Integrated Analysis of Climate Change Impacts and Adaptation Measures in Austrian Agriculture

Integrierte Analyse von Klimawandelauswirkungen und Anpassungsmaßnahmen in der österreichischen Landwirtschaft

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Abstract

An integrated modelling framework (IMF) has been developed and applied to analyse climate change impacts and the effectiveness of adaptation measures in Austrian agriculture. The IMF couples the crop rotation model CropRota, the bio-physical process model EPIC and the bottom-up economic land use model PASMA at regional level (NUTS-3) considering agri-environmental indicators. Four contrasting regional climate model (RCM) simulations represent climate change until 2050. The RCM simulations are applied to a baseline and three adaptation and policy scenarios. Climate change increases crop productivity on national average in the IMF. Changes in average gross margins at national level range from 0% to +5% between the baseline and the three adaptation and policy scenarios. The impacts at NUTS-3 level range from -5% to +7% between the baseline and the three adaptation and policy scenarios. Adaptation measures such as planting of winter cover crops, reduced tillage and irrigation are effective in reducing yield losses, increasing revenues, or in improving environmental states under climate change. Future research should account for extreme weather events in order to analyse whether average productivity gains at the aggregated level suffice to cover costs from expected higher climate variability.

Key Words

land use; modelling; climate change impact; adaptation; integrated analysis; EPIC; PASMA

Zusammenfassung

Anhand eines integrativen Modellverbundes werden die Auswirkungen des Klimawandels auf die öster-reichische Landwirtschaft und die Effektivität von Anpassungsmaßnahmen untersucht. Grundlage der Szenarienanalyse sind vier kontrastierende regionale Klimasimulationen, angewandt auf ein Baseline-szenario und drei Anpassungs- und Politikszenarien bis 2050. Der integrative Modellverbund koppelt das Fruchtfolgemodell CropRota, das bio-physikalische Prozessmodell EPIC mit dem ökonomischen Land-nutzungsmodell PASMA, berücksichtigt Agrarumwelt-indikatoren und wird auf NUTS-3-Ebene angewandt. Die Klimasimulationen lassen im nationalen Durch-schnitt auf Produktivitätssteigerungen in der Pflan-zenproduktion schließen. Im Vergleich zur Baseline steigen die durchschnittlichen nationalen Deckungs-beiträge je nach Klimasimulation und Anpassungs- und Politikszenario um 0% bis +5%. Auf NUTS-3-Ebene ergibt sich aufgrund standörtlicher Unter-schiede (z.B. Klimawandel, Landnutzung, naturräum-liche Gegebenheiten) ein differenzierteres Bild mit Änderungen zwischen -5% und +7%. Der Zwischen-fruchtanbau, die reduzierte Bodenbearbeitung und die Bewässerung sind effektive Anpassungsmaß-nahmen, die zur Verringerung von Ertragseinbußen, Steigerungen von Erlösen oder zur Verbesserung der Umweltsituation beitragen. Weiterführende For-schungsarbeiten sollten vermehrt auf die Auswirkun-gen von Extremereignissen in der Landwirtschaft eingehen und klären, ob die durchschnittlichen Pro-duktivitätssteigerungen ausreichen, die Kosten einer erwarteten höheren Wettervariabilität zu kompen-sieren.

Schlüsselwörter

Landnutzung; Modellierung; Klimawandeleffekte; An-passung; integrative Analyse; EPIC; PASMA

1   Introduction

The WORLD ECONOMIC FORUM (2013) highlights future rising greenhouse gas (GHG) emissions and water supply crises among the top-five risks with respect to the likelihood of occurrence and failed climate change adaptation among the top-five global risks with respect to their impacts. However, public authorities as well as private agents are confronted with a considerable degree of uncertainty upon the severity of impacts and effectiveness of mitigation and adaptation measures. Under such conditions, it is reasonable that the awareness on climate change adaptation is growing on importance either as supplement or substitute to mitigation efforts in political discourses. In its White Paper on "Adapting to climate change: Towards a European framework for action", the European Commission acknowledges the unavoidability of impacts and calls for coordinated and targeted adaptation action (EUROPEAN COMMISSION, 2009). In 2012, the Austrian government signed the national adaptation strategy (NAS), which is the result of an extensive political process under participation of stakeholders from public administration, science, interest groups, and the civil society (BMLFUW, 2012). The NAS reinforces the EU perspective by planning climate change actions on the two pillars mitigation and adaptation. It elaborates procedures for fields of activity (e.g. health, spatial planning) and important economic sectors (e.g. agriculture) and highlights further research demand. According to the NAS, robust adaptation measures in agriculture should i) consider integrative systems perspectives such as the soil-plant-water nexus, ii) rest upon a sustainability perspective considering farming inputs and natural production factors, and iii) take global change into account including international market developments.

Adaptation studies in agriculture cover a broad range of methods including quantitative and qualitative surveys and agronomic or integrated economic modelling with spatial ranges from single fields to global scales. Quantitative and qualitative surveys among farmers and agricultural experts provide knowledge on climate change impacts, potential adaptation measures and behaviour or constraints to adaptation (e.g. ENETE et al., 2012; OLESEN et al., 2011). Only a few research approaches apply backward looking empirical methods such as econometrics (e.g. REIDSMA et al., 2009; WANG et al., 2009). Both methods, surveys and econometric studies, inform about past and present systems processes and behaviour of land users. Such results supplement a third group of methods, i.e. quantitative model applications e.g. by determining assumptions on adaptation measures or scenarios (e.g. CLAESSENS et al., 2012). The bulk of climate change impact and adaptation studies belongs to this third group, which applies simulation and optimization techniques including (normative) assumptions on agents and scenario parameters. Agronomic modelling studies analyse climate change impacts and effectiveness of adaptation measures in alleviating yield losses or exploiting yield gains (e.g. EASTERLING et al., 2007; MORIONDO et al., 2010; ROSENZWEIG et al., 2013) and assess environmental impacts, e.g. on soil erosion or water resources (e.g. KLIK and EITZINGER, 2010; THALER et al., 2012). These studies provide valuable insights into climate-crop-environment interactions but are insufficient to exclusively support private and public decision making under resource constraints. Agronomic studies do not inform whether the costs of adaptation are covered by its gains, i.e. increases in yield levels and yield stability or reductions in yield losses. In general, they do not account for changes in market and policy conditions, which can be substantial within the time horizon of climate change studies. Integrated modelling approaches combine bio-physical and economic models to overcome such deficiencies. At case study level, they analyse the efficiency of specific adaptation measures for single crops (e.g. FINGER et al., 2010; MITTER et al., 2014) up to farming systems (e.g. BRINER et al., 2012; DONO et al., 2013) to judge the future profitability of certain crops and agricultural systems under a changing climate. Integrated studies at the continental to global scale must simplify the representation of the bio-physical and economic systems. However, they can reveal climate induced changes in productivity and vulnerability of world regions, the effectiveness of adaptation technology development, or regional impacts from changing global demand and supply in agricultural products (e.g. HERMANS et al., 2010; IGLESIAS et al., 2011; LECLÈRE et al., 2013; LOBELL et al., 2013). Recent inter-model comparisons are valuable to trace and quantify climate change impacts across regions and sectors as well as to assess model and climate data uncertainties (e.g. NELSON et al., 2013; VON LAMPE et al., 2014). To complement our knowledge from field and continental to global assessments, there remains demand for regional studies to better account for soil-climate-crop-management interactions under existing and likely future agricultural markets and policies (OLESEN et al., 2011).

This article builds on a research project that has been funded to guide the implementation of the Austrian NAS in the agricultural sector. It takes the above revealed need for integrated climate change impact assessments at regional scale into account. Until now, quantitative investigations of climate change impacts on Austrian agriculture are limited to bio-physical impacts, certain regions, farm types, crops, adaptation alternatives, or single climate change models (e.g. ALEXANDROV et al., 2002; STRAUSS et al., 2012; MITTER et al., 2014; SCHÖNHART et al., 2013). We build on the above cited three policy criteria i) – iii) of robust adaptation measures and apply an integrated agricultural modelling framework to analyse the bio-physical and economic impacts of climate change and the effectiveness of adaptation measures on Austrian agriculture at 1km² and NUTS-3 resolution up to 2050.

This article is structured as follows. Section 2 presents methods and data, followed by the presentation of results (section 3) and a discussion on quantitative results and the applied methods (section 4). Section 5 concludes on the results and directly responds to the information needs of the policy community.

2 Methods and Data

2.1 Integrated Modelling Framework

The quantitative integrated agricultural modelling framework (IMF) links three stand-alone models, i.e. the crop rotation model CropRota (SCHÖNHART et al., 2011), the bio-physical process model EPIC (Environmental Policy Integrated Climate; WILLIAMS, 1995) and the sectorial bottom-up land use model for Austria PASMA (Positive Agricultural Sector Model for Austria; SCHMID and SINABELL, 2007; SCHMIDT et al., 2012). The IMF is applied to the Austrian agricultural sector to analyse impacts of four regional climate model (RCM) simulations from the European EN-SEMBLES project (VAN DER LINDEN and MITCHELL, 2009) for one baseline and three combined adaptation and policy scenarios.

CropRota generates crop rotations typical to each NUTS-3 region. The crop rotations are derived from observed land use data and are chosen in order to maximize the total agronomic value, which is the sum of expert-based judgements on the suitability of pre-crop – main crop combinations and subject to agronomic constraints such as on the frequency of certain crops in a rotation (for full details see SCHÖNHART et al., 2011).

EPIC simulates the impacts from daily climate parameters (i.e. minimum and maximum temperature, precipitation, relative humidity, wind speed, and solar radiation) and specified crop and grassland management practices (e.g. crop rotations from the CropRota model), timing of planting, harvesting, tillage operations, fertilization, and irrigation, as well as level of irrigation and fertilization) on crop yields, grassland forage yields and abiotic environmental outcomes (Figure 1). EPIC requires homogeneity in input data, i.e. weather data, soil type, slope and elevation level. Such data are provided by homogeneous response units (HRU), which also serve as interface to PASMA (SCHMID, 2007; STÜRMER et al., 2013). A 1 km pixel is unique with respect to soil properties, slope and elevation. Pixels are classified along these characteristics to delineate the HRU layer. The HRU layer is merged with daily climate data at 1km pixel resolution as well as data on crop and grassland management practices to feed into EPIC. The validated EPIC for Austria (SCHMID, 2007; SCHMID et al., 2004; STRAUSS et al., 2012; STÜRMER et al., 2013) simulates annual bio-physical output (i.e. crop yields, environmental indicators; see Figure 1) by RCM simulations and crop and grassland management practices at 1 km² spatial resolution. This output is aggregated to NUTS-3 levels as well as averaged for three 20-years periods – i.e. 1991-2010 (climatologic reference period), 2011-2030 and 2031-2050 – to serve as input to the economic land use optimization model. CO_2 fertilization effects are taken into account in EPIC.

PASMA is a regional land use optimization model that maximizes the aggregated gross margin in each of the 35 Austrian NUTS-3 regions subject to regional resource endowments (livestock housing capacity, land area and quality, historic subsidy and quota entitlements). It takes revenues and variable costs from all major land use and livestock activities as well as subsidy schemes into account. PASMA portrays the natural, economic and policy contexts of Austrian agriculture and forestry in detail. All major land use categories (e.g. cropland, permanent grassland including alpine meadows, forests), major field crops and grassland variants, livestock categories (e.g. dairy cows, suckler cows, pig fattening), and management alternatives (e.g. conventional/organic production, fertilization intensity, soil management) are represented. Farm size determines variable costs in PASMA to take account of economies of scale and impacts from region-specific farm structure. With respect to the Common Agricultural Policy (CAP), both the 1st and 2nd pillar are considered including the Single Farm Payment

Figure 1. The bio-physical impact component of the integrated agricultural modelling framework
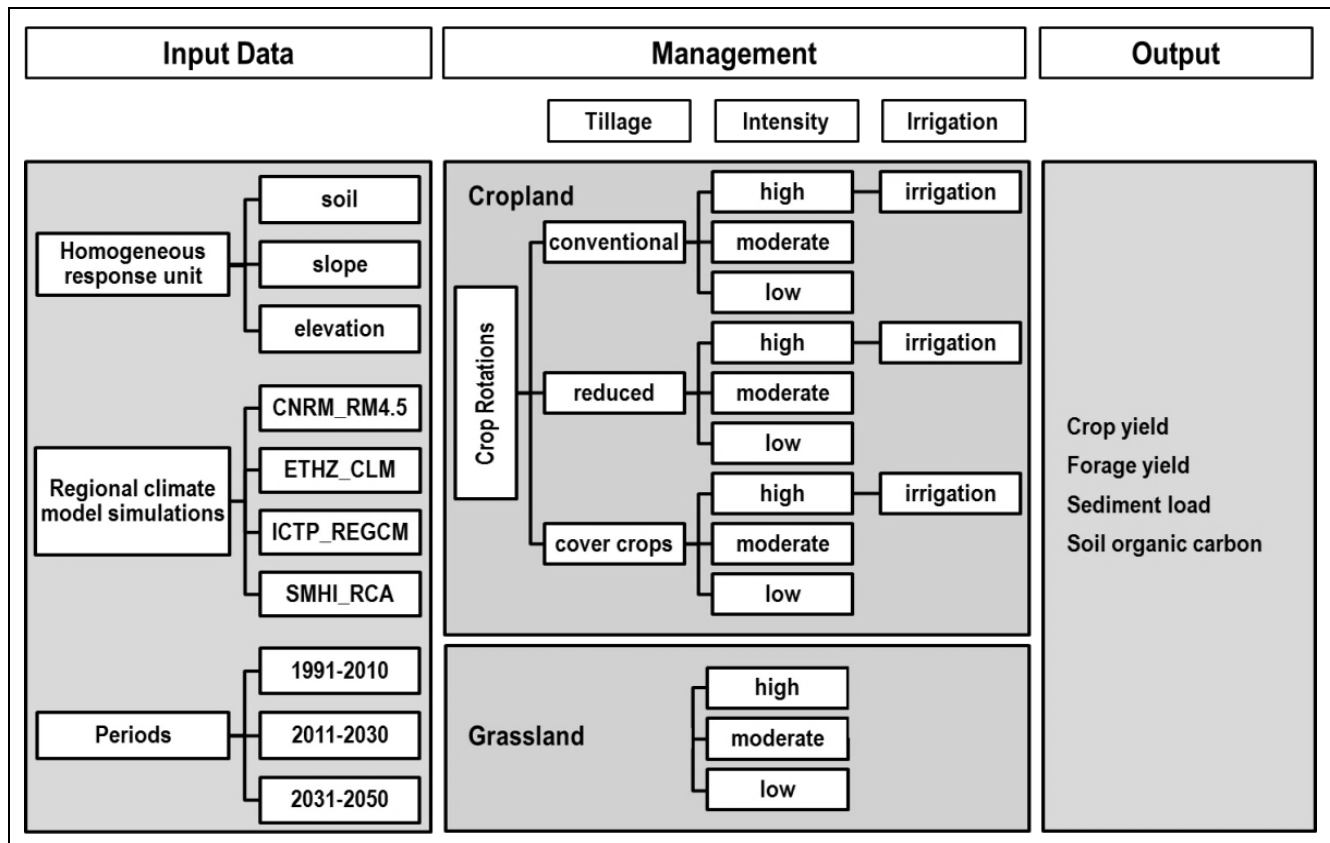
Source: own construction

scheme and other direct payments, selected measures of the Austrian agri-environmental program ÖPUL, and less favoured area payments. The land and livestock categories and crop management intensities are calibrated to an observed 2008 reference scenario using positive mathematical programming (PMP; HOWITT, 1995). PASMA adapts a quadratic variable production cost function to the circumstances of each NUTS-3 region (for details see SCHMID and SINABELL, 2005). It builds on major land use data and statistical sources such as the Integrated Administration and Control System (IACS), farm survey data, and data from the farm accountancy network (LBG). Furthermore, PASMA is made widely consistent with the Austrian economic accounting system for agriculture (LGR). National estimates on gross margins (standard gross margins; BMLFUW, 2008) and statistics on input and output prices provide major economic data. Technical coefficients on livestock and crop production (e.g. manure production, crop and livestock yields, animal and plant nutrition, crop rotation constraints) complement the bio-physical components in PASMA. The NUTS-3 and climate specific crop and grassland yields from EPIC adjust the statistical crop yield coefficients in PASMA. Orchards, vineyards, and forests are represented in PASMA as well. How-

ever, we do not consider climate change impacts for these land uses in this analysis.

The IMF estimates bio-physical and economic land use indicators. PASMA arranges land use and livestock such that the regional aggregated gross margin is maximized within the given constraints. Changes in gross margins at the NUTS-3 level indicate impacts from climate change and effectiveness of adaptation measures and policies on farm wealth. Changes in soil organic carbon (SOC) content in the top-30cm layer indicate impacts on soil fertility and carbon sequestration. Soil sediment losses from water erosion are modelled in EPIC based on the Revised Universal Soil Loss Equation (RUSLE) similar to MITTER et al. (2014). The nitrogen and phosphorus fertilizer application rates, irrigation areas, and land use changes (e.g. towards extensive permanent grasslands) are surrogate indicators for impacts on landscape appearance and biodiversity.

2.2 Climate Simulations

Physically based global General Circulation Models (GCMs) are nowadays the most common way to derive future climate states under the course of prescribed GHG emission scenarios. However, their utilization for assessing climate change impacts on a

regional level is strongly limited due to their coarse spatial resolution in the order of hundred kilometres. In order to bridge this scale-gap, RCMs are nested within the GCM large-scale atmospheric circulation over a limited area (e.g. GIORGI and MEARNS, 1991, 1999; MCGREGOR, 1997; WANG et al., 2004). In this article, regional climate change is represented with data from the EU FP6 Integrated Project ENSEMBLES (http://ensembles-eu.org), which produced a set of 21 RCM simulations with a horizontal resolution of 25 km until 2050. The ENSEMBLES project mainly addresses uncertainty in boundary conditions (choice of GCM) and RCM model formulation (VAN DER LINDEN and MITCHELL, 2009). In this respect, DÉQUÉ et al. (2007, 2011) showed that both the choice of the GCM and RCM are major sources of uncertainty and HEINRICH et al. (2014) could demonstrate that the ENSEMBLES multi-model dataset does not underestimate uncertainty due to sampling of only a few driving GCMs. Since the choice of the GHG emission scenario is less important until the mid of the 21st century (PREIN et al., 2011), only the A1B emission scenario (NAKICENOVIC et al., 2000), which is characterized by rapid economic growth and a balanced emphasis on all energy sources, was used to force the climate simulations in this article.

We selected four RCMs to cope with the uncertainty in climate models including CNRM_RM4.5, ETHZ_CLM, ICTP_RegCM, and SMHI_RCA, which are forced by four distinct GCMs. The models were selected according to their average climate change signals between the two periods of 1991-2010 and 2031-2050, aiming at representing the spread of the entire ensemble. For example, the ETHZ_CLM represents above median warming (+1.8°C) in combination with decreasing mean annual precipitation sums (-2.2%). The other RCM with above median warming (CNRM_RM4.5, +1.1 °C) projects increasing precipitation sums (+6.2%). ICTP_RegCM was selected as average scenario, since it meets the median for both criteria (+1.0°C and 0% precipitation change), and SMHI_RCA was chosen for resulting in below median warming and slightly decreasing precipitation sums (+0.8°C and -0.2%). A quantile based error correction approach (Quantile Mapping; QM) is applied in order to account for errors in the RCM simulations (e.g. FREI et al., 2003; HAGEMANN et al., 2004; SUKLITSCH et al., 2008, 2010) and spatial refinement (THEMEßL et al., 2011, 2012). In this article, QM is based on a 1 km interpolated observational grid for Austria (SCHÖNER and CARDOSO, 2004) in order to produce error corrected and downscaled RCM projections for daily weather parameters such as air temperature and precipitation sums, which feed into EPIC to simulate climate change impacts on bio-physical outcomes.

2.3 Adaptation Scenarios

We run one reference scenario for 2008 to calibrate PASMA, two baseline scenarios for 2020 and 2040, and three adaptation and policy scenarios (SZEN1-3) under four RCM simulations and two time steps 2020 and 2040 (Table 1). The baseline scenarios for 2020

Table 1. Overview and description of the adaptation and policy scenarios

Scenario name	Climate signal	Time steps	Description
Reference	no	2008	• representation of observed land use for model calibration
Baseline	no	2020, 2040	• major elements of Common Agricultural Policy (CAP) reform • price and productivity developments • loss of agricultural land: 0.1% per year from the reference 2008
Impact (SZEN1)	4 RCMs	2020, 2040	• all baseline assumptions • forced reproduction of baseline plant and livestock production • adaptation in planting and harvesting dates in EPIC • adaptation of nutrient levels to changed plant productivity in PASMA
Autonomous adaptation (SZEN2)	4 RCMs	2020, 2040	• all SZEN1 assumptions except forced reproduction • changes among crop cultivars and land use intensities • shifts between land use categories • adaptation of soil management systems • adaptation of livestock feeding, herd sizes and species

Policy-induced adaptation (SZEN3)	4 RCMs	2020, 2040	• all options from SZEN2
			• irrigation on selected crop land
			• agri-environmental premiums to reduce adverse effects from autonomous adaptation and stimulate favourable soil management, i.e.:
			  – reduced tillage where applicable in the crop rotation (40 €/ha)
			  – reduced tillage plus winter cover crops where applicable in the crop rotation (160 €/ha)

Source: own construction

and 2040 do not consider climate change. The 2020 baseline accounts for expected reforms of the CAP such as the abolition of milk quotas, the transition towards regionally uniform decoupled direct payments, greening of the 1st pillar and premium reductions in the 2nd pillar of the CAP. Furthermore, we take losses in agricultural land due to infrastructural developments into account. Data on productivity and price developments are drawn from OECD-FAO (2011) forecasts and expert assumptions. For 2040, we assume no further changes in the CAP, productivity and prices due to considerable uncertainties. This allows us to reveal climate change impacts and effectiveness of adaptation measures and policies.

Three adaptation scenarios are analysed. A first impact scenario (SZEN1) reproduces the baselines 2020 and 2040 with respect to land use and livestock levels to approximate the vulnerability of agriculture to climate change. Adaptation is limited to mainly cost neutral adjustments in field operation schedules. The scenario on autonomous adaptation (SZEN2) builds on SZEN1 and allows shifts in cropping systems and management (i.e. crop choices, fertilization, irrigation and soil conservation tillage). Shifts among land use categories (i.e. grassland, cropland, forests) are possible. Forests can only increase in size due to strict legislation in Austria. Livestock management includes changes among livestock categories, herd sizes, and feeding diets. In SZEN3, policies are included that aim at limiting possible adverse environmental effects from adaptation and foster sustainable land use development. It includes agri-environmental premiums to induce planting of cover crops and reduced tillage. Irrigation is introduced as further adaptation option in SZEN3. It is assumed as planned long-term investment despite the fact that irrigation facilities are already available on some farms in Austria. Consequently, irrigation is considered by the sum of variable costs and investment annuities. Water for irrigation is assumed to be free of charge and sufficiently available. This choice of adaptation measures in SZEN2 and SZEN3 reflects the scientific literature as well as stakeholder positions in the Austrians NAS (cf. STICKLER et al., 2010).

3 Results

3.1 Simulated Crop Yield Impacts

Figure 2 shows the variability of relative changes in average dry matter crop yields between the climatologic reference period (1991-2010) and a future period

(2031-2050) for the four RCM simulations and different crop management practices. It represents the direct crop yield effects of climate change. In Figure 2 changes in average crop yields have been calculated at 1 km pixel resolution and relate to the respective crop management in the past. ICTP_RegCM follows the multi-model median for mean annual temperature and precipitation sums. It provides the most "optimistic" results at the national average, i.e. the median change of average crop yields increases between +3% and +6%. SMHI_RCA with below median warming and almost median precipitation sums shows the most "pessimistic" results, i.e. the median change of average crop yields is between -3% and +3%.

Compared to the climatologic reference period, average crop yields increase for each crop management except with SMHI_RCA. This RCM shows slight decreases in the median change of average crop yields with soil conservation measures (-0.5% with reduced tillage and -1% with winter cover cropping) as well as with moderate (-0.3%) and low fertilization intensity (-2%). Irrigation is likely to compensate adverse climate change impacts and leads to similar increases in the median change of average crop yields with all RCMs (between +3% and +6.5%). The size of a boxplot indicates the variability of crop yield changes by RCM simulation and crop management practice among all pixels. The variability is biggest for ETHZ_CLM regardless of the crop management practice, which indicates a high variation in climate change impacts among Austrian regions. Compared to the other three RCMs, ETHZ_CLM shows considerably higher average temperature and lower precipitation sums leading to more extreme impacts on crop yields as well. Increasing crop yields are simulated for most parts of Austria (see Appendix 1). However, they slightly decrease in south-east Austria in three RCM simulations (CNRM_RM4.5, ETHZ_CLM, and SMHI_RCA), and in north-east Austria in one RCM simulation (SMHI_RCA). Crop yields appear mainly driven by the interaction of changes in temperature and precipitation.

The variability of relative changes in average forage yields on permanent grasslands between the climatologic reference period (1991-2010) and the period 2031-2050 are presented in Appendix 2 for four RCM simulations and four grassland management practices. Calculations are based on 1 km pixels and refer to three fertilization intensities. Similar to the cropland results, the highest positive forage yield impacts are projected with ICTP_RegCM (increases in the median change of average forage yields between

Figure 2. Boxplots of relative changes in average crop yields between the climatologic reference period 1991-2010 and 2031-2050 by crop management practices
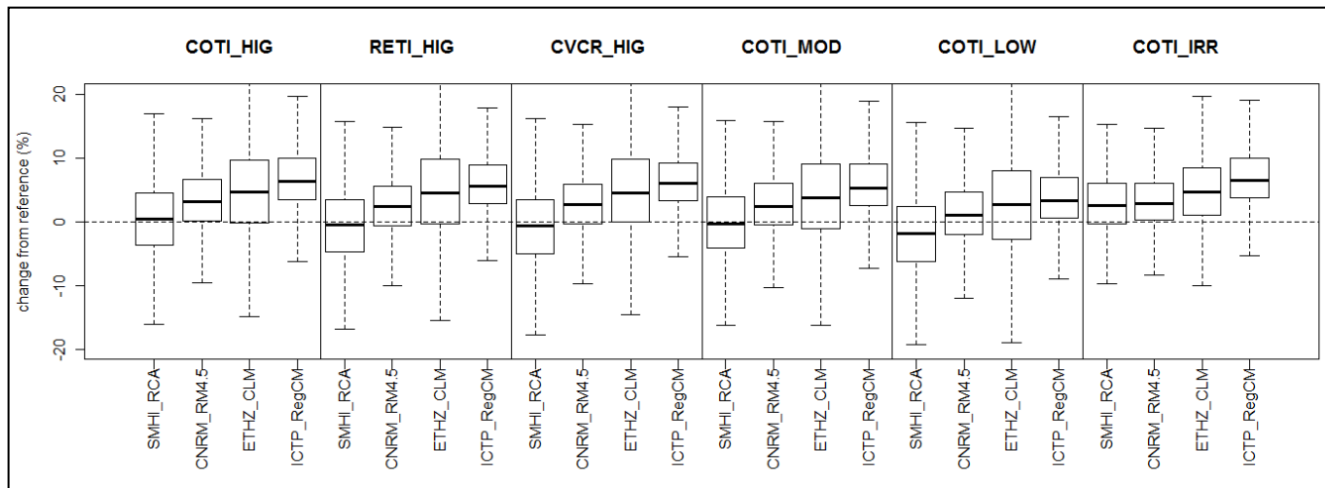

Note: the outliers are not presented. COTI = conventional tillage, RETI = reduced tillage, CVCR = winter cover crops, HIG = high fertilization intensity, MOD = moderate fertilization intensity, LOW = low fertilization intensity, IRR = irrigation
Source: own construction

+14% and +18%) and the lowest with SMHI_RCA (increases in the median change of average forage yields between +6% and +14%). Compared to the climatologic reference period, the model results show mainly increasing forage yields regardless of the management practice. It indicates that grassland is likely to benefit from higher temperatures and CO_2 fertiliza-tion. This is mainly because grassland dominates in areas where water is not limiting plant growth current-ly. Figure 3 shows regional characteristics of relative changes in average forage yields on grassland with high fertilizer intensity between the periods 1991-2010 and 2031-2050. The results indicate increasing average forage yields in almost all grassland regions.

Figure 3. Relative changes in average grassland forage yields with high fertilizer intensity between the climatologic reference period 1991-2010 and 2031-2050
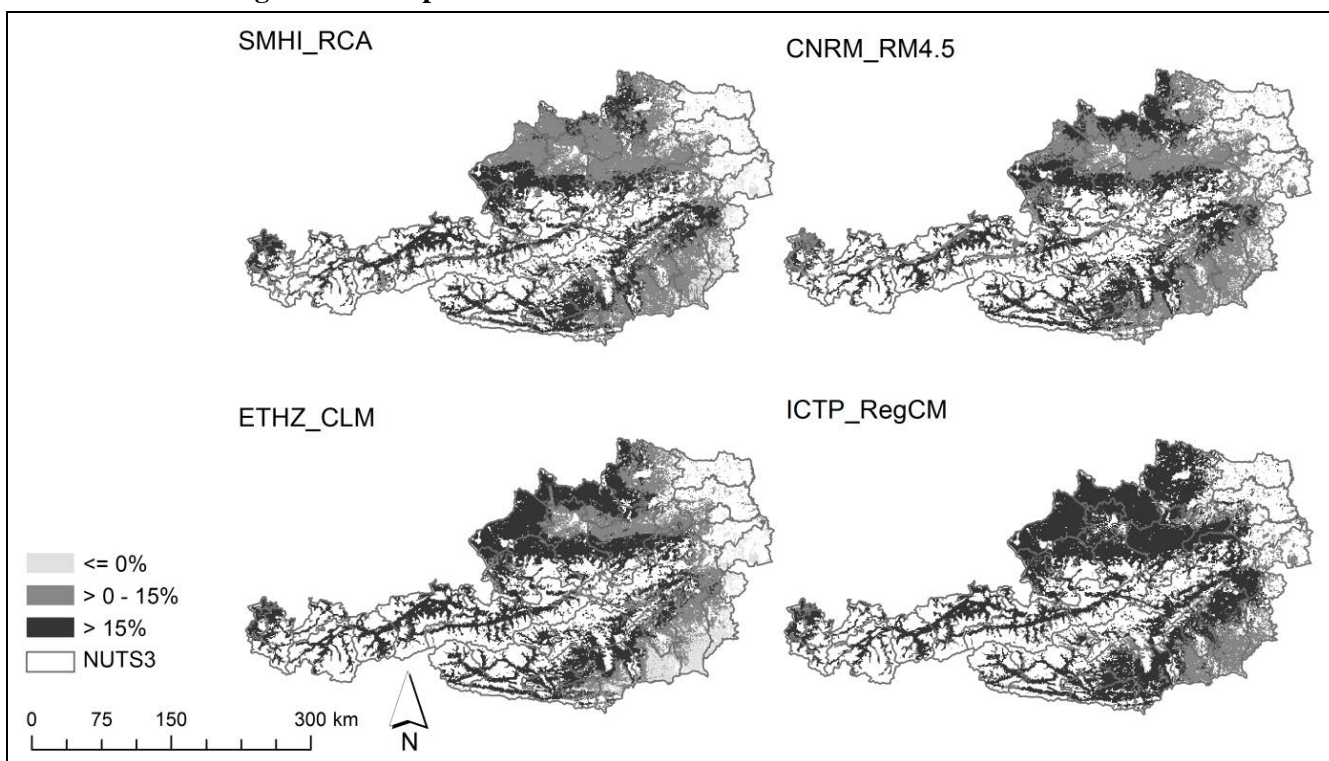
Note: grasslands in white areas are not considered.
Source: own construction

The highest increases are projected for alpine regions, i.e. the alpine foreland in the north, some inner-alpine valleys, and parts of Carinthia in the south. The lowest increases (CNRM_RM4.5, ICTP_RegCM, and SMHI_RCA) or even small decreases (ETHZ_CLM) are simulated for south-east Austria, which seems to be the most vulnerable region due to low precipitation levels. It results from rising average temperatures leading to water shortages during the growing season.

3.2 Modelled Economic Impacts

Figure 4 presents relative changes in gross margins aggregated over all Austrian NUTS-3 regions for the four RCM simulations and the three adaptation and policy scenarios in 2020 and 2040. Compared to the 2020 and 2040 baselines, changes in gross margins including subsidies range between 0% (SMHI_RCA and CNRM_RM4.5, SZEN1, 2020) and +5% (ICTP_RegCM, SZEN3, 2040). Three out of the four RCM simulations (i.e. CNRM_RM4.5, ETHZ_CLM, ICTP_RegCM) lead to higher gross margins in all three adaptation and policy scenarios, while impacts from climate change for SMHI_RCA in SZEN1 are negligible at the aggregated level. Positive impacts from the four RCM simulations increase over time on average, while effects of ETHZ_CLM in 2040 more or less remain at 2020 levels. Aggregated gross margins increase from SZEN1 to SZEN3 due to the increasing availability of adaptation measures as well as agri-environmental premiums in SZEN3. When comparing aggregated changes in gross margins among SZEN1 and SZEN2, we observe only minor impacts from the assumed autonomous adaptation measures (SZEN2) in the 2020 model output. Impacts on gross margins become more pronounced in 2040 and for SZEN3 with about +2%-points due to the introduced policies and irrigation options. Increases in SZEN3 are accompanied by changes in public budget spending. The ratio between changes in aggregated gross margins and budget spending (SZEN3 compared to SZEN2) helps to locate premium levels on the range between insufficient incentives and overcompensation, i.e. lacking additionality. Corrected by the gains from irrigation, the ratios for 2040 are between 0.83 (ETHZ_CLM) and 0.81 (CNRM_RM4.5) on average, which means a capitalization of 83% of premiums in the gross margins in CNRM_RM4.5. It indicates a mismatch between premium levels, assumptions on variable costs of technology adoption, and yield effects from reduced tillage and cover crops. However, fixed costs and management costs are neglected in the calculation of gross margins.

Figure 4 also presents changes in aggregated gross margins from which subsidies have been excluded. Climate change and adaptation effects in SZEN1 and SZEN2 become more pronounced and indicate the income stabilizing effects of subsidies. In 2040, adaptation of plant and livestock production increases aggregated gross margins excluding subsidies in SZEN2 compared to SZEN1 by about 1%-point for all four

Figure 4. **Relative changes of gross margins including and excluding subsidies from the 2020 and 2040 baselines aggregated over all Austrian NUTS-3 regions by the four RCM simulations and the three adaptation and policy scenarios (SZEN1-3)**
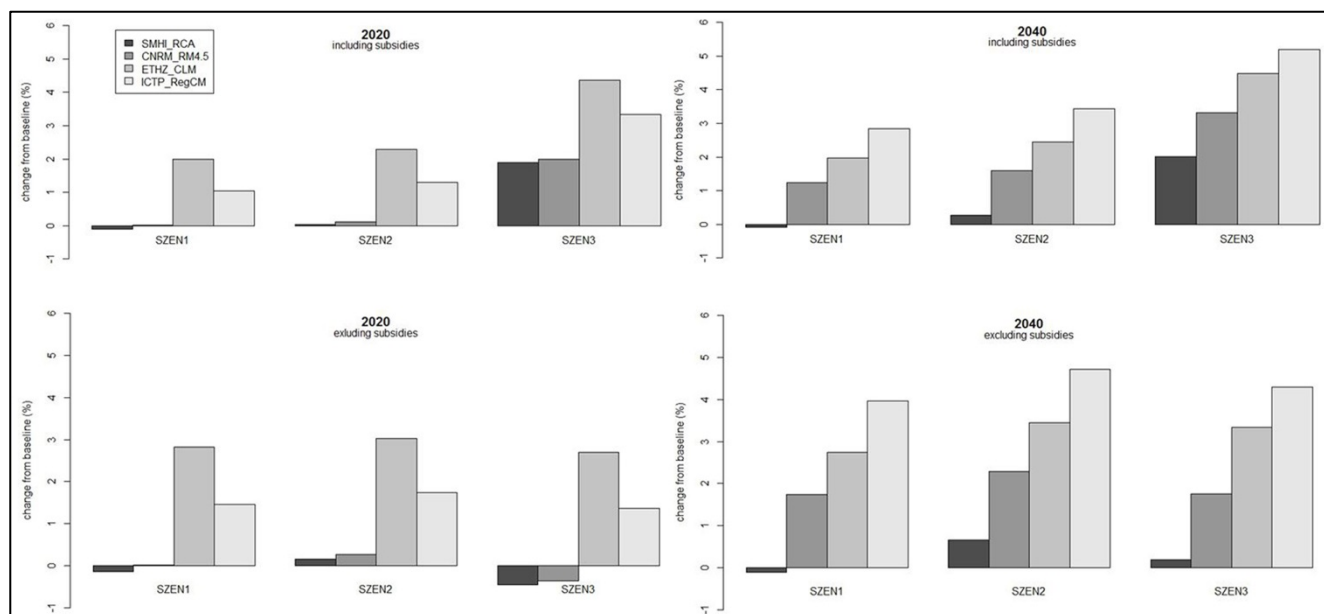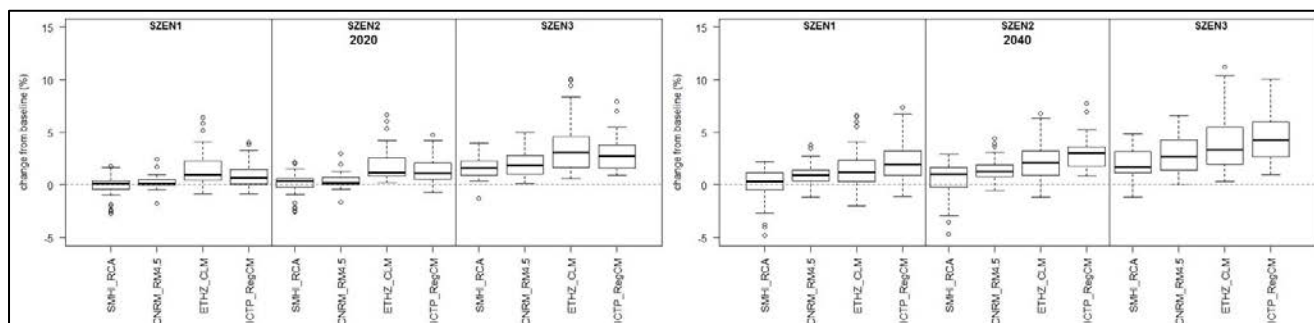

Source: own construction

RCM simulations. In SZEN3, two out of four RCM simulations even show decreasing aggregated gross margins compared to the baseline 2020 when subsidies are subtracted. It indicates the effectiveness of the agri-environmental premiums in impacting land use choices in the model, but does not prove the effectiveness of the measure in achieving its underlying policy objectives (see therefore section 3.3 and the discussion on premium levels).

Aggregated impacts of climate change at national scale can be misleading under heterogeneous natural and socio-economic conditions. Figure 5 presents the distribution of changes in aggregated gross margins (including subsidies) among all 35 NUTS-3 regions for the years 2020 and 2040 and all three adaptation and policy scenarios. While aggregated gross margins for SZEN1 range from 0% to +2% in 2020 and 0% to +3% in 2040 (see Figure 4), results at the regional level show ranges from -3% to +6% in 2020 and -5% to +7% in 2040. Effects become even more pronounced by introducing adaptation policies in SZEN3 with ranges from -1% to +10% in 2020 and -1% to

+11% in 2040.

The results indicate substantial variability in aggregated gross margins among the RCM simulations, adaptation and policy scenarios and time periods, which is also shown in Figure 6. It presents Kernel density estimates for changes in aggregated gross margins among all 35 NUTS-3 regions and three adaptation and policy scenarios. Both, levels and variability in the changes of aggregated gross margins increase from 2020 to 2040. Standard deviations of changes in aggregated gross margins in SZEN1 for four RCM simulations range from +0.68% to +1.73% in 2020 and +1.17% to +2.15% in 2040. For SZEN3, standard deviations range from +1.10% to +2.70% in 2020 and from +1.28% to +2.91% in 2040. These results indicate climate change impacts, adaptation potentials and costs as well as effectiveness of agri-environmental premiums to support adaptation to be heterogeneous across NUTS-3 regions. With respect to the latter, the ratios of changes in aggregated gross margins and budget spending among NUTS-3 regions and scenarios range between 0.61 and 0.95 in 2040.

Figure 5. Boxplots of relative changes in aggregated gross margins (incl. subsidies) among Austrian NUTS-3 regions from the 2020 and 2040 baselines by four RCM simulations and three adaptation and policy scenarios (SZEN1-3) (N=35)

Source: own construction

Figure 6. Kernel density estimates of changes in aggregated gross margins (incl. subsidies) by the 2020 and 2040 baselines and four RCM simulations [N=105 (35 NUTS-3 regions * 3 adaptation and policy scenarios)]
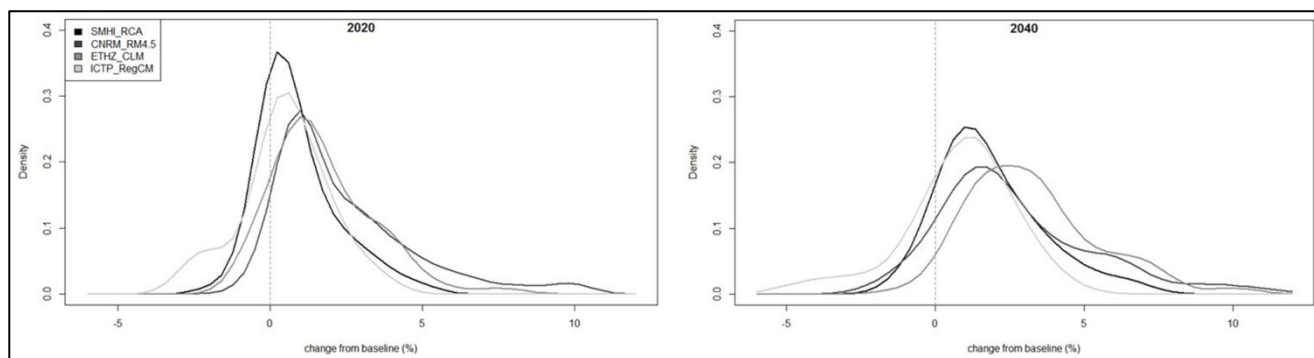
Source: own construction

3.3 Environmental Impacts

Environmental impacts from climate change and adaptation are indicated by changes in SOC, soil sediment loss on cropland, nutrient supply, and land use change. The cumulative effects of SOC change are presented in the two upper graphs of Figure 7 for permanent grasslands and in the two centre graphs for cropland. The SZEN1 results represent climate-soil-plant interactions under unmodified management and indicate direct climate change impacts compared to the baselines 2020 and 2040. Higher temperatures and CO_2 levels in general increase above and below ground biomass production subject to sufficient soil water and nutrient availability. Higher inputs of organic matter can lead to increasing mineralization rates. On permanent grasslands and croplands, these mixed effects lead to either slightly increasing or decreasing SOC levels in 2020 with ranges among RCMs and NUTS-3 regions between -6% and +3% on permanent grasslands and -2% to +3% on croplands, on average. However, one has to acknowledge different absolute levels with higher SOC rates on permanent grasslands than croplands in general. In 2040, three out of the four climate simulations show slightly declining SOC rates on permanent grasslands. SOC

changes range from -6% to +4% on permanent grasslands and -4% to +4% on croplands. While changes in management hardly impact SOC levels on permanent grasslands in the model, median SOC levels on croplands turn from losses in SZEN2 to gains in SZEN3 (Figure 7). It is the result of additional soil conservation measures induced by agri-environmental payments in SZEN3.

Soil sediment losses on croplands (Figure 7, lower graphs) appear more sensitive to climate change than SOC. Median changes on croplands in SZEN1 range from -15% to +8% in 2020 and -7% to +8% in 2040 among all four RCM simulations. Three out of the four RCMs show increasing soil sediment loss, which indicates increasing risks of soil loss from climate change. On cropland, the changes among NUTS-3 regions and RCM simulations range from -36% to +39% in 2020 and from -37% to +34% in 2040, respectively. Similar to the SOC development in SZEN3, soil sediment loss is declining under soil conservation measures, i.e. reduced tillage and winter cover crops.

Figure 8 presents average changes in total nitrogen and phosphorus application. All scenarios show increasing fertilizer application rates with ranges

Figure 7. Boxplots of relative changes in soil organic carbon (SOC, top-30cm layer) on permanent grasslands and croplands and of relative changes in soil sediment losses on croplands (in t/ha) for all Austrian NUTS-3 regions from the 2020 and 2040 baselines by four RCM simulations and three adaptation scenarios (SZEN1-3) (N=35)
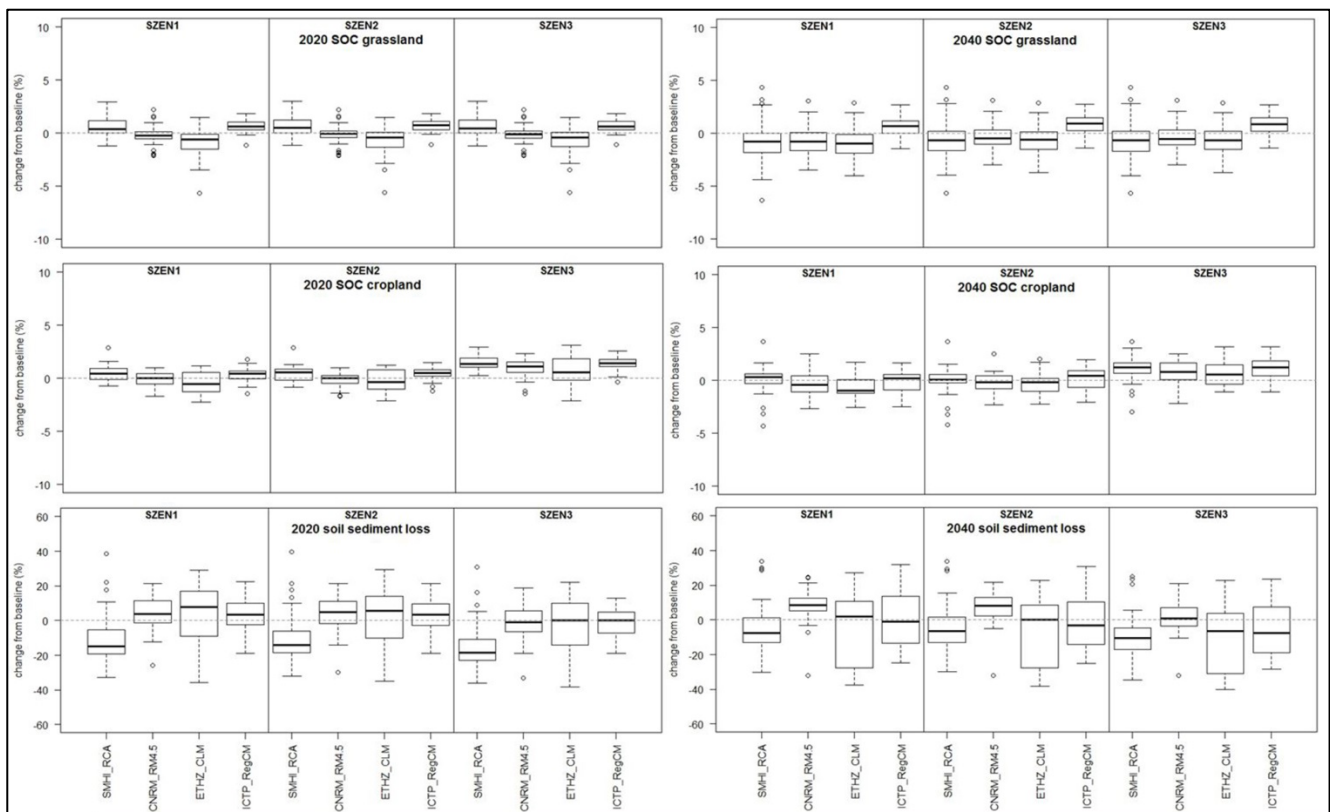
Source: own construction

Figure 8.   Relative changes in nitrogen and phosphorus applications from the 2020 and 2040 baselines aggregated over all Austrian NUTS-3 regions by the four RCM simulations and the three adaptation and policy scenarios (SZEN1-3)
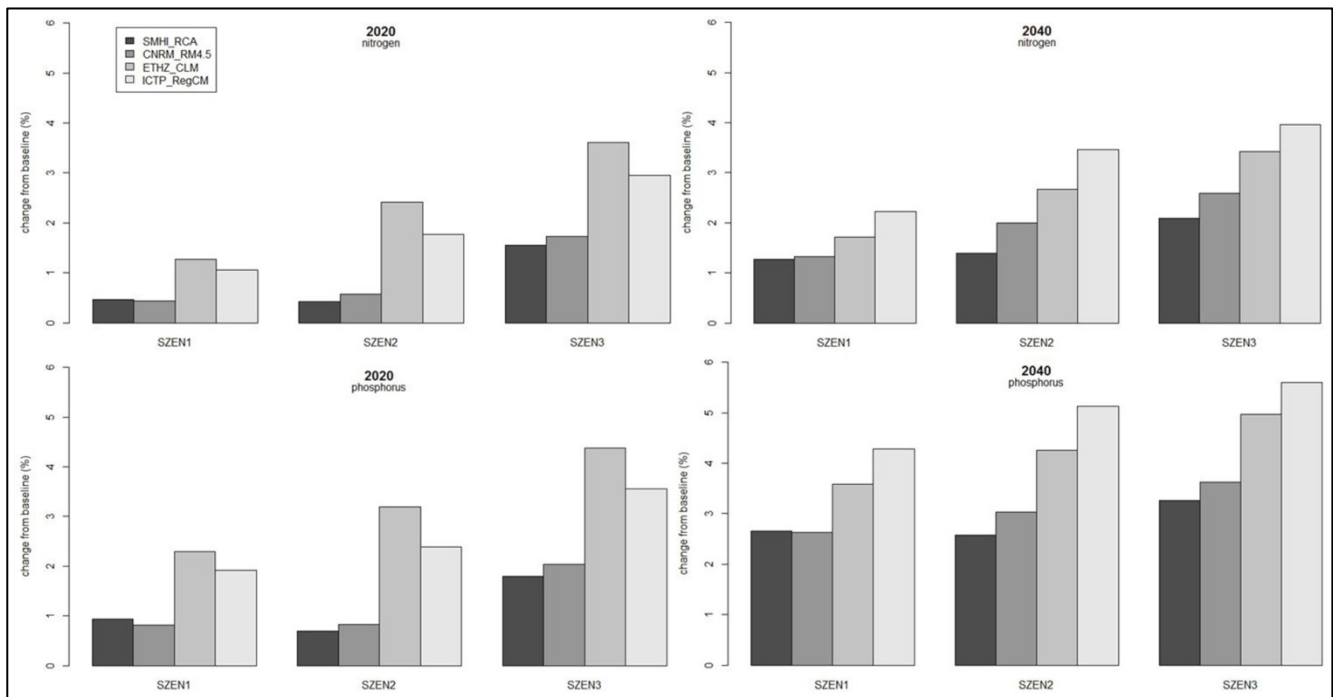
Source: own construction

among the four RCM simulations between 0% and +4% for nitrogen and between +1% and +6% for phosphorus. Again, SZEN1 indicates direct climate change impacts compared to the baselines 2020 and 2040. Changes in aggregated nutrient demand follow changes in i) growing conditions, ii) management intensity, iii) manure availability, and iv) agricultural land use. Total nutrient levels in SZEN3 are higher compared to SZEN2 due to cropland expansion – the agri-environmental premiums make it more profitable in the model compared to SZEN2 – as well as shifts towards irrigated high intensity cultivation (compare to Figure 9). However, increasing fertilization does not necessarily increase nutrient emissions if it is accompanied by proper management (e.g. cover crops), fills existing nutrient gaps (e.g. shift from policy- or market-induced extensive management such as organic farming), or meets growing nutrient demand from productivity changes (e.g. climate change).

All applied environmental indicators are driven by changes in both climate and land use. Figure 9 shows changes of three land use categories: "cropland", "intensive grassland", and "extensive grassland" (for aggregation details see captions of Figure 9). It compares SZEN2 and SZEN3 results to the baselines. SZEN1 land use is per definition identical to the baseline. A larger cropland area in SZEN3 is the result of

both agri-environmental premiums that support soil protection measures as well as irrigation which increases cropland profitability. Obviously, regional climate determines the direction and magnitude of change for all categories. Extensive grassland is negatively impacted and decreases in 2040 under all four RCM simulations.

Irrigation supplements the set of adaptation measures available on cropland in SZEN3. Water limitations trigger irrigation if marginal benefits exceed marginal irrigation costs in the model. Due to minor adoption of irrigation in the baselines 2020 and 2040, relative changes in irrigated areas appear large. Those two RCM simulations with above average warming (CNRM_RM4.5 and ETHZ_CLM) trigger more pronounced changes. Above average precipitation in CNRM_RM4.5 changes the irrigated area by +71% in 2020 and -64% in 2040. On the contrary, ETHZ_CLM (above average warming and below average precipitation) increases the irrigated area by +234% in 2020 and +1 092% in 2040. While of limited importance at the national scale – only 31 out of 140 NUTS-3 and RCM combinations (35 * 4) apply irrigation – it has substantial regional impacts according to the model. Irrigation increases gross margins up to +45% in some eastern regions of Austria for selected scenarios, mainly ETHZ_CLM.

Figure 9. **Land use change of cropland, intensive and extensive grassland from the 2020 and 2040 baselines over all Austrian NUTS-3 regions by the four RCM simulations and two adaptation and policy scenarios SZEN2-3**
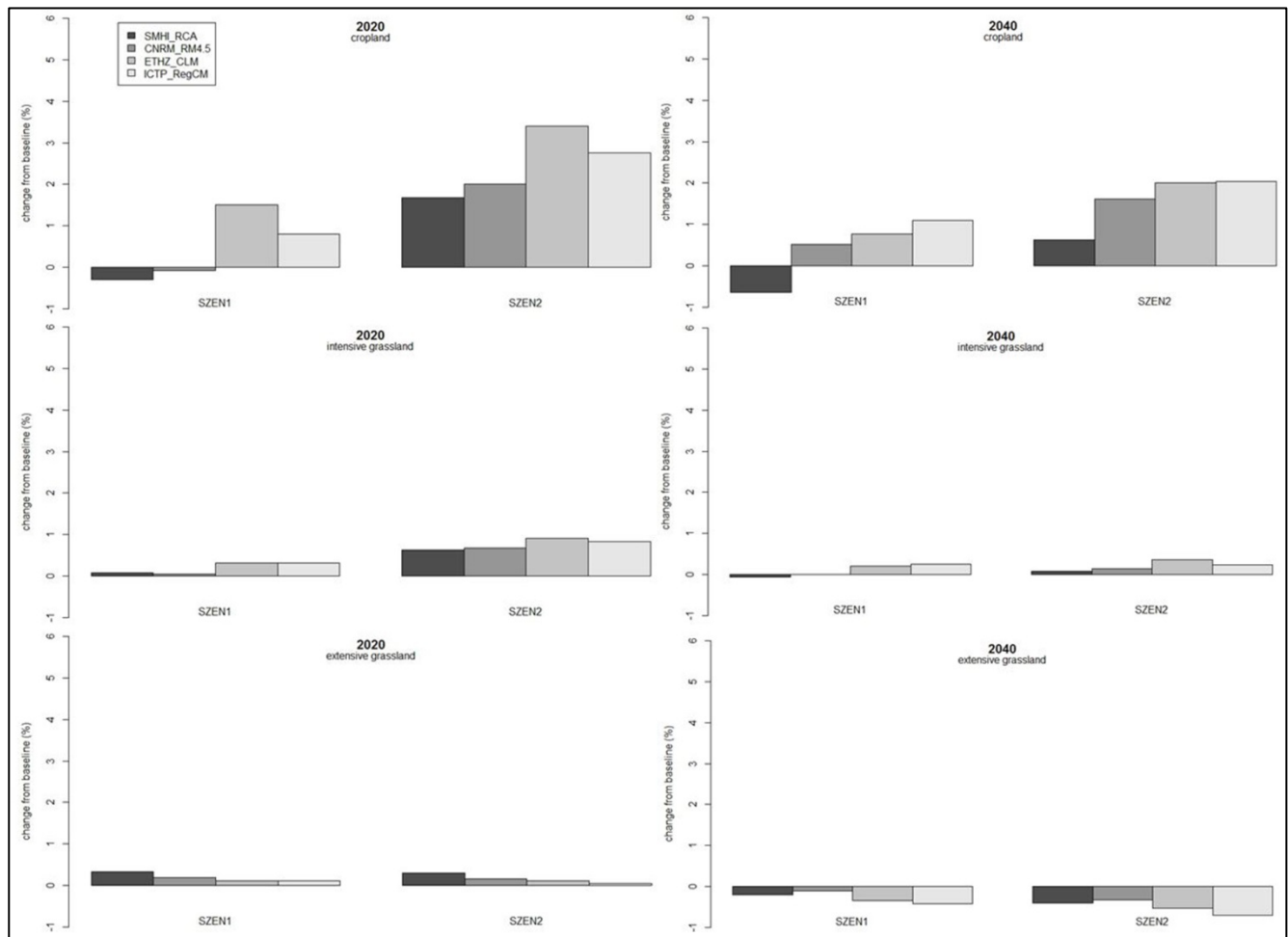
cropland = cropland, permanent crops (e.g. short rotation forestry, orchards, vineyards); int. grassland = permanent grassland > 1 harvest/yr., < 35% slope; ext. grassland = remaining permanent grassland (e.g. meadows < 2 harvests/yr., alpine meadows, extensive pastures)
Source: own construction

4 Discussion

4.1 Bio-physical Climate Change Impacts

We have performed an integrated climate change impact analysis of agricultural production in Austria at 1 km raster resolution until 2050. The bio-physical EPIC simulations indicate increasing average crop and grassland forage yields for most climate change simulations and regions. The directions and magnitudes of change are in line with other research studies. For instance, EASTERLING et al. (2007) provide a meta-analysis for mid- to high-latitude regions showing moderate productivity gains for temperature changes up to +2°C (maize) and +3°C (wheat). Similarly, IGLESIAS et al. (2011) have modelled average land productivity increases of +12% to +15% for Europe under climate change. A European wide assessment by CISCAR et al. (2011) results in a moderate average change in crop yields of +3% subject to a temperature

increase of 2.5°C. However, the authors reveal a considerable spread among regions from -9% (British Isles) to +37% (Northern Europe). A plus of 2.5°C in the south of Central Europe including Austria results in +5%, which turns to -3% when temperatures increase by +5.4°C. While many studies focus on croplands, there is limited information on changes in grassland productivity. For example, HENSELER et al. (2009) have analysed the Upper Danube basin including some provinces in western Austria with changes in cereal yields of -3% to +9%, fodder crop yields of +30% to +50% and grassland yields of +3% to +8% until 2020. FINGER and CALANCA (2011) have modelled grassland yields for a Swiss region and estimate changes between +10% and +24%. In contrast to our results and the even more pronounced yield increases in HENSELER et al. (2009) the changes reported by FINGER and CALANCA (2011) appear moderate considering the underlying climate change scenario for

the period 2071-2100, i.e. increasing daily minimum and maximum temperature of several °C and reduction in summer rainfall of -28% to -47% between June and September. However, FINGER and CALANCA (2011) emphasize the substantial increase in production risks from increasing variability of weather conditions. All these studies assume a CO_2 fertilization effect, which is well documented from experimental data but still uncertain in its magnitude of impacts on crop growth (TUBIELLO et al., 2007). LEHMANN et al. (2013b) do not consider CO_2 fertilization in their Swiss case study on winter wheat and grain maize production in 2050. They show decreases in the certainty equivalent, i.e. an economic measure of farm utility, of -7% to -15% despite farm management adaptation. Productivity developments for wheat, potatoes, and grassland are estimated by HERMANS et al. (2010) for Europe from 2005 to 2050 under a changing climate, CO_2 concentration and technology. Their results for Austria are in a similar magnitude as presented in this article. However, without CO_2 fertilization crop yields decline under climate change – from -25% for grassland in eastern Austria to -2% for wheat in western Austria and potatoes in eastern Austria – for all three Austrian NUTS-1 regions and all crops with only one exception (i.e. grassland in western Austria) (HERMANS et al., 2010). CO_2 concentrations may make the difference between yield gains and losses in the future according to the results from HERMANS et al. (2010). This is in line to results from other world regions in the northern hemisphere such as China (PIAO et al., 2010).

On average, Austria and other European countries likely will face productivity increases during the next decades due to climate change as well as increasing CO_2 levels. This is supported by our findings as well as comparable regional to European wide studies. However, such average trend conceals the heterogeneity of regional climate change impacts. In many studies, we can see a similar pattern of moderate aggregated effects based on regionally much more diverse results with sometimes even changing signs (e.g. LECLÈRE et al., 2013). According to our model output, the most negatively impacted areas in Austria are located in the east where precipitation is limiting plant growth. These regions are specifically prone to extreme weather events such as droughts (STRAUSS et al., 2013). Other studies support our results of average productivity increases with decreasing productivity in the Pannonian region (TRNKA et al. 2010; OLESEN et al., 2011; THALER et al., 2012). However, these regions are endowed with high shares of cropland and

therefore appear more flexible in adaptation in general. On the contrary, the grassland dominated western parts of the country may benefit from increasing temperatures but may face less flexibility in cropping plans. To extend our current knowledge on regional differences in climate change impacts and vulnerability, the effects of both, site-specific conditions (such as soil or topography) and climate conditions (such as temperature and precipitation development), as well as their interactions over time need to be analysed in detail. Another aspect yet to be explored are the direct climate change impacts on livestock such as heat stress. Impacts may be limited for moderate temperature increases of +1 to +2°C (MADER et al., 2009) but still may require some adaptation in livestock facilities and management (FUHRER et al., 2013). Assessments of more pronounced changes, which are expected for the second half of the 21st century, should take such direct impacts on livestock and eventually capital intensive adaptation efforts into account.

4.2 Effectiveness of Climate Change Adaptation

We applied one climate change impact scenario (SZEN1) and two adaptation and policy scenarios (SZEN2 and SZEN3) to analyse the effectiveness of adaptation measures. Aggregated gross margins increase by about one percentage point between SZEN1 and SZEN2. Despite substantial effects from irrigation in some eastern regions, further increases in gross margins from SZEN2 to SZEN3 are the result of agri-environmental premiums with substantial variation among Austrian NUTS-3 regions. Spatial targeting of agri-environmental programs can decrease budget spending and may become even more important under climate change due to a likely increasing variability of natural conditions over space and time. The results on irrigation indicate the high sensitivity of this adaptation measure to a changing climate.

Bio-physical impact studies such as those by EASTERLING et al. (2007) frequently show more pronounced adaptation effects as presented in this article. Besides likely differences among bio-physical modelling of adaptation measures, results from the IMF consider crop yield potentials, economic and policy constraints and incentives as well as interactions of land use and livestock systems. Consequently, such modelling system prevents solutions where marginal adaptation costs exceed benefits. This is analogous to the dumb farmer assumptions (SCHNEIDER et al., 2000) underlying SZEN1, which will hardly be observed in practice due to autonomous adaptation activities by

land users (REIDSMA et al., 2009). However, autonomous adaptation can be challenged by the "noisy nature of the climatic system", i.e. a high degree of weather variability, which can conceal climate trends (SCHNEIDER et al., 2000). Long-term incremental changes, such as observed for example for soil sediment loss, can be beyond the awareness of land users (MONTGOMERY, 2007) apart from potentially high private adaptation costs. It can justify research efforts and adaptation policies such as modelled in this article.

While average productivity changes can be severe for some regions or individual land users, several studies conclude that impacts from changes in agricultural policies, markets, and technologies likely will be more important over the coming decades (BINDI and OLESEN, 2010; FINGER et al., 2010; HERMANS et al., 2010; LEHMANN et al., 2013a; YE et al., 2013). By comparing the baseline scenario 2020 to the reference scenario in 2008 – although not further elaborated in this article – we can draw a similar conclusion. Results also indicate that crop management practices may have more impacts on crop yields and environmental indicators than climate change until 2050. Yet, the output response from climate change in the coming decades may still be important for food supply and the environment and likely becomes more pronounced, uncertain and potentially negative in the distant future (MORIONDO et al., 2010; ROSENZWEIG and TUBIELLO, 2007).

4.3 Environmental Impacts of Adaptation

The IMF output feeds into environmental indicators – SOC, soil sediment loss, land use intensity, irrigated area – to reveal direct and indirect climate change impacts. Results for changes in SOC and soil sediment loss are diverse depending on the RCM simulation. SOC tends to decrease until 2040 on both grasslands and croplands and challenges climate change mitigation from land use. Soil sediment losses on croplands tend to increase until 2020 but tend to decrease until 2040. More extreme impacts have been modelled for an Austrian case study with changes in soil sediment losses under conventional tillage of -55% to +56% depending on the climate simulation (KLIK and EITZINGER, 2010). Such mixed results reveal both the importance of high resolution impact assessments as well as uncertainty from regional climate modelling and site conditions (see section 4.4). Despite the median, extreme values are an important indicator to reveal regions prone to soil sediment loss (Figure 7). Both, changes in SOC and soil sediment losses highlight the link between climate change and

soil degradation (OLESEN et al., 2011). Soil conservation measures in SZEN3 increase SOC and decrease soil sediment loss rates on cropland. Changes in land use intensity are indicated by fertilizer application rates and extensive grassland management. Improving growing conditions lead to higher nutrient demands in all RCM simulations (SZEN1) which further increase due to autonomous adaptation in crop management (SZEN2). Climate change may also impact nutrient leaching, which has not been taken into account in the IMF. Irrigation is introduced in SZEN3 and can be seen as an effective adaptation measure, but only for selected field crops due to its high costs (e.g. QIU and PRATO, 2012). However, our model results likely overestimate the flexibility in irrigation choices due to neglected real world water constraints, which may even increase in the future under increasing competition from industry and domestic demand (OECD, 2012).

BINDI and OLESEN (2010) draw three adaptation pathways for farming systems in Europe, i.e. intensification, extensification, and land abandonment. In our scenarios, extensive grassland is declining in the model output in 2040 in all climate simulations. It can result from deteriorating production conditions or increasing productivity of extensive grasslands. The latter increases opportunity costs and may trigger intensification. With regards to indirect effects, improving production conditions on intensive grassland and temporary grassland (i.e. cropland) can increase forage supply and – given a certain livestock capacity – force extensive grasslands out of production. This second pressure appears more plausible in reality due to topographical constraints on intensification for typical extensive grasslands (e.g. alpine meadows), but can be biased by a rather inelastic capacity for livestock housing in PASMA. Consequently, whether or not maintenance of extensive grassland will benefit from climate change is also determined by forage demand, i.e. the development of livestock (ruminant) numbers (cf. BRINER et al., 2012; HENSELER et al., 2009). Furthermore, fertile production sites may face increasing intensification pressures (e.g. conversion from permanent grasslands to cropland) in the long run (compare to results from LECLÈRE et al., 2013), which would challenge CAP efforts on agri-environmental measures and maintenance of permanent grasslands (e.g. 1st pillar "greening" measure) and would likely further release SOC. Intensification and declining extensive grassland areas may negatively impact biodiversity despite likely pressures from direct climate change on natural and semi-natural habitats (cf. RENETZEDER et al., 2010).

4.4 Uncertainties

Our IMF results are uncertain from two major sources, i.e. input data and model structure. The former include climate, bio-physical and economic data such as plant and livestock production coefficients, input and output prices and agricultural policy assumptions. Bio-physical and economic data are drawn from national and international statistics, scientific literature, and stakeholder consultations and have been applied and improved in a number of modelling efforts. Their uncertainty is of minor importance in this article, as we focus on relative climate change impacts and the effectiveness of adaptation measures. A major source of uncertainty with respect to input data are climate change signals. Consequently, we analyse four contrasting RCM simulations based on different GCMs and only transmit relative changes on crop yields and environmental outcomes from EPIC to PASMA. EPIC results are averaged for three periods of 20 years to control for the variability in daily weather and to take non-linearity in climate trends into account. The latter can result in changing land use patterns among periods for an individual RCM simulation. For example, Figure 9 shows diverging trends for cropland between the climatological reference period 1991-2010 and the future period 2031-2050 for ETHZ_CLM and ICTP_RegCM. Our results confirm the importance of such procedure as climate change impacts and adaptation differ in magnitude, variability and sign.

Using multiple RCMs for impact and adaptation analysis allows stakeholders to develop strategies that cover a broad range of plausible futures. However, increases in aggregated gross margins for 2020 and 2040 appear as general pattern among all four climate simulations, while environmental indicators show mixed results. EASTERLING et al. (2007) discuss impact model uncertainties and point to three sources, i.e. large variation among GCM predictions on regional precipitation, poor representation of extreme events and assumptions on CO_2 fertilization effects. We include CO_2 fertilization (see discussion in 4.1) but do not test for its sensitivity. GCM and RCM uncertainty is addressed by the selection procedure of the four contrasting RCMs. Important to climate change impact analysis is the consideration of changing weather variability (MORIONDO et al., 2010; ROSENZWEIG and TUBIELLO, 2007) as well as extreme events. This is frequently claimed by stakeholders such as experts from extension services (MITTER et al., 2014). We cover some of these aspects by simulating bio-physical processes at daily time steps in EPIC.

It includes extreme weather situations such as dry and wet periods but does not take into account sub-daily heavy rainfall or hail events. Extreme weather events can have substantial impacts on farm resources (e.g. soils, infrastructure, buildings) and farm incomes (e.g. partial to full harvest losses, price variability from international markets). It should be analysed whether average productivity gains at the aggregated level suffice to cover costs from expected higher variability in the long run. By averaging crop results from multi-year simulations of crop rotations in EPIC, impacts of changing climate variability and effectiveness of crop management are covered by EPIC and transmitted to PASMA. However, aggregated impacts neglect probability estimates of individual crop performance, which would be required to analyse stability and resilience of production as demanded by ROSENZWEIG and TUBIELLO (2007). Even moderate changes in precipitation patterns can impact soil management schedules and, consequently, on-farm labour and machinery demand (RODRIGUEZ et al., 2011). We did not take labour and fixed capital constraints into account due to a lack of data and the regional modelling perspective in PASMA. It neglects some important farm constraints, which should be analysed by complementary bio-economic farm model studies. The second major source of uncertainty corresponds to model assumptions, which are discussed in the following section.

4.5 Model Assumptions

SCHNEIDER et al. (2000) point to the importance of revealing model assumptions, mainly those on adaptive agents, in integrated assessments in order to derive meaningful policy conclusions. We utilize positive mathematical programming (PMP) to calibrate land use and livestock management in PASMA to a reference scenario in 2008. This method substitutes for imperfect input data and systems knowledge by replacing linear with regionally calibrated quadratic cost functions. PMP enhances model performance as long as correct cost functions are chosen but also has important caveats such as its inability to consider management alternatives that have not been observed yet (cf. HENSELER et al., 2009). Consequently, PMP is well suitable for short to medium term time horizons with minor system changes. We assume that the current CAP reform as well as climate change assumptions are not fundamental enough to induce major system changes. According to recent decisions, Austria will abolish its suckler cow premium as a result of the CAP reform. This is not covered in our baseline scenario for 2020 and 2040 but – in combination to

the abolishment of dairy quotas – could be fundamental to Austrian farm structure. Moderate temperature increases and changes in precipitation as provided by the four RCM simulations may lead to changes in cropping patterns and management but may not lead to fundamental land use changes such as large scale conversion of cropland to grassland and vice versa. We are aware that the appropriateness of PMP in climate change adaptation studies is open to debate. However, it is beyond the scope of this article to test adaptation under alternative model structures.

The set of available adaptation measures in a model is crucial to reveal the vulnerability of agricultural systems. HOWDEN et al. (2007) raise concerns that many studies only take a small subset of adaptation measures into account focusing on marginal changes in production programmes (e.g. changing varieties, sowing dates, tillage operations) and consequently may underestimate adaptive capacity of agriculture to climate change. We have modelled a broad set of adaptation measures in the IMF, which are well established in the scientific literature and frequently claimed by stakeholders (cf. Austrian NAS; STICKLER et al., 2010). Land users are assumed to have homogeneous management skills and possess or at least have access to capital and farm equipment for adaptation (e.g. direct seed equipment). However, we do not consider new crop species in a NUTS-3 region. Instead, we apply convex combinations of crop mixes based on observed land use from the IACS data base to provide sufficient choice among production options while at the same time limiting unrealistic overspecialisation (cf. MCCARL, 1982). Agriculture will likely face more opportunities and impacts (e.g. new technologies not yet available) as well as constraints (e.g. lack of capital and access to technology) for adaptation than modelled in the IMF. Such alternatives, either new crops, crop varieties or other technologies, depend on a proper representation in the bio-physical modelling part. It includes important changing interactions with the natural system, e.g. new plant pests and diseases (HOWDEN et al., 2007; TUBIELLO et al., 2007), which are not represented in our results. Social science methods such as in-depth interviews with agricultural experts and farmers (e.g. OLESEN et al., 2011) may help in complementing quantitative modelling studies in situations with high uncertainty about the future as well as lacking data and system knowledge, although experts can be overwhelmed by this uncertainty and systems complexity at the same time. We assumed land users to have homogeneous management skills and to possess or at least have access to capital and farm equipment for adaptation (e.g. direct seed equipment). Lacking heterogeneity at the farm level likely leads to overestimating adaptive capacity as has been concluded by GIBBONS and RAMSDEN (2008). It is another example, where social science methods could improve integrated modelling approaches.

Impact and adaptation studies applying integrated modelling approaches frequently assume fixed input and output prices based on the small country assumption (cf. LECLÈRE et al., 2013). We take scenarios on future changes in supply and demand into account based on the OECD-FAO outlook (OECD-FAO, 2011). However, future prices do neither represent climate induced changes in market equilibrium of agricultural inputs and outputs nor developments beyond 2021. We must accept such inconsistencies within our model assumptions due to the high degree of uncertainty on future developments. Consequently, we may overestimate the positive impacts from climate change due to downward price effects from European wide productivity increases but conclusions on the effectiveness of particular adaptation measures likely hold even under such conditions. Nevertheless, national sectorial assessments should be complemented by studies that take developments of competitors in international markets into account. For example, HERMANS et al. (2010) analysed future competitiveness of the European farm sector based on three indicators: economic size, performance under climate change, and technological development. They conclude that Austria among other European countries will face increasing competition from north-western European states in the future due to small farm structures (HERMANS et al., 2010). Consequently, more favourable production conditions from climate change in absolute terms can be misleading if changes in competitiveness on international markets are neglected.

5 Conclusions

In this article, an integrated agricultural modelling framework (IMF) has been applied to analyse impacts from climate change and effectiveness of adaptation measures on Austrian agriculture. Modelled impacts from four regional climate model (RCM) simulations mainly show increasing productivity on average even in the absence of adaptation. However, impacts are regionally diverse due to heterogeneous climate change, land use, and bio-physical preconditions. Adaptation measures can alleviate impacts by reducing losses or increasing gains. Similar conclusions

have been derived by other authors such as WANG et al. (2009) for Chinese agriculture. Austria faces a situation typical for many industrialized countries where low risks are the result of slightly negative or even positive impacts and high adaptive capacity (see IGLESIAS et al. (2011) for a global impact assessment). The climate simulations in this article assumed annual temperature increases over Austria between +0.8°C and +1.8°C and changes in precipitation between -2.2% and +6.2% within 40 years. Limited losses or even gains from climate change may question climate change mitigation and adaptation efforts from the perspective of private and public stakeholders in temperate regions. However, such attitude is hazardous from a global perspective. It neglects impacts from climate change on many natural and human dimensions including human health or biodiversity, high vulnerability of agricultural regions mainly in the south and more severe impacts, which are expected also for temperate regions for the second half of the 21st century.

This article proves the value of integrated modelling tools for climate change impact analysis at two stages. Bio-physical models transfer climate change signals into crop yield changes stratified by site conditions and crop management choices. This allows interpretation and comparison of multiple climate simulations over decades to a baseline and is superior to surveys, where agricultural experts are easily overwhelmed by the amount of data, complexity of natural systems, and uncertain future conditions beyond personal experience. Secondly, by linking bio-physical process model output to an economic bottom-up land use optimization model, we are able to account for opportunity costs that limit adaptation response in reality. Hence, we differentiate between technical potential and economic feasible adaptation such as demanded by OLESEN et al. (2011). Substantial uncertainties remain, though, and should be covered by future research. It should account for extreme weather events in order to analyse whether average productivity gains at the aggregated level suffice to cover costs from expected higher climate variability. Climate change impacts on livestock, crop pests and diseases as well as the effectiveness of agri-environmental programs are further research issues to be covered in subsequent studies.

Many adaptation measures are autonomously applied by individual farmers. Nevertheless, policies are crucial in facilitating adaptation and in avoiding adverse adaptation effects. They mainly interfere at the level of planned adaptation including changes in farming systems, breeding of new crop varieties, or development of technologies or infrastructure (BINDI and OLESEN, 2010; HOWDEN et al., 2007). In this article, we analyse the role of policies to foster the uptake of typical adaptation measures, i.e. adoption of irrigation, reduced tillage, and planting of winter cover crops. The latter measures are supported by premiums comparable to current agri-environmental payments in Austria and prove to be effective in reducing topsoil carbon losses and soil sediment losses despite potential budget gains from spatial targeting. We have also analysed irrigation, which proves to be effective for certain crops and regions with high variability among the RCM simulations. Water limitations have not been taken into account, which likely overestimates irrigated land under climate change. However, policies impact water availability at various stages such as by legislation on water rights, water pricing and infrastructure development. Consequently, all policies towards climate change adaptation need to take regional heterogeneity into account (cf. BINDI and OLESEN, 2010).

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Appendix 1. Relative changes in average crop yields with conventional tillage and high fertilizer intensity between the climatologic reference period 1991-2010 and the future period 2031-2050
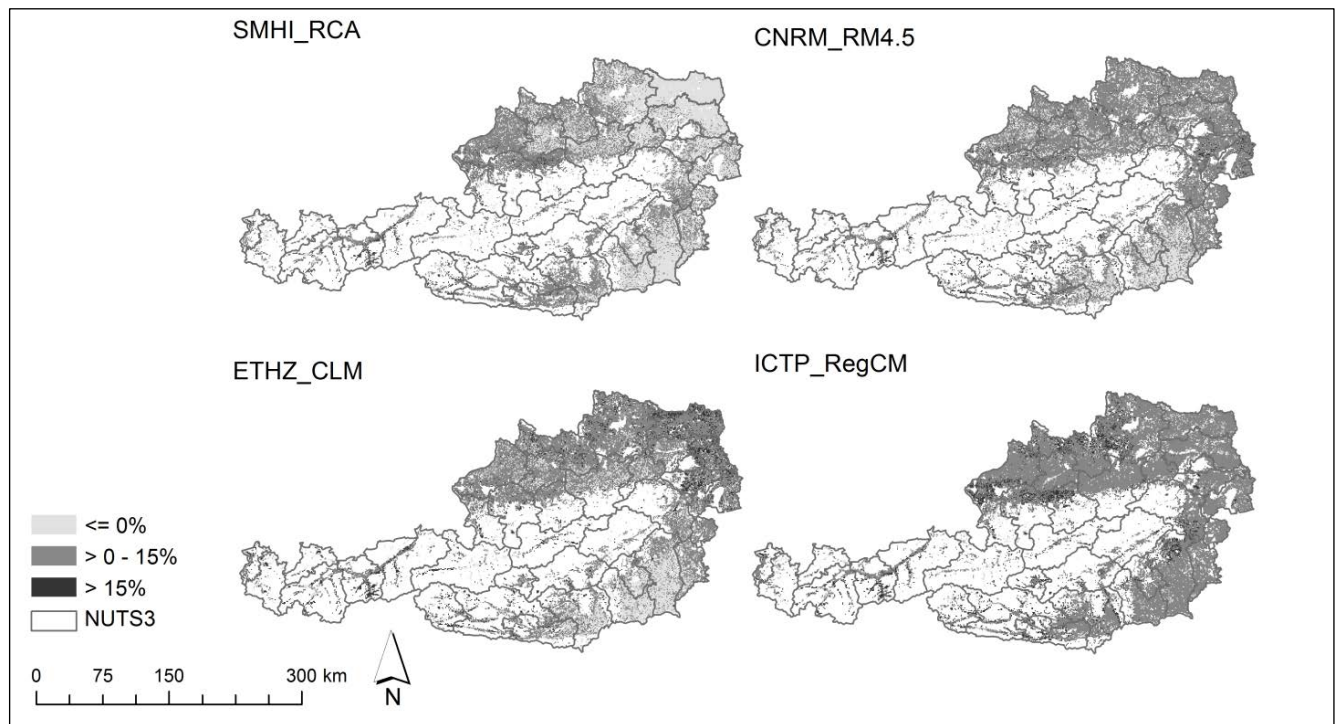
Note: cropland in white areas not considered.
Source: own construction

Appendix 2. Boxplots of relative changes in average grassland forage yields between the climatologic reference period 1991-2010 and the future period 2031-2050 by fertilization intensities
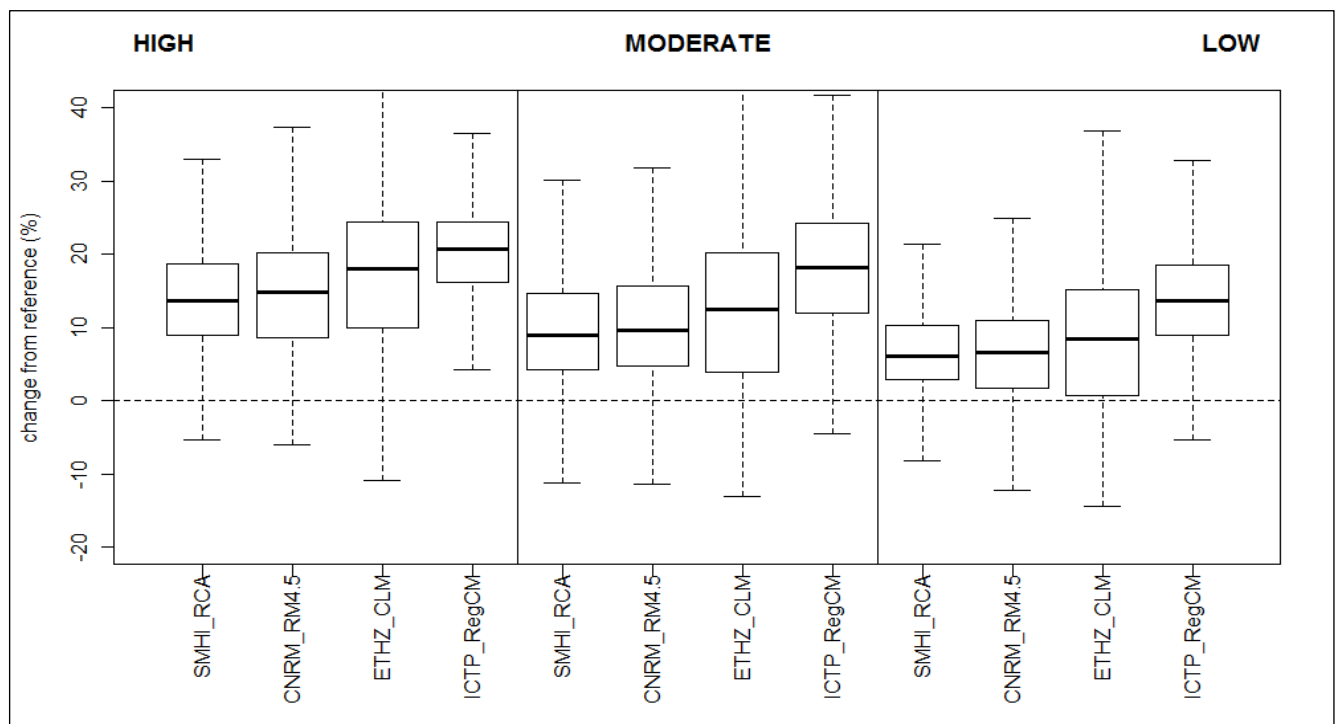
Note: the outliers are not presented.
Source: own construction