Detailed global land use and land cover projections under the Shared Socio-Economic Pathways: An integrated Computable General Equilibrium analysis with sub-national resolution for Europe

1. Introduction

Land use and land cover (LULC) developments are crucial for the future of our planet: Land use related carbon stock changes are among the main drivers of climate change. Against this, afforestation, improved carbon sequestration in agricultural soils and the substitution of fossil resources by cultivated biomass are promising mitigation options (Intergovernmental Panel on Climate Change (IPCC) 2019)(Rose et al. 2012). Land further provides food, feed, fibre and numerous ecosystem services and therefore affects many sustainability issues relating to food safety, biodiversity and environmental protection (Smith et al. 2013). Future LULC is largely determined by socio-economic drivers, the nature of which is itself uncertain. To account for different developments both in the drivers and in the resulting future LULC, the climate research community follows a scenario approach: Contrasting futures are explored by varying socio-economic drivers in line with pre-defined narratives (Stehfest et al. 2019). The most recent socio-economic scenarios are the five so-called Shared Socio-Economic Pathways (SSPs) (Riahi et al. 2017)(van Vuuren et al. 2014). Their storylines comprise descriptions of demographic, humanitarian, economic, lifestyle-related, political, institutional, technological and environmental developments resulting in futures with different challenges to adaptation and mitigation (O'Neill et al. 2017). The SSP framework further comprises country-specific quantitative projections of demography (KC und Lutz 2017)(Jiang und O'Neill 2017) and gross domestic product (GDP) (Crespo Cuaresma 2017)(Dellink et al. 2017)(Leimbach et al. 2017) throughout the 21th century. Figure 1 summarises the key aspects of the five SSPs.

Figure 1: Overview of the five Shared Socio-Economic Pathways (SSPs)

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Source: Own illustration based on (O'Neill et al. 2014)(O'Neill et al. 2017).

Remark: L-/ M-/ HIC stands for low-/ middle-/ high-income countries.

LULC under the SSPs is quantified for aggregated world regions as part of a comprehensive modelling exercise with five Integrated Assessment Models (IAMs) (Popp et al. 2017) and is subject to continuous improvement processes (Doelman et al. 2018)(Zeng et al. 2022). The sectoral and regional resolution of these existing projections is however deemed not sufficient for specific studies. Moreover, modelling of LULC is characterized by high uncertainty and there is a consensus to use a variety of models and approaches to investigate potential effects of LULC developments (Alexander et al. 2017)(Popp et al. 2017). Against this background, this paper presents a new set of global LULC projections under the SSPs up to the year 2050. They provide an unprecedented level of detail regarding the regional coverage and the considered (agricultural) land uses. The study focus is on the so-called EURO-Cordex region, a sub-area of the Cordex initiative to improve regional projections of climate change (WRCP). Within this area, European Union (EU) countries (incl. accession candidates), Norway, Switzerland and the United Kingdom are covered with sub-national detail at the level of the Nomenclature des Unités territoriales statistiques (NUTS)-2[1]. The remaining regions are captured at the level of broader Agro-Ecological Zones (AEZs). Outside the EURO-Cordex, country aggregates are built as in previous SSP quantifications, again at the level of broader AEZs. In terms of land use, 30 cropland activities further distinguishing between rainfed and irrigated agriculture, four pastureland activities and the management of forest area are considered. Instead of using model couplings as in IAM exercises, this analysis depicts integrated assessment features in a highly detailed global recursive-dynamic Computable General Equilibrium (CGE) analysis drawing on the CGE modelling platform CGEBox (Britz und van der Mensbrugghe 2018) and the latest release of the Global Trade Analysis Project (GTAP) Data Base Version v11 (Aguiar et al. 2022). Relying on the GTAP-based Recursive-Dynamic Economic Model (G-RDEM) (Britz und Roson 2019)(Roson und Britz 2021), important drivers of structural change are explicitly taken into account in this analysis. Integrated assessment features are addressed through the additional coupling of G-RDEM with CGEBox’ GTAP-AEZ, GTAP-E and Emission-Accounting modules. Moreover, the quantifications translate the SSP narratives into comprehensive assumptions of LULC drivers and they are based on updated versions of the SSP-specific demography and GDP projections (IIASA 2024).

The next section provides a comprehensive overview of the CGE analysis conducted in this study and its structure. Section 3 presents the CGEBox baseline and sensitivity analysis results at an aggregated level[2]. In Section 4, the results are classified in the existing literature and discussed before Section 5 draws a conclusion and provides an outlook.

[1] NUTS is a regional classification system for collecting statistical data which is administrated by the Statistical Office of the EU. Level 2 thereby covers districts with the same regional policy eurostat.
[2] Full resolution results are available open-access via *Data in Brief* (source).

2. Methodology

Economic models are suitable for capturing the effects of interrelated socio-economic drivers on LULC: Changes in consumption and production reflect purchasing power, preferences, technology and factor availability and political measures and affect the supply and demand of land as a production factor via a price mechanism. However, economic models are only able to simulate integrated assessment features to a limited extent. Moreover, there is a trade-off between capturing economic interaction and trade and capturing detailed economic production and market specifications. CGE models offer the advantage that they encompass the entire interacting economy but typically show less spatial and sectoral detail compared to partial equilibrium (PE) models. In existing SSP quantifications, these issues are addressed by model linking, for example by integrating an economic model into an IAM framework (Riahi et al. 2017)(Delzeit et al. 2020). In contrast, this study presents a methodology in which a CGE model resolution is extended to the one of a detailed PE model and in which integrated assessment features are enabled in the CGE simulation itself. The quantification of the SSPs in this CGE analysis is based on two components: Demographics and GDP differ based on SSP-specific, exogenous projections which is also reflected in the considered drivers of structural change. Furthermore, numerous scenario-specific assumptions translate the SSP narratives with regard to LULC drivers.

2.1 Database and Modelling Framework

The database used in this analysis is based on the GTAP v11 Power data (Aguiar et al. 2022) which provides a snapshot of the global economy in 2017 including power generation, emission, air-pollution and land use information (GTAP 2023). To use computational resources wisely, these are aggregated according to the study focus: Nations outside the Euro-Cordex are grouped into world region aggregates[3], the individual power products are combined into one electricity product and the five labour-related production factors are aligned into a skilled and an unskilled labour group. Other components of the GTAP v11 Power data, against this, are split to achieve the desired level of detail in terms of sectoral and regional resolution. The EU countries (incl. accession candidates), Norway, Switzerland and the United Kingdom are split into 317 NUTS-2 sub-regions[4]. The twelve agricultural and the 8 food-related production activities and products are split into 38 and 19 respectively based on FAOSTAT data (source)[5]. Lastly, irrigation water is added to the production factors which further splits up the cropland production activities into irrigated and rainfed variants. The final database comprises 47 regions, 317 sub-regions, 143 production activities, 103 products and 6 production factors. The upper right part of Figure 2 depicts the database and its generation process graphically;

[3] The grouping is based on world regions found in previous SSP quantification: ASIA, LAM (Latin America), MAF (Middle East and Africa), OECD, REF (reforming economies of the former Soviet Union).
[4] The sub-regional split methodology is described in detail in XXX.
[5] The agri-food split follows the methodology described in Britz 2022b but relies on updated data.

Appendix 1 contains a detailed description of the database entries and their mapping to the original GTAP v11 Power elements.

Figure 2: Overview of the conducted Computable General Equilibrium (CGE) analysis

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Source: Own illustration.

The CGE model in this analysis is configured on the open-source modelling platform CGEBox (Britz und van der Mensbrugghe 2018)[6] with G-RDEM (Britz und Roson 2019)(Roson und Britz 2021) at its core, highlighted in blue in Figure 2. G-RDEM builds on the GTAP standard model (van der Mensbrugghe 2018) but is specialised in the generation and analysis of long-term future baselines. For this purpose, it introduces three common recursive-dynamic CGE features in the analysis: Region-specific endogenous total factor productivity (TFP) shifters target exogenous GDP projections in each model solve, demography and labour stocks are updated based on exogenous projections and capital accumulation is depicted as an additional key driver of economic growth. To better reflect long-term developments and structural change, G-RDEM further extends the core of the GTAP standard model. It introduces a modified rank three implicit directly additive demand system (MAIDADS) in private consumption to enable realistic demand estimates under strong income changes. Moreover, TFP changes differ across three broad economic sectors based on econometric work and the use of multi-layered nested CES production functions reflects substitution effects between products more precisely. Beyond that, G-RDEM updates exogenous variables relevant for structural change in between two solution points. This includes future revenue flows to the lenders generated by foreign savings as an exogenous part of the balance of payment. Further, several model parameters are updated based on econometrically estimated relations to the exogenous socio-economic developments. This comprises macro-saving rates, sector-specific cost shares, government and investment expenditure shares, calorie intake per capita, the caloric content of food products and built-up area developments[7]. Lastly, the particularly sensitive developments of cropland and yield are fixed to specialised projections provided by the Food and Agricultural Organization of the United Nations (FAO) (FAO 2018). The latter is realised by endogenizing additional specific productivity shifters.

To capture important features for the integrated assessment, G-RDEM is coupled to other CGE modules via the modelling platform. The use of CGEBox' AEZ module contributes to an improved quantification of LULC. It builds on the GTAP AEZ model (Lee et al. 2009) and data (source) by dis-

[6] CGEBox builds on the GAMS replication of the GTAP standard model version 7 (van der Mensbrugghe 2018) and allows to configure it flexibly. This comprises changes to the model structure as well as the development and combination of model extensions. All CGEBox features are documented in Britz 2022a.

[7] While the econometric estimation of the first four elements originates from the development of G-RDEM, built-up area development is updated based on available literature (Chen et al. 2020).

aggregating land in each region into up to 18 AEZs with similar cultivation conditions and by improving the substitution between different land use types. Compared to the original AEZ model, the CGEBox implementation shows three modifications: First, the Constant-Elasticity-of-Transformation (CET) land supply function is replaced by an additive one based on (van der Mensbrugghe und Peters 2016) to ensure closed area balances. Second, the original four-level land supply nesting is extended to six levels to further differentiate transformation elasticities between annual and perennial crops. And third, an econometrically estimated correlation determines the extent to which cropland changes stem from grassland or managed forest conversion or from converting unmanaged land (Britz 2022a). The use of the CO_2 and non-CO_2 emission accounting modules reports emissions relevant for climate change and allows their taxation, drawing on the respective GTAP data (Chepeliev 2020)(Chepeliev 2022). CGEBox' GTAP-E module replicates the original GTAP-E model (McDougall und Golub 2007) to better represent substitution possibilities in energy use. To improve this further, energy use is accounted in million tonnes of oil equivalents (MTOE). Lastly, the CGE model set-up integrates CGEBox' sub-region module which dis-aggregates production functions and factor markets to sub-national units (Britz 2022a).

2.2 Shared Socio-Economic Pathway (SSP) Quantifications in CGEBox focusing on Land Use and Land Cover (LULC)

CGEBox' SSP quantifications are designed as five baselines with biennial resolution from 2017 up to 2050. They differ firstly in terms of G-RDEM's exogenous drivers: SSP- and country-specific GDP and demographic developments draw on version 3.1 of the projections of the OECD Env-Growth model and the WiC-POP model, made available by the International Institute for Applied Systems Analysis (IIASA 2024). Based on this, the baselines differ in terms of the drivers of structural change which are empirically estimated depending on GDP and demographics. The development of the built-up area contributing to land competition and losses of natural vegetation is to be particularly emphasised at this point. However, GDP and demographics themselves are also important drivers of LULC. Higher income increases per capita food demand and shifts consumption towards (animal-based) diets requiring higher land input and a growing population naturally increases the pressure on land as the overall demand rises (Alexander et al. 2015). Moreover, G-RDEM relies on exogenous cropland and yield projections from the FAO (FAO 2018). These are available for a towards sustainability (TSS) scenario based on SSP1, a business as usual (BAU) scenario based on SSP2 and a stratified societies (SSS) scenario based on SSP3 and SSP4. In this analysis, the SSS projection is assigned to SSP3. In addition, two more scenarios are derived to depict SSP4 and SSP5. The first one, MIX, assigns the values from SSS, BAU and TSS to low-, middle- and high-income countries (L-/ M-/ HICs) respectively in accordance with the narrative of SSP4. The second one, fossil-fueled development (FFD), is designed to generate yield and cropland evolutions slightly below those of SSS representing the idea of SSP5. While cropland itself is a land cover competing with others, crop yield developments influence the land input required to produce the quantity demanded. In the past, yield improvements have made a significant contribution to reducing land conversion. However, it is unclear to what extent yields can continue to increase, both in terms of bio-physical limits and in terms of negative environmental impacts related to intensification (Alexander et al. 2015)(van Zeist et al. 2020).

Beyond the exogenous projections, the SSP baselines draw on bundles of additional exogenous assumptions driving LULC which are quantified in accordance to the narrative of the respective SSP. Their selection reflects the current literature on LULC change, assumptions made in existing IAM-based SSP quantifications and the implementation options in CGEBox. Table 1 provides an overview of all LULC drivers considered in the SSP baselines, with the additional assumptions from row six onwards. The table further informs about the model implementation, the SSP-specific quantification of each driver and its expected effect on natural land cover (NLC). The additional assumptions include a bundle relating to technical progress in agriculture and forestry. Besides yield developments, the available production technologies, both in primary production and in processing, contribute to the land input required. A second assumption bundle concerns food demand. Conscious consumption, for example

Table 1: Land Use and Land Cover (LULC) drivers in CGEBox' Shared Socio-Economic Pathway (SSP) quantifications

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Abbreviations: LMH: Assumptions of SSP3 are assigned to LICs, assumptions of SSP2 to MICs and assumptions of SSP1 to HICs.

Source: own illustration. References: [1] IIASA (2024), [2] FAO (2018).

by reducing the intake of highly processed or animal-based foods, helps to reduce the pressure on land. On the production side, the available technology and the handling of waste products play decisive roles. The remaining assumption bundles relate to policies. Various environmental protection strategies are considered which protect natural resources (incl. NLC) directly or indirectly by reducing the pressure on land. Moreover, common cropland subsidies which artificially increase the value of land and thereby remove incentives for productivity are addressed. Energy relates to LULC through the substitution possibilities with bioenergy and the climate effects of carbon stock changes. It is to be noted that CGEBox does neither allow a detailed mapping of bioenergy nor the taxation of carbon stock changes. However, implicit assumptions are made in this context. Trade, on the one hand, promotes the efficiency of production and has the potential to reduce the necessary land input. Yet, it also goes hand in hand with growth in prosperity and increasing consumption, effects which have already been addressed when discussing GDP developments (Alexander et al. 2015) (Stehfest et al. 2019). The GAMS code from which details on the technical implementation of the additional assumptions can be taken is available in Appendix 2.

2.3 Sensitivity analysis of the Land Use and Land Cover (LULC) development results

To analyse the sensitivity of the LULC results to the scenario-specific exogenous LULC driver assumptions and to determine the most important drivers of LULC developments, further model runs, so-called sensitivity runs, are carried out in addition to the baseline runs. In each of these, one of the assumptions is removed by switching off the relevant code part using globals. The technical implementation can also be found in the GAMS code in Appendix 2.

3. Results

This section first describes the results of the SSP baselines created with CGEBox. Thereby, the focus is on food, biomass and LULC. Subsequently, the results of the sensitivity analysis are presented.

3.1 CGEBox' SSP Baselines

As shown in Table 1, the exogenous GDP and population projections driving the baselines depict global increases in all SSPs. On average, global GDP growth outweighs population growth so that real GDP per capita as a measure of consumption increases in all five SSPs by 2050. This improvement is highest in SSP5 with +127.74%, followed by SSP1 with +97.56%, SSP2 with +73.54%, SSP4 with +67.03% and SSP3 with +43.69%. None of the regions in this analysis records a decline in per capita real GDP. G-RDEM uses an empirically estimated MAIDADS for private consumption which reacts to changes in income and saving rates, adjusts the marginal budget shares of different product groups, retains fixed commitment terms and explicitly controls the total calorie intake to prevent an overestimation of the demand for necessities. In interaction with the SSP-specific LULC drivers which also include assumptions on preferences shifts towards vegetarian diets and on a meat tax, this results in food demand changes not only dependent on per capita real GDP changes.

Figure 3: Global calorie consumption and prices

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Source: own illustration.

Figure 3 records global increases in the per capita calorie demand for all SSPs (5 > 3 > 2 > 4 > 1). The high food consumption in SSP5 reflects a narrative with unsustainable diets, implying higher meat, dairy and out-of-home consumption, while the per capita demand for plant-based calories decreases significantly and the one for other processed food stagnates. The per capita demand for staple food also falls in the other SSPs, but to more moderate levels. In the regionally focused SSP3, this decrease is particularly limited reflecting the comparatively low growth of purchasing power. According to the superimposed scenario assumptions, the per capita calorie demand for meat and animal products records a decline in the SSPs 1, 2 and 4. Preference shifts away from animal products and more favourable price developments of other food groups increase the per capita calorie demand for vegetable oils in the SSPs 1 to 4. These SSPs further show a growth in the per capita demand for out-of-home consumption in line with the higher purchasing power. The per capita demand for calories from processed food also rises, but the differences between the SSPs are negligible. A breakdown of calorie demand and prices by product group can be found in Appendix 3.

Due to the different population projections, the total demand for calories draws a different picture than the per capita demand. Here, the increase is highest in SSP3, followed by SSP4, SSP2, SSP5 and

SSP1. Although the per capita demand for staple calories falls in all SSPs, only SSP5 shows a decline in absolute terms. Regarding vegetable oils, all SSPs record an increase in overall demand. While the SSPs 1, 2 and 4 show an overall decline in meat calories, for other animal products this only applies to the sustainable SPP1 with the strongest scenario assumptions in this regard. SSP3 and SSP5 show increases in both, meat and other animal product calorie supply. The increase in SSP5 is significantly higher than in SSP3 reflecting higher per capita incomes and the scenario assumptions. Concerning other processed foods, SSP5 ranks below SSP1, while the demand found for the other SSPs appears to be primarily determined by the overall population. The total demand for out-of-home consumption is determined by the improvement in purchasing power. In terms of the price per calorie, all SSPs record a significant growth (+57.3% to +65.2%) which can also be seen in Figure 3. This reflects a growing pressure on land which is only partially offset by rising yields and therefore results in rising land rents. Considering the change in purchasing power, the affordability of food improves in the SSPs 1 and 5, while it remains almost unchanged in the SSPs 2 and 4 and deteriorates in SSP3 which coincides with the narratives of the scenarios. In addition to demand, price trends, especially for unprocessed food, are largely determined by the SSP-specific LULC drivers addressing technological development and the competition for land.

Regarding the total biomass demand depicted in Figure 4, SSP5 records the highest global increase by 2050, followed by SSP3, SSP4, SSP2 and SSP1. The numbers in square brackets give the changes in per capita demand. Here, the order of the SSPs is almost similar, with only SSP4 occupying a lower position. These results primarily reflect the narratives of the SSPs which are further confirmed when looking at the composition of biomass demand. The sustainable SSP1, recording the lowest total and second-lowest per capita growth in biomass demand, shows a trend away from less sustainable (livestock, fish) towards more sustainable biomass consumption (crops). The increase in forestry demand can be explained by substitution with non-renewable raw materials and can therefore also be evaluated as environmentally friendly. This is contradicted by the results of SSP5. The unsustainable consumption pattern underlying the narrative of this SSP becomes particularly evident when considering the change in per capita biomass demand by +43.2% which is 15.0% to 20.1% higher than in the other scenarios. While SSP5 is positioned at the lower end of crop demand, it records significant increases in the demand for livestock, fish and forestry. The high consumption of animal calories plays a decisive role here. As animals themselves consume plant-based calories and some of these can also be used directly as food for humans, the dietary shift in SSP5 implies higher biomass demand per calorie supplied compared to the other SSPs. In the case of SSP5, the additional forestry demand does further not reflect a substitution with non-renewable raw materials but rather the generally higher consumption.

The remaining SSPs are positioned in between these two extreme scenarios. SSP3, characterised by high population and low GDP growth in line with a policy focused on regional security, still shows a high increase in biomass demand. For income reasons, this is based largely on crops. Yet, the demand for livestock, fish and forestry also rises which illustrates the lower environmental awareness in this scenario compared to the SSPs 1, 2 and 4. Concerning livestock biomass, it is noticeable that solely the middle-of-the-road SSP2 and the uneven developments in SSP4 record per capita declines, while the total demand still rises. The absolute increase in the demand for other animal products is one reason for this. However, for this and other processed food, intermediate demand by the food industry is a substantial part of total demand, delivering the calories and other nutrients comprised in processed food and out-of-home consumption. The results of SSP2 and SSP4 are quite similar due to similar GDP projections and equalization effects between LICs and HICs in SSP4. However, the results per capita or at regional level differ more between these SSPs. That SSP4 records the lowest per capita increase in total biomass demand can be explained by two aspects: The same (environmental) assumptions hold in this scenario for HICs as in SSP1, but M-/ LICs have significantly fewer consumption options as their real GDP per capita growth is lower.

Figure 4: Global biomass demand and its composition

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Note: The values in square brackets indicate the change in per capita demand over time for comparison. The aggregation behind total biomass, crops, livestock, forestry and fish can be found in Appendix 4.

Source: own illustration.

In addition to demand, LULC is largely determined by the SSP-specific assumptions on LULC drivers. Of particular importance is the development of cropland which follows the FAO projections described in Section 2. As can be seen in Figure 5, the cropland area increases in SSP2, followed by SSP4, SSP5 and SSP3, while it decreases in SSP1. When comparing LULC with the demand for crop-based biomass, SSP5 is particularly striking with the lowest growth in demand but the highest one in land. Two aspects stand in the way of demand growth in this scenario: As can be seen in Table 1, SSP5 records an increase in food waste and only slight yield improvements. For the remaining SSPs, biomass demand, yield development, cropland projections and the development of food waste go hand in hand. In the sustainable SSP1, for example, yield improves significantly and food waste decreases. In combination with the moderate growth of crop demand, this enables the projected reduction in cropland area. In SSP3, against this, an increase in food waste and only limited yield improvements contribute to an expansion of the cropland area in addition to the high crop demand. It is also worth noting that due to the different cropland projections and the other scenario-specific assumptions for SSP2 and SSP4, there are further components that differentiate the results between these scenarios on the production side. Concerning the use of chemicals per output unit of crops, all SSPs record a decrease. This is similarly pronounced in the SSPs 1, 2, 4 and 5 (-35.27% to -36.86%) and is slightly lower in SSP3

(-28.58%). Cropland expansion therefore does not appear to be determinant for the intensity of land use.

Figure 5: Land Use and Land Cover (LULC) in CGEBox' SSP baselines

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Source: own illustration.

Looking at the development of pastureland, it is noticeable that despite the increasing livestock biomass demand, all SSPs record a decline. This is least pronounced in SSP3 and becomes more pronounced in SSP5, followed by SSP2, SSP4 and SSP1. On the one hand, livestock biomass stems to a large extent from non-grassland fed animals. On the other hand, the high competition with cropland, the yield trends and the scenario-specific livestock intensification assumptions play a decisive role. Managed forest is also in direct competition with cropland. This is particularly noticeable looking at the results of SSP3. For the other SSPs, the land area shows the same trends as the biomass demand (5 > 2 > 5 > 1). However, SSP3 occupies the position between SSP5 and SSP2 in terms of biomass demand, while it ranks at the lower end of the chain behind SSP1 in terms of LULC. The SSP-specific assumptions regarding the intensity of forestry production and technological progress in the processing of wood are lowest for SSP3, as can be seen in Table 1. It can therefore be assumed that the competition with cropland, indirectly determined by the SSP-specific assumption concerning the available land buffer, is a key determinant for the development of the managed forest area. The development of built-up area is calculated on the basis of a statistical estimate depending on GDP and demographic trends. It rises in all SSPs (5 > 1 > 4 > 2 > 3). The four land covers described so far are cultivated and are in direct competition with NLC. According to the scenario narratives, the model results show an increase in NLC (natural forest and other natural land) in SSP1, whereas the other SSPs record decreases. While the declines in SSP2 and SSP4 are moderate, they are more pronounced in SSP3 due to the strong growth population and in SSP5 due to the strong increase in consumption. The SSP-specific assumptions concerning the land buffer also play a key role here.

3.2 Effect of the scenario-specific exogenous assumptions on the development of Land Use and Land Cover (LULC)

In the following, the results of the sensitivity analyses are described with the aim to analyse the effect of the SSP-specific LULC driver assumptions on the model results.

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