Integrated assessment of climate change impacts on multiple ecosystem services in Western Switzerland

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Abstract

Climate change can affect the provision of ecosystem services in various ways. In this study, we provide an integrated assessment of climate change impacts on ecosystem services, considering uncertainties in both climate projection and model parametrization. The SWAT model was used to evaluate the impacts on water regulation, freshwater, food, and erosion regulation services for the Broye catchment in Western Switzerland. Downscaled EURO-CORDEX projections were used for three periods of thirty years: base climate (1986-2015), near future (2028-2057), and far future (2070-2099). Results reveal that in the far future, low flow is likely to decrease in summer by 77% and increase in winter by 65%, while peak flow may decrease in summer by 19% and increase in winter by 26%. Reduction in summer precipitation reduces nitrate leaching by 25%; however, nitrate concentrations are projected to increase by 14% due to reduced dilution. An increase in winter precipitation increases nitrate leaching by 44%, leading to an increase of nitrate concentration by 11% despite increasing discharge and dilution. Yields of maize and winter wheat are projected to increase in the near future but decrease in the far future because of increasing water and nutrient stress. Average grassland productivity is projected to benefit from climate change in both future periods due to the extended growing season. This increase in productivity benefits erosion regulation as better soil cover helps to decrease soil loss in winter by 5% in the far future. We conclude that water regulation, freshwater and food services will be negatively affected by climate change. Hence, agricultural management needs to be adapted to reduce negative impacts of climate change on ecosystem services and to utilize emerging production potentials. Our findings highlight the need for further studies of potentials to improve nutrient and water management under future climate conditions.

Keywords: Climate change; water regulation; freshwater; food; erosion regulation; SWAT

1. Introduction

Ecosystem services are benefits of natural ecosystems for human wellbeing. They can be classified into provisioning, regulating, supporting, and cultural services that are interacting in a complex dynamic (MEA, 2005). Ecosystem services are under increasing pressure from climatic and socioeconomic drivers. With an increasing world population, the demand for provisioning services is increasing; at the same time, provisioning as well as regulating ecosystem services might be negatively affected by progressing climate change (IPCC, 2014). According to global climate projections, temperatures may increase by up to 5 °C towards the end of the century, and precipitation patterns will most likely change to result in more extended drought periods and increasing frequency of extreme events (IPCC, 2013; Vaghefi et al., 2019). These events could affect ecosystem services such as water regulation and food (Schröter et al., 2005). Variation in water quantity such as an increase in winter discharge due to higher snowmelt and precipitation, reduction in summer discharge because of a reduction in the snow storage in winter, and increase in evapotranspiration could be expected (Brunner et al., 2019). Climate change is also altering biophysical production conditions, leading both to increase risks and emerging potentials for agricultural production. Global warming may create more suitable growing conditions in northern Europe, but due to water limitations, a less suitable one in southern Europe (Olesen et al., 2011).

Furthermore, increasing frequency of extreme events and annual climatic variability may also lead to additional crop yield losses (Henne et al., 2018) and reduce food provisioning services. In response to these changes, farmers will need to adapt their management in order to maintain or even increase production to satisfy the demands of a growing world population. Autonomous adaptation measures implemented by individuals or groups of farmers may aggravate conflicts between provisioning services and regulating/maintenance services or induce resource-use conflicts (e.g. for water and land). For example, an increase in irrigation to stabilize production under climate change may induce conflicts of water use or even lead to the overexploitation of water resources. To prevent such maladaptive responses, it is necessary to take an integrated perspective on climate change impacts, anticipating not only impacts on provisioning services, but also on regulating and supporting services, which are essential prerequisites for sustainable farming systems. A better understanding of joined responses of ecosystem services to climate and management drivers is helpful to support adaptation planning and avoid maladaptive developments (Holzkämper, 2017; Reidsma et al., 2015).

For a case study in the Broye catchment in Western Switzerland, Klein et al. (2014) provided first estimates of climate change impacts on food, freshwater, and erosion regulation service indicators; however, this study applied a field-scale cropping system model (CropSyst) to investigate impacts of climate change for different spatial subunits of the catchment considering heterogeneity of soil and climate conditions (Stöckle et al., 2003). This model did not allow for the consideration of lateral flows and impacts of climate change on the hydrological cycle. Due to this lack of an explicit integration of system linkages between agricultural management activities at local and regional scales and hydrological cycle emerging risks of water pollution and limitations in water availability during extended drought periods could not be evaluated. Milano et al. (2015, 2018) also highlighted the need for assessing possible reductions in water quality and quantity in Switzerland under climate change.

In this study, we aim to bridge this gap and provide a first integrated assessment of climate change impacts for the Broye catchment considering linkages between catchment properties, climate, and management drivers on the hydrological cycle and freshwater provision. A previously built (Zarrineh et al., 2018) and calibrated agro-hydrological SWAT (Soil and Water Assessment Tool) model (Arnold et al., 2012) was utilized to address the impact of climate change on multiple ecosystem services. Based on the previous study by Zarrineh et al. (2018), we considered water regulation, freshwater, food, and erosion regulation as key ecosystem services and considered indicators described in Table 1.

Table 1 Ecosystem services and selected indicators.

Ecosystem services	**Indicators**
Water regulation (regulating)	Average seasonal low flows [m3/s] and peak flows [m3/s] at the outlet
Freshwater (provisioning)	Average total seasonal nitrate load [kgN/ha] and average seasonal nitrate concentration [mg/l] at the outlet
Food/ fodder (provisioning)	Average annual maize, winter wheat, and temporary ley yield [t/ha]
Erosion regulation (regulating)	Average seasonal transported sediment [t/ha] at the outlet

2. Materials and methods

2.1. Case study

The study was carried out in the Broye catchment, which is located in the South-Western part of the Swiss Central Plateau and covers an area of 630 km^2. The Broye catchment has a mean elevation of about 664 m above sea level, and the mean slope is 10.7% (6.1°). Average annual precipitation at Payerne station during 1981–2015 was 865 mm, average maximum temperature was 14.2 °C, average minimum temperature was 5.1 °C, and average daily discharge was 8 m^3/s with a maximum value of 147 m^3/s and a minimum value of 0.4 m^3/s (Fig. 1).

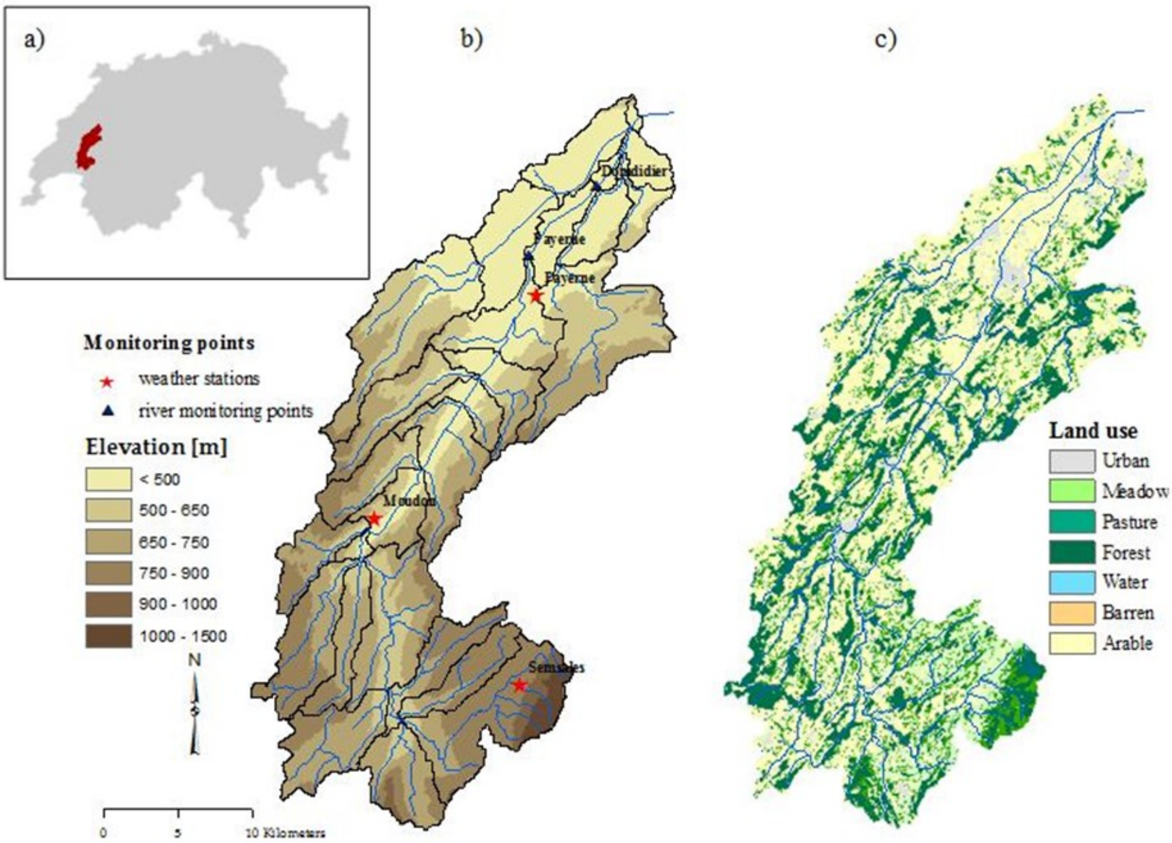

Fig. 1. The Broye catchment, located in western Switzerland illustrated in the top-left map (a). Altitude distribution of the Broye catchment with the three weather monitoring stations at Payerne, Moudon, and Semsales, discharge station at Payerne, and water quality station at Domdidier are shown in map (b) and land uses of the Broye catchment are illustrated in map (c).

Agricultural land use is dominant in the catchment (67%) consisting of arable, meadow, and pasture land uses (Fig. 1). It is, therefore, a relevant region for studying climate change impacts on the provision of multiple agroecosystem services, including food, freshwater, water regulation, and erosion regulation services.

2.2. Ecosystem service indicators

Low flows [m^3/s] and peak flows [m^3/s] at the outlet of the catchment were selected as the ecosystem service indicators of water regulation services to study the impact of climate change on discharge in all seasons. Low flows were calculated at the 5th percentile, and peak flows at the 95th percentile of simulated daily flows at the outlet of the catchment for each season. Total instream seasonal nitrate load [kgN/ha], as well as average seasonal nitrate concentration [mg/l], calculated at the outlet of the catchment, were selected as ecosystem service indicators for freshwater provisioning services. Crop yields of the main arable crops maize and winter wheat were considered as food service indicators; grassland yields were considered as an indicator for fodder provision. To identify the changes in the limiting factors to agricultural production under climate change, changes in water and nutrient limitations, as well as irrigation water use, were also explored. Total seasonal transported sediment at the watershed outlet was considered as the indicator for the erosion regulation service.

2.3. Data and model

SWAT was set up and calibrated/validated for the Broye catchment for 1981-2018 (35 years) with 27 sub-basins and 815 hydrological response units (HRUs) as described in Zarrineh et al. (2018). For all arable HRUs crop rotations were defined according to regional information on crop shares (FOAG, 2015) following national recommendations for crop rotations (Vullioud, 2005). Grain maize, winter wheat, and temporary ley were used as the main rotating crops to assess climate change impact on crop yield. We calibrated the SWAT model for daily discharge [m^3/s], nitrate load [kgN], and annual low flow[m^3/s]. In this study, we used a limited set of behavioral parameters with high Nash-Sutcliffe Efficiency (NSE) values≥0.65 for daily discharge, PBIAS≤±10% for low flow, and PBIAS≤±25% for nitrate load (see Zarrineh et al. 2018, for more detail) to investigate the impact of climate change. With these restricted criteria indicating good solutions (Moriasi et al., 2007) five sets of parameters were selected (see supplementary Table S1 and Figures S1-S2 for calibration and validation results with calibrated uncertainty bounds of SWAT parameters and supplementary Table S2 for selected SWAT parameters with calibrated range). Yield simulation performances had been evaluated in Zarrineh et al. (2018) with satisfactory results for maize (PBIAS= +4% and Willmott index = 0.5) and winter wheat (PBIAS= -2% and Willmott index = 0.7), respectively (Willmott, 1981).

2.4. Climate change scenarios

Bias-corrected climate change scenarios for this study were derived from climate scenarios for Switzerland “CH2018” (Feigenwinter et al., 2018). The ensemble of 68 downscaled EURO-CORDEX (Jacob et al., 2014; Kotlarski et al., 2014) model projections were evaluated for remaining biases in terms of seasonal precipitation with focus on summer and winter. As a selection criterion, total bias error was estimated as a sum of average bias errors of summer and winter for each station compared to measured climate data for 1981-2015. Model projections with these three criteria were selected: a total percentage bias error of less than 30% (approximately less than 10% for each station), the greatest projected reductions in summer precipitation, and the greatest projected increases in winter precipitation. With these criteria, four models were selected. All selected models were based on Representative Concentration Pathway 8.5 (RCP 8.5) to account for extreme situation in projected changes in water regulation services (reduction in summer flow, increase in winter flow). Table 2 provides an overview of the four climate models that were used as climate input data in this study (CH2018, 2018).

Table 2 Overview of assessed climate model projections including GCM (General Circulation Model), RCM (Regional Climate Model), RCP (Representative Concentration Pathway), and resolution (12 km grid: EUR11 and 50 km grid: EUR44).

RCM	Institute (Abbreviation)	GCM	Institute (Abbreviation)	RCP	Resolution	Abbreviation used in this work
CCLM4-8-17	CLM Community (CLMCOM)	HadGEM2-ES	Met Office Hadley Center (MOHC)	8.5	EUR11	CLMCOM-CCLM4-HADGEM-EUR11
CCLM4-8-17	CLM Community (CLMCOM)	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	8.5	EUR11	CLMCOM-CCLM4-MPIESM-EUR11
REMO2009	Climate Service Center (CSC)	MPI-ESM-LR	Max Planck Institute for Meteorology (MPI-M)	8.5	EUR44	MPICSC-REMO2-MPIESM-EUR44
RCA4	Swedish Meteorological and Hydrological Institute (SMHI)	EC-EARTH	Irish Centre for High-End Computing (ICHEC)	8.5	EUR11	SMHI-RCA-ECEARTH-EUR11

Transient climate projections for the period 1981-2099 were divided into four main periods: 1981-1985 was considered a warm-up period for the SWAT model; 1986-2015 was considered as base climate; 2028-2057 as near future, and 2070-2099 as far future. Seasonal climatic variability for these three periods (base climate, near future, and far future) is illustrated in Figure 2 for Payerne station.

Fig. 2. Climatic variation for four models and three considered periods (base climate (1986-2015), near future (2028-2057), and far future (2070-2099)) for annual and seasonal precipitation (a) and average annual temperature (b) for Payerne station. Values in the precipitation bar plots indicating seasonal precipitation.

3. Results

3.1 Water regulation

Model results suggest that water availability will decrease under climate change in all seasons except winter (Fig. 3). CLMCOM-CCLM4-HADGEM-EUR11 and SMHI-RCA-ECEARTH-EUR11 project the highest reduction in low flows in all seasons except summer (Fig. 3) as well as the most substantial decrease in precipitation (Fig. 2a) and the highest increase in temperature compared to the other models (Fig. 2b). In SMHI-

RCA-ECEARTH-EUR11 (Fig. 3b), the level of low flows in summer dropped to below 0.5 [m^3/s] in the far future, which indicates a possibility of the river to dry up during summer. Also, MPICSC-REMO2-MPIESM-EUR44, which projected a precipitation increase for all seasons, predicted a reduction of low flows in summers. All selected scenarios and sets of parameters suggest that low flow will decrease in the future (Fig. 3b). As indicated by the range of boxplots and spread of points in Fig. 3, uncertainties due to climate models and SWAT will increase with time.

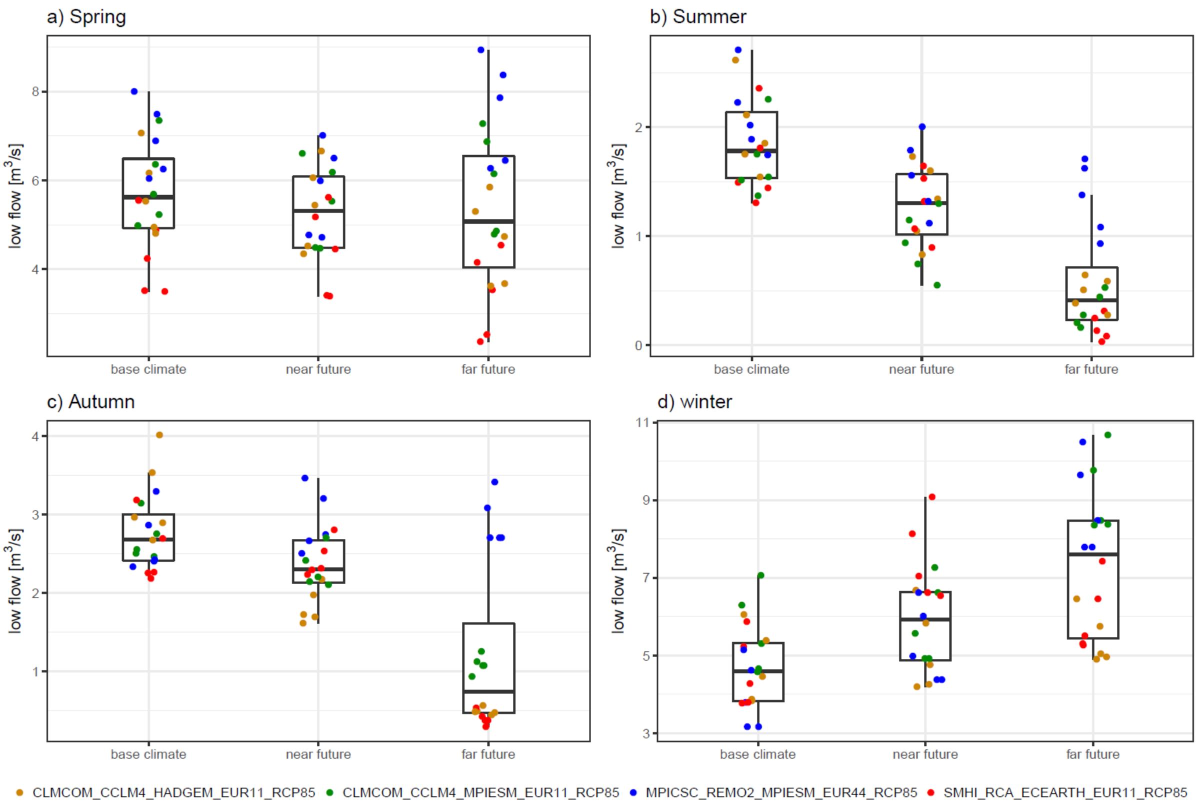

Fig. 3. Impact of climate change on the average seasonal low flow [m^3/s] for the three periods (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099). Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25th and 75th percentiles as box; and 5th and 97.5th as lines). Low flow will decrease during summer and autumn and increase during winter.

Peak flows are expected to decrease in summer (Fig. 4b), increase in winter (Fig. 4d), and remain unchanged during spring and autumn (Fig. 4a, c). Models that predict a reduction in precipitation (e.g., CLMCOM-CCLM4-HADGEM-EUR11 and SMHI-RCA-ECEARTH-EUR11), also predict a reduction in peak flows. Contrary, a wet scenario like MPICSC-REMO2-MPIESM-EUR44, predicts a likely increase in peak flow in spring, summer, and autumn (Fig. 4a, b, c).

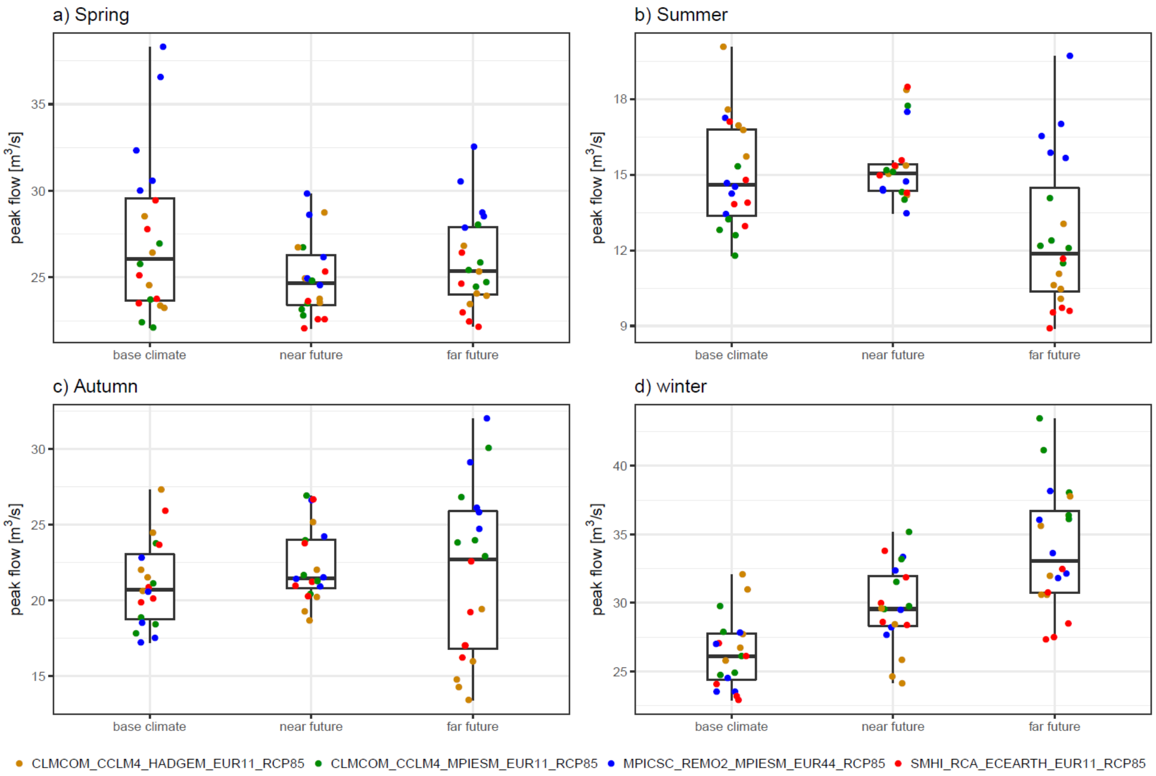

Fig. 4. Impact of climate change on the average seasonal peak flow [m^3/s] for the three periods (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099). Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25^{th} and 75^{th} percentiles as box; and 5^{th} and 97.5^{th} as lines). Peak flow will decrease in summer and increase in winter.

3.2. Freshwater

Our results show that nitrate loads in the river decrease during summer under climate change due to reduced leaching with lower precipitation (Fig. 5b). On the contrary, nitrate loads are projected to increase during autumn and winter (Fig. 5c, d). These changes are driven by precipitation increases projected for these seasons. During spring, a small reduction in nitrate load (Fig. 5a) is expected, which can be explained by the fact that warmer spring temperatures in the near future provide better conditions for crop growth and nutrient uptake. In the far future, reduction in crop productivity returns nutrient uptake to the same level as base climate, as productivity is negatively affected by climate change in the long term (Fig. 5a and Fig. 7).

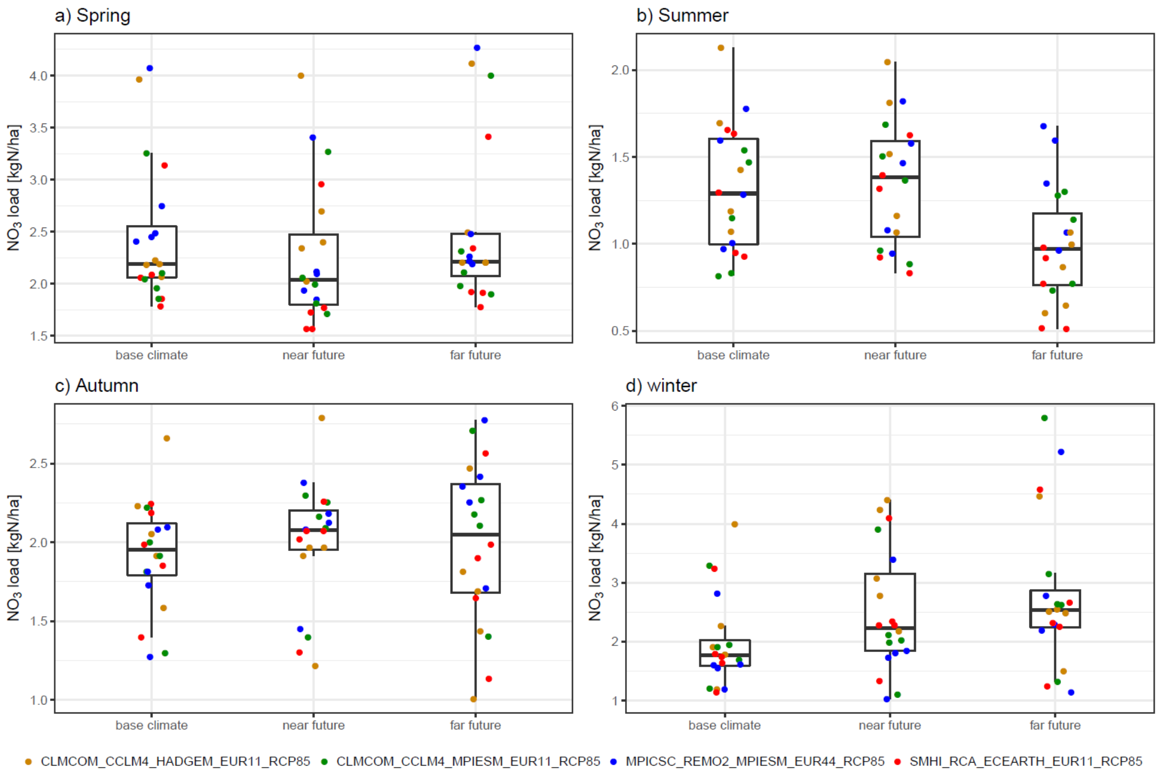

Fig. 5. Impact of climate change on the total nitrate load [kgN/ha] per season for each period (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099). Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25th and 75th percentiles as box; and 5th and 97.5th as lines). Nitrate load will increase during winter in both future periods and decrease in summer in the far future.

Nitrate concentrations are projected to increase in the future in all seasons (Fig. 6). Although nitrate loads are expected to decrease during summer in the far future (Fig. 5b), reduced dilution with lower discharges during summer results in increased nitrate concentrations (Fig. 6b). The highest nitrate concentration is projected to be in autumn due to higher nutrient availability in the soil and low diluting water (Fig. 6c).

CLMCOM-CCLM4-HADGEM-EUR11 predicted extremely high nitrate concentrations for the growing season of autumn 2048 to summer 2049, because a frost period without nitrate uptake was followed by a heavy precipitation period (See Supplementary Figures S3-S6 for more detailed explanation and supporting graphics). We, therefore, removed these extreme values in the illustration of Figure 5.

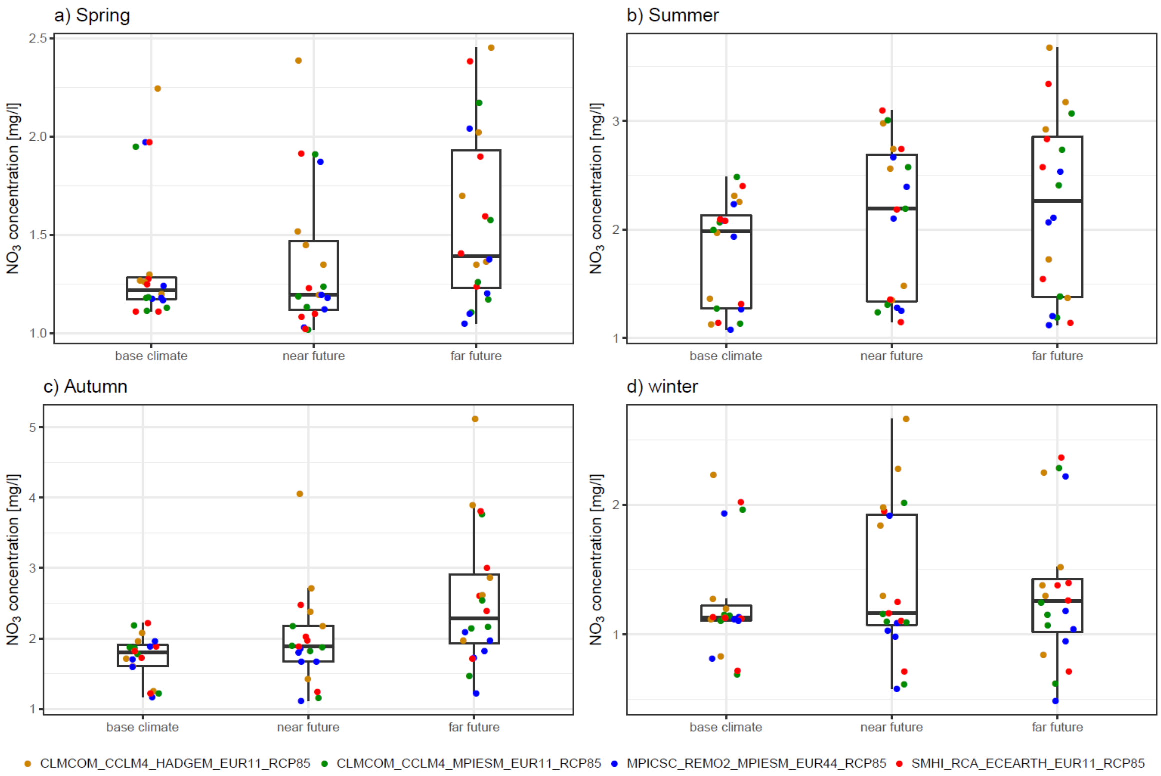

Fig. 6. Impact of climate change on the average seasonal nitrate concentration [mg/l] for each period (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099). Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25th and 75th percentiles as box; and 5th and 97.5th as lines). Nitrate concentration will increase in the future.

3.3. Food / fodder

Crop productivity is projected to increase in the near future but declines afterward in the far future for both maize (Fig. 7a) and winter wheat (Fig. 7b). Grasslands productivity is projected to increase continuously as a result of an extended growing season with warmer temperatures (Fig. 7c). Nutrient and water stress are projected to increases in the future (Fig. 7d, f). Even in MPICSC-REMO2-MPIESM-EUR44 that projects an overall increase in precipitation, irrigated water consumption increases due to increased evaporative demand with elevated temperatures (Fig. 7e). Uncertainty in the simulated indicators of food service (crop yield) as well as related indicators (nitrogen and water stress and irrigation water) increases by time (Fig. 7).

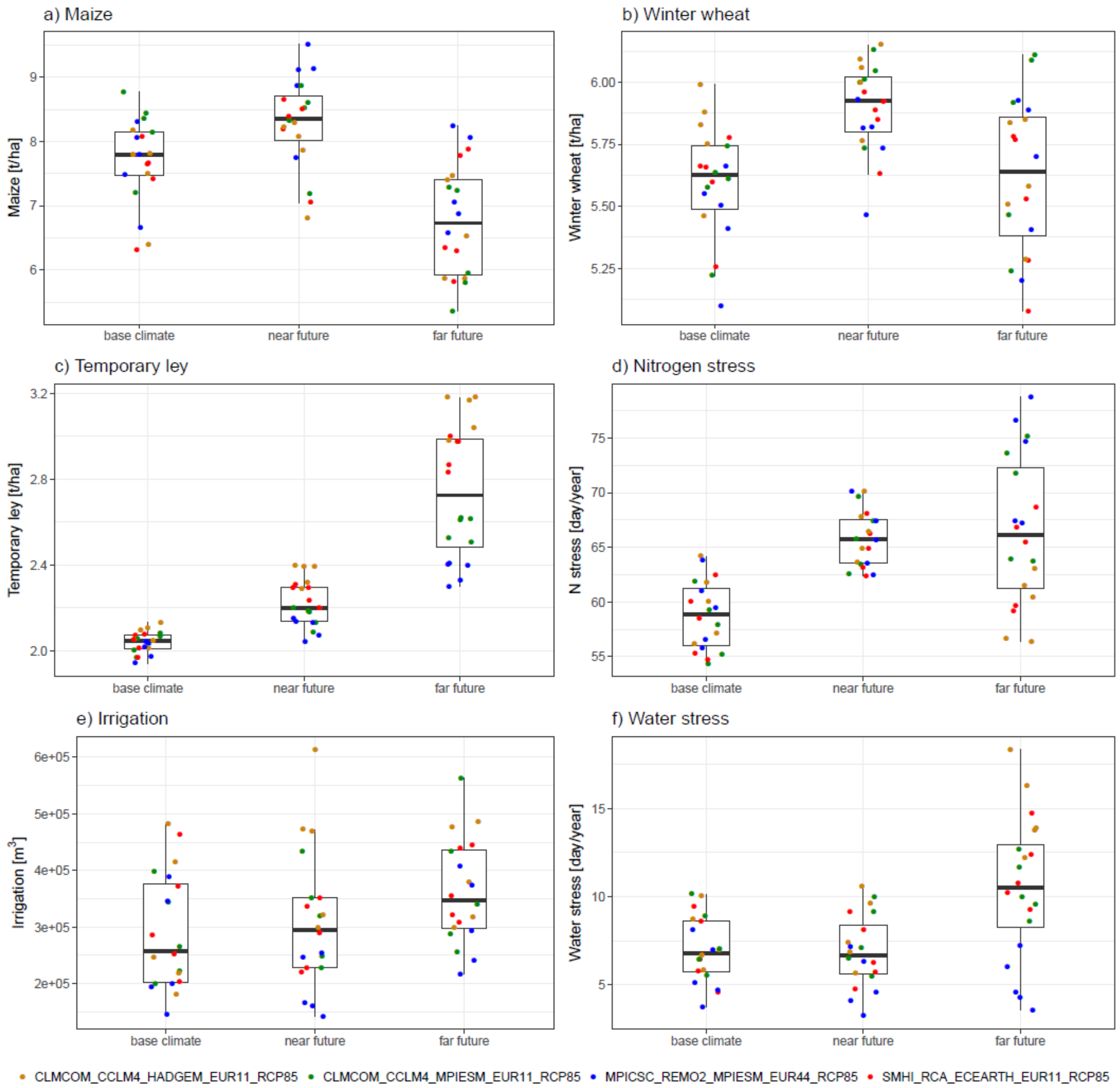

Fig. 7. Impact of climate change on the average crop yield production [t/ha] for each period (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099) for a) maize (spring crop), b) winter wheat (winter crop), and c) temporary ley (cropped grass within rotation); and stress factors: d) Nitrogen stress days per year and f) water stress days per year; and e) average annual irrigation water amount [m^3]. Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25^{th} and 75^{th} percentiles as box; and 5^{th} and 97.5^{th} as lines). Maize and winter wheat yield will reduce in the far future, but in the contrary, grassland yield will increase in the future. Water and nitrogen demand will increase in the future.

3.4. Erosion regulation

Soil loss is projected to increase in spring because of an increase in rainfall intensity (Fig. 8a), but decrease in summer with decreasing summer precipitation (Fig. 8b). Increasing winter precipitation, however, does not lead to an increase in sediment loads (Fig. 8d) due to a compensating effect in higher grassland growth (Fig. 7c). In autumn, transported sediment is projected to increase slightly in the near future and decrease slightly afterward until the end of the century with very high uncertainty. These changes are also driven by the compensating effects of soil cover and precipitation changes.

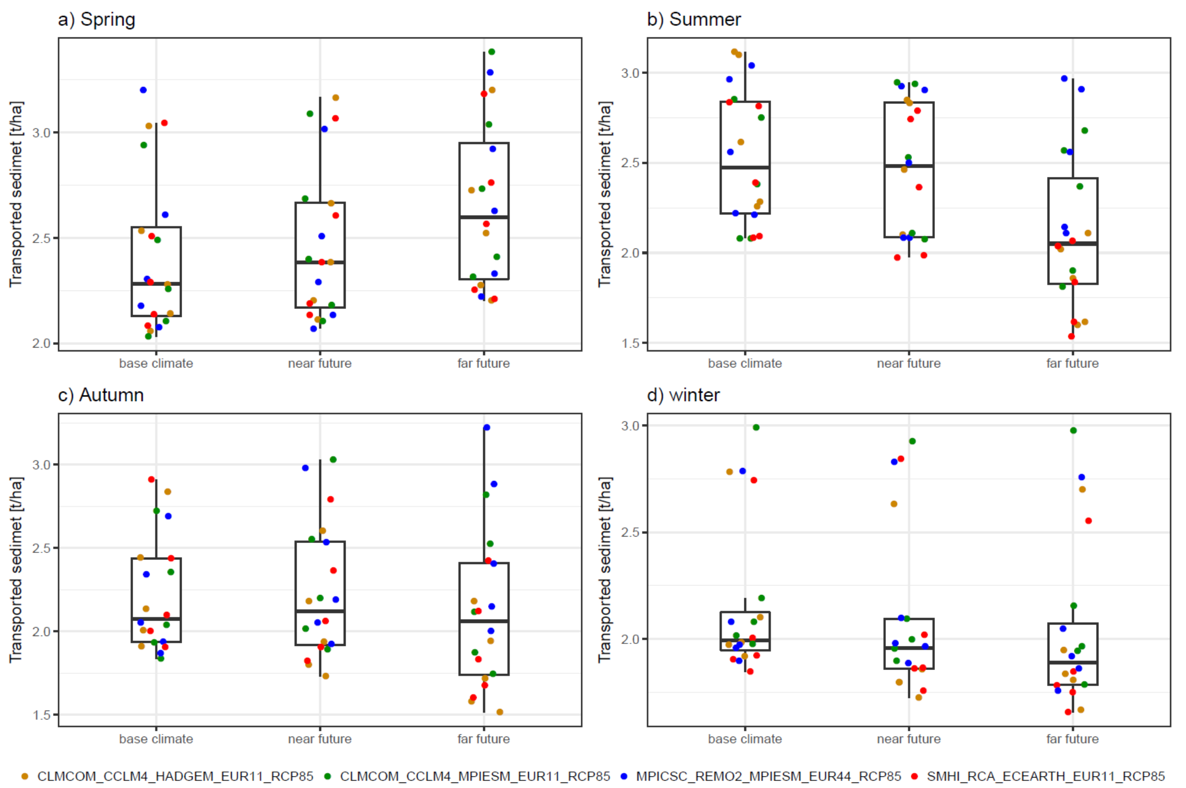

Fig. 8. Impact and uncertainty of climate change on the average seasonal transported sediment [t/ha] for each period (base climate: 1986-2015, near future: 2028-2057, and far future: 2070-2099). Points show indicator estimates with four different climate projections (colors) and five SWAT sets of parameters; boxplots indicate overall uncertainty distributions (median, 25^{th} and 75^{th} percentiles as box; and 5^{th} and 97.5^{th} as lines). Transported sediment will decrease during summer and winter, and increase in spring.

The average impacts of climate change on all mentioned ecosystem indicators are summarized in Supplementary Table S3.

4. Discussion

4.1 Water regulation

We found that low flows and water quantity in the Broye channel are likely to decrease severely in the future, especially during summer months. This change is driven not only by decreasing precipitation but also by increasing evapotranspiration under elevated temperatures. These findings are in line with Brunner et al. (2019) and Milano et al. (2015) who obtained similar results for the Swiss Plateau, where the Broye catchment is located.

The projected decreases in low flows in the Broye river imply that water availability for irrigation will become more and more limiting during the times it is most needed to satisfy crop water demands. The results of this study suggest that low flow is likely to decrease under climate change decreasing water availability for irrigation during the period of the year, when it is needed most. However, peak flow may increase during winter due to an increase in precipitation. As findings of Froidevaux et al. (2015) and Köplin et al. (2014) suggest, this could also imply an increase in flood risk during winter in the Broye catchment.

4.2 Freshwater

This study shows that freshwater provisioning services are likely to be negatively affected by climate change. This is partly a result of higher nitrate leaching in spring, autumn, and winter, and partly due to lower dilution with reducing discharge rates in summer and autumn (Mehdi et al., 2015; Yang et al., 2018). The reduction in water quality can be improved by adjusting crop rotation (e.g., by increasing cover crops and grass) to maintain soil coverage all-year-round. Transforming the arable land to the forest or permanent grasslands can be an option to reduce the nitrate leaching (Di and Cameron, 2002). Moreover, increases in grass production can lead to increases in extensive grassland areas, increasing fodder production to support livestock, but diffuse pollution from livestock production needs to be assessed to prevent reduction in water quality. Furthermore, increasing riparian buffer strips along the river can be an option to reduce nitrate pollution in the river. Such possible adaptation options should be studied in depth in future research to evaluate their potentials to improve water quality and reduce tradeoffs between freshwater and other ecosystem services such as food/ fodder under climate change to support adaptation planning (Milano et al., 2018; Reyjol et al., 2014).

As illustrated in Figure 2a, there are differences in projections of seasonal precipitation changes in the selected models (e.g., increasing, decreasing, and together first increasing then decreasing), but temperature is projected to increase in all models (Fig. 2b). The highest increase of temperature is estimated in CLMCOM-CCLM4-HADGEM-EUR11 as well as the highest reduction in annual precipitation. Extremely high leaching values were projected for CLMCOM-CCLM4-HADGEM-EUR11 in 2048-2049 resulting from interactions between extreme climate events and land management. These values had been excluded, as this study aimed to investigate the average impacts of climate change (see Supplementary Figures S3-S6 for detailed explanations). However, the incident highlights the need for further studies of the risk of leaching under climate change with particular emphasis on climate extremes and compound effects (Zscheischler et al., 2018).

4.3 Food/ fodder

Our results suggest a positive impact of climate change on crop productivity in the near future as was also found by Reidsma et al. (2015) and Webber et al. (2018); however, for the far future, model results suggest a decline in crop yields (Fig. 7a and b). Increases in atmospheric CO_2 concentration, which were not quantified in this study, could imply a greater crop yield and water use efficiency benefits especially for C3-crops such as winter wheat (Guo et al., 2010). The elevated CO_2 concentration (CO_2 fertilization effect) could partly reduce the projected negative impact on crop yield in the far future. In comparison to our study, Klein et al. (2013) estimated higher yield decreases with climate change on the basis of the field-scale crop model CropSyst. Discrepancies could originate from the choice of climate models, structural differences between crop growth modules and crop parametrizations. Uncertainties in estimated climate change impacts are generally known to be large, especially in the region investigated in this study (e.g. Rosenzweig et al. (2014) and Holzkämper et al. (2015)). However, more detailed comparative analyses are required to investigate in depth which differences in model structure and parametrization drive these discrepancies in impact estimates besides climate projection uncertainties. Despite differences in crop yield change projections, results of both models agree in their projections of increasing water stress under climate change. Besides water stress, also high temperatures are projected to limit crop productivity in the far future. Maize and winter wheat yield show temperature increase to be a dominant limiting factor for growth, whereas, a reduction in crop yield in MPICSC-REMO2-MPIESM-EUR44 is not due to water stress (Fig. 7 a, b, f). Grassland productivity may be limited periodically and in extreme drought years. However, the extension of the growing season in the cold season with higher temperatures overcompensates warm season limitations, which implies an increase in average grassland productivity. Warmer temperatures increase biomass production in winter crops and grasslands, which makes these cold season crops more preferable in agricultural management under climate change; a finding that is in line with previous results from Klein et al. (2013). Based on our results, we recommend that in the future, allocating larger areas to extensive grassland can reduce agricultural management intensity to improve water quantity and quality, and decrease soil erosion, while increasing grass production.

Our results reveal that nutrient and water stress increase in the future; a finding that is supported by other studies (Neset et al., 2018). Increasing nutrient inputs, however, could put additional pressure on water quality; highlighting the importance of adopting “best management practices” for fertilizer application. Water quality problems will be aggravated if farmers use increasing amounts of pesticides to counteract increasing pest risks with warmer temperatures (Bindi and Olesen, 2011; Stoeckli et al., 2012; Seidl et al., 2016).

4.4 Erosion regulation

Differences in seasonal soil loss are caused by the seasonally varying factors soil cover and rainfall intensity. In the summer, soil erosion is reduced because of lower precipitation; whereas in the winter, better soil cover limits erosion (Fig. 8b, d). The projected increase in spring sediment load is in line with a previous study by Klein et al. (2013, 2014). However, our model does not suggest an increase in annual soil loss, as reported by Klein et al. One reason for this discrepancy lies in the difference in projected soil cover. SWAT simulates a smaller reduction in crop productivity than what is predicted by Klein et al. (2013, 2014). Therefore, soil loss is smaller despite higher rainfall in the fall – an effect that was also reported by Nearing et al. (2004). As stated by Li and Fang (2016), interactions between direct influences of rainfall intensity and indirect effects of changes in soil cover imply high projection uncertainty in climate change impacts on soil loss. Further studies should investigate in more depths which structural and parametrization differences between both models are responsible for discrepancies besides climate projection uncertainties to help reduce uncertainties in climate change impacts assessments, which are generally known to be large (e.g. Asseng et al. (2013), Rosenzweig et al. (2014), and Dams et al. (2015)).

Climate projection and SWAT model parameter uncertainties tend to increase by time; the spread of uncertainty in impact estimates is widening. This implies that considerations of the robustness of adaptation alternatives are relevant in particular for the far future. Future research on alternative adaptation pathways should account for these uncertainties.

The projected increase in spring sediment loads could be reduced by earlier sowing to improve soil cover in spring, conversion to grassland or forest, and reduced tillage, as improving soil cover.

4.5 Integrated impact assessment

Results of this model-based integrated assessment focusing on key ecosystem service indicators reveal critical system linkages between climate, land use, hydrological cycle, and water quality (Van Vliet and Zwolsman, 2008; Delpla et al., 2009). As shown here, freshwater provisioning services could deteriorate under climate change. These changes are driven by changes in precipitation patterns, affecting discharge dynamics and their interactions with plant productivity and agricultural management (i.e. fertilizer application). Reduced summer precipitation leads to reduced summer discharge and lower dilution; nitrate concentrations increase despite reduced leaching. Interactions with plant productivity are also relevant in this context: climate-induced reductions of crop productivity can reduce nutrient uptake; soil nutrients are then subject to wash-off in case of heavy and extended precipitation periods. Such influences of compound effects on ecosystem services and linkages between them should be studied in more depth in future studies to support the development of improved nutrient management strategies. This is particularly important as model projections also suggest increasing limitations of crop productivity through nutrient stress, implying that farmers may increase fertilizer application rates to reduce these limitations in the future and thereby aggravating water quality issues. Water limitations to crop productivity are also projected to increase under climate change, suggesting a possible increase in irrigation water abstractions under climate change. With the projected decrease in low flows, water availability for irrigation from the main channel of the Broye could decrease considerably – especially during the summer when irrigation water is most needed. Therefore, there may be a need to establish alternative adaptation options to prevent crop losses to drought and deteriorating effects of water abstractions on water quality (e.g. shifting to alternative cultivars, crops, adapting cropping cycles).

5 Conclusion

In this study, we demonstrate the usefulness of an integrated modelling approach to assess climate impacts studies on interconnected ecosystem services (i.e., food, freshwater, water regulation, and erosion regulation). Study results presented here suggest a possible risk of maladaptation as farmers may increase inputs to compensate for increasing nutrient and water limitations. With this, negative impacts of climate change on the freshwater service could be aggravated. To prevent such maladaptive responses to climate change, it is important to guide adaptation efforts in the region towards improving agricultural nutrient-management to reduce leaching, water-saving practices, and use of alternative water sources for irrigation (e.g. Lake Neuchâtel).

The SWAT model proved to be beneficial for modeling climate change impacts on multiple ecosystem service indicators in this study. The modelling tool employed in this study provides an excellent basis for further studies of land use/management alternatives in their potential to mitigate emerging risks of maladaptation. Furthermore, it could be applied in other regions to study the potential risks of maladaptation systematically. Also, impacts of climate and management changes on other pollutants such as phosphorus and pesticides could be integrated.

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Supplementary

Table S1: Performance metrics of selected sets of parameters.

Objective	Criteria	Calibration	Validation
Daily flow	NSE[-]	0.66±0.007	0.73±0.009
Low flow	PBIAS[%]	-3.44±6.51	-4.34±4.71
Monthly nitrate	PBIAS[%]	7.38±16.93	8.22±17.01

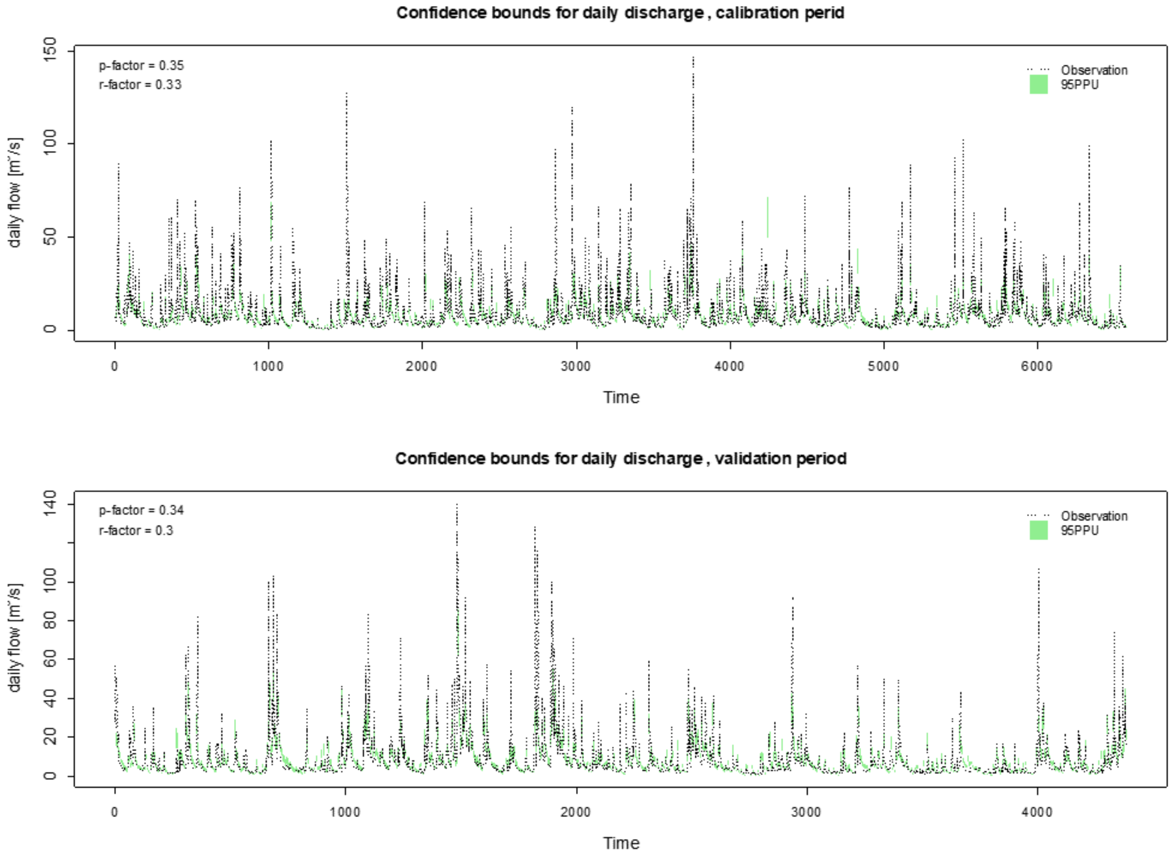
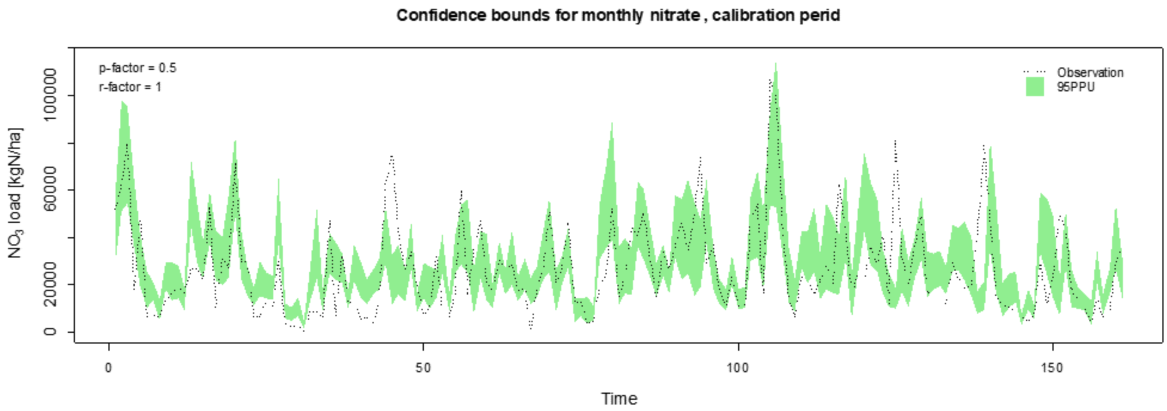


Fig. S1. Model simulation for daily river discharge in the calibration period (up) and validation period (down). SWAT was setup for 35 years (1981-2015). The first 5 years were assumed as model warm up period. 1986-2015 were divided into different periods as 18 years for calibration (1986-1990, 1996-2000, 2006-2010, 2013-2015), and 12 years for validation (1991-1995, 2001-2005, 2011-2012).



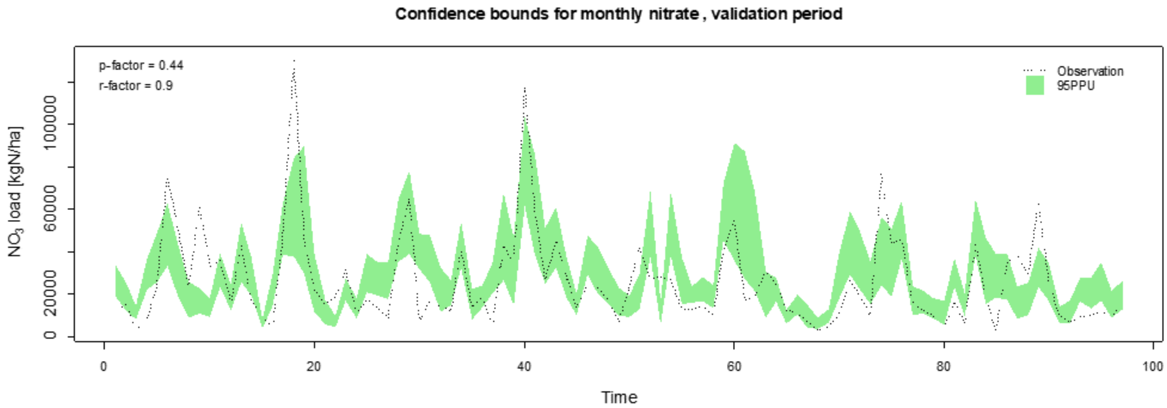


Fig. S2. Model simulation for monthly nitrate load in the calibration period (up) and validation period (down). SWAT was setup for 35 years (1981-2015). The first 5 years were assumed as model warm up period. 1986-2015 were divided into different periods as 18 years for calibration (1986-1990, 1996-2000, 2006-2010, 2013-2015), and 12 years for validation (1991-1995, 2001-2005, 2011-2012).

Table S2: Calibrated uncertainty bounds for selected SWAT parameters.

Process	Category	Change type[1]	Parameter name	Extension	Lower boundary	Upper boundary
Climate	Snow processes	V	SFTMP	basin.bsn	1.100000	1.100000
		V	SMTMP	basin.bsn	6.300001	6.300001
		V	SMFMX	basin.bsn	6.300000	6.300000
		V	SMFMN	basin.bsn	3.700000	3.700000
		V	TIMP	basin.bsn	0.335000	0.335000
Channel processes	Channel water routing	V	IRTE	basin.bsn	1	1
		V	MSK_CO1	basin.bsn	0.750	0.750
		V	MSK_CO2	basin.bsn	0.250	0.250
		V	MSK_X	basin.bsn	0.200	0.200
		V	CH_N2	*.rte [2]	0.102294	0.183364
Hydrologic cycle	Potential and actual evapotranspiration	V	IPET	basin.bsn	2	2
		R	ESCO	basin.bsn	-0.680138	-0.141853
		R	EPCO	basin.bsn	0.143399	0.572499
	Surface runoff	R	CN2	*.mgt	-0.142779	-0.019323
	Soil water	R	SOL_AWC()	*.sol	0.028236	0.498887
		R	SOL_K()	*.sol	-0.604028	-0.103492
		R	SOL_BD()	*.sol	-0.053649	0.497812
	Groundwater	V	ALPHA_BF	*.gw	0.115856	0.678776
		R	GW_DELAY	*.gw	-0.350502	0.125102

		R	GWQMN	*.gw	-0.653267	-0.136916
		R	GW_REVAP	*.gw	-0.127131	0.320941
		R	REVAPMN	*.gw	-0.400998	-0.023275
		R	RCHRG_DP	*.gw	-0.071214	0.557755
Nutrients	Nitrogen cycle/runoff	V	NPERCO	basin.bsn	0.0401	0.433173
		V	RCN	basin.bsn	2.105502	10.274324
		V	N_UPDIS	basin.bsn	30.721289	59.872311
		V	CMN	basin.bsn	0.00017	0.001283
		V	ERORGN	*.hru	2.936241	6.033375
		V	SOL_NO3()	*.chm	77.507797	121.161118
		V	SHALLST_N	*.gw	365.738251	683.014587
		V	HLIFE_NGW	*.gw	3.830594	109.008598

[1] Change types include i) R: relative change, ii) V: replace the absolute value.

[2] The sign " * " indicates that parameter is changed in all HRUs.

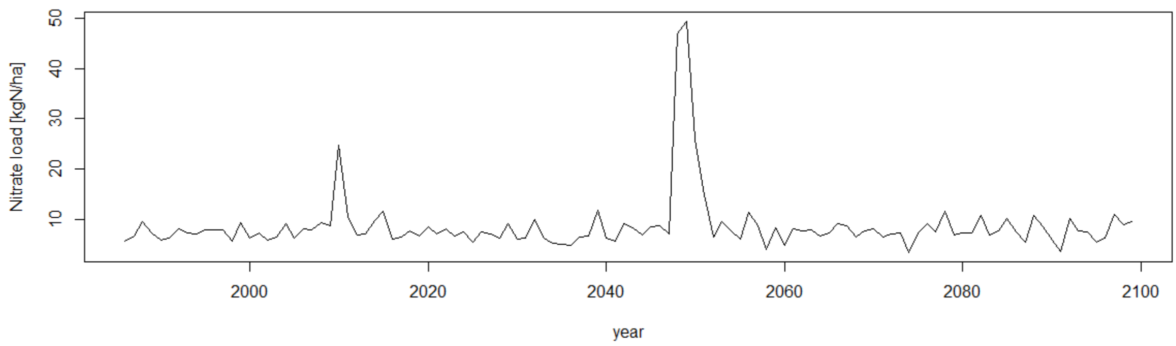


Fig. S3. Annual nitrate load [kgN/ha] in the Broye river at the outlet for the period 1986-2099 indicating an exceptional peak in the period 2048-2049.

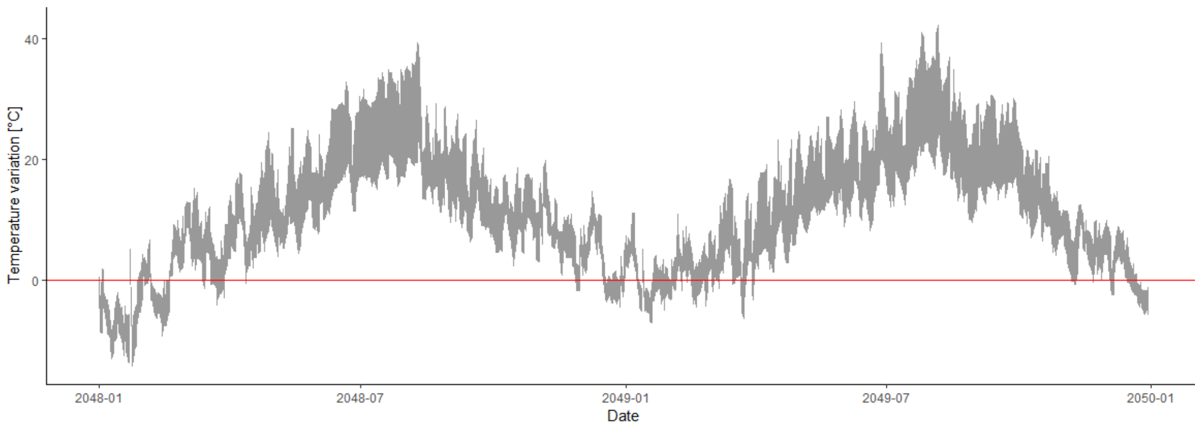


Fig. S4. Daily Temperature [°C] data for the sample HRU for the period 2048-2049, and vertical red lines indicating 0 [°C]. Projected temperature data for winter 2048 is exceptionally cold.

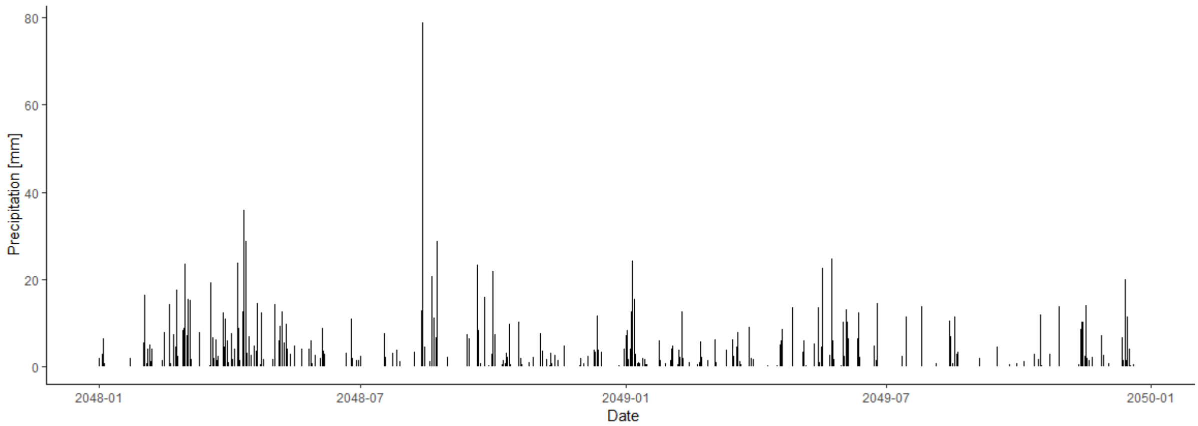


Fig. S5. Daily precipitation [mm] data for the sample HRU for the period 2048-2049

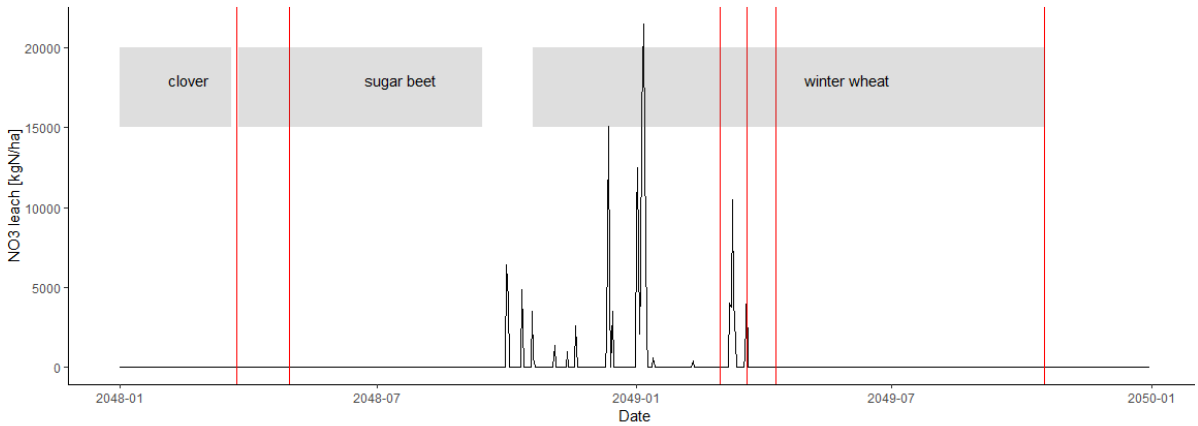


Fig. S6. Daily nitrate leaching [kgN/ha] data for the sample HRU for the period 2048-2049, and vertical red lines indicating fertilizer application practices. Low biomass production in clover and sugar beet subjecting excess nitrate in the soil. Leaching was estimated to occur in the rainfall events first in autumn 2048 on the bare soil after harvesting sugar beet, second leaching peaks occur between two frost periods in winter 2049, and third leaching occurs after fertilizer application.

Table S3: Illustrating the median of anticipated percentage change of each ecosystem service indicators in two selected future periods in comparison with the base climate (1986-2015).

Ecosystem service	indicator	Season	2028-2057 [%]	2070-2099 [%]
Water quantity regulation	Low flows	Spring	-5.59	-9.73
		Summer	-26.69	-76.88
		Autumn	-14.2	-72.28
		Winter	28.85	65.49
	Peak flows	Spring	-5.37	-2.72
		Summer	3.19	-18.57
		Autumn	3.56	9.67
		Winter	13.16	26.5
Water quality regulation	Nitrate load	Spring	-6.81	1.02
		Summer	7.09	-24.67
		Autumn	6.43	4.96
		Winter	26.26	43.51
	Nitrate concentration	Spring	-1.83	14.14
		Summer	10.32	13.83
		Autumn	4.51	26.55
		Winter	2.63	11.04
Food provision	Maize	-	7.24	-13.59
	Winter wheat	-	5.29	0.18
	Temporary ley	-	7.62	33.4

	Nitrate stress	-	11.62	12.36
	Irrigation	-	14.19	34.64
	Water stress	-	-2.26	54.05
Erosion regulation	Transported sediment	Spring	4.43	13.72
		Summer	0.26	-17.12
		Autumn	2.27	-0.61
		Winter	-1.74	-5.21