StartClim 2024

Systemdynamische Betrachtung von Szenarien zur Klimawandelanpassung im Kontext der Erreichung der SDGs in Österreich

Identifizierung von Dynamiken, Wechselwirkungen und Synergiepotentialen

Bundesministerium Land- und Forstwirtschaft, Klima- und Umweltschutz, Regionen und Wasserwirtschaft

Bundesministerium Frauen, Wissenschaft und Forschung

klima+ energie fonds

Land Oberösterreich

ober österreich

umweltbundesamt

BOKU University

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BOKU Zentrum für globalen Wandel und Nachhaltigkeit

Diese Publikation sollte folgendermaßen zitiert werden:

Wretschitsch, E.; Kirchner, M., Spittler, N. (2025): Systemdynamische Betrachtung von Szenarien zur Klimawandelanpassung im Kontext der Erreichung der SDGs in Österreich: Identifizierung von Dynamiken, Wechselwirkungen und Synergiepotentialen. Endbericht von StartClim2024.E in StartClim2024: Extremereignisse, Ökosysteme und gerechte Transformation, Auftraggeber: BMLUK, BMFWF, Klima- und Energiefonds, Land Oberösterreich.

Wien, im September 2025

Druck, November 2025

StartClim2024.E

Teilprojekt von StartClim2024

Projektleitung von StartClim:

BOKU University, Department für Ökosystemmanagement, Klima und Biodiversität

Institut für Meteorologie und Klimatologie, Gregor-Mendel-Straße 33, 1180 Wien

www.startclim.at

StartClim2024 wurde aus Mitteln des BMK, BMWFW, Klima- und Energiefonds und dem Land Oberösterreich gefördert.

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E-1 Kurzfassung

Der fortschreitende Klimawandel und seine immer spürbareren Auswirkungen stellen eine erhebliche Herausforderung für die Verwirklichung einer nachhaltigen Entwicklung dar, wie sie in den Sustainable Development Goals (SDGs) angestrebt wird. Dieses Projekt hat daher zum Ziel Auswirkungen des Klimawandels und Maßnahmen zur Anpassung in den Kontext der SDGs zu setzen, und deren Wechselwirkungen, Dynamiken und Trends zu analysieren. Der Fokus wird dabei auf den Landwirtschaftssektor gelegt, der besonders vom Klimawandel betroffen ist. Dazu werden einerseits drei unterschiedliche Klimaszenarien sowie die Ausweitung der biologischen Landwirtschaft und ein Eindämmen des Flächenverbrauchs als Anpassungsszenarien mit dem systemdynamischen iSD-AT Modell simuliert. Diese Methode ermöglicht es auf aggregierter Ebene ein besonderes Augenmerk auf Wechselwirkungen zwischen sozio-ökonomischen und ökologischen Zielen zu legen. Des Weiteren validiert und komplementiert ein Expert:innen Workshop die Modellergebnisse, indem die Ergebnisse diskutiert werden und aufgezeigt wird, welche Dynamiken, die das Modell nicht abbilden kann, noch berücksichtigt werden sollen. Die Ergebnisse zeigen eine Intensivierung der Landwirtschaft durch Klimaauswirkungen im Sinne eines höheren Wasserbedarfs sowie gesteigertem Einsatz mineralischer Düngemittel. Der Erhalt landwirtschaftlicher Fläche erhöht die gesamte landwirtschaftliche Produktion und wirkt dem Beschäftigungsrückgang in der Landwirtschaft entgegen, erhöht aber den Druck auf die Reduktion von THG-Emissionen in der Landwirtschaft. Eine Umstellung auf biologische Landwirtschaft kann diese negativen Umweltauswirkungen abschwächen. Als Trade-off zeigt sich bei der Umstellung auf biologische Landwirtschaft die Reduktion des Ertrags pro Hektar. Neben den Dynamiken, die sich in den Modellergebnissen zeigen, wurden im Zuge des Expert:innen Workshops soziale Aspekte wie die Auswirkung auf Lebensmittelpreise und langfristige Ertrags- und Einkommenssicherheit hervorgehoben. Die Ergebnisse zeigen, dass sich auf solch aggregierter Modellierungsebene wesentliche Dynamiken und Wechselwirkungen gut abbilden lassen. Eine zukünftige Kopplung mit detaillierten Bottom-up-Sektormodellen bietet darüber hinaus die Möglichkeit, die Vorteile beider Ansätze zu vereinen.

E-2 Abstract

The ongoing climate crisis and its increasingly noticeable impacts pose a significant challenge to achieving sustainable development as outlined in the Sustainable Development Goals (SDGs). This project aims to set the impacts of climate change and adaptation measures in context of the SDGs, analyse their interactions, dynamics, and trends. The focus is on the agricultural sector, which is particularly affected by climate change. Three different climate scenarios, along with two adaptation scenarios, the expansion of organic farming and the reduction of land consumption, are simulated using the system dynamics iSD-AT model. This method enables an aggregated analysis with a particular emphasis on the interactions between socio-economic and ecological goals. Additionally, an expert workshop validates and complements the model results by discussing the findings and identifying dynamics not captured by the model that should be considered. The model results indicate an intensification of agriculture due to climate impacts, reflected in higher water consumption and increased use of mineral fertilizers. Preserving agricultural land boosts overall agricultural production and counters the general trend of a decline in agricultural employment but increases pressure to reduce greenhouse gas (GHG) emissions in the sector. A shift to organic farming can mitigate these negative environmental impacts, though it comes with the trade-off of reduced yields per hectare. Beyond the dynamics revealed in the model results, the expert workshop highlighted social aspects, such as the impact on food prices and long-term yield and income security. The findings demonstrate that key dynamics and interactions can be effectively represented at this aggregated modelling level. Future coupling with detailed bottom-up sector models could further combine the strengths of both approaches.

E-3 Introduction

E-3.1 Motivation and background

With the progression of climate change, the global temperature has been increasing especially over the last decades. In Austria, the average temperature change lies above the global warming rate with an increase of 2.9°C until 2023 compared to the pre-industrial reference period (1850-1900) (Chimani et al., 2024). This rapid warming stresses the urgent need for timely and effective action to reduce greenhouse gas emissions and adapt to the effects of climate change. These impacts are already evident and are expected to intensify significantly in the future, making climate change adaptation essential for ensuring a sustainable future.

The Sustainable Development Goals (SDGs) have been launched in 2015 within the Agenda 2030 with the aim to establish 17 goals to ensure sustainable development holistically and across all countries worldwide (United Nations, 2015). While this framework of the SDGs puts emphasis to approaching these goals as "integrated and indivisible", interaction effects among the social, economic and ecological goals can cause trade-offs. At the same time, the potential for synergies between the SDGs must also be identified and leveraged.

While Austria has made progress on many SDGs (European Commission, 2022; Statistics Austria, 2024), major challenges remain regarding SDG12 and SDG13 and significant challenges regarding SDG2, SDG4, SDG8, SDG15 and SDG17 (Sachs et al., 2024).

The importance of combating climate change is emphasized by SDG13 (Climate action) However, climate impacts, greenhouse gas mitigation measures, and adaptation strategies also influence progress on many other SDGs (Filho et al., 2023; Fuldauer et al., 2022; Fuso Nerini et al., 2019). To mitigate the climate change impacts on SDGs and at the same time avoid conflicts between adaptation and the SDGs, adaptation measures need to be well defined in order to avoid maladaptation. Thereby, vulnerability in the short as well as long term can be reduced (IPCC, 2022).

E-3.2 Climate change adaptation in agriculture

In Austria, the first national strategy on climate change adaptation was adopted in 2012, with an updated version published in 2024 (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2024). The updated strategy identifies 14 key areas requiring adaptation measures, spanning sectors such as agriculture, forestry, tourism, and healthcare.

Agriculture is particularly vulnerable to changes in temperature and precipitation. Adaptation measures are required to secure agricultural production and food security (Jandl et al., 2024). Rising average temperatures may extend the growing season, with studies showing positive impacts on crop yields in regions without water limitations. However, regions already experiencing water scarcity and droughts are likely to see negative impacts on yields (Borsky et al., 2024). Autonomous adaptation by farmers, such as intensification in areas with potential yield increases, can lead to adverse ecological consequences, including higher greenhouse gas emissions and biodiversity loss (Borsky et al., 2024).

Besides the impacts of a change in temperature, high uncertainty in future scenarios exists regarding the change in precipitation. Regional variations in precipitation and drought occurrences will exacerbate water stress, as increased evaporation driven by higher temperatures further reduces water availability (Jandl et al., 2024).

In the context of the SDGs, both trade-offs and synergies are anticipated from climate change impacts and (autonomous) adaptation in agriculture (Jandl et al., 2024). On the one hand, land-use conflicts are intensifying due to factors such as the expansion of settlement areas, the loss of agricultural land, soil degradation, and the diminishing availability of clean water resources (International Council for Science, 2017). Furthermore, agricultural practices themselves exacerbate these challenges by negatively impacting water resources through the use of pesticides and fertilizers, while also contributing to biodiversity loss (International Council for Science, 2017). As a key driver of land use and land degradation, agriculture can create trade-offs between achieving SDG2 (Zero Hunger) and SDG15 (Life on Land).

On the other hand, adaptation in agriculture also offers opportunities for synergies with the SDGs. For example, organic farming has been shown to enhance water quality (SDG6) and public health (SDG3), while dietary shifts toward plant-based diets support SDG2, SDG3, and SDG 13 (Climate Action). A qualitative study on the impacts of climate change adaptation measures on the SDGs in the Swiss context finds synergy potentials of adaptation measures in agriculture especially with respect to SDG2 and SDG15, but also with SDG6, SDG12 (Responsible Consumption and Production) and SDG13 among others (Reimann & Pütz, 2024).

E-3.3 Research questions and project objectives

In this context, this project addresses the following research questions:

- What linkages exist between climate change adaptation in agriculture and the Sustainable Development Goals (SDGs)?
- What dynamics, synergies and conflicts arise from this?

In addition to analyzing the impacts of temperature and precipitation changes, the project examines two specific policy interventions:

First, the expansion of organic farming is analysed. The switch to organic farming has been identified as a promising strategy for adapting to climate change as it entails different measures and agricultural practices that increase the resilience against weather extremes and also has multiple synergy effects with other SDGs, for example SDG3 (Good Health and Well-Being) and SDG6 (Clean Water and Sanitation) (Jandl et al., 2024).

With the second policy intervention, impacts of agricultural land loss are analysed. Agricultural land loss, driven by climate change impacts, soil sealing, and urban expansion, poses a significant challenge. Studies in Austria indicate a decline in agricultural self-sufficiency, which could lead to higher food prices, more intensive land use, increased reliance on mineral fertilizers and water, and a subsequent decline in biodiversity (Jandl et al., 2024). Land-use conflicts, exacerbated by both climate impacts and adaptation measures, further complicate efforts to achieve sustainable development.

E-3.4 Methodology overview

To address these research questions the literature consistently emphasizes the importance of systems thinking and systemic approaches to find holistic solutions and to avoid silo-thinking in implementing the SDGs, which is still a remaining gap (Miola et al., 2019; Nilsson et al., 2018).

System dynamics is highlighted as a suitable approach for analyzing feedback interactions among various biophysical and socio-economic systems and thereby supporting a holistic assessment of policies by analysing scenarios over a long-term horizon. Additionally, participatory modelling and stakeholder engagement are emphasized as essential processes for fostering a shared understanding of systems (Elsawah et al., 2017).

In this project, the quantitative system dynamics model iSD-AT has been applied in this context. The iSD-AT model is a national model for Austria that has a broad coverage of sectors and indicators relating to the SDGs and especially emphasized the interaction effects and feedbacks within this system. An expert workshop was held to validate and complement the model findings.

E-3.5 Structure of the report

This project report proceeds by explaining the methods applied in this project, with a particular focus on the iSD-AT model. Following this, the report presents the modelling results alongside the outcomes of the expert workshop, analyzing and contextualizing their relationship. The final section concludes and provides an outlook on potential directions for future research.

E-4 Methodology

In this section, the applied methodology is presented by first describing the quantitative modelling approach, including a short overview of the underlying system dynamics theory and a description of the iSD-AT model. Following this, the application of the iSD-AT in the context of this project is described in more detail covering relevant modelling assumption, analysed indicators and scenarios and data inputs. Finally, the implementation of the expert workshop is described.

E-4.1 System dynamics modelling

The aim of system dynamics is to explain patterns and trends over time by highlighting and analyzing underlying system structures (Meadows, 2008). The focus lies thus on identifying behavior and therein dynamics of a system and not on exact predictions about future development (Pruyt, 2013). System dynamics encompasses qualitative as well as quantitative methods, such as Causal-Loop-Diagrams or quantitative simulation models (Dangerfield, 2014). An important component of this method are feedback loops that can cause either accelerating (reinforcing) or balancing, goal-seeking behavior (Meadows, 2008).

The iSD-AT model that is applied in this project represents a computational quantitative system dynamics model. Beyond the feedback structures, these models include stock and flow variables. Stocks are variables capturing accumulation over time. Examples for stock variables are population or the concentration of CO2 in the atmosphere. Flows, on the other hand, cause changes in stocks and are either "inflows" that increase the stock, or "ouflows". Flows are defined by auxiliary variables and are time dependent, as for example net migration per year increasing population, or greenhouse gas emissions per year increasing the atmospheric concentration of CO2. From the stock-flow and feedback structures in such models arise delays and non-linearities, which are a key characteristic of system dynamics models (Dangerfield, 2014).

Boulanger & Bréchet (2005) also emphasize the strengths of system dynamics modelling from a process and application perspective as it allows for interdisciplinarity and feedbacks among variables from different disciplines, long-term simulations, and the integration of stakeholders and experts without modelling knowledge due to the transparent structure.

E-4.2 The iSD model

The iSD model is a quantitative simulation system dynamics based model. It originates from the Limits to Growth model, which was nationalized and became the Threshold21 model, which has been developed for over 30 years. The model's intend is to support national development planning and analyse pathways towards sustainable development (see for example Allen et al., 2019; Li et al., 2024; Pedercini et al., 2018). The model structure consists of 24 modules and additional sub-modules that each include stocks, flows and auxiliary variables and the causal relations between them. These are transparently stated in the model structure, which has enabled discussions with stakeholders and integration of expert knowledge over the years.

The 24 modules can be roughly grouped into 8 for each social, economic and ecological aspects. Examples for these sectors are *Energy*, *Population* or *Primary Production*. These sectors have their own underlying dynamics containing more submodules but are also linked to other sectors and add to their structure. This is graphically demonstrated in figure E-1 as blue arrows. The iSD covers most aspects of the SDGs framework and is therefore able to analyse the progress towards the goals on the basis of most UN indicators. Furthermore, the structure was also influenced by the concept of the planetary boundaries (Rockström et al., 2009).

As a national blueprint model, the idea of the iSD is to be adjusted to different country contexts. To apply the model in the Austrian context, it was calibrated to Austrian data for the period of 2000 to

2023 (Spittler & Kirchner, 2022). In the calibration process, constant elasticities are derived based on historic data that describe the causal relation between two variables. Future scenarios are then simulated for the time period from 2024 to 2050. So far, the iSD-AT has also been applied in the ACRP project SDGVisionPath to analyse sustainable development pathways based on Stakeholder driven policies and measures (Wretschitsch et al., 2024) and also in the Earth4All project to analyse national engagement scenarios (Earth4All: Austria, 2024).

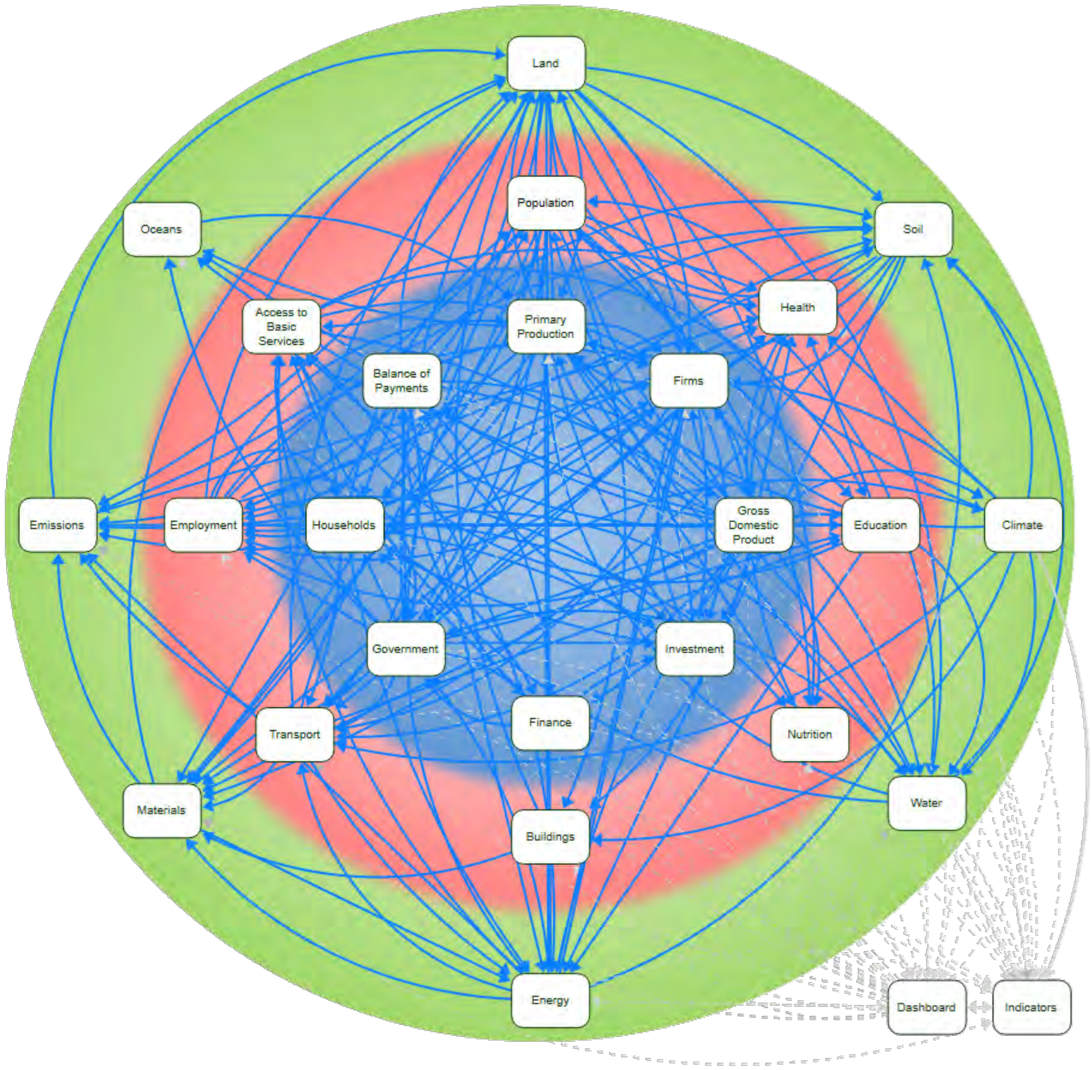

Abb. E-1: Overview of the sectors in the iSD model (Millennium Institute, 2021)

As the iSD model spans a wide range of sectors, the data sources are multifold: Data is derived, on the one hand, from international databases such as the UN, FAO, the IMF or the World Bank (Millennium Institute, 2021). On the other hand, in the case of Austria, data has been supplemented with data from Eurostat as well as national sources (e.g. Statistics Austria, Environmental Agency Austria).

Dynamics relevant to the agricultural sector in the iSD-AT are captured in different modules: Central to dynamics of crop production is the *Primary Production* module, in which attainable yield per hectare and the actual total crop production is calculated. This requires input from other modules, such as temperature and precipitation from the *Climate* module, nutrient availability from the *Soil* module, water availability from the *Water* module, labor and capital availability from the *Employment* and the *Firms* module respectively as well as the agriculture land from the *Land* module. The result of total crop production then also influences dynamics in other modules, for example *Gross Domestic Product*, *Emissions* or *Energy*.

The dynamics that determine behavior and trends concerning the agriculture sector are highly aggregated as they are limited to dynamics at the national level (i.e. without regional differentiation) and with regards to crop production only distinguishes between two crop types (cereals and non-cereal crops).

E-4.3 Model application

E-4.3.1 Modelling assumptions

As the iSD-AT model represents dynamics on a very aggregated level and ignores details to a certain degree in order to focus on the main dynamics, the modelling results are based on a set of assumptions which impact the model results[1].

First, elasticities that are derived in the calibration process are kept constant in all scenarios. This also applies to the effect of temperature changes on potential crop yields. However, with strongly increasing temperatures and potential tipping points that are surpassed the causal relation between average temperature and potential crop yields might change, especially after the simulated period, in the second half of the current century.

Second, while crop rotation and management practices are partly autonomous adaptation measures to a changing climate (Borsky et al., 2024), the share or crop types on harvested land is kept constant throughout the simulation period.

Third, the iSD-AT model accounts for autonomous adaptation in fertilizer application and water use for irrigation. However, this is based on a set of assumptions: On the one hand, water utilization efficiency for harvested yield is assumed to remain constant and is only differentiated between the two crop types. Additionally, the model does not account for any limitations on the general availability of (ground)water for irrigation. On the other hand, regarding nutrient availability, the model assumes that soil organic carbon density increases as a stock as long as there is a nutrient surplus, with no threshold value defined for this stock.

E-4.3.2 Indicators and scenarios

While the iSD-AT model is able to represent dynamics around most of the official UN indicators for progress on the SDGs, not all indicators are suitable for the Austrian context, and data is not available for all of these indicators. Therefore, indicators on the national as well as European level have been added to better capture national circumstances (European Commission, 2022; Statistics Austria, 2024).

To take a closer look at the interaction between climate adaptation in agriculture the SDGs, more specific indicators were selected. These go beyond the indicators used in progress reports by national, regional or international initiatives. Nevertheless, these indicators still relate to SDGs as well as they were chosen to consider all of the three dimensions of sustainability and the SDGs framework.

The indicators selected in this analysis are the following:

- Average yield per area (SDG2),
- Total crops production (SDG2),
- Irrigated cropland and water consumption for irrigation (SDG6),
- Real GDP in the agricultural sector (SDG8),
- Employment in the agricultural sector (SDG8),

[1] Assumptions regarding the implementation of policy measure are discussed in section E-4.3.1.

- Greenhouse gas emissions in the agricultural sector (SDG13),
- Use of mineral nitrogen fertilizers (SDG15),
- Agriculture land (SDG15).

The development of the indicators until 2050 was analysed for eight different scenarios. These scenarios were defined based on different climate change impacts regarding the change in temperature as well as the change in precipitation (see Tab. E-1). For temperature increase, it was assumed that the current increase of 0.6°C per decade is continued until 2050 (Formayer et al., 2025).

We also consider two different precipitation scenarios, one with an increase of 7.1 % in precipitation compared to the period 2000-2021 and one with a gradual decrease in precipitation towards 2050. Adapted from Jost et al. (2025), precipitation in this scenario is on average lower by 5.1% compared to the period 2000-2023.

To distinguish the general trend based on historical developments and calibrated causal relationships from climate and policy effects, a counterfactual scenario is presented. This scenario hypothetically assumes no further change in average temperature after 2023 and maintains the same average precipitation levels for the period 2021–2050 as observed during 2000–2021.

Tab. E-1: Climate scenarios

Scenario	Average temperature increase per decade	Average precipitation 2021-2050 relative to 2000-2021
Counterfactual	0	0
Climate Scenario (Wet)	+0.6	+7.1%
Climate Scenario (Dry)	+0.6°C	-5.1%

Furthermore, two different policy interventions and one scenario with both interventions combined were analysed for each climate scenario (see Table E-2). First, the impact of an expansion in organic farming was modeled. While the share of harvested area that was managed organically increased in the past from 5.6 % in 2000 to 27.5 % in 2023 (Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft, 2024) this policy scenario considers a linear increase up to 100% reached in 2050. In this policy scenario, this increase is exogenously determined and not resulting from certain policy implementations and potentially associated governmental subsidies are not considered.

Second, as the decline in agriculture land is a key aspect of climate change adaptation, progress on the SDGs and part of multiple conflicts. Hence, one policy scenario was based on the assumption of no further loss in agricultural land. While in the baseline, the trend that has been observed in the past would continue and, in 2050, lead to a decrease in agriculture land by around 12 % compared to 2023, this decrease is stopped after 2023. Also in this case, the future development is exogenously implemented and not resulting from any concrete policy measures. As in the model, the development of agriculture land is in general derived endogenously, the future trend is mainly driven by land demand for settlement and infrastructure as well as afforestation. These dynamics are neglected in the policy scenario Pol_Land.

Finally, a third policy scenario considers the impacts of both policies in combination which allows to detect possible interactions among them.

Tab. E-2: Policy Scenarios

Scenario	Share of harvested area organically managed	Change in agriculture land
Policy Scenario A (Pol_Orga)	1	No policy
Policy Scenario B (Pol_Land)	0,274	Limitation of conversion from agriculture to settlement land
Policy Scenario C (Polc_Comb)	1	Limitation of conversion from agriculture to settlement land

E-4.3.3 Feedbacks and interactions

While temperature change and precipitation as well as the two implemented policies impact multiple modules, the most important modules where the key dynamics play out are *Climate*, *Emissions*, *Employment*, *Primary Production*, *Water*, *Soil* and *Land use*.

Temperature changes are accounted for in the *Climate* module, where the average temperature is represented as a stock which annually increases or decreases depending on the exogenously defined long term trend. In the same module, precipitation is defined also according to exogenous input (according to table E-1). With respect to the agriculture sector, the temperature change impacts the potential yield. Precipitation changes influence the water availability for crops, the amount of water used for irrigation as well as nutrient loss.

Furthermore, the results are influenced by multiple feedback loops in the system. Among others, they relate to irrigation and economic and employment dynamics:

(1) Most feedback loops center around the economic aspect of the agriculture sector. Almost all loops are reinforcing, causing accelerating behavior, and one balancing loop, stabilizing the dynamics around an equilibrium. Figure E-2 highlights the reinforcing dynamics around the increase of capital input in agriculture caused by an increase in total crops production which further increases the capital stock (R2). This loop would lead to a constantly growing crop production, if not balanced out by an increase in employment which decreases investment in capital (B).

The policy interventions considered in these analyses influence these loops in multiple ways: The expansion of sustainable agriculture decreases potential crop yield, but increases employment. Also, more agricultural land is available which influences the total crop production.

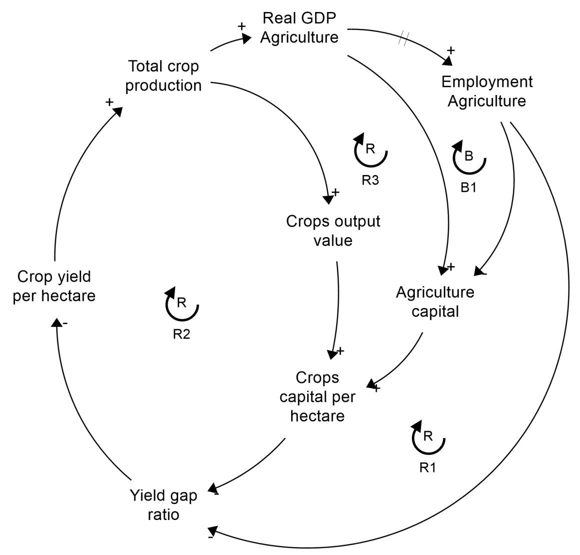

Abb. E-2: Balancing (B) and reinforcing (R) Feedback loops in the iSD-AT model with respect to real GDP in agriculture, capital and employment. Arrows represent causal links. If they are assigned a (+) then both variables move in the same direction, if they are assigned a (-) then the variables move in opposite directions.

(2) The dynamics of irrigation on cropland as an endogenous decision to adapt to changing climate are captured by a balancing loop. Irrigation is applied in case the water requirement by the crops exceeds the water availability, e.g. caused by too little precipitation. The degree to which a shortage of water availability can be compensated by irrigation is determined by the share of cropland that has the possibility to irrigate as well as by the average maximum amount of water per hectare of irrigated area. If a water limitation persists, the irrigated area is expanded with a time delay. These dynamics continue until the there is no more shortage of water (so called "goals-seeking behavior").

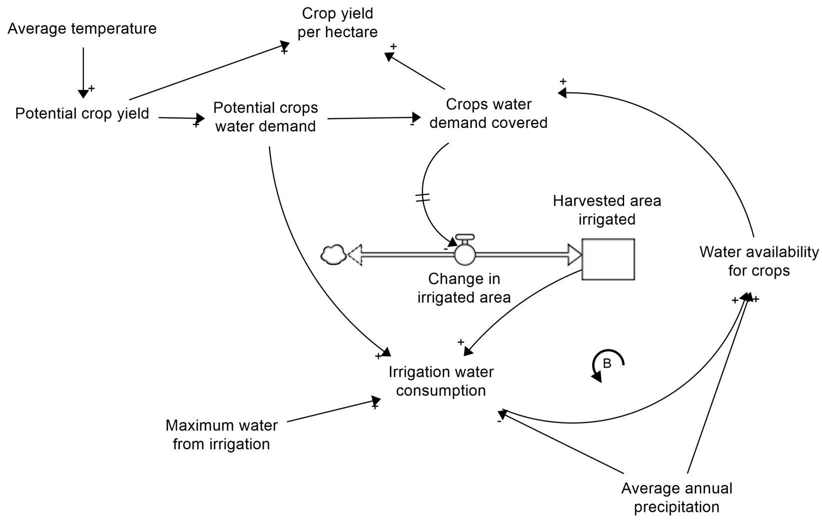

Abb. E-3: Balancing (B) and reinforcing (R) feedback loops in the iSD-AT model with respect to irrigation of cropland. Arrows represent causal links. If they are assigned a (+) then both variables move in the same direction, if they are assigned a (-) then the variables move in opposite directions.

Mineral fertilizer consumption is driven by both exogenous and endogenous input factors but, in contrast to irrigation, not affected by feedback dynamics. Key drivers of mineral fertilizer use include the potential nutrient uptake based on crop yield potential, the proportion of sustainably managed harvested areas, and the average fertilizer price. While the latter two factors are defined exogenously, potential nutrient uptake by crops is influenced by temperature changes and crop-specific nutrient requirements, which are also exogenously determined. Mineral fertilizer consumption directly impacts the nutrient balance, which in turn affects soil organic carbon density and nutrient availability, both of which are critical for achieving potential crop yields.

E-4.3.4 Data inputs

As described in the overview of the iSD-AT model in section E-4.2, multiple data sources are used. Data sources relevant in this analysis for land use are the Environment Agency Austria emission inventory (Environment Agency Austria, 2024), for emissions we used data from Eurostat and also the national emission inventory of the Environmental Agency Austria. Economic data regarding GDP, production and employment are retrieved from Eurostat, yields and crop production from FAO. The analysis of agricultural water consumption and mineral fertilizer inputs is based on a combination of data sources and key drivers. Data on agricultural water consumption was obtained from the FAO AquaStat database, while information on the harvested area under irrigation in Austria was sourced from the 2021 report "Wasserschatz Österreich" (BMLRT, 2021). For mineral fertilizer inputs, data was sources from "Grüner Bericht 2024" (Bundesministerium für Land- und Forstwirtschaft, Regionen und Wasserwirtschaft, 2024). Historical trends in fertilizer prices, as reported by the USDA National Agricultural Statistics Service, indicate a slight increase over time with extreme price spikes in recent years. According to Brunelle et al. (2015), fertilizer prices are expected to continue rising, with all scenarios assuming a 2.5-fold increase in future prices.

E-4.4 Expert Workshop

In the course of this research project an expert workshop was held on 18.03.2025 at BOKU University. The workshop lasted four hours and 12 experts and stakeholders from administration and the scientific community with expertise in climate change adaptation in agriculture and/or the SDGs participated.

The first part included a short introduction of the research project and the modelling approach with a focus on the dynamics around irrigation and nutrient availability. Also, first preliminary model results were shown to validate and discuss with the participants.

The second half of the workshop was devoted to identifying potential impacts of single adaptation strategies on the progress of the SDGs. The aim was to obtain a model independent perspective and insights from experts. This enabled us to validate model findings and consider impacts that are not covered in the iSD-AT, due to the current model structure or due to this choice of modelling approach in general.

The participants were divided into three groups of four. Each group could choose one adaptation strategy from a list which was based on the Austrian climate change adaptation strategy with the option to also set a specific focus or make individual changes to it. All groups were provided with a flipchart sheet where all 17 SDGs were arranged in a circle. The adaptation strategy was to be placed in the center. The task was then to indicate impacts of this strategy on the SDGs with arrows and also to add causal explanations regarding this relation. The workshop was concluded with an open discussion round on the results found in the separated groups.

E-5 Results and Discussion

In the following chapters, first the modelling results are shown with a focus on trends and dynamics regarding the selected SDG related indicators. These results are first put in context with the current findings from literature and then also in context of the results from the expert workshop. The results from the workshop are described later in this section.

E-5.1 Modelling results

E-5.1.1 Impact on SDG indicators

This chapter analyses the impact of climate and policy scenarios on selected indicators and discusses influential variables for these results. The results show possible long-term future trends and scenarios. Especially in the agriculture sector, which is heavily depending on weather conditions, fluctuations in yield and economic output are to be expected based on historic data. These yearly fluctuations cannot be accounted for in simulation models such as the iSD-AT. Results are shown relative to the base year 2023. The impacts of the policy interventions relative to the underlying climate scenario are provided in the Appendix (see figures Abb. E-19: to Abb. E-27:).

Average yield in tonnes/ha and total crops production in tonnes/year

In general, figure Abb. E-4: shows an increase in the average yield per hectare in the counterfactual scenario compared to 2023 due to increasing productivity and capital input (counteracting the decreasing number of employees (as shown in Abb. E-12:), which contribute to a narrowing difference between achievable yield and actual yield. This increase, however, gradually levels off during the second half of the simulation period.

In both climate scenarios, the rise in average temperature leads to an increase in average yield compared to both the reference year and the counterfactual scenario. However, the figure only presents the average yield across the two crop types distinguished in the iSD-AT model. The positive effect of rising temperatures on potential yield is more pronounced for cereal crops, driving the overall increase in average yield. In contrast, non-cereal crops experience a decline in average yield, which ultimately results in a reduction in their total production under the climate scenarios (see Abb. E-17: and Abb. E-18: in the Appendix).

At the same time, reduced precipitation and the resulting drought pose challenges. In the dry climate scenario, the decrease of precipitation dampens the average effect of the temperature increase, as water limits the attainable yield. In this scenario, water consumption is increased heavily (see Abb. E-7:) and partly compensates for the limited water availability and affects a stabilization of the average yield especially in second half of the simulation period. Since this scenario does not take into account a limitation of water availability for irrigation, the effect of temperature increase on aggregate yield is potentially overestimated. At the end of the period Austria may thus also experience aggregate losses in crop yields in a dry climate scenario compared to the counterfactual scenario.

All policy scenarios have a negative impact on the average yield per area. An expansion of organic farming leads to the strongest decline. In the beginning of the simulation period, when organic farming has not yet been fully established, the increasing effect of temperature on average yields dominates. Afterwards the yield that can be achieved is limited by the availability of nitrogen. While mineral nitrogen fertilizers are used in the other scenarios to realize the increased yield potential compared to the baseline, this is not possible in organic farming. The increase in organic fertilizer and plants that can fix nitrogen is not enough to compensate for this loss.

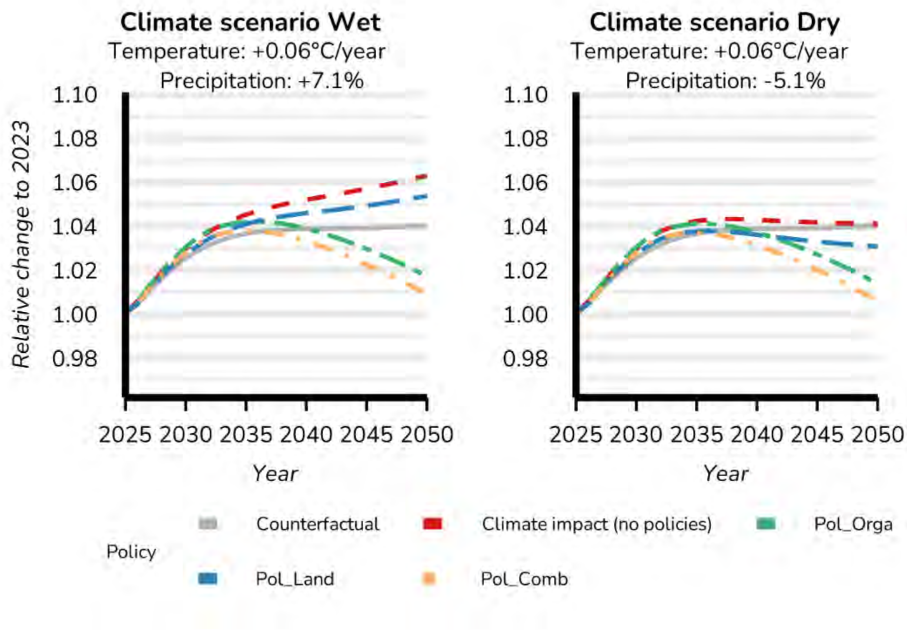

Abb. E-4: Impact on the indicator "average yield in tonnes/hectare".

The Pol_Land scenario also exhibits a decline in average yield per hectare compared to the climate scenarios, while in the wet scenario it is still increasing compared to 2023. The significant expansion of agricultural land in this scenario is not accompanied by a correspondingly substantial increase in nutrient or water availability, leading to reduced average yield per hectare compared to the climate scenarios without policies. However, in total, crops production can be significantly increased in the Pol_Land scenario as well as in the scenario with both measures combined. In the scenario Pol_Comb, the decrease in total crops production caused by the expansion of organic farming can be compensated.

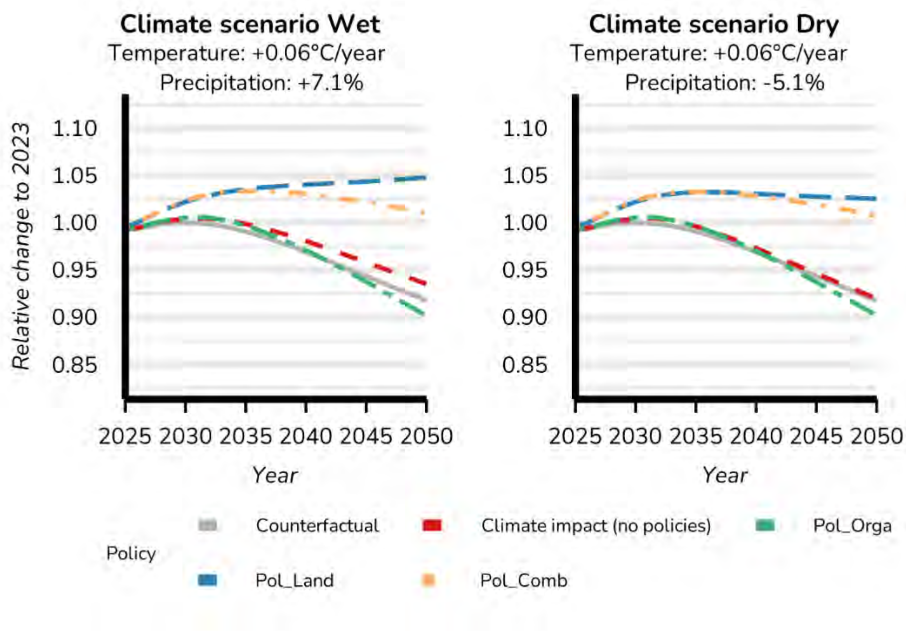

Abb. E-5: Total crops production in tonnes/year.

Irrigated cropland

One key factor influencing potential yield is the extent to which water demand can be met, which is highly dependent on the underlying climate scenario. The development of irrigation is mainly driven by two variables: On the one hand, the change in the average temperature determines the potential yield and water demand. On the other hand, the water availability for crops, mainly influenced by precipitation, determines whether water is a limiting factor. In such a case, the irrigated areas are expanded. Compared to 2023, irrigated cropland increases in all scenarios. The counterfactual scenario shows the trend of an increase in irrigated area, as irrigation is further expanded where water is currently scarce and also average yield per hectare increases due to productivity gains.

With respect to the different climate scenarios, the driving factor here is the development of precipitation as can be seen in comparing both climate scenarios. The average precipitation decreases in the dry climate scenario which causes irrigated cropland to increase by nearly 15% compared to 2023. In the wet climate scenario, precipitation increases, which leads to less irrigated land compared to the counterfactual The trend of all policy scenarios in this scenario suggests that the irrigated area reaches a balance by the end of the simulation period, stabilizing at a level slightly above that of 2023.

In contrast to the different climate scenarios, irrigated cropland is hardly influenced by the different policy scenarios.

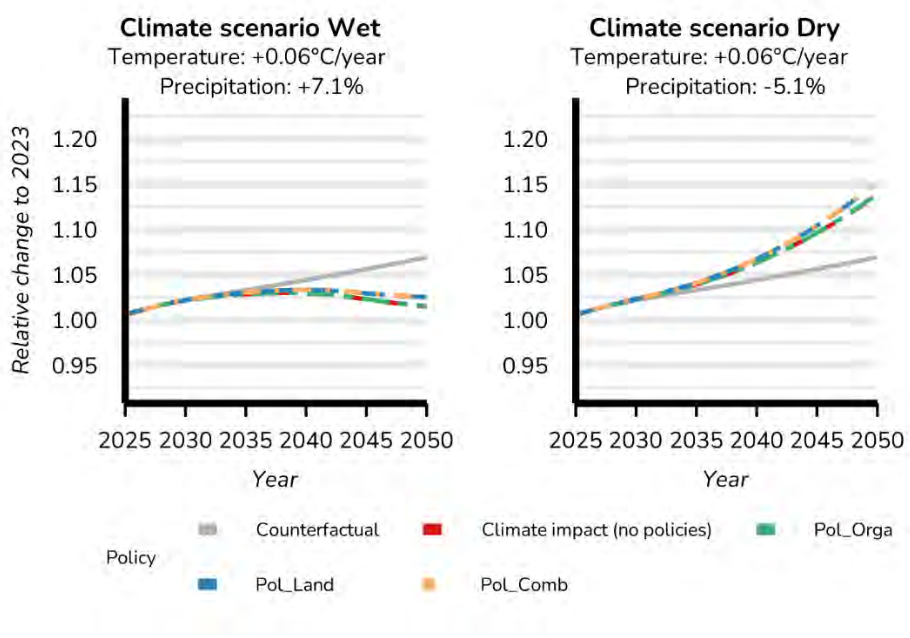

Abb. E-6: Impact on the indicator "irrigated cropland".

Water consumption for irrigation

Accordingly, the trends regarding the development of the irrigated area also have an impact on water consumption in agriculture. Compared to 2023, water consumption increases the most in the dry climate scenario by over 15%. In the wet climate scenario water consumption increases compared to 2023, but it is below the counterfactual[2].

[2] As the model structure currently does not take dynamics of evapotranspiration into account, the water consumption for irrigation in the climate consumption might be underestimated.

With regard to the policy scenarios, water consumption reacts primarily, but also only slightly, to changes in agriculture land. In scenario Pol_Land, which restricts land use, water consumption increases by around 1% compared to a scenario without this measure.

The future scenarios of water consumption as well as irrigated cropland are strongly influenced the model assumption that sufficient water is always available for irrigation. This assumption neglects potential water use conflicts, which may arise at regional and local levels.

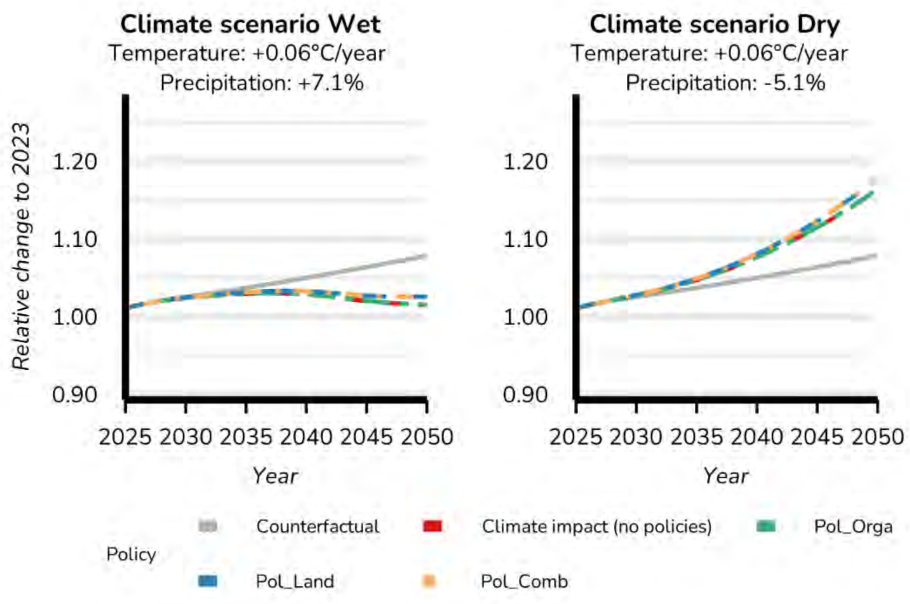

Abb. E-7: Impact on the indicator "water consumption for irrigation".

Use of mineral nitrogen fertilizer per hectare

Nutrient availability plays a role as a further possible limitation to achieving the potential yield. Nitrogen fertilizer use has been declining in recent years, which has been attributed to rising energy prices (Jandl et al., 2024). The price of mineral nitrogen fertilizers is expected to continue to rise in the future (Brunelle et al., 2015). This counteracts other influences that increase the use of fertilizers such as the increased yield potentials due to temperature increase which is observable in both climate scenarios in comparison to the counterfactual scenario without climate change. Mineral nitrogen fertilizer consumption per hectare increases by up to 3 % compared to 2023.

The most pronounced effect on mineral fertilizer use has the complete transition to organic farming until 2050, as no more mineral fertilizers will be used. Further impacts relate to the average yield per hectare as shown above, but also to employment and greenhouse gas emissions which is shown below. Although the preservation of agricultural land has an absolute effect on the use of fertilizers, it is constant in relation to the total area.

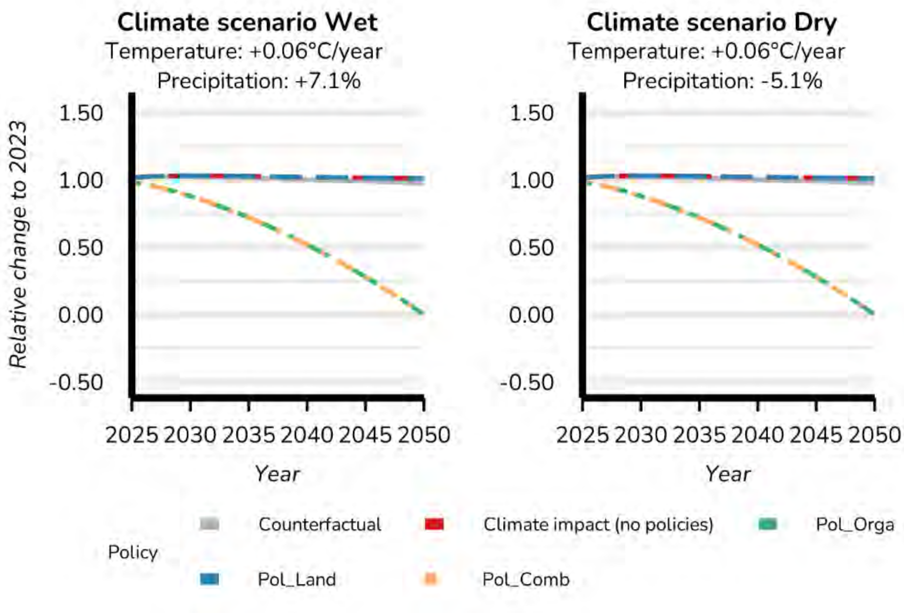

Abb. E-8: Impact on the indicator "use of mineral nitrogen fertilizer per hectare".

Natural input of nitrogen in tonnes/year

For both climate scenarios, no clear trend is observed in the natural nitrogen input, which encompasses nutrient contributions from manure application, biological fixation, nutrient deposition, and sedimentation. The values remain relatively stable around the 2023 level, with a slight increase until 2035, which is true for the underlying counterfactual scenario as well as the climate scenarios.

The transformation to organic farming has a significant effect on the use of mineral fertilizers. While the transformation progresses gradually, the reducing effect is initially moderate and more pronounced towards the end of the simulation period. The nutrient availability here amounts to manure application and natural nitrogen input such as nitrogen fixation by plants. Although the available nitrogen from these sources increases with the full adoption of organic farming, it is not sufficient to compensate for the reduction from mineral fertilizer. Since more manure is produced in scenario Pol_Land due to the preservation of agriculture land and an increasing effect also on livestock production, this policy also has an increasing effect on the availability of nitrogen. Thus, the two measures together lead to a more pronounced effect.

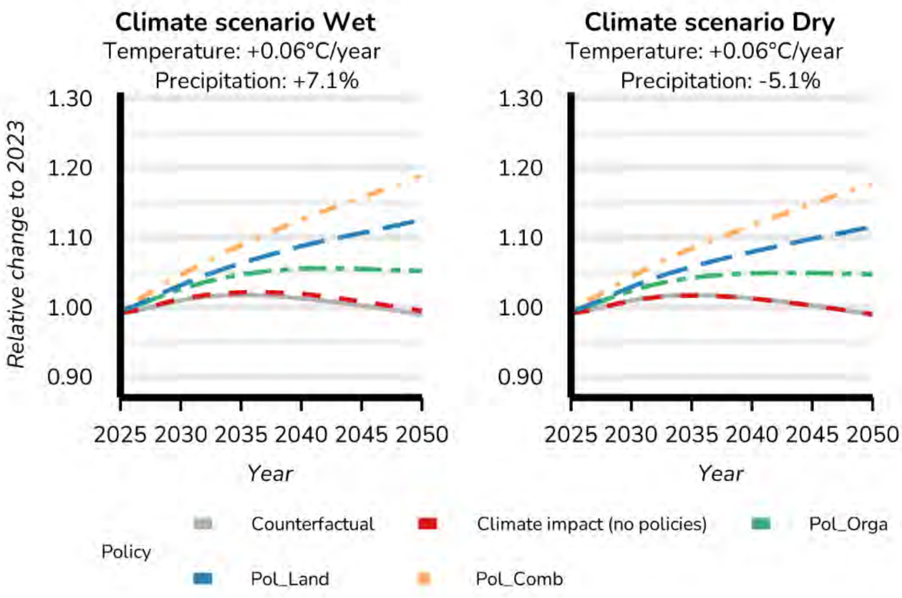

Abb. E-9: Impact on the indicator "natural nitrogen input" in tonnes per year.

Agriculture land

The development of agriculture land continues the decreasing trend of the past as shown in the counterfactual scenario, regardless of the climate scenario. This decline is mainly driven by the expansion of settlement area for buildings and infrastructure, such as roads, but also by reforestation. With increasing population and economic output, this land pressure continues to increase. By 2050, agricultural land will decline by more than 10% compared to 2023.

The trends in the two climate scenarios do not differ significantly. The more the yield per hectare increases, the less agricultural land is needed, which is why the area in all policy scenarios in the wet climate scenario decreases slightly more than in the dry climate scenario.

The measure of expanding organic farming also increases the agricultural area, as less agricultural land is lost due to degradation. Compared the scenario Pol_Land, however, the effect is small. In this policy scenario, the conversion of agriculture land to settlement land is exogenously limited, which means that the agricultural area will remain almost constant compared to 2023. This weakens the land pressure on agriculture, which shows to dominate the increasing effect of organic farming on agriculture land.

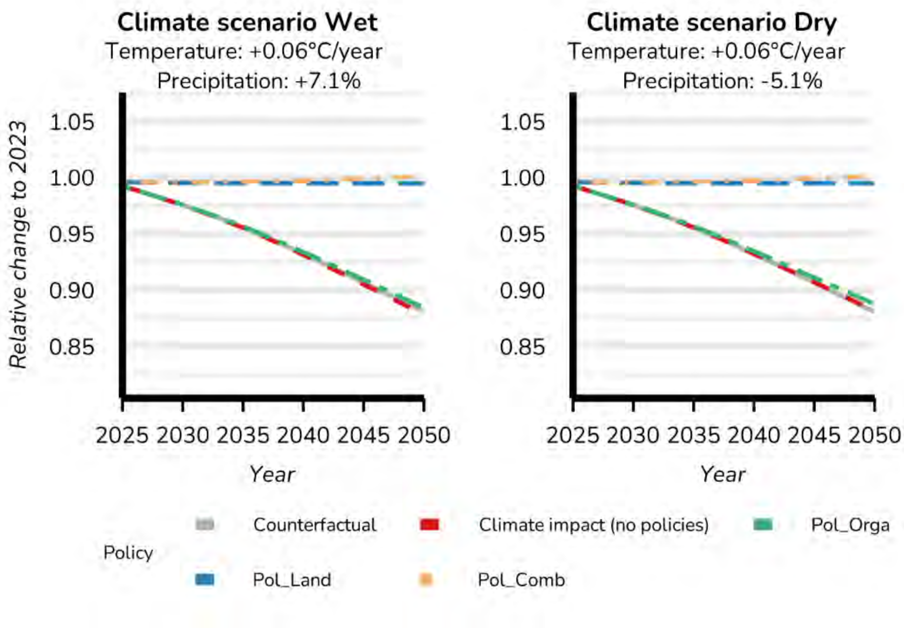

Abb. E-10: Impact on the indicator "agriculture land".

Real GDP Agriculture

Real GDP in the agriculture sector, as shown in the counterfactual scenario, reflects a general trend influenced not only by crop production but also by other parts of the agricultural sector, such as livestock production and forestry. However, in both climate scenarios, real GDP is lower compared to the counterfactual scenario. While rising temperatures in both scenarios lead to an overall increase in total crop production, the two crop types respond differently to the temperature changes (see Abb. E-17: and Abb. E-18: in the Appendix). This results in a shift in the composition of total crop production towards cereal crops. Since non-cereal crops are associated with higher economic output per tonne, this shift negatively impacts real GDP. In the dry climate scenario, real GDP is further lowered by the limitation of water and the need to expand irrigation.

With regard to the effect of the different policy scenarios, the preservation of agricultural land leads to an increase of around 10%. Despite the decline in yield per area, the expansion of organic farming has only a slightly negative impact, since the decline in yield is counteracted by an expansion of agriculture land and lower input costs for mineral fertilizers.

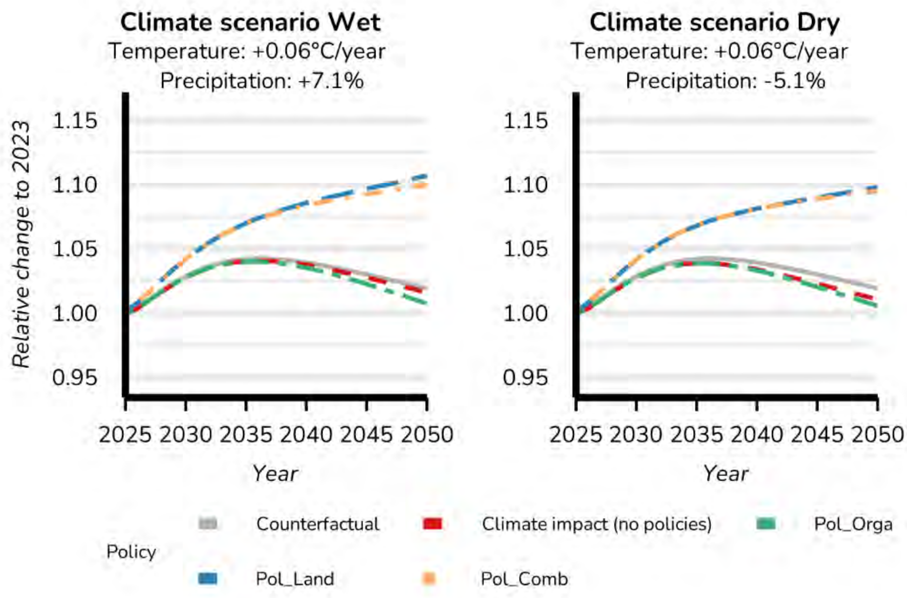

Abb. E-11: Impact on the indicator "real GDP in the agriculture sector".

Employment in Agriculture

Although the historical trend of a declining number of people employed in the agricultural sector is expected to continue regardless of the climate or policy scenario, policies demonstrate the potential to mitigate this trend: First, the expansion of organic farming leads to an increase in the workforce in the agricultural sector, as this type of farming is more labour-intensive. Secondly, the measure to preserve agricultural land also leads to higher employment compared to the baseline, due to a higher area to be cultivated given the ratio of labour input to available agricultural land. In these two cases, the effect can be observed regardless of the climate scenario.

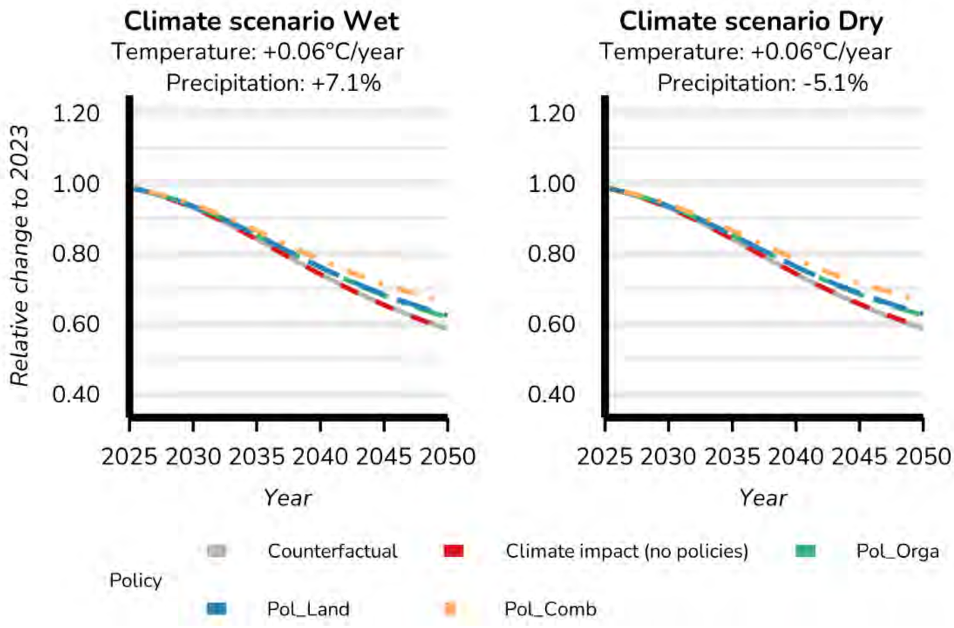

Abb. E-12: Impact on the indicator "employment in agriculture".

GHG emissions in the agricultural sector

The development of greenhouse gas emissions in the agricultural sector (excluding emissions from energy) is also influenced by different developments: In both climate scenarios, emissions are only slightly above the counterfactual scenario, but showing the same trend. The increase in average yield due to higher temperatures and the resulting increased use of mineral fertilizer causes a slight increase in emissions.

A large part of these emissions can be attributed to the use of mineral fertilizers. Accordingly, emissions fall by roughly 10% compared to 2023 in all climate scenarios as a result of the switch to organic farming. The preservation of agricultural land without changing the type of cultivation increases emissions, on the one hand due to a higher total use of mineral fertilizers, and on the other hand also due to higher livestock production. Implemented together, these two policies counteract each other and finally do not lead to significant changes compared to the climate scenario without policies.

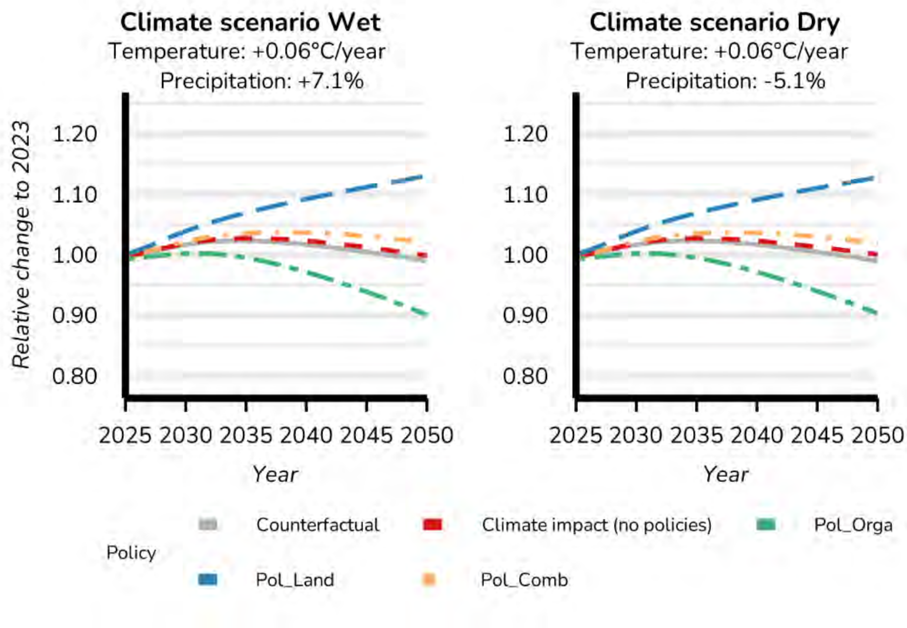

Abb. E-13: Impact on the indicator "GHG emissions in the agricultural sector".

E-5.1.2 Sensitivity analysis

Use of mineral nitrogen fertilizer per hectare

The modelling results have shown that the main impacts in this analysis on the consumption of mineral fertilizer per hectare relate to the change in potential yield caused by an increase in temperature and to the change to organic farming. It is assumed in the model that the use of mineral fertilizer is reacting to changes in prices[3]. Therefore, the results are strongly impacted by the scenario assumptions of further increasing prices in the future. The figure below shows different scenarios of price development and their impacts on the results regarding two wet climate scenarios (no policy and policy Pol_Orga). If the price stays constant compared to the level in 2023, then the reference fertilizer consumption increases compared to the original scenario due to the increase in potential yield and resulting intensification (price scenario p1). The strongest increase in fertilizer consumption, is achieved with the assumption of a decreasing price by 6 % (price scenario p0.94). Assuming a stronger price increase than in the reference scenarios lowers the fertilizer consumption compared to 2023 which will have further implications on economic indicators such as real GDP as well as on environmental indicators such as GHG emissions as described above.

Regarding the impact of varying prices for mineral nitrogen fertilizer in a scenario involving the expansion of organic farming, the price level does not affect the final outcomes in 2050, when agriculture is fully organic. However, lower fertilizer prices intensify the dynamics that counteract the reduction in mineral fertilizer use, leading to a steeper decline before 2050. This is illustrated by the red line (price scenario p0.94) in the figure on the right, which represents the lowest price compared to the other scenarios and is also lower than the price level in 2023.

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[3] Although the elasticity of the mineral fertilizer consumption is only small with -0.1678.

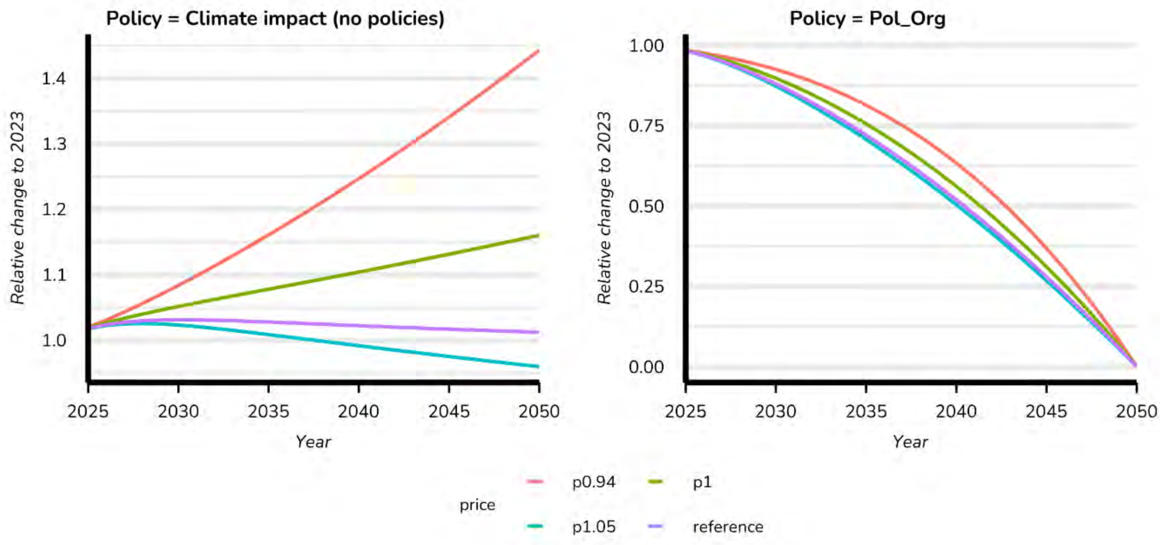

Abb. E-14: Impact of assumptions on future relative change in mineral fertilizer price compared to 2023 on mineral nitrogen fertilizer consumption per hectare.

Impact of the assumption of increasing potential yields due to temperature increase

The elasticities of potential crop yields, without considering water or nutrient availability, to warming are derived in the calibration processes. As they only distinguish between two crop types, these elasticities are highly uncertain, while they have important influences on the modelling results. The following figures show the results of different scenarios and indicators, for which in the section above the change in temperature has been identified as an important driver, without the temperature effect on potential yields (i.e. the elasticity is assumed to be zero for the future simulation period).

Regarding the indicator for average yield per hectare, the results show that the assumption on positive impact of temperature increases (on average) on potential yield cause an upward lift compared to the scenarios without this effect. However, the overarching trend is not affected. The same is true also for the development of irrigation water withdrawal and mineral fertilizer consumption.

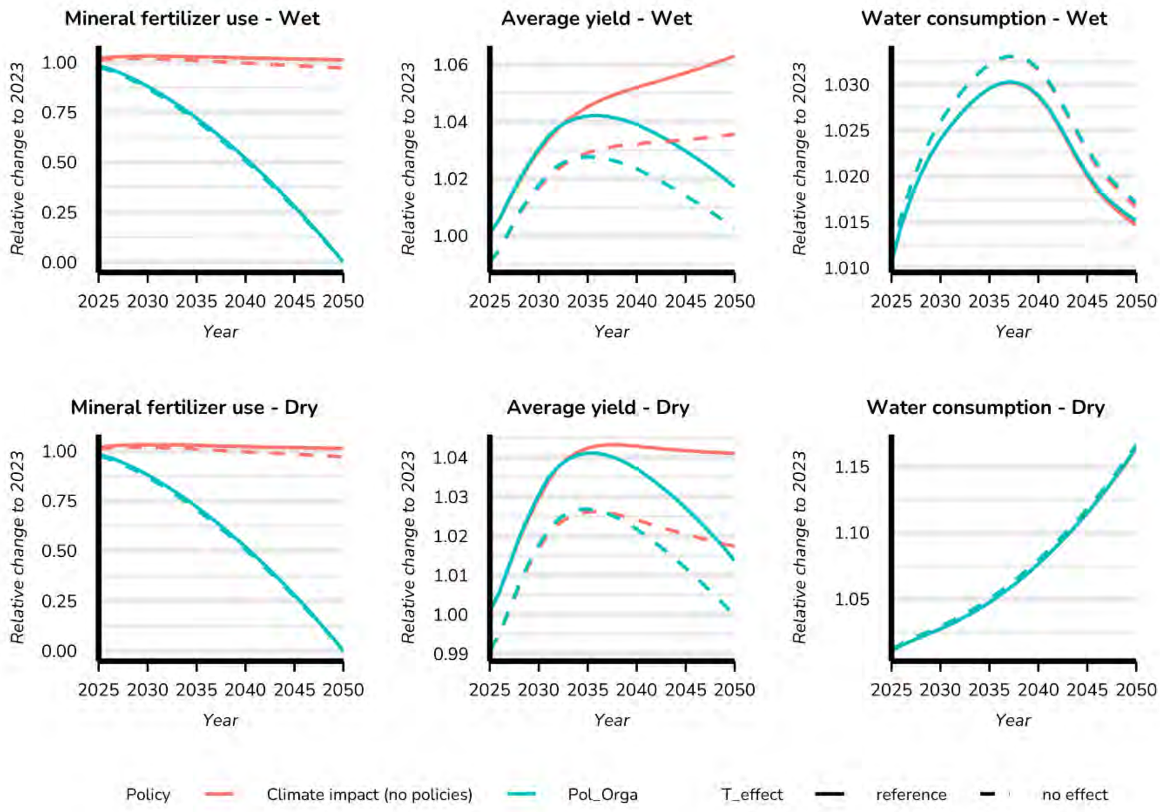

Abb. E-15: Impact of the assumption on the temperature effect on potential crop yields.

E-5.1.3 Comparison of modelling results with existing literature

Average crop productivity increases in the light of climate change. In the best-case scenario, crop yields are found to increase between 3-6%. In the most pessimistic scenario yields actually decrease by up to 3% (Schönhart et al., 2014). Irrigation was identified as an adaptation strategy that can compensate for negative yield impacts, however, the potential for profit varies by region, with already dry areas experiencing negative impacts on yields (Schönhart et al., 2014). Also Kirchner et. al (2016) and Mitter et al. (2015) support this results: Their findings suggest that favorable areas are likely to experience intensified land use, while marginal regions may undergo extensification. Intensification is associated with negative environmental impacts, whereas extensification can lead to positive effects, particularly regarding nitrogen and greenhouse gas emissions.

The literature indicates that organic farming in Austria generally results in lower yields compared to conventional agriculture, with reductions ranging from 27% to 49%, depending on the crop type and region (Brückler et al., 2018). Despite this, organic farming often achieves higher monetary returns due to lower expenditures on fertilizers and pesticides, subsidies, and premium market prices (Jandl et al., 2024). In the iSD-AT model results, the observed decrease in average yield for organic farming is relatively modest compared to findings in the literature. This is likely because the analysis primarily focuses on the impact of not using mineral fertilizers, while other factors, such as pesticide use and changes in management practices, are not considered. Furthermore, the model results only account for the positive monetary effects of reduced mineral fertilizer use, without factoring in other potential influences, which might explain why the real GDP in agriculture shows to be slightly lower than in the climate scenario (see Abb. E-11:).

Compared to the iSD-AT model results, literature findings suggest a stronger impact of future climate change on irrigation: A study on agricultural irrigation scenarios projects that irrigated areas could expand by 57% to 63% by 2050 compared to current levels, depending on the climate scenario. Correspondingly, water consumption for irrigation is expected to increase by 65% to 70% (BMLRT, 2021). The analysis by Mitter & Schmid (2019) examines more severe reductions in precipitation and increased drought occurrences compared to the analysis in this report. Their findings reveal that multi-seasonal dry spells in Austria lead to a significant shift from rain-fed to irrigated agriculture, particularly in the semi-arid eastern regions, with the share of irrigated cropland increasing substantially under moderate and severe dry spell scenarios. This shift results in a 3- to 6-fold increase in irrigation water use under more extreme conditions.

E-5.2 Results from the expert workshop

In the group work of the expert workshop, the following three climate change adaptation strategies with focus on agriculture were selected from the current Austrian adaptation strategy:

- Adaptation of agricultural management (conservative vs. organic farming),
- Sustainable management, restoration and conservation of soil, and
- Evaluation of the site suitability of crops and cultivation of climate-adapted crops.

An overview on the identified impacts is shown in Tab. E-3:. The results revealed that these strategies have implications for nearly all Sustainable Development Goals (SDGs), except for SDG14 ("Life below water"), SDG16 ("Peace, justice and strong institutions") and SDG17 ("Partnerships for the goals"). Also, all strategies had in common to enhance efficiency in the use of resources such as water use for irrigation, fertilizers or pesticides. However, the findings also highlighted certain dynamics that may work in opposing directions, leaving uncertain which effects will ultimately prevail.

The workshop highlighted that significant environmental impacts are associated with the use of pesticides, water, and fertilizers. These inputs influence energy consumption, greenhouse gas emissions, and biodiversity. A more sustainable use of these resources can contribute positively to achieving Sustainable Development Goals (SDGs) such as SDG 6 (Clean Water and Sanitation), SDG 13 (Climate Action), and SDG 15 (Life on Land). All three strategies discussed during the workshop promote more sustainable land management, for example, by adapting crops to changing climatic conditions or improving soil quality, which enhances water retention capacity.

The socio-economic impacts of sustainable agriculture were also a key focus. Income security was identified as a critical factor in reducing vulnerability to climate impacts. However, yield losses may occur as a result of transitioning to sustainable agricultural practices. Other socio-economic considerations include the affordability of food, the potential for subsidies to explicitly promote women in agriculture, and the health benefits associated with sustainable practices.

Certain impacts remained ambiguous and require further investigation, as for instance, the effect of organic agriculture on food prices, affordability and inequality. Additionally, while climate-resilient crops offer significant potential for synergies (e.g., reduced water and energy consumption, lower fertilizer and pesticide use, and decreased greenhouse gas emissions), there is also a risk of maladaptation. Intensified agriculture or the cultivation of crops in less suitable locations could lead to increased resource use.

The discussions also addressed land-use conflicts and yield effects in the context of sustainable resource use strategies. In agriculture, yield losses may occur if land is repurposed or no longer used for farming. However, long-term improvements in soil fertility could lead to increased yields, which is particularly important from an intergenerational perspective. Land-use conflicts were found to intersect with several SDGs, including SDG 7 (Affordable and Clean Energy) in the context of renewable energy generation, SDG 8 (Decent Work and Economic Growth) and SDG 9 (Industry, Innovation, and

Infrastructure) in relation to economic performance and industrial location, and SDG 11 (Sustainable Cities and Communities) in terms of housing and housing prices.

Tab. E-3: Overview of the impacts identified in the group work and the following discussions

	Adaptation of agricultural management	Sustainable management, restoration and conservation of soil	Evaluation of the site suitability of crops and cultivation of climate-adapted crops
SDG 1	Increase in food expenditure (depending on market effect and subsidies)	-	Fewer harvest losses, resulting in more affordable food and secure income in agriculture
SDG 2	Less yield per hectare, impacting food security; change in diets	Increasing soil fertility improving food security (especially for future generations)	Fewer harvest losses and higher food security
SDG 3	Change in diets improves health	-	Less use of pesticides; if cultivation on less suitable sites is aspired then higher use of pesticides and negative health effects
SDG 4	Better quality of education leads to more sustainable farming practices	Education for sustainable development is stepped up to increase the connection to agriculture	Research is stimulated
SDG 5	In the course of subsidies for organic farming, support for especially women (and their adaptation) can be encouraged	-	Subsidies can be designed to especially support advanced training for women
SDG 6	Water resources are less polluted, as organic N2 is less harmful and easier to dose	Increasing the buffer function of the soils	Less water use, less pesticides and less fertilization are needed; but higher yield expectation increase the use (more use of water, pesticides and fertilizers)
SDG 7	-	Conflicts are caused with the use of land for the production of bioenergy; but innovative approaches such as agri-PV are stimulated	Less use of resources as energy; but higher yield expectation increases the use

SDG 8	More labour input in agriculture is needed; working conditions are questioned	By avoiding deterioration of agricultural land, income losses are prevented	Less harvest losses increase the security of income
SDG 9	-	Causes conflicts with industrial sites; but stimulated new approaches to ease conflicts such as facade or roof greening	Stimulates innovation
SDG 10	Food becomes more expansive which increases inequality	-	Expansion of genetically modified plants benefit mostly large firms
SDG 11	Promotes the formation of cooperatives	Aim for more green spaces leads to denser settlement and the use of vacancies; but less available settlement land leads to higher housing prices	-
SDG 12	Promotes circular economy approaches	-	-
SDG 13	Less resources are needed per tonne of yield	Prevents the loss of agriculture land and can help for climate change adaptation in order areas such as flood protection	Less resources are needed per tonne of yield
SDG 14	-	-	-
SDG 15	Soil biodiversity increases; reduced tillage (but use of pesticides might increase)	Higher capability to retain nutrient and buffer function improves the habitat for animals	Use of resources decreases which supports biodiversity conservation
SDG 16	-	-	-
SDG 17	-	-	-

E-5.3 Discussion of modelling and workshop results

Impacts on the SDGs

Figure E-16 summarizes the impacts of climate and policy scenarios on the Sustainable Development Goals (SDGs) based on the iSD-AT model results. The indicators were assigned to the SDGs as outlined in section E-4.3.2. For cases where multiple indicators were associated with the same SDG, an equally weighted average was calculated.

The figure highlights that especially SDG6 and SDG8 face significant challenges across all scenarios. For SDG6, these challenges are primarily driven by climate scenarios, particularly reduced precipitation and increased drought events. SDG2 relating to food security shows a slight improvement in some scenarios. However, it is negatively affected by organic farming, a finding that is also supported by the results of the expert workshop.

For SDG8, the progress is strongly influenced by the general trend of decreasing employment in the agricultural sector, although this decline is mitigated across all three policy scenarios. The group of experts who discussed organic farming during the workshop also agreed on this effect. While the other groups did not explicitly address the impact of their chosen adaptation strategies on employment, they identified a positive effect on income security in relation to SDG8, which could also suggest a potential positive impact on employment.

Progress on SDG13 was found to be slightly negatively affected by the assumptions on temperature and precipitation change in the two climate scenarios. This is mainly caused by the increase in mineral fertilizer prices that prevents a significant increase in fertilizer consumption following an increase in potential yield. While organic farming achieves progress regarding SDG13 due to the decrease in mineral fertilizer use and total agricultural production, this progress is offset by the additional policy intervention of maintained agricultural land.

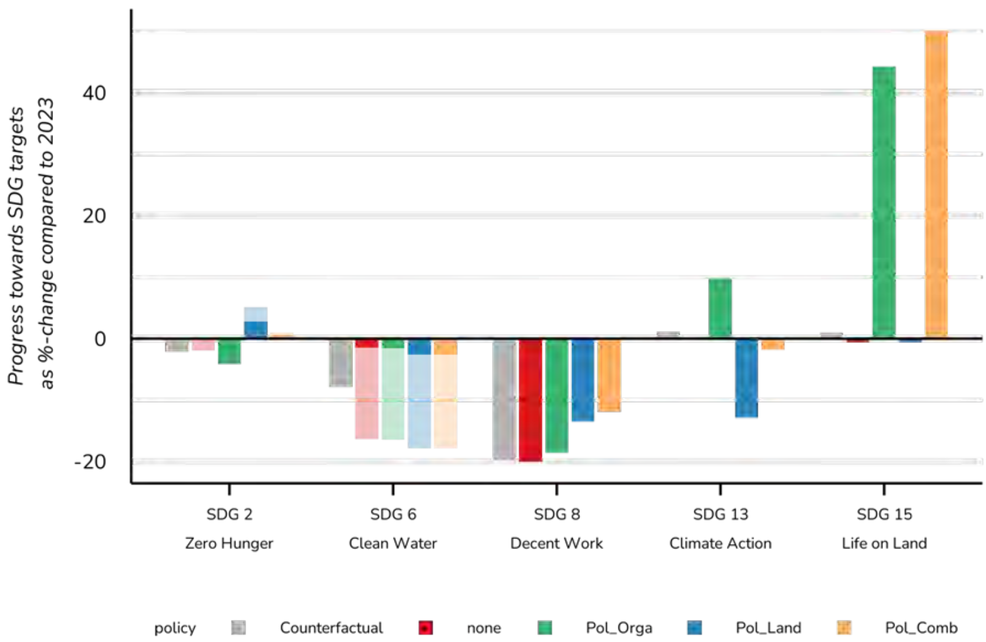

Abb. E-16: Modelling results on the impacts on the SDGs as indicated by the selected indicators. Different shades of colors show the different effect of climate scenarios.

Biodiversity

The loss of biodiversity globally and in Austria is critical in terms of both its scale and its pace (Jandl et al., 2024). Compared to other sectors, agriculture is especially connected to biodiversity and has been identified as one of the main drivers of biodiversity loss. With ongoing global warming biodiversity loss will further intensify. Therefore, it is of great importance to reduce negative impacts of land use and intensive agriculture on biodiversity.

In the context of climate change adaptation measures in Austria, several opportunities for synergies exist, such as in the case of biodiverse landscapes with crops adapted to the changing climate or hedges against wind and evaporation, extensively used areas or crop rotations (Jandl et al., 2024). These synergy effects were also emphasized in the workshop results, which advocate for increasing soil biodiversity, enhancing habitats through sustainable management and soil conservation, and reducing the use of mineral fertilizers and pesticides, all of which have a positive impact on biodiversity.

However, the iSD-AT model's highly aggregated structure limits its ability to fully analyse biodiversity, given the complexity of the topic. Also as the data availability is still insufficient in some cases, as for example on insects (Jandl et al., 2024), incorporating dynamics on biodiversity in such a quantitative and highly aggregated model is challenging[4].

However, certain dynamics that have been found as drivers of biodiversity loss can still be analysed with the model results, for example the use of mineral nitrogen fertilizer (see Abb. E-8:) or changes in average yield per hectare (see Abb. E-4:) indicating agricultural intensity.

Organic Farming

Organic farming is widely regarded in the literature as a promising strategy for achieving synergies between climate change adaptation and multiple SDGs (Jandl et al., 2024).

In addition to its positive impacts on biodiversity, the expert workshop identified numerous synergies that extend beyond those captured by the iSD-AT model: Positive impacts relate to SDG3 in the sense of changes in diets that lead to better health. Besides a lower need of water use for irrigation due to an improved water use efficiency, which supports progress on SDG6, the workshop participants also pointed out the positive impact of organic farming on the water quality.

Both the model and workshop results highlight synergy effects related to SDG13. While the iSD-AT model primarily captures the reduction in greenhouse gas emissions resulting from decreased mineral fertilizer use and lower overall agricultural production, workshop participants offered a broader perspective, emphasizing the reduced use of resources, including energy.

Despite these synergies, trade-offs were also identified. Both the iSD-AT model and the workshop results agree on lower yields per hectare and increased labor input associated with organic farming. In the iSD-AT model, dynamics around food prices and food affordability are not captured, so model results miss out on the important trade-off between organic farming and food affordability that was stressed in the expert workshop and relate to SDG1 (No Poverty) and SDG10 (Reduced inequality).

Irrigation and water consumption in agriculture

In the current iSD model structure, irrigation water consumption and the share of harvested area are endogenously increased responding to a shortage in water availability caused by a decrease in precipitation. The model results indicate a significant rise in irrigation water consumption, which could lead to regional water-use conflicts, although no general limitation on water resources is considered in the model. The Austrian climate change adaptation strategy highlights several approaches to address drought, including the implementation of efficient irrigation technologies that are both water- and energy-efficient (Bundesministerium für Klimaschutz, Umwelt, Energie, Mobilität, Innovation und Technologie, 2024).

While such interventions were not included in the analysis, they could reduce irrigation water consumption. However, referring to figure Abb. E-3:, these measures do not address the underlying feedback loop driving the expansion of irrigation systems. The adaptation strategy also emphasizes higher-leverage measures, such as sustainable soil management, crop rotations, and the adoption of drought-resistant crop types, to reduce vulnerability to droughts and precipitation variability.

Adaptation measures relating to crop rotations cannot be considered in the current iSD model structure, meaning important synergies associated with these measures are not captured. Expanding the model to include more detailed dynamics related to crop rotations could enable a more comprehensive analysis of these adaptation measures and their synergies. However, such an expansion would exceed the scope and purpose of the current model. A more feasible approach for future analyses would involve collaboration with sectoral models to incorporate their outputs into the iSD-AT framework.

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[4] The original UN indicator on biodiversity loss which is part of SDG15 would be the "Red-list-index". On a national level, the Statistics Austria applies the "Common Farmland Bird index" to assess progress on the target on biodiversity loss.

Regionalisation

The iSD-AT model results are also influenced by its lack of regionalization, which is particularly relevant for climate change adaptation in agriculture. Regional differences influence, for example, the climate change impact on average yield or the expansion of irrigation as an adaptation strategy. As the model focuses on national-level dynamics, it does not account for regionally specific climate change impacts or adaptation options. Similarly, synergies and trade-offs may be more pronounced at the regional level than indicated by the model results. Despite these limitations, the model still provides valuable insights into trends that may be observable in certain regions.

E-6 Conclusion

This study underlines the importance of macro-level modelling approaches, such as the iSD-AT model, for analyzing the complex dynamics of climate change adaptation measures and their interactions with the Sustainable Development Goals (SDGs). By focusing on cross-sectoral interactions and feedback loops, the iSD-AT model provides a broader, aggregated perspective that complements more detailed, sector-specific models. However, the findings highlight the need to further enhance the model's capabilities and explore new applications to better address the systemic nature of climate change adaptation.

The findings from the iSD-AT model and the stakeholder workshop provide valuable insights into the systemic impacts of climate change adaptation measures, highlighting both synergies and trade-offs across multiple SDGs. For instance, organic farming was shown to generate synergies with SDG13 (Climate Action) by reducing greenhouse gas emissions through decreased mineral fertilizer use and lower overall agricultural production. It also supports SDG6 (Clean Water and Sanitation) by improving water quality and reducing irrigation needs, while enhancing biodiversity. However, both the model and the workshop results emphasized trade-offs, such as lower yields, which could negatively impact food security (SDG2) and affordability, with potential implications for SDG1 (No Poverty) and SDG10 (Reduced Inequalities). These trade-offs underscore the need for complementary strategies to mitigate adverse effects, such as addressing food price increases.

While the iSD-AT model intends to analyse systemic interactions, its aggregated structure limits its ability to provide detailed, sector-specific insights, such as biodiversity dynamics or regional climate impacts. These limitations could be addressed through integrated model coupling, where results from detailed, bottom-up models are integrated with the iSD framework. Such an approach would combine the strengths of detailed sectoral models with the systemic perspective of system dynamics and enable a more differentiated analysis of climate change adaptation strategies and their region-specific impacts.

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E-8 Appendix

E-8.1 Further modelling results

The following figures show the impact of the different policy scenarios on total crop production differentiated by crop type:

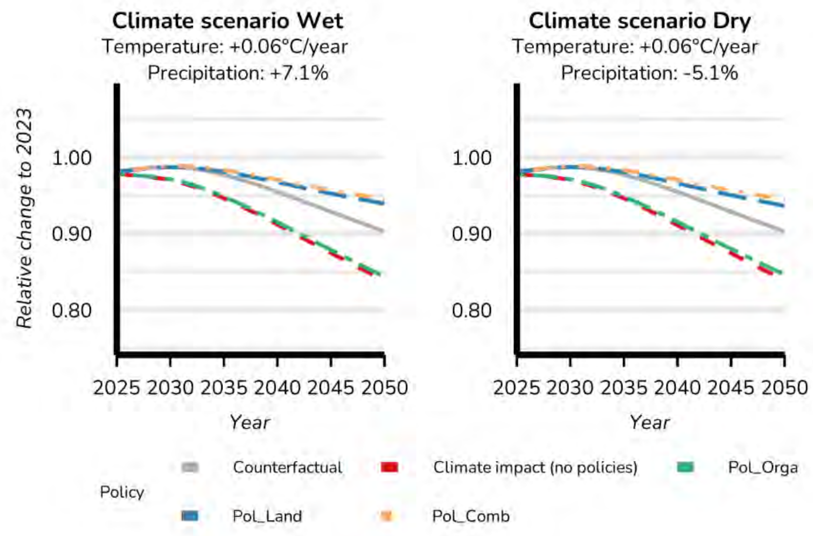

Abb. E-17: Total crop production in tonnes/year of crop type 1 (non-cereal crops)

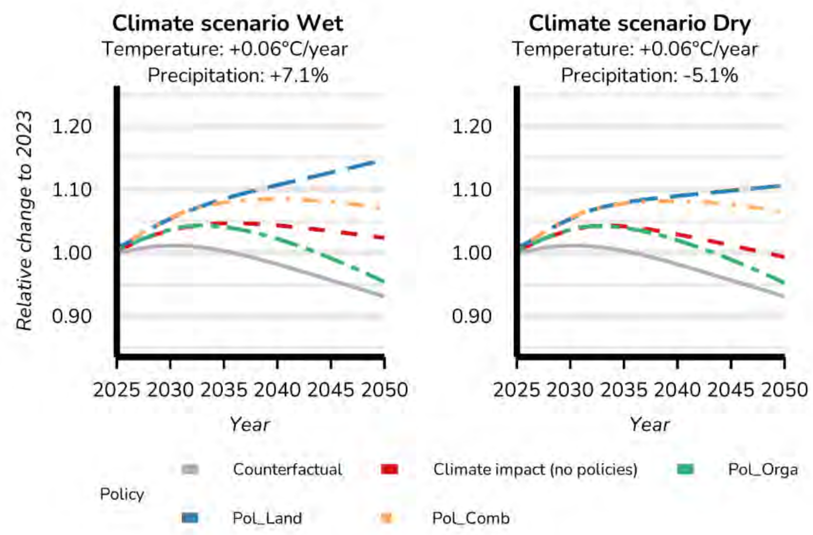

Abb. E-18: Total crop production in tonnes/year of crop type 2 (cereal crops)

The following figures show the impact of the three policy scenario compared to the underlying climate scenario:

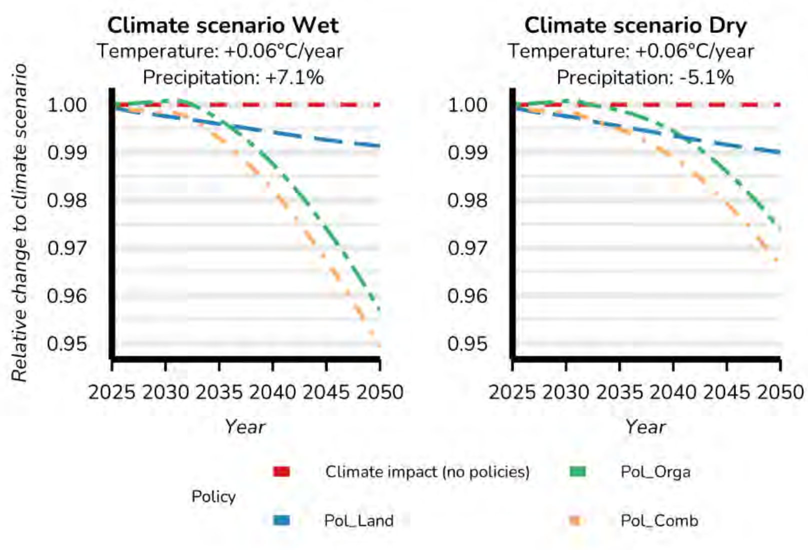

Abb. E-19: Average yield per hectare

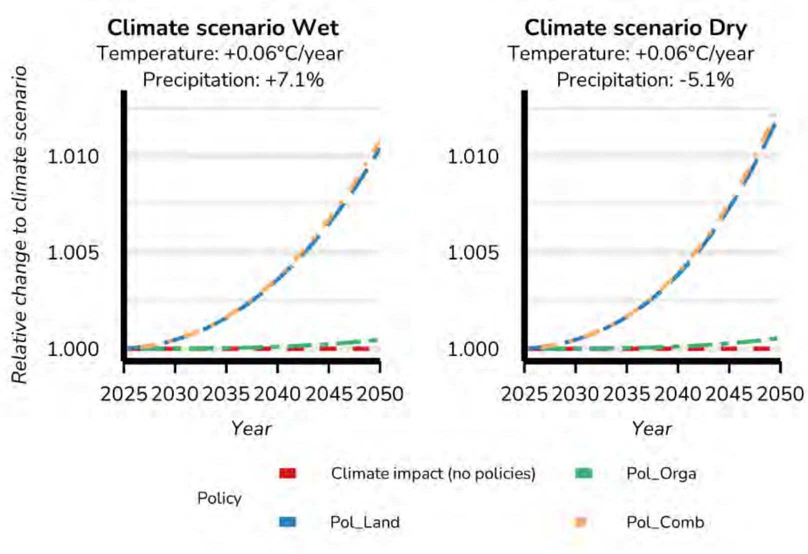

Abb. E-20: Irrigated cropland

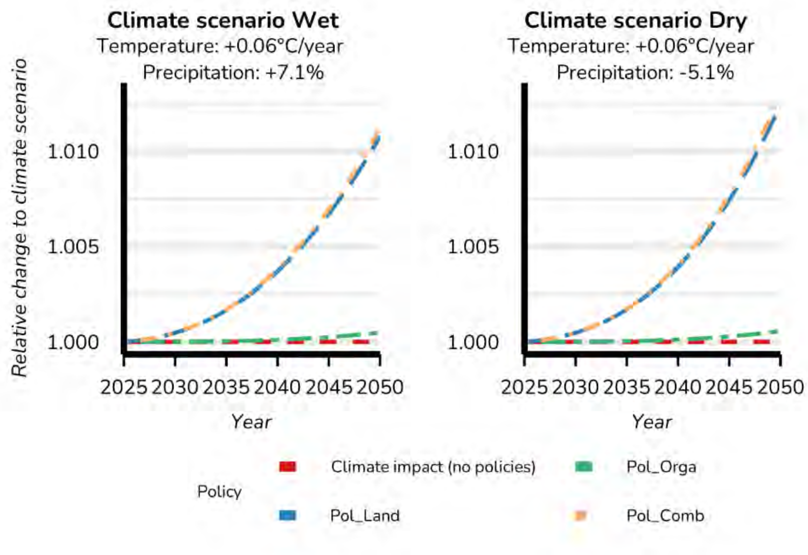

Abb. E-21: Water consumption for irrigation

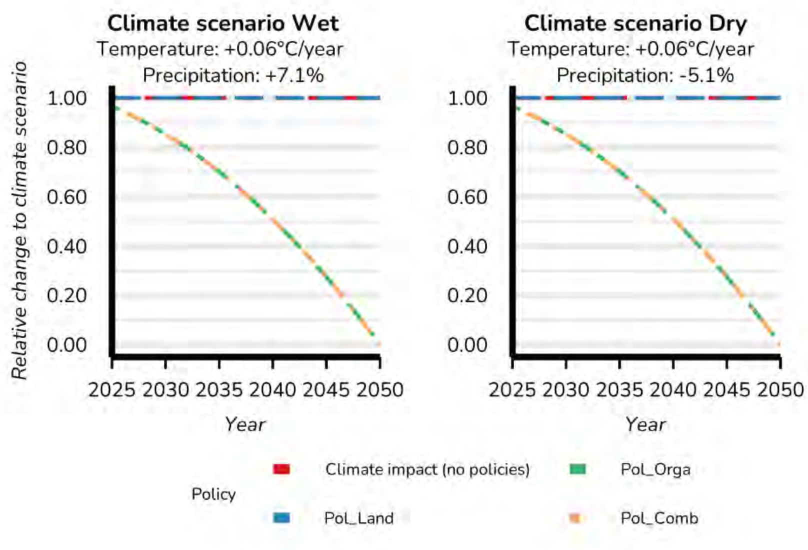

Abb. E-22: Consumption of mineral nitrogen fertilizer per hectare

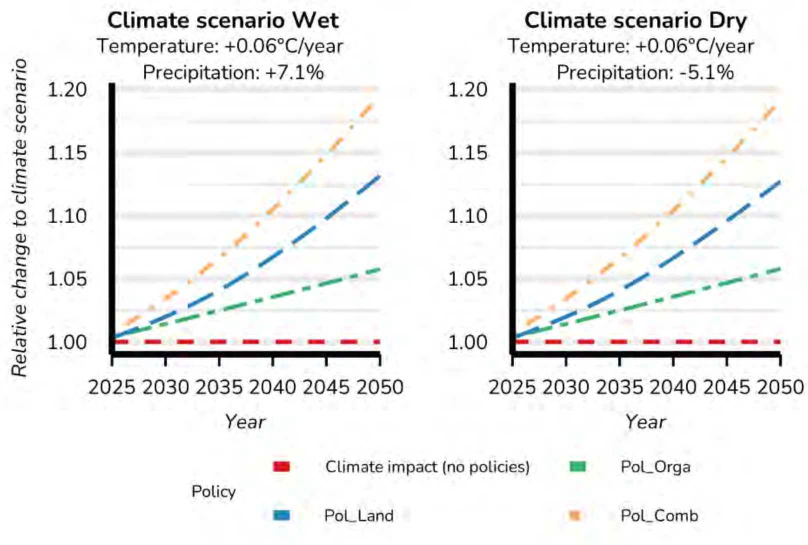

Abb. E-23: Natural nutrient availability

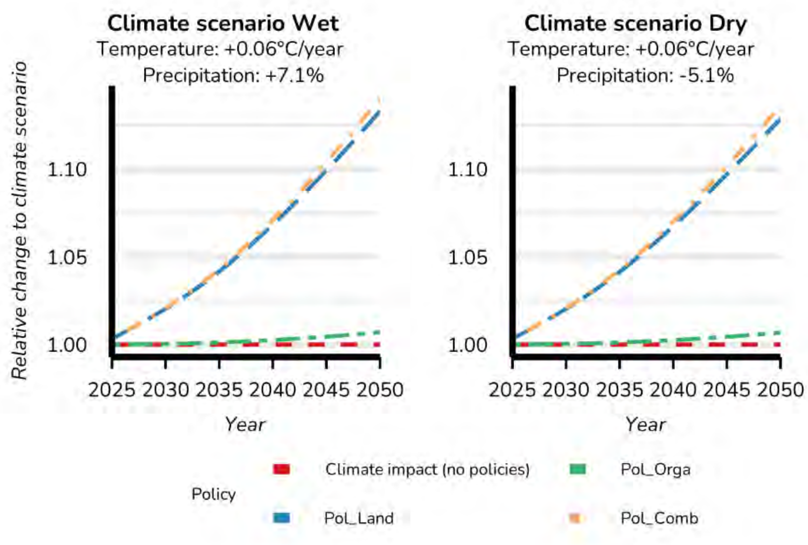

Abb. E-24: Agriculture land

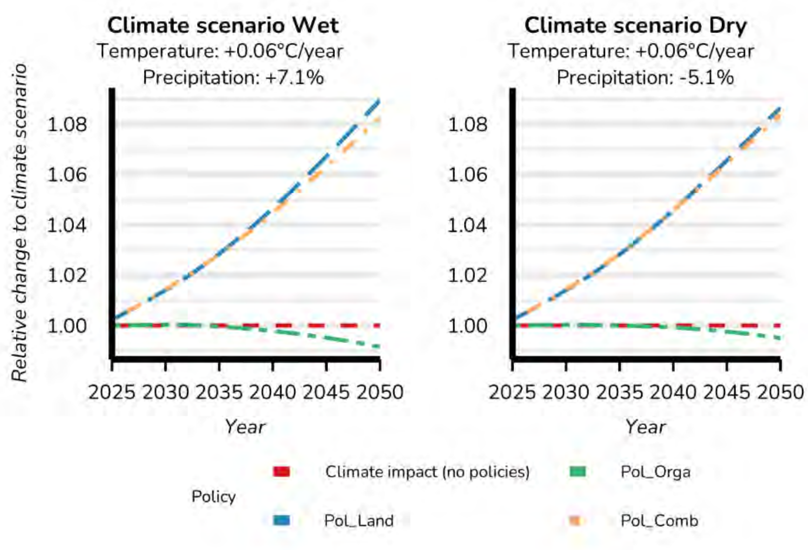

Abb. E-25: Real GDP Agriculture

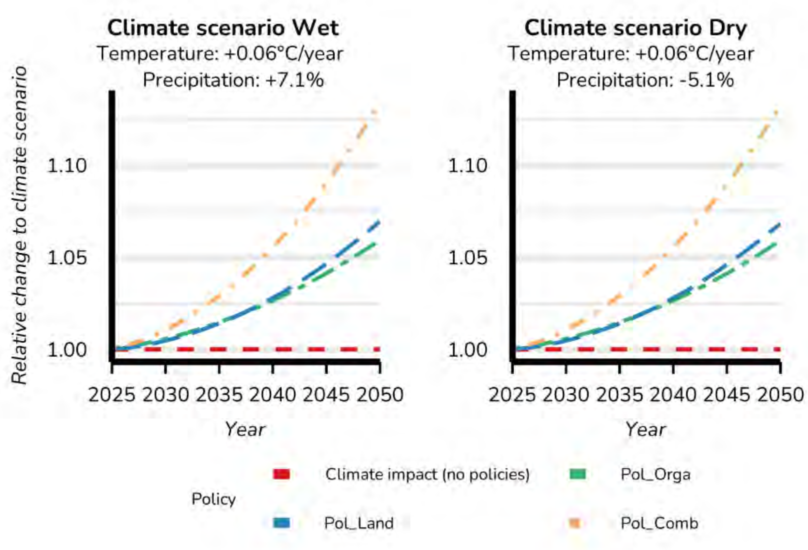

Abb. E-26: Employment in agriculture

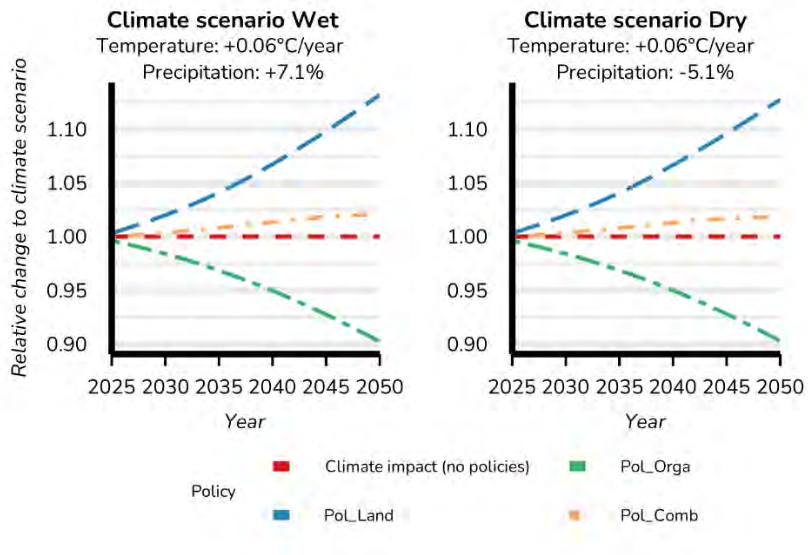

Abb. E-27: Greenhouse gas emissions in the agriculture sector

E-8.2 Expert workshop - results

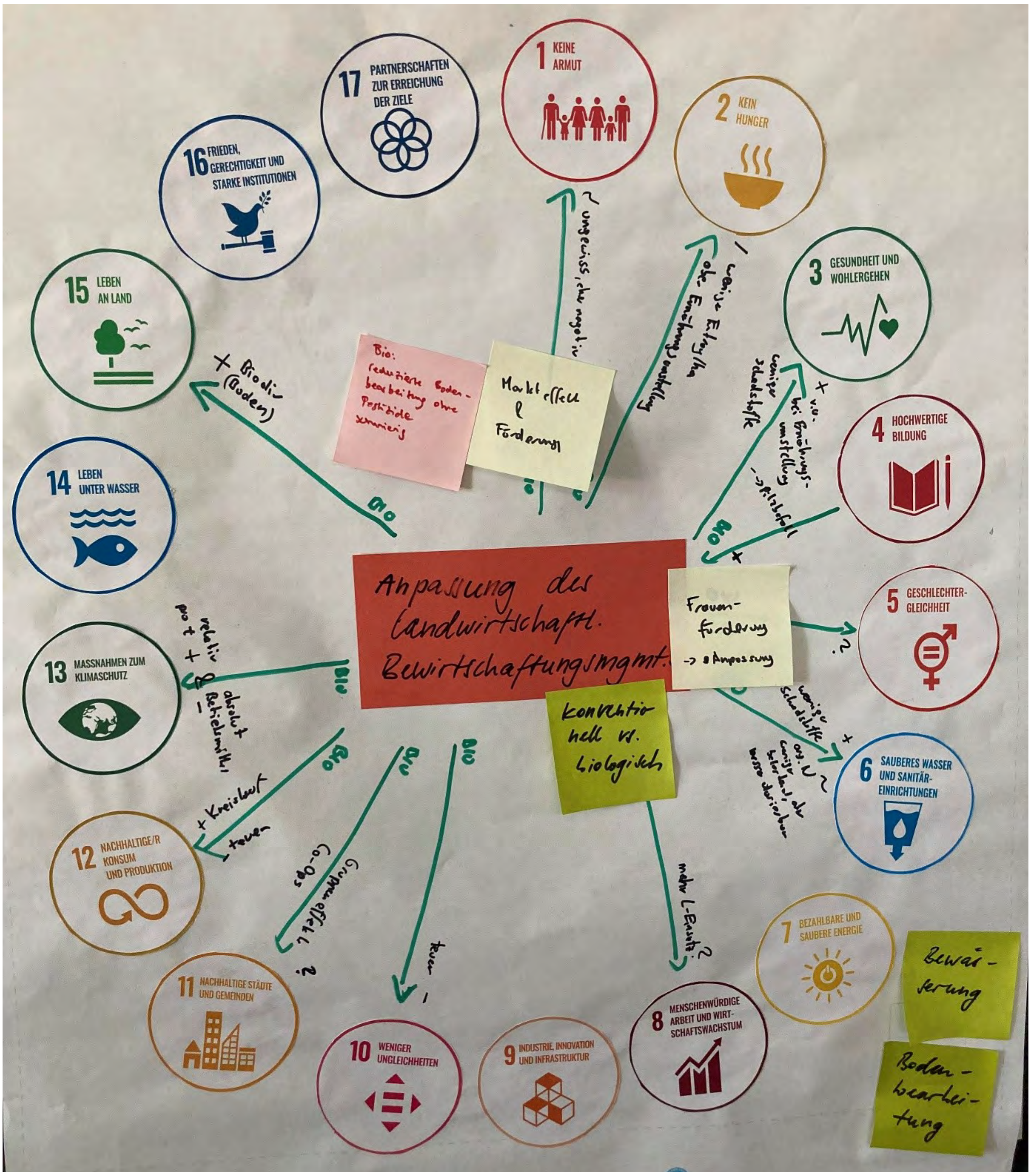

Abb. E-28: Result from group "Anpassung des landwirtschaftlichen Bewirtschaftungsmanagements (konventionell vs. biologisch)

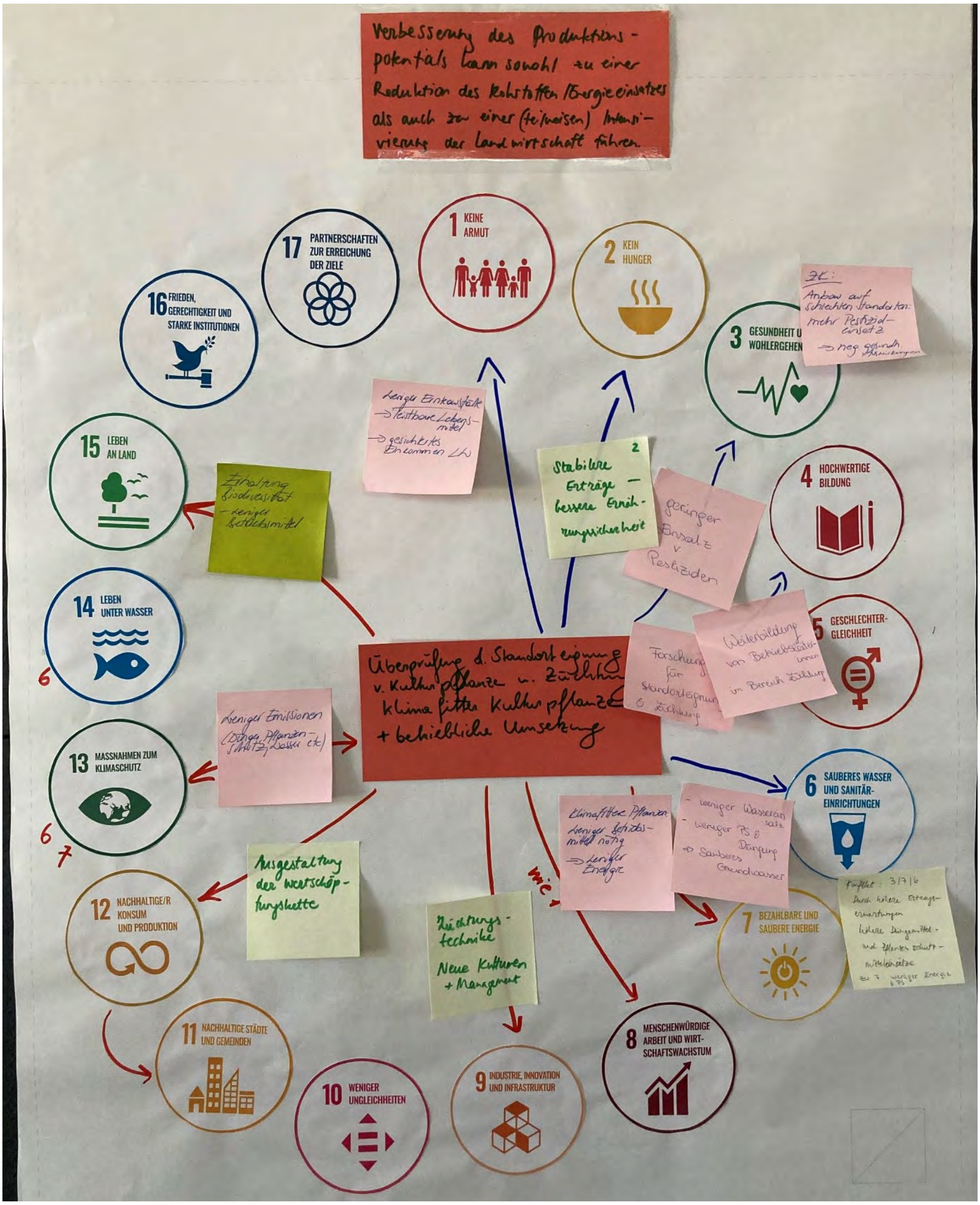

Abb. E-29: Result from group "Überprüfung der Standorteignung von Kulturpflanzen und Züchtung klimafitter Kulturpflanzen + betriebliche Umsetzung"

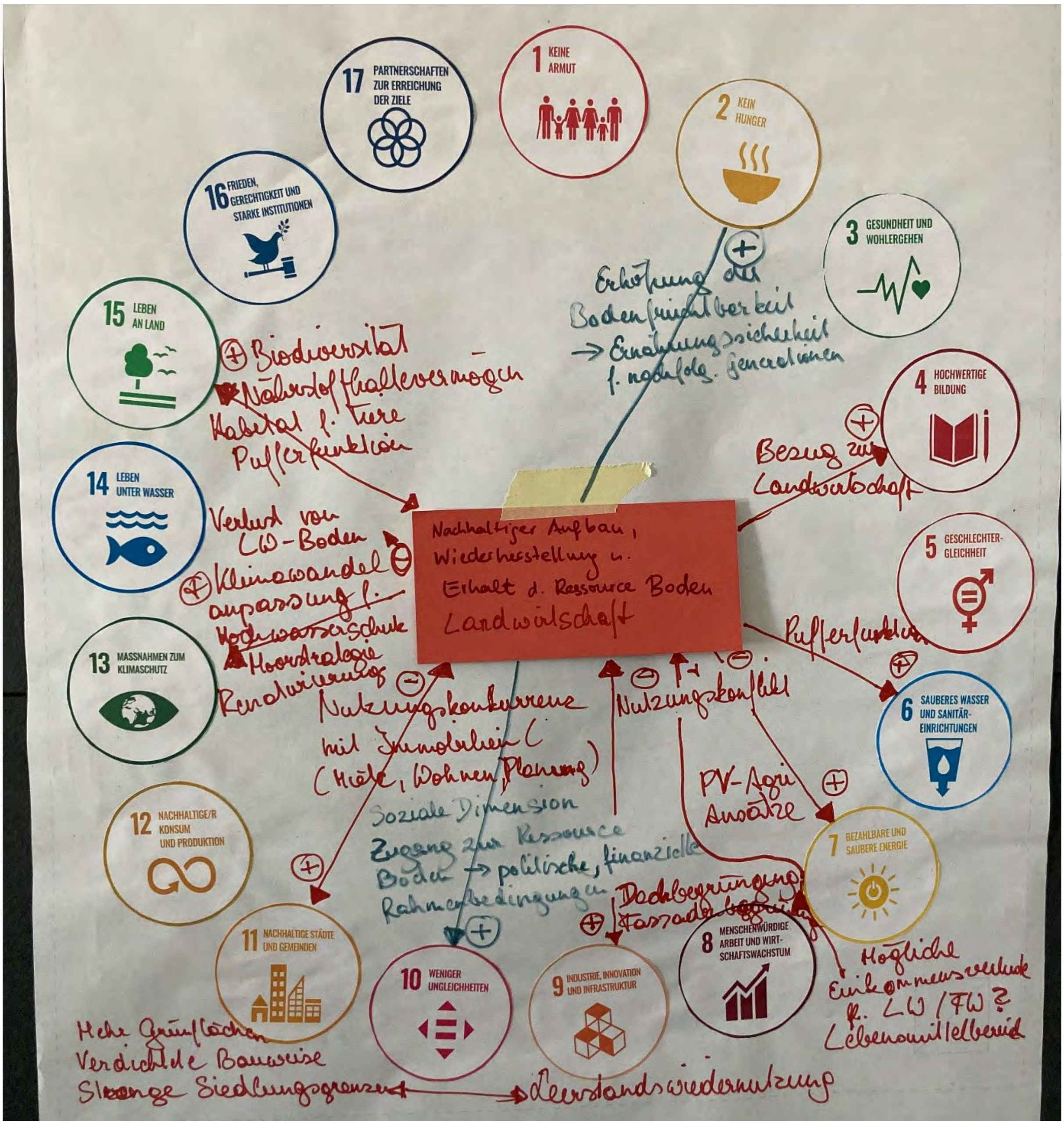

Abb. E-30: Result from group "Nachhaltiger Aufbau, Wiederherstellung und Erhalt der Ressource Boden (Landwirtschaft)"