

Assessing climate change impacts on managed grassland production using a bio-economic modelling approach

Robert Finger^A, Pierluigi Calanca^B and Simon Briner^C

^A Wageningen Hollandseweg 1, 6706 KN Wageningen, The Netherlands

^B ART Research Station, ART Reckenholzstrasse 191, 8046 Zürich, Switzerland

^C ETH Zurich, Sonneggstrasse 33, 8092 Zurich, Switzerland

Contact email: robert.finger@wur.nl

Abstract. We develop a bio-economic model that combines the process based grassland simulation model PROGRASS with an economic decision model, which accounts for income risks and yield quality, to derive optimal nitrogen application rates in a grass-clover system in Switzerland. The model is applied to current as well as to future climate conditions. Though nitrogen increases yields, it also leads to a higher variance and more negative skewness of yields, *i.e.* is risk increasing. Accounting for farmers' risk aversion thus reduces optimal nitrogen use. We find climate change, *ceteris paribus*, to lead to higher grassland yields but also to increase the variability of yields substantially. Optimal adaptation responses to climate change were found to be sensitive to the consideration of yield quality and the level of farmer's risk aversion.

Keywords: Risk modeling, downside risk, adaptation, Switzerland, grass-clover.

Introduction

Climate change is expected to affect grassland production by influencing grassland productivity, production risks, fodder quality and the frequency of occurrence of weed species, which will have consequences for future food supply and land use (*e.g.* Soussana and Lüscher 2007). To investigate the impact of (changes in) environmental conditions and management practices on grassland systems, a wide range of process-based biophysical models has been developed (*e.g.* Schapendonk *et al.* 1998; Peters 2011; Soussana *et al.* 2012). Studies based on these models mainly focus on the impact of management decisions and environmental conditions on the performance of grassland yields and fodder quality as well as on agro-ecological indicators. This focus, however, addresses only indirectly the effects on income of farmers managing these grasslands. To allow a comprehensive perspective that accounts for both biophysical processes and farmers' decision making, biophysical models have thus to be combined with economic information and assumptions on farmers' behaviour. With respect to investigations focussing on climate change impacts, this also allows to consider adaptation responses likely to be taken by farmers.

This need for integrated modelling perspectives has motivated the use of bio-economic models that combine biophysical and economic modelling approaches in grassland production (*e.g.* Berentsen *et al.* 2000; Herrero *et al.* 1999). In these modelling approaches, farmers' goal functions are often represented using a profit maximization framework. This perspective has been extended in recent studies by recognizing that also the consideration of risk and risk management is crucial to depict farmers' decision making process properly (*e.g.* Louhichi *et al.* 2010; Janssen *et al.* 2010; Finger *et al.* 2010). But, risk is represented in

these models mostly exclusively by the second moment of yield or income distributions (*i.e.* standard deviation or variance). By making this restriction, these models overlook the fact that decision makers also aim to reduce downside risks, *i.e.* to avoid possibilities of extremely low outcomes (*e.g.* Moschini and Hennessy 2000). This is due to the fact that years with exceptionally low profits may affect significantly the economic viability of a farm. Farmers' behavior with respect to downside risks has received particular attention in studies investigating observed decisions taken by farmers (*e.g.* Koundouri *et al.* 2006; Torkamani and Shajari 2008)¹. Downside risks are also expected to be of particular relevance for grassland production because the skewness of rainfall patterns and other climate variables spills directly over to distributions of grassland yields (Torell *et al.* 2010) and farm income. This also concerns the relationship between grassland yields and nitrogen use. Even though nitrogen application increases grassland yields, the extent of these yield increases critically depends on uncertain weather conditions. Thus, increasing levels of nitrogen application are expected to lead to higher but more volatile yield levels with more negative skewness, *i.e.* to increase (downside) risks. A risk-averse decision maker accounts for these relationships if making decisions on optimal nitrogen use. Despite this potential relevance, downside risks have not been explicitly considered in bio-economic modeling approaches focusing on grassland production so far². We aim to contribute filling this gap by integrating downside

¹ But downside risks have been considered only in a few bio-economic models (*e.g.* Holden and Shiferaw 2004; Holden *et al.* 2004; Finger 2013; Briner and Finger 2013).

² Finger and Calanca (2011) account for downside risks in grassland production but base their analysis directly on quasi-experimental data without integration in a modeling approach.

risks in a bio-economic model representing optimal nitrogen use in grassland production using a case study from Switzerland. To this end, we combine a process-based grassland simulation model with an economic decision model accounting for farmers' risk aversion and yield quality considerations.

Material and Methods

Our modelling approach consists of three main steps: First, the process based grassland model PROGRASS was used to simulate grassland yields with respect to different levels of nitrogen use under current and future climate conditions. Second, the relationship between mean, variance and skewness of grassland yields and nitrogen use are estimated empirically using the moment based approach. Third, information on the relationship between the first three moments of yield distributions and input use is combined with information on costs and benefits in grassland production in an economic model. The goal function underlying our analysis represents the utility maximization rationale of a risk averse decision maker. The here presented approach furthermore accounts for the effect of nitrogen use on expected yield quality expressed in protein contents.

Application of the PROGRASS model

We use the PROductive GRASland Simulator (PROGRASS) (Lazzarotto *et al.* 2009) to simulate responses of a hay production system to changes in climate and fertilization at a representative location on the Swiss Plateau (Oensingen, 7°44'E, 47°17'N, 450 m a.s.l.). The model simulates a typical grassland system consisting of a variable mixture of perennial ryegrass (*Lolium perenne* L.) and white clover (*Trifolium repens* L.). PROGRASS accounts for above- and belowground interactions between plant functional types relatively to light interception and the acquisition of soil mineral nitrogen (N). The model requires the specification of weather inputs, management options (cutting dates, dates of the fertilizer applications, fertilizer amounts) and initial conditions for above- and belowground biomass, soil organic and mineral N pools and soil moisture content. PROGRASS explicitly considers the effects of elevated CO₂ concentrations on plant dynamics (photosynthesis, stomatal conductance, biological N fixation). Further details concerning the model structure, setup and validation are presented in Lazzarotto *et al.* (2009).

We assume an intensive production system with 5 cuts per year. We distinguish between 13 different levels of fertilisation, with annual amounts varying from 0 to 600 kg N/ha/y in steps of 50 kg N/ha/y applied in 5 doses per year. This experimental design is simulated assuming both current and future climate conditions. The future climate scenario represents climatic conditions as projected by the CHRM regional climate model (Vidale *et al.* 2003) for 2071-2100 under the A2 emission scenario (Vidale *et al.* 2003). This scenario implies a marked increase in temperature in particular during summer (+3.5°C and +5.5°C for daily minimum and maximum temperature, respectively, on average for June, July and August), a strong reduction of summer rainfall amounts (-35% as an

average for June, July and August) but an increase in winter precipitation (+22% for the months December to March) (for details see Finger *et al.* 2010, Finger and Calanca 2011). For this scenario, we also assume atmospheric CO₂ concentrations of 700 ppm compared to 370 ppm under current climate conditions. For both climate scenarios, the model is driven by 25 years of weather data generated with the LARS-WG stochastic weather generator (*e.g.* Semenov *et al.* 1998). Combining these 25 years with 13 levels of N-use results in 325 observations for each climate scenario. The output used for subsequent steps is for each simulation the level of total yield and the composition of this yield (*i.e.* the fraction of clover and grass, respectively).

The Economic Model

To integrate farmers' preferences on mean, variance and skewness of profit margins arising from grassland production in our analysis, certainty equivalents are used as goal function in our economic model. The certainty equivalent represents a sure amount of money that is rated by the farmer identically as the volatile profit margins from (risky) grassland production. In the certainty equivalent (CE) framework, the loss of utility due to the presence of risk (*i.e.* due to variance and skewness of profit margins) is defined as the risk premium RP, which is the difference between the expected profit margin $E(\pi)$ and the CE.

$$CE = E(\pi) - RP \quad \dots\dots (1)$$

Following Di Falco and (2009), we define the (approximate) risk premium as follows:

$$RP = \frac{1}{2} r_2 \sigma_\pi^2 + \frac{1}{6} r_3 \sigma_\pi^3 \quad \dots\dots (2)$$

where: σ_π^2 and σ_π^3 are the variance and (unstandardized) skewness of profit margins, r_2 and r_3 characterize the decision maker's aversion against variance and (negative) skewness. Following Chavas *et al.* (2009), we base our analysis on a power utility function

$$U = \frac{1}{1 - \tau} \pi^{1-\tau}$$

With r_2 and r_3 being defined as $-U''/U'$ and $-U''' / U'$, respectively, where a prime denotes a derivative with respect to π , this choice implies

$$r_2 = \frac{\tau}{\pi} \quad \text{and} \quad r_3 = -\frac{\tau^2 + \tau}{\pi^2}$$

Thus, we assume constant relative risk aversion, *i.e.* absolute risk aversion increases if expected profit margins approach zero. Important for the purpose of our paper, the latter term shows that both higher variance and more negative skewness (*i.e.* a higher downside risk) of profit margins increase the risk premium, *i.e.* reduces farmer's CE.

The goal function underlying our model is $\max_{N, CE} \square$ *i.e.* derive optimal, *i.e.* certainty equivalent maximizing, levels of nitrogen use. To investigate the role of risk aversion on optimal nitrogen use decisions, we follow Finger (2013) and investigate optimal input use for

different scenarios³ with τ being either 0, 1, 2 or 3. Thus, the employed scenarios represent a gradient from zero to moderate (downside) risk aversion.

In order to transform the simulations made in PROGRASS to information that is usable in the economic model, some empirical steps are required that are presented in the following subsection.

Empirical approach

Estimation strategy: We use a moment based approach (Antle 1983) to investigate the effect of fertilizer use on mean, variance and skewness of grassland yields. This allows a more flexible representation of production risks than approaches used in existing bio-economic models accounting for risk in grassland production (e.g. Finger et al. 2010; Janssen et al. 2010). First, the effect of nitrogen use (N) on the expected (i.e. average) yield $E(Y(N_i))$ is estimated, with i denoting the respective level of N-use (Equation 3).

$$E(Y(N_i)) = \alpha_0 + \alpha_1 N^{0.5} + \alpha_2 N \quad \dots (3)$$

In a second and third step, the effects of nitrogen use on the variance and skewness of yields are estimated as depicted in Equations 4 and 5. In the moment based approach, these steps are based on the magnitude and type of deviations of the actual observations from their expected level, i.e. regression residuals, estimated in Equation 3 (see e.g. Chavas et al. 2009, for details).

$$E \left[\left(E(Y(N_i)) - Y(N_i) \right)^2 \right] = \beta_0 + \beta_1 N^{0.5} \quad \dots (4)$$

$$E \left[\left(E(Y(N_i)) - Y(N_i) \right)^3 \right] = \gamma_0 + \gamma_1 N^{0.5} \quad \dots (5)$$

We compared different specifications of the functional forms in Equations 3-5 using Wald tests, with the superior being presented in the paper. Furthermore, we corrected for heteroscedasticity in all estimation steps.

Specification of profit margins and output prices: To enable the maximization of certainty equivalents, we transform information on yields and nitrogen use into profit margins accounting for revenues, costs and direct payments (Table 1). We assume yield to be sold as (ground dried) hay directly from the swath at a price P_Y . For each observation i , the profit margin also accounts for the price of nitrogen P_N , other (fixed) costs FC as well as direct payments DP and is thus calculated as follows:

$$\pi_i = \rho_Y E(Y(N_i)) - FC + DP - \rho_N N_i \quad \dots (6)$$

We use two scenarios for the price of hay. First, we use the current (average) price for hay of $\rho_Y = 150$ CHF/t (see Table 1). This (average) price, however, does not account for quality differences with respect to the nutrient value of the hay produced. In our second price scenario we directly implement quality adjusted prices in our model by

accounting for the protein content. This is based on 3 assumptions: (1) a 1% higher fraction of clover in a grass/clover mixture leads to a 0.5% increase of the protein content (Buchgraber 2009); (2) a 1% increase in the protein content causes a price increase by 1% (adapted from Agrigate 2012); (3c) the above used (average) price of 150 CHF/t is paid for hay with a protein content of about 15%, which is in line with the usually recommended minimum clover fraction (CF) of 30%⁴.

Based on these assumptions, a quality adjusted price is calculated for all observations (325 for each combination of climate and price scenario), based on the clover fraction resulting from PROGRASS simulations. Since the clover fraction (and thus protein content) is mainly dependent on the level of nitrogen fertilization (see Finger et al. 2010), we estimate the relationship between fertilization level and price for hay empirically. To this end, a linear regression between quality adjusted prices and the level of nitrogen use is estimated as follows:

$$\rho_Y(N) = \delta_0 + \delta_1 N$$

This relationship represents the expected effect of nitrogen use on output prices (via expected changes in yield quality), which the farmer considers in his fertilizer decisions.

Finally, we combine information on the first three moments of grassland yield distributions taken from the empirical relationships described in Equations 3-5 with the information on prices, costs and direct payments (Table 1) to derive mean, variance and skewness of profit margins that are input for the economic optimization model. Combining equation 1 with the subsequently introduced steps and transformations leads to the following final maximization problem:

$$\max CE = \left[[p]_Y E(Y(N)_i) - FC + DP - p_N N \right] - \left[\frac{1}{2} r_2 \sigma_Y^2 p_Y^2 + \frac{1}{6} r_3 \sigma_Y^3 p_Y^3 \right]$$

The first part of the right-hand side of the equation represents the expected profit margin, while the second part represents the risk premium.

Results and Discussion

Table 2 summarizes the data generated with PROGRASS for current and future climate scenarios. Some general insights can be drawn from these summary statistics. First, nitrogen application increases yields, however with a decreasing rate. Second, higher nitrogen applications also induce higher variability of yields (in terms of standard deviation SD). Third, the clover fraction decreases with increasing use of nitrogen. The latter is caused by the competitive advantages of the grass under high N application, both with respect to light interception (Hautier et al. 2009) as well as soil mineral N acquisition (Lazzarotto et al. 2009).

We find yield levels to be higher and more variable (in terms of SD) under climate change than under current

³ Due to these choices of τ , r_2 is equal to 0, $\frac{1}{\pi}$, $\frac{2}{\pi}$ and $\frac{3}{\pi}$, and r_3 is equal to 0, $-\frac{2}{\pi^2}$, $-\frac{6}{\pi^2}$ and $-\frac{12}{\pi^2}$, respectively, in these scenarios.

⁴ Lehmann et al. (1981) recommend that clover fractions be in the range 30-50% for productive grasslands in Switzerland. This range is based on the digestibility and the nutritive value of the grassland yield.

Table 1. Assumption on economic parameters.

Item	Assumption	Source
Price for Yield	Price Scenario 1: 150 CHF/t Price Scenario 2: quality adjusted	Agrigate (2012)
General Direct Payments	1040 CHF/ha	
Plant Protection Costs	53 CHF/ha	
Insurance Costs	72 CHF/ha	
Price of nitrogen fertilizer	2.36 CHF/kg of nitrogen fertilizer	AGRIDEA and FiBL (2010)
Variable nitrogen application costs	0.04 CHF/kg of nitrogen fertilizer	
Costs for mowing, tedding and raking	106 CHF/ha cut	Briner <i>et al.</i> (2012)
Risk aversion	Sensitivity analysis with $\tau = 0, 1, 2, 3$	

Table 2. Summary statistics of the data generated with PROGRASS.

Nitrogen use (N)	Current climate			Climate change scenario		
	Mean Yield (t/ha)	SD Yield (t/ha)	Clover fraction (%)	Mean Yield (t/ha)	SD Yield (t/ha)	Clover fraction (%)
$N \leq 100$	9.11	1.41	50.73	10.82	2.22	52.29
$N > 100$ and $N \leq 200$	11.49	1.49	20.76	12.56	2.17	23.20
$N > 200$ and $N \leq 300$	13.78	1.78	14.88	14.70	2.40	14.76
$N > 300$ and $N \leq 400$	15.49	2.07	13.18	16.72	2.79	12.53
$N > 400$ and $N \leq 500$	16.64	2.31	12.72	18.27	3.15	11.82
$N > 500$	17.45	2.49	12.68	19.42	3.45	11.88

conditions. Furthermore, the clover fraction is found to be higher under future climate at nitrogen rates equal to or below 200 kg/ha, but is lower for higher rates of N-use. This finding is expected to be due to the fact that higher CO₂ concentrations stimulate photosynthesis in clover more than in grass and has therefore positive effects on symbiotic N fixation (Hebeisen *et al.* 1997). This competitive advantage (reflected in higher clover fraction under low N-application rates) disappears if fertilisation levels increase.

The ranges of clover ratios in our samples are 10%-73% and 9%-76% under current and future climate, respectively. This implies output prices after adjustment for protein contents to range from 144 to 195 CHF/t and 143 to 197 CHF/t, respectively. These prices are used to establish an empirical relationship between nitrogen use and expected price levels in a subsequent step.

The effects summarized above are also reflected in the estimated relationships between nitrogen use and the first three moments of the grassland yield distribution following equations 3-5 (Table 3). More specifically, our estimations for the current climate show a positive but saturating effect of nitrogen on the expected yield level and a positive effect of nitrogen use on the variance of yields. Furthermore, nitrogen is found to lead to a more negatively skewed yield distribution, *i.e.* to increase downside risk. This is due to the fact that also with high nitrogen application rates (that on average lead to higher yields) the lowest yield levels may be as small as with small nitrogen application rates since other parameters are limiting (*e.g.* in case of a drought), causing significant economic losses.

Furthermore, we find that climate change leads to a higher variance and a more positive skewness of yields. Higher variance under future climate is expected to be caused by more frequent occurrences of extreme climate conditions (*e.g.* Calanca 2007) that trigger low yield events in grassland production (*e.g.* Finger *et al.* 2013). The resulting more frequent yield observations at the lower tail of the yield distribution may also reduce the negative skewness of yields (*i.e.* very low yield events are no longer exceptional).

Table 3. Coefficient estimates for mean, variance, skewness and price functions.

	Current climate	Climate change scenario
(a) Expected yield level		
α_0 (Intercept)	7.89 (39.74)***	9.72 (30.49)***
α_1 (N)	0.025 (12.97)***	0.019 (6.89)***
α_2 (N ²)	-0.00001 (-4.09)***	-0.0000038 (-0.78)
R ² and F-test	0.74***	0.59***
(b) Yield variance		
β_0 (Intercept)	0.86 (1.86)*	2.81 (3.39)***
β_1 (N ^{0.5})	0.009 (3.93)***	0.014 (4.07)***
R ² and F-test	0.05***	0.06***
(c) Yield skewness		
γ_0 (Intercept)	1.05 (0.37)	2.75 (0.52)
γ_1 (N ^{0.5})	-0.03(-1.80)*	0.02 (0.71)
R ² and F-test	0.02**	0.001
d) Adjusted Prices ¹		
δ_0 (Intercept)	172	173
δ_1 (N)	-0.057***	-0.061***
R ² and F-test	0.61***	0.66***
Observations	325	325

Statistics in parentheses are t statistics. Single, double and triple asterisks (*) denote statistical significance at the 10%, 5% and 1% level, respectively. ¹ Price levels are measured in CHF/t.

Estimating the relationship between quality adjusted output prices and nitrogen use, we find nitrogen to significantly reduce expected prices (Table 3), which is caused by the reduction of clover and thus protein content due to increasing nitrogen application (Table 2). More specifically, we find that one additional kilogram of nitrogen decreases the output price by 0.057 and 0.061 CHF/t under current and future climate, respectively. The steeper response curve under the climate change scenario is due to a stronger reaction of clover fraction to N-application (*cp.* Finger *et al.* 2010).

These estimated relationships are used as input for the economic decision model, in which the level of nitrogen application is chosen to maximize certainty equivalents under different scenarios on risk aversion. The resulting

Table 4. Optimal production patterns in present and future climate.

Scenario on climate and risk aversion	Without quality adjusted prices			With quality adjusted prices		
	Nitrogen (kg/ha)	Certainty Equivalent (CHF/ha)	Expected Yield (t/ha)	Nitrogen (kg/ha)	Certainty Equivalent (CHF/ha)	Expected Yield (t/ha)
Current climate						
Risk neutral: $\tau = 0$	355	1929	14.98	199	1878	12.30
Risk averse: $\tau = 1$	340	1900	14.75	191	1859	12.14
Risk averse: $\tau = 2$	323	1869	14.48	181	1838	11.94
Risk averse: $\tau = 3$	305	1837	14.19	170	1817	11.72
Climate change scenario						
Risk neutral: $\tau = 0$	575	2142	19.61	100	2086	11.62
Risk averse: $\tau = 1$	513	2084	18.66	81	2060	11.27
Risk averse: $\tau = 2$	457	2034	17.79	62	2037	10.91
Risk averse: $\tau = 3$	406	1991	16.96	44	2017	10.57

optimal levels of N-use as well as certainty equivalents and yield levels are shown in Table 4. Under current climate conditions (upper panel of Table 4) we find a sharp reduction of optimal nitrogen application levels for increasing levels of risk aversion. This is due to the properties of nitrogen to increase yield variability and to decrease skewness (Table 2-3). The difference in optimal nitrogen use between a risk neutral and a risk-averse decision maker under current climate is up to 50 kg/ha (about 14%). Though the derived optimal N-use levels of about 305-355 kg/ha are in line with observations in other European countries (e.g. Nevens and Rehuel 2003), they are above the currently observed N-application rates in Switzerland (e.g. AGRIDEA and FiBL 2010). In contrast, we find substantially lower optimal fertilization rates if fodder quality is considered by adjusting price levels according to protein contents. More specifically, optimal fertilizer use ranges between 170 kg/ha for risk averse decision makers ($\tau = 3$) and 199 kg/ha for risk neutral decision makers ($\tau = 0$). These results are in line with observed levels of N-use in intensive grassland production in Switzerland (Walther *et al.* 1994) and this modification of the model leads furthermore to expected yield levels that are closer to the observed yield levels in Swiss (intensive) grassland production (AGRIDEA 2010). Thus, accounting for quality aspects in calculating returns from grassland production allows a more realistic representation of management decisions. Similar to the case without price adjustments, the relative differences in optimal nitrogen applications due to risk aversion (comparing the cases $\tau = 0$ and $\tau = 3$) are up to 15%.

The results for the climate change scenario are shown in the lower panel of Table 4. Due to the higher productivity and stronger yield responses to nitrogen application, optimal N-levels are substantially higher (e.g. 575 kg/ha for a risk neutral decision maker) if yield quality is not considered. Thus, more intensive production is used as a strategy to take advantage of climate change. This result is in line with the findings of Bindi and Olesen (2011) that adaptation responses to climate change may lead to a further intensification of agriculture in northern and western Europe. Furthermore, we find that climate change leads to an increase of farmers' certainty equivalents, which underlines earlier findings that intensive production systems in European agriculture may benefit from climatic warming to some extent (Olesen and Bindi 2002). Comparing the current climate and the climate change

scenario, risk aversion is found to have a stronger impact on optimal levels of nitrogen use assuming future climate scenario. For instance, going from a risk neutral to a risk averse decision maker with $\tau = 3$ leads to a reduction of N-use by about 30% (compared to 14% for current climate conditions). This higher sensitivity to risk considerations is due to the fact that grassland yields become much more volatile under climate change (cp. Table 2 and 3).

If accounting for quality aspects in determining optimal nitrogen application levels, we find that optimal levels of N-use under the climate change scenario are smaller than under current climate. Thus, even though nitrogen application leads to higher yield levels it also implies a large reduction of the quality adjusted price. For a risk neutral decision maker, we find the optimal level of nitrogen application to drop to 100 kg/ha. Accounting for risk aversion in this situation even leads to more substantial reductions of optimal nitrogen use (by up to 56%). These results show that adding a quality dimension to the assessment of adaptation to climate change may reverse optimal strategies from an intensification to an extensification response. This finding is in line with other studies that point out different magnitudes or even signs of climate change impacts and adaptation if the level of investigation (e.g. regional- or farm- instead of field level, e.g. Reidsma *et al.* 2009) is changed or if additional aspects are considered (e.g. accounting for constraints or investigating integrated grassland-livestock production instead of grassland production only, e.g. Falloon and Betts 2010).

Limitations

The main limitation of the presented modelling approach is that it does not account for the on-farm use of grassland production but assumes grass to be sold as hay. Even though there are viable markets for fodder (including hay and other grass silage) in Swiss agriculture⁵, the on-farm use in animal production is much more important. Thus, the integration of subsequent production steps in this modelling approach should be considered further (see e.g. Briner and Finger 2013, for an example). We are aware that analysing farmers' decision making in such whole-farm frameworks may lead to less emphasized changes in optimal manage-

⁵ This is also underlined by the fact that there exist also market platforms for grass (e.g. <http://www.futterboerse.ch/>) and recommended prices for grass in form of hay or silage are specified by extension services (e.g. Agrigate, 2012).

ment practices due to changes in risk preferences and environmental conditions. This is because additional adaptation responses can be considered in these models. More general, including a wider set of adaptation measures may help to derive a more precise understanding on climate change impacts and farmers' adaptation responses. Furthermore, we are aware that our modelling approach is not capable to represent all potential effects of climate change and management practices on the quality of grassland production. For instance, our model does not account for other management measures affecting clover abundance (e.g. over-seeding, adjustments of cutting schedules). Furthermore, we do not consider that the occurrence of weeds may have a more distinct role in the future, in particular under drought conditions (e.g. Finger *et al.* 2013). Future research should also consider a wider set of climate change scenarios. Even though the here presented climate change scenario is in line with the general tendencies made by other predictions for Switzerland, the use of additional climate scenarios may also allow to draw conclusions on the uncertainty caused by differences across climate scenarios. Finally, our analysis relied on a case study on intensive grassland production in Switzerland. The here derived results may thus not be applicable to grasslands and grassland management in other regions.

Summary and Conclusion

We find that nitrogen fertilization increases grassland yield but also leads to a higher variance of yields. Furthermore, we find nitrogen to increase the negative skewness of yields, i.e. to increase downside risks, under current climate. The influence of moderate risk aversion on optimal nitrogen application rates was found to be up to about 15% under current climate. More specifically, higher risk aversion implies lower optimal levels of N-use because the input is risk increasing. Thus, accounting for risks in bio-economic models representing grassland production may improve the representation of farmers' behaviour in these models. Furthermore, we find that accounting for quality differences in grassland yields by using quality adjusted price levels resulted in optimal nitrogen rates better reflecting current management practices in Swiss grassland production. Our results show that climate change, *ceteris paribus*, leads to higher grassland yields but also to substantially higher variability of yields. The optimal adaptation responses to climate change are ambiguous. If not accounting for quality differences, higher yield potentials under the climate change scenario trigger an increase of the optimal nitrogen application rate. In contrast, we find optimal nitrogen use to be smaller than under current climate if quality aspects are considered. Furthermore, optimal adaptation responses can be highly dependent on the risk preferences of farmers. Accounting for risk aversion may lead to decreases of optimal N-use by between 30 and 56% under the climate change scenario. The increasing relevance of risk considerations is due to higher production risks under future climate. Our findings that expected adaptation responses may depend critically on risk preferences as well as on the consideration of yield quality aspects show that conclusions on climate change impacts and adaptation are sensitive to the preferences of farmers. Thus, recommendations on adaptation strategies

should account for differences across farmers with respect to their goal functions.

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