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Model-Based Evaluation of Land Management Strategies with Regard to Multiple Ecosystem Services

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Abstract: In agroecosystem management, conflicts between various services such as food provision and nutrient regulation are common. This study examined the trade-offs between selected ecosystem services such as food provision, water quantity and quality, erosion and climate regulations in an agricultural catchment in Western Switzerland. The aim was to explore the existing land use conflicts by a shift in land use and management strategy following two stakeholder-defined scenarios based on either land sparing or land sharing concepts. The Soil and Water Assessment Tool (SWAT) was used to build an agro-hydrologic model of the region, which was calibrated and validated based on daily river discharge, monthly nitrate and annual crop yield, considering uncertainties associated with land management set up and model parameterization. The results show that land sparing scenario has the highest agricultural benefit, while also the highest nitrate concentration and GHG emissions. The land sharing scenario improves water quality and climate regulation services and reduces food provision. The management changes considered in the two land use scenarios did not seem to reduce the conflict but only led to a shift in trade-offs. Water quantity and erosion regulation remain unaffected by the two scenarios.

Keywords: SWAT model; model parameterization; land sharing; land sparing; water quantity; water quality; greenhouse gas emissions; agriculture; multifunctionality

1. Introduction

Ecosystem services (ES) are benefits that humans receive from their environment. Processes driving the provision of ES are simultaneously interacting in a complex dynamic [1]. Human well-being depends on sustainable ecosystem functioning [2]. Different categories of ES include provisioning, regulating and maintenance and cultural services [3]. A common management problem is that increases in benefits from one service often result in decreases in the provision of other services. Agricultural systems, in particular, provide many examples of conflicts between multiple ES, for example nutrient management affecting crop yield and nutrient runoff. Increased food provision often degrades other ES such as water quality and water quantity regulation [4]. Studies of land management impacts on conflicts and synergies in ES provision are needed to support planners and policy-makers in their efforts to improve the sustainability of agricultural management [5].

Various land management strategies are used to achieve a balance between ES such as integrating the provision of different functions in the same space or by segregating the regulation of several services in separate spatial compartments. The concept of land sharing (i.e., integrating the provision of multiple ES on the same land) and land sparing (i.e., spatially segregating the provision of different ES—usually segregating agricultural production from nature protection) provide two opposing ideas for how to achieve a balance [6,7]. As considerable agricultural subsidies are spent on measures promoting either of the two approaches, it is worth investigating if a shift in management strategy can better mitigate conflicts between ES.

In this study, we evaluated changes in land use and management practices representing shifts towards land sharing or land sparing. The Soil and Water Assessment Tool (SWAT) [8] was used to evaluate land management scenarios defined by local stakeholders. SWAT was deemed to be an appropriate tool for this study as it can simulate agricultural management practices, crop growth, hydrology and water quality processes at a catchment scale [9]. SWAT is a semi-distributed, process-based, complex and physically based model, which is capable of simulating multiple ecosystem functions simultaneously and allowing for quantifying impacts of land use and management changes on the ES indicators of concern (Table 1). Based on the assessed implications of selected ES, we discuss the benefits and drawbacks of a shift in strategy towards either of the two scenarios.

Table 1. Selected ecosystem services (ES) and representative indicators.

Ecosystem Services	**Indicators**
Water quantity regulations	Low flow [m^3/s], defined as 5th percentile of daily river discharge for the entire period [10]
Water quality regulation	Yearly nitrate concentration [mg N/L] in the outlet of the catchment
Erosion regulation	Yearly transported sediment [t/ha]
Food provision	Agricultural benefit [Mio CHF/year] = benefit from crop production − applied fertilizer cost + milk production benefit from assumed livestock in the model
Climate regulation	Greenhouse gas (GHG) emissions [CO_2 equivalent kt/year]

2. Materials and Methods

2.1. Case Study

The Broye catchment is in the South-Western part of the Swiss Central Plateau, where agricultural production plays a dominant role and potential adverse effects on water quality and availability are of significant concern. The catchment covers an area of 630 km^2 (Figure 1). Mean elevation of the basin is about 664 m above sea level (lowest point 372 and highest 2369 m above sea level) and the mean slope is 10.7% (6.1°). Average precipitation is 865 mm per year and the average temperature is 9.6 °C with an average maximum value of 14.2 °C and an average minimum value of 5.1 °C (data from the Payerne station for the period 1981–2015; Figure 2). The average daily discharge at the Payerne station is 8 m^3/s for the period 1981–2015 with a maximum value of 147 m^3/s and a minimum value of 0.4 m^3/s. Approximately 67% of the area is agricultural land including arable, meadow and pasture land uses cultivated for food and fodder production (Figure 1).

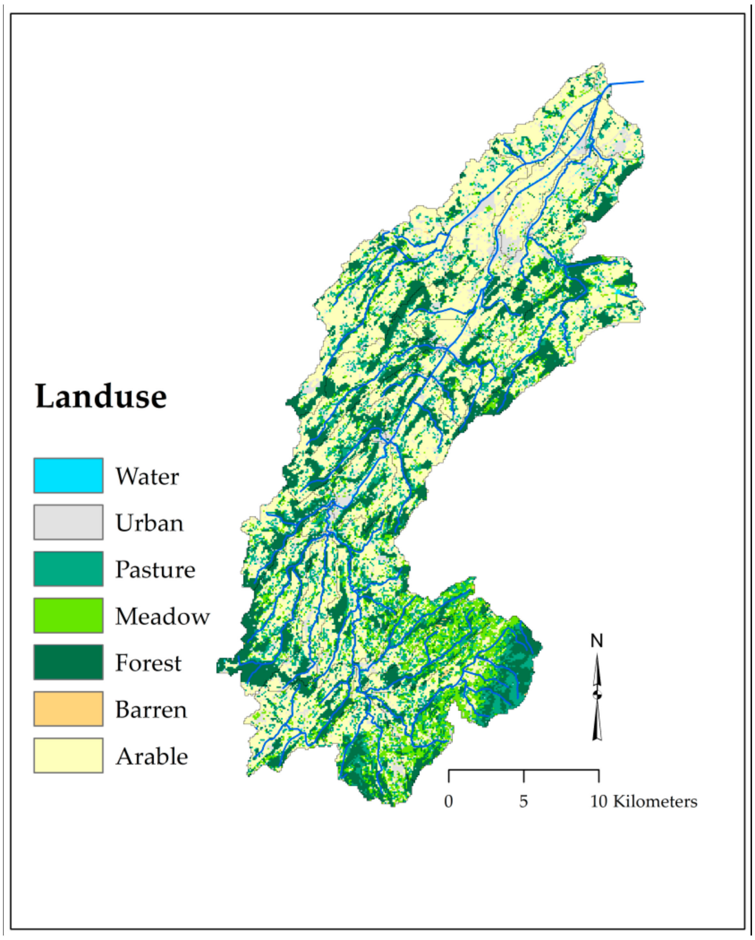

Figure 1. Land use map of the Broye catchment which is predominantly used as agricultural land.

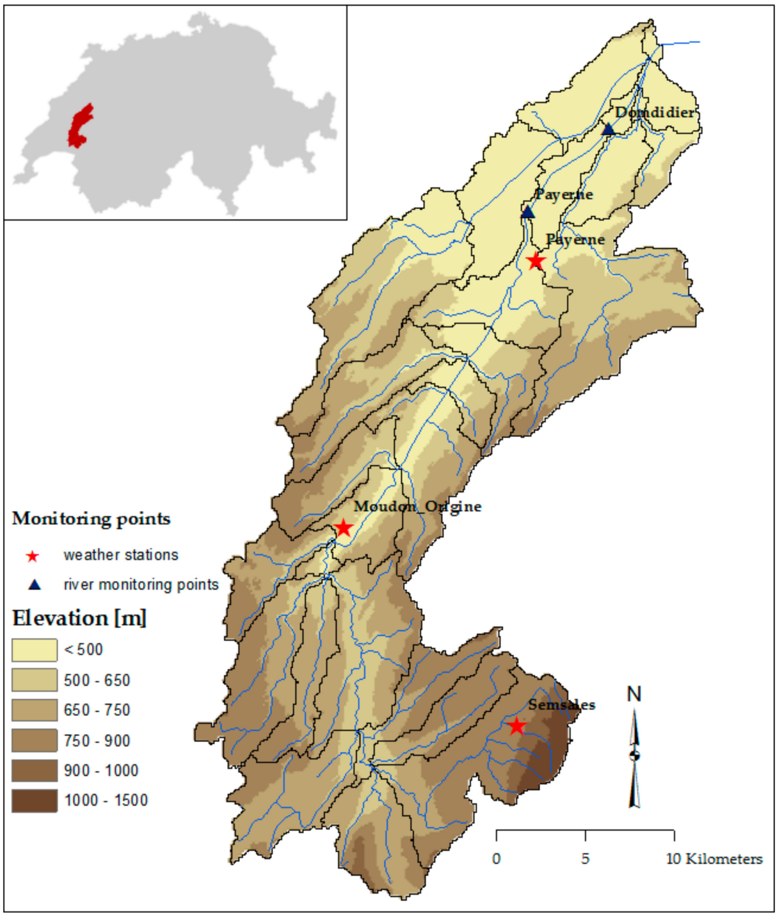

Figure 2. Broye catchment SWAT model with 27 sub basin, climate (Payerne, Moudon-Origine and Semsales), discharge (Payerne) and water quality (Domdidier) stations.

Following previous studies in this region [11] and by perceptions of regional stakeholders, five indicator variables were selected to represent five ES of concern in the study area (Table 1).

2.2. Data and SWAT Model Setup

Our approach for the model application consisted of four main steps (Figure 3). These include (i) SWAT model setup; (ii) SWAT model parameterization (calibration and validation); (iii) development of land management scenarios and finally (iv) applying a parameterized SWAT model to land management scenarios and carrying out post-processing methods for calculating ES indicators and statistical analysis.

Primary data used to setup the SWAT model includes a digital elevation map (DEM), a soil map and a database of soil parameters, a land use map and a database of crop parameters, river segments and climate data (Table 2). Available data for SWAT model calibration and validation were daily river discharge measurements, nitrate concentrations and crop yields of the main arable crops. To specify land management for the current situation and the generated land use scenarios, data containing crop and permanent grasslands shares, an irrigation map, a land use map and a soil suitability map were used (Table 2).

The Broye catchment was divided into 27 sub-basins and 815 hydrological response units (HRUs). Each HRU has been delineated with the homogenous soil, land use and slope. Agricultural management inputs consist of management plans in arable and permanent grasslands areas. The specification of land management in arable regions requires information on crop rotations, irrigation and the amount and timing of fertilizer applied to each crop. For this study, crop rotations were generated stochastically based on available information on crop shares at the municipal level [12], accounting for crop rotation recommendations [13]. Spring crops (potato, sugar beet, grain maize and silage maize) were irrigated automatically based on crop demand in designated irrigation areas [14]. Grasslands were divided into pasture and meadow of two intensity levels according to [15] and [12]. The two intensity levels for pasture (with variation in livestock density and respective nutrient inputs) and meadows (with a change in the number of cuts and the amount of applied fertilizer) were defined based on [16]. Pasture management was defined as four livestock units per hectare during the grazing period for intensive pastures and one livestock unit per hectare for extensive pastures. Meadow management was assumed as four cuts per year and 30 [kg N] organic fertilizer per cut for intensive meadows and two cuts per year and 25 [kg N] organic fertilizer per cut for extensive meadows.

Current management of the area was defined as the baseline scenario and the model was calibrated and validated for daily river discharge [m^3/s] and monthly nitrate load [kg N] with baseline land management inputs. SWAT outputs used for impact analysis of land management scenarios were: daily river discharge [m^3/s], average yearly nitrate concentration [mg/L] (calculated with daily nitrate loads [kg N] and daily river discharge [m^3/s]), yearly transported sediment [t/ha], yearly crop yield [t/ha], annually applied nitrogen [kg N] and annually leached nitrate [kg N] (applied nitrogen and leached nitrate were used for calculating GHG emissions).

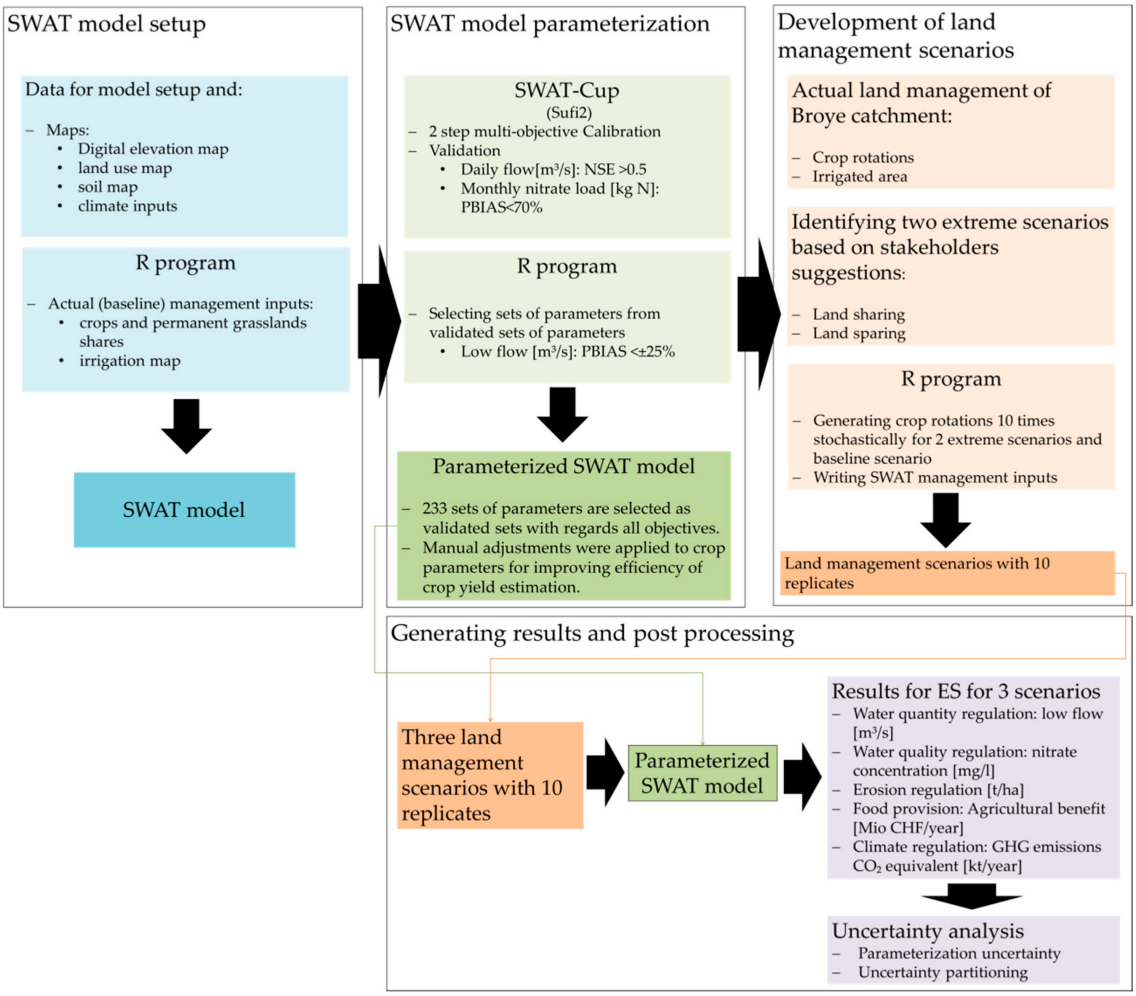

Figure 3. Schematic overview of applied approach.

2.3. SWAT Model Parameterization

The 35 years of available data were divided into three parts. The first five years were used as model warm up period (1981–1985). The remaining 30 years were divided into 18 years for calibration (1986–1990, 1996–2000, 2006–2010, 2013–2015) and 12 years for validation (1991–1995, 2001–2005, 2011–2012). This division ensured a better representation of the climate variability between the calibration and validation periods. The SWAT model was calibrated for daily river discharge [m^3/s] in Payerne station (1981–2015) and for monthly instream nitrate load [kg N] in Domdidier station (1986–2010). Nitrate concentrations were sampled four times a month from Domdidier station, while river discharge observations were not collected from the site. Observed discharge from the closest discharge station, Payerne, was used to relate measured concentrations to simulated nitrate mass. A point source was added in the middle part of the catchment before Payerne station to account for contributions from water treatment plants and other sources to reduce systematic error in underestimating simulated river discharge. To this purpose, the measured river discharge of Payerne station was filtered by "Baseflow Filter Program" [17] and added as a point source to the system before parameterizing.

Table 2. Data and sources used in model setup, parameterization and land management scenarios.

Section of Use	Data	Details and Sources
SWAT model setup	Digital elevation map (DEM)	25 m [18]
	River network	[18]
	Land use map	100 m [15]
	Soil map	[19]
	Weather stations: - P: Payerne - M: Moudon-Origine - S: Semsales	Daily climate data 1981–2015 (35 years): Precipitation ^{P,M,S}, temperature ^{P,M,S} wind speed ^{P}, solar radiation ^{P} [20]
SWAT model parameterization (calibration and validation)	Water quantity	Daily river discharge [m^3/s] (Payerne station 1981–2015) [21]
	Water quality	Monthly nitrate concentration [mg/L] (Domdidier station 1986–2010) [21]
	Crop yield	Estimated crop yield in the area [22]
Development of land management scenarios	Crop rotations	Municipality level data consisting of area of 8 dominant crops (winter wheat, winter barely, winter rapeseed, corn, silage corn, potato, sugar beet and temporary ley [12] Crop management (sowing and harvesting dates and fertilizer) [16,23] Feasibility table of rotations [13]
	Irrigation	Map of irrigated areas [14]
	Permanent grasslands (meadow and pasture)	Management assumptions for 2 intensity levels [16] Meadow: - Intensive: 4 cut/year, 30 kgN fertilizer per cut - Extensive: 2 cut/year, 25 kgN fertilizer per cut Pasture: - Intensive: 4 livestock unit/ha and grazing period - Extensive: 1 livestock unit/ha and grazing period
	Soil suitability map	To select areas with low fertility [19]

SWAT model was calibrated and validated with Sequential Uncertainty FItting ver.2 (SUFI-2) algorithm [24] provided in the SWAT-CUP software package as a semi-automated inverse modelling for the combination of calibration and uncertainty analysis [25]. Due to non-unique results of the inverse modelling, outputs are expressed as the 95% prediction bounds (95PPU). For quantifying the quality of the parameterization, SWAT-CUP uses two indices (i) the *P-factor* quantifying the percentage of measured data bracketed by the 95PPU (ranging between 0 and 1, which 1 is indicating

100% bracketing of measured data); and (ii) the *R-factor* measuring the thickness of the 95PPU bound, which is defined as the average difference between the upper and lower 95PPU divided by the standard deviation of the measured data. A value around 1 or lower is suggested as a practically acceptable value [25]. Ideally, high *P-factor* values and low *R-factor* values are desirable. In this study, the selection of acceptable parameter sets was also based on an adequate representation of low flow. This additional criterion slightly decreased the R-factor (narrower boundaries) and consequently, also the P-factor.

With a multi-objective and stepwise calibration strategy, the SWAT model was first parameterized for water quantity (river discharge [m^3/s]) in a daily time step, followed by water quality (monthly instream nitrate load [kg N]) in monthly time step. Finally, crop yield was calibrated by adjusting SWAT crop parameters (harvest index and bio-efficiency) to decrease PBIAS and to increase Willmott index [26].

In each step, two iterations with 2000 simulations were used for parameterizing the SWAT model to increase Nash Sutcliff Efficiency (NSE) for daily river discharge and to reduce PBIAS for monthly nitrate load. In a third step, a subset of the sets of parameters were selected for further model applications based on the selection criteria for satisfactory performance listed in Table 3 [27]. The selected sets of parameters were checked for calibration and validation periods for all objectives. In total, 233 sets of parameters were selected to represent model non-uniqueness and applied to the three land management scenarios.

Table 3. Calibration and validation criteria.

Variable	**Criteria**
Daily river discharge [m^3/s]	NSE > 0.5
River low flow (5th percentile of daily discharge) [m^3/s]	PBIAS < ±25%
Monthly nitrate load [kg N]	PBIAS < ±70%

2.4. Development of Land Management Scenarios

Two workshops were conducted with regional stakeholders to derive visions for the implementation of land sharing and land sparing strategies. Suggested management changes in comparison to the current land use situation are listed in Table 4. These stakeholder suggestions were transformed into model inputs based on GIS operations using ArcGIS [28]. Table 5 shows a summary of applied transformation rules.

Table 4. Suggested land management and land use changes from stakeholders' workshop.

Land Management Scenarios	**Stakeholders' Suggestions**
Land sharing	- No irrigation - Extensification: all permanent grasslands transformed to extensive, increase share of ley and grain legumes within rotations - No land use change
Land sparing	- Unlimited irrigation in lowlands (slope is lower 7.5% in arable area) and highly fertile soils - Intensification: all permanent grassland with highly fertile soil transformed to intensive, increase share of potato, increasing fertilizer by 25% - Transforming arable areas with highly fertile soil on steep slope (slope higher 7.5%) to intensive meadow - Low fertile areas turned to the nature protection areas (forest)

For each land management strategy, changes in land use and land management have been defined (Table 5). Land use change was only applied to the land sparing scenario and consisted of transforming low fertile areas to forest and arable lands on steep slope to permanent grassland. Variations in land management consist of changes in the level of intensity for permanent grasslands and in managing arable lands such as crop rotations, irrigated areas and applied fertilizers.

Table 5. Applied transformations on Soil and Water Assessment Tool (SWAT) model inputs.

Scenario	Land Use/Management in Baseline Scenario	Slope [%]	Soil Fertility	Transformed Land Use/Management
Land sharing	Arable, 143 kg N/ha fertilizer	-	-	Arable, 132 kg N/ha fertilizer
	Intensive permanent grasslands [1]	-	-	Extensive permanent grasslands
	Extensive permanent grasslands [1]	-	-	
Land sparing	Arable, 143 kg N/ha fertilizer	Slope lower 7.5	Low	Forest
			High	Arable, unlimited irrigation, 180 kg N/ha fertilizer
		Slope higher 7.5	Low	Forest
			High	Intensive meadow
	Intensive permanent grasslands	-	-	Intensive permanent grasslands
	Extensive permanent grasslands	-	-	

[1] Intensive permanent grasslands include intensive pastures and meadows and extensive permanent grasslands include extensive pastures and meadows.

Changes in the intensity level of arable lands are applied to crop rotations based on suggestions in Table 4. In land sparing, potato shares are increased to increase the arable benefit and in land sharing, temporary ley and grain legumes shares are increased to reduce the intensity level of arable management. For each HRU, crop sequences are generated stochastically following regional planting rules described in Reference [13] and reproducing crop shares at the spatial level of postcode areas using R program [29]. Due to the stochastic nature of the crop rotation generation process (different crop sequences can fulfil the requirements of planting rules and crop shares), 10 replicates of rotations were produced. With these 10 replicates, we account for land management setup uncertainty. The parameterized SWAT model was applied to evaluate land management scenarios on the basis of these 10 replicates and 233 sets of parameters selected as described in Section 2.3.

2.5. Agricultural Financial Benefit

Agricultural benefits are estimated based on simulated crop yields and area of permanent grassland. The financial benefit from arable land was estimated based on market prices for dry yield (see Appendix A Table A3) minus costs to fulfil crop-specific fertilizer requirements (1.02 CHF/kgN) [30]. Detailed information on crop rotations in the different land management scenarios and crop prices is provided in Appendix A Table A2. For estimating benefits from permanent grassland, we assumed grazing by dairy cows in pastures with varying stocking densities depending on management intensities (Table 2). The total number of livestock units (i.e., dairy cows) was multiplied by an annual milk production value of 8000 [kg/head] according to [30] to derive a proxy for livestock productivity. The assumed milk price was 0.55 [CHF/kg] [30].

2.6. Greenhouse Gas Emissions

GHG emissions are calculated based on the methodologies in the national agricultural greenhouse gas inventory of Switzerland [31]. According to this standardized procedure, CH_4 and N_2O missions from enteric fermentation and manure management of dairy cows are estimated by multiplying the number of livestock units by an emission factor of 4.1 and 0.40 t CO_2 equivalents per head and per year, respectively. Based on applied amounts of mineral and organic fertilizer on arable land and grassland, direct emissions of N_2O are estimated, assuming a loss of 1% kg N_2O-N per kg of N input [31]. Indirect N_2O emissions after volatilization of NH_3 and NO_x from mineral and organic fertilizers are estimated assuming emissions of 0.67 and 2.56 kg CO_2 equivalents per kg N input, respectively [31]. Furthermore, 5.3 kg CO_2 equivalents per kg N are assumed to be emitted during the production of mineral fertilizers [32]. Accordingly, for each of the three land management scenarios the total nitrogen amount applied on arable land is multiplied by this emission factor from the greenhouse gas inventory. Indirect NO_2 emissions after leaching of NO_3 are estimated by multiplying the NO_3 load calculated by the SWAT model with the N_2O emission factor of 0.0075 kg N_2O-N per kg N leached [31].

2.7. Uncertainty Analysis

Two different sources of uncertainty are assessed in this study: (i) SWAT model parameterization uncertainty and (ii) land management setup uncertainty. To account for the first source, SWAT model parameter uncertainty is represented by uncertainty bounds (95PPU) based on 233 selected sets of parameters (see Section 2.3). For the second source, 10 replicates of land management scenarios are produced to assess management setup uncertainty. Analysis of variance (ANOVA) was used to partition total uncertainty originating from model parameterization and replicates of multiple land management scenarios to quantify the relative contribution of each source to the overall uncertainty [33].

3. Results

3.1. Parameterization

The average of performance metrics for 233 selected sets of parameters for selected SWAT chosen outputs for calibration and validation are summarized in Table 6.

Table 6. Results of parameterization for all selected objectives for two independent data sets, calibration and validation and results of manual adjustment for predicting crop production (see Appendix A Table A4 for each crop separately).

Method	SWAT Output	Criteria	Calibration	Validation
Parameterization with SWAT CUP	Daily river discharge [m^3/s] Monthly nitrate load [kg N]	NSE [-] PBIAS [%]	0.6 ± 0.044 17.5 ± 31.76	0.66 ± 0.045 18.41 ± 30.56
Selection of parameterized sets of parameters with R	Low flow [m^3/s]	PBIAS [%]	−6.52 ± 13.22	−7.62 ± 12.32
Manual adjustments	Yearly crop yield [t/ha]	PBIAS [%] Willmott index [-]	0.37 ± 2.6 0.6 ± 0.1	- -

River discharge and in-stream nitrate load were simulated quite well in the SWAT model (Figures 4 and 5). For the 233 selected sets of calibrated parameters the *P-factor* and *R-factor* for daily discharge were 0.60 and 0.63, respectively, indicating acceptable values. These values for the validation period were 0.58 and 0.56. The calibrated model brackets about 60% of observed discharges with a relatively small uncertainty. See Appendix A Table A1 for calibrated uncertainty bounds for selected parameters. Calibrated parameters are related to catchment characteristics and are assumed to be valid for evaluating land management changes. Nash Sutcliff efficiency (NSE) is higher than 0.50 and bias error for low flow is lower than ±25% for all selected sets of parameters. As the focus of this study is on low flow, rather than average discharge, selected sets of parameters were constrained to reproduce observed low flow realistically. For this reason, the peak flows are systematically underestimated.

In water quality parameterization, selected criteria were less restrictive. Uncertainty bounds are therefore much wider and P-factor is higher in comparison with water quantity, as 86% of measured points are bracketed in the uncertainty bounds for calibration period and 82% for the validation period.

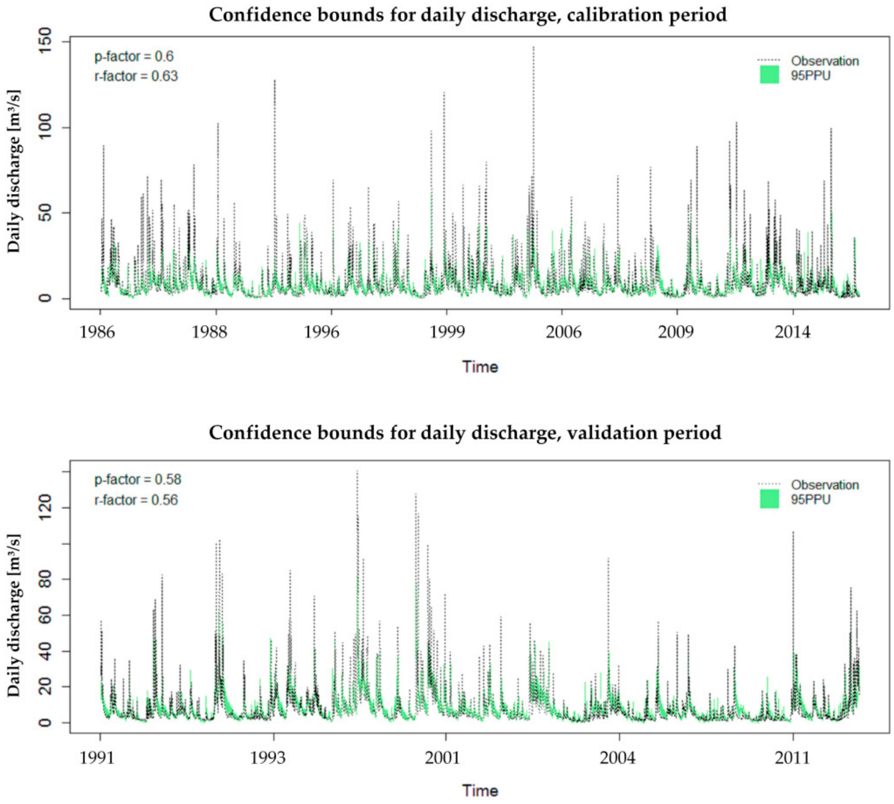

Figure 4. Model simulation for daily river discharge in the calibration period (**up**) and validation period (**down**).

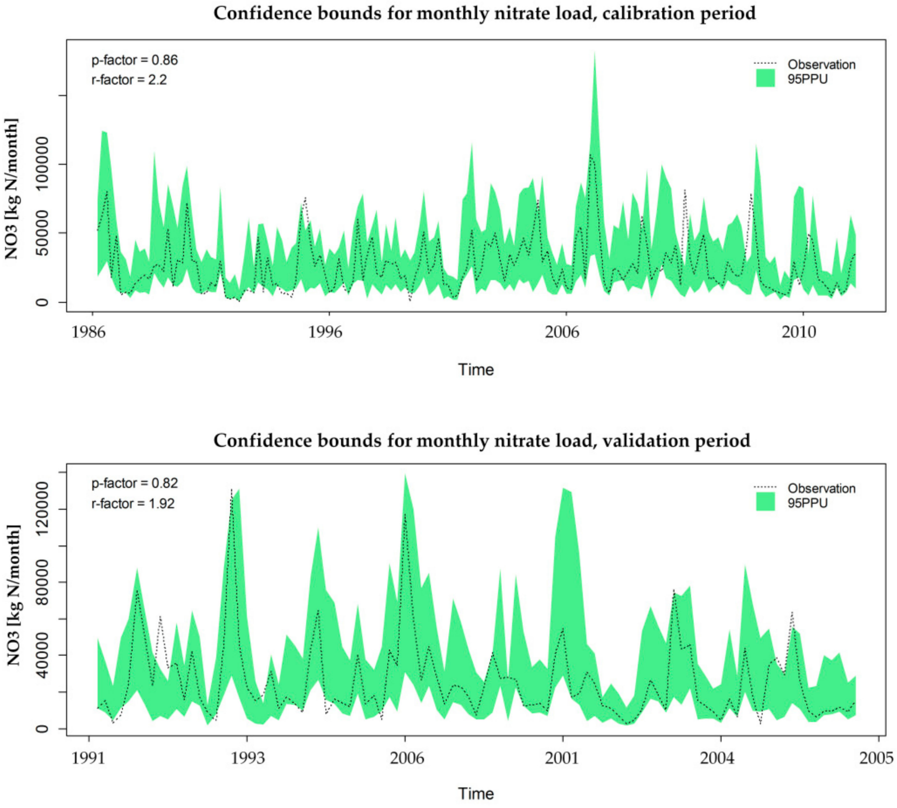

Figure 5. Model simulation for monthly nitrate load in the calibration period (**up**) and validation period (**down**).

3.2. Land Management Scenarios Analysis

As Figure 6 and Table 7 illustrate, the area of arable land use decreases in the land sparing scenario and instead areas of permanent grasslands and forest land uses increase. Arable area decreases in land sparing but arable management is intensified by increasing irrigation and potato shares in rotations. There is no land use change in the land sharing scenario but less intensive arable management was applied by rising shares of temporary ley and field pea in rotations and stopping irrigation.

Results of the baseline scenario representing the current status of ES in the Broye catchment are presented in Table 8. In the land sparing scenario, agricultural benefit increases and at the same time nitrate concentration and GHG emissions increase. In the land sharing scenario, nitrate concentration and GHG emissions decrease along with a decrease in agricultural benefit.

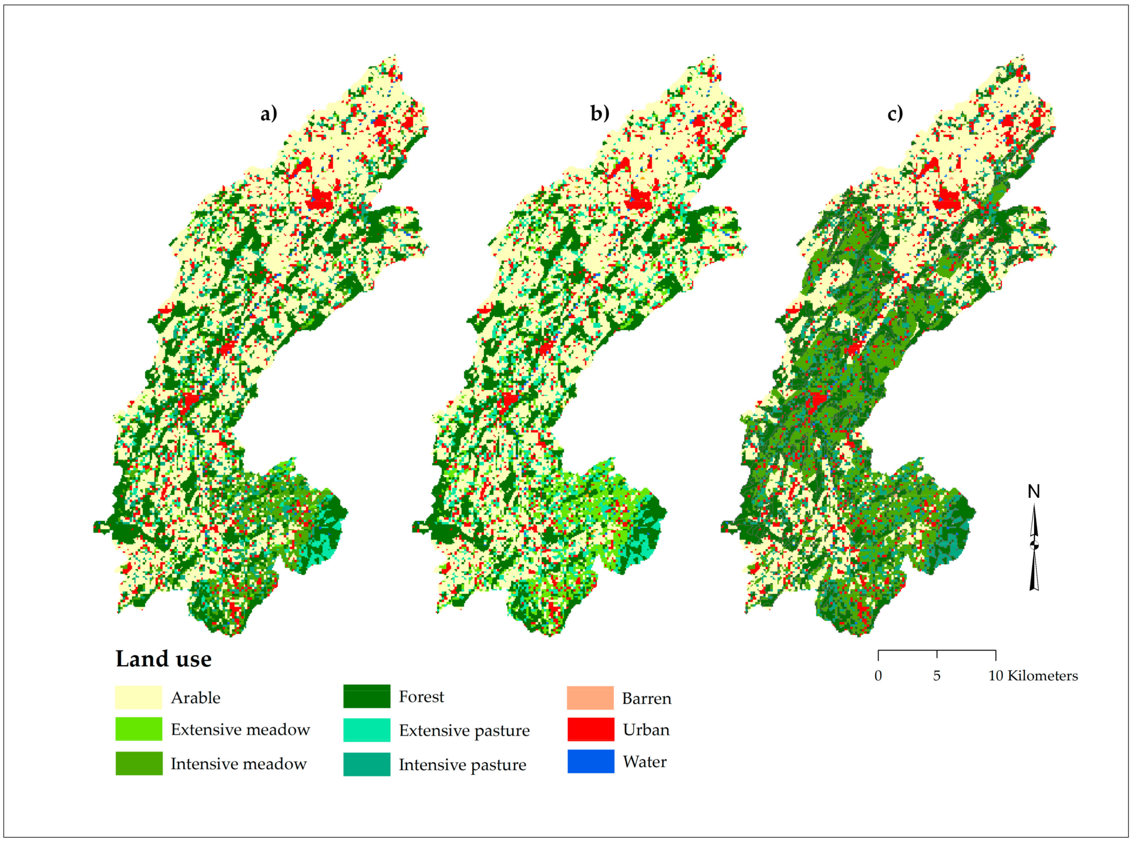

Figure 6. Land use maps of the three scenarios: baseline (**a**), land sharing (**b**) and land sparing (**c**) as derived from GIS-based transformation of stakeholder suggestions into SWAT model inputs.

Table 7. Summary of the results of suggested transformations in land uses and land management areas [ha].

Land Use	Land Management	Baseline	Land Sharing	Land Sparing
Permanent grasslands (meadows and pastures)	Intensive	9184	0	20,007
	Extensive	3678	12,862	0
Arable	Total arable	29,576	2,9576	20,178
	Potato	1506	1252	2281
	Field pea	1791	3190	1143
	Temporary ley	8254	10,219	5257
	Irrigated arable area	1130	0	6096
Forest	-	14,635	14,635	16,889

Changes indicated in Table 8 are illustrated by a radar plot for average values (scaled to maximum value) in Figure 7 (average of 2330 values to have a unique value representative of all assumptions for comparison between scenarios). The radar plot in Figure 7 visualizes average values scaled to a maximum value for each service indicating trade-offs between ES indicators (agricultural benefit versus water quality and climate regulation).

Figure 8 shows uncertainty distributions of percentage change of the two extreme scenarios in comparison to the baseline scenario. Values were averaged over the replicates to represent only SWAT parameterization uncertainty. Change in low flow is very small, as only a small increase in low flow is observed in the land sharing scenario and changes estimate is distributed around zero in land sparing (no significant change). There is a significant decrease in nitrate concentration for the land sharing scenario for all SWAT parameter sets. On the contrary, nitrate concentrations tend to increase significantly in the land sparing scenario. There is no significant change in transported sediment for the land sparing scenario but a small significant decrease is seen for the land sharing scenario. Agricultural benefits show a clear reduction in land sharing and an increase in land sparing for all optimized sets of parameters. GHG emissions decreased considerably in the land sharing scenario and increased in the land sparing scenario with a very low variation due to SWAT parameterization. The main driver of GHG emissions is the intensity of pasture management and the other components play a minor role. As the total number of livestock units held in the catchment is assumed to be constant for all simulation runs within one scenario, overall GHG emissions show only little variation (due to variation in nitrate leaching and applied fertilizer) within each scenario.

Table 8. Average values of 2330 simulated values (233 optimized sets of parameters with 10 replicates) for assumed indicators for the three land management scenarios (average ± standard deviation).

Scenarios	**Low Flow [m^3/s]**	**NO$_3$ Concentration [mg/L]**	**Sediment [t/ha]**	**Agricultural Benefit [Mio CHF/Year]**	**GHG Emissions [CO$_2$ eq. kt/year]**
Baseline	1.29 ± 0.2	1.72 ± 0.47	10.05 ± 2.11	143.48 ± 3.29	152.35 ± 1.15
Land sharing	1.31 ± 0.21	1.36 ± 0.38	9.98 ± 2.07	77.12 ± 2.74	82.54 ± 1.04
Land sparing	1.28 ± 0.2	1.90 ± 0.52	9.92 ± 1.96	163.75 ± 2.88	186.53 ± 1.22

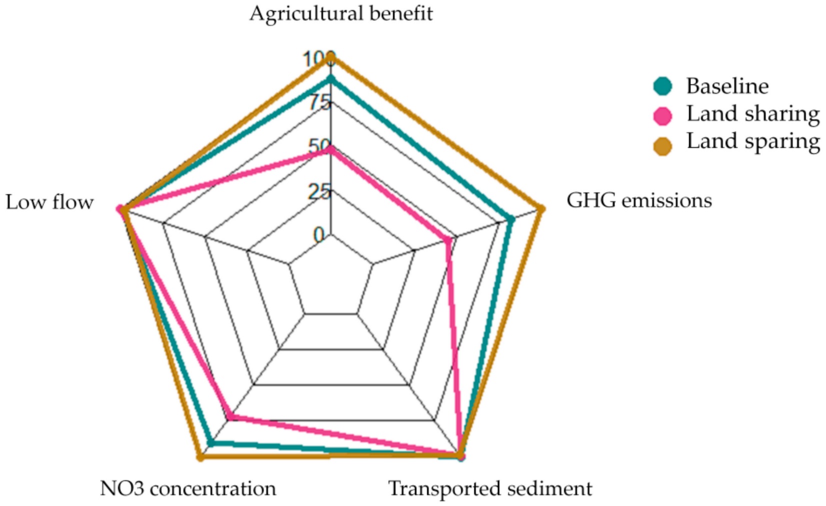

Figure 7. Visualization of average values scaled to maximum value for each ecosystem service for the three scenarios.

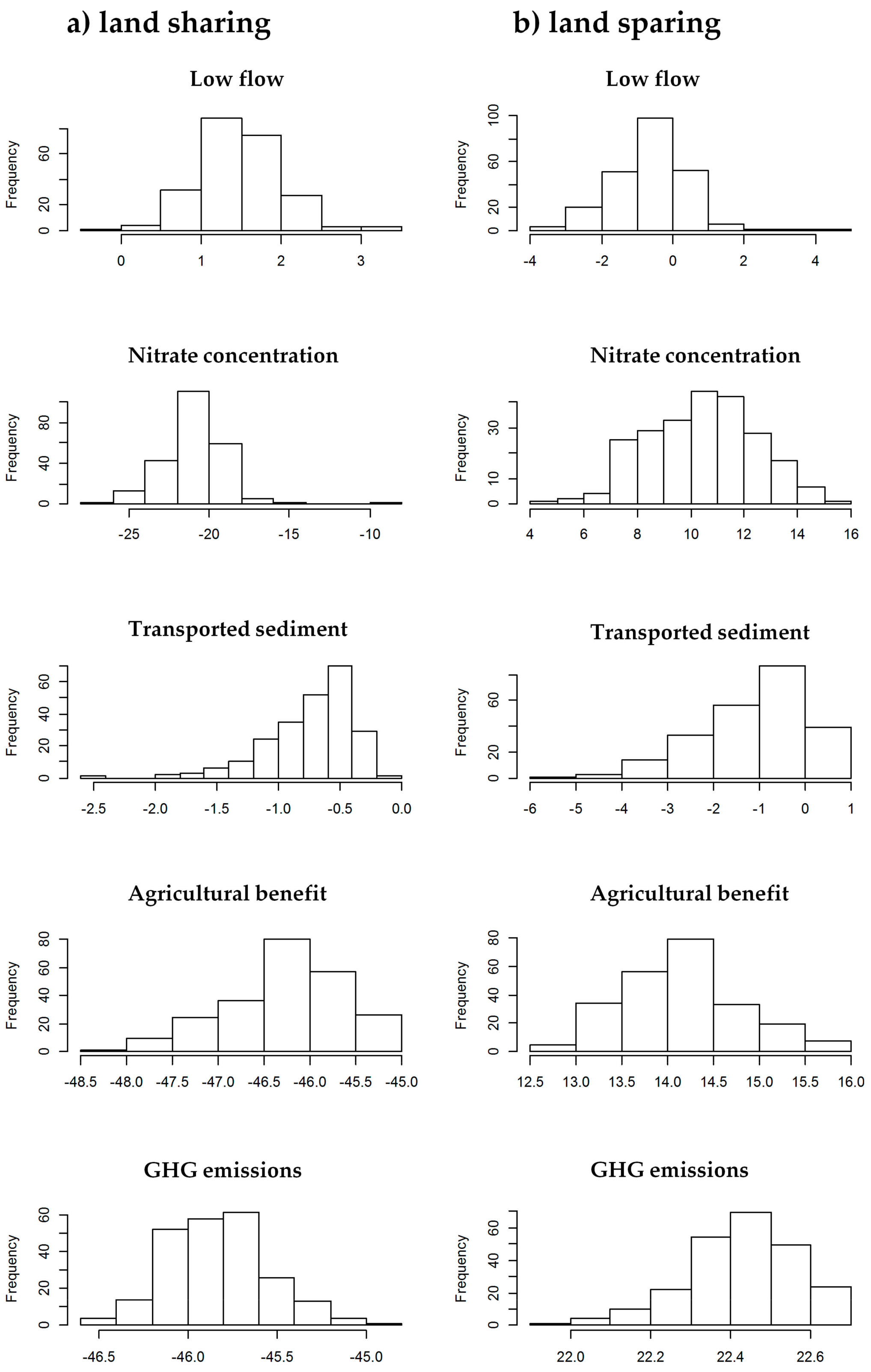

Figure 8. Changes [%] in ES indicators in comparison to the baseline scenario for (**a**) the land sharing scenario and (**b**) the land sparing scenario (uncertainty distribution of the changes estimated by the SWAT according to the 233 sets of parameters).

Table 9 describes three components of agricultural benefits (arable and livestock benefits and fertilizer cost). Assumed number of livestock units (dairy cow) for baseline, land sharing and land sparing scenarios are 19,734, 6647 and 26,587, respectively. These numbers were the basis for deriving estimates of livestock productivity (see Table 9) and GHG emissions from pastures (Table 10). Agricultural subsidies (i.e., direct payments to farmers) were not included here, because they are considered to be an external policy driver for the implementation of a particular land management strategy. Fodder requirements of livestock for the three scenarios were estimated based on [16] to validate that enough fodder can be produced in the region and no additional cost for fodder imports arises. As Table 9 indicates, livestock benefit, directly related to pasture management and stocking density, has the highest influence on total agricultural benefits. Low prices for temporary ley reduced benefits from crop production in the land sharing scenario, which has the same arable area as the baseline scenario. Crop rotations used in the baseline scenario provide higher net benefits than those practiced in the land sharing scenario. Furthermore, when we compare benefits from arable production between baseline and land sparing scenarios, we see that the more intensive arable management (increased fertilization levels and irrigation) and higher shares of potato (producing greater net benefits) in the land sparing scenario could not compensate for the decrease in arable area.

Table 9. Estimated benefits and cost for agricultural productions [Mio CHF/year] for the three scenarios (the whole region).

Scenarios	Crop Production Benefit	Applied Fertilizer Cost	Livestock Benefit	Total Benefit
Baseline	62.14	5.49	86.83	143.48
Land sharing	52.59	4.71	29.24	77.12
Land sparing	52.74	5.97	116.98	163.75

Most GHG emissions are due to intensive pasture in baseline and land sparing scenarios (Table 10). Arable land is the second source of GHG emissions and produces even higher emissions than extensive pasture in the land sharing scenario. GHG emissions from leaching have the lowest share (below 10%) in all three scenarios.

Table 10. Estimated greenhouse gas (GHG) emissions from different land uses for the three scenarios.

	Baseline		Land Sharing		Land Sparing	
Source	GHG Emissions [kt CO_2 eq./year]	Percentage of Total Emissions [%]	GHG Emissions [kt CO_2 eq./year]	Percentage of Total Emissions [%]	GHG Emissions [kt CO_2 eq./year]	Percentage of Total Emissions [%]
livestock (enteric fermentation and manure management)	89.55	59%	30.16	37%	120.65	65%
fertilizer (production and application)	53.03	35%	44.28	54%	54.88	29%
Nitrogen leaching	9.73	6%	8.07	10%	10.97	6%

3.3. Uncertainty Analysis

ANOVA results (Table 11) show that among all assessed SWAT outputs just for applied fertilizer and crop production outputs, uncertainties originating from land management setup (replicates) play a role (85–100% and 20–22%, respectively). All other outputs in all scenarios are mainly affected by SWAT model parameterization (>99%).

Table 11. Proportions of uncertainties originating from either SWAT model parameterization (parameters) or management setup (replicates) for each ES indicator and each land use scenario.

Ecosystem Services Indicators	Representative SWAT Simulated Objectives	Baseline		Land Sharing		Land Sparing	
		Parameters	Replicates	Parameters	Replicates	Parameters	Replicates
Water quantity	Low flow	0.9984	0.0005	0.9985	0.0006	0.9983	0.0005
Water quality	Nitrate concentration	0.9994	0.0002	0.99	0.0001	0.9993	0.0001
Erosion	Sediment	1	0	1	0	1	0
Agricultural production	Crop production	0.7755	0.2227	0.7844	0.2136	0.7971	0.2008
GHG emissions	Applied fertilizer	0	1	0.0159	0.9185	0.0147	0.8531
	Nitrate leaching	0.9934	0.0032	0.9883	0.0013	0.9975	0.0004

4. Discussion

4.1. Scenario Analysis

The land sparing scenario has the highest agricultural benefit, while also the highest nitrate concentration and GHG emissions. Increasing food provision degrades water quality and climate regulations services but water quantity and erosion regulation remain unaffected by assumed land use and land management changes in this scenario. In line with field observations by [34], a more detailed analysis of our model results shows that water infiltration rate for permanent grasslands was higher than for temporary ley and both were higher than other field crops, which had an impact on low flow results in this scenario. In the land sparing scenario, decreasing the area of arable land, while increasing the area of intensive meadows has been compensated by more intensive arable management, a lower share of temporary ley, a higher share of potato and more irrigation of spring crops. Different compensating factors are the reason that there is no significant change in transported sediment in the land sparing scenario: more intensive arable management in a smaller area increases sediment loss, while at the same time the area of intensive meadow, with reduced soil loss, increases. Increasing forest area in the land sparing scenario might have additional benefits regarding biodiversity conservation but this was not specifically quantified in this study. Further possibilities for reducing conflicts between ES in the land sparing scenario could be investigated in future studies (e.g., implementing buffer strips along the river to minimize nutrient wash off into the river channel, changing the arable land to extensive pasture). In agreement with [10], agricultural benefits can be increased with land sparing but at the expense of other ES. This study also shows that food provision, water quality (nitrate leaching) and GHG emissions are strongly affected by pasture management (Tables 8 and 9). The land sparing scenario causes the highest nitrate pollution and GHG emissions. This can be explained by the higher nutrient inputs on intensively managed arable and grassland areas as well as by the high livestock density.

The land sharing scenario improves water quality and climate regulation services and reduces food provision while water quantity and erosion regulations remain mostly unaffected. In the land sharing scenario, the small increase in low flow (Figure 8) is related to applied land management changes that can be explained by higher infiltration in temporary ley [34], more temporary ley in rotations and stopping irrigation. These changes have positive impacts on water quantity and may be investigated further in climate change adaptation studies. As [35] also found in their research, in comparison with spring crops, winter crops reduce total sediment loss due to better soil coverage [36]. This is the reason for the observed small decrease in transported sediment in the land sharing scenario. The land sharing scenario has the lowest agricultural benefits but also the lowest nutrient leaching and GHG emissions, as all permanent grasslands are managed extensively, decreasing overall diffuse nutrient pollution and GHG emitted in the catchment. A general extensification of land management in the land sharing scenario will have positive implications for the biodiversity of grassland species in particular [37]. Simulated results of the baseline scenario (Table 8) quantify ES provision of the current situation in the Broye catchment. Average yearly nitrate concentration is estimated at 1.72 [mg/L], indicating a good water quality on average concerning nitrate concentration according to [38]. The baseline scenario performed between the two extreme scenarios; showing higher agricultural benefit in comparison to the land sharing scenario and lower pollution in comparison to the land sparing scenario. However, higher arable benefit in the baseline scenario (Table 9) suggests that more economically productive field crops are used in the baseline scenario compared to the land sharing scenario. Intensifying crop rotations by increasing nutrient and irrigation inputs as well as increasing the share of potato which provides higher benefit in the land sparing scenario could not compensate for the reduction in arable land area.

As Figure 7 shows, agricultural benefits, nitrate concentration and GHG emissions are the indicators most affected by land management scenarios; low flow and transported sediment indicators are mostly unaffected by changes in land management. This shows that the central conflict lies between food provision on the one hand and water quality and climate regulation on the other hand. These results agree with previous findings of [11], who also found that nutrient leaching is a primary concern in the Broye catchment. While they assessed ES trade-offs based on the field scale model, our study also considered linkages between agricultural land management and the hydrological cycle (i.e., water quantity and quality) as well as GHG emissions. Results of our extended study show that land management impacts on water quality are substantial but water availability is hardly affected by implemented management changes.

Neither of the two extreme scenarios outperforms the current land management strategy regarding reducing the dominant ES conflict. This may suggest that the current land use and management situation is close to a Pareto-optimal land use solution in the region (i.e., cannot be improved about one objective without reducing the performance of another objective). This would confirm that land management policies have been successful in implementing multifunctional agriculture in the region.

4.2. Uncertainty Analysis

Results of the uncertainty analysis show that the uncertainty bounds for river discharge are narrower than for nitrate, indicating that uncertainty in water quality prediction is higher in comparison with water quantity. This is related to a less restricted criterion selected for nitrate loads (PBIAS < ±70%).

By quantifying model uncertainty originating from two possible sources, findings derived from the scenario analysis can be considered more robust, increasing decision-makers' confidence in simulation results. While effects of SWAT parameterization uncertainty have been studied extensively (e.g., [25,39–41]), only a few studies have been conducted to investigate the relevance of other uncertainty sources on SWAT model outputs. For example, van Griensven et al. [42] found that the influence of input uncertainty (i.e., climate and pollution data) is minor in comparison to SWAT parameterization uncertainty. Similarly, Ma et al. [43] found that parameters uncertainty is the most significant factor in uncertainty analysis in comparison with precipitation input uncertainty. Our results indicate that the uncertainty in management setup a minor role in the overall uncertainty. ANOVA results (Table 11) suggest that uncertainty of SWAT model parameterization represents the most substantial fraction of the total uncertainty. Land management setup uncertainty has a minor impact on the total uncertainty. The maximum impact of replicates was found in crop production estimates (20–22% of total variance) and applied fertilizer (80–100% of total variance). For the other of variables it is less than 1%.

The stepwise approach of uncertainty analysis considering SWAT parameterization and land management setup uncertainty can be applied to any other catchment. However, calibrated boundaries for SWAT parameters would be different for catchments with different characteristics and climate. Land management setup can be adjusted for a different catchment based on regional data such as crop rotations and irrigation. Uncertainty contributions may differ in various case studies with different characteristics, climate, land use and management practices. For future modelling studies, various improvements are possible to reduce uncertainties in model parameterization (e.g., variance in sediment modelling was high in this study and can be reduced by adding to multi-objective calibration if data becomes available); also more restricted criteria could be assumed for model calibration and validation.

5. Conclusions

The SWAT-based analysis of stakeholder-defined scenarios could provide insights into the practical benefits and drawbacks of shifts in management strategies towards either land sharing or land sparing. Model results revealed the most critical land use conflict/trade-off in the case study: benefits from agricultural production conflict with diffuse pollution and GHG emissions. Low flows and sediment loads were on average hardly affected by the land use and management changes.

As two potentially significant sources of uncertainty were considered and quantified in this study, a robust evidence base is provided. Quantitative estimates of changes in ES indicators can be useful for planners and policy makers thinking about prioritizing land management strategies to control water quality and climate regulation services with also considering food provision services. From the model-based evaluation of stakeholder-defined scenarios of land sharing and land sparing, a definite recommendation for a shift in management strategy cannot be derived. None of the investigated scenarios could reduce the dominant land use conflict in general but only induce a shift in trade-offs. If an increase in agricultural productivity (i.e., net benefits) was desirable, this could best be achieved by increasing grassland management intensities and related livestock (milk) production. The potential to improve production gains in arable areas is limited as yield potentials are largely exploited under current conditions (i.e., nutrient and water limitations in arable production are small). However, if grassland and livestock production are increased, this may induce new conflicts not considered in this study so far (e.g., increased biological pollution). Water quality and climate regulation problems can best be controlled by a reduction in management intensity as shown for the land sharing scenario. However, this may only be achievable if direct payments are increased to compensate for farmers' loss in income.

By studying the uncertainty from management setup and parameterization in SWAT, this work adds to the understanding of relevant uncertainty sources in agro-hydrological modelling in general and in SWAT modelling in particular. The uncertainty related to the management setup was negligible for most outputs, except for crop yield and applied fertilizer.

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Appendix A

Table A1. 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]	0.069258	0.223092
Hydrologic cycle	Potential and actual evapotranspiration	V	IPET	basin.bsn	2	2
		R	ESCO	basin.bsn	−0.683887	0.105387
		R	EPCO	basin.bsn	−0.047387	0.857887
	Surface runoff	R	CN2	*.mgt	−0.19139	0.425889
	Soil water	R	SOL_AWC()	*.sol	−0.092887	0.721387
		R	SOL_K()	*.sol	−0.713887	0.095387
		R	SOL_BD()	*.sol	−0.114387	0.656887
	Groundwater	V	ALPHA_BF	*.gw	0.071113	0.690387
		R	GW_DELAY	*.gw	−0.442387	0.185887
		R	GWQMN	*.gw	−0.878137	0.040637
		R	GW_REVAP	*.gw	−0.166637	0.500137
		R	REVAPMN	*.gw	−0.866887	0.044387
		R	RCHRG_DP	*.gw	−0.141637	0.575137
Nutrients	Nitrogen cycle/runoff	V	NPERCO	basin.bsn	0	0.609888
		V	RCN	basin.bsn	1.201688	10.400812
		V	N_UPDIS	basin.bsn	12.286263	70.763741
		V	CMN	basin.bsn	0.000045	0.002015
		V	ERORGN	*.hru	2.074313	6.223186
		V	SOL_NO3()	*.chm	46.536274	139.613724
		V	SHALLST_N	*.gw	337.862549	1013.637451
		V	HLIFE_NGW	*.gw	0	118.778091

[1] Change types include: (i) R: relative change; (ii) V: replace absolute value; [2] The sign "*" indicates that parameter is changed in all HRUs.

Table A2. Average crop shares in rotation in different land management scenarios.

Crop	Baseline	Land Sharing	Land Sparing
Potato	5%	4%	11%
Field peas	6%	11%	6%
Temporary ley	28%	35%	26%
Sugar beet	6%	5%	5%
Silage maize	12%	10%	11%
Grain maize	5%	4%	5%
Winter rapeseed	9%	7%	8%
Winter wheat	21%	17%	19%
Winter barely	8%	7%	7%

Table A3. Crop prices CHF/ton for dry yield [30].

Crop	Price Dry Yield CHF/Ton
Potato	2159
Field peas	428
Temporary ley	307
Sugar beet	417
Silage maize	460
Grain maize	545
Winter rapeseed	808
Winter wheat	608
Winter barely	404

Table A4. Manual calibration for crop yield based on estimated crop yield.

Crop	PBIAS [%]	Wilmott Index [-]
Potato	3.2	0.68
Sugar beet	0.5	0.67
Grain maize	3.8	0.49
Winter rapeseed	−1.8	0.48
Winter wheat	−1.9	0.7
Winter barely	−1.6	0.6

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