The impact of climate change on the profit-maximising timing of grassland use and conservation costs

Gerling, Charlotte and Strum, Astrid and Wätzold, Frank

Brandenburg University of Technology Cottbus-Senftenberg

15 September 2020

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Gerling, C.[1]
charlotte.gerling@b-tu.de
+49 (0) 355 69 2094

Sturm, A.[1]
sturm@b-tu.de

Wätzold, F.[1]
waetzold@b-tu.de

[1] Chair of Environmental Economics, Brandenburg University of Technology Cottbus-Senftenberg, Erich-Weinert-Straße 1, Building 10, 03046 Cottbus, Germany

Abstract

Grasslands make up a large part of cultural landscapes, for example in Europe, and provide an important habitat for many species. Climate change impacts grasslands directly by influencing the climatic conditions that determine grass growth. This may lead to changes in the profit-maximising timing of grassland use by farmers. Additionally, by influencing the yield of the grassland, climate change may have an impact on the opportunity costs of conservation. We have developed a model to investigate these two factors: 1) How does climate change impact the profit-maximising timing of grassland use and 2) How does it impact selected opportunity costs of conservation? The model includes a climate model and a vegetation model to assess the changes in a case study region in Schleswig-Holstein, Germany. We consider two RCP scenarios. Results show that the timing of the first cut is expected to occur increasingly early under climate change and costs of conservation measures are larger under more profound climate change.

Keywords: *climate change impact, grassland, conservation, timing of land use*

1. Introduction

Grasslands make up around 20% of Europe (Eurostat 2020) and are an important habitat for many species (Tälle et al. 2016). The impact of climate change on agriculturally used grassland is therefore important both for farmers and the conservation of species that inhabit these areas. Increasing temperature and CO_2 concentration are expected to generate an increase in grass growth in Europe (Hopkins & Del Prado 2007). This may lead to a change in the timing of the profit-maximising grassland use (Höglind et al. 2013) and may also influence the costs of grassland conservation measures. However, increasing precipitation in Northern Europe may reduce the suitability of pastures for farming under climate change (Hopkins & Del Prado 2007). Models may be useful to understand the impact of different climate change scenarios on grassland ecosystems and should be developed further (Kipling et al. 2016, van Oijen et al. 2018).

Models have been developed to assess the impact of climate change on grass growth. Some early models focus on grass growth and its processes and model the impact of climate change on grass growth (Armstrong & Castle 1992, Chen et al. 1996). Other authors include more complex economic considerations. In Höglind et al. (2013), changes to the timing and frequency of grassland use and to the dry matter yield are modelled. Yang et al. (2018) consider the impact on dry mass, and specifically examine heat stress. Persson and Höglind (2014) consider changes to the number of cuts and dry matter. Jing et al. (2014) additionally consider changes to nutritive values specifically.

Regarding grassland conservation efforts, some models have been developed to understand species distribution (Kleinbauer et al. 2010, Nixon et al. 2016, Smith et al. 2017) as well as the impact of the timing of grassland use on species (Johst et al. 2015, Wätzold et al. 2016, Gerling et al. 2019). However, little research has been undertaken to examine the impact of climate change on grassland conservation measures. A notable exception is Majaura (2016), who developed a model to assess the impact of climate change on the effectiveness of agri-environment schemes. Furthermore, Tainio et al. (2016) use various climate change scenarios and impact models in order to examine the cost-effectiveness of different conservation measures for grassland butterflies in Finland. However, the impact of climate change on the costs of conservation is not considered.

To our knowledge, so far no model examining the costs of conservation measures under climate change exists. Understanding the impact of climate change on the yield and timing of grassland use, and on the costs of conservation measures is essential for designing cost-effective conservation measures under changing climatic conditions. In this paper, we therefore develop a model to analyse the impact of climate change on 1) the timing of the profit-maximising grassland use and 2) on the costs of conservation measures. We consider grasslands in the German federal state of Schleswig-Holstein as a case study area. Future research may combine this model with an ecological model examining the impact of the changing timing of grassland use in order to determine the ecological impact of the profit-maximising grassland use and conservation measures on biodiversity under climate change.

2. Case study area

Schleswig-Holstein is the Northern most Federal State in Germany and has coastlines at both the North and Baltic Seas. Around 63% of the State's 15,800 km² are used agriculturally (Business Development and Technology Transfer Corporation of Schleswig-Holstein n.d., Statistisches Amt für Hamburg und Schleswig-Holstein n.d.), and 3,200km² are permanent grassland (Statistisches Amt für Hamburg und Schleswig-Holstein 2019).

For modelling purposes we divide the case study area into grassland cells of 250x250m. Each grassland cell contains information on its grassland productivity. Grassland productivity information is provided according to the German "grassland numbers", which derive an overall quality index dependent on soil parameters, water availability and others (BMEL n.d.). This index can, in principle, take any value between 1 and 100 (Reguvis n.d.) with higher values indicating higher quality, although extreme cases are rare. In our case study area the grassland number values range from 8 to 78. We have divided the grassland in four quality categories dependent on their grassland number (cp. Mewes et al. 2014). These categories are summarized in Table 1:

Table 1: Grassland productivity categories according to grassland numbers

Grassland productivity category	Range of grassland numbers
1	1-34
2	35-44
3	45-54
4	55-100

In this paper, we consider five measures that are thought to benefit species as the measures consist of relatively early and late grassland use dates, compared to typical timings of the profit-maximising grassland use (Mewes et al. 2014, Johst et al. 2015). We have included 1 and 2-cut measures (see Table 2).

Table 2: Overview of conservation measures

Measure name	General description	Specific requirements
M1a	Early mowing	Mowing until 7 weeks after the beginning of the vegetation period, maximum 1 cut
M1b		Mowing until 9 weeks after the beginning of the vegetation period, maximum 1 cut
M2a	Late mowing	Mowing after 21 weeks after the beginning of the vegetation period, maximum 1 cut
M2b		Mowing after 23 weeks after the beginning of the vegetation period, maximum 1 cut
M3	2-cut meadow	Mowing until 7 and after 23 weeks after the beginning of the vegetation period, maximum 2 cuts

We have chosen to include the temporal restriction of measures not as a fixed date, but as a time relative to the beginning of the vegetation period in order to account for possible changes of the development of the species due to climate change. The beginning of the vegetation period is estimated by using temperature sums: The vegetation period begins when the temperature sum reaches 200°C (LKSH n.d.). The temperature sum *T* is calculated as follows:

$$T = \sum_{i=1}^{i} (x \times c_i) \ \forall \ i \ until \ T \geq 200$$

Where x=0.5 for $1 \leq i \leq 31$, x=0.75 for $32 \leq i \leq 59$, x=1 for $60 \leq i \leq 90$

c_i= daily mean temperature in °C of day *i*; $c_i > 0$ (if $c_i \leq 0$ then assume $c_i = 0$)

This method accounts for including the temperature of days in January only as 50%, days in February only as 75% and only days from March are counted as 100%.

3. Modelling procedure

3.1. Overview of the modelling procedure

The purpose of the model is to determine the timing of grassland use (of both the profit-maximising grassland use and conservation measures) and the costs of conservation measures. We compare the results of two time slices, 2020-2039 and 2060-2079, to capture any differences that may result from climate change.

In the model, four sub-models interact (Fig. 1): the climate model provides input data into all other sub-models. The vegetation model determines the quantity of grass growth dependent on soil quality and climate data. This is used as an input to determine the timing of grassland use for each year. Finally, all sub-models feed into the agri-economic cost assessment to determine the costs of chosen conservation measures for each grassland cell and year. Note that we do not examine how climate change may influence the costs of certain agricultural operations. All cost factors and prices are assumed to remain stable. They are influenced by a large variety of factors and predicting their development would be mere speculation over such long time periods. Therefore, any changes in the costs of conservation measures reported in the results section are solely due to changes in yield. The final result of the agri-economic cost assessment is a grassland cell specific overview of 1) the potential timing of both the profit-maximising grassland use and all conservation measures and 2) the costs of all potential conservation measures.

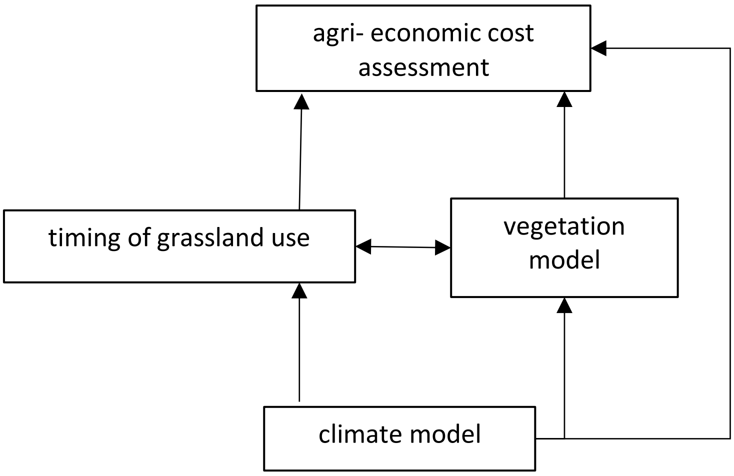

Figure 1: Overview of the modelling procedure

3.2. Climate model

Climate data is derived from climate projections with the regional climate model COSMO-CLM (Rockel et al., 2008, Früh et al. 2016). For more detailed information on the climate sub-model see Gerling et al. (*in preparation and available on request*). Data is given with a spatial resolution of 12x12km on a daily basis. As grassland cells have a size of 250x250m, several grassland cells belong to the same climate cell.

The following climate parameters are provided:

- mean temperature at the ground
- accumulated precipitation
- total sink for the soil water balance (sum of evapotranspiration, surface- and groundwater-runoff)
- total soil moisture content over the first 8 soil layers (about 4m deep).

For this paper, we use the RCP scenarios 4.5 and 8.5.

3.3. Vegetation model

The purpose of the vegetation model is to determine changes of grass quantity on a daily basis. This is given in biomass (g/m²) and grass height. A model by Schippers and Kropff (2001) has been simplified for this purpose – see Gerling et al. (*in preparation and available on request*) for further details. The main processes included in the model are plant mortality, biomass assimilation, allocation of biomass, and mowing. These processes are influenced by daily temperature (explicitly considering frost days), soil quality, soil humidity, absorbed radiation, and a number of plant species-specific parameters.

When mowing, the vegetation is cut down to 5cm (Oomes 1992). The vegetation model automatically subtracts these 5cm from the biomass present when providing information on the biomass as input to subsequent sub-models.

3.4. Timing of grassland use

This chapter explains how the timing of grassland use is determined. We first determine an initial approximation of the timing of grassland use which is equal for all grassland cells within the same climate cell, regardless of their productivity, and depends on biomass growth. Further factors may then influence the timing of individual grassland cells in a second step.

3.4.1. Biomass-dependant timing of the profit-maximising grassland use

The timing of grassland use depends on reaching certain biomass levels, which may be determined either according to biomass (g/m²) or according to grass height. To determine the timing of grassland use, we determine the timing of a grassland cell of good quality (i.e., a hypothetical grassland cell with a grassland productivity value of 65) and assume that all grassland cells within the same climate cell are cut at the same time, regardless of their productivity. This is to provide a first approximation of the timing considering local climatic conditions. The grassland cell-specific timing is then determined in the next step.

In order to determine the timing of grassland use in the hypothetical grassland cell, we determine its vegetation growth and compare it to expected values at the time of harvest. Once the grassland cell approaches its typical harvest yield, it is ready for harvest. The typical yields for the different cuts of the hypothetical grassland cell are summarized in Table 3. For example, the first cut typically yields around 360g/m² of biomass. The first cut occurs when the hypothetical grassland cell reaches 85% of the expected yield, i.e. 306g/m², or 36cm of height (as local conditions may lead to postponing the cutting date we take 85% instead of 100% to allow for some room for adaptation). This timing of the first cut is relevant for all grassland cells within this climate cell.

Table 3: Typical yield values of the different cuts of a grassland cell of soil quality of 65.

Number of cut	Typical yield value (g/m²)
1	360
2	240
3	230
4	220

The timing of the subsequent cuts is determined in a similar manner: again, the cut occurs when the hypothetical grassland cell reaches a certain minimum height (here: 25cm) or 85% of the expected yield. This is equal to 204g/m², 195.5g/m² and 187g/m² for the second, third and fourth cut, respectively (cp. expected yields in Table 1). The timing of the subsequent cuts depends on climatic conditions, but occurs roughly 6 weeks after the previous cut under current climatic conditions (Mewes et al. 2015).

3.4.2. Further factors influencing the timing of grassland use

In the next step, the “biomass-dependent timing” may be influenced by two other factors: the restrictions placed by conservation measures and weather.

1) Due to conservation measure restrictions, the “biomass-dependent timing” of the profit-maximising cut determined previously may not be allowed. In this case, the timing is adapted to lie within the allowed timeframe of the measure and as close to the “biomass-dependent timing” as possible. For the profit-maximising grassland use, no restrictions apply.

2) In a second step, the impact of weather events is considered. We consider inundations and precipitation. We assume that the farmer will consider the weather forecast in order to adapt the timing of grassland use to expected weather conditions and assume that the weather forecast predicts the weather for the following week accurately.

Considering moderate weather events, i.e. precipitation and inundations of up to 7 days, the timing of mowing may either be brought forward up to 6 days if the conditions at the previously-determined timing are not suitable for mowing, or be delayed if this is not possible. It is also possible that a grassland cell is not cut at all if the conservation measures do not allow for any further delays (see Appendix A1 for details).

Considering long inundations of 7 days or more, the quality of yield is damaged in such a way that further usage is impossible. Once the meadow has dried off it is mown and the harvest is discarded at a cost. This happens one week after drying off in order to allow the heavy mowing machinery to enter the meadow. After this, the grass starts growing again, but the next harvest is delayed as reaching the required harvest biomass will take some time.

The outcome of this part of the model is the potential grassland cell-specific timing of up to four cuts of the profit-maximising grassland use and all conservation measures. However, four cuts are not profit-maximising on every grassland cell. To determine how many of those cuts are profit-maximising, the agri-economic cost assessment is necessary.

3.5. Agri-economic cost assessment

The agri-economic cost assessment is used to determine the yield, revenue and costs of a grassland use. This information is then used for two purposes: first, to determine whether all four cuts determined previously are actually implemented on each grassland cell, and second, to determine the costs of each conservation measure on each grassland cell.

3.5.1. Calculation of yield, revenue and costs

Calculation of yield

Both quality and quantity of the grass are relevant for determining the yield. We determine the net energy content of the yield for which a market price can easily be approximated.

The yield of a cut c_i on a grassland cell *g* for a certain year *y* is calculated as follows:

$$Y_{y,g,c_i} = B_{c_i} \times EC_{c_i} \times D_{c_i}$$

Where Y_{y,g,c_i} is the yield of a cut c_i in year *y* for grassland cell *g,* B_{c_i} is the total biomass to be cut on grassland cell *g* at the timing of cut c_i,, EC_{c_i} is the energy concentration on grassland cell *g* at the timing of cut c_i, and D_{c_i} is the digestibility of the grass on grassland cell *g* at the timing of cut c_i. The timing of cut c_i has been determined previously as described above.

The quantity of the yield is determined by the factor B_{c_i}, as given by the vegetation model.

The quality is determined by EC_{c_i} and D_{c_i}. Cutting a meadow during the "biomass-dependent timing" (cp. above) with no drought or inundation events represents ideal conditions, leading to ideal values of digestibility. For silage this is 650MJ NEL/dt and for hay 550MJ NEL/dt (early grassland uses are used as silage, a late cut (when quality is too low for silage) as hay) (Mewes et al. 2014).

Any change in the timing of grassland use influences both the quantity (as determined by the vegetation model) and quality of the yield. If the timing of grassland use is changed due to measure restrictions or climatic conditions, EC_{c_i} and D_{c_i} decrease over time until levelling off, leading to a decrease in quality (Kornher et al. 1991). These changes in quality are considered by taking average values published in the literature as described in Mewes et al. (2014).

Droughts influence grass growth (Küchenmeister et al. 2014). This factor is included in the vegetation model. However, inundations influence the quality of yield. Short inundations of up to 3 days do not have any considerable impact on digestibility. Long inundations of 7 days or more lead to a complete loss of harvest, as the digestibility has fallen below the minimum level of 0.53 (Soffe 2011). This corresponds to minimum digestibility values of 520MJ NEL/dt for silage and 500MJ NEL/dt for hay (Mewes et al. 2014). Medium inundations of more than 3 but less than 7 days reduce the digestibility of the harvest. The digestibility values are interpolated in this case.

Calculation of revenue and costs

In order to determine the revenue R_{y,g,c_i} of a cut c_i on grassland cell *g* in year *y*, the net energy content of the yield (i.e., Y_{y,g,c_i}) is assigned a monetary value by multiplying it with the price for concentrated feed (*P*) (Mewes et al. 2015) according to the following formula:

$$R_{y,g,c_i} = Y_{y,g,c_n} \times P$$

Costs consist of the costs of different farming operations such as sowing, fertilization, plant protection, mowing, transportation and others. Each operation causes costs in terms of machinery used (the machinery itself as well as diesel) and labour, and may include other factors (such as the costs of fertilizer). The cost values have been taken from the literature (Mewes et al. 2014) and have been summarized into the categories needed for this paper (cp. Table 3). Any missing values were interpolated from existing values. Costs of harvest deposition were added with data from stakeholder partners of the Ecoclimb project (https://www.b-tu.de/en/ecoclimb) who are active in the region.

As better-quality land generates a higher yield, this may translate into the more intensive use of machinery and thus, higher costs. An overview of the summarised costs of different farming operations is given in Table 3:

Table 3: Cost of different farming operations according to the grassland cell's quality

Farming operation	Costs according to quality category			
	1	2	3	4
1-cut meadow	173€/ha	173€/ha	180€/ha	180€/ha
2-cut meadow	252€/ha	252€/ha	263€/ha	263€/ha
3-cut meadow	380€/ha	380€/ha	393€/ha	412€/ha
4-cut meadow	509€/ha	509€/ha	522€/ha	561€/ha
Cost of disposing of harvest	25€/t	25€/t	25€/t	25€/t
Costs of fertilization	3€/ha	3€/ha	3€/ha	3€/ha

3.5.2. Number of grassland uses per grassland cell

The timing of grassland use is determined by the „timing of grassland use" box (Fig. 1). However, depending on the quality of a grassland cell, an intensive grassland use of four cuts may not be profitable on all grassland cells. For each grassland cell, it is therefore decided whether the second, third and fourth cut are actually implemented or not by considering the costs and additional revenue to be gained from this additional cut. If the revenue generated by the cut at least covers the costs of this cut the cut is implemented. Otherwise, it is not. This may occur on grassland cells of low quality and/ or when restrictions placed by conservation measures and climatic conditions lead to very unsuitable timings.

3.5.3. Calculation of profit differences

Once the number of cuts on a grid cell has been determined for a chosen year, the profit differences between the profit-maximising cut and a conservation measure can be calculated as follows:

$$\Delta P_{y,g} = \left(\sum_{c_1}^{c_n} (R_{y,g,c_n,pm}) - C_{y,g,pm} \right) - \left(\sum_{c_1}^{c_n} (R_{y,g,c_n,cm}) - C_{y,g,cm} \right)$$

Where $\Delta P_{y,g}$ is the change in profit on a grid cell *g* in a year *y*, $\sum_{c_1}^{c_n}(R_{y,g,c_n,pm})$ is the sum of revenue gained from cuts c_1 to c_n by implementing the profit-maximising grassland use (*pm*) on grassland cell *g* in year *y*, and $C_{y,g,pm}$ are the costs of implementing the profit-maximising grassland use (*pm*) on grassland cell *g* in year *y*. Similarly, $\sum_{c_1}^{c_n}(R_{y,g,c_n,cm})$ is the sum of revenue gained from cuts c_1 to c_n by implementing a chosen conservation measure (*cm*) on grassland cell *g* in year *y*, and $C_{y,g,cm}$ are the costs of implementing a conservation measure (*cm*) on grassland cell *g* in year *y*. The resulting value represents the opportunity costs of implementing the conservation measure instead of the profit-maximising grassland use. These costs are calculated for all conservation measures.

3.5.4. Output: determination of grassland cell-specific timing and costs

Once the timing and quantity of grassland uses and the associated costs are determined, the final output of the agri-economic cost assessment is a grassland cell specific overview of 1) the timing of both the profit-maximising grassland use and the different conservation measures in each year and 2) the costs of all potential conservation measures.

4. Results: changes in grassland use timing and costs

Changes in timing of profit-maximising grassland use

Table 1 shows the average timing of the first grassland use in the case study region for both RCP scenarios and time slices.

Table 1: Timing of the first grassland use in days since the beginning of the year for time slices 2020-2039 and 2060-2079 for RCP 4.5 and 8.5 scenarios.

	2020-2039	2060-2079
RCP 4.5	124	119
RCP 8.5	125	118

In both scenarios the timing of grassland use is earlier in the second time slice. The difference between the two scenarios is marginal, but the difference between the two time slices is larger for the RCP 8.5 scenario than for the RCP 4.5 scenario.

Changes in costs of conservation measures

Figure 2 summarises the differences in costs between the different measures and time slices for the RCP 4.5 and 8.5 scenarios.

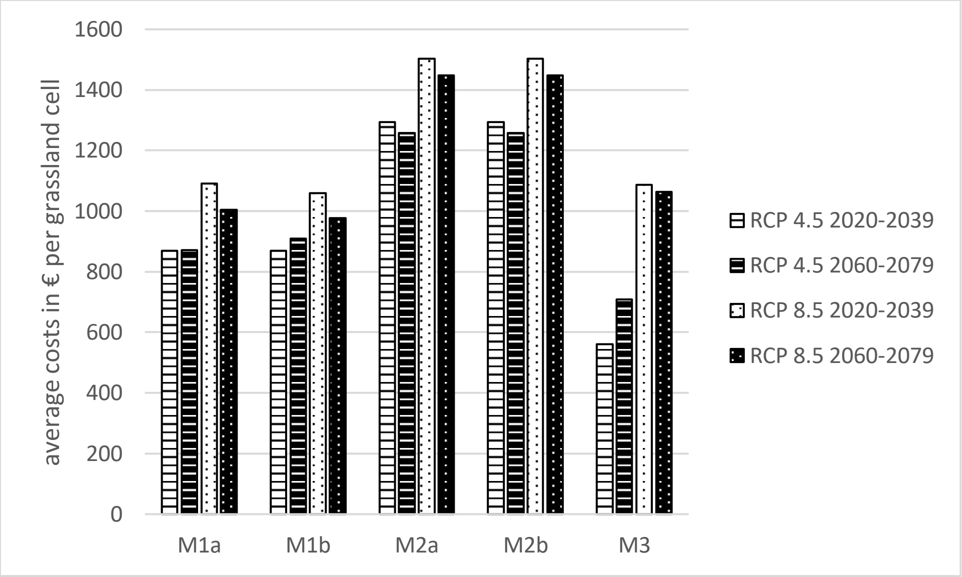

Figure 2: Average costs of conservation measures for the time slices 2020-2039 and 2060-2079 for RCP scenarios 4.5 and 8.5

Generally, the costs of measures are higher in the 8.5 scenario. This suggests that the more profound climate change impact results in larger opportunity costs, i.e. the profit of the profit-maximising grassland use increases and/ or the profit of the conservation measures decreases.

The costs of the late measures (measures M2a and M2b) are consistently higher than the costs of the early measures (measures M1a and M1b). As may be expected, the costs of measure M3, the 2-cut measure, are lower than the costs of the 1-cut measures (M1a, M1b, M2a and M2b) in the RCP 4.5 scenario. In the RCP 8.5 scenario the costs are similar to those of measures M1a and M1b, which suggests that the second cut allowed in this scenario is either not implemented or generates very little additional profit.

Considering the RCP 8.5 scenario, the costs of all measures are lower in the second time slice than in the first time slice. In the RCP 4.5 scenario only the costs of measure M2a and M2b are lower in the second time slice. In the other measures there is either very little difference or costs increase in the second time slice.

5. Discussion and Conclusion

We have developed a model to determine the changes in timing of grassland use and costs of conservation measures under climate change. Our results show that the timing of the first cut is projected to occur earlier, although the differences between the two considered RCP scenarios is marginal. Regarding the costs of conservation measures, the differences between the RCP 4.5 and 8.5 scenarios is larger than the differences over time within one scenario. Depending on the measure and scenario, the average costs may be largely similar, increase or decrease over time. However, the costs of all measures are larger in the RCP 8.5 scenario than in the RCP 4.5 scenario.

Our results show that the impact of climate change on the costs of conservation measures is by no means uniform. Generally, and especially in the RCP 8.5 scenario, the costs of conservation seem to decrease. A possible reason for this is the increasing risk of a loss of harvest due to more frequent flooding early in the year. As this reduces the profit to be obtained from the profit-maximizing grassland use, the relative costs of conservation measures (with late cutting dates) decrease. However, and somewhat contradictorily, the costs in the RCP 8.5 scenario are larger than in the RCP 4.5 scenario.

This suggests that overall, the profit of the profit-maximising grassland use is larger in the RCP 8.5 scenario, especially in the early time slice. Comparing the cost differences of the two RCP scenarios, one can observe that the difference between time slices is much larger in the RCP 8.5 scenario than in the 4.5 scenario. Given that the RCP 8.5 scenario represents a larger climate change, this may not be surprising.

Our model is subject to limitations: the impact of climate change on grass growth is still not completely understood and consists in part of contradicting factors. For example, increasing CO_2 concentrations are thought to positively impact grass growth (Chen et al. 1996, Lee et al. 2010), while an increase in extreme events such as flooding (Morris & Brewin 2013) and droughts (Lei et al. 2015, Wang et al. 2018) may have negative impacts. Apart from the inherent challenges of including a variety of impacts on grass growth, a comprehensive model such as ours needs to simplify complex processes in order to remain manageable. Therefore, despite the effort to include some major influences on grass growth, the vegetation model can only represent an approximation. Similarly, the underlying climate model is subject to uncertainties. We have tried to take these into account by reporting results for two distinct climate scenarios. Finally, we assume that the costs of grassland use remain stable. As these costs are influenced by a variety of factors such as the price of labour or crude oil, predicting their development over such long time periods would be mere speculation.

Finally, in order to better understand the impact of climate change on the costs of conservation measures, one could analyse other climate scenarios and case study regions. This may shed light on the underlying factors of some of the results observed above. Nonetheless, the results show that the model is able to assess the impact of climate change on both the timing of grassland use and the costs of conservation measures. This is an important starting point for further investigating the cost-effectiveness of conservation measures under climate change.

Acknowledgements

This research has been funded by the Federal Ministry of Education and Research (economics of climate change).

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Appendix

Appendix A1: processes for determining in how far the grassland use is brought forward or delayed

I) Bring grassland use forward by up to 7 days
  a) Flooding:
    - On which days (day determined previously and 6 previous days) is the area not flooded?
    - Considering conservation measures, are all of these days still within the permitted time frame?
    - Have the previous 7 days also been flood-free?
    - ➔ Rank flood-free days that are still permitted and where the previous 7 days have also been flood-free, starting with the day determined previously; then continue with part Ib)
    - ➔ If no suitable days are found, go to part II)
  b) Precipitation: are the following conditions given for the flood-free day of first choice determined in part a)?
    - Previous day: maximum gentle rain of ≤1mm/day
    - No precipitation on day of harvest and following day (for silage) or following 3 days (for hay)?
    - ➔ If yes: timing of grassland use is determined
    - ➔ If no: repeat part b) with flood-free day of second choice, until a day has been found or no other flood-free days available; then: continue with step II)

II) Delay grassland use, if no timing has been found in step I)
  a) Flooding:
    - When is the next day that the area has not been flooded for 7 days?
    - Considering conservation measures, is this day still within the permitted time frame?
  b) Precipitation: are the following conditions given for the flood-free day determined in part a)?
    - Previous day: maximum gentle rain of ≤1mm/day
    - No precipitation on day of harvest and following day (for silage) or following 3 days (for hay)?
    - ➔ If yes: timing of grassland use is determined;
    - ➔ If no: repeat part a) to find the next possible flood-free day until a day has been found or no further delay is allowed. In case of the latter, no grassland use is possible.