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Integrated modelling of protein crop production responses to climate change and agricultural policy scenarios in Austria

Hermine Mitter[1,*], Erwin Schmid[1], Franz Sinabell[2]

[1]**University of Natural Resources and Life Sciences, Vienna, Institute for Sustainable Economic Development, Feistmantelstrasse 4, 1180 Vienna, Austria**

[2]**WIFO – Austrian Institute of Economic Research, Arsenal Object 20, 1030 Vienna, Austria**

ABSTRACT: Climate and policy changes are likely to affect protein crop production and thus trade balances in Europe, which is highly dependent on imports. Exemplified for Austrian cropland, we developed an integrated modelling framework to analyze climate change and policy scenario impacts on protein crop production and environmental outcomes. The integrated modelling framework consists of a statistical climate change model, a crop rotation model, the biophysical process model EPIC, and the economic bottom-up land use optimization model BiomAT. EPIC is applied to simulate annual dry matter crop yields for different crop management practices including crop rotations, fertilization intensities, and irrigation, as well as for 3 regional climate change scenarios until 2040 at a 1 km grid resolution. BiomAT maximizes total gross margins by optimizing land use choices and crop management practices subject to spatially explicit cropland endowments. The model results indicate that changes in agricultural policy conditions, cropland use, and higher flexibility in crop management practices may reduce protein import dependence under changing climatic conditions. Expanding protein crop production is most attractive in south-eastern Austria with its Central European continental climate where maize is most often replaced in crop rotations. However, the acreage of protein crops is limited by agronomically suitable cropland. An intended side effect is the reduction of nitrogen fertilizer inputs by about 0.1% if total protein crop production increases by 1%.

KEY WORDS: Climate change impact · Adaptation · Soybean · EPIC · Common Agricultural Policy · Land use

1. INTRODUCTION

The European food and feed industry highly depends on imported protein crop commodities and processed products (see e.g. the discussion on the 'EU protein deficit' in European Parliament 2011). Net imports elevate greenhouse gas emissions outside the EU (Davis & Caldeira 2010) mainly due to land use changes in the exporting countries (Castanheira & Freire 2013, Kim & Kirschbaum 2015). Soybean (*Glycine max*) and processed products are mostly imported from Brazil, Argentina, and the US (FAOSTAT 2015). From a global perspective, soybean cultivation has become more profitable in the last decades due to increasing mean annual crop yields and decreasing inter-annual crop yield variability (Iizumi et al. 2014). Among other outcomes, this development has contributed to the observed increases in geographical spread and abundance of soybean in national food supplies (Khoury et al. 2014). In the EU, commonly used soybean varieties are not competitive compared to maize (*Zea mays*)

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*Corresponding author: hermine.mitter@boku.ac.at

or wheat (T*riticum*) (Schreuder & de Visser 2014), although their positive effect on subsequent crops has been shown (see e.g. Brisson et al. 2010), and some progress in breeding has been made (see e.g. Sato et al. 2014). Cultivating protein crops such as field pea (*Pisum sativum*) and faba bean (*Vicia faba*) is even less attractive for farmers in the EU. Whether this situation will prevail in the next decades is heavily dependent on changes in climate and agricultural policies which may affect protein crop production.

With respect to protein crops, climate change impact and adaptation studies are limited to soybean, whereas minor crops such as field pea and faba bean are typically not considered. Simulation results for soybean are mixed. For example, Tai et al. (2014) projected decreases in mean soybean production in Europe under the RCP4.5 and RCP8.5 for the next decades. According to Lobell et al. (2011), soybean production does not exhibit a significant trend at the global scale, meaning that gains in some countries are swamped by losses in others. For Europe, they found slightly negative impacts. Similarly, Deryng et al. (2014) identified high regional disparities in soybean yield responses until 2050 and 2080, i.e. a similar number of areas show positive and negative effects, respectively. For Austria, slightly increasing soybean yields are projected until 2040 under a moderate climate change scenario (Mitter et al. 2015c). Climate change impacts on soybean yields are likely more beneficial than for maize, which is seen as the most competitive crop to soybean (Schreuder & de Visser 2014). Soybean requires higher temperatures for optimal growth (Sakurai et al. 2011, Parent & Tardieu 2012), it is more tolerant to extreme temperatures (Schlenker& Roberts 2009), and as a C3 plant, it is expected to benefit more from CO_2 fertilization (see e.g. Ainsworth et al. 2002, 2008, Long et al. 2004, Deryng et al. 2014).

Changing climatic conditions stress the need for adequate policy and farm management responses in order to facilitate sustainable cropland use and to maintain or increase global food production and quality (Porter & Semenov 2005, Rosenzweig et al. 2014). In the EU, food supply may be enhanced by devoting more cropland to food production and optimizing crop management choices (Foley et al. 2011). Policy incentives by the Common Agricultural Policy (CAP) may support such developments (Finger 2010, Benton et al. 2011). One important element is the 'greening component' introduced by the recent CAP reform (European Commission 2011, European Parliament & European Council 2013). Most farmers have to establish ecological focus areas (EFAs) on 5% of their cropland in order to be eligible for direct payments. EFAs primarily aim at protecting and promoting biodiversity and landscape features. The environmental benefits of the greening are discussed critically (see e.g. Matthews 2013), since cropland — as compared to grassland and set-aside land (i.e. land that is not used for any agricultural purpose) — typically affords fewer environmental benefits (Mouysset 2014). However, land use effects on biodiversity are mainly driven by local and regional conditions as well as the species deserving protection (Tscharntke et al. 2012, Schneider et al. 2014) and policies that have robust propositions are rare. Since nitrogen-fixing crops such as soybean, field pea, and faba bean may be planted on EFAs (European Parliament & European Council 2013), this policy change could increase protein crop supply in the EU.

Protein crop production, climate change, and agricultural policy reforms are interrelated, but systematic quantitative studies including minor crops such as field pea and faba bean are still lacking. Previous investigations mostly focused on the response of single protein crops (e.g. soybean) to climate and policy change (e.g. Iglesias et al. 2012), and only a small number of studies compared different crop rotations including crops with limited geographical spread (White et al. 2011). Still, the integration of minor crops in quantitative analyses has been identified as being important in spatially explicit assessments at regional and national scales in order to derive robust results and conclusions (Mitter et al. 2015a). Furthermore, the competitiveness of protein crop production in Europe has been identified as a knowledge gap (Schreuder & de Visser 2014).

In order to address these aspects, we provide a spatially explicit, integrated modelling framework with direct links between protein crop production, climate change, and policy impacts in a temperate climate zone. Exemplified for Austrian cropland, the modelling framework consists of a statistical climate change model for Austria (ACLiReM; Strauss et al. 2012, 2013a), the crop rotation model CropRota (Schönhart et al. 2011), the bio-physical process model 'Environmental Policy Integrated Climate' (EPIC; Williams 1995), and a bottom-up economic land use optimization model for Austria (BiomAT; Asamer et al. 2011, Stürmer et al. 2013).

The integrated analysis is guided by 2 research questions: (1) How will climate change affect the competitiveness of protein crops relative to other crops, and (2) What are the likely impacts of the CAP 2013 reform on protein crop production and land use

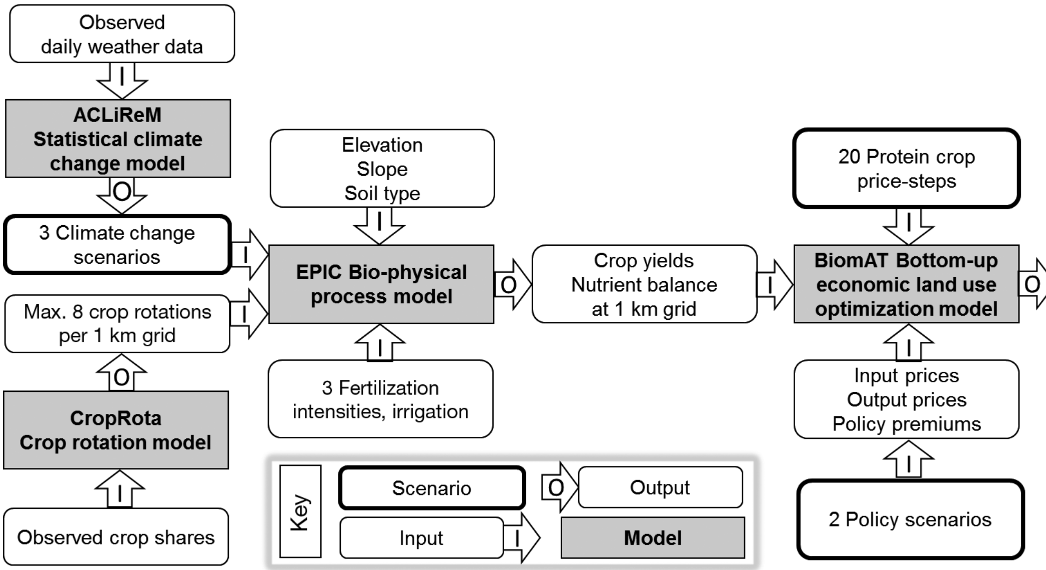

Fig. 1. Integrated modelling framework. Components of the diagram are defined in the key

in Austria? We investigated this topic from 4 different angles:

(i) We quantified the impacts of 3 regional climate change and 2 agricultural policy scenarios on protein crop production (i.e. soybean, field pea, and faba bean) considering that additional cropland will be available due to the recent CAP reform.

(ii) We computed marginal opportunity costs of expanding protein crop production on land that was previously set-aside and by changing crop rotations and crop management intensities.

(iii) We used the marginal opportunity costs to assess the economic potential of domestic protein crop production considering different degrees of flexibility in crop rotation choices.

(iv) We analyzed environmental effects of expanding domestic protein crop production by changes in nitrogen fertilizer and irrigation water inputs.

2. INTEGRATED MODELLING FRAMEWORK

The integrated modelling framework couples 4 stand-alone models, viz. ACLiReM, CropRota, EPIC, and BiomAT (see corresponding sub-sections below). The models are sequentially employed in order to produce results on the economic potential of protein crop production on Austrian cropland at a 1 km grid resolution. The spatially explicit model outputs of ACLiReM, CropRota, and EPIC mainly serve as input into the BiomAT model, although the results of each modelling step are worthy of analysis as well. An overview of the modelling framework and the model interfaces is provided in Fig. 1.

2.1. Statistical climate change model for Austria (ACLiReM)

The Austrian Climate Change Model using Linear Regression (ACLiReM; Strauss et al. 2012, 2013a) provides physically, spatially, and temporally consistent climate change scenario data with a spatial and temporal resolution of 1 km and 1 d, respectively, for the period 2010–2040. It builds on historically observed daily weather station data from 1975–2007. Methodologically, the model consists of 2 main components. Firstly, a linear regression model with linear and seasonal time dependencies was employed to estimate a national temperature trend for the historical period. The identified linear temperature trend of approximately +0.05°C per year was extrapolated to the future period 2008–2040, resulting in a mean temperature increase of about 1.5°C until 2040. The temperature trend serves as a basis for all climate change scenarios. Secondly, repeated bootstrapping was applied for historical temperature residuals, and observations of precipitation sums, wind speed, solar radiation, and relative humidity. Scenarios combining the linear temperature trend with the bootstrapped weather parameters form the basis of exogenously assumed changes in precipitation sums. Three precipitation scenarios are used in our analysis. Mean daily precipitation sums are assumed to remain similar as in the past (reference scenario REF), increase by 20% (scenario WET), or decrease by 20% (scenario DRY) compared to the reference scenario REF. The climate change scenarios are considered to span the currently expected range of climate projections in Austria until 2040 (see e.g. Loibl et al. 2009, 2011, Gobiet et al. 2012, 2014). ACLiReM captures small-scale climate patterns and the development of local and regional climates in the next decades. This is of particular relevance in a topographically heterogeneous region such as Austria, where regional climate model (RCM) projections face particular uncertainties (Schiermeier 2010). However, the applied statistical approach is limited by the assumption that the observed temperature trend will remain similar in the next decades (Strauss et al. 2012, 2013a). Such limitations may be overcome by using downscaled and error-corrected climate data from general circulation models (GCMs) or RCMs instead.

2.2. Crop rotation model (CropRota)

CropRota generates crop rotations typical to each Austrian municipality. The CropRota database consists of agronomic data and observed crop mixes from more than 2000 municipalities. The crop rotations are derived by maximizing their total agronomic value, which is based on expert judgments on the suitability of pre-crop/main-crop combinations and subject to agronomic constraints including, for instance, the maximum frequency of a crop in a crop rotation (see Schönhart et al. 2011). At present, the model accounts for 22 crops, including winter and spring cereals, maize, oil and protein crops, root crops, and temporary grasslands. The crops cover about 90% of the approximately 1.27 million ha of Austrian cropland. The crop rotations computed at the municipality level are assigned to the observed cropland shares of each 1 km cropland grid cell (see Fig. S1 in the Supplement, available at www.int-res.com/articles/suppl/c065p205_supp.pdf) in order to derive spatially explicit results.

For this analysis, CropRota was applied to develop 8 crop rotation scenarios per cropland grid cell. The crop rotations typically consist of 1 to 6 crops in a sequence. They are limited to the present crop portfolio in the respective municipality but differ in the abundance of crop groups, i.e. new crops are not allowed in the crop rotations, but the share of already observed crops (e.g. soybean) or crop groups (e.g. protein crops) can be changed. This assumption seems reasonable because farmers tend to introduce more suitable cultivars in preference to new crops (Olesen et al. 2011). The scenario ‘hist’ reflects historical crop mixes, i.e. the cropland share of each crop summed over all simulated crop rotations at a 1 km grid level represents the historically observed crop mix at the municipality level. Contrary to ‘hist,’ land previously set-aside can be used for crop production in the other crop rotation scenarios, although according to the greening requirements, we assume that grassland is maintained, i.e. not converted to cropland. The scenarios differ with respect to the crops that are allowed to be produced on a larger proportion of the cropland than observed in the past, i.e. whether the 3 simulated protein crops soybean, field pea, and faba bean (‘prot 1–3’) or only soybean (‘soy 1–3’) replace set-aside land. ‘Prot 1–3’ respond to the recent CAP reform, which allows for cultivating soybean, field pea, and faba bean on EFAs. ‘Soy 1–3’ are motivated by the efforts devoted to the promotion of genetically modified organism (GMO)-free soybean cultivation and processing in the Austrian and European Danube region by the Danube Soya initiative (see www.donausoja.org for further details on the Danube Soya initiative and the introduction of the trademark Danube Soya). The 3 different crop rotations prot 1–3 (and soy 1–3, respectively) are derived by alternative assignment of simulated crop rotations to the cropland grid cells within the municipality. In addition, a maize-dominated crop rotation (‘maize’) is simulated in order to better reflect the competition between protein crops and maize-dominated crop rotations.

Agronomic restrictions are also taken into account in the simulations. Protein crop production is limited to cropland grid cells with similar physical, agronomic, and climate characteristics as in the regions where production currently takes place. Providing up to 8 crop rotations per cropland grid cell increases the flexibility in production choices in the subsequent modelling steps.

2.3. Bio-physical process model (EPIC)

EPIC (Williams 1995) simulates bio-physical processes in the soil–crop–atmosphere system in order to derive outputs on annual dry matter crop yields (i.e. grain and forage yields at 0% moisture) and environmental parameters for different crop management practices. Among other factors, input data comprise spatially explicit information on daily weather parameters, soil characteristics by soil layer, topography, and crop management. Daily weather data for maximum and minimum temperature, precipitation, solar radiation, relative humidity, and wind speed are provided by ACLiReM. Soil data include silt, sand, and clay contents, humus content, pH, calcium carbonate content, and the content of coarse fragments (extracted from http://gis.lebens ministerium.at/eBOD/frames/index.php?&146=true&gui_id=eBOD). Topographic information is expressed by elevation and slope and is derived from the digital elevation model from the global shuttle radar topography mission. Crop management practices include changes in timing of cultivation (e.g. sowing, tillage, fertilizer application, and harvesting dates), 8 crop rotations (as described in Section 2.2), 3 fertilization intensity levels (high, moderate, low) in rain-fed agriculture, and irrigation. Timing of cultivation is determined by EPIC and is scheduled by fractions of heat unit accumulations. It changes from the historical to the future period but remains similar for the 3 climate change scenarios because of the assumed uniform temperature trend (see Section 2.1).

The fertilization rates differ by crop and are defined according to legal standard policy guidelines, e.g. Guidelines for Appropriate Fertilization (BMLFUW 2006), Action Program Nitrate 2012 (BMLFUW 2012), and Special Directive ÖPUL 2015 (BMLFUW 2015). The Action Program Nitrate 2012, which implements Directive 91/676/EWG (Council of the European Communities 1991), defines legally binding maximum levels of crop-specific nitrogen inputs. With respect to phosphorus inputs, farmers need to respect the reference values specified by BMLFUW (2006, 2012) in order to be eligible for agri-environmental payments (BMLFUW 2015). On average, total nitrogen and phosphorus inputs are reduced by about 20 and 40% in moderate and low treatments, respectively, compared to high fertilization intensity. Irrigation is assumed to take place only on intensively cultivated cropland, i.e. combined with high fertilization intensity. This is the predominant irrigation practice in Austria because high investment costs for irrigation equipment are only profitable if high crop yields and gross margins can be achieved. The application of irrigation water is automatically triggered in EPIC such that 90% of the crop growing period is water stress free for the crops. The maximum annual irrigation volume is limited to 500 mm. Irrigation water constraints are not considered.[1] The CO_2 fertilization effect is taken into account in EPIC. The potential evapotranspiration is estimated with the Penman-Monteith method in order to capture the effects of changes in CO_2 (Monteith 1965, Monteith & Moss 1977, Stockle et al. 1992).

EPIC simulations were performed for the historical period (1975–2005) and the 3 climate change scenarios (REF, WET, DRY) in the future period (2010–2040). In the historical period, 1 crop rotation ('hist') is considered in combination with the 3 fertilization intensities and irrigation, resulting in 4 alternative crop management practices. In the future period, 8 crop rotations are combined with the 3 fertilization intensities and irrigation, leading to 32 distinct crop management practices. The simulations were performed at a 1 km grid resolution for a total number of 40 244 cropland grid cells in Austria.

2.4. Bottom-up economic land use optimization model (BiomAT)

BiomAT (Asamer et al. 2011, Stürmer et al. 2013) seeks to maximize the sum of average crop gross margins of alternative crop management practices including 8 crop rotations, 3 fertilization intensities, and irrigation subject to the spatially explicit cropland endowments at 1 km grid cell resolution. The modelling is performed in 2 steps. (1) Average annual crop gross margins are calculated by crop management practice and cropland grid cell, and include revenues, variable production costs, and agricultural policy premiums. Revenues are calculated by multiplying annual crop yields simulated with EPIC by the average commodity prices of the period 2007–2009 as reported by Statistics Austria (2013b). Variable production costs cover expenses for seeds, fertilizers, herbicides, fungicides and pesticides, fuel and electricity, costs of repair, insurance, irrigation, and labor and are mainly taken from the standard gross margin catalogue (BMLFUW 2008) and other data sources (e.g. Heumesser et al. 2012). Additionally, annualized capital costs for irrigation equipment of 213 € ha^{-1} are included (for further details see Table S1 in the Supplement and Heumesser et al. 2012). Two agricultural policy scenarios are considered in the investigations. (i) In the first scenario, agricultural policy premiums involve a uniform decoupled payment (DP) of 290 € ha^{-1} and agri-environmental payments (AEP) for moderate (50 € ha^{-1}) and low fertilization intensity levels, i.e. abandonment of commercial nitrogen fertilizer inputs (115 € ha^{-1}; BMLFUW 2009). We refer to this scenario as 'DP-AEP'. (ii) The 'no AEP' policy sce-

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[1] In Austria, statistical data on irrigation volumes are limited to the year 2010. Average input volumes amounted to 690 mm in 2010, with markedly higher inputs applied in gardening companies and below-average inputs reported for crop farms. Protein crops were cultivated on 0.11% of the total irrigated cropland (Statistics Austria 2013a). However, these values are driven by weather conditions in 2010 and are not representative for a longer period of time. Irrigation relies mainly on groundwater availability (Statistics Austria 2013a). Since information on groundwater levels and flow is limited, we assume that sufficient irrigation water is available across Austria.

Table 1. Scenario overview. Policy scenarios: DP: decoupled payment (290 € ha^{-1}), AEP: agri-environmental payments (50 € ha^{-1} for moderate and 115 € ha^{-1} for low fertilization intensity levels), REF: reference. Climate scenarios: PAST: observed daily temperature and precipitation. REF, WET, and DRY refer to a temperature increase of 0.05°C yr^{-1} and differ in assumed changes in mean annual precipitation sums. In the PAST scenario, the crop rotation 'hist' is applied. In REF, WET, and DRY under the 'DP-AEP' policy scenario, 8 crop rotation scenarios are applied, in which the number of crop rotations considered in the BiomAT simulations is increased gradually, i.e. from 1 to a maximum of 8 crop rotations. The crop rotation scenario in 'no AEP' considers 8 crop rotations. The results presented in Section 3 refer to the model runs including all 8 crop rotations, the sole exception being Fig. 6 where additional crop rotation scenarios are shown. CAP: Common Agricultural Policy

	PAST 1975–2005	REF 2010–2040		WET 2010–2040		DRY 2010–2040	
Policy scenarios	DP-AEP	DP-AEP	no AEP	DP-AEP	no AEP	DP-AEP	no AEP
Crop rotation scenarios	1	8	1	8	1	8	1
CAP set-aside (%)	ca. 5	0	0	0	0	0	0
Protein crop price-steps	20	20	20	20	20	20	20

nario assumes that the uniform decoupled payment remains the same as in the 'DP-AEP' scenario, but agri-environmental payments are abolished.

(2) We computed marginal opportunity costs of expanding protein crop production, e.g. on previously set-aside land. The marginal opportunity costs measure the marginal net benefit of the best cropping alternative that has to be sacrificed for each additional hectare of protein crop (soybean, field pea, and faba bean). Commodity prices of protein crops are assumed to be representative of their marginal costs, which is reasonable in competitive markets. We used 20 commodity price-steps for the 3 protein crops (ranging from −90 to +300% of the average protein commodity price in the period 2007–2009) to compute corresponding production quantities and marginal opportunity costs. The first price-step refers to a price decline of 90%, the tenth price-step reflects the historically observed price level, and the last price-step denotes a 3-fold price increase of protein crop commodities. Only protein crop prices change, while prices of other crops and operating inputs remain unchanged. Additional costs associated with bringing set-aside land into production are not included in the analysis.

The model was separately solved for each cropland grid cell for the historical period (1975–2005) and the future period (2010–2040) as well as for the 20 protein crop price-steps. In the historical period, 1 crop rotation ('hist') was applied with the 'DP-AEP' policy scenario. For the future period, we performed 27 model runs, i.e. 9 model runs for each of the 3 climate change scenarios REF, WET, and DRY. The model runs differ by the employed crop rotation(s) and policy scenario. All 8 crop rotations (i.e. 'hist,' 'prot1–3,' 'soy1–3,' and maize) are combined with the 2 policy scenarios (i.e. 'DP-AEP,' 'no AEP') to filter out potential agricultural policy impacts. Additionally, the number of crop rotations is gradually increased in the simulations in order to show the effect of higher flexibility in crop management choices under the 'DP-AEP' policy scenario. Table 1 provides an overview of the scenario specifications in BiomAT. The optimization problem is given in Eq. (1):

$$\begin{aligned} &\max \text{TGM} = \sum_{i,m} \pi_{i,m} x_{i,m} \\ &\text{s.t.} \sum_{m} x_{i,m} \leq b_i \qquad \forall \ i \end{aligned} \tag{1}$$

where TGM is the total crop gross margin in € that is going to be maximized, and π is the average annual crop gross margin in € ha^{-1} that can be achieved with different crop management practices *m* at each 1 km cropland grid cell *i* (in total 40 244). Crop management practices *m* include alternative crop rotations, fertilization intensities, and irrigation, which amount to a total of 32. *x* represents the share of cropland in ha with regard to crop management practices *m* by cropland grid cell *i*. 's.t.' stands for 'subject to' and defines the resource constraint. The resource constraint *b* denotes total available cropland area in ha per cropland grid cell *i*.

3. RESULTS

We analyzed climate change and policy impacts on the economic potential of protein crop production in Austria by modelling their marginal opportunity costs in various scenarios. Climate change is captured by the 3 climate change scenarios REF, WET, and DRY. In addition, 2 policy scenarios were assessed. The first one ('DP-AEP') represents the current agricultural policy premiums, whereas the second one assumes the abolition of agri-environmental payments ('no AEP'). In both scenarios, set-aside land is made available for future crop production and is mainly used for protein crops; this refers to the

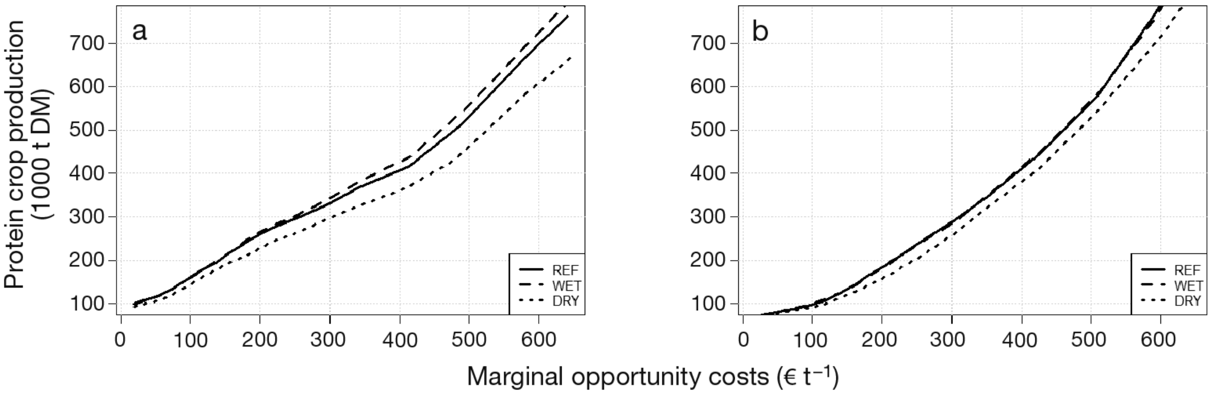

Fig. 2. Computed protein crop production responses and associated marginal opportunity costs for the 3 climate change scenarios REF (reference scenario, in which mean daily precipitation sums are assumed to remain similar to those in the past), WET (20% increase in daily precipitation sums compared to REF), and DRY (20% decrease in daily precipitation sums compared to REF) in the policy scenarios (a) 'DP-AEP' and (b) 'no AEP' in Austria, where DP is a uniform decoupled payment of 290 € ha^{-1} and AEP are agri-environmental payments for moderate (50 € ha^{-1}) and low fertilization intensity levels (115 € t^{-1}). DM: dry matter

greening component of the recent CAP reform. Commodity price-steps for protein crops complement the set of assumptions. Note that the model results in Subsections 3.1–3.5 refer to BiomAT model outputs obtained by applying the integrated modelling framework described in Section 2.

3.1. Marginal opportunity costs of expanding domestic protein crop production

Protein crop supply responses to stepwise changes in protein crop commodity prices are presented in Fig. 2 for the 3 climate change scenarios REF, WET, and DRY at the national level. Fig. 2a refers to the 'DP-AEP' policy scenario, whereas Fig. 2b assumes that agri-environmental payments are abolished ('no AEP'). Expanding protein crop production leads to increasing marginal opportunity costs, regardless of the climate change and policy scenario, although slightly stronger rises are simulated for the 'no AEP' policy scenario up to a production volume of about 400 000 t. For instance, protein crop production of around 250 000 t is associated with marginal opportunity costs of around 200 € t^{-1} in 'DP-AEP' and of around 250 € t^{-1} in 'no AEP'; protein crop production of around 400 000 t leads to marginal opportunity costs of around 400 € t^{-1} in both policy scenarios. In order to obtain the same level of protein crop output, marginal opportunity costs are higher in the climate change scenario DRY. This suggests that average gross margins are lower under dry production conditions and makes protein crop cultivation slightly less attractive in DRY compared to the scenarios REF and WET. Marginal opportunity costs of protein crop production expansion under humid climate conditions (WET) are similar to those in the scenario REF, with precipitation sums similar to those observed in the past.

At the national level, an expansion of the current protein crop production by about 25% leads to an increase in marginal opportunity costs by about 45% in the climate change scenario REF and in the policy scenario 'DP-AEP', although there are regional differences in the shares of protein crops on cropland as shown in Fig. 3. The maps refer to the climate change scenario REF and the policy scenario 'DP-AEP' and different levels of marginal opportunity costs in expanding protein crop production in Austria, i.e. 19, 115, 194, 294, and 642 € t^{-1}.[2] In general, the marginal opportunity costs are low, between 19 and 115 € t^{-1}, if previously set-aside land is used for expanding protein crop production. They are higher, between 294 and 642 € t^{-1}, in the current crop production hotspots in the northwestern and eastern parts of the country where crops such as maize are partly replaced by soybean, field pea, or faba bean.

If protein crops are included in the crop rotations in around 10% of the cropland grid cells, marginal opportunity costs of expanding their production amount to 19 € t^{-1} (Fig. 3a). Expanding protein crops to about 23 and 46% of the cropland grid cells increases their

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[2] The maps look similar for the 'no AEP' policy scenario in REF and for the climate change scenarios WET and DRY ('DP-AEP' policy scenario). They are shown in Figs. S2–S4 in the Supplement. Topographical information on Austrian cropland is provided in Fig. S7 in order to facilitate the spatial interpretation of the results. Land that was set aside in the historical period (1975–2005) is shown in Fig. S8

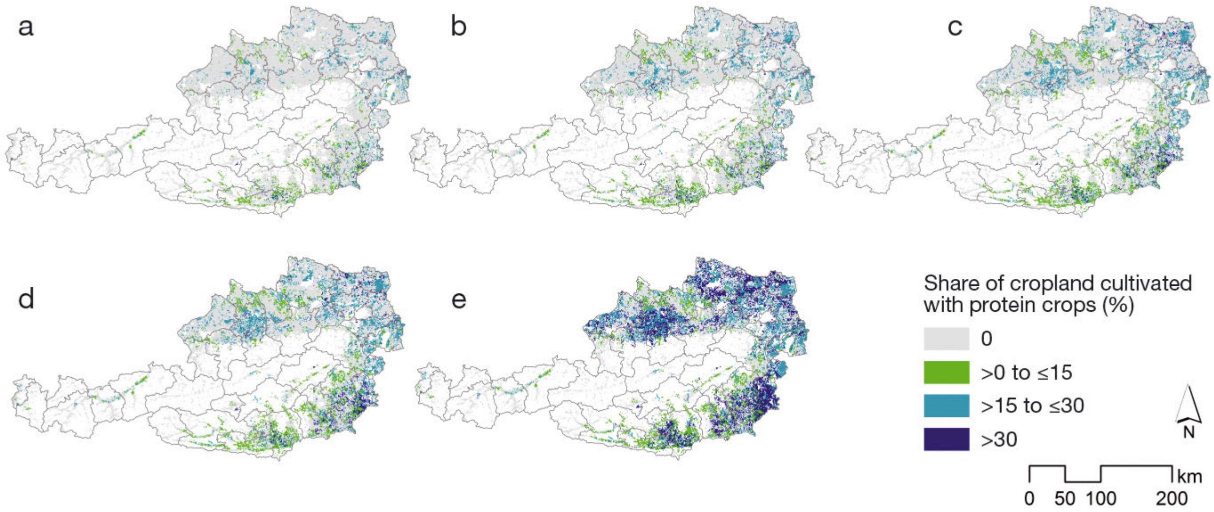

Fig. 3. Relative shares of protein crops on cropland at 5 levels of marginal opportunity costs in the climate change scenario REF and the policy scenario 'DP-AEP' (see Fig. 2 for scenario definitions). The maps show 5 levels of marginal opportunity costs in expanding protein crop production and the associated shares of protein crops on cropland, i.e. (a) 19, (b) 115, (c) 194, (d) 294, and (e) 642 € t^{-1}. Cropland in white areas is not considered. Administrative boundaries (Nomenclature of Territorial Units for Statistics, NUTS 3) are shown for better orientation

marginal opportunity costs to 194 € t^{-1} (Fig. 3c) and 642 € t^{-1} (Fig. 3e), respectively. Increasing relative shares of protein crops in cropland grid cells will increase the marginal opportunity costs. If protein crops dominate cropland grid cells (relative shares exceed 30%), the marginal opportunity costs of expanding their production rise to 294 € t^{-1} (in particular in the southeast) or to 642 € t^{-1} (in particular in the north and the south). Thus, the model results indicate that extending protein crop production is more favorable in southeastern Austria.

3.2. Land use change and crop management choices

Relative shares of different crop groups cultivated on Austrian cropland are depicted in Fig. 4 for the reference climate change scenario REF and the policy scenario 'DP-AEP' at different levels of marginal opportunity costs in expanding protein crop production in Austria. The national shares of protein crops on cropland range between 2 and 17%, with marginal opportunity costs in expanding protein crop production between 19 and 642 € t^{-1}. The largest increases are found for soybean, followed by faba bean and field pea. The highest share of cropland (between 46 and 47%) is allocated to cereals in each climate change and policy scenario. While barley (*Hordeum vulgare*) and triticale seem to benefit in the crop rotations, the shares of other cereals such as rye (*Secale cereale*) or oats (*Avena sativa*) are diminishing. Acreages of maize, oil crops, root crops, and other

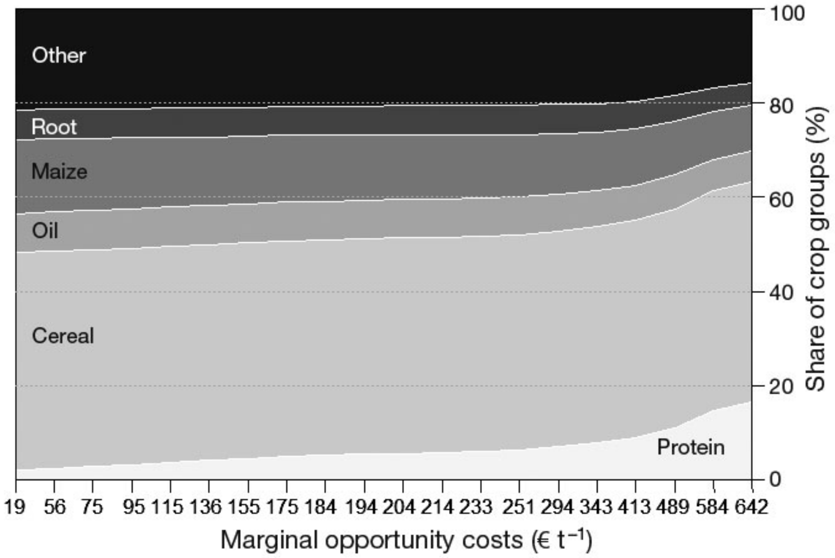

Fig. 4. Relative shares of 6 crop groups on cropland by marginal opportunity costs of expanding protein crop production in the climate change scenario REF and the policy scenario 'DP-AEP' in Austria (see Fig. 2 for scenario definitions). Crop groups (differentiated by color shades in the graph) include protein crops, cereals, oil crops, maize, root crops, and others

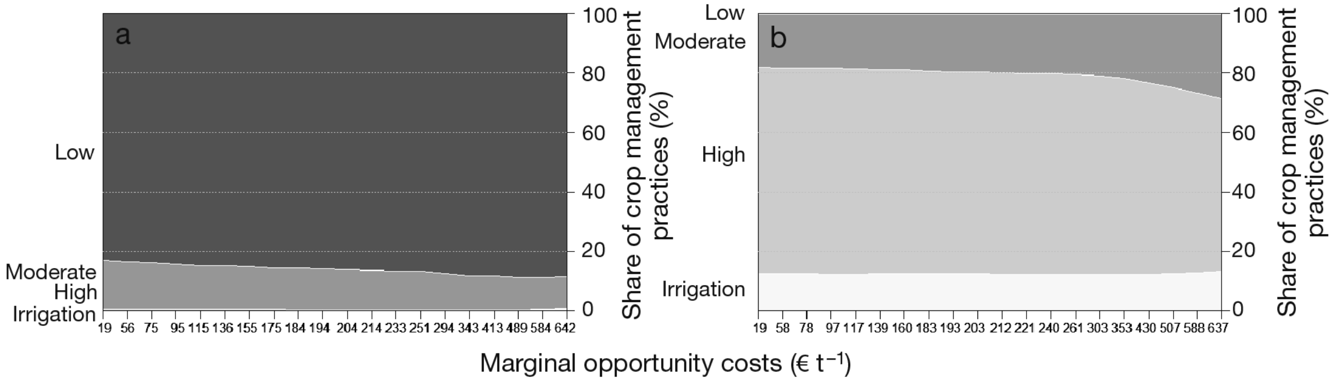

Fig. 5. Relative shares of crop management practices on cropland by marginal opportunity costs of expanding protein crop production in the climate change scenario REF and the policy scenarios (a) 'DP-AEP' and (b) 'no AEP' in Austria (see Fig. 2 for scenario definitions). Crop management practices include high fertilization intensity on irrigated cropland as well as high, moderate, and low fertilization intensity on rain-fed cropland (differentiated by color shades in the graph)

crops decline steadily when protein crops are expanded. The largest decreases are found for maize (about 38%). The cropland shares of alternative crop groups are similar for the climate change scenarios WET and DRY and the policy scenario 'no AEP', as shown in Fig. S5 in the Supplement. With respect to protein crops, soybean expansion is predominant in all scenarios, although, in relative terms, faba bean and field pea benefit more in the 'no AEP' compared to the 'DP-AEP' scenario. This is mainly due to smaller absolute reference values for faba bean and field pea in 'no AEP', meaning that the ratio of protein crop acreages is similar in 'DP-AEP' and 'no AEP'. Our model results suggest that neither climate change nor the abolishment of AEP may considerably impact crop mixes in temperate cropping regions like Austria in the next decades if input prices and commodity prices of non-protein crops are assumed to remain constant and new crops are not allowed in the crop rotations. However, a 2-fold increase in domestic protein crop production may be achieved if previously set-aside land is devoted to nitrogen-fixing crops (e.g. soybean, field pea, and faba bean) such as targeted in the greening component of the CAP.

Both total crop production and average annual protein crop yields are highest in WET, followed by REF and DRY, which underlines the importance of sufficient soil water availability for plant growth. Total crop production decreases slightly with an expansion of protein crop production. This is mainly because simulated average dry matter crop yields of protein crops per hectare are considerably lower than those of e.g. maize and root crops.

Climate and policy change may affect land use and crop management practices. While crop choices are mainly influenced by relative price changes, crop management choices respond principally to the combined effects of climate and policy change (Fig. 5 and Fig. S6). In the policy scenario 'DP-AEP' (Fig. 5a), low fertilization intensity is the predominant crop management practice, regardless of the climate change scenario. It is applied to >80% of the cropland and is more widely used with an increasing share of protein crops in the crop rotation. Irrigated cropland amounts to less than 1% in REF and WET, and reaches a maximum of 3.2% in DRY at a high expansion level of protein crop production. High fertilization rates are of marginal importance and mostly invariant to the climate change scenario and the level of protein crop production expansion. Moderate fertilization inputs are most important in the climate change scenario WET (between 13 and 19%), followed by REF (between 11 and 16%) and DRY (between 7 and 13%). Both high and moderate fertilization intensity decline with increasing shares of protein crops.

A consequence of abolishing agri-environmental payments in the 'no AEP' policy scenario is a notable intensification of fertilizer use and irrigation water input. High fertilization intensity dominates in REF (between 58 and 69% of total cropland) and WET (between 73 and 84% of total cropland). In DRY, high fertilizer inputs on rain-fed and irrigated cropland are similarly important, with shares of around 45% each. Moderate fertilization intensity is most relevant in REF, and its importance grows with increasing levels of protein crop production expansion. Low fertilization rates amount to a maximum of 0.5% in REF, WET, and DRY, indicating that it is not profitable for farmers without agri-environmental payments.

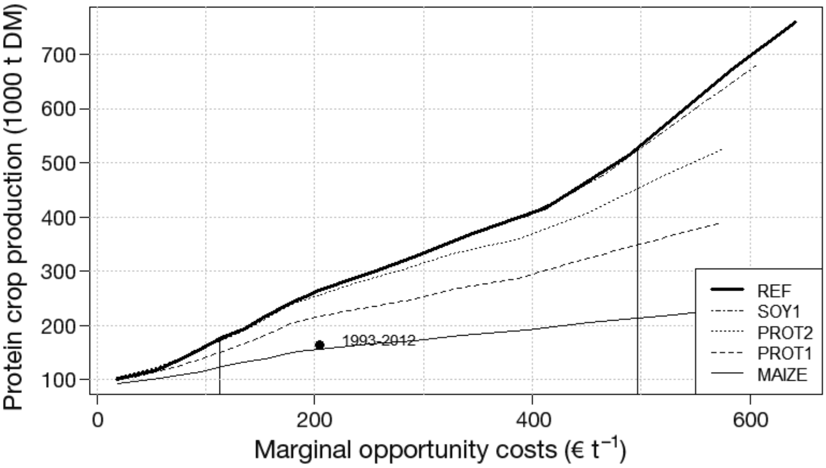

Fig. 6. Economic potentials of protein crop production at different levels of flexibility in crop management choices and marginal opportunity costs in the climate change scenario REF and the policy scenario 'DP-AEP' in Austria (see Fig. 2 for scenario definitions). In REF, the model can choose from 8 crop rotations. Maize/PROT1/PROT2/SOY1 refer to model runs in REF where an increasing number of crop rotations is made available. 'MAIZE' allows for the 2 crop rotations 'hist' (which reflects historical crop mixes) and 'maize'; 'PROT1' ('PROT2') allows for 'hist', 'maize', and 'prot1' (and 'prot2'); and 'SOY1' allows for 'hist', 'maize', 'prot1–3', and 'soy1'. 'PROT3' (allowing for 'hist', 'maize' and 'prot1-3' in the crop rotations) and 'SOY2' (allowing for 'hist', 'maize', 'prot1-3' and 'soy1-2' in the crop rotations) look similar to 'SOY1' and are therefore not shown. In 'SOY3', the model can choose from 8 crop rotations. Accordingly, 'SOY3' is identical to 'REF'. The black dot represents the mean of reported values on protein crop production and prices (including agricultural payments in the years 1993 and 1994) for the period 1993–2012. The vertical lines indicate the bandwidth of reported producer prices for protein crop commodities in the period 1993–2012. DM: dry matter

3.3. Economic potentials of protein crop production

The computed economic potentials of protein crop production combined with the effect of increased flexibility in crop rotation choices is presented in Fig. 6 for the climate change scenario REF and the policy scenario 'DP-AEP.' The solid line shows the economic potential of expanding protein crop production represented by the marginal opportunity costs assuming high flexibility in crop rotation choices. It is identical to the solid line in Fig. 2a. The other lines in Fig. 6 show 4 other realizations of the BiomAT model in selecting from gradual declining sets of crop rotations based on the climate change scenario REF and the policy scenario 'DP-AEP.'[3] A smaller number of crop rotations implies lower flexibility in farm management practices to respond to exogenous changes. This analysis suggests that the investigated crop management choices (as facilitated by policy changes) have a higher influence on the protein crop production potential than the simulated climate change scenarios (as shown in Fig. 2).

Fig. 6 also shows the Austrian mean protein crop production level (around 162 000 t) and the bandwidth of reported producer prices including agricultural payments (113–497 € t^{-1}) for the period 1993–2012. The observed production is considerably lower than the modelled economic potential presented in REF. Explanations are that simulated crop yields are on average higher than the observed ones, that severe weather extremes are not accounted for (e.g. hail), and that the model allows for high flexibility in crop management choices which are induced by protein crop price changes. The mean of observed production levels is within the range of the model runs, indicating that the model results are reasonable.

3.4. Effects of protein crop production on operating inputs

Increasing shares of nitrogen-fixing crops (e.g. soybean, field pea, and faba bean) leads to commercial fertilizer savings. In order to evaluate this effect, we estimated the elasticity of nitrogen fertilizer input to changes in protein crop production levels at the national level. BiomAT model results from the climate change scenarios REF, WET, and DRY are considered in this analysis. We estimated the elasticity by using a log-linear regression model. The elasticities are estimated separately for the 'DP-AEP' and the 'no AEP' policy scenarios. The results show that simulated total nitrogen fertilizer input decreases by about 0.09% if total protein crop production increases by 1% in the 'DP-AEP' policy scenario (or 0.07% in the 'no AEP' scenario). Nitrogen fertilizer input is therefore inelastic relative to protein crop

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[3] In REF, 8 crop rotations are available. The number of crop rotations is smaller in the other realizations. For instance, 'MAIZE' allows for the 2 crop rotations 'hist' and 'maize;' 'PROT1' allows for 'hist', 'maize', and 'prot1'; and 'SOY1' allows for 'hist', 'maize', 'prot1–3', and 'soy1'. The model runs 'PROT3' and 'SOY2' look similar to 'SOY1' and are therefore not shown. 'SOY3' is identical to REF because it considers the 8 crop rotations

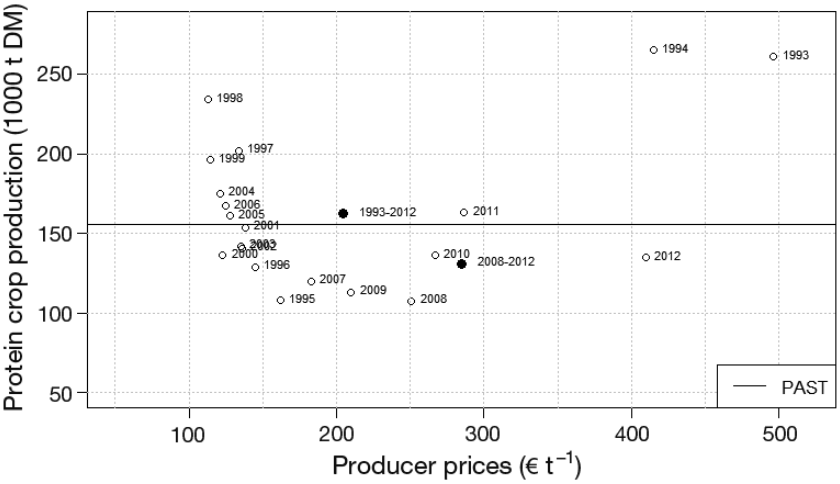

Fig. 7. Observed protein crop production volumes and prices in the years 1993–2012. The black dots represent the mean of reported values for the periods 1993–2012 and 2008–2012. The horizontal line indicates results for protein crop production levels for the period 1975–2005 (PAST) from BiomAT. The *x*-axis refers to producer prices, including coupled direct payments for protein crop production in 1993 and 1994. DM: dry matter

production. The slight differences between the 'DP-AEP' and the 'no AEP' scenarios are mainly due to minor variations in protein crop production areas. Furthermore, the nitrogen fertilizer use efficiency, which is defined as the ratio of total crop production to the total nitrogen fertilizer input, is highest at a moderate level of protein crop production expansion in the policy scenario 'DP-AEP' and at a high expansion level in the scenario 'no AEP,' regardless of the climate change scenario.

Irrigation water input is driven by climate change and the policy scenarios. Thus, elasticities are estimated by climate change and policy scenarios. In the 'DP-AEP' policy scenario, irrigation water input ranges between 5 and 17 million m^3 in REF and increases to between 21 and 76 million m^3 in DRY. Total irrigation water input changes by 0.4 % in REF and DRY and by 0.2 % in WET if total protein crop production is increased by 1 %. Thus, irrigation water input is inelastic relative to protein crop production, with elasticities of 0.4 (REF and DRY) and 0.2 (WET). Positive elasticities for irrigation water input are mainly attributable to expanding protein crop production to areas with limited mean annual precipitation sums, i.e. in northeastern and southeastern Austria.

In the 'no AEP' policy scenario, intensification (including irrigation) gains in importance. Irrigation water input amounts to between 332 and 352 million m^3 in REF, and between 1051 and 1151 million m^3 in DRY. Relative changes in irrigation water input are similar for all climate change scenarios with increasing total protein crop production. Estimates of the elasticity are around −0.03 (i.e. irrigation water input decreases by about 0.03 % if total protein crop production is increased by 1 %). Reductions in irrigation water inputs may be attributed to the changes in crop shares. Soybean, field pea, and faba bean are among the 5 crops with the lowest average annual irrigation water input in EPIC, regardless of the climate change scenario.

3.5. Model validation

For validation, we compare BiomAT outputs for the historical period 1975–2005 (PAST) with observed production in 2008–2012. Simulation results for the historical period are used to control for climate change impacts. Observations are averaged over a period of 5 yr in order to even out annual weather anomalies. The simulated mean annual protein crop production amounts to approximately 155 000 t. Observed average production in 2008–2012 for soybean, field pea, and faba bean is about 16 % lower and amounts to approximately 130 000 t (Statistics Austria 2013c; Fig. 7). Simulated mean annual soybean yields for the period 1975–2005 amount to 2.7 t ha^{-1} and are approximately 6 % above the 20 yr average of observed soybean yields of 2.5 t ha^{-1} (1993–2012; Statistics Austria 2013c). Inter-annual yield variability as indicated by the standard deviation is similar for simulated and reported soybean yields (amounting to about 0.3 t ha^{-1}). Simulated absolute crop yields are higher mainly because natural events such as hail, sub-daily weather extremes, pests, and weeds are not yet taken into account in the EPIC model (see Balkovič et al. 2013 for a European validation study on crop yields simulated with EPIC and Mitter et al. 2015c for a discussion on uncertainties related to EPIC).

The second aspect of validation is the protein crop production response to changes in commodity prices. We compared model results for the historical period 1975–2005 (see PAST in Fig. 7) with output volume and nominal producer prices provided by Statistics Austria (2013b,c) for the period 1993–2012. The highest production volume with more than 260 000 t was observed in 1993 and 1994, when Austrian farmers received hectare payments for protein crops amounting to 509 € ha^{-1} (see Bundeskanzleramt 1992 and

Holzer & Reischauer 1991). Protein crop production volumes decreased gradually between 1998 and 2008, which was mainly due to unfavorable relative prices. Producer prices for protein crops have increased steadily since 2007 and peaked in 2012 due to a severe drought and heat wave in the US which limited protein crop supply. In Austria, soybean plants were badly damaged in mid-May when temperatures fell below −5°C (see Mitter et al. 2015c). Protein crop production responses lag behind compared to the average of the period 2000–2006. Again, this can be explained by different relative prices in these periods, although rises in protein crop prices have recently tended to slightly exceed price rises of other crops (Statistics Austria 2013b).

4. DISCUSSION

4.1. Response of protein crop production to climate change and policy scenarios

An integrated modelling framework was applied to analyze protein crop production responses to climate change and agricultural policy scenarios in Austria. Our focus was on domestic protein crop production because of the high import dependence and the observed fast response of Austrian farmers to (un)favorable market and policy conditions (the acreage ranged between around 40 000 and 110 500 ha during the last 25 yr; FAOSTAT 2015). Our model results are sensitive to policy restrictions on land use (e.g. set-aside obligation which was abolished in 2009 or EFAs which were introduced in 2015) and the promotion of extensive farming practices in agri-environmental programs. Allowing for protein crops on previously set-aside land may almost double protein crop production. An abolition of agri-environmental payments (‘no AEP’ policy scenario) leads to similar shares of protein crops in the crop rotations but to considerably higher nitrogen fertilizer (around 1.6-fold increase) and irrigation water inputs (around 10- to 70-fold increase), compared to the ‘DP-AEP’ policy scenario.

Higher soil nitrogen and water contents typically increase crop yield responses to elevated atmospheric CO_2 concentrations (Tubiello et al. 2007), which may lead to agricultural intensification under changing climatic conditions (Ghahramani & Moore 2015, Kirchner et al. 2015, Mitter et al. 2015a). Our model results show that the climate change scenarios REF, WET, and DRY greatly affect the optimal choice of crop management practices and, to a very limited extent, the choice of crops. This indicates the potential for prioritizing and targeting adaptation measures. Irrigation gains in importance in the scenario with decreasing precipitation sums (DRY), especially in drought-prone regions, which confirms results of Mitter et al. (2015b). Decreases in average gross margins seem to be larger for protein crops than for other crop groups under dry production conditions, which makes their cultivation slightly less attractive in DRY, compared to REF and WET.

Observed acreages of protein crops expanded under favorable economic conditions, either because commodity prices were relatively high or because production was stimulated by hectare payments. Such conditions are considered in our analysis by computing marginal opportunity costs of expanding protein crop production. High marginal opportunity costs are found if protein crops are mainly cultivated at the expense of maize, which is confirmed by other studies (Eder 1993, Seifried et al. 2015, Schreuder & de Visser 2014). Model results show that oil crops, root crops, and forage crops are replaced as well. Pistrich et al. (2014) identified about 540 000 ha of Austrian cropland to be suitable for soybean production. Accounting for crop rotation restrictions, they estimated the agronomic production potential of soybean to be about 125 000 ha. According to our results, such an acreage of protein crops implies marginal opportunity costs of around 440 € t^{-1}. The observed maximum acreage (110 500 ha in 1992) is consistent with marginal opportunity costs of protein crop production of around 410 € t^{-1} according to our analysis.

Biological nitrogen fixation may help to meet the fertilizer requirements of high-yielding crops. Globally, soybean, field pea, and faba bean are calculated to fix about 17.3 Tg of nitrogen per year, of which soybean accounts for almost 95 % (Herridge et al. 2008). Data from field studies indicate that 50 to 60 % of soybean nitrogen demand can be provided by biological nitrogen fixation (Salvagiotti et al. 2008), although results vary between soils, climatic conditions, and crop management practices (Huth et al. 2010, Jensen et al. 2012). Our model results show that a 1 % increase in total protein crop production would reduce nitrogen fertilizer inputs by about 0.1 %.

4.2. Integrated modelling framework

The integrated modelling framework presented in this study considers various aspects affecting agricultural land use choices, i.e. bio-physical and climatic conditions, alternative crops, and crop management practices, as well as changes in protein crop prices and agricultural policies. In order to highlight these features, we analyzed protein crop production potentials in Austria by assessing climate change and policy scenario impacts and allowing for agronomic adaptation (e.g. timing of cultivation, levels of fertilization and irrigation) and allocating more cropland (e.g. previously set-aside land) to protein crop production.

Several supply side factors are not considered in order to focus the analysis. Keeping input prices and commodity prices of non-protein crops constant and neglecting other market feedbacks allows us to single out potential impacts of climate change and policy scenarios on protein crop supply. Such an approach does not require assumptions on long-term economic developments and simplifies the interpretation of the results (Ciscar et al. 2011).

The modelling framework could be extended by considering farmers' adaptation behavior and risk attitudes. Such an extension would be relevant for analyzing production responses to extreme events including droughts and floods and more volatile market conditions. Extreme weather events are causing growing concerns (see e.g. Mitter et al. 2014) since they are likely to increase in frequency and severity in the next decades (see e.g. Meehl & Tebaldi 2004, Min et al. 2011, Dai 2013) and may induce substantial changes in commodity prices. For example, Strauss et al. (2013b) accounted for production risks in a long-term drought scenario and found crop yield losses between 10 and 30% in the semi-arid eastern parts of Austria. Farmers' risk attitudes were considered by Mitter et al. (2015a), who showed that higher levels of risk aversion lead to crop management diversification which induces slightly lower average outputs.

Weed, pest, and disease pressure constrain crop production and might increase under changing climatic conditions (Olesen et al. 2011). For instance, a field experiment on soybean revealed yield losses between 0.4 and 0.6 t ha^{-1} under strong weed competition (Vollmann et al. 2010). Other studies suggested that diversifying crop rotations by cultivating protein crops may reduce the incidence of cereal pathogens and pests (see e.g. Köpke & Nemecek 2010 and Jensen et al. 2012 for detailed reviews). In addition, field characteristics and landscape structures (Mitchell et al. 2014) as well as progress in breeding may influence pest pressure. Such factors were not included in the presented modelling framework.

Crop production choices are optimized for small regions in our modelling approach. In practice, however, decisions are made at the farm level (see e.g. Reidsma et al. 2010, Troost & Berger 2015). For instance, pig farmers typically require large amounts of maize for feeding, but livestock production is not explicitly considered in BiomAT. Conversely, farmers close to processing plants are more likely to opt for protein crops in the crop rotations, but transport cost differentials were not accounted for either.

Expanding domestic protein crop production aims at decreasing import dependence and increasing the supply of GMO-free soybeans. Although set-aside land is made available for crop production in the integrated modelling framework, protein crops also replace other crops such as maize. The consequences of indirect land use changes are not accounted for even though they are deemed relevant for defining policy targets.

5. SUMMARY AND CONCLUSIONS

We have carried out a spatially explicit integrated assessment of climate change and agricultural policy impacts on protein crop production and environmental outcomes in Austria. The assessment involves 3 contrasting climate change (REF, WET, DRY) and 2 agricultural policy scenarios ('DP-AEP,' 'no AEP') and differentiates between a variety of crop management practices including alternative crop rotations, fertilization intensities, and irrigation. We use Austria as an example to quantify how a policy reform may reduce the currently high Austrian and European protein deficit under changing climatic conditions. Environmental effects of expanding protein crop production are analyzed by changes in nitrogen fertilizer and irrigation water inputs. The integrated modelling framework employed in the analysis proved effective in undertaking a detailed bottom-up investigation for various climate change and policy scenarios. The modelling framework is designed in a way to be transferable to other temperate production regions in Europe and beyond, provided that the required data are available at high spatial resolution.

The model results indicate that climate and policy change may stimulate domestic protein food and feed supply. As facilitated by the recent CAP reform, devoting previously set-aside land to protein crops could lead to a 2-fold increase in protein crop production under the assumption that input prices and commodity prices of non-protein crops remain constant. The estimated elasticities of irrigation water input with respect to protein crop production are similar for the 3 climate change scenarios (REF, WET, and DRY), which suggests that an expansion of protein crop production under changing precipitation conditions would not raise irrigation water input. The abolition of agri-environmental payments (‘no AEP’ policy scenario) leads to notable intensification of fertilizer use and to a 10- to 70-fold increase in total irrigation water inputs, compared to the ‘DP-AEP’ policy scenario which represents the current policy environment. Extending protein crop production in the ‘no AEP’ scenario could, however, slightly reduce irrigation water inputs, as indicated by slightly negative elasticities. Commercial fertilizer savings are an intended side effect of expanding protein crop production. Our results reveal that nitrogen fertilizer input is inelastic relative to protein crop production with elasticities of 0.09 (0.07) in the ‘DP-AEP’ (’no AEP’) policy scenarios.

Economically, the model results show that expanding total protein crop production by about 12% results in rising marginal opportunity costs of about 20% in the reference climate change (REF) and the ‘DP-AEP’ policy scenario. If protein crops are mainly planted on land that was previously set-aside, the marginal opportunity costs remain low (between 19 and 115 € t^{-1} in REF and ‘DP-A EP’). At higher marginal opportunity costs, protein crops most frequently replace maize, which is deemed the most competitive crop to soybean. Import dependence would still remain high, due to limited availability of cropland suitable for protein crop production (i.e. agronomic potential) as well as the reported gradual increase in domestic use.

An even more elaborate integrated modelling framework is needed to analyze consequences of extreme events which are expected to exacerbate the projection of levels and variability of crop yields. Important production options such as livestock farming are also not considered here. However, the gains in elaboration of the study method must be weighed against the costs of higher complexity and thus higher uncertainty.

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