socioeconomic trends. The results of the first round of modelling analysis highlights that an assessment of the main bottlenecks in the nexus for specific regions need to focus on the local interactions between the demand and supply of food, water and energy, as these drive local bottlenecks. Therefore, for each region the insights from the modelling and scoping analysis can be brought together in an integrated perspective on the local nexus issues.

179. The countries in the Middle East face extreme water scarcity and have developed their resource supply systems accordingly: energy is used to compensate for the lack of water. The energy consumption of the water sector has increased in recent years because of strong economic and demographic growth,

[15]For instance, see on this http://www.nytimes.com/2015/04/12/science/drinking-seawater-looks-ever-more-palatable-to-californians.html?_r=0

subsidies to energy consumption and to agriculture production, deeper groundwater pumping and long distance transport and desalination. Land resources in the regions are limited; i.e. 93.5% of all potentially suitable land is already in agricultural use in Middle East (see Section 3.5). Relaxing certain land supply constraints did not really affect the agricultural land supply in these regions, indicating that agriculturally suitable land is already a scarce resource; i.e. the counterfactual scenario could alleviate this scarcity only a little. Energy is used for groundwater pumping for irrigated agriculture, and can thus also be considered as a means to not only increase agricultural yields but also to reduce land competition. Energy and water bottlenecks are therefore closely linked to land competition in these regions, with water bottlenecks being obviously most relevant in these regions. Indeed, this study found that a potential groundwater bottleneck could seriously affect yields and associated land use; i.e. projected yield impacts were so substantial that the regional demand for certain crops could not be met without increasing imports (see also Section 4.2). Moreover, climate change exacerbates this even further.

180. Major parts of South West USA, South Australia and part of Southern Europe (e.g. Spain) are in a state of systemic water deficit and occasionally face long periods of drought that may multiply with climate change. In US and Australia, demographic growth is high in arid regions. In addition energy and agricultural systems need to adjust. Thanks to the limiting groundwater scenario, the analysis shows that the agricultural system is not very affected by the water bottlenecks as overall large reliance on abundant surface water which helps to compensate for the local effect of water scarcity. The scoping analysis in this report tends to show that energy system appears is vulnerable to water scarcity. The power supply is still highly dependent on water availability for cooling and the regional compensations of local water scarcity are limited by the structure of the power grid. But, as in the US, the vulnerability of the energy system can be limited by the penetration of solar PV. In US and Australia, shale gas and shale oil increase the stress on water. For these regions, all the aspects of the nexus are very tight, but there is an institutional capacity to transform water, energy and agricultural sectors.

181. In Northern US and Canada, energy security concerns come first. Water is abundant and largely used for biofuel crops. There is a large increase of non-conventional oil and gas resource with impacts on land and on water quality.

182. The nexus bottlenecks are very strong in Asia, in particular in India. Demographic and economic growth is high, and there is a need to have access to cheap energy, to water and to food. Agricultural water supply relies mostly on rainfall and therefore is hit by extreme events due to climate change. The power generation and energy production capacity will increase and face constraints on water (this holds especially for India), while energy security becomes crucial for development. Water pollution is also become a more urgent issue. There is also a trade-off between development of abundant shale oil and gas resources and water security in North East China.

183. In Brazil, water is abundant at the country level, but there are water stressed regions. Agriculture depends on surface water availability. The energy system is very vulnerable to water stress. Climate change and energy security policies have boosted very large-scale development of bioethanol production, thereby increasing competition for land and water.

184. Africa is the continent facing globally the strongest demographic growth within the next decades. In addition, many African countries suffer from a lack of access to water and/or energy which results in a high vulnerability from climate change impacts. Furthermore, land for agriculture is scarce, in particular in Sub-Saharan countries. Due to the limited use of irrigation, groundwater depletion has little impact on agriculture. But important water bottlenecks can appear from the change in rainfall due to climate change. Other significant effects can be expected from the impacts on the potential for hydropower which is a key technology for improving energy security in the region.

185. North Africa is also a water scarce region. Significant part of the food supply is local. Agriculture is concentrated in less water stressed areas and relies on surface water. Demographic and economic growth will increase the need for water energy food. The lack of additional land for agriculture, the low hydrology and, not least, the potentially important effects of climate change in this region can seriously threaten water and food security.

# 5 RESULTS FOR THE BENEFITS OF POLICY ACTION

*[This Chapter will be elaborated in the second phase of the project, from November onwards]*

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# ANNEX I. THE MAIN SOCIOECONOMIC TRENDS UNDERLYING THE MODELLING ANALYSIS

186. The socioeconomic trends that form the basis for the baseline and counterfactual simulation projections in this report are described in OECD (2015). Here, they most relevant information is reproduced.

187. A baseline projection is characterised by an absence of new climate policies, the continuation of current policies for other policy domains (including energy) and plausible socio-economic developments, including demographic trends, urbanisation and globalisation trends.[16] A baseline projection is not a prediction of what will happen, but rather a plausible scenario describing a certain storyline for how these key trends affect future economic development in the absence of unexpected shocks. Chateau *et al*. (2011) describe the baseline calibration procedure in more detail, although the numerical calibration of the model has since been updated to reflect more recent data.

188. Demographic trends play a key role in determining long run economic growth. Projections of detailed movements in population by gender, age and education level determine future employment levels and human capital that drives labour productivity. While population and employment are correlated, the regional trends are differentiated by changes in participation rates for specific age groups (most prominently for people over the age of 65), changes in unemployment levels and changes in the age structure of the population (including aging).

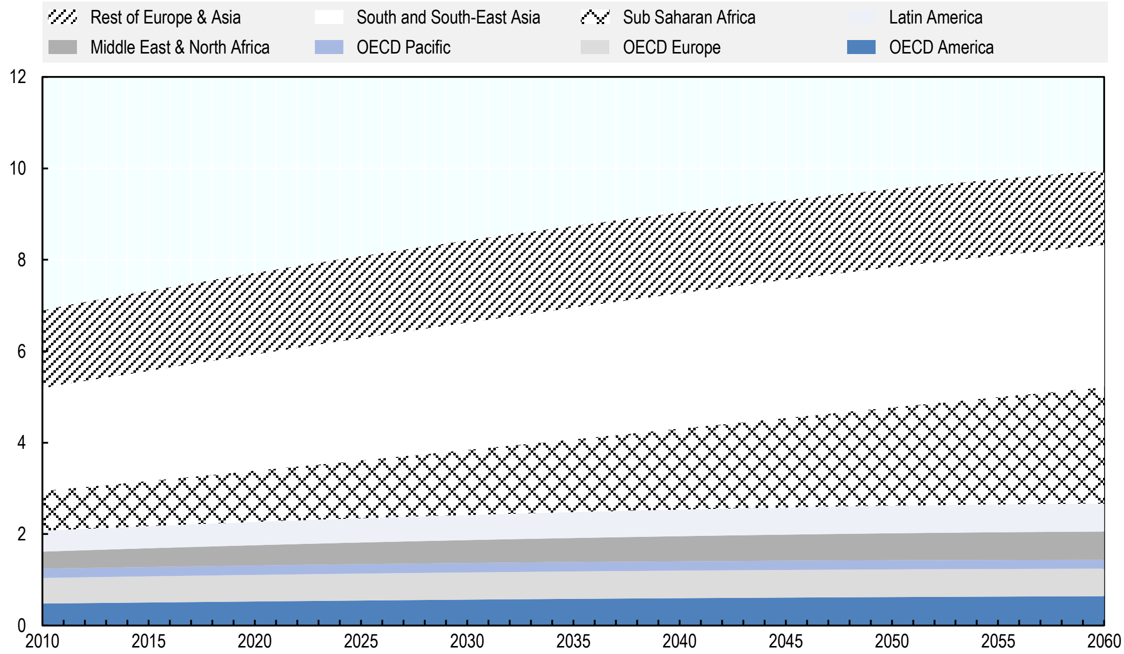
189. Figure 23 presents the baseline projection (excluding climate feedbacks) of total regional population, based on the medium variant projection of the United Nations' World Population Prospects database (UN, 2013) and EUROSTAT (2013) for European countries.[17] At global level, population will increase from around 7 billion people in 2010 to almost 10 billion people in 2060. Despite the large increase, population growth by the middle of the century is projected to be substantially lower than it currently is. While this is true in most world regions, population keeps increasing at a steep rate in Sub-Saharan Africa.

16 More specifically, any policy that is not yet fully implemented, or that still requires an effort to be reached, is not included in the baseline. This assumption is only to provide a reference point for the assessments of the costs of inaction and the benefits of policy action, and does not reflect a view on the state of current climate policies.

17 Alternative population projections are available for the SSP scenarios (Lutz and KC, 2015); for example, in the medium SSP2 scenario, there is a stronger effect of female education on fertility than assumed here, leading to lower population levels later in the century. Using different population projections may substantially affect the numerical analysis in this chapter.

**Figure 23. Trend in population by region, baseline projection**

(Billion people)




*Source*: UN (2013) as used in the ENV-Linkages model.

190. GDP growth is influenced by changes in labour, man-made capital and the use of land resources. In all cases, GDP growth is driven by a combination of increased supply of the production factors, changes in the allocation of resources across the economy, and improvements in the productivity of resource use (the efficiency of transforming production inputs into production outputs). Table 8 shows the average GDP growth rates for the current decade (2010-2020), the medium term (2020-2040) and the long term (2040-2060). In most countries, short-term growth is primarily driven by a variety of sources, depending on the characteristics of the current economy. These short-term projections are based on the official forecasts made by OECD (2014a) and IMF (2014). In the longer run, a transition emerges towards a more balanced growth path in which labour productivity as a driver of economic growth is matched by increases in capital supply.

191. Table 8 illustrates the main trends in economic development for the coming decades: continued slower growth in the OECD than in non-OECD countries (with a few exceptions), declining growth rates in emerging economies and relatively strong growth in Africa and most other developing countries.

**Table 8. Economic growth over selected periods by region**

(Average annual percentage GDP growth rates)

| | | 2010-20 | 2020-40 | 2040-60 | | | 2010-20 | 2020-40 | 2040-60 |
|---|---|---|---|---|---|---|---|---|---|
| OECD America | | | | | Rest of Europe and Asia | | | | |
| | Canada | 2.2 | 2.0 | 1.9 | | China | 7.6 | 4.2 | 1.6 |
| | Chile | 4.7 | 2.4 | 1.4 | | Non-OECD EU | 2.2 | 2.5 | 1.7 |
| | Mexico | 3.6 | 3.4 | 2.5 | | Russia | 3.6 | 2.1 | 0.9 |
| | USA | 2.4 | 1.9 | 1.5 | | Caspian region | 6.3 | 4.8 | 2.6 |
| OECD Europe | | | | | | Other Europe | 2.4 | 3.3 | 2.0 |
| | EU large 4 | 1.5 | 1.6 | 1.3 | Latin America | | | | |
| | Other OECD EU | 1.9 | 2.0 | 1.3 | | Brazil | 3.3 | 3.0 | 1.8 |
| | Other OECD | 3.6 | 2.6 | 1.7 | | Other Lat.Am. | 3.6 | 3.7 | 3.1 |
| OECD Pacific | | | | | Middle East & North Africa | | | | |
| | Aus. & NewZ. | 3.2 | 2.6 | 2.1 | | Middle East | 3.4 | 3.7 | 2.3 |
| | Japan | 0.9 | 1.0 | 1.1 | | North Africa | 3.9 | 4.9 | 3.2 |
| | Korea | 4.0 | 2.3 | 0.6 | South and South-East Asia | | | | |
| | | | | | | ASEAN 9 | 4.8 | 4.2 | 3.1 |
| | | | | | | Indonesia | 6.1 | 4.6 | 3.3 |
| | | | | | | India | 6.6 | 5.8 | 3.6 |
| | | | | | | Other Asia | 4.2 | 4.2 | 3.7 |
| | | | | | Sub-Saharan Africa | | | | |
| | | | | | | South Africa | 4.9 | 4.2 | 1.9 |
| | | | | | | Other Africa | 5.9 | 6.5 | 6.0 |
| OECD | | 2.2 | 1.9 | 1.5 | World | | 3.5 | 3.1 | 2.2 |

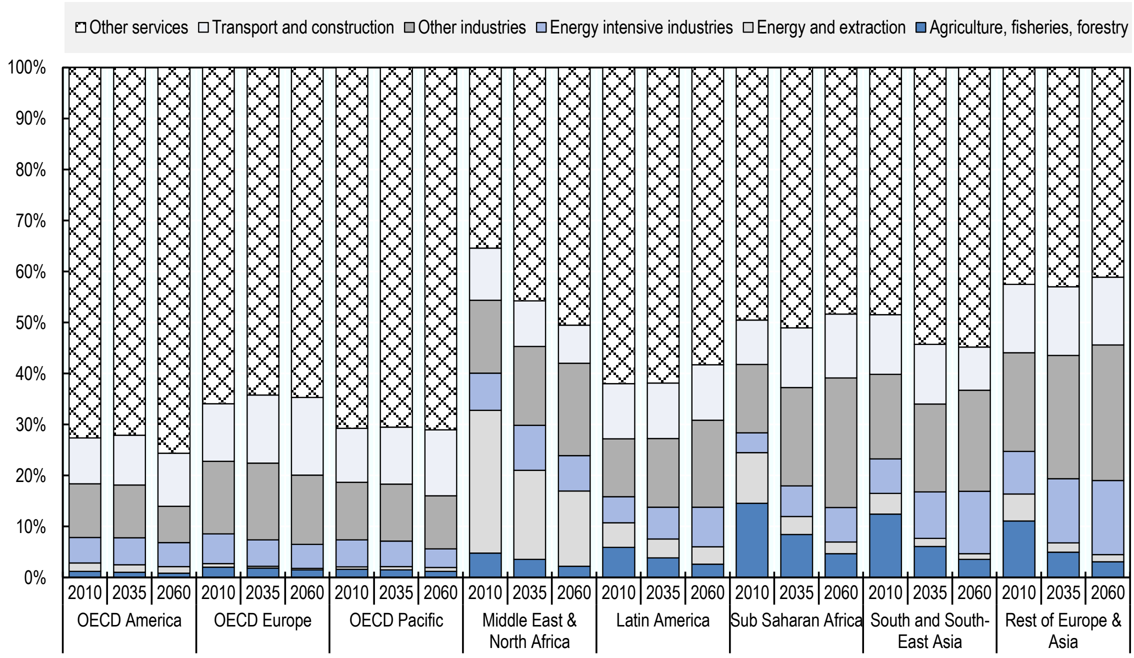
*Source*: OECD (2014) for OECD countries and ENV-Linkages model for non-OECD countries.

192. For an understanding of the future economy, it does not suffice to look at the macro economy only. To name just a few examples, projected productivity increases vary between different sectors, increasing incomes imply a change in demand for various goods, there will also be changes in the preferences of consumers, and international trade patterns may gradually adjust to stabilise trade balances.

193. Figure 24 shows how the sectoral structure in the OECD economies evolves, with the services sectors accounting for more than half of the GDP (i.e. value added) created in the future OECD economies. Generally, the shares of the various sectors in the economy tend to be relatively stable, although there are undoubtedly many fundamental changes at the sub-sectoral level that are not reflected here. The major oil exporters in the Middle East and northern Africa are projected to gradually diversify their economies and rely less on energy resources. In developing countries the trend for a decline of the importance of agriculture is projected to continue strongly. Given the high growth rates in many of these economies, this does not mean an absolute decline of agricultural production, but rather an industrialisation process, and, in many cases, a strong increase in services.

**Figure 24. Sectoral composition of GDP by region, baseline projection**

(Percentage of GDP)



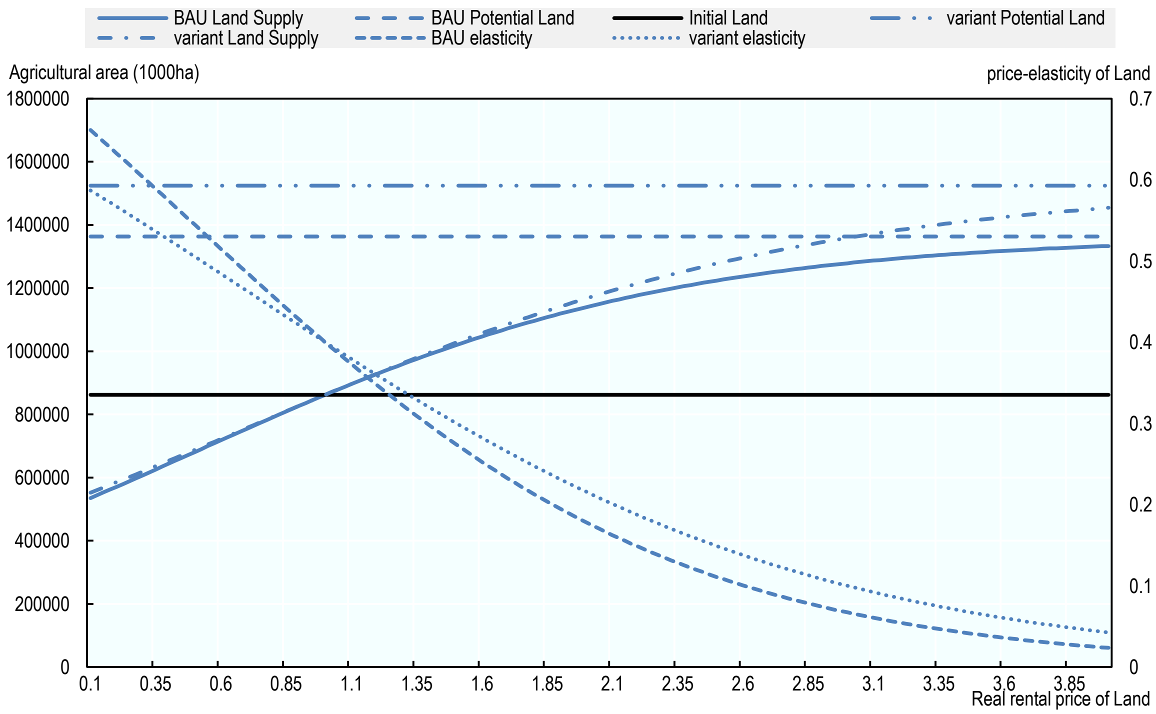

*Source*: ENV-Linkages model.

## ANNEX II. LAND SUPPLY SHIFTS WITH CHANGES IN POTENTIAL LAND

194. Figure 25 illustrates the shift in land supply for Sub-Saharan African countries when the potential land incrases. The horizontal axis shows the real rental of the land and the left axis report land variables in 1000ha. The lower horizontal line is the initial land while the upper bound is the potential land. The land supply curve in the bau shows that effective land is increasing with its real rental price. But the more the land level come closer to the potential Land the less land supply is elastic to its prices (the elasticity reported in the right axis is decreasing). Note also that the land supply crosses the initial land line for an initial land price of 1.

195. When the land potential (e.g. the upper bound) is higher is higher, the land supply curve will shift upward, such that for a given rental price (superior at 1) the effective land is now higher because it is far away from the new potential land that it was from the initial potential land.

**Figure 25. Agricultural land supply function for Sub-Saharan African countries**




*Source*: ENV-Linkages model.

## ANNEX III. ESTIMATION OF THE VOLL

196. The Value of Lost Load represents (VOLL) the average cost to consumers per unit of unserved electricity due to outages (Stoft 2002). This cost can be split into two parts: the direct damages due to the loss of assets and the indirect damages coming from the interruption of activity. Three methods are generally used to valuate VOLL.

- The production function approach: in this case the VOLL is the value lost by companies due to suspension of their activities as the outage supposed to stop or to harm activity in the sectors that use electricity. This approach is very aggregated and doesn't take into the account the very high vulnerability of some specific industries, for instance those which rely on information technologies. In addition, it doesn't account for the losses of capital cause by the outage.

- In the revealed preferences (market-based) approach, the expenditures made by economic agents to prevent from interruption or the level of compensation contracted from interruptions are used to evaluate the cost of the outage. For instance, it is possible to use the electricity contracts with interruption clause to see how much agents' their willingness to accept (WTA) outages. However, with this method there are many difficulties of coverage since, for instance interruptible contracts are in general available for big companies only.

- In the stated preference approach, surveys or experiments are used so that a sample of agents give their ; WTA outages or their willingness to pay (WTP) for not being interrupted.

197. For similar approaches, the results are of similar order of magnitude. But results based on different methods are quite different, ranging from less than 20 cents per kWh to 68 Euro per kWh (Praktiknjo et al 2011). Even the WTA and WTP revealed preference give quite different results. The case studies where one evaluates the damages and the losses realised can be used as complementary information. But they have limitations, since they miss some segments of the economy, and in general they provide very contrasted estimates.

198. Overall the cost of outages depends on several factors that are region specific: sectoral and geographical characteristics, duration, frequency and timing of the outage, experience and mitigation measures take. Current economic trends, with IT technologies and complex manufacturing process could increase the costs in the future. Taking these elements into account could help the make the stated preference analysis more robust.