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Water Demand in Swiss Agriculture – Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change

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Content

Foreword

The National Research Programme "Sustainable water management" (NRP 61) is laid out not only to investigate water use per se, but also to deal with the relevant issues in a holistic, interdisciplinary and transdisciplinary fashion. In addition, the research programme aims both to assess the measures aiming to ensure the use of water according to economic and social criteria (justice), and to take into account threats to the sustainability of ecosystems caused by water use. With regard to the practical usability of the results, which is one of the fundamental objectives of each NRP, new and innovative strategies, tools and methods are to be developed. These should be designed in a way to find answers to future challenges of water management in Switzerland. At stake here are the sustainability of natural systems under changing environmental conditions, the handling of risks and conflicts associated with water use, and efficient management systems for sustainable and precautionary water use from a broad perspective. Changes related to climate change play a particularly important role here, especially with regard to agriculture; as temperatures rise, the water demand for crops increases, while at the same time the available irrigation resources decline owing to changes in the discharge regime of numerous rivers of the Swiss Central Plateau.

With various actors from Agroscope and the Swiss Federal Institute of Technology Zurich (ETH Zurich), the AGWAM project has faced the challenge, and is dealing with the question of Swiss agriculture's water demand in terms of both adaptive options for water and land use on the regional and farm level, as well as prevention of the negative effects of climate change on the environment. Using the example of two regions (Broye and Greifensee), the integrated consideration of water use in association with the involved resources, such as the soil, provides demand-oriented management alternatives to purely technical solutions for improving water supply.

The project group proposes three different strategies which are possible on the regional level for adaptation to climate change, although each has different trade-offs: 'maximum productivity', 'minimum environmental impacts' and a 'compromise solution'. In addition, it is shown that a farm's water use can be reduced via the introduction of water quotas or increased water prices without significantly decreasing the farm profit. In this way, scientists give both policy-makers and agricultural practitioners the opportunity to critically examine for themselves the options of various approaches, bearing in mind cost-effectiveness and environmental impacts so as to avoid conflicts and minimise risks, and then to come to a decision. These proposed solutions are highly practical, easily understandable, clearly outlined and theoretically sound. The presentation of new methods for developing an optimal land- and farm-management system is also entirely within the objectives of the NRP 61.

With these results, AGWAM makes a very valuable contribution to NRP 61. The present report gives an overview of the project with its aims, methods, selected results and recommendations to the stakeholders. It makes exciting reading for agricultural experts, government agencies and farmers alike.

Prof. emeritus Dr. C. Leibundgut
President of the NRP 61 Steering Committee

Summary

Project "Water Demand in Swiss Agriculture and Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change (AGWAM)" of the National Research Programme "Sustainable water management" (NRP 61)

Increasing temperatures and decreasing rainfall during the summer months, as projected by climate models for the next decades, will lead to higher crop water demand and reduced soil water availability, which would lead to more irrigation to secure stable yields of high-value crops. But, where the discharge of rivers is low, water availability may be limited. For these situations, strategies are needed to reduce the dependency of agricultural production on additional water. The focus of the AGWAM project was therefore to develop recommendations for an optimal use of water in agriculture under scenarios for climatic, price, and political developments, while maintaining economic profitability and environmental standards, and to identify regulatory actions needed to implement adaptive measures. Relevant decision levels were considered, i.e., the regional level, at which planners need to develop strategies for agricultural land use and water retention, and the farm level, where farmers need to adapt land and farm management while maintaining profitability. Two contrasting case study areas were selected: the western Broye catchment and the central Greifensee catchment in Switzerland. The two regions differ in their current climate and land use.

At both the regional and the farm level, productivity and other functions were simulated with the locally calibrated crop model CropSyst in combination with a livestock model using identical parameters and input data. For optimization of land use and management at the regional level, results were used in a multi-objective optimization routine generating a large range of solutions depending on weights assigned to different goals (productivity, water protection, soil protection, irrigation). From the ensemble of solutions, three were selected as possible alternative strategies with a focus on productivity, environmental protection, or a “compromise” between the two. At the farm level, CropSyst was coupled to an economic model to find solutions that provide maximum profitability and minimum income risk. With a Life Cycle Assessment (LCA), additional environmental impacts of the various solutions were evaluated: global warming potential, aquatic and terrestrial biodiversity loss, and freshwater eutrophication. The approach and the results were discussed with stakeholders from administration, interest groups, and the farming community.

Main results:

- Increased water requirements will be a key issue in adaptation to climate change in agriculture. But agricultural productivity in terms of dry matter yield could be maintained by a balanced, regional adaptation strategy that minimizes the increase in irrigation water requirement, caused by climate warming, by changing land use patterns and soil management (“compromise” solution). This strategy may help to avoid water shortages in regions with frequent low-flow situations. However, this strategy shifts production from arable crops to grassland and thus significantly reduces the production of human nourishment in terms of Megajoules digestible energy (MJ dig. en.), leading to a decreased environmental efficiency of production within the affected regions.

- Optimization can be implemented in a sub-regional approach taking into account differences in environmental conditions and topography. In the case of the Broye catchment, this would lead to a focus on intensive, irrigated crop production in the most suitable part of the catchment (around Payerne), whereas land in the hilly sub-regions would be used for grassland production and some non-irrigated crop production, depending on soil type.

- In a stepwise approach, initially only "soft" measures, such as changes in land operations and adjustments in crop cultivar and crop choice *(= incremental adaptation),* should be implemented, followed by measures requiring investment in infrastructure with longer lead times of 10–15 years *(= systems adaptation)*. Changing location, i.e., altering spatial organization of production, should be the last step *(= transformational adaptation)*.

- Extrapolation of the specific results for the two case study regions, however, is difficult as the strategic goals may differ between regions and regional differences exist in trade-offs between different agricultural functions. In each region, the availability of water in terms of its variability (i.e., the frequency of low-flow situations) needs to be considered when planning future irrigation activities. In economic terms, some crops, such as potato, should preferentially be irrigated even when water resources are limited.

- At the farm level, environmental impacts of production (related to the amount produced) are expected to increase in the future climate. Strategies maximizing farm economic profitability in the future aggravate water-related impacts; however, most other environmental impacts (per amount produced) are lower for economically optimized farms than for farms without adaptation to the future climate, although in the future, productivity and eco-efficiency will decrease.

- The water policy currently in use does not only encourage farmers to irrigate intensively whenever irrigation is possible but also increase farmers' income risks (e.g., production of potato). Under future climate conditions, both the implementation of a volumetric water price and the introduction of a water quota would significantly reduce a farm's total water consumption and water-related impacts, with minor reductions in farm income but an important decrease in the amount and eco-efficiency of production in terms of energy units.

- At the farm level, effects of changes in policy (i.e., direct payments) and even more so in prices are more important than climate change. Hence, adaptation may be driven by changes in the system of direct payments. Because of differences between regions regarding trade-offs between productivity and environmental impacts, as well as between water availability and demand, such changes would need to be regionally differentiated. Subsidies for irrigation infrastructure should be limited to efficient systems. Water quotas for individual farms could be handled similarly to those quotas currently used for N and P, i.e., by regulating direct payments based on "evidence of ecological performance" ("Ökologischer Leistungsnachweis, ÖLN"; adapted to regions and crop types).

- Increasing the production efficiency is essential because aggregated impacts that potentially reach levels of concern include aquatic biodiversity loss and freshwater eutrophication. However, efforts to increase the production efficiency need to be combined with complementary measures to address resulting impacts on aquatic biodiversity. Such measures could include quotas in order to effectively limit the use of water resources and to encourage the use of groundwater rather than river water. This is particularly important if a level of food self-sufficiency above 50 % is to be maintained for a large population facing changing climatic conditions and declining land resources.

In conclusion, increasing water use for irrigation to boost production under growing water limitation in specific vulnerable regions leads to increasing environmental impacts and puts pressure on natural reservoirs, such as rivers and lakes. AGWAM results offer options for planning adaptation at regional and farm levels that are more sustainable and robust alternatives to purely technological solutions, such as building reservoirs and pipelines to access additional water under climate change.

Zusammenfassung

Projekt «Wasserbedarf in der schweizerischen Landwirtschaft und nachhaltige Anpassungsstrategien der Land- und Wassernutzung, mit dem Ziel, die Auswirkungen des Klimawandels zu entschärfen (AGWAM)» des Nationalen Forschungsprogramms «Nachhaltige Wassernutzung» (NFP 61)

Steigende Temperatur und sinkender Niederschlag im Sommer, wie von Klimamodellen für kommende Jahrzehnte projiziert, werden zu einem steigenden Wasserbedarf der Kulturen und zu abnehmender Wasserverfügbarkeit führen. Dadurch wird der Bewässerungsbedarf steigen, um stabile Erträge von hochwertigen, landwirtschaftlichen Kulturen zu sichern. Folglich wird dort, wo der Abfluss gering ist, die Wasserlimitierung verstärkt ausfallen. Für diese Situationen sind Strategien vorzusehen, um die Abhängigkeit der Produktion von zusätzlichem Wasser zu verringern. Das Ziel des Projekts AGWAM war es deshalb, zum einen Empfehlungen für den Umgang mit Wasser unter verschiedenen Szenarien für Klima, Preise und Politik auszuarbeiten, unter welchen Rentabilität und Umweltstandards erhalten bleiben, und zum anderen Möglichkeiten der Regulierung zur Zielerreichung zu identifizieren. Zwei Entscheidungsebenen wurden berücksichtigt: die regionale Ebene, auf welcher Strategien für die Planung der Land- und Wassernutzung nötig sind, und die Betriebsebene, auf welcher Bewirtschaftung und Betriebsführung anzupassen sind. Die Untersuchungen wurden für das Broye-Tal und das Einzugsgebiet des Greifensees durchgeführt, zwei Regionen, die sich in Klima und Landnutzung unterscheiden.

Auf beiden Ebenen wurden aufgrund identischer Parameter und Inputdaten Produktivität und andere Funktionen mit Hilfe des lokal kalibrierten Modells CropSyst in Kombination mit einem Tiermodell simuliert. Für die regionale Optimierung flossen die Ergebnisse in eine multi-kriterielle Optimierung ein, welche je nach Gewichtung der vier Ziele (Produktivität, Wasserschutz, Bodenschutz, Bewässerung) eine große Anzahl von Lösungen generierte. Aus diesen wurden drei alternative Strategien abgeleitet, die ihren Fokus entweder auf Produktion, auf Umwelt oder auf einem Kompromiss zwischen beiden haben. Auf der Betriebsebene wurde CropSyst mit einem ökonomischen Modell gekoppelt, um Lösungen mit maximalem Profit und minimalem Einkommensrisiko zu definieren. Anhand einer Life-Cycle-Analyse (LCA) wurden zusätzliche Kategorien bewertet: Erwärmungspotenzial, aquatische und terrestrische Biodiversität und Gewässereutrophierung. Vorgehen und Ergebnisse wurden mit Vertretern aus Verwaltung, Interessensgruppen und Landwirtschaft diskutiert.

Hauptergebnisse:

- Der steigende Wasserbedarf wird im Zusammenhang mit der Anpassung der Landwirtschaft an den Klimawandel ein zentraler Aspekt sein. Aber mit einer ausgewogenen, regionalen Strategie kann die Zunahme des Wasserbedarfs beschränkt werden, indem Landnutzung und Bewirtschaftung angepasst werden (= Kompromiss). Diese Strategie trägt dazu bei, dass in Gebieten mit zukünftig häufiger auftretenden Abflussdefiziten ein Wassermangel vermieden wird. Allerdings wird dabei Ackerland durch Grasland ersetzt, wodurch die Produktion von Nahrungsmitteln pro Energieeinheit deutlich sinkt, was zu einer verringerten Umwelteffizienz der Produktion innerhalb der Region führt.

- Die Optimierung kann aber auf sub-regionaler Ebene implementiert werden, so dass kleinräumige Unterschiede in den Umweltbedingungen und in der Topographie berücksichtigt werden können. Im Fall des Gebiets der Broye bedeutet dies, dass die intensive, bewässerte Produktion nur in den günstigsten Lagen des Einzugs-

gebiets (um Payerne) konzentriert ist und die hügligen Gebiete hauptsächlich für die Graswirtschaft und, je nach Bodentyp, für einzelne, nicht-bewässerte Ackerkulturen genutzt werden.

- In einem schrittweisen Vorgehen sollten zuerst einfache Maßnahmen in der Bewirtschaftung und bei der Sorten- und Kulturwahl ergriffen werden *(= incremental adaptation)*, gefolgt von Maßnahmen, welche Investitionen in Infrastruktur, neue Vorschriften und technische Fortschritte erfordern *(= systems adaptation)*. Die Änderung der Raumordnung sollte der letzte Schritt sein *(= transformational adaptation)*.

- Die Ergebnisse für die ausgewählten Testgebiete können nicht beliebig auf andere Gebiete übertragen werden, da sich strategische Ziele und mögliche Zielkonflikte (sog. Trade-offs) zwischen verschiedenen landwirtschaftlichen Funktionen regional unterscheiden. In jeder Region müssen die Verfügbarkeit von Wasser und ihre Variabilität bei der Planung der Wassernutzung durch die Landwirtschaft berücksichtigt werden. Aus wirtschaftlichen Gründen steht die Bewässerung spezieller Kulturen, wie z.B. von Kartoffeln, prioritär, auch wenn Wasser knapp ist.

- Es wird erwartet, dass auf der Betriebsebene die Umweltauswirkungen (bezogen auf die Produktionsmenge) unter dem Einfluss des Klimawandels steigen und Strategien zur Maximierung des Betriebsprofits wasserbezogene Probleme intensivieren könnten. Die meisten Auswirkungen sind aber – wenn auf die Produktion bezogen – bei angepassten, optimierten Betrieben geringer als bei Betrieben ohne Klimaanpassung, obwohl Produktivität und Umwelteffizienz in beiden Fällen abnehmen werden.

- Die heutige Politik zur Regulierung der Wasserbezüge ermutigt die Landwirte zu einer intensiven Bewässerung, solange Wasser vorhanden ist. Gleichzeitig hat die heutige Wasserpolitik negative Auswirkungen auf das Einkommensrisiko (z.B. beim Kartoffelanbau). In Zukunft könnte die Einführung von Wasserkontigenten oder die Erhöhung des Wasserpreises die Wassernutzung der Betriebe und die wasserbezogenen Auswirkungen deutlich senken, ohne dass es zu großen Profitverlusten für die Landwirte kommt. Derartige Maßnahmen wären allerdings mit einem Verlust an Menge und Umwelteffizienz der Produktion von Nahrungsmitteln verbunden.

- Auf der Betriebsebene wirken sich Preise und besonders die Politik (Direktzahlungen) stärker auf die Betriebsrentabilität aus als der Klimawandel. Anpassungen könnten folglich wirkungsvoll über das Direktzahlungssystem gesteuert werden. Wegen bestehender regionaler Unterschiede in Bezug auf Trade-offs zwischen Produktion und Umweltwirkungen und zwischen Wasserbedarf und -dargebot müssten solche Änderungen differenziert erfolgen. Wasserkontingente könnten ähnlich gehandhabt werden wie die Kontingente für Stickstoff (N) und Phosphor (P) im Rahmen des «Ökologischen Leistungsnachweises, ÖLN» für Direktzahlungen (angepasst an Regionen und Kulturen).

- Eine Steigerung der Produktionseffizienz ist vorrangig, da Umweltauswirkungen wie Biodiversitätsverlust und Eutrophierung ein besorgniserregendes Ausmaß annehmen könnten. Die Steigerung der Produktionseffizienz muss daher durch Maßnahmen ergänzt werden, welche die Auswirkungen auf die aquatische Biodiversität mindern, z.B. Wasserkontingente zur Begrenzung der Entnahme von Wasser aus Flüssen. Dies ist besonders unter dem Gesichtspunkt wichtig, dass bei einem Selbstversorgungsgrad von über 50 % und einer wachsenden Bevölkerung der Bedarf an einheimischer Produktion auf begrenzter Landfläche steigt.

Zusammenfassend lässt sich sagen, dass eine Zunahme der Bewässerung für eine maximale Produktion unter zunehmender Wasserlimitierung in bestimmten, gefährdeten Regionen negative Umweltfolgen hat und Druck auf die natürlichen Reservoire wie Flüsse und Seen erzeugt. Die Ergebnisse von AGWAM zeigen Möglichkeiten für eine Anpassungsstrategie auf, welche robust und nachhaltig sind und Alternativen zu rein technischen Lösungen, wie dem Bau von Reservoiren oder von grösseren Zuleitungen zur Erhöhung der Wasserzufuhr unter Klimawandel, darstellen.

Résumé

Projet «Demande d'eau dans l'agriculture suisse et options adaptatives durables pour la gestion du territoire et de l'eau, dans le but d'atténuer les effets du changement climatique (AGWAM)» du Programme national de recherche «Gestion durable de l'eau» (PNR 61)

Selon les prévisions des modèles climatiques pour ces prochaines décennies, l'augmentation des températures et la diminution des précipitations en été vont accroître le besoin en eau des cultures et réduire les réserves d'eau disponible. Il faudra donc davantage irriguer afin de garantir un rendement stable des cultures agricoles de grande valeur. Cependant, la disponibilité d'eau sera plus fortement limitée là où les débits sont faibles. Dans de telles situations, des stratégies sont nécessaires afin de réduire le besoin impératif d'eau supplémentaire pour la production agricole. L'objectif du projet AGWAM était donc d'élaborer des recommandations en faveur d'une gestion optimale de l'eau qui préserve à la fois la rentabilité et l'environnement dans différents scénarios climatiques, financiers et politiques. Un deuxième objectif était l'identification de moyens pour réglementer la mise en œuvre des mesures à prendre. Deux niveaux de décision furent pris en considération: le niveau régional, qui nécessite des stratégies de planification de l'utilisation du sol et des eaux, et le niveau de l'exploitation, dont la gestion doit être adaptée. Les recherches ont été menées dans la vallée de la Broye et dans le bassin-versant du Greifensee, deux régions dont le climat et l'utilisation du sol sont différents.

La productivité et d'autres fonctions ont été simulées aux deux niveaux en utilisant des paramètres et des intrants identiques, à l'aide du modèle CropSyst calibré à l'échelle locale, combiné avec un modèle animal. Pour l'optimisation régionale, les résultats ont été utilisés dans une optimisation multicritère qui a généré un grand nombre de solutions selon l'importance attribuée aux quatre objectifs fixés. A partir de ces solutions, trois stratégies possibles ont été sélectionnées et axées, soit sur la productivité, soit sur l'environnement, ou sur un compromis entre ces deux aspects. Au niveau de l'exploitation, CropSyst a été couplé avec un modèle économique afin de trouver des solutions comportant un profit maximal et un risque minimal de perte de revenu. Le potentiel de réchauffement climatique, la biodiversité aquatique et terrestre ainsi l'eutrophisation des eaux ont aussi été évalués à l'aide d'une analyse du cycle de vie (Life Cycle Analysis LCA). L'approche et les résultats ont été discutés avec des parties prenantes de l'administration, de groupes d'intérêt et de l'agriculture.

Résultats principaux:

- Le besoin croissant en eau sera une question clé dans l'adaptation de l'agriculture au changement climatique. Avec une stratégie régionale équilibrée, il sera cependant possible de freiner l'accroissement de ce besoin en adaptant l'utilisation et l'exploitation du sol (solution de compromis). Cette stratégie contribuera en outre à éviter la pénurie d'eau dans les régions où les déficits d'écoulement seront de plus en plus fréquents. Toutefois, les terres assolées seront remplacées par des herbages et la production de denrées alimentaires diminuera donc nettement en termes de calories, ce qui entraînera une baisse de l'efficacité environnementale de la production dans cette région.

- L'optimisation peut toutefois être mise en œuvre au niveau sous-régional afin de tenir compte des différences à petite échelle des conditions environnementales et de la topographie. Dans la région de la Broye, cela signifie que la production intensive de cultures irriguées ne se concentre que dans les endroits favorables du bassin-versant (autour de Payerne) et que les zones de collines sont principalement utilisées pour la production d'herbages et, selon le type de sol, pour les cultures non irriguées sur des terres assolées.

- Dans une approche progressive, des mesures «douces» devraient d'abord être prises dans la gestion et le choix des variétés et des cultures *(= adaptation incrémentale)*, suivies de mesures exigeant des investissements dans l'infrastructure, de nouvelles prescriptions et des progrès techniques *(= adaptation systémique)*. Les changements dans l'aménagement du territoire devraient s'opérer en dernier lieu *(= adaptation transformationnelle)*.

- Il est difficile d'extrapoler les résultats obtenus dans les deux régions étudiées à d'autres régions, car les buts stratégiques peuvent varier d'une région à l'autre, tout comme les compromis souhaités entre les diverses fonctions agricoles. Dans chaque région, la disponibilité de l'eau et la variabilité de celle-ci doivent être prises en compte lors de la planification de l'utilisation de cette ressource par l'agriculture. Pour des raisons économiques, l'irrigation de cultures spéciales, comme celle de la pomme de terre, est prioritaire même si les ressources sont limitées.

- Selon les prévisions au niveau de l'exploitation, les impacts environnementaux de la production (rapportés à la quantité produite) devraient augmenter sous l'effet du changement climatique. Les stratégies visant à maximaliser les profits de l'exploitation pourraient aggraver les problèmes liés à l'eau. Mais la plupart de ces impacts – s'ils sont rapportés à la production – seront plus faibles dans les exploitations optimisées et adaptées au futur climat que dans celles qui ne le sont pas, même si la productivité et l'éco-efficacité diminueront dans tous les cas sous le changement climatique.

- La politique actuelle de l'eau encourage les agriculteurs à irriguer intensivement tant que l'eau est disponible, mais elle augmente en même temps le risque de perte de revenu (p.ex. dans la production de la pomme de terre). A l'avenir, l'introduction de contingentements des eaux ou l'augmentation des prix de l'eau pourrait réduire considérablement l'utilisation de cette ressource et les impacts qui s'y rapportent, sans occasionner de grandes pertes de revenu pour les agriculteurs. Il s'en suivrait toutefois une importante baisse de la quantité et de l'éco-efficacité de la production de denrées alimentaires destinées à la consommation humaine.

- Au niveau de l'exploitation, les prix et notamment la politique (paiements directs) influent davantage sur la rentabilité de l'exploitation que le changement climatique. Des adaptations peuvent donc être efficacement dirigées par le biais du système des paiements directs. En raison des différences régionales dans les compromis souhaités entre la production et les impacts environnementaux, et entre le besoin d'eau et sa disponibilité, de telles adaptations devraient être différenciées par région. Les contingentements des eaux pourraient être gérés de la même manière que ceux qui sont en vigueur pour l'azote et le phosphore dans le cadre des Prestations Ecologiques Requises (PER) pour les paiements directs, qui sont adaptés aux régions et aux cultures.

- Il est essentiel d'améliorer l'efficacité de la production, car les impacts environnementaux, tels que l'appauvrissement de la biodiversité et l'eutrophisation, pourraient prendre une importance préoccupante. Cependant, l'augmentation de l'efficacité de la production doit être complétée par des mesures atténuant les impacts sur la biodiversité aquatique, tel que le contingentement des eaux destiné à limiter le prélèvement de cette ressource dans les rivières. Ceci est particulièrement important dans le contexte d'un taux d'autosuffisance de plus de 50 % et une population croissante, où le besoin de produits indigènes augmente malgré un sol d'une superficie imitée.

En conclusion, augmenter l'irrigation pour une production maximale alors que l'eau est de plus en plus limitée a des effets négatifs sur l'environnement dans certaines régions sensibles et met sous pression les réserves naturelles telles que les lacs et les rivières. Les résultats d'AGWAM montrent les stratégies d'adaptation possibles, qui soient robustes et durables; ils présentent aussi des variantes purement techniques, comme la construction de réservoirs ou de grosses conduites permettant d'augmenter l'alimentation en eau sous l'effet du changement climatique.

1 Introduction

1.1 Background

Agriculture is an economic sector that is strongly sensitive to climate change (Fuhrer & Gregory 2014). In cool temperate regions of Europe, climate change during the next decades is expected to produce positive effects on agriculture through higher crop productivity, expansion of suitable areas for crop cultivation, and introduction of adapted crop species and new varieties (IPCC 2007b). However, increasing water shortage and extreme weather events during the cropping season may cause more frequent crop loss and yield instability and render areas less suitable for traditional crops (Olesen & Bindi 2002). Changes in temperature and in precipitation pattern may lead to water-related risks in agricultural production in combination with changes in economic conditions, competition for land and water resources, and the need for biodiversity conservation (Lotze-Campen *et al.* 2008).

As a consequence of the variable spatial pattern of climate change, implications for agriculture need to be assessed at the scale at which decisions are taken. This requires using climate scenarios downscaled from global climate model outputs to estimate anomalies relative to the current climate at local and regional scales. Regional projections suggest a spread of summertime water deficits to northwest Europe including Switzerland (Fuhrer *et al.* 2006), where the trend in increasing temperature already exceeds the hemispheric trend. Here, a further warming until 2050 and beyond will affect hydrological regimes and seasonal patterns of evapotranspiration and runoff, and thus alter the balance between water demand and availability (Fuhrer & Jasper 2012). Water availability will fluctuate between water shortage during summer and intense rainfall during winter and spring, and associated environmental impacts will be caused by soil and nutrient losses. The drought risk on the Central Plateau may increase from about 15 % to over 50 % with future climate change (Calanca 2007). In Swiss agriculture, this trend is expected to have negative impacts on productivity and to increase production risks by the end of the century (e.g., Fuhrer *et al.* 2006; Torriani *et al.* 2007; Finger & Schmid 2008). However, projections of the frequency of climate extremes remain uncertain (CH2011 2011). In the short term, the signal is small relative to natural variability, while in the longer term, the signal is larger, but projections remain uncertain due to both uncertain greenhouse gas emissions and climate model outputs (Hawkins & Sutton 2009). Hence, robust adaptive strategies for agricultural water resource management are needed to cope with the expected but uncertain change in climatic conditions, taking into account a possible increase in the costs for supplemental water. A robust solution is defined as the one with best performance for the worst-case scenario (Soares *et al.* 2009). According to Vermeulen *et al.* (2013), adaptation of agricultural systems involves both better management of agricultural risks and incremental adaptation to progressive climate change. This strategy should result in higher climate resilience of the production systems. Measures may include adjustments of crop rotations (e.g., shifting from high- to low-water-demanding crops) and of production intensities, use of conservation soil management, adoption of irrigation with an efficient technology and choice of sufficient water sources (surface water or groundwater), retention of water in reservoirs (e.g., rainwater harvesting with cisterns), introduction of suitable landscape elements to reduce runoff, or changes in stocking rates and livestock types.

Farmers who have sufficient access to capital and technologies should be able to continuously adapt their farming system by changing the mix of crops, adopting irrigation, and adjusting fertilization and plant protection (Easterling & Apps 2005; Vermeulen *et al.* 2012). Furthermore, agricultural systems are intrinsically dynamic, and adoption of new practices is not new. However, in connection with climate change, new practices might intensify existing impacts on the environment and lead to new conflicts with other landscape functions (MA 2005; Schröter *et al.* 2005; IPCC 2007c). For example, increased water use for irrigation could conflict with water demands for domestic or industrial uses and lead to negative ecological implications (Bates *et al.* 2008). Also, soil loss through erosion may increase due to climate change, an effect that could be aggravated through changes in land management (e.g., Lee *et al.* 1999; O'Neal *et al.* 2005). To prevent continued degradation of natural resources, policy will need to support farmers' adaptation while considering the multi-functional role of agriculture (Olesen & Bindi 2002; Betts 2007). Hence, effective measures to minimize productivity losses and preserve finite natural resources need to be developed at all decision levels, and scientists need to assist planers and decision makers in this process (Salinger *et al.* 2000, 2005). Finally, human activity and land management must be considered in conjunction with environmental system processes in order to produce multiple benefits across the landscape. This complex interaction of ecosystems, land use, and land management presents a major challenge in reaching sustainable and climate-resilient agricultural production systems (Sayer *et al.* 2013). Using scenario analysis and optimization on different spatial scales may help to identify important trade-offs between land use and ecosystem services (Seppelt *et al.* 2013), but further developments are necessary to make this approach acceptable to stakeholders for their decision-making process.

In the framework of the National Research Programme "Sustainable water management" (NRP 61) it was possible to launch a project addressing climate change and land and water use in Swiss agriculture. The project started in 2010 and ended in 2013. The present report provides an overview of the project with its goals, methods, and selected key results. It provides some recommendations for stakeholders that could be used in adaptation planning at the regional and farm levels.

1.2 Original objectives and relevance of the research project

The principal objectives of Swiss agricultural policy are set out in the federal constitution, according to which agriculture in this country must fulfill multi-functional tasks by making a major contribution towards ensuring food supplies for the population based on production methods that ensure that future generations will have fertile soils and clean drinking water. This means that ecological standards are an important objective of Swiss agricultural policy. With climate change, these key agricultural tasks are among those most directly affected. Moreover, maintaining the current level of self-sufficiency for a future growing population while the agricultural land area declines, requires high productivity (i.e., high crop yield per unit of land area). Hence, visions and strategies for the future development of Swiss agriculture need to consider changes to adapt to new conditions and to increase the resilience to climate variability, but without losing ecological standards. With climate change, there is the possibility that an increasing agricultural water demand could lead to an overuse of freshwater to boost irrigation for maximum production – with negative implications for the amount and quality of water, especially in small rivers on the Central Plateau – and to trade-offs with other functions.

In response to these projections, the original objective of this project was…
…to investigate sustainable strategies for future agricultural land use and farm management to mitigate the negative consequences of climate change for water demand in Swiss agriculture.

Based on two contrasting case study catchments, the focus was on developing recommendations for an adapted use of water under scenarios for climatic, socioeconomic, and political developments, while maintaining economic profitability and environmental standards, and on identifying regulatory actions needed to implement adaptation measures.

More specifically, the project aimed to investigate the following three research questions:

- What is the water consumption by agriculture in two selected regions (catchments) under present and future conditions (considering climate, economy, and agricultural policy), and how large is the risk to agricultural production due to reduced water availability?

- How can we optimize strategies for water conservation in agricultural land use (forage, crop, and livestock production) at the regional (i.e., catchment) scale and at the scale of individual farms, and what are the environmental impacts of such strategies?

- What recommendations for management and policy can be made to implement sustainable water use in Swiss agriculture considering a range of possible climate change scenarios?

Such information concerning different possible measures at the levels of farm management, land use, and landscape organization is needed, for instance, in the context of national climate change adaptation policies. In the “Climate Change Adaptation Strategy” of the Federal Office of Agriculture, it is stated that adaptation to increasing drought risks is one of the main areas where proactive action is needed. Such adaptive action, however, needs to consider the multi-functional role of agriculture. Multifunctionality of agriculture primarily concerns productivity and environmental protection, but it also has relevant effects on several other functions, such as the management of soil and water, the maintenance of landscape, the conservation of biodiversity, and the contribution to the socioeconomic viability in rural areas. Thus, the project needed to apply an integrated approach that considered the mitigation of productivity losses at minimal environmental and economic costs.

2 Research design, theoretical frame, methods and data used

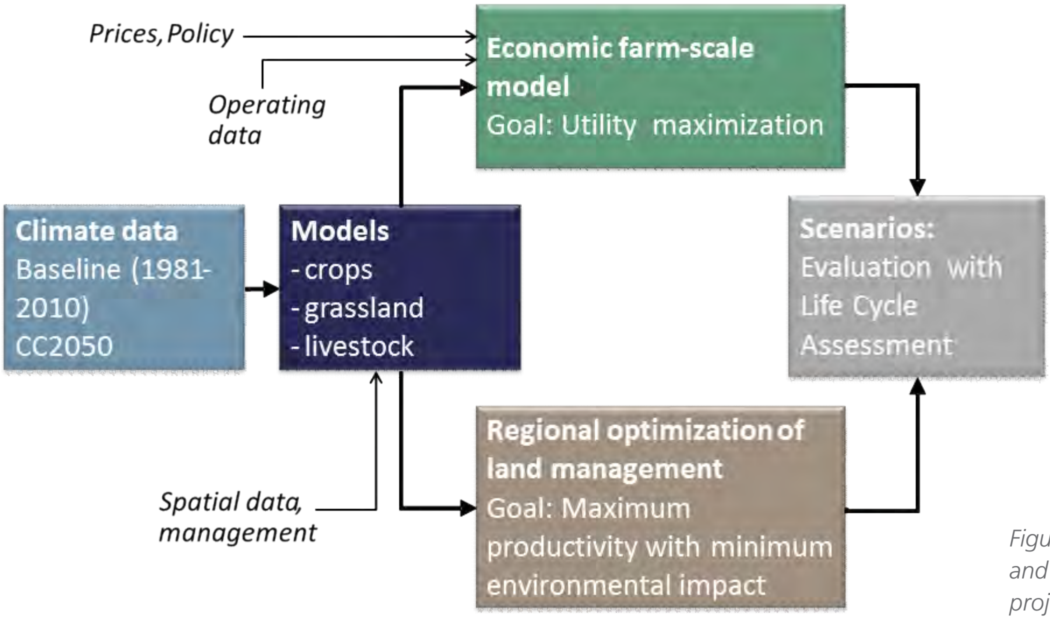


Figure 2.1.1.: Main components and inter-linkages of the AGWAM project.

2.1 Project structure

The project was organized in different components (= work packages) with each having a specific but complementary task (Figure 2.1.1.). A common data base with climate information, spatial data, and region-specific management data was established and used as the starting point for modeling at both the farm level and the regional (landscape) level. For both levels, common component models for crops and livestock were used. At the end, selected results were subjected to a Life Cycle Assessment to investigate a large range of overall environmental impacts of different strategies.

2.2 Case study regions

The two case study regions are shown in Figure 2.2.1.

The Broye catchment covers an area of 598 km^2. Its main river is the Broye (average discharge of 11.73 m^3/s at the outlet into Lake Morat). The region can be divided into a hilly area (max. altitude 1,500 m asl, average temperature 7.1 °C, and average annual precipitation 1,535 mm at weather station Semsales) and a flat lowland area (altitude from 400 to 600 m asl, average temperature 9.6 °C, and average annual precipitation 886 mm at weather station Payerne). Land use is dominated by agriculture with mixed dairy and arable crop production in the hilly area and mostly arable crop production in the lowland area (Figure 2.2.2.). The latter is an important potato production region in Switzerland. Significant amounts of irrigation water, mainly pumped from the river Broye and its tributaries, are already required in the present climate, with a yearly average of 1.13 × 10^6 m^3 applied to 1,377 ha (Robra & Mastrullo 2011). Irrigation is used primarily for potato (50 %), maize (15 %), tobacco (15 %), and sugar beet (8 %).

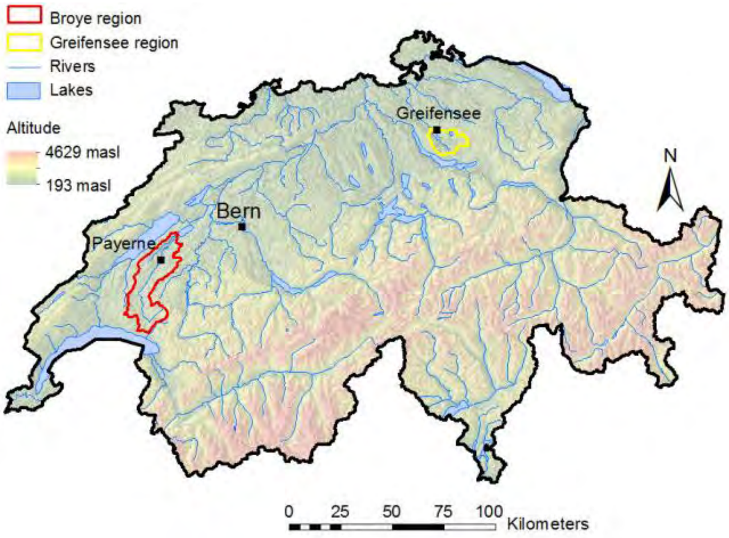


Figure 2.2.1.: AGWAM case study regions of Broye and Greifensee.

This water is currently price free (and capital costs, such as irrigation infrastructure, tend to be subsidized). Due to dry conditions, water withdrawal in the canton of Vaud was banned over the period 1998–2011 in seven out of the last nine years, mostly in late summer (Lehmann 2013a). Climate change is expected to worsen the situation and affect this region severely; therefore, the farm-scale models focused on this part of the region.

The Greifensee region is a catchment of 164 km^2. Its main river is the Glatt (average discharge of 4.01 m^3/s at the outlet from Lake Greifensee, volume 0.148 km^3). This region also presents a hilly area (maximum altitude 1,030 m asl, average annual precipitation 1,388 mm, and average tem-

Figure 2.2.2.: Current land use in the Broye region (500 x 500 m) and picture of the landscape near Payerne.

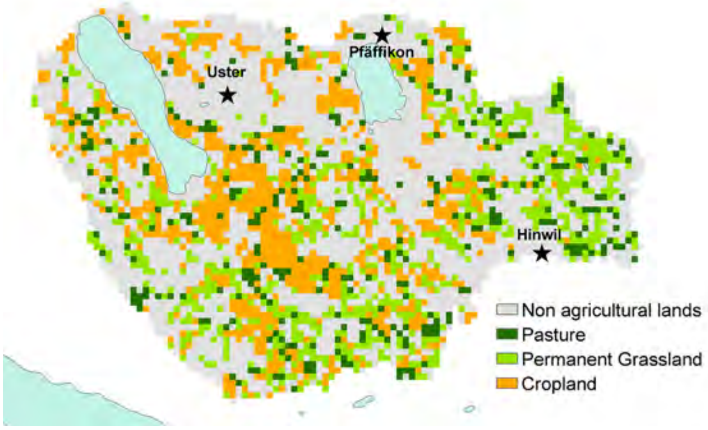


Figure 2.2.3.: Current land use in the Greifensee region.

perature 9.8 °C (at weather station Hinwil) and a lowland area (altitude from 400 to 500 m asl) with average annual precipitation 1,187 mm, and average temperature 10.5 °C (at weather station Uster). Similar to the Broye region, arable crop production is concentrated in the lowland area, and dairy production is concentrated in the hilly area (Figure 2.2.3.). Precipitation in the region is above the optimum level for agriculture, and therefore irrigation is required only for vegetable and potato production. For this region, too, farm-scale modeling focused on the lowland area.

2.3 Climate change scenarios 2050

Climate change scenarios considered the projections for 2050 (2036–2060) based on the A1B SRES emissions scenario. Both an extreme and a moderate change signal were used, developed using either the ETH_CLM regional model (ETHZ) or the SMHIRCA regional model (SMHI) as provided by the ENSEMBLES data base. Regional climate model (RCM) projections were downscaled to a 25-year series of daily weather data required for the crop growth model using the weather generator LARS WG. The following Table 2.3.1. lists the monthly anomalies for main climate parameters for one representative meteorological station in each study region.

2.4 Policy scenarios

Agricultural production in Switzerland is influenced strongly by policy and price levels. To account for possible shifts in these boundary conditions, the following scenarios were used in bioeconomic farm-level modeling in combination with climate change scenarios:

- Change in direct subsidies according to currently planned changes in the Swiss subsidy system (PA14). Since direct payments for specific ecological services (e.g., payments for biodiversity conservation, "Biodiversitätsbeiträge") as they are planned for the next years could not be taken into account, direct payments in the PA14 scenario were reduced compared to the reference scenario.

- Changes in agricultural product prices due to potential market liberalization in Europe. This liberalization would essentially cause a decrease in product prices. In this scenario, prices were assumed to be at the current European level (rather than the current Swiss level), using Austrian prices (AUT).

- Water restriction policies: (a) water price set at 1 CHF/m^3, (b) a water quota fixed at 4,000 m^3/yr for the farm.

The reference is the optimized farm under the current climate (i.e., a 25-year simulated daily weather series). This reference does not exactly correspond to the current real situation, because it is the result of a modeled optimally

Table 2.3.1.: Changes in monthly mean minimum and maximum temperature (ΔT_{min} and ΔT_{max}) and in the monthly mean radiation (ΔRad) and precipitation sum (ΔPrecip) as projected for 2050 by simulations with the ETHZ and SMHI regional climate models. PAY: Payerne (Broye region); UST: Uster (Greifensee region).

	ETHZ								SMHI							
Month	ΔT_{min} (°C)		ΔT_{max} (°C)		ΔRad (%)		ΔPrecip (%)		ΔT_{min} (°C)		ΔT_{max} (°C)		ΔRad (%)		ΔPrecip (%)	
	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST	PAY	UST
Jan	+2.51	+2.58	+2.51	+2.60	-3	-3	-4	-4	+2.33	+2.21	+1.74	+1.67	-6	-5	+14	+8
Feb	+1.82	+1.84	+2.00	+2.07	-4	-5	-2	-2	+1.90	+1.87	+1.34	+1.37	-4	-4	+6	+6
Mar	+1.91	+1.89	+2.14	+2.28	-4	-5	-2	-1	+1.31	+1.31	+1.11	+1.05	-3	-4	+2	+8
Apr	+2.06	+2.12	+2.15	+2.24	-2	-5	-3	+3	+1.03	+1.04	+1.07	+0.90	-2	-2	-2	+8
May	+1.85	+1.92	+2.07	+1.84	+2	-2	-6	+6	+1.48	+1.54	+1.59	+1.43	+0	-2	-7	+1
Jun	+2.18	+2.11	+3.08	+2.64	+7	+5	-18	-7	+2.00	+2.10	+2.13	+2.02	+1	-1	-8	-1
Jul	+2.82	+2.67	+4.23	+3.90	+9	+9	-30	-24	+2.08	+2.21	+2.15	+2.16	+0	-1	-3	+3
Aug	+3.11	+2.96	+4.39	+4.19	+8	+9	-28	-23	+2.00	+2.12	+1.98	+2.04	-2	-2	-1	+6
Sept	+2.78	+2.70	+3.41	+3.29	+3	+5	-11	-5	+1.67	+1.72	+1.61	+1.53	-2	-3	+4	+1
Oct	+2.29	+2.36	+2.36	+2.39	+0	+1	-1	+1	+1.46	+1.43	+1.32	+1.17	-5	-6	+16	+19
Nov	+2.28	+2.44	+2.23	+2.42	+0	+1	-4	-6	+1.86	+1.77	+1.56	+1.45	-8	-8	+24	+22
Dec	+2.69	+2.80	+2.60	+2.81	-2	-1	-4	-6	+2.34	+2.21	+1.92	+1.79	-8	-7	+22	+17

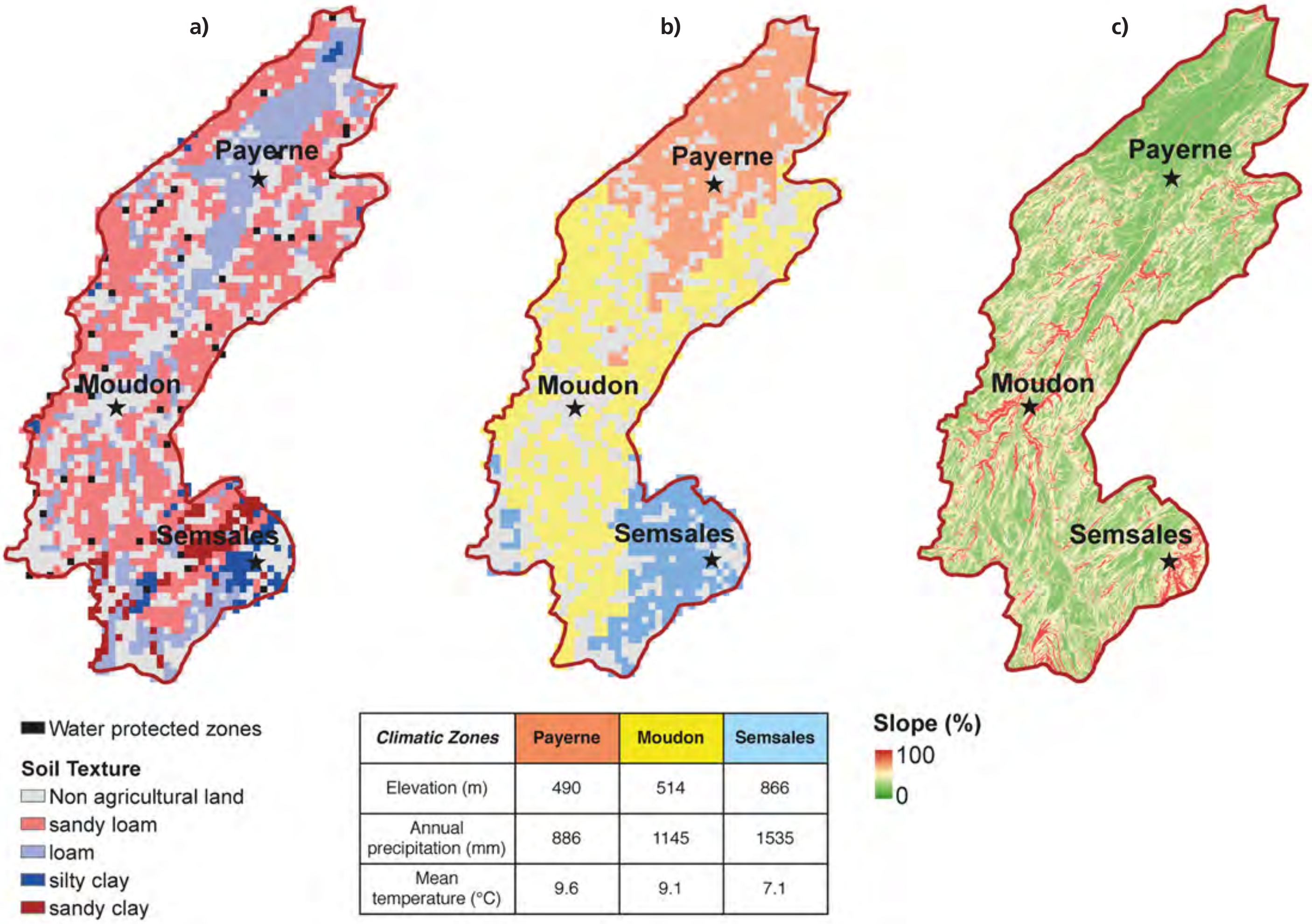
managed farm. However, it is considered realistic and enables an objective comparison of the effects of the scenarios without including a bias due to the effect of the model compared to reality.

2.5 Regional optimization

CropSyst (version 4.13.04), an integrated process-based model, was used as the main modeling tool in the regional optimization. It allows for simulating a wide range of management options currently practiced in the study regions. It simulates not only crop yield but also soil erosion, N-leaching, and crop water use. Details are given in Klein *et al.* (2013a). Potential biomass production was calculated as a function of crop potential transpiration and intercepted radiation. Potential growth was corrected by factors reflecting water and N limitations to compute actual daily biomass gain. Final crop yield was the total biomass accumulated over the growing season multiplied by a harvest index. For regional aggregation, individual crop yields were scaled from 0 to 1 using the maximum and minimum possible yields and averaged over the rotation. To account for the lack of animal production in CropSyst, empirical functions were used to estimate daily grazing needs and N excretion on the fields (for more details, see Klein *et al.* [2013b]).

CropSyst was calibrated for local conditions based on a novel calibration method relying on the widely available Farm Accountancy Data (FADN) as the reference (Klein *et al.* 2012). The calibration procedure included the Morris method for parameter screening and a genetic algorithm for automatic parameter estimation. To identify options for agricultural land management adaptation, important drivers for different functions (i.e,. scaled yield, soil loss, N-leaching, water use) were analyzed with CropSyst (Klein *et al.* 2013a). This analysis was done for the Broye catchment only, and two different soil types were considered to test the importance of local environmental constraints. In a two-step approach, cropping practices that explain high proportions of variance of the different indicators were first identified by an ANOVA-based sensitivity analysis. Then, most suitable combinations of practices to achieve best performance with respect to each indicator were extracted, and trade-offs between identified functions were analyzed.

In order to run the model, spatially explicit inputs were needed for (i) climatic variables (e.g., temperature, radiation, and precipitation), (ii) soil texture, and (iii) slope (Figures 2.5.1. and 2.5.2.). Soil information for each pixel was derived from the Soil Suitability Map of Switzerland (BFS 2012) and was adjusted with soil profile information from the Swiss Soil Monitoring Network (BUWAL 2003). Groundwater protection zones defined by the Swiss Federal Office of Environment (FOEN 2012) also were considered. Climate data from three weather stations were available from the monitoring network of the Swiss Federal Office of Meteorology and Climatology (www.meteoschweiz.ch); each pixel in the study region was allocated to one of the stations according to the minimum difference between annual precipitation amount observed and interpolated annual precipitation amount obtained from Frei *et al.* (2006) and Frei and Schär (1998). Information on slope steepness, necessary for computing soil loss rates, was inferred from a digital elevation model (Swisstopo 2001).



Climatic Zones	Payerne	Moudon	Semsales
Elevation (m)	490	514	866
Annual precipitation (mm)	886	1145	1535
Mean temperature (°C)	9.6	9.1	7.1

Figure 2.5.1.: Spatial representation of the Broye catchment used to drive the simulation models: (a) soil texture and groundwater protection zones, (b) climatic zones, and (c) slopes; the three weather stations that were available in the study area are indicated with star symbols.

Table 2.5.1.: Management options used as decision variables in the spatial optimization

Management option		Levels
Land use		Cropland, permanent grassland, pasture
Crop sequence		50 crop rotations generated stochastically
Intensity	N fertilization (all) Clipping (grassland) Stocking density (pasture)	Recommended: Average N fertilization (in kg N) [a], 5 cuts/yr, 3 LSU [b]/ha Reduced: Recommended N fertilization -25 %, 4 cuts/yr, 2 LSU/ha Low: Recommended N fertilization -50 %, 3 cuts/yr, 1 LSU/ha
Irrigation		Rain fed or supplemental [c] (automatic)
Soil management	Tillage operation Residue management	Conventional: regular tillage & harvest residues removed Conservation: reduced tillage & harvest residues retained

[a] Recommended N fertilization was derived from Flisch *et al.* (2009)
[b] LSU: Livestock Unit (1 LSU = 1 dairy cow)
[c] Only potato, sugar beet, and grain maize can be irrigated, because irrigation is not profitable for other crops (Lehmann *et al.* 2013).

To solve the optimization problem individually for every pixel and by neglecting interactions with neighboring pixels, the following management options were considered: land use type, crop rotation, intensity (e.g., fertilization), irrigation, soil management, and livestock type (Table 2.5.1.).

Reference land management representing current conditions was used as a basis for evaluating impacts of climate change and for expressing the benefits of adaptation. The observed distribution of pasture, grassland, and cropland was defined according to data from BFS (2010). Spatial distribution of crop rotations was not available and was approximated by defining a combination of the 50 generated crop rotations that reproduced the observed crop shares from FOAG (2011). Spatial extension of actual irrigated fields was derived from Robra and Mastrullo (2011). Management intensity was set to the recommended level in the entire region. According to Ledermann and Schneider (2008), 2.7 % of conservation soil management was assumed for the study area, and this management type was allocated with the priority given to pixels with steep slopes. It was assumed that the use of reduced (or no) till occurred preferentially on steep slopes to avoid high soil loss rates leading to land degradation.

In a spatial multi-objective optimization routine, a series of optimum trade-off solutions for regional adaptation was produced by varying the weights of the different sub-goals (i.e., maximum scaled yield, P'; minimum erosion, E'; minimum N-leaching, L'; minimum water consumption for irrigation, I'). Individual weights W were varied systematically to produce a wide range of potential adaptation options with different priorities and to identify possible trade-offs between objectives. Each weight was varied from 0 to 1 with an increment of 0.1 with the constraint that the sum of all weights equaled 1. Individual objectives were scaled from 0 to 1 (P', E', L', I') based on regional maximum and minimum values for current climate. The simulations were repeated with different sets of management options for each pixel. Optimal solutions determined with respect to the objective function J were selected. In our approach, J was calculated with all N possible combinations of management

$$(\{J_k\}_{k=1}^{N})$$

separately for the ETHZ (J^E) and SMHI (J^S) climate scenarios to account for climate projection uncertainties and identify robust optimum solutions. This means in practice that, for every k, the minimum between J^E and J^S was selected to make a new series J^* that was maximized for every pixel.

$$J = \max\{W_p P' + W_i(1-I') + W_e(1-E') + W_l(1-L')\}$$

where $W \in [0,1]$ with an increment of 0.1 and $\sum W = 1$

In CropSyst, supplemental irrigation is triggered when soil moisture falls under a crop-specific threshold and is refilled to a user-defined level. Minimum soil moisture and refill point values were determined by Lehmann *et al.* (2013), who found that, under climate change in the study region, irrigation is economically profitable only for potato, sugar beet, and grain maize. Therefore, the management option "irrigation" was included for only these crops. An irrigation efficiency of 77 % was assumed, which corresponds to the irrigation efficiency of sprinkler irrigation systems (the most common irrigation technique for cropping systems in the Swiss Plateau).

The following Figure 2.5.3. provides an overview of the main steps involved the identification of opti-

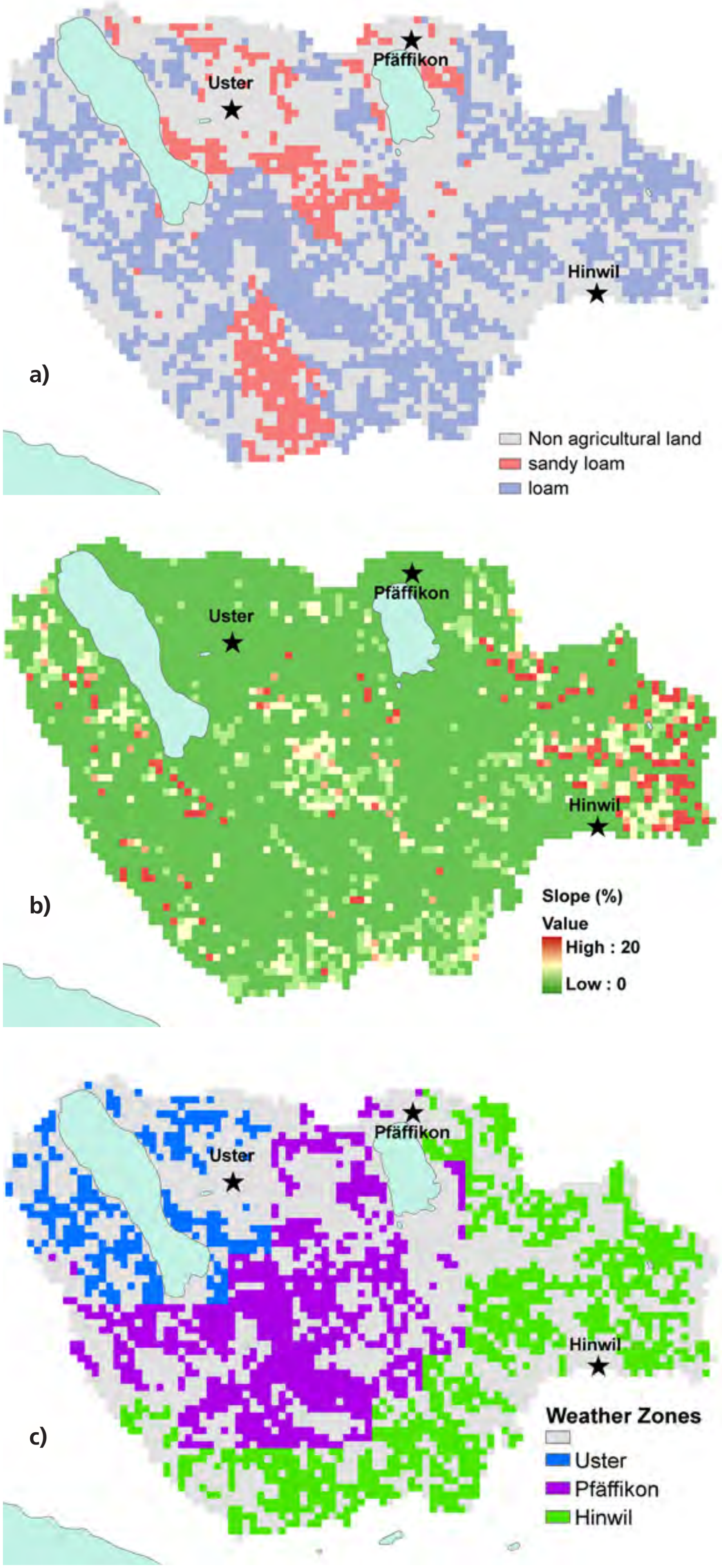


Figure 2.5.2.: Spatial representation of the Greifensee region used to drive the simulation models. (a) Soil type, (b) slope, and (c) climate zones.

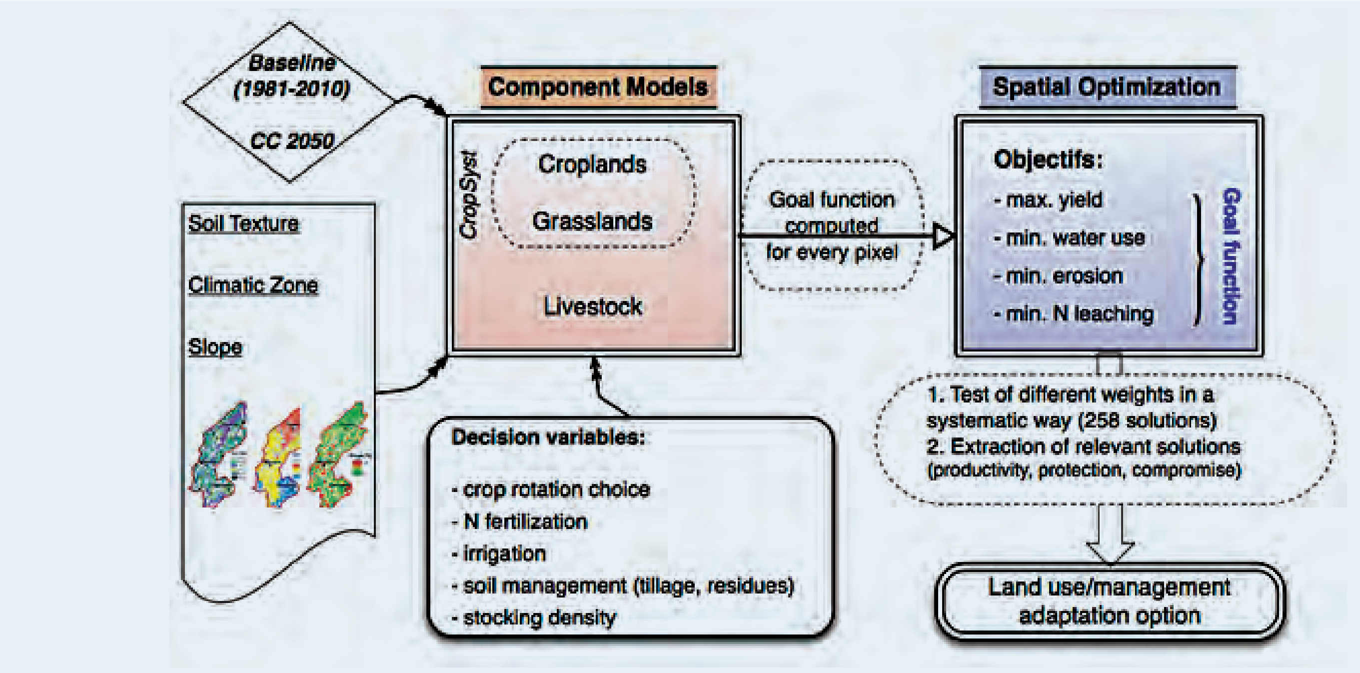


Figure 2.5.3.: Overview of the steps involved in the development of land management adaptation options.

mum management schemes with regard to agricultural productivity (crop yield in t/[ha yr]), minimum irrigation amounts (m^3/[ha yr]), minimum erosion (t/[ha yr]), and minimum N-leaching (kg N/[ha yr]). For more details, see Klein (2013) and Klein *et al.* (2013b).

From an ensemble of 258 solutions, three were selected through a clustering method (so called Self-organizing Maps, SOMs) to represent three different adaptation strategies.

- ***Strategy 1***: Maximum productivity *("productivity")*
- ***Strategy 2***: Minimum environmental impact *("environment")*
- ***Strategy 3***: "Compromise" solution *("compromise")*, i.e., no loss in productivity, water demand not exceeding the average available supply through river runoff, and soil loss and N-leaching minimized

2.6 Economic farm-scale model

Bioeconomic models were developed that operate either at the single-crop or at the whole-farm level. These models coupled the biophysical crop model (CropSyst) with an economic decision model (Figure 2.6.1.).

A bioeconomic model is generally known as a link between models from different disciplines to provide multi-scaled and multi-disciplinary answers to a given problem (Flichman *et al.* 2011). In agriculture, a bioeconomic model is defined as a model that links formulations describing farmers' resource management decisions to formulations illustrating current and alternative production possibilities (i.e., in terms of required inputs) in order to achieve certain outputs and associated externalities (Janssen & van Ittersum 2007). Both the single-crop and the whole-farm model used the "certainty equivalent" (CE) as target value, which enabled the simultaneous consideration of the average income and income risks in the objective function. While maximizing the CE, the developed modeling approaches optimized a wide range of agricultural management decisions, such as crop choice and land allocation to different crop types as well as crop-specific N fertilization and irrigation strategies under different climate, crop price level, water policy, and direct payment scenarios. Besides allowing changes in optimal management schemes, the use of these bioeconomic models also allowed to investigate effects of scenarios on agricultural income, income variability, and agricultural water demand.

Most recent studies using bioeconomic field- or farm-scale models are based on linear programming (see Janssen and van Ittersum [2007] for an overview). However, linear programming approaches can be used only under the assumptions that farm managers have perfect knowledge, that decisions are made in a risk-neutral environment, and that the market is perfectly competitive (El-Nazer 1984). In addition, linear programming techniques are limited to linear objective functions and constraints. Thus, if stochastic weather and price data are incorporated into the modeling approach and risk-averse decision makers are assumed, other programming techniques are required. In order to overcome these limitations, a genetic algorithm (GA) was used as optimization technique in this study.

GAs belong to the class of evolutionary algorithms and are a heuristic optimization technique. They were developed originally by Holland (1975) and are based on the biological concept of genetic reproduction by mimicking the natural selection processes of evolution (Radcliffe & Wilson 1990). In contrast to linear optimization techniques, GAs can handle any kind of objective function or constraint defined in the discrete, continuous, or mixed search space (Gen & Cheng 2000). Furthermore, the incorporation of stochastic variables into the optimization model is possible using GAs.

The following three main characteristics can be assigned to GAs (Yu & Gen 2010):

- *GAs are population based:* GAs maintain a group of individuals (= potential solutions), called a population, to optimize the problem in a parallel way.
- *GAs are fitness oriented:* Every individual is represented by its code, and its performance is evaluated by its fitness value. Individuals with better fitness values are preferred.
- *GAs are variation driven:* Individuals undergo a number of variation operations (e.g., mutation, crossover, or recombination) to mimic genetic changes.

The following Figure 2.6.2. (page 20) provides an overview of the modeling systems for arable and mixed farms. Optimal solutions were sought that maximized the farmer's utility in crop production relative to the certainty equivalent (CE). The CE accounts for both average profit levels and production risks, i.e., profit variability, and can be interpreted as the guaranteed payoff that a risk-averse decision maker views as equally desirable as higher but more uncertain levels of payoffs.

In the following, only the economic component model of the arable-farm model is presented in detail. The economic component model of the mixed-farm model is an extension of the arable-farm model and was developed in an analogical way. The technical details of the mixed-farm model can be taken from Lehmann (2013b).

For the arable-farm model, the CE is defined as the sure sum of money with the same utility as the expected utility of a risky alternative (Keeney & Raiffa 1976) and is expressed as follows:

$$CE = E(\pi) - \frac{1}{2} \cdot \frac{\gamma}{E(\pi)} \cdot \sigma_\pi^2$$

where $E(\pi)$ is the expected profit margin, σ_π^2 is the variance of the annual profit margins, and γ is the coefficient of relative risk aversion. For this study, γ is fixed at a value of 2, which corresponds to a moderate risk-averse decision maker and implies decreasing absolute risk aversion (Di Falco & Chavas 2006).

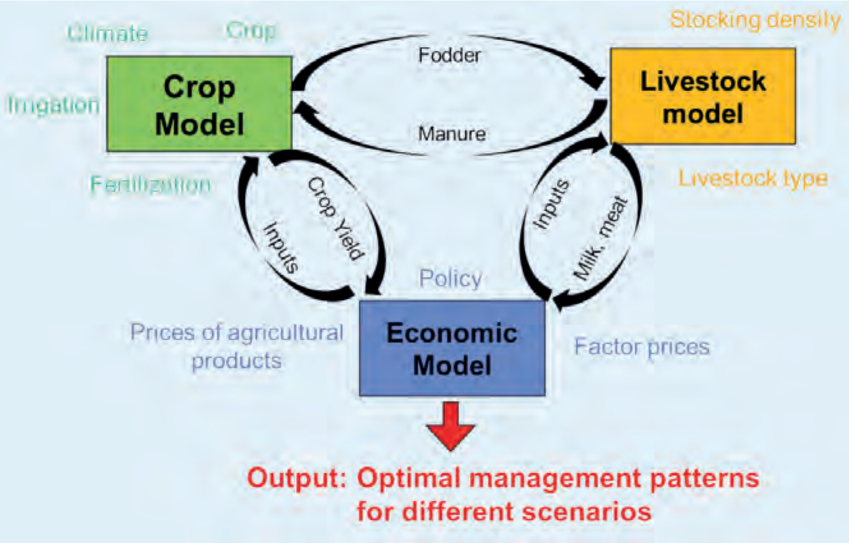


Figure 2.6.1.: Modeling framework with linkages between a crop model, a livestock model (for mixed farms), and an economic model.

The economic decision model at the farm scale considers crop revenues and direct payments as well as fixed and variable costs. The fixed and variable crop-specific costs as well as average crop prices as currently observed in Switzerland are summarized in Table 2.6.1. In a first step, annual profit margins were computed at farm level for each of the 25 simulation years according to the following equation:

$$\pi = \sum_{i=1}^{N} a_i \cdot (\rho_i + DP_i + c_{fix,i} + c_{irrig,i} - c_{var,i})$$

where π is the annual profit margin at farm level, a_i is the cultivated surface of crop *i*, ρ_i is the revenue of crop *i*, and DP_i are the governmental direct payments for crop *i*. The term $c_{fix,i}$ stands for the fixed costs (excluding irrigation systems), $c_{irrig,i}$ for the fixed costs of the irrigation systems, and $c_{var,i}$ for the variable costs of crop *i*.

Besides production risks resulting from variable weather, we also accounted for crop price volatility. Note that the uncertainty faced by the farmer with respect to output prices was expected to influence farm management and especially irrigation decisions (Finger 2012). More details on this approach are given in Lehmann and Finger (2012b). The expected profit margin and its variance were subsequently derived from the 25 annual profit margins, and finally, the farmer's CE, which was the target value in the optimization routine, could be computed. Variable crop price data for the 25 simulation years was generated by a multi-variate normal distribution (Ripley 1987) using observed mean, variance, and covariance data of Swiss crop prices obtained from the FAOSTAT database in the period 2002–2009 (www.faostat.fao.org).

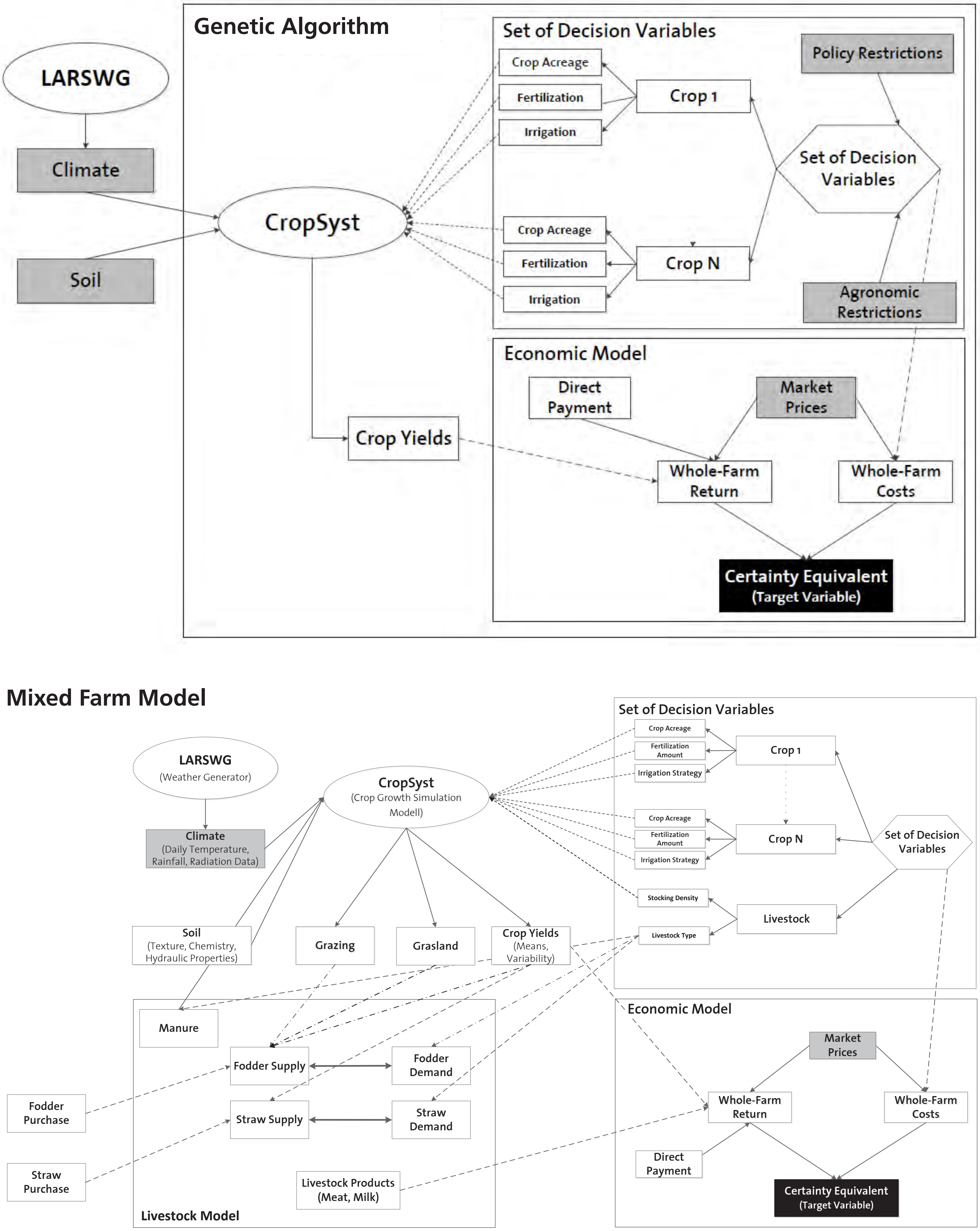


Figure 2.6.2.: Structure of the modeling system for arable farms (top) and mixed farms (bottom). At each iteration of the genetic algorithm (GA), a set of decision variables was generated for each individual. These decision variables were passed to CropSyst and used to simulate crop yields. Daily weather data needed as input data in CropSyst was provided by the LARS WG weather generator. The simulated crop yields were further passed to the economic decision model, where the farmer's certainty equivalent (CE) (i.e., target variable) was computed. The latter information was fed back into the GA. This procedure was repeated until the CE converged to a maximum value.

Table 2.6.1.: Revenues and costs	Winter wheat	Winter barley	Winter rapeseed	Grain maize	Potato	Sugar beet
Revenue						
Crop price levels (in CHF/t). Averages of the period 2002–2010 (Standard deviation in parentheses) [a]	506 (41)	372 (39)	787 (96)	371 (53)	456 (29)	66 (8)[b]
Direct payment						
Direct payment (CHF/ha) [c]	1680	1680	2680	1680	1680	3580
Fixed costs						
Seed (CHF/ha) [c]	218	143	108	268	3585	407
Plant protection (CHF/ha) [c]	265	265	250	220	800	525
Plant growth regulant (CHF/ha) [c]	41	41	0	0	0	0
Contract work and machinery costs (CHF/ha) [c]	783	783	787	844	2591	1409
Fixed irrigation costs						
Irrigation system costs (CHF/ha) [d]	447	447	447	447	447	447
Variable costs						
Nitrogen fertilizer (CHF/kg N) [c]	1.4	1.4	1.4	1.4	1.4	1.4
Other fertilizer costs (CHF/kg N) [c]	0.72	0.73	0.94	1.54	3.49	1.41
Hail insurance (% of crop yield revenue) [c]	2.4	2.4	5.6	3.6	2.4	2.4
Cleaning, drying costs (CHF/t) [c]	39.5	32.5	58.5	71.3	1.5	0
Other costs (CHF/t) [c]	6.7	1.2	16.3	0	0.5	12
Variable irrigation costs (CHF/[mm ha]) [d]	1.00	1.00	1.00	1.00	1.00	1.00
Interest rate (%) [c,e]	3.0	3.0	3.0	3.0	3.0	3.0

[a] Source: FAO (2011)

[b] Since in Switzerland in the year 2009 the reference sugar beet price decreased by more than 30 %, we used German sugar beet prices. In order to account for higher price levels of agricultural products in Switzerland, we multiplied the German prices by a factor of 1.3. This procedure ensured that mean prices and coefficients of variation remained as observed in Switzerland.

[c] Source: AGRIDEA and FIBL (2010)

[d] Source: Spörri (2011)

[e] The interest claim was computed as product of the interest rate and the invested capital (fixed costs, fixed irrigation costs, and variable costs) for an average commitment of 6 months.

Table 2.6.2.: Model constraints

Subject	Constraints imposed in the modeling approach	Sources
Crop acreage	The farmer is obliged to cultivate a minimum of four different crops. Winter wheat is limited to a maximum acreage of 50 %. The sum of all cereals (without grain maize) is limited to 66 % of the total arable surface. The maximum crop share of grain maize is 40 %. The maximum crop share of winter rapeseed, potato, and sugar beet is 25 % of the total surface.	Cross compliance obligations (BLW 2013).
Nitrogen use	Maximum yield-depended N amounts are specified for all crops, but N demand and supply have to be balanced at farm level. N fertilization amount for potato and sugar beet is restricted to a maximum of 150 kg/ha and 130 kg/ha, respectively.	Cross compliance obligations, following "Suisse Bilanz" (AGRIDEA & FIBL 2010). Higher N fertilization in potato and sugar beet is currently not applied in practice due to quality considerations (A. Zimmermann, personal communication).
Workload	The farmer's maximum available work time per season amounts to 2,800 h. We assumed a total workload of 41 h/ha for winter wheat and winter barley, 43 h/ha for winter rapeseed, 37 h/ha for grain maize, and 258 and 67 h/ha for potato and sugar beet, respectively.	Following current practices in Swiss arable farms, derived from AGRIDEA and FIBL (2010).
Field work days	Field work possibilities are restricted to half the days of the vegetation period (due to weather conditions) during 12 h/day. Vegetation period ranges from 220 days (current climate conditions) to 250 days (future climate conditions). The required field work time per crop was defined as follows: winter wheat, winter barley: 16 h/ha; winter rapeseed: 18 h/ha; grain maize: 11 h/ha; potato: 218 h/ha, and sugar beet: 27 h/ha.	Field work days from Luder (1996) and Musshoff and Hirschauer (2009). Vegetation period according to Calanca and Holzkämper (2010). Crop-specific field work time from AGRIDEA and FIBL (2010).

Table 2.6.3.: Soil profile and initial soil conditions at Payerne (Broye) and Uster (Greifensee)

Payerne

Depth (m)	**0–0.2**	**0.2–0.3**	**0.3–0.7**	**0.7–0.9**	**0.9–1.2**
Sand (%)	56.0	57.0	60.0	57.0	65.0
Clay (%)	14.0	11.0	10.0	10.0	12.0
Silt (%)	30.0	32.0	30.0	33.0	23.0
Organic matter (%)	2.8	2	2	2	2
NO_3 (kg N/ha)	5	5	5	5	5
NH_4 (kg N/ha)	5	5	5	5	5
Volumetric permanent wilting point (m^3/m^3)	0.105	0.094	0.090	0.090	0.097
Volumetric field capacity (m^3/m^3)	0.221	0.213	0.206	0.212	0.201
pH	7.1	7.3	7.7	8.0	8.2

Uster

Depth (m)	**0–0.20**	**0.20–0.45**	**0.40–0.86**	**0.80–1.0**	**1.0–1.2**
Sand (%)	52.6	59.2	58.2	74.4	86.0
Clay (%)	17.6	14.4	15.6	8.7	4.0
Silt (%)	29.8	26.4	26.2	16.9	10.0
Organic matter (%)	2.8	2.0	2.0	2.0	2.0
NO_3 (kg N/ha)	5	5	5	5	5
NH_4 (kg N/ha)	5	5	5	5	5
Volumetric permanent wilting point (m^3/m^3)	0.118	0.106	0.111	0.082	0.054
Volumetric field capacity (m^3/m^3)	0.236	0..217	0.222	0.176	0.134
pH	6.2	5.9	6.7	7.5	7.5

Following Lehmann and Finger (2012a), restrictions at the crop and farm levels that represent real-world constraints due to agricultural policy obligations, resource endowments, and crop quality were implemented in the optimization model (Table 2.6.2.).

Farm-scale modeling was performed for two farm types in both study regions:

- **Arable farms:**
  Broye (Payerne)
  30 ha of cropland (surface of grassland not considered); 6 crops: sugar beet, winter barley, grain maize, winter wheat, potato, winter rapeseed.
  Greifensee (Uster)
  30 ha of cropland (surface of grassland not considered); 6 crops: sugar beet, winter barley, grain maize, winter wheat, potato, winter rapeseed.

- **Mixed crop-livestock farms:**
  Broye (Payerne)
  30 ha total area; 9 crops: sugar beet, silage maize, winter barley, grain maize, winter wheat, potato, grassland, winter rapeseed, pasture; 4 livestock types: dairy cow, suckling cow, fattening veal, fattening bull
  Greifensee (Uster)
  30 ha total area; 9 crops: sugar beet, silage maize, winter barley, grain maize, winter wheat, potato, grassland, winter rapeseed, pasture; 4 livestock types: dairy cow, suckling cow, fattening veal, fattening bull

The soil data used for the simulations are summarized in the following Table 2.6.3.

2.7 Life Cycle Assessment (LCA)

The strategies described above were evaluated for their broad environmental impacts using Life Cycle Assessment (LCA).

"Environmental impacts" is a broad term covering many different aspects related to ecosystem quality, biodiversity, resource preservation, and greenhouse gas emissions, to name but a few. It is essential to consider as many relevant indicators of environmental impacts as possible in order to ensure that potential trade-offs between different aspects are captured and burden shifting is avoided (Van Der Werf & Petit 2002). LCA is a framework for assessing the environmental impacts of a product, process, or system, which considers the impacts of the entire "life cycle" (from resource extraction to processing and consumption to waste disposal). Multiple environmental indicators can be addressed in order to reflect a multi-criteria view of the generic term "environmental impacts". LCA thus enables identification of burden shifting along the life cycle and of trade-offs between environmental indicators. LCA has been found to be an adequate framework for assessing whole-farm environmental impacts.

The objectives of LCA at the farm scale were to:

- Evaluate the environmental impacts of farm adaptation scenarios to climate change in two case study regions in Switzerland
- Identify an optimal environmental impact indicator set in this context
- Identify trade-offs between environmental indicators and with the economic objectives of the adaptation scenarios
- Determine whether the adaptation scenarios also mitigate climate change (by reductions in their global warming potential)

The system boundary considered for the farm LCA was "cradle-to-gate", which included all inputs to the farm and each input's own life cycle impact as well as on-farm processes and direct emissions (such as field operations; pesticide, nutrient and greenhouse gas emissions; etc.). It did not include processing and consumption of products after the farm gate. The following input groups were considered based on the SALCA methodology for farm LCA (Nemecek *et al.* 2010, 2011):

- Infrastructure and machinery (e.g., stables, storage buildings, tractors, irrigation infrastructure, etc.)
- Energy carriers (e.g., diesel, electricity, etc.)
- Mineral fertilizers (e.g., mineral nitrogen, phosphate, potassium, etc.).
- Pesticides
- Seeds
- Water for irrigation (assumed to be river water) and animals (assumed to be tap water)
- Animals for herd replenishment
- Fodder (e.g., concentrated feeds as well as silage maize and hay in case of insufficient on-farm production)

On-farm processes included field operations, grain and hay drying, storage, and milking (in case of dairy cows); manure and slurry were applied only if sufficient on-farm quantities were available and if sufficient demand for application was present (i.e., first fertilization of arable crops, fertilization of grassland). Processes occurring after the farm production system were not considered (e.g., transport of products, processing, retailing).

Three functional units (FU) were used initially, representing the three main functions of agriculture:

- Gross profit margin in Swiss francs (CHF), representing the function of generating economic livelihood
- Megajoules digestible energy for humans (MJ dig. en.) produced, representing the function of production; this FU enables aggregation of different products into a single unit.
- Per ha*yr, representing the function of land management and occupation in view of optimizing land management of a certain area. However, results per ha*yr do not consider the productivity achieved by the scenario and, therefore, ignore consequential impacts caused by a potential decrease in productivity. In contrast, the FU MJ dig. en. reflects the double goal of minimizing impacts per area while maximizing productivity per area.

The FU CHF was available only at the farm scale, due to the explicit modeling of gross profit margin in the relevant model. However, results per CHF showed very similar trends to results per MJ dig. en. Therefore, at the farm scale, only the FU MJ dig. en. was retained for detailed result analysis. At the regional scale, both MJ dig. en. and ha*yr were retained, which enabled identification of potentially problematic impacts for a region when related to the area of the entire region, rather than to the amount of production.

Table 2.7.1. (page 24) lists the initial set of 13 environmental indicators used for assessment, based on their relevance for farm systems (Nemecek *et al.* 2011), their expected relevance in the study context (i.e., aquatic biodiversity), and the interest expressed by stakeholders (i.e., terrestrial biodiversity).

At the regional scale, LCA focused on the crop production level since animals and farm-specific management were not a major variable in the scenarios assessed, following the SALCA methodology for crop LCA (Nemecek *et al.* 2010, 2011). The system boundary was cradle-to-gate, thus including the farm inputs but not the processing and the consumption of products after the farm gate. Internal transport was, however, not considered, because the land use allocation in the regional model did not respect realistic farm structural constraints in any case, and therefore any assumption of transport from one farm to another was not possible. Emissions from livestock were included and were estimated using the relevant animal module for the SALCA farm methodology. This simplified form of agricultural LCA enabled the consideration of spatially explicit factors in the calculation of direct emissions for the LCA: these factors were crop rotation, slope, erosion, N-leaching (as provided by the regional agricultural models), and climate humidity class. The inventory of inputs and emissions for each pixel was then aggregated for the whole region using an area-weighted sum. Animal emissions as well as necessary fodder imports were added. This provided the inventory for the whole region. For inventory flows, which were not available from the regional optimization model, consistent assumptions were made based on inventories of farm reference models previously developed for Switzerland (Hersener *et al.* 2011) and on reference norms for Swiss agriculture (Flisch *et al.* 2009). Direct farm emissions (apart from erosion and N-leaching) were modeled using the SALCA models (Richner *et al.* 2006; Prasuhn 2006; Freiermuth 2006). Background inventory data was sourced from the SALCA database (Flisch *et al.*

Table 2.7.1.: Initial indicators considered

Indicator (impact category)	Method	Description	Important contributors in agriculture
Non-renewable energy demand	Ecoinvent (Frischknecht *et al.* 2004)	Direct and indirect energy resource use (including fossil resources and uranium)	Diesel, fertilizer production
Global warming potential (GWP) for 100 years	IPCC (2007a)	Emissions of carbon dioxide, dinitrogen oxide, methane	Fertilizer production, organic fertilizer application, animals
Tropospheric ozone formation potential	EDIP 2003 (Hauschild & Potting 2005)	Emissions of nitrogen oxides, volatile organic compounds	Exhaust gases
Acidification potential	EDIP 2003 (Hauschild & Potting 2005)	With and without regionalization	Animal emissions and fertilizer application
Freshwater eutrophication (FWE), marine eutrophication	ReCiPe (Goedkoop *et al.* 2009), EDIP 2003 (Hauschild & Potting 2005)	Nutrient enrichment of ecosystems due to emissions of nitrogen and phosphorous	Fertilizer application
Terrestrial eutrophication	EDIP 2003 (Hauschild & Potting 2005)	Nutrient enrichment of ecosystems mainly due to emissions of nitrogen	Animal emissions and fertilizer application
Aquatic ecotoxicity potential (AEP), terrestrial ecotoxicity potential (TEP), human toxicity potential	UseTox (using UseTox-recommended factors only) (Rosenbaum *et al.* 2008), CML (Guinée *et al.* 2001)	Toxic emissions to ecosystems and humans	Pesticide application, heavy metal emissions from fertilizers
Land use competition	Ecoinvent (Frischknecht *et al.* 2004)	Total land area and time occupied	Direct land occupation, fodder imports
Potential aquatic biodiversity loss (ABL)	Tendall *et al.* (2013)	Fish species richness loss due to on-site river water consumption	On-site irrigation
Reduction of potential terrestrial biodiversity (TBR)	SALCA Biodiversity (adapted) (Jeanneret *et al.* 2006)	Decrease in on-site potential terrestrial biodiversity relative to the best score achievable	Crop mix, fertilization intensity, stocking density

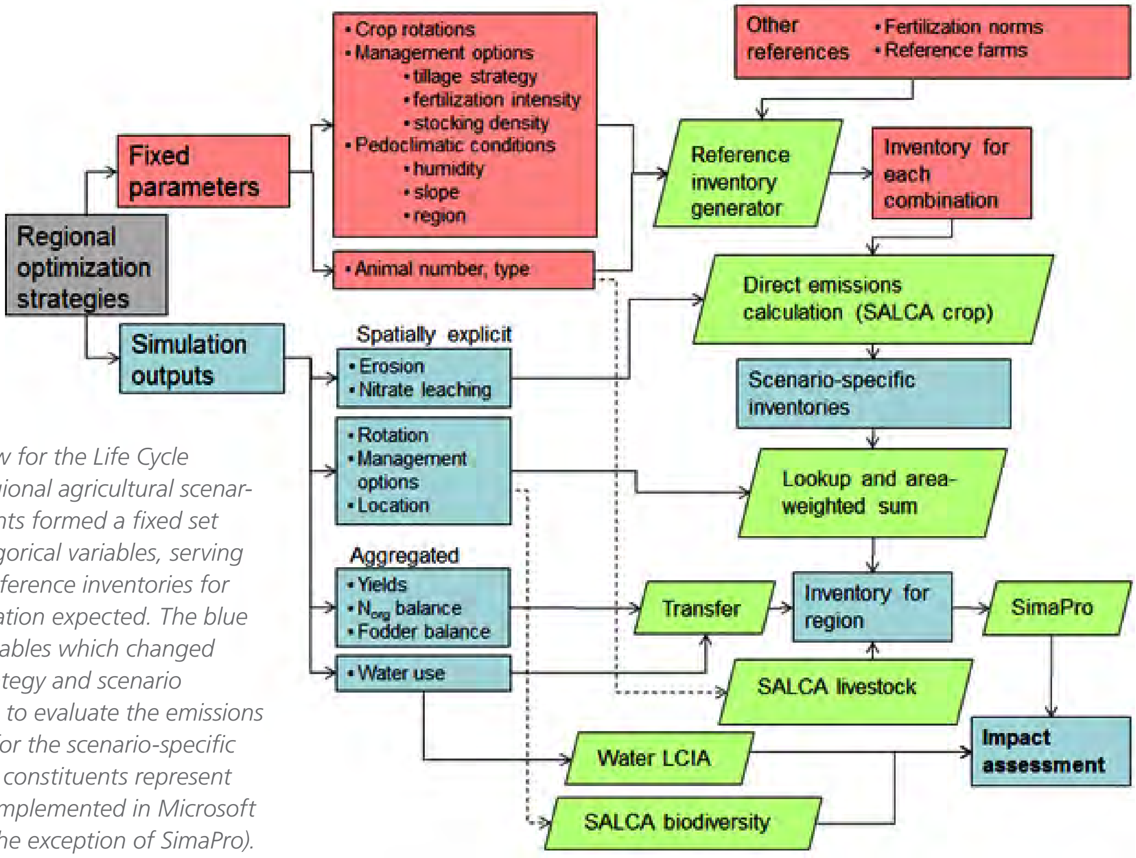


Figure 2.7.1.: Workflow for the Life Cycle Assessment of the regional agricultural scenarios. The red constituents formed a fixed set of reference and categorical variables, serving to establish a set of reference inventories for each possible combination expected. The blue constituents were variables which changed according to each strategy and scenario modeled. They served to evaluate the emissions of each combination for the scenario-specific conditions. The green constituents represent calculation modules (implemented in Microsoft Excel and VBA, with the exception of SimaPro).

Table 2.7.2.: Summary of scenarios considered at the farm and regional scales and correspondence with scenarios used in chapters 2.5 and 2.6. "Optimum" designates the economically optimized farm (i.e., maximizing the certainty equivalent) or the optimal strategy at the regional scale.

Scale	Scenario name (agricultural optimization models)	Scenario name (LCA)	Assumption
Farm	Reference	Reference	Optimum under current climate, prices, and subsidies
	CC2050, same crops	Ext2050 without adaptation	Same crops and animals as in reference, but under extreme climate scenario in 2050
	CC2050	Ext2050	Optimum under extreme climate scenario in 2050 (ETHZ simulation)
	-	Mod2050	Optimum under moderate climate scenario in 2050 (SMHI simulation)
	CC2050, PA14	Ext2050, subsidy change	Optimum under extreme climate scenario in 2050, with subsidy change
	CC2050, AUT	Ext2050, European prices	Optimum under extreme climate scenario in 2050, with product price change
	CC2050, water price	Ext2050, water pricing	Optimum under extreme climate scenario in 2050, with water pricing
	CC2050, water quota	Ext2050, water quota	Optimum under extreme climate scenario in 2050, with water quota
Region	Reference	Reference	Reference situation under current climate, similar to real current situation
	No adaptation	Ext2050 without adaptation	Same management as in the reference, but under the climate in 2050 (assuming an extreme climate change scenario)
	Productivity	Ext2050, productivity	Management maximizing the productivity (in terms of on-field yield of agricultural products in kg) under the climate in 2050
	Environment	Ext2050, preservation	Management minimizing erosion, N-leaching, and water use under the climate in 2050 (thus maximizing the preservation of the environmental resources soil, groundwater, and surface water)
	Compromise	Ext2050, compromise	Management for a weighted compromise between productivity and preservation
	-	Ext2050, productivity, ground water	Same scenario as in "Ext2050, productivity," but a part of the irrigation water is sourced from groundwater instead of river water
	-	Ext2050, productivity, shading 0.5	Same scenario as in "Ext2050, productivity", but the riparian shading factor of the river is increased to 0.5

2009) and from the Ecoinvent database (Ecoinvent 2010). Environmental impacts were then derived for the aggregated regional inventory using SimaPro (Pré Consultants 2013). The workflow for the regional-scale LCA, shown in Figure 2.7.1., was implemented in Microsoft Excel (2010) and in the VBA (Visual Basic for Applications) programming language in order to enhance compatibility with existing SALCA tools (which were likewise implemented in Microsoft Excel and VBA).

Environmental indicators at the farm and regional scales were selected using statistical methods that identified the set of indicators with the highest information content while reducing redundancy. This resulted in two partly different sets of indicators for the farm scale and the regional scale (due to differences in the modeling approaches applied at the two scales) (Table 2.7.2.). At both scales, global warming potential (GWP) and potential aquatic biodiversity loss (ABL) were retained; in addition, terrestrial ecotoxicity potential (TEP) and freshwater eutrophication (FWE) were retained at the farm scale, whereas reduction in potential terrestrial biodiversity (TBR) was retained at the regional scale.

An important adaptation option identified is the use of river water for irrigation, which may affect aquatic biodiversity. A corresponding impact assessment method, applicable for large spatial coverage, was developed using species-discharge relationships (Tendall *et al.* 2013, Figure 2.7.2.). An alternative approach was developed using river water temperature modeling. The use of groundwater and the riparian shading of the river were additionally assessed as alternative or complementary catchment management options.

The potential change in species due to a change in discharge was calculated using the derivative of the species-discharge relationship, assuming marginal changes in discharge. If assuming non-marginal changes, an average characterization factor could be used (indeed, the species-discharge relationships used were not linear over large ranges of discharge): the species loss per unit of discharge

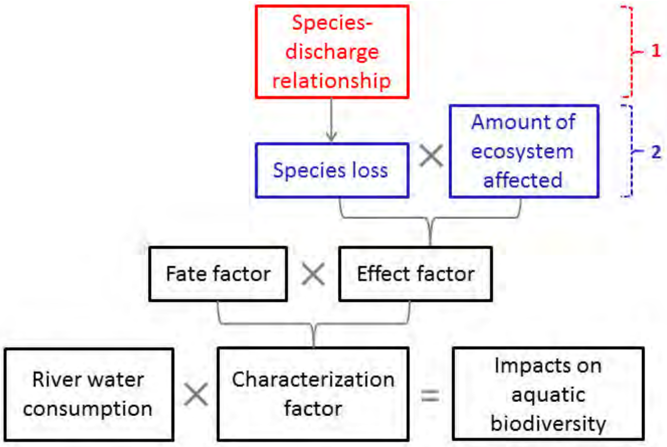


Figure 2.7.2.: Impacts of river water consumption on aquatic biodiversity were estimated using a characterization factor (CF). This CF consisted of a fate factor (FF, change in river discharge due to change in water consumption) and an effect factor (EF, change in species richness due to change in river discharge). The latter consisted of an estimate of species loss in a certain amount of ecosystem affected (time-volume). The species loss was estimated based on a species-discharge relationship (SDR). We addressed principally the EF by providing regionalized SDRs and SDRs for additional taxa and by testing an alternative regression function (component "1" in red); the new method for CF calculation used both a different SDR approach (in red) and a modified estimation of species lost and amount of ecosystem affected (component "2" in blue) (from Tendall et al. 2013).

reduction was estimated as the slope between the original species richness and zero (rather than the slope of the species-discharge relationship derivative at the original discharge, as used for the marginal characterization factor) and was therefore the average species loss over the entire discharge available.

$$CF_{nm,j} = \sum_{i=j}^{mouth} (\frac{SR_{Q_{0,i}}}{Q_{=0,i}} (RF_i \cdot TF_i)$$

where $CF_{nm,j}$ is the average characterization factor for a non-marginal withdrawal in zone *j*, aggregating impacts on all subsequent downstream zones, which are also non-marginally affected (in [GSE yr]/m^3) (GS=global species extinction equivalents, weighted by vulnerability; $SR_{Q_{0,i}}$ is the original species richness in zone *i* predicted using the species-discharge relationship with original discharge $Q_{0,i}$ in zone *i*; and RF_i and TF_i are the zone rarity and threat factors, respectively, for zone *i*. This characterization factor always gives a more extreme estimate than the marginal characterization factor. More details are given in Tendall (2013).

Watershed-level species-discharge relationships were developed specifically for Switzerland for fish and for a subgroup of macro-invertebrates consisting of ephemera, plecoptera, and trichoptera taxa (commonly referred to as EPT). EPT are generally regarded as sensitive to disturbances, and 62 % of Swiss EPT species are considered threatened or near threatened according to the IUCN Red List criteria (Lubini *et al.* 2012). Thus, the impacts of river water withdrawals (i.e., for irrigation) on both of these important components of aquatic biodiversity could be considered. The cumulative Weibull function was applied for the Swiss species-discharge relationships (Tendall *et al.* 2013).

2.8 Effects of groundwater withdrawals on groundwater level and related ecosystems

As a possible environmental impact mitigation strategy in the Broye region, it was assumed that the water requirements not provided by the river were sourced from the local aquifer, to the extent that the latter could provide these requirements entirely. For this scenario, a groundwater model was established for the Broye region, providing a water balance and groundwater head for climate change and irrigation scenarios (Gomez 2012). The aquifer extent is shown in Figure 2.8.1.

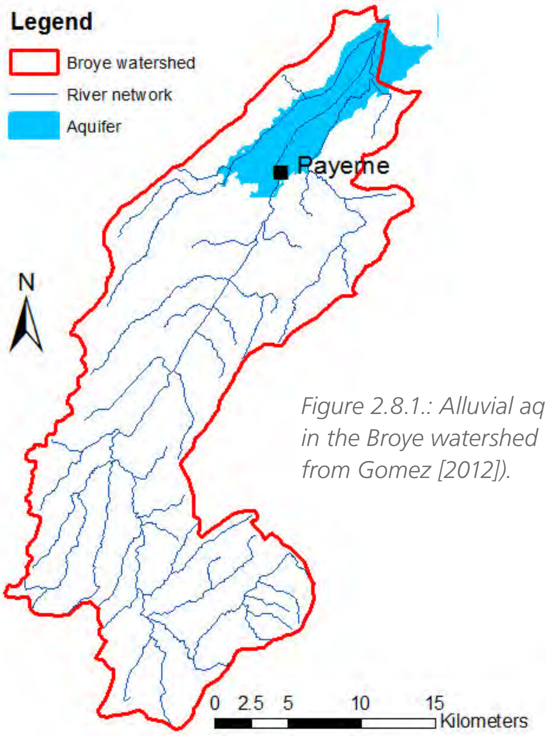


Figure 2.8.1.: Alluvial aquifer extent in the Broye watershed (adapted from Gomez [2012]).

This model was then coupled with an existing impact assessment method for groundwater withdrawals (Van Zelm *et al.* 2011) in order to include the impacts specifically occurring in this case. This impact assessment linked the drop in groundwater head with a potential effect on terrestrial plant biodiversity in the form of potentially disappeared fractions of plant species. The available effect factor was developed for the Netherlands but, since it was developed for plant species of temperate climate zones in Europe, was assumed here to be valid for Switzerland.

3 Results

3.1 Regional optimization of land management

3.1.1 Variability of model outputs

We first analyzed the sensitivity of indicators of three important agricultural functions, i.e., crop yield (production function), soil erosion (soil conservation function), and nutrient leaching (clean water provision function), to a wide range of agricultural practices for current and future climate conditions using two soil types:

- Sandy loam soil characterized by rather coarse texture with 65 % sand, 25 % silt, and 10 % clay
- Loamy soil characterized by a finer texture with 40 % sand, 40 % silt, and 20 % clay

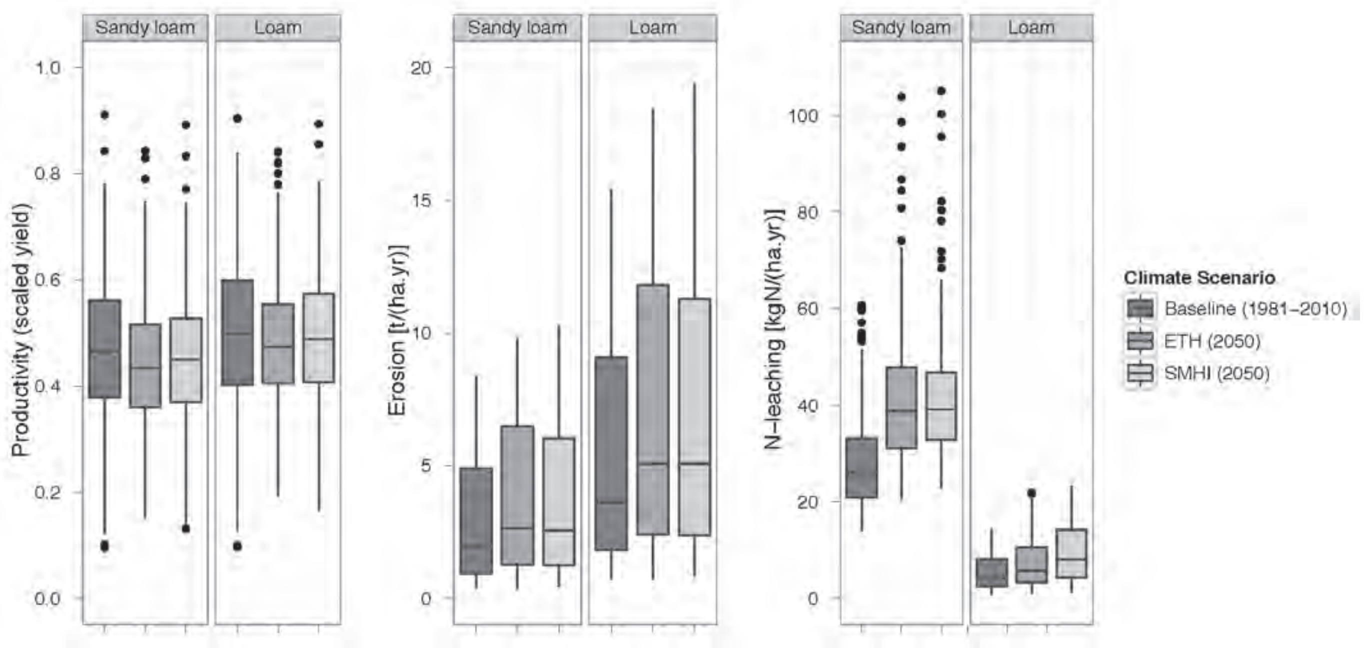


Figure 3.1.1.1.: Variability due to agricultural practices for two soil types and for two climate scenarios for 2050 (ETHZ and SMHI, A1B SRES emission scenario), relative to the baseline (1981–2010), for the. (a) Agricultural productivity (average scaled yield over rotation); (b) soil erosion; (c) N-leaching.

Relative to the reference, under climate change, productivity tends to decrease, erosion tends to increase due to shorter crop growth cycles and increased rainfall intensity in fall/winter, and N-leaching tends to increase as a consequence of a higher mineralization rate. However, productivity and soil loss due to erosion are highly variable not only with climate scenarios but also across cropping practices and soil types, suggesting that negative impacts of climate change can reduced through an adequate choice of management (Figure 3.1.1.1.). Erosion is much higher (+50 %) and more variable for loamy soil compared to sandy loam soil. Moreover, extreme values occur more frequently, but no outliers are found. The trend towards increased erosion under climate change is attributed to shorter growing cycles with more frequently uncovered soil in fall/winter, coinciding with increased precipitation intensity during this period of the year.

In contrast to productivity and soil erosion, variability of N-leaching across different sets of practices is very small. Indeed, simulated N-leaching is driven mostly by soil type, with high values on sandy loam soil and low values on loamy soil. In general, N-leaching increases under climate change due to enhanced organic matter mineralization as a consequence of higher temperatures, with values sometimes exceeding 100 kg N/(ha yr) on sandy loam soil.

3.1.2 Most suitable agricultural practices

Table 3.1.2.1. lists the combinations of practices identified for achieving best performances in terms of productivity, erosion, and N-leaching. Highest productivity is reached by highly fertilizing the crop rotation with sugar beet–silage maize–winter barley–maize–winter wheat under conventional soil management. Note that highest productivity is reached with identical sets of practices irrespective of soil type and climate scenario. Irrigation contributes to increased yield under climate change for this particular set of practices, especially in the case of sandy loam soil, where productivity increases by 48 % and 52 % with irrigation for SMHI and ETHZ, respectively, as compared to the same set of practices without irrigation. As expected, the amount of irrigation increases substantially under climate change. Conservation soil management, i.e., low soil disturbance and retaining of residues after harvest, leads to the lowest soil loss rates. The use of cropped grassland within rotations is also beneficial to reduce soil loss, although the effect is small compared to that of soil management, probably because only two years of grassland were included in

Table 3.1.2.1.: Most suitable agricultural practices for maximum productivity, minimum soil erosion, and minimum N-leaching. WW: winter wheat, WB: winter barley, MAI: grain maize, SMAI: silage maize, POT: potato, SB: sugar beet, WR: winter rapeseed, GRASS: cropped grassland, c: winter cover crop.

Loamy Soil

Climate change scenario	Crop rotation	Irrigation (m^3/[ha yr])	Intensity (kg N/[ha yr])	Soil management
Maximum productivity				
Baseline	SB SMAI WB c MAI WW c*	988	136*	Conventional*
ETHZ	SB SMAI WB c MAI WW c*	1,415	136*	Conventional
SMHI	SB SMAI WB c MAI WW c**	1,190	136*	Conventional
Minimum soil erosion				
Baseline	WW GRASS GRASS WW c MAI	0	188/5 cuts	Conventional***
ETHZ	WW GRASS GRASS SB WW	577	186/5 cuts	Conventional***
SMHI	WW GRASS GRASS SB WW	360	186/5 cuts	Conventional***
Minimum N-leaching				
Baseline	WR c MAI WW c MAI WW***	452	71	Conventional
ETHZ	WR c MAI WW c MAI WW***	865	64	Conventional
SMHI	WR c MAI WW c MAI WW***	637	64	Conventional

Sandy Loam Soil

Climate change scenario	Crop rotation	Irrigation (m^3/[ha yr])	Intensity (kg N/[ha yr])	Soil management
Maximum productivity				
Baseline	SB SMAI WB c MAI WW c*	986	136*	Conventional*
ETHZ	SB SMAI WB c MAI WW c*	1,383	136*	Conventional
SMHI	SB SMAI WB c MAI WW c*	1,213	136*	Conventional
Minimum soil erosion				
Baseline	WW GRASS GRASS WW c SMAI	0	188/5 cuts	Conventional***
ETHZ	WR GRASS GRASS SB WW	568	186/5 cuts	Conventional***
SMHI	WW GRASS GRASS WW c SMAI	0	186/5 cuts	Conventional***
Minimum N-leaching				
Baseline	SB MAI POT c MAI WW c***	831	58	Conventional
ETHZ	WR c SMAI POT c SMAI WB***	811	70	Conventional
SMHI	SB MAI POT c MAI WW c***	901	58	Conventional

Variance explained: 0.25*, 0.5**, 0.75***

the experimental plan. Regarding N-leaching, results differ strongly between soil types. On loamy soil, the most suitable crop rotation contains high proportions of winter wheat and maize (winter rapeseed–maize–winter wheat–maize–winter wheat). On sandy loam soil, the most suitable crop rotation also contains two years of maize but a lower proportion of winter wheat and a higher proportion of other crops (e.g., potato).

3.1.3 Trade-offs

To explore possible trade-offs between production and environmental impacts, we compared estimates of productivity, erosion, and N-leaching for the most suitable agricultural practices presented in Table 3.1.2.1. Results in Figure 3.1.3.1. reveal a strong trade-off between production and erosion/N-leaching. Suitable cropping practices for obtaining lowest erosion and lowest N-leaching are generally associated with medium or low productivity. Conversely, high productivity can be achieved only at the expense of high environmental impacts. Erosion is significantly higher on loamy soil because of higher runoff, whereas N-leaching is substantially higher on sandy loam soil due to higher infiltration, but similar yield levels are reached on both soil types. It appears that the conflicts between agricultural productivity and environmental impacts on soil erosion and N-leaching are likely to be aggravated by climate change (Klein *et al.* 2013a).

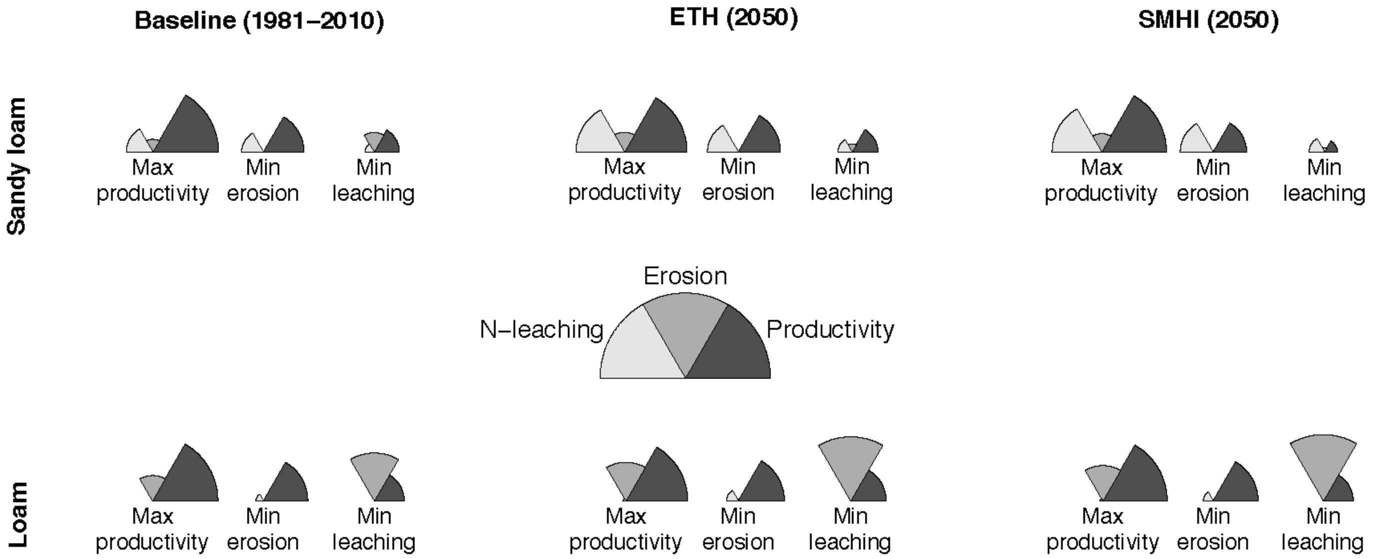


Figure 3.1.3.1.: Trade-offs reached under the most suitable adaptation strategies (Table 3.1.2.1.) to achieve best performance with respect to the different indicators.

Results show a positive impact of residues removal on productivity, which is in contrast to the view that management decisions like no-till and returning crop residues to the field increase soil organic matter content. Residues removal improves infiltration and soil water retention and thus helps to maintain soil fertility and increase the resilience of cropping systems to climate change. However, the positive effect of conventional soil management is short-lived as CropSyst simulates a decline in soil fertility in the long term.

Overall, for the Broye region, the use of cropped grassland in combination with conservation soil management appears to be the most judicious choice to maintain productivity and avoid conflicts with erosion and N-leaching. Rotations including a grass/legume crop can be beneficial for productivity as grassland serves as a good pre-crop and a high proportion of grassland also reduces erosion and N-leaching. Conservation soil management prevents excessive soil erosion and soil organic matter loss thus maintaining soil fertility in the long run. Moreover, conservation soil management improves water quality protection. Indeed, N-leaching is substantially reduced on sandy loam soil due to reduced mineralization, while the decrease in runoff and thus increase in permeability due to this management type have low effects on a soil that is already very permeable and prone to N-leaching. As a downside of conservation soil management, productivity is decreased under current climatic conditions due to reduced mineralization. However, under climate change, this effect is smaller, which indicates that the synergistic effects of conservation soil management could increase in the future.

In comparison, the Greifensee region is less subject to conflicts than the Broye region, but the room for adaptation is more limited. Erosion is generally lower than in the Broye region due to smoother topography, and therefore management plays a minor role in limiting soil losses. In addition, it has been shown that N-leaching does not vary much with management, which is particularly the case in the Greifensee region. Indeed, N-leaching is expected to increase compared to the baseline regardless of the adaptation option (even with the “environment” solution).

3.1.4 What is the impact of climate change without adaptation?

Without changes in agricultural land management, aggregated regional yield of crops in both catchments will decrease in parallel with an increase in environmental impacts and, in the Broye region, an increase in water needs (Figure 3.1.4.1.). Thus, in order to cope with increasing environmental pressure on water resources, adaptation is particularly needed in the Broye region either through the adjustment of agricultural practices (e.g., crop rotations, tillage operations, etc.) or through the redistribution of agricultural land use.

3.1.5 What are the effects of different adaptation strategies?

A wide range of adaptation options exist depending on the objectives (goals) to be achieved. These were grouped into 16 clusters (as shown for the Broye region in Figure 3.1.5.1.), from which those clusters representing the three main objectives were selected. Acceptable solutions can be identified as “compromise” solutions (clusters 11 and 16), with one of them (cluster 16) performing much better than the reference (1981–2010) with regard to three of the four objectives for both climate scenarios. The only objective that cannot be improved in the Broye region is water

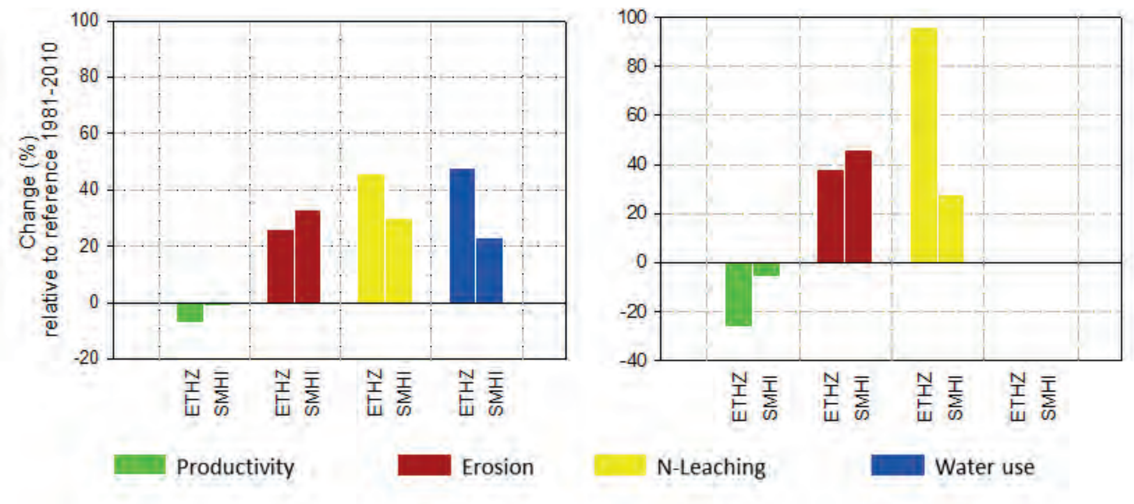


Figure 3.1.4.1.: Impact of climate change scenarios on different agricultural functions in the case of "'no adaptation" to climate change. Left: Broye region; right: Greifensee region.

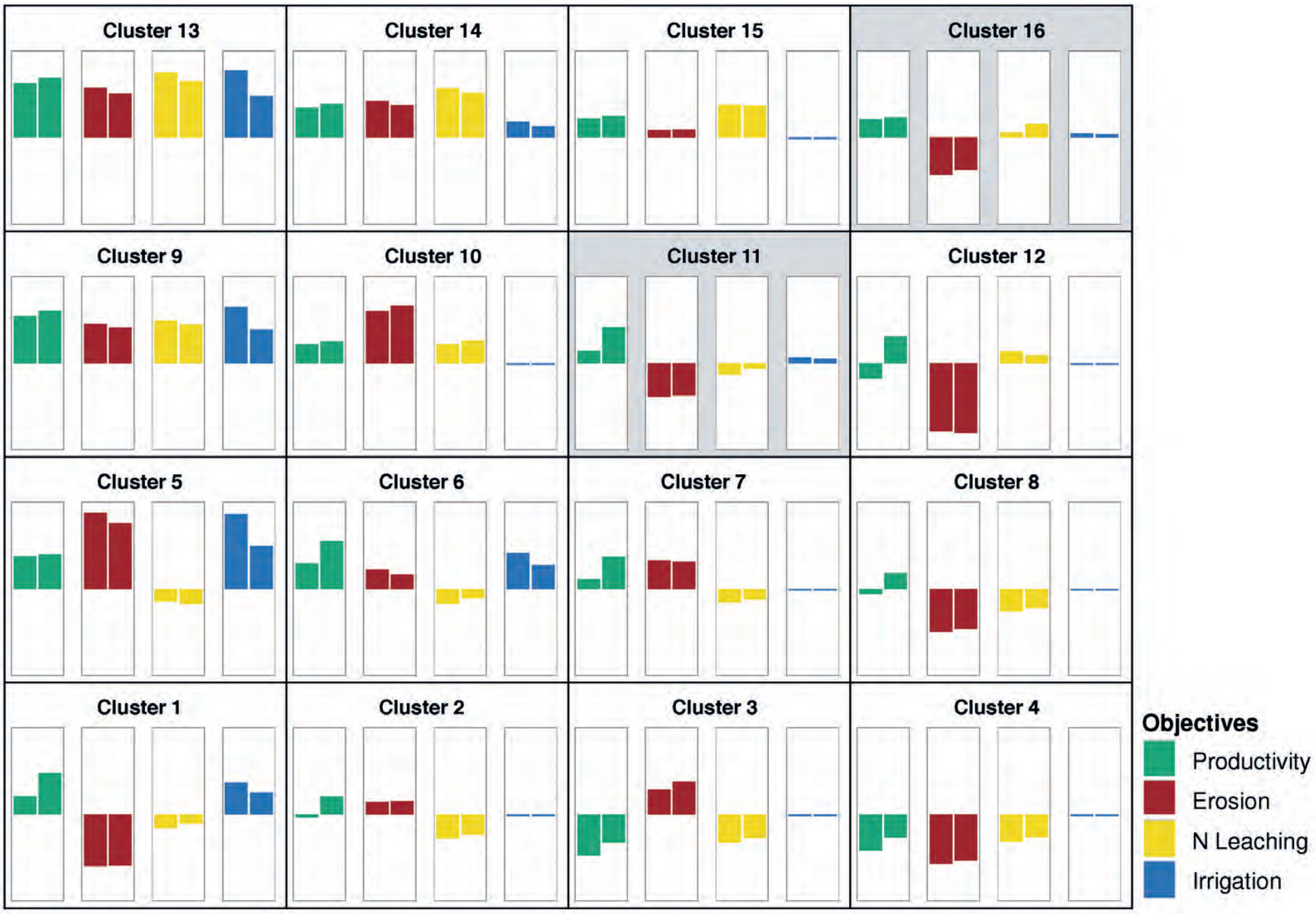


Figure 3.1.5.1.: Impacts for the Broye region of climate change with adaptation (left: ETHZ 2050, right: SMHI 2050), expressed as change relative to the reference (1981–2010), for the 16 solutions closest to the clusters' centroids defined by SOMs (Self-organizing Maps); to facilitate the graphical interpretation, different scales are used for the objectives, but scales are identical across clusters to compare the latter qualitatively (a quantitative analysis can be found in the text); the two "compromise" solutions are highlighted with gray background.

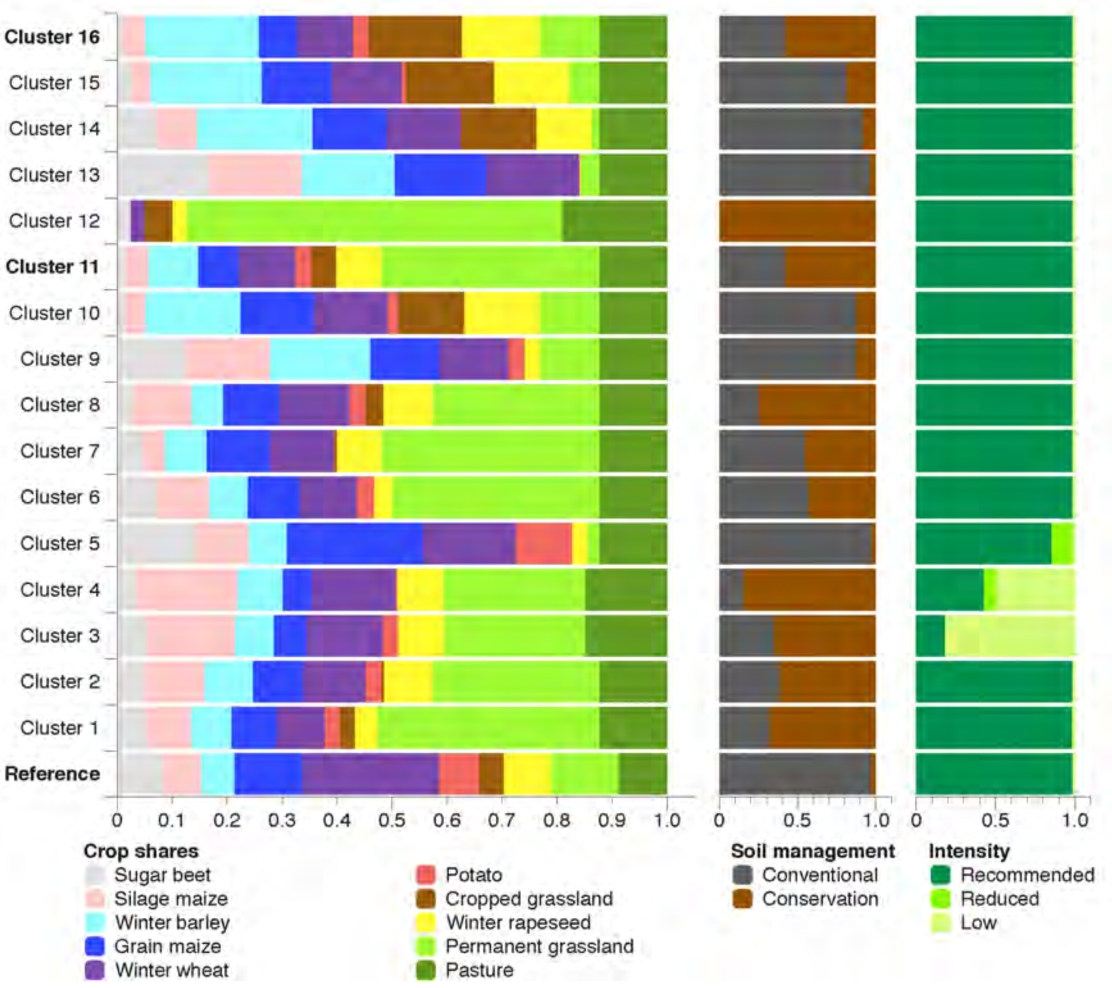


Figure 3.1.5.2.: Proportion of area of management for the reference and for each cluster.

saving due to a substantial increase in water needs, which, nevertheless, remain below available surface water on average (see below).

Mean proportions of area allocated to different agricultural practices are represented in Figure 3.1.5.2. for each cluster separately. Land management differs much across the different clusters. For instance, a high proportion of permanent grassland in combination with conservation soil management is necessary to minimize erosion (cluster 12). Best performance with regard to productivity (cluster 13) is achieved with conventional soil management and a crop mix of a few crops (i.e., heavily irrigated sugar beet, silage/grain maize, winter barley, and winter wheat). To minimize N-leaching (clusters 3 and 4), the sequence silage maize – winter wheat with low fertilization is best in order to ensure constantly low soil N concentrations with high N uptakes due to deep rooting systems and short fallow times.

If aggregated productivity is the main objective, then nearly all grassland of the Broye region should be converted to cropland with high shares of irrigated maize and sugar beet. In these conditions, cropping will expand into higher regions due to more favorable temperatures, and thus aggregated crop yields will increase compared to the current level. However, consequences for the environment will be disastrous, leading to an increase in soil loss and N-leaching (Figure 3.1.5.3.). Furthermore, irrigation will strongly increase, regularly exceeding the average surface water availability during summer months. In the Greifensee region, irrigation is required only in the “productivity” scenario. In contrast, if the main objective is to reduce environmental impacts, then yield will decrease in both regions, while N-leaching will nevertheless increase in the Greifensee region.

The selected “compromise” solution (cluster 16) indicates that yield will be higher with adaptation than without adaptation, but without increasing negative impacts on other functions. In the Greifensee region, however, soil loss and N-leaching remain higher than in the reference, even with the “compromise” solution (Figure 3.1.5.3.).

The three solutions lead to different land use patterns as compared to the reference. Figure 3.1.5.4. for the Broye region shows that the “compromise” solution projects more permanent grassland in the lower part of the catchment and more pasture in the higher southern parts. In terms of the crop mix, the “compromise” solution reveals a higher

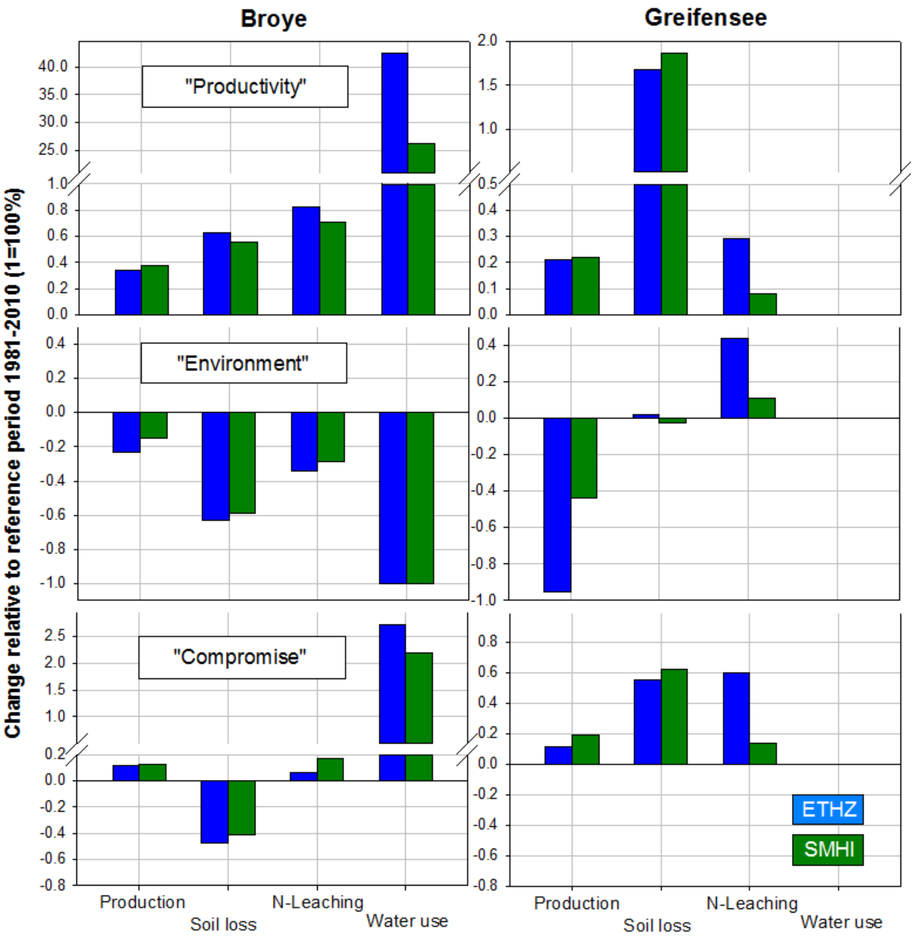


Figure 3.1.5.3.: Implications of three different strategies on selected agricultural functions, aggregated for the entire catchments. Greifensee: Irrigation increase under "productivity" is not plotted. Note the different scales (Y-axis).

share of winter crops and grassland as compared to the "productivity" solution.

In terms of management, the "productivity" solution leads to a higher fraction of irrigated land compared to the reference, which is managed mostly conventionally and intensively (Figure 3.1.5.5.). In contrast, reduced soil management and higher share of land with low and medium intensity characterizes the "environment" solution. The "compromise" solution is characterized by a moderate share of irrigated land, high intensity management, and a substantial fraction of land under conservation soil management to reduce the risk of erosion in the hilly parts of the region.

Simulated changes in land use patterns with or without considering a scenario for urban expansion in the Greifensee catchment are shown in Figure 3.1.5.6. Whereas the "environment" solution produces much more grassland, the "compromise" solution produces a situation with more crops in the higher southern part and more grassland in the lower part, particularly near Lake Greifensee. However, the share of grassland in the latter is reduced, while in terms of crop mix, the difference between the "compromise" and the "productivity" solutions is small, although the latter requires higher management intensity and a lower fraction of conservation soil management.

3.1.6 Water demand vs. availability

The different strategies lead to different amounts of potential water consumption. On average, irrigation needs are always below the availability with the "compromise" but not with the "productivity" solution. For the latter, the water available in the Broye river (measured at the gauge Payerne) would not be sufficient under climate change (ETHZ) during the summer months. Irrigation needs are higher with ETHZ than SMHI (not shown). About 10 % of all agricultural areas are irrigated for the "compromise" solution (Figure 3.1.6.1.), with irrigated areas almost exclusively located around the city of Payerne (i.e., at low elevation with high air temperature) on sandy loam soils with low water retention capacity.

The following Table 3.1.6.1. shows that the frequency of the monthly water requirement exceeding the available water in the Broye river is low with the "compromise" solution but considerably higher with the "productivity" solution. In the worst case, by 2050 the potential water demand exceeds the available water in rivers in the Broye region during June and July in 4 out of 10 years.

Table 3.1.6.1.: Frequency (in %) of the monthly exceedance of water resources in the Broye catchment (aggregated values for 2050 (2036–2065)

	"Compromise"		"Productivity"	
	ETHZ	SMHI	ETHZ	SMHI
April	0	0	0	0
May	0	0	15	5
June	0	0	40	15
July	15	0	40	40
August	15	0	20	15
September	0	0	0	0

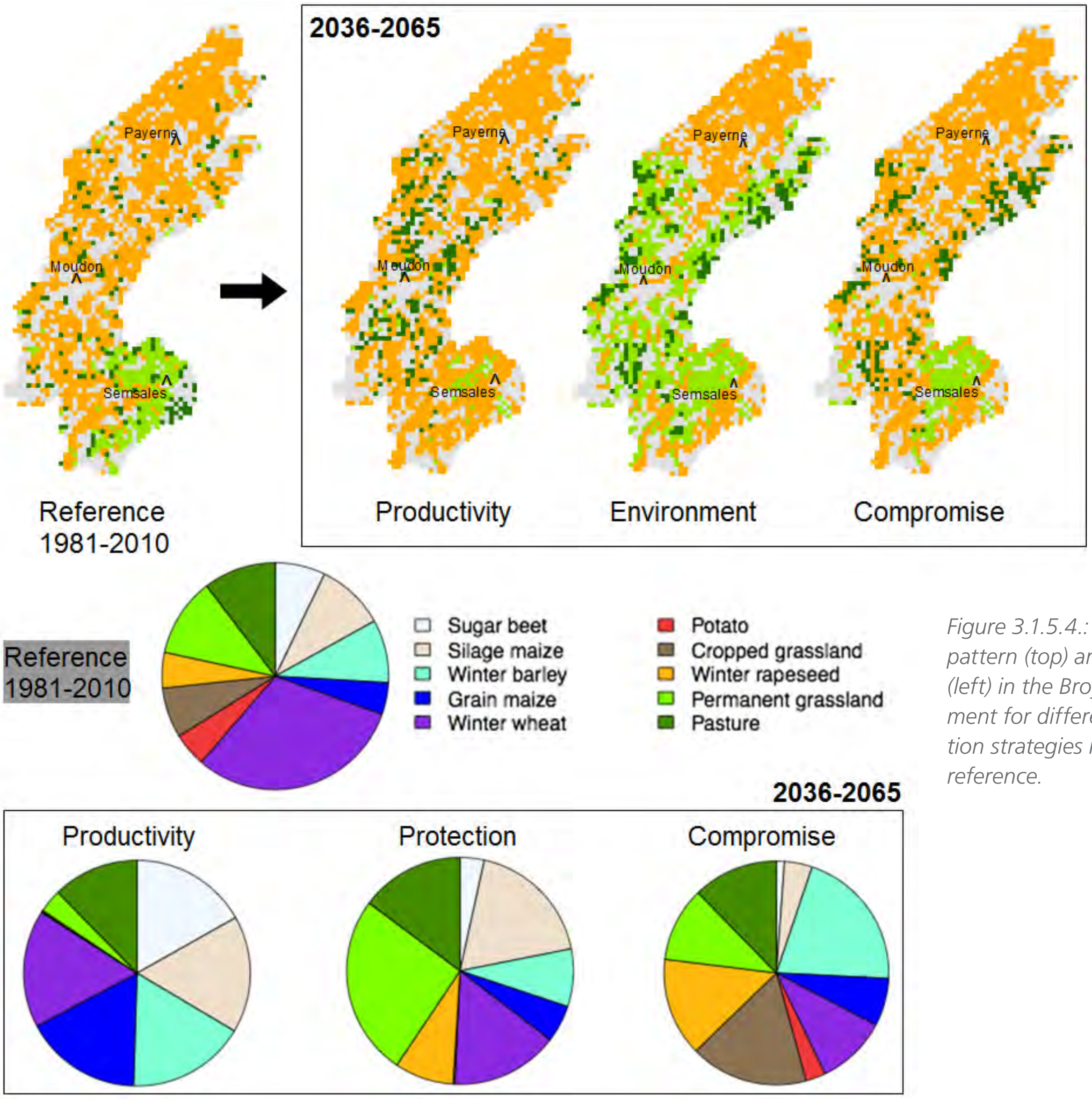


Figure 3.1.5.4.: Land use pattern (top) and crop shares (left) in the Broye catchment for different adaptation strategies relative to the reference.

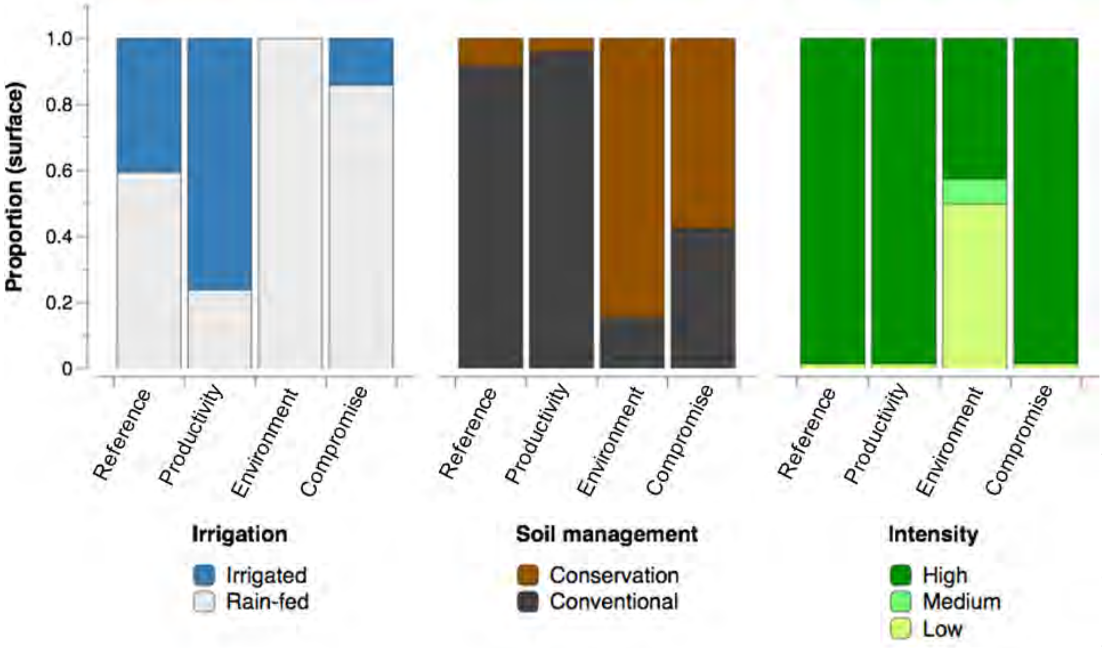
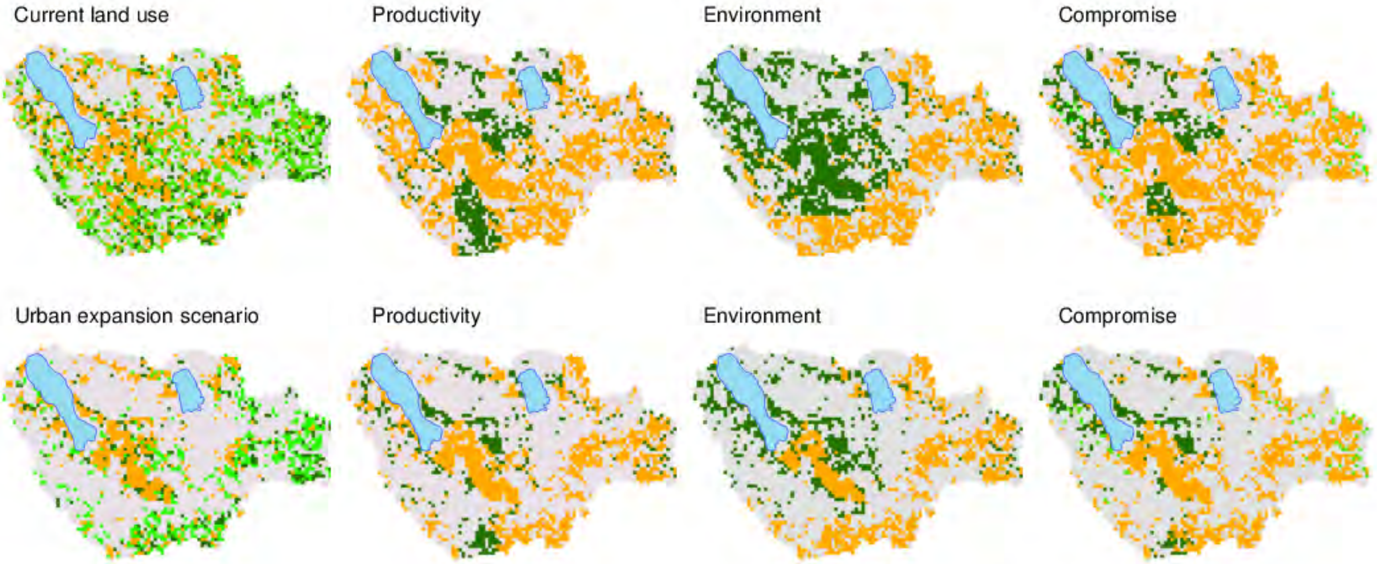


Figure 3.1.5.5.: Land fraction with different types of management in the Broye region for the different strategies (2036–2060) and for the reference period.



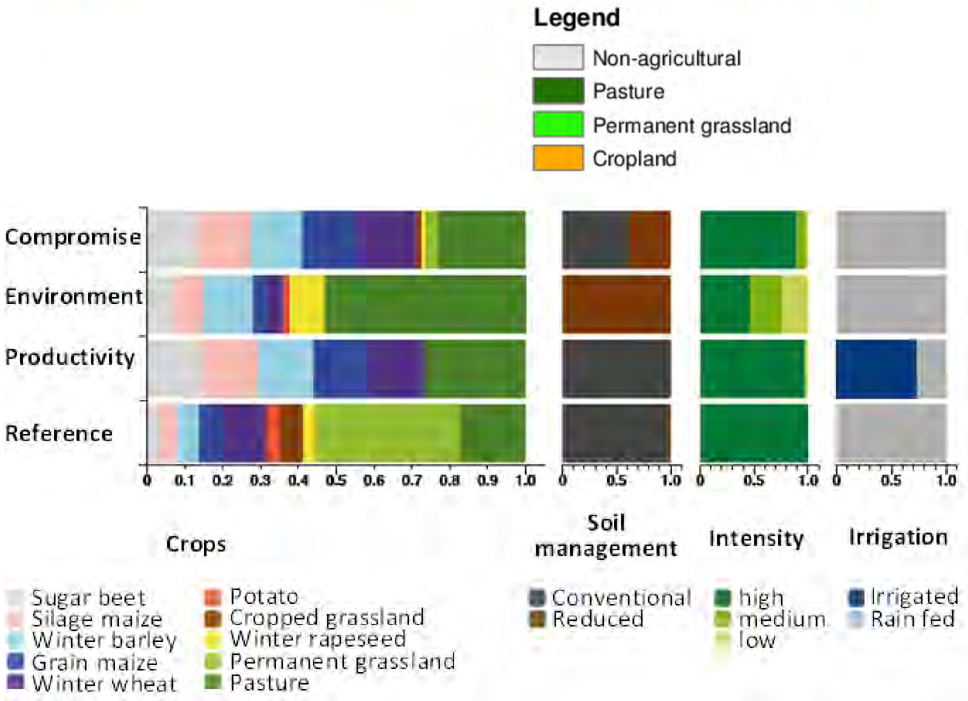
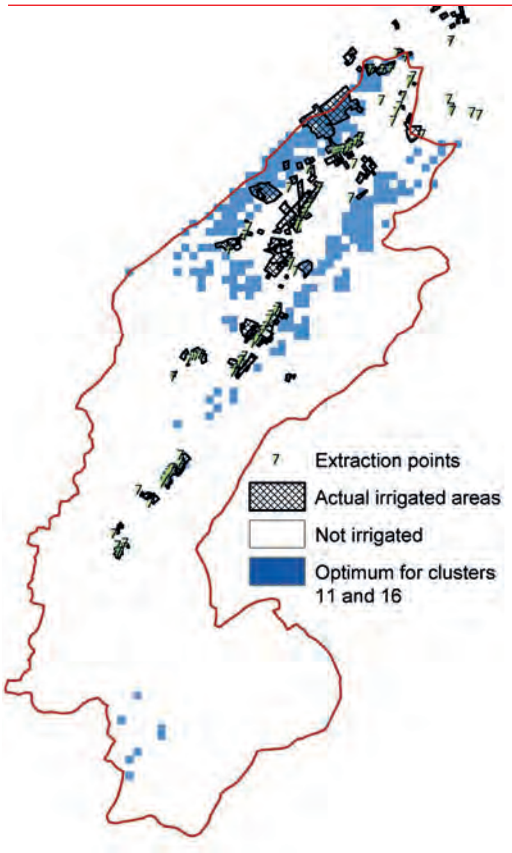


Figure 3.1.5.6.: Land use patterns (top) and crop mix and management options (right) for the different adaptation strategies in the Greifensee catchment. The data in the lower panel reflects the scenario without urban expansion.

3.1.7 Sub-regional analysis

Implementation of the "compromise" solution across an entire catchment may not be realistic due to small-scale differences in environmental and topographic conditions. For instance, to use irrigation in the entire catchment of the Broye to boost production would require extensive new infrastructures for widespread supply with water. Hence, in the case of the Broye catchment, a sub-regional analysis was performed for the three climatic zones. The results are shown in Figure 3.1.7.1. The analysis reveals that intensive crop production will be limited to the sub-region around Payerne. On sandy loam soil, main crops are winter barley, winter rapeseed, potato, and silage maize. Irrigation will be limited to this soil type. Erosion in this sub-region will be low due to the flat topography, but N-leaching will remain considerable, in contrast to the situation with loamy soil, where grain maize and winter wheat production are important, and irrigation will not be necessary. In the intermediate zone around Moudon, a higher share of grassland (pasture, permanent grassland, and cropped grassland) will dominate together with winter barley on sandy loam soil, and grain maize will be important on loamy soil. In the hilly area around Semsales, crop production favored by climate change will be limited to loamy soil. Intensity will largely be unchanged in all sub-regions, but conservation soil management will be more important in the sub-regions of Moudon and Semsales than in the sub-region of Payerne.



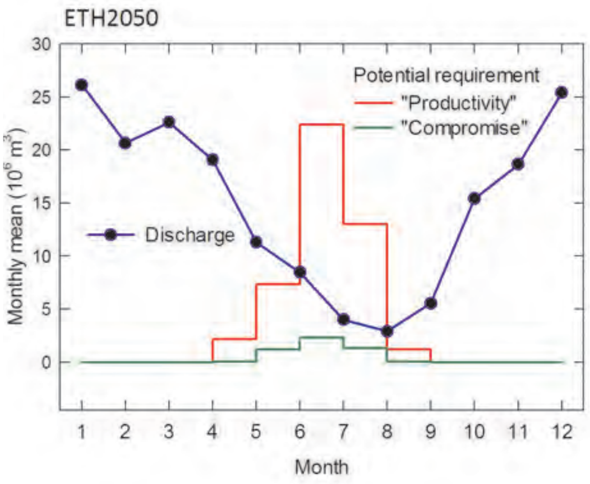


Figure 3.1.6.1.: Mean monthly discharge of the Broye river at Payerne compared to the potential water requirement for irrigation for the "productivity" and "compromise" solutions. Data for scenario ETHZ. Left: Distribution of irrigated areas under current climatic conditions and for the "compromise" solution.

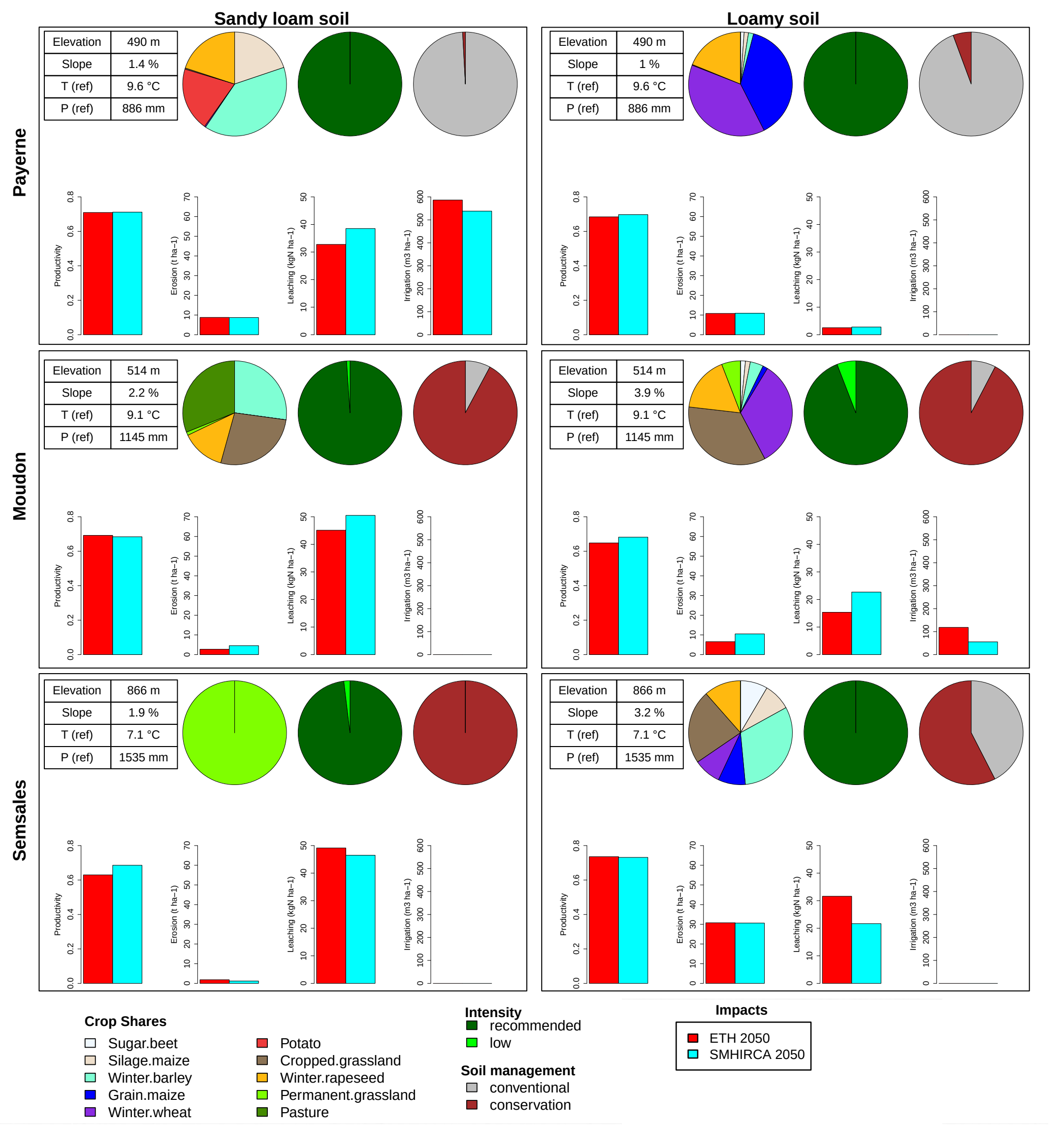


Figure 3.1.7.1.: Analysis of crop shares and environmental impacts, including irrigation, in three subregions of the Broye catchment for the case of the "compromise" solution.

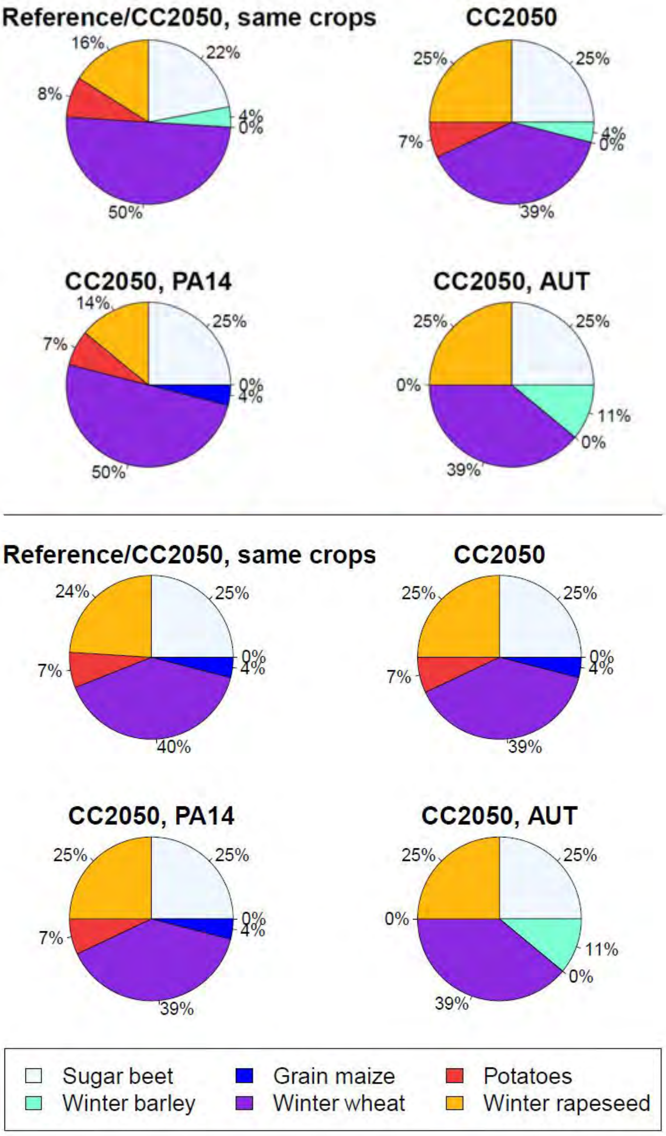


Figure 3.2.1.1.: Changes in the optimal crop mix of an arable farm in the Broye (top) and Greifensee (bottom) regions under different climate, price, and policy scenarios.

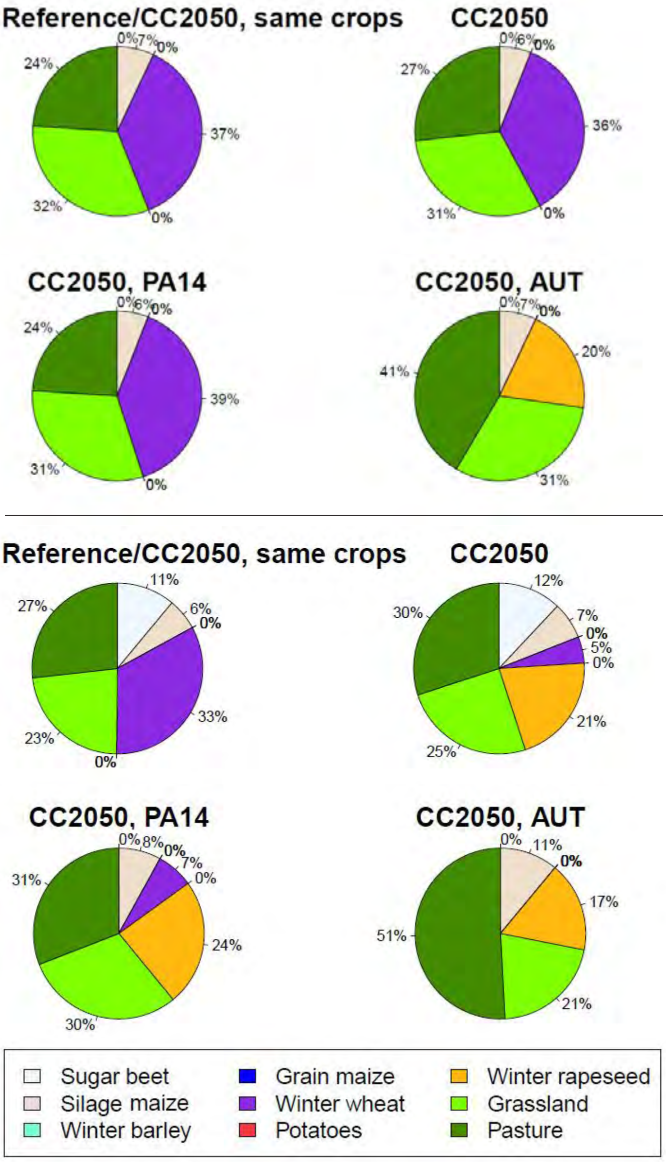


Figure 3.2.1.2.: Changes in the optimal crop mix of a mixed farm in the Broye (top) and Greifensee (bottom) regions under different climate, price, and policy scenarios.

3.2 Economic farm-scale model

3.2.1 Crop shares

The effect of the different scenarios on the land area allocated to different crops on arable farms is shown in Figure 3.2.1.1. In the Broye region, climate change generally promotes the cultivation of winter rapeseed because climate change has almost no negative impacts on average yield levels of this crop, and production of oil crops is highly subsidized. Furthermore, under climate change, grain maize is marginal or absent in an optimal crop mix. This is due mainly to the relatively low profit margin in grain maize production compared to the other crops and to the region's dry climate conditions in mid-summer months. Irrigation of maize, however, is not as profitable as it is for high-value crops, such as potato and sugar beet.

In the Greifensee region, shifts in optimal crop mix are mostly absent, and climate is not the driving force of crop land uses. In the first three scenarios, implemented constraints lead to almost identical land use schemes. Winter rapeseed and sugar beet are subsidized highly, and these crops are thus present in all scenarios at upper limits. If lower crop prices are assumed (AUT), grain maize and potato disappear, while winter barley takes over because of a smaller relative price decrease. PA14 has only a small effect on the optimal land use.

In both regions, largest shifts in the crop mix occur under the European price scenario, thus demonstrating the stronger effect of policy versus climate change.

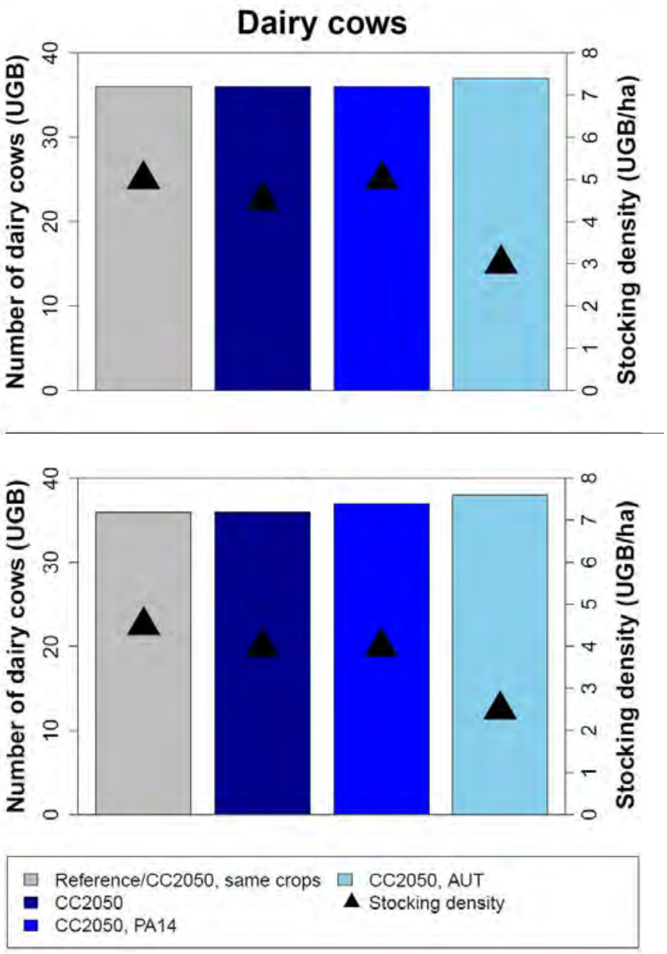


Figure 3.2.1.3.: Number of dairy cows and stocking density in the Broye (Payerne, top) and Greifensee (Uster, bottom) regions.

Under the reference scenario representing current climate conditions and Swiss prices of agricultural outputs, it is optimal for a mixed farm to focus on dairy cow production. In doing so, most of the farm's agricultural surface is used for animal feed production (i.e., grassland, pasture, and silage maize) and for the cultivation of winter wheat. Furthermore, only silage maize is irrigated in an optimal solution in the reference scenario. It is important to mention that for simulations of mixed farms, it was assumed that climate change has no direct impact on dairy cow productivity, i.e., a dairy cow produces the same amount of milk under climate change as under current climate conditions. This assumption ignores potential negative impacts of heat stress. With this assumption, dairy cow production remains the most beneficial livestock activity for the mixed farm in all considered climate, price, and policy scenarios.

As shown in Figure 3.2.1.2., the optimal solution of the livestock model is driven by selected kind and number of livestock, and thus much of the agricultural surface must be used to produce feedstuff for the selected livestock. In both regions, under the low-price scenario (AUT), the number of cows increases while the stocking density decreases (Figure 3.1.2.3.). Hence, more grassland is needed for feedstuff production. As for the arable farm model, with climate change, winter rapeseed becomes more profitable than winter wheat.

3.2.2 Intensity of production

In the Broye region (Figure 3.2.2.1., page 38), climate change leads to a decrease in fertilization intensity of almost all crops but to an increase in irrigation intensity for potato, sugar beet, and grain maize. With PA14, changes are small compared to CC2050, but with the low-price scenario (AUT), optimal fertilization intensity is decreased strongly. Under the latter scenario, irrigation of sugar beet is still profitable because of low assumed variable water costs and Swiss price levels of sugar beet are already close to European price levels.

On the mixed farm, climate change causes increased fertilization and irrigation intensities in silage maize production. (Note that yield of silage maize increases by about 14 % in the CC2050 scenario compared to the reference scenario.) Also, grassland will be irrigated under climate change leading to an increase in grassland yields by about 10 %. Compared to CC2050, PA14 causes only small changes, whereas the low-price scenario (AUT) reduces the optimal fertilization intensity. Under the latter scenario, irrigation of grassland is abandoned, because fixed costs of irrigation systems become too high. Moreover, winter rapeseed is produced with no additional fertilizer, because fertilizer costs are high (from a relative perspective and compared with crop prices) and soil's nitrogen availability is generally increased under climate change due to high soil temperatures leading to increased mobilization of nitrogen.

In the Greifensee region, with climate change, fertilization intensity decreases in almost all crops, and irrigation increases in sugar beet, whereas grain maize is never irrigated. Results for PA14 are identical to those for CC2050. Low crop prices (AUT) lead to a very intensive production scheme, and irrigation of sugar beet is profitable because of the low water price. Furthermore, Swiss price levels of sugar beet are close to European price levels.

For the mixed farm, the results in Figure 3.2.2.2. (page 39) show that apart from sugar beet, which is irrigated under the CC2050 scenario, none of the crops is irrigated under climate change, and climate change effects on optimal fertilization intensity are rather small, but cultivation tends to be less intensive.

With respect to irrigation, the key results concern the Broye catchment. As shown in Figure 3.2.2.3. (page 40), irrigation is already under current climate and crop price conditions a profitable management option for the cultivation of grain maize, potato, and sugar beet and is well in

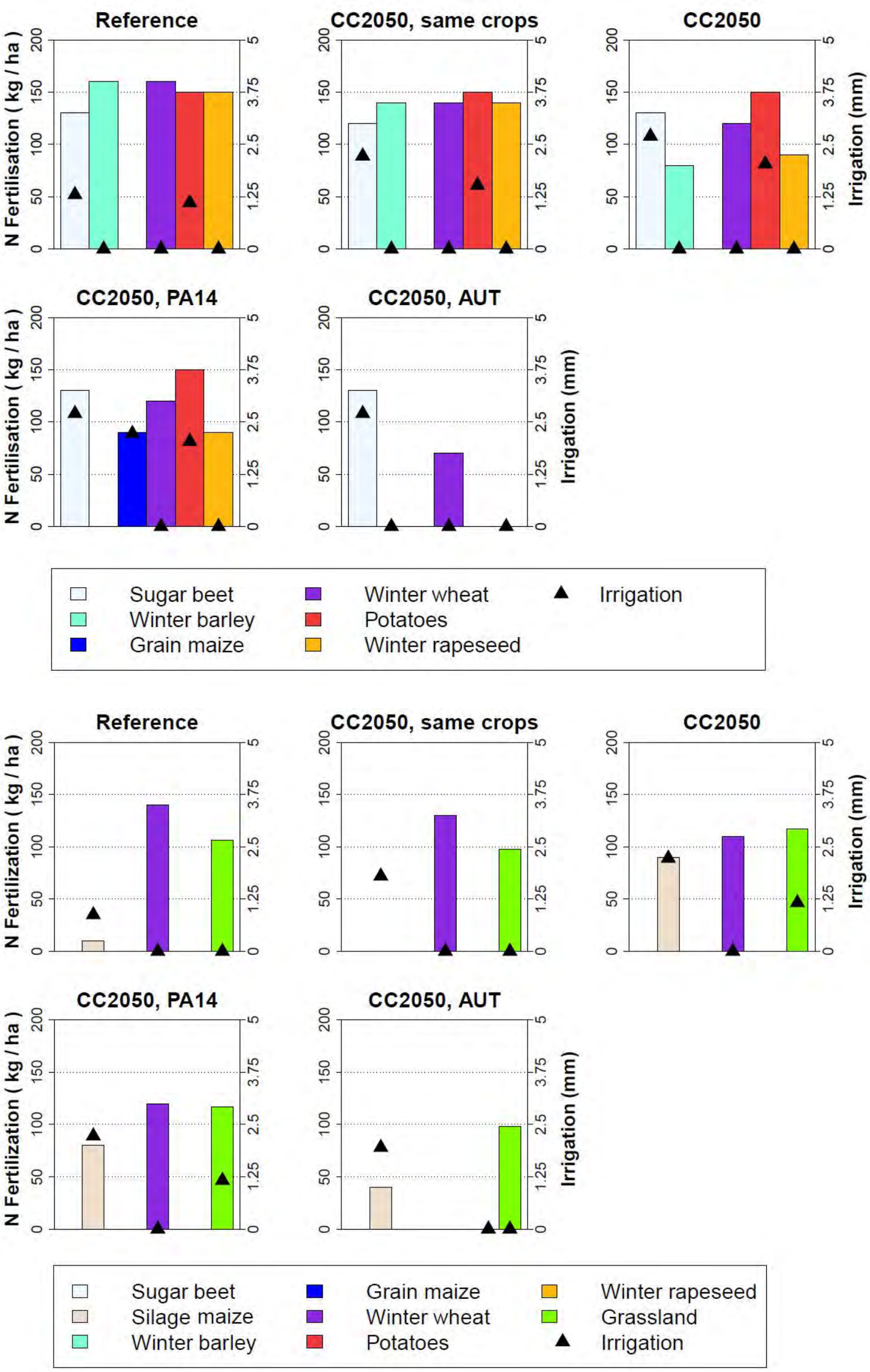


Figure 3.2.2.1.: Optimal irrigation and nitrogen fertilization strategy in the case of an arable farm (top) and a mixed farm (bottom) in the Broye region.

line with the observed situation. Assuming expected climate conditions for 2050, water consumption in arable farming can be expected to further increase by 30 % to 100 % at the farm level. This increase is due solely to increased water requirements for the production of potato and sugar beet. For other crops that are currently rain fed, such as winter cereals and winter rapeseed, irrigation under warmer and drier climate conditions will not give an advantage from an economic point of view. Thus, the irrigated surface will not necessarily increase.

For the mixed farm, water use increases by a factor of 8 under climate change, but agricultural income is at a high level if irrigation is possible. Thus, effects of climate change, and of price and policy scenarios, are much smaller in the case of the mixed farm as compared to the arable farm.

In the Greifensee region, a crop farm's water consumption also increases under all applied climate change scenarios, but the farm's absolute water consumption is much lower

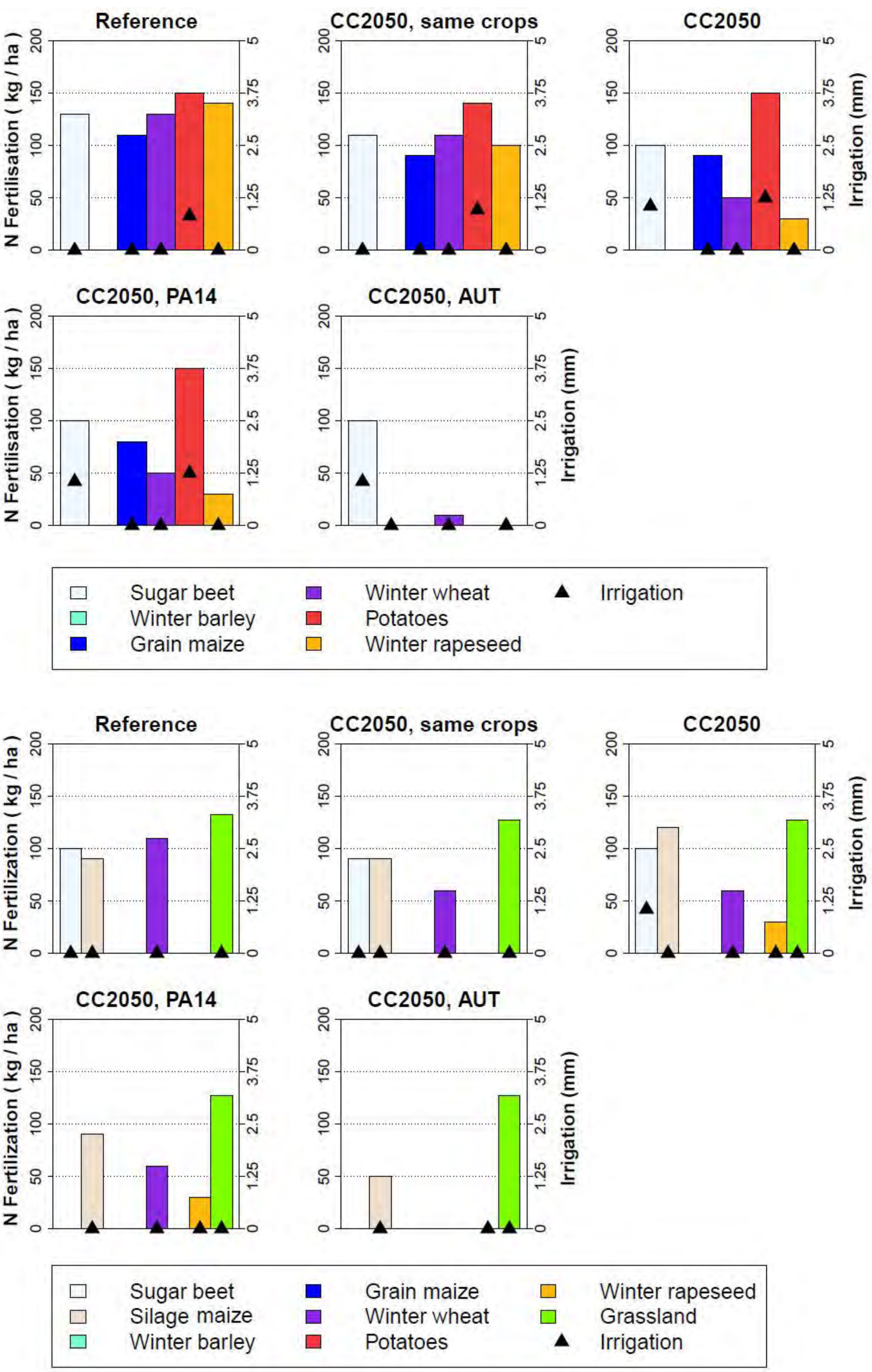


Figure 3.2.2.2.: Optimal irrigation and nitrogen fertilization strategy in the case of an arable farm (top) and a mixed farm (bottom) in the Greifensee region.

than in the Broye region (Figure 3.2.2.4., page 40). Regarding the agricultural income, the results show that the applied policy and price scenarios are more important than climate change, but climate change has larger negative effects on income in the Greifensee region (Uster) than in the Broye region (Payerne). The latter is due to the fact that crop yields decrease under climate change more at Uster than at Payerne, which can be explained by higher mean temperatures and thus higher sensitivity to a further warming.

In case of the mixed farm, irrigation only occurs under the CC2050 scenario. Negative climate change effects are small, because the productivity of the farm's principal business activity, i.e., raising dairy cows, is assumed not to be affected by climate change. Negative impacts on agricultural income of changed agricultural policy and lower price levels are much more important, but negative climate change effects on agricultural income are smaller than for the arable farm.

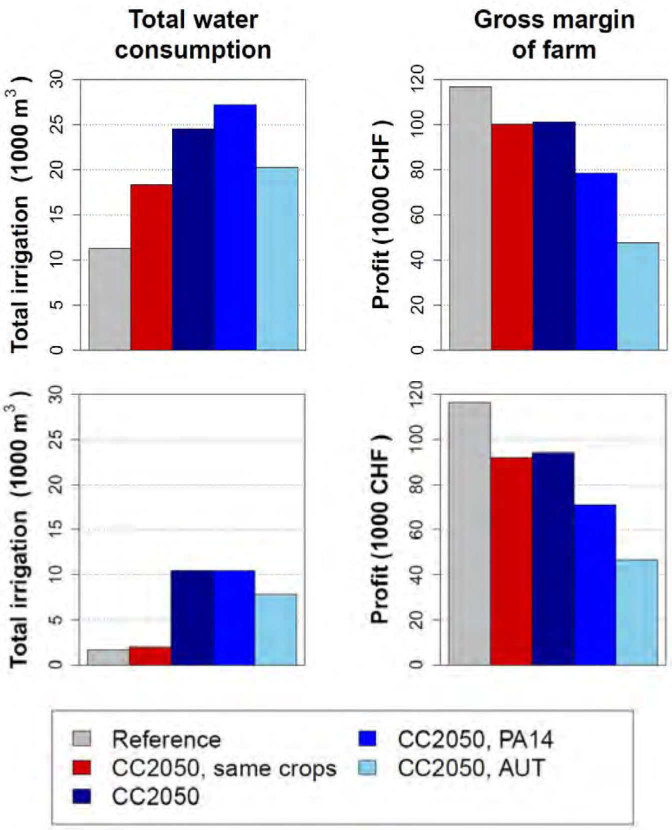


Figure 3.2.2.3.: Farm water consumption in and gross margin of an arable farm (top) and a mixed farm (bottom) in the Broye region under current or changed climatic conditions, with or without a change in policy (PA14) or price (AUT).

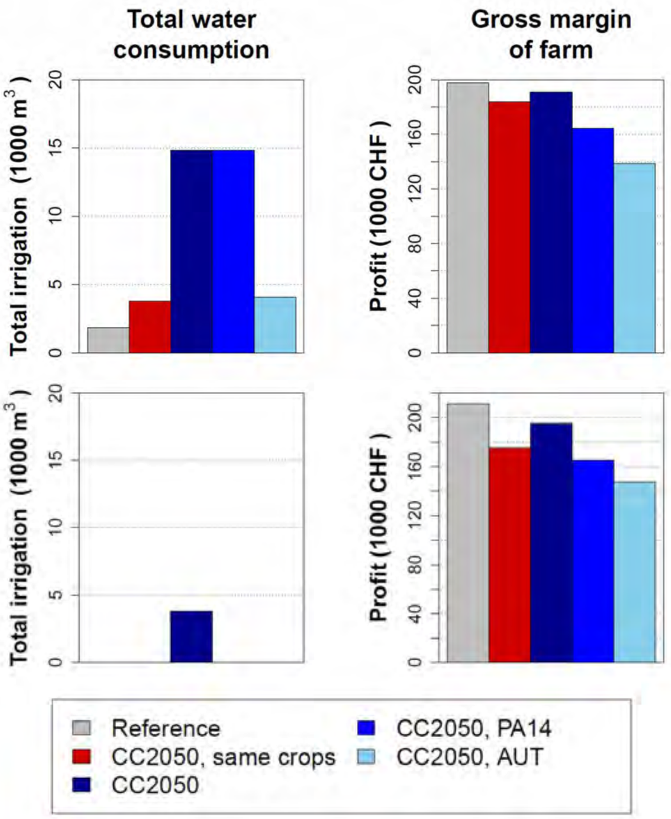


Figure 3.2.2.4.: Water consumption and income under different scenarios for an arable farm (top) and a mixed farm (bottom) in the Greifensee region (Uster).

Overall, climate change impacts on the income and on optimal production schemes are much smaller for mixed farms than for arable farms. Nevertheless, climate change in combination with lower agricultural output prices leads to more extensive production schemes (i.e., lower nitrogen fertilization and irrigation intensities), whereby the cultivation of winter wheat is replaced with winter rapeseed production. However, as in the case of arable farms, climate change will sharply increase the mixed farm's total water demand if current water policies and Swiss agricultural output prices are assumed. This is due particularly to increased irrigation requirements in grassland and silage maize production.

Crop prices as currently observed in the European Union (EU) are likely to cause much larger changes in the optimal management schemes and agricultural income levels than local climate change effects. The arable-farm model projects losses in average farm income of about 50 % under EU crop prices. Although crop prices have a more significant impact on future agricultural practices and income levels than local climate change, the latter still requires major consideration in the Broye catchment. Irrespective of crop price scenario, climate change sharply increases the modeled arable farm's water demand for irrigation by up to 100 %. Interestingly, this increase in agricultural water consumption is not due to an expanded irrigated surface area but solely resulting from higher irrigation water requirements in potato and sugar beet production. For winter crops, such as winter wheat or winter barley, irrigation is even under rather strong climate change signals not a viable adaptation measure.

3.2.3 Which water policies are suitable to reduce the region's water demand under current and future expected climate conditions?

The most important factors determining agricultural water consumption are crop choice, crop land allocation, and irrigation intensity. A farm that uses most of its surface for the cultivation of winter cereals and winter rapeseed has relatively low water consumption. On the other hand, cultivation of potato, for instance, will be possible under future climates only with irrigation. Therefore, agricultural policies that systematically promote the cultivation of typically rain-fed crops, such as winter cereals or winter rapeseed, will be one option for water conservation in the Broye catchment. (Note: Potato is in all scenarios either produced with supplemental irrigation or not included in an optimal crop mix, and currently, farmers must only bear electricity costs incurred for water pumping.)

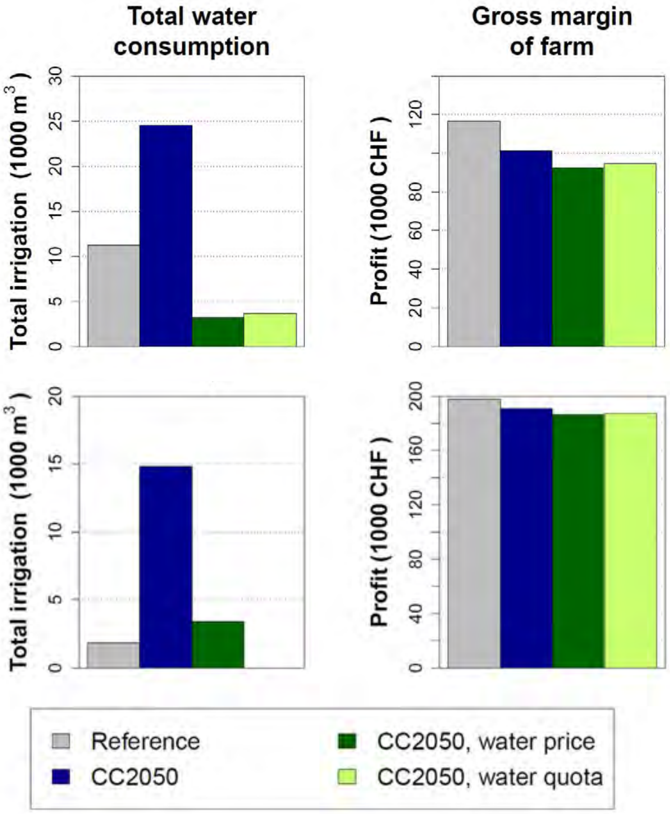


Figure 3.2.3.1.: Changes in water consumption of an arable (top) and a mixed (bottom) farm in the Broye region under climate change with or without introduction of higher water prices (1 CHF/m^3) or a water quota (4,000 m^3/yr).

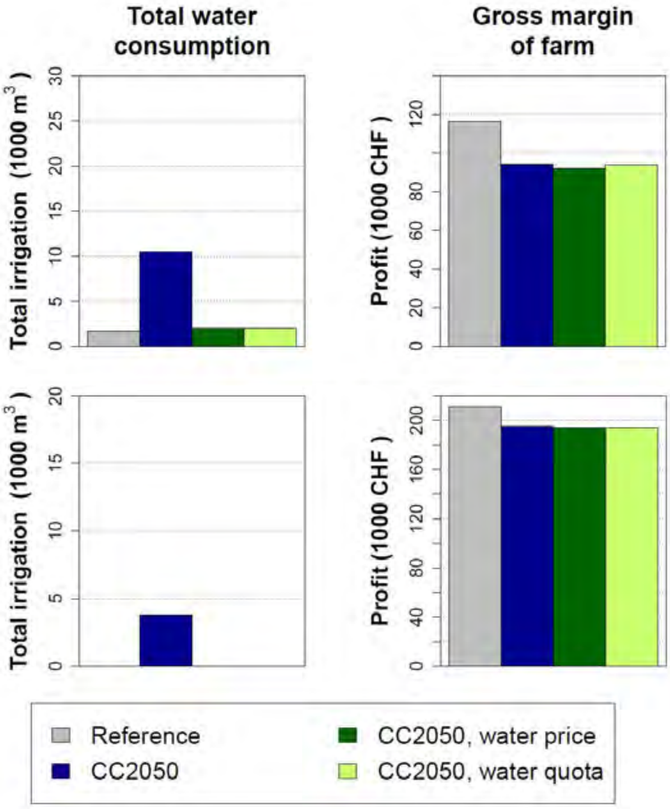


Figure 3.2.3.2.: Changes in water consumption of an arable (top) and a mixed (bottom) farm in the Greifensee region under climate change with or without introduction of higher water prices (1 CHF/m^3) or a water quota (4,000 m^3/yr).

Both the introduction of a variable volumetric water price and the implementation of a water quota are very effective policy measures to induce a reduction in an arable farm's average water consumption (Figure 3.2.3.1.). Under current climatic conditions, introduction of such water policies decreases the average income of an arable farm by less than 5 % in the Broye region and 3 % in the Greifensee region, while significantly reducing the farm's water consumption. Under the strong climate change scenario (ETHZ), such water policies lead to a decrease in the arable farm's water demand by more than 90 %, whereas the related decrease in the farm's average income is smaller than 10 % in the Broye region. In the Greifensee region, water consumption is reduced by more than 80 % (compared to the CC2050 scenario), while the farm's income decreases by less than 3 % (Figure 3.2.3.2.). The relative impacts of the different climate change and policy scenarios on the farmer's CE, which is the target variable in the whole-farm optimization approach, are in the same range as the relative effects of the applied scenarios on the average profit margins. The reason for the relatively small effects on income lies in the fact that the model takes into account a wide range of possible adaptation measures. Thus, by adjusting management schemes, farmers can not only minimize utility losses caused by climate change (i.e., through adaptation) but also partially avoid negative effects on their utility caused by the implementation of specific water policies. Besides lowering the required water quantity for irrigation, both water policies also reduce the total applied nitrogen fertilization amount at the farm scale, with associated benefits for the environment (Lehmann 2013a). Nevertheless, under future climate conditions, both policies can increase downside risks in crop farming. In exceptionally warm and dry years, a higher water price or a water quota will lead to very low agricultural income levels, even if adjustments in the farms' management schemes are accounted for. The introduction of new agricultural insurance products (e.g., farm revenue insurances, index-based insurances) designed to provide revenue protection might be one option to cope with these increased production risks (Kapphan *et al.* 2012).

The effects of a higher water price or a water quota on the farm's optimal crop mix are particularly obvious under climate change. In the Broye region, implementation of a water quota, for instance, decreases the land used for potato production, which requires irrigation in all scenarios, while more land is allocated to rain-fed crops (e.g., winter rapeseed and winter barley). Assuming a higher water price, the crop share of sugar beet is reduced, while the proportion of winter rapeseed is increased by the same amount. Note that due to the high direct payments of currently 1,900 CHF/ha for sugar beet production, this crop is profitable even without or with reduced irrigation and thus is maintained at a small percentage in an optimal crop mix (i.e., due to high price elasticity). Since climate change effects are relatively small in sugar beet compared to other crop types, a partial redistribution of these direct payments to cereals can help to increase the self-sufficiency of bread cereal in Switzerland under future climate and crop price scenarios. In turn, this will make cultivation of cereals more profitable compared to irrigated crops and thus also can decrease the region's total irrigated surface.

For potato cultivation, a single-crop model shows that through implementation of a water quota, it is possible to save water by lowering irrigation frequency and intensity without any major decreases in yield levels (Lehmann 2013a). In contrast, because of the low price elasticity, irrigation remains high even with a higher water price.

It is important to keep in mind that cantons and the Confederation currently subsidize about 50 % of the total costs of water extraction and water transportation systems. This governmental support facilitates local investments in irrigation systems. Furthermore, since irrigation water is not priced volumetrically, farmers have a strong incentive to make excessive use of irrigation. Introducing a water quota limiting the annual extraction of water is efficient at both the single-crop level (e.g., in potato production) and the whole-farm level. However, a water quota increases the risk of income losses due to potentially low crop yields in years when irrigation requirements largely exceed the allocated amount of water. Such higher risks may be hedged by new insurance products, such as crop yield–based or revenue-based insurance schemes.

3.3 Evaluation with Life Cycle Assessment (LCA)

3.3.1 Effects of climate change and adaptation strategies at the regional level

For the Broye region (shown in detail), simulated environmental impacts are shown for the current reference situation as well as for four strategies (i.e., "no adaptation", "productivity", "environment", and "compromise") for 2050 used in the regional optimization (see 3.1). Impacts displayed are global warming potential (GWP), aquatic biodiversity loss (ABL), reduction in potential terrestrial biodiversity (TBR), and freshwater eutrophication (FWE) per MJ dig. en. (Figure 3.3.1.1.) and per ha*yr (Figure 3.3.1.2.).

In general, "no adaptation" under the future climate leads to very little change in the evaluated impacts, compared to the reference situation, except for freshwater eutrophication (i.e., N-leaching and erosion increase, and yields decrease slightly). It can also be observed that no single strategy simultaneously mitigates all impact categories, with a trade-off between GWP and ABL in particular. This suggests that if productivity is to be maintained under the future climate while negative effects of climate change are mitigated, measures must be developed to mitigate or compensate the expected impact on aquatic biodiversity.

For the Greifensee region, summarized results shown in Figure 3.3.1.3. indicate that all adaptation options cause an increase in GWP and TBR relative to the "no adaptation" option but show a clear benefit of the "compromise" and "environment" solutions relative to the "productivity" solution in the biodiversity-related indicators TBR and ABL.

It should be noted that in the regional LCA, the agricultural system was simplified in order to allow a compromise between spatial explicitness and computational feasibility. This simplification causes a slight imprecision in the results; however, it is estimated that this imprecision is negligible (with the exception of internal transportation). Indeed, the parameters identified in the emissions modeling as highly sensitive to location are kept spatially explicit. Spatial detail within the case study regions for other parameters is expected to be superfluous and to contribute only a marginal improvement in precision compared to the uncertainties residing in the emissions models themselves as well as in the impact assessment models for each impact category. Internal transportation (e.g., of manure or fodder) was not modeled here; this omission may, however, contribute in a non-negligible way to further GWP, for example.

Moreover, the regional adaptation strategies did not consider any scenarios of land use change (e.g., agricultural land use loss) in the case study regions, although this also may change by 2050. Such a change will affect the total production in the region but may not necessarily affect the impacts per ha*yr or per MJ dig. en. of the remaining agricultural production, as found in a study in the Greifensee region considering urban expansion (results not shown).

3.3.2 Evaluation at the farm level

The scenarios assessed in LCA at the farm level correspond to those considered in the farm-scale modeling of adaptation. Additionally, adaptation at the farm level under a moderate climate change scenario was assessed, using the SMHI scenario as applied in the regional-scale adaptation modeling; this is indicated here with "Mod2050" (see Table 2.7.2. for definitions).

3.3.2.1 Overview of functional units and global warming efficiency

The following graphs show the relationships of production (as MJ dig. en.) to profit (in CHF), GWP (as an example of

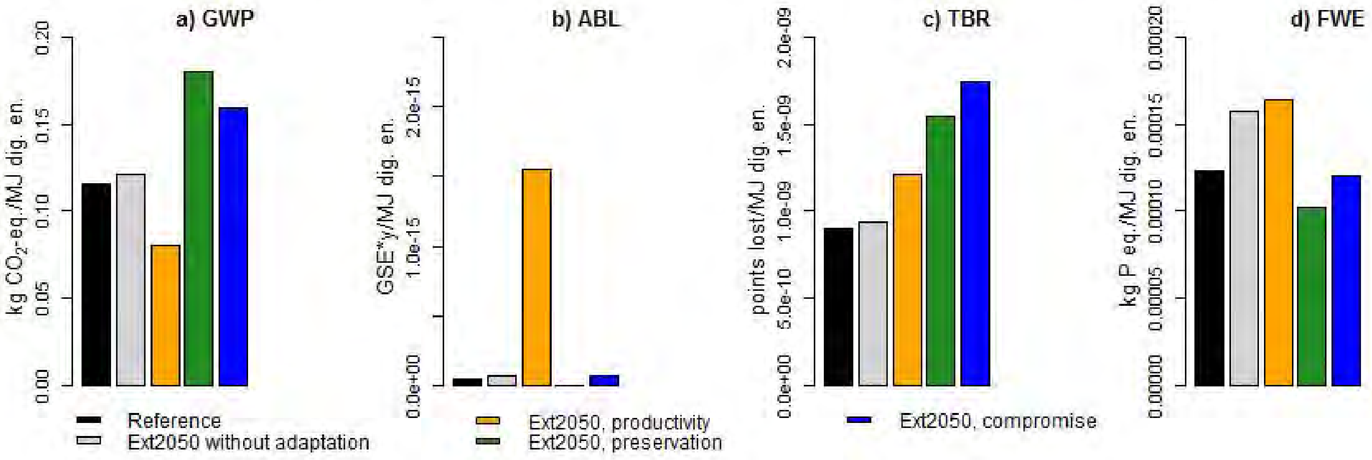


Figure 3.3.1.1.: Environmental impacts per MJ dig. en. in the Broye region for the reference situation and under climate change for four strategies: no change in management, maximization of production, preservation of natural resources, and "compromise"; (a) global warming potential, (b) potential aquatic biodiversity loss, (c) reduction in potential terrestrial biodiversity, (d) freshwater eutrophication potential.

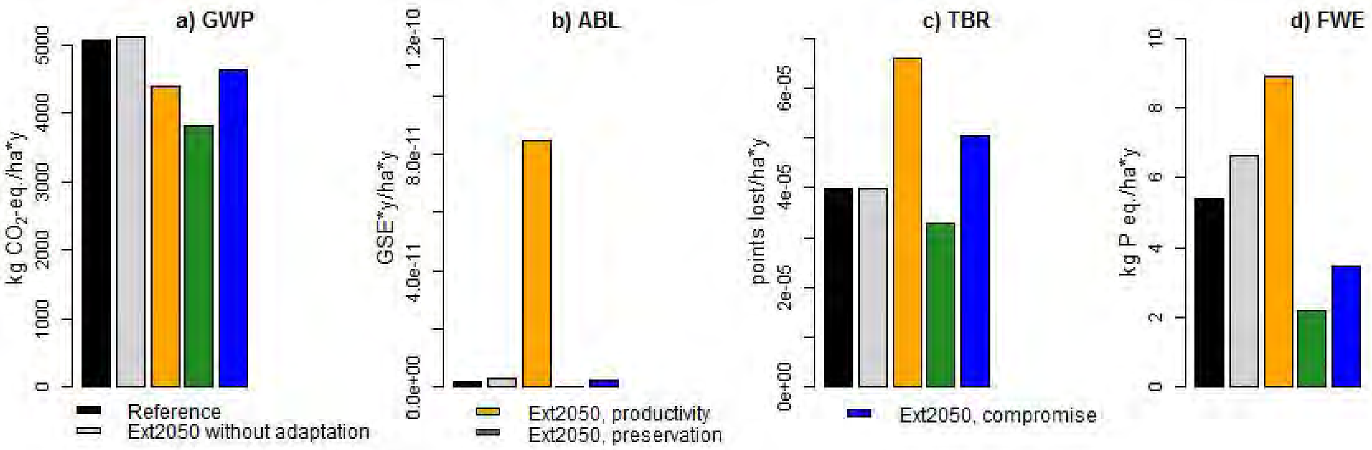


*Figure 3.3.1.2.: Environmental impacts per ha*yr in the Broye region for the reference situation and under climate change for four strategies: no change in management, maximization of production, preservation of natural resources, and "compromise"; (a) global warming potential, (b) potential aquatic biodiversity loss, (c) reduction in potential terrestrial biodiversity, (d) freshwater eutrophication potential.*

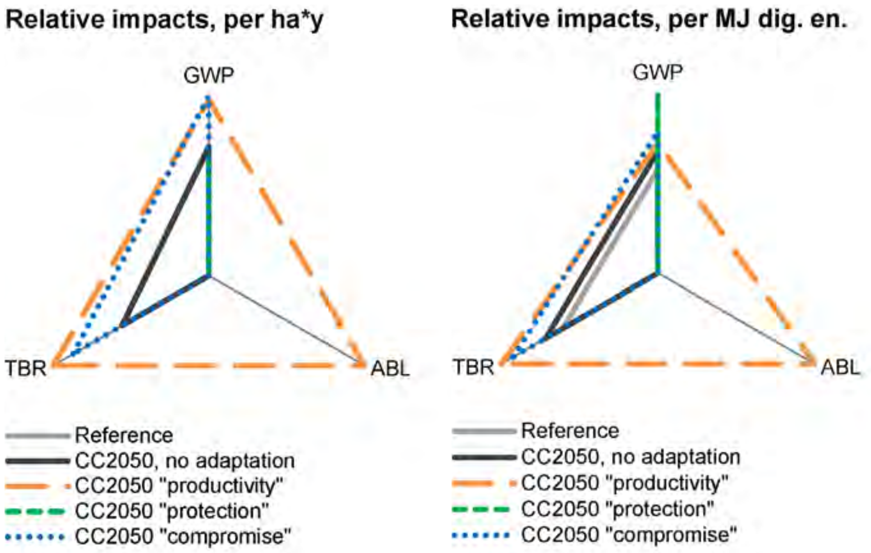


*Figure 3.3.1.3.: Impacts of different scenarios at the regional level for the Greifensee region. Impacts per ha*yr (left) and per MJ dig. en. (right).*

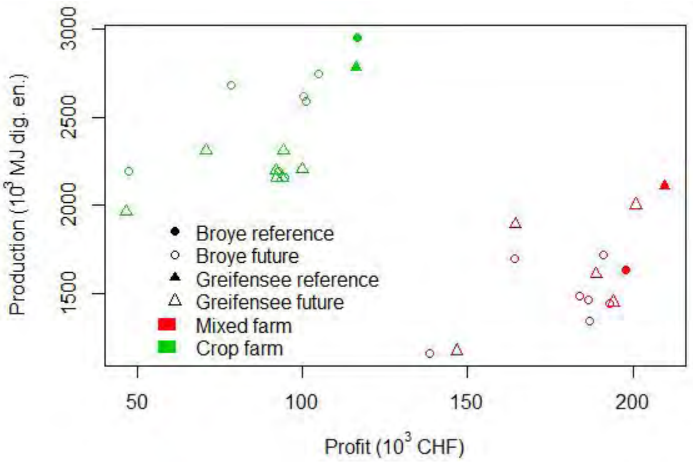


Figure 3.3.2.1.: Production (as MJ dig. en.) versus profit for all scenarios. Colors distinguish farm types, shapes distinguish regions, and symbol fill distinguishes the references from the future scenarios.

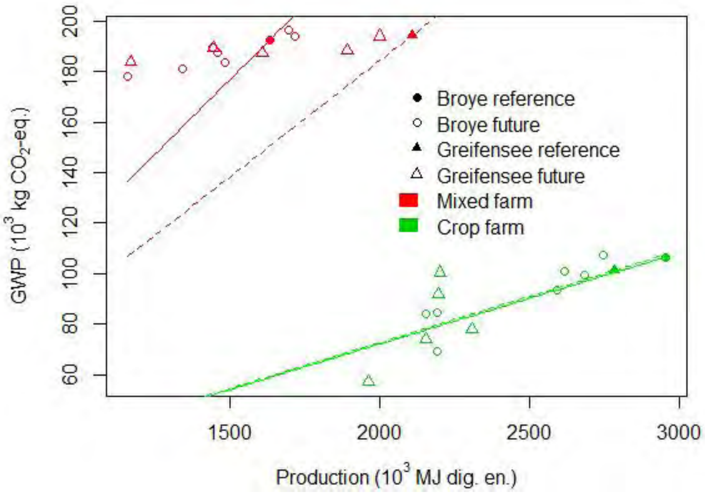


Figure 3.3.2.2.: GWP versus production (as MJ dig. en.) for all scenarios. Colors distinguish farm types, shapes distinguish regions, and symbol fill distinguishes the references from the future scenarios. As a reference for each farm type, full lines represent the ratio GWP/production for the Broye reference scenario, and dashed lines represent the same ratio for the Greifensee reference scenario.

environmental impacts) to production, and GWP to profit. They give an overview of the production, profit, and GWP for all scenarios, distinguished according to farm type, region, and period (current reference or future climate, the latter including both "Ext2050" and "Mod2050").

Figure 3.3.2.1. shows that profit is higher for mixed farms, whereas production of energy for humans is higher for almost all crop farms. Generally, crop farms are more productive in the Broye region than in the Greifensee region and will see a decrease in both profit and production in the future. Mixed farms are generally more productive in the Greifensee region than in the Broye region; both profit and productivity decrease in the future in the Greifensee region, whereas in the Broye region, a few scenarios see a slight increase in production. Generally, an increase in profit is correlated with an increase in production for both farm types.

Global warming potential in relation to production is shown in Figure 3.3.2.2. as GWP versus the production of energy for humans. An increase in production generally leads to an increase in GWP, more markedly for crop farms than for mixed farms. Crop farms are more efficient than mixed farms: GWP is systematically lower, while similar or higher production is achieved. There is no notable difference between the efficiencies of the Broye region and of the Greifensee region for crop farms, whereas for mixed farms, the Greifensee region is more efficient in most cases. Climate change causes a decrease in GWP in most cases. It causes a decrease in efficiency for mixed farms but shows no significant trend for crop farms.

Eco-efficiency is shown in Figure 3.3.2.3. as the GWP versus the profit of the farm. Here, efficiencies are similar for both farm types and both regions, whereby mixed farms have a slightly lower efficiency than crop farms, and the Broye region has a slightly lower efficiency than the Greifensee region. Mixed farms have both higher profits and higher GWP. Climate change tends to cause a decrease in efficiency for most cases.

3.3.2.2 Impacts of climate change and economic optimization

The selected environmental impacts per MJ dig. en. (displayed as relative to the maximum) for optimized farms under current and future climate (using the extreme change signal as a "worst case") are shown in Figure 3.3.2.4. for the case of mixed farms and Figure 3.3.2.5. for the case of crop farms. For the future climate, results are additionally shown for a farm without adaptation to climate change.

Main observations for mixed farms (Figure 3.3.2.4.):

- All impacts increase if no adaptation to climate change occurs (except ABL in the Greifensee region).
- ABL increases for optimization under future climate.
- GWP and TEP decrease slightly for optimization under future climate in the Broye region but increase in the Greifensee region.

Without adaptation under the future climate, the increase in impacts compared to the current situation is due mainly to a decrease in production of 30 %. Climate change in the Broye region enables an increase in production if the farm is optimized; this increase is higher than the corresponding increase in GWP (caused by an increase in fertilization intensity), and therefore the efficiency is improved. In this case, climate change mitigation and economic adaptation are compatible. An increase in irrigation is the main adaptation undertaken to maintain yields in the future climate in order to compensate the decrease in precipitation and increase in temperature during the growing period. This adaptation leads to the observed increase in ABL.

In the Greifensee region, economic optimization does not lead to mitigation of impacts. This is explained by the drop in production in the future climate: indeed, the increase in temperature in this location, which is already warmer than the Broye region, is unfavorable for the yields of most of the cereal crops modeled. In this case, climate change has a negative impact on the economic profitability of the farm as well as its environmental impacts.

Main observations for crop farms (Figure 3.3.2.5.):

- All impacts increase if no adaptation to climate change occurs.
- ABL and TEP increase for optimization under future climate.
- GWP is stable or decreases for optimization under future climate.

The increase in impacts is caused by a drop in production in both regions due to a general extensification of fertilization. However, the extensification is enough to compensate the GWP emissions per unit production: GWP can thus be stabilized or even mitigated through adaptation to climate change. Thus, for both farm types and regions, impacts increase in the future climate if there is no adaptation, and they increase with optimization, except for GWP. In most cases, GWP is mitigated when adaptation is optimized to climate change, unless future temperature is too unfavorable for yields. Optimization in the future climate also allows maintaining profits or avoiding significant decreases in profits. The major trade-off with the benefits of optimization is ABL.

3.3.2.3 Water restriction scenarios

Options to reduce ABL caused by optimization include setting a price on water (WP) and attributing a water quota (WQ) to the farm in order to limit irrigation water consumption. The impacts of optimization under such scenarios are shown in Figure 3.3.2.6. for the Broye region (for both mixed and crop farms).

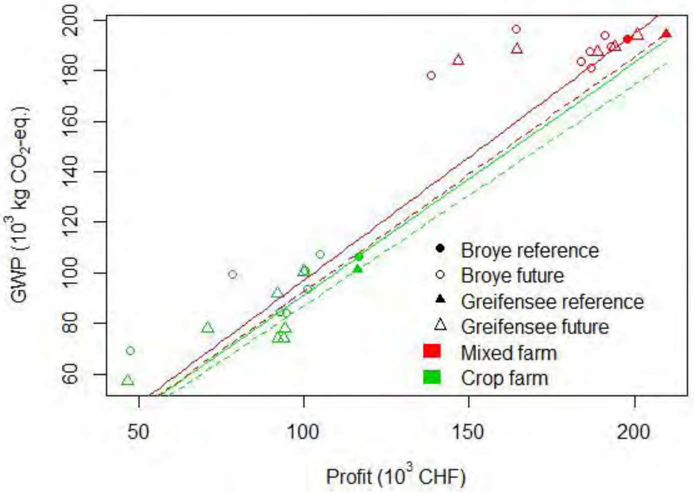


Figure 3.3.2.3.: GWP versus profit for all scenarios. Colors distinguish farm types, shapes distinguish regions, and symbol fill distinguishes the references from the future scenarios. As a reference for each farm type, full lines represent the ratio GWP/profit for the Broye reference scenario, and dashed lines represent the same ratio for the Greifensee reference scenario.

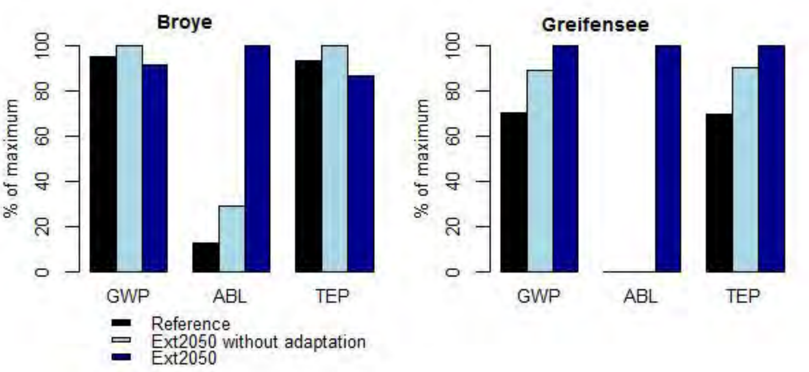


Figure 3.3.2.4.: Mixed farm: environmental impacts per MJ dig. en. (relative to the maximum) for the Broye and Greifensee regions under current and future climate.

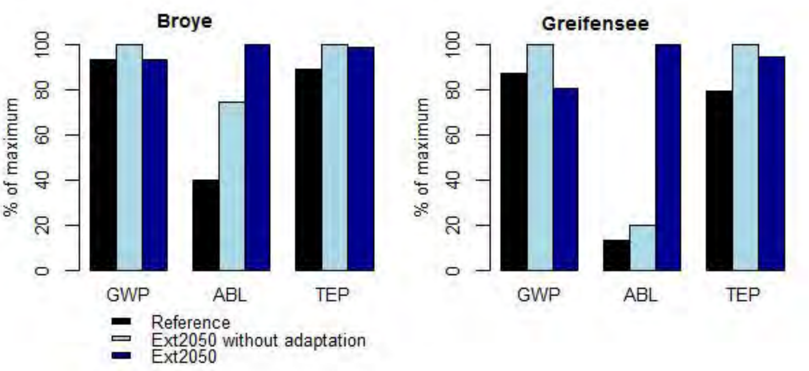


Figure 3.3.2.5.: Crop farm: environmental impacts per MJ dig. en. (relative to the maximum) for the Broye and Greifensee regions under current and future climate.

Main observations for the Broye region (Figure 3.3.2.6.):

- ABL is reduced with both water use restriction scenarios, for both farm types.
- GWP and TEP increase with both water use restriction scenarios, for both farm types.

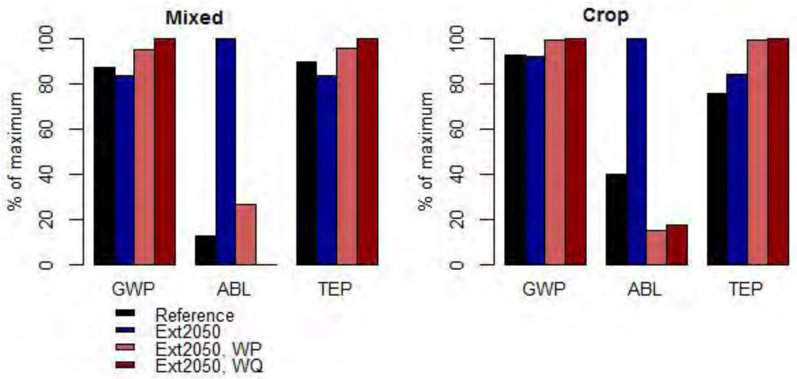


Figure 3.3.2.6.: Environmental impacts per MJ dig. en. (relative to the maximum) of optimized farms under future climate and water use restriction scenarios for the Broye region: WP=Water price; WQ=Water quota.

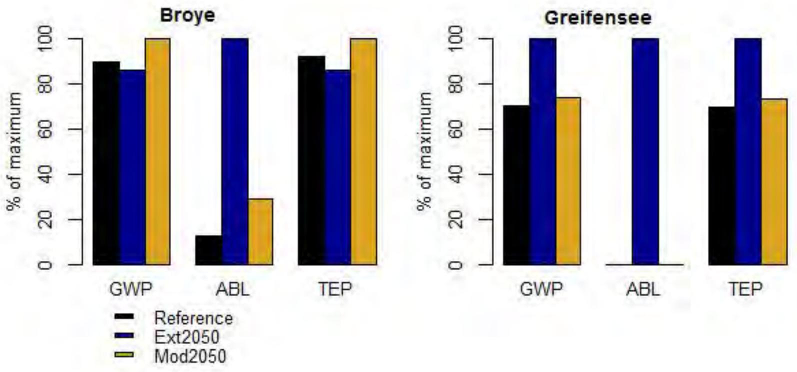


Figure 3.3.2.7.: Mixed farm: environmental impacts of the optimized farm under different future climate scenarios (extreme change signal and moderate change signal) per MJ dig. en. (relative to the maximum).

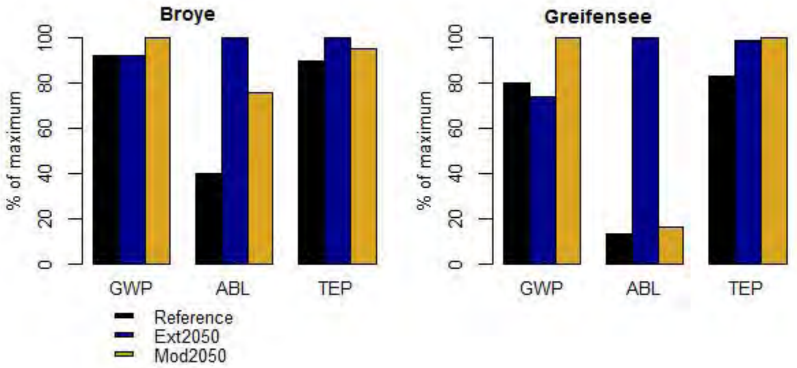


Figure 3.3.2.8.: Crop farm: environmental impacts of the optimized farm under different future climate scenarios (extreme change signal and moderate change signal) per MJ dig. en. (relative to the maximum).

The decrease in ABL is explained by the decrease in profitability of irrigation (either because the variable costs increase in the case of a water price, or because the payback time of the capital costs increases in the case of water quota). For both farm types, production decreases for both water use restriction scenarios (by 15 % to 21 %), causing the increase in GWP and TEP. This result shows that the previously modeled increase in irrigation demand is expected only if water prices are negligible and water availability is unconstrained. The drawback of water use restriction is a decrease in productivity; thus, avoiding ABL impacts is feasible but at the cost of other impact categories. Water use restriction will require policy intervention; indeed, according to the model, farmers show preference for using irrigation as long as water is available and irrigation is profitable (although the decrease in profits for water price and water quota is only 2 %).

3.3.2.4 Sensitivity to climate scenario

The impacts of the optimized farm according to different future climate scenarios are shown in Figure 3.3.2.7. for mixed farms and Figure 3.3.2.8. for crop farms.

Main observations for mixed farms (Figure 3.3.2.7.):

- Impacts under moderate climate change increase slightly (except ABL in the Greifensee region).
- Compared to extreme climate change, moderate climate change leads to higher impacts in the Broye region (except ABL) and lower impacts in the Greifensee region.
- ABL is highest under extreme climate change.

Main observations for crop farms (Figure 3.3.2.8.):

- Impacts increase under moderate climate change, compared to the reference.
- ABL decreases under moderate climate change, compared to extreme climate change.

The moderate climate change scenario is less favorable for yields in the Broye region than the extreme climate change scenario, for which temperature approaches the optimum. As mentioned earlier, temperature exceeds the optimum in the Greifensee region for extreme climate change. This can be explained by the background climate in each region: The Broye region is slightly cooler, therefore a large increase in temperature (such as for "Ext2050") is more profitable to crop yields than a moderate increase in temperature (such as for "Mod2050"). The extreme climate change scenario involves decreases in precipitation of up to 30 %, whereas the moderate climate change scenario leads to decreases in precipitation of up to 10 % only. This explains the behavior of ABL.

In summary, the choice of climate change scenario has a significant influence on the impacts; the sensitivity is lower in the Broye region, where both climate change scenarios are beneficial for crop yields. Nevertheless, both climate change scenarios lead to an increase in impacts in most cases.

3.3.2.5 Sensitivity to price and subsidy scenario

The impacts of the optimized farm according to the different policy and subsidy scenarios under future climate are shown in Figure 3.3.2.9. for mixed farms and Figure 3.3.2.10. for crop farms.

Main observations for mixed farms (Figure 3.3.2.9.):

- A decrease in prices causes a decrease in ABL and an increase in GWP and TEP.
- A decrease in subsidies has little influence in the Broye region but causes a decrease in impacts in the Greifensee region.

Main observations for crop farms (Figure 3.3.2.10.):

- Crop farms are less sensitive to price and policy scenarios than mixed farms.
- ABL remains above the reference level for all cases.

With lower product prices, crop production becomes more extensive with much lower yields. Irrigation in particular decreases due to a decrease in profitability. More surface is allocated to grassland and pasture, which are, however, still intensively fertilized leading to an increase in GWP per MJ dig. en. (due to N_2O emissions from organic fertilization of grassland) despite the decrease in fertilization of the arable crops. In the Greifensee region, the change in subsidies provokes an increase in intensity and yields, resulting in impacts similar to the reference.

In summary, impacts are more sensitive to the price scenario than the subsidy scenario, and crop farms are less sensitive than mixed farms. A decrease in prices consistently causes a decrease in ABL in the future climate; however, GWP may either increase or decrease according to the farm type.

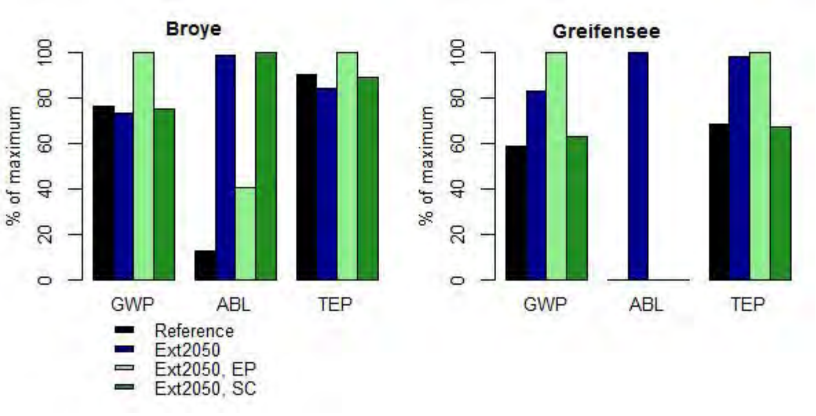


Figure 3.3.2.9.: Mixed farm: environmental impacts of the optimized farm for different policy scenarios (European prices and changes in subsidies) under future climate (extreme change signal) per MJ dig. en. (relative to the maximum).

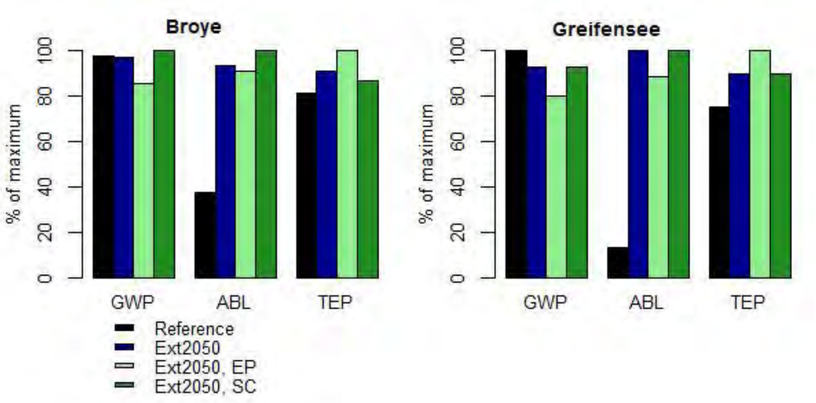


Figure 3.3.2.10.: Crop farm: environmental impacts of the optimized farm for different policy scenarios (European prices and changes in subsidies) under future climate (extreme change signal) per MJ dig. en. (relative to the maximum).

3.4 Effects of groundwater withdrawals on groundwater level and related ecosystems

For the scenario simulating a productivity strategy and partial withdrawals from the groundwater in 2050 under extreme climate change, the water was assumed to be withdrawn from 10 pumping wells (located close to the irrigation perimeters, with suitable local aquifer properties and as far away from the river as possible in order to avoid effects on the base flow). The amount to be withdrawn, mainly from May to September, was set at 18.5 mio m^3/yr. This amount, however, represents only 50 % of the irrigation water requirements and cannot be provided by the river discharge during July and August (see Figure 3.1.6.1., page 48). It was assumed that the aquifer, due to its hydraulic characteristics, cannot supply this amount of water during July and August.

These withdrawals (with consideration of any return flow to the groundwater from the field) lead to a significant drop in the groundwater head during the most critical month (August), as well as on average during the year, as shown in Figure 3.4.1.

The agricultural pumping wells are clearly visible at the locations of the highest head drop (Fig. 3.4.1.). The main domestic pumping well for the region was also modeled and is visible to the right of Payerne. An increase in withdrawals from this well due to a linear increase in population extrapolated from past population growth, with a constant per capita water consumption, was assumed for the future situation. However, this domestic well was excluded from the calculation of the impacts due to the agricultural water withdrawals. The head drop caused by only the latter will lead to a reduction in potential terrestrial biodiversity according to the method and characterization factor of van Zelm *et al.* (2011). Additionally, the groundwater withdrawals lead to a decrease in the recharge from the aquifer to the river from 0.73 to 0.20 m^3/s during the month of August (for which the base flow in the river is around 1 m^3/s) and from 0.80 to 0.58 m^3/s on average throughout the year. This effect alone will cause a loss of aquatic biodiversity in the river, but it amounts to only 16 % of the impacts that would be caused if all irrigation water was withdrawn from the river (with the use of reservoirs).

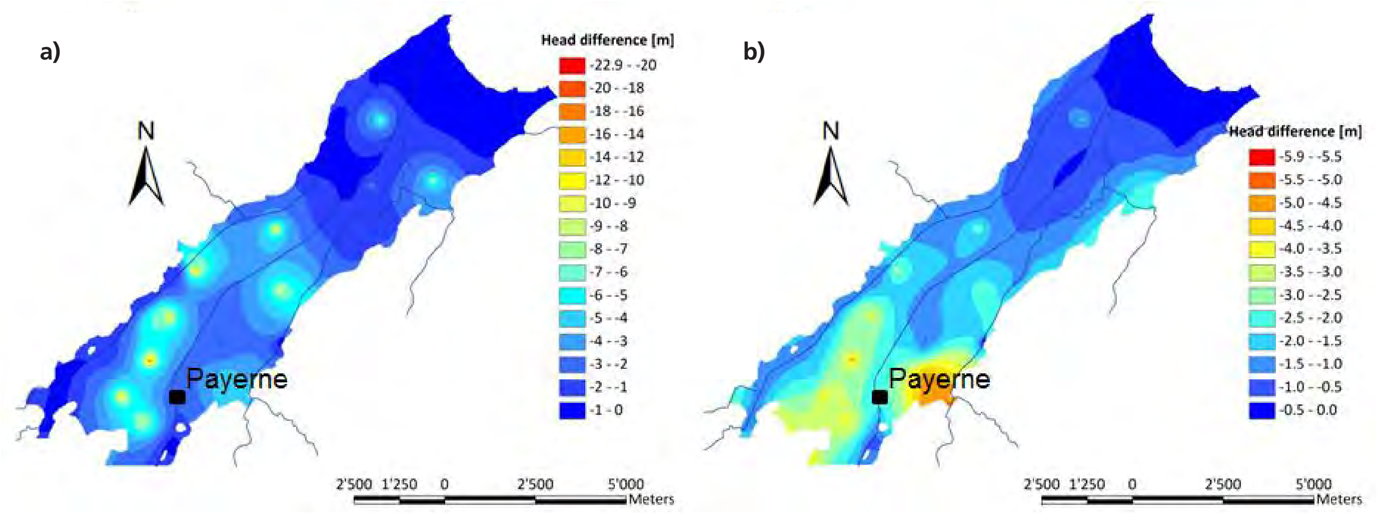


Figure 3.4.1.: Groundwater head drop for the simulated withdrawals (a) during the month of August and (b) on average during the year (adapted from Gomez [2012]). Note the different scales for figures (a) and (b).

Thus, 84 % of the impacts on the aquatic biodiversity of the river will be avoided if 50 % of the peak water demand in July and August is extracted from the groundwater. However, this also implies renouncing the other 50 % of this irrigation water demand and, in turn, is expected to affect the yield performance of the region. Even if the remaining water is extracted from the river, spread over several months using reservoirs in order to ensure availability during July and August, the total impacts on aquatic biodiversity are nevertheless reduced by 30 % thanks to the contribution of groundwater. The estimated potential impacts on terrestrial biodiversity due to groundwater consumption probably overestimate the actual impacts to be expected, because the large majority of the land use above the aquifer is agricultural, and thus there are hardly any terrestrial ecosystems that actually will be affected by the groundwater head drop.

Therefore, the alternative sourcing of a part of the irrigation water from the local aquifer may avoid a significant part of impacts on the river without dramatically increasing other impacts for this particular case, but it cannot satisfy the full irrigation water requirements of the maximum productivity scenario in the future climate.

4 Stakeholder involvement

Figure 4.1.: Impressions from workshops with stakeholders in the Broye region.

In the course of the AGWAM project, stakeholder groups have been involved by attending workshops. These groups included representatives of the federal and cantonal administrations, of regional interest groups (such as the association "Broye source de vie" or the "Greifensee Stiftung"), of the Foundation for Landscape Conservation, and of the farming community (Figure 4.1.). The goal of the workshops was initially to get feedback on the aims and approaches of the project in the two case study regions and to identify relevant data sources to be considered. These initial workshops also helped to identify existing regional strategies to cope with water issues. With respect to water use for irrigation, stakeholders in the Broye were much more involved, whereas problems of water quality appeared more relevant to stakeholders in the Greifensee region. The perception of climate change was also very different: In the Greifensee region, climate change seemed less important, and a reduction in rainfall in summer was seen rather as an advantage, given that excessive rainfall often limits agricultural production. In contrast, in the Broye region, climate change was seen as a more relevant issue, particularly because water shortage is already a problem and authorities are planning measures to cope with increasing water scarcity. Based on the initial workshops, the framing of the modeling could be better adapted to the conditions in the two regions and to the needs of the stakeholders.

In subsequent workshops, intermediate results were presented and discussed with similar stakeholder groups, mainly in the Broye region, where, in contrast to the Greifensee region, the interest was much more pronounced and stakeholders were more involved. These critical discussions revealed the discrepancy between modeled theoretical solutions and the perception of the stakeholders. This helped to make further adjustments to the modeling, in particular with respect to the definition of the reference conditions (which should be as close to reality as possible) and the formulation of recommendations. It became clear that there is a strong preference to maintain the status quo and to search for more technical solutions (i.e., water pipelines to increase water availability) rather than to implement internal changes in the production systems and in landscape organization. A final workshop was organized together with representatives of the federal and cantonal administrations in order to discuss the results in terms of the three selected strategies for adaptation and to discuss the recommendations for adopting adaptation strategies.

For the Broye region, the following main points were drawn from these workshops:

1. Large increases in irrigation were seen to be of limited feasibility, due to the important infrastructure they would require, the low probability that society would be willing to provide the necessary subsidies, and the limited amount of water resources available within the region.

2. Large changes in crop mixes or shifts from arable crop production to livestock production were not considered realistic, due to reluctance of farmers to change. However, stakeholders generally considered these approaches with a relatively short-term perspective, where large and rapid changes are not desirable. In the long term, if pressure becomes sufficiently large, such changes may nevertheless become more acceptable. Maintaining the productivity of existing crops in a region relatively favorable for arable crops was seen as an important contribution to the self-sufficiency of Switzerland. Livestock farming would reduce farmers' living quality (e.g., due to less flexible working hours) and require important capital investment.

3. Adaptation options to climate change foreseen by the stakeholders included stepwise technical solutions, such as the use of new cultivars with higher resistance to drought and the improvement of irrigation techniques to use water more efficiently. Large changes of the entire farm strategy were not prioritized. These technical solutions were not considered among the management variables of the economic model, due to high uncertainties in the prediction of cultivar improvements and the focus on strategic changes rather than incremental changes. Therefore, it seems more likely that voluntary adaptation to climate change by the farmers may follow such stepwise trends in the near future; larger changes like those assessed here may require policy intervention in order to promote their application. In this context, improvements in farmers' education would seem essential in order to foster better management of an indispensable but limited resource.

5 Synthesis, recommendations, and outlook

5.1 What are the key conclusions of this study?

- Increased water requirement will be a key issue under climate change. In the Broye catchment, a more intense use of irrigation will be one of the main measures for arable cropping systems, in contrast to the Greifensee region. However, since the Broye region's water availability already is restricted in dry and hot years, this increased water demand will intensify water scarcity, most strongly if no changes are made in land use and management and in water policies.

- Agricultural productivity (in terms of aggregated dry matter yield) can be maintained by a balanced regional adaptation strategy ("compromise" solution) with a reasonable increase in irrigation water requirement caused by climate warming, relative to the current situation. This strategy may help to avoid water shortages due to more frequent low-flow situations, and it presents an alternative to building new water canals to supply additional water from large lakes (e.g., Lake Neuchâtel) via large water distribution systems. However, this strategy shifts production from arable crops to grassland and causes the production of human nourishment in terms of MJ dig. en. to decrease significantly, leading to a decreased environmental efficiency of production within the region.

- Optimization can be implemented in a sub-regional approach accounting for differences in environmental conditions and topography. In the case of the Broye catchment, this approach would lead to a focus on intensive, irrigated crop production in the most suitable part of the catchment (around Payerne), whereas the hilly sub-regions would be used for grassland production and, depending on soil type, for some non-irrigated crop production.

- Water use and its impacts are a major environmental trade-off in adaptation to climate change. While intensification tends to lead to higher absolute impacts per area and higher productivity but generally lower impacts relative to production (except concerning aquatic biodiversity loss), extensification tends to lead to lower absolute impacts and lower productivity, often resulting in higher impacts relative to production.

- The regional "compromise" strategy would limit the water requirement by (1) applying optimal technologies with high irrigation efficiency, adapted soil management, and choice of most suitable crop cultivars, (2) Introducing a water quota to avoid environmental impacts and protect sensitive water sources, and (3) changing the crop mix and spatial organization of cropping areas.

- These "compromise" measures should be implemented in a stepwise approach along with the increase in climate risks:
  - Initially, "soft" measures should be employed and could include changes in soil management, adjustments in crop cultivar and crop choice, and improvements of irrigation technology accompanied by education and training *(=incremental adaptation)*.
  - Next, measures requiring investment in infrastructure with longer lead times should be applied *(=systems adaptation)*. Use of new irrigation infrastructure, such as pipelines, should include some form of regionally adapted and/or farm-specific water quotas to consider the limitation of extractable water in small reservoirs.
  - Changing crop location, i.e., altering spatial organization of production, should be the last step *(=transformational adaptation)*.

- Extrapolation of the specific results for the two case study regions, however, is difficult as the strategic goals may differ between regions, and regional differences exist in trade-offs between different agricultural functions. In each region, the availability of water in terms of its variability (i.e., the frequency of low-flow situations) needs to be considered when planning future irrigation activities. In economic terms, some crops, such as potato, should preferentially be irrigated even when water resources are limited.

- At the farm level, environmental impacts of production (related to the amount produced) are expected to increase in the future climate. Strategies maximizing farm economic profitability in the future aggravate water-related impacts, but most other environmental impacts (per amount produced) are lower for economically optimized farms than for farms without adaptation to the future climate, although in the future, productivity and eco-efficiency will decrease.

- The water policy currently in place does not only encourage farmers to irrigate intensively whenever irrigation is possible but also increase farmers' income risks (e.g., for production of potato). Under future climate conditions, both the implementation of a volumetric water price and the introduction of a water quota will significantly reduce the farm's total water consumption. At the same time, reductions in farm income caused by these policies are relatively small, because farmers increase the surface of the most profitable rain-fed crops (e.g., winter rapeseed) at the expense of the surface area of irrigated crops.

- Compared to a volumetric water price, the water quota might be easier to be implemented, and farmers can be expected to prefer a water quota, which does not increase production costs, over a volumetric water price, which increases variable production costs for irrigated crops.

- Nevertheless, both alternative water policies increase the farm's downside risks of low incomes. Thus, new innovative agricultural insurance products (e.g., farm revenue insurance, index-based insurance) might be one option to reduce the farm's high risk exposure to low incomes under such water policies. Both alternative water policies also decrease productivity in terms of MJ dig. en. and thus the environmental efficiency of the farm.

- Adaptation at the farm level may be driven by changes in the system of direct payments. Because of differences between regions in terms of trade-offs between productivity and environmental impacts and between water availability and demand, such changes will need to be differentiated. Subsidies for irrigation infrastructure should be limited to efficient systems. Water quotas for individual farms could be handled similar to those quotas currently used for N and P in the framework of the "proof of ecological performance" ("Ökologischer Leistungsnachweis, ÖLN") for direct payments (adapted to regions and crop types).

- Increasing the production efficiency is essential because aggregated impacts that potentially reach levels of concern include aquatic biodiversity loss (i.e., potential loss of up to one fifth of species in the watershed due to climate change and irrigation) and freshwater eutrophication (i.e., emissions of nutrients up to ten times the national average). However, efforts to increase production efficiency need to be combined with complementary measures to address resulting impacts on aquatic biodiversity; such measures could include quotas in order to effectively limit the use of water resources and to promote the use of groundwater rather than river water. This is particularly important if a level of food self-sufficiency above 50 % is to be maintained for a growing population challenged with changing climatic conditions and declining land resources.

5.2 Which guidelines can be provided for adapting regional agricultural land management in dry regions to climate change in 2050?

Adaptation of agricultural land management to climate change in the Broye catchment will be necessary for the time horizon 2050. In order to cope with changing climate conditions and to maintain productivity, while minimizing environmental impacts, general recommendations have been identified:

- Maintaining intensity level. Today's intensity level (official recommendation) is and will be best, as it has a positive effect on productivity, which in turn has an influence on erosion (i.e., the more biomass, the better the soil protection) without leading to high N-leaching rates. This solution also best maintains environmental efficiency.

- Increased use of conservation soil management. Reducing tillage and retaining harvest residues are known to improve soil organic matter and conserve soil fertility while increasing soil surface protection and reducing runoff. In addition, impacts on soil temperature and N mineralization become less important as air temperature increases. However, conventional soil management can still be applied on flat areas that are not subject to erosion.

- Conversion of grassland to cropland in the hilly southern areas. Crop cultivation is currently not possible in these areas due to limiting temperatures, but it becomes possible in a warmer climate. However, grassland should remain at high elevations on coarse soils to reduce erosion and decrease soil temperature and consequently N-leaching.

- Decrease in the share of irrigated spring crops. Water stress–sensitive crops (e.g., potato) should be replaced partly by winter rapeseed. Winter rapeseed is an environmentally friendly crop that can serve as a catch crop to reduce N-leaching during the autumn-winter period thanks to its high capacity to take up nitrate from the soil; furthermore, winter rapeseed is relatively resistant to soil loss, is not irrigated, and performs well under climate change.

- Irrigation should preferably be applied on coarse soils around Payerne. Optimal irrigation patterns do not differ significantly from currently irrigated areas, because irrigation is and will be worthwhile only in lowlands of the Broye region. However, it would be preferable to apply water extracted from the Broye river on coarse soils that are more distant from the river – as opposed to the current practice where irrigation is mostly applied on soils that are located close to the river bed and have high water retention capacities. This approach would require additional infrastructure for water distribution.

- Water should be taken only from large natural or artificial reservoirs for which quotas may not be necessary. Withdrawal from sensitive sources of water, such as small rivers, should be avoided, or restrictive quotas for water pumping from such sources should be implemented.

- In order to build the necessary competence in adapted land management and optimal irrigation techniques, education plays a major role and should be improved in the mid-term.

5.3 Outlook

In addition to incremental and transformational adaptation options, systems adaptation, such as breeding technology improvements, could be included in future crop modeling. For instance, development of slower-maturing crops to take advantage of longer growing seasons already occurs, and it is anticipated that this approach would reduce the trade-offs between productivity and environmental impacts due to shorter fallow times and hence reduced erosion and N-leaching. However, benefits of such cultivars are still highly uncertain, and implementation in models is complicated when considering crop rotations.

AGWAM focused on the assessment of the benefits and environmental impacts of agricultural adaptation scenarios to climate change; however, a full sustainability assessment should also include relevant social and economic criteria. The latter were considered partly in the farm scenarios used (i.e., profit and variability of profit), but social criteria were not included. The bioeconomic model used in this project considered income and income risks as main economic decision markers. But the objective function in this approach did not include other decision-influencing processes, such as the minimization of workload and thus the maximization of work effectiveness, personal preferences regarding the cultivation of particular crops, or maximal independence from government direct payments. Furthermore, the models did not include social impacts related to required inputs and imports associated with the scenarios. Since all these factors also play a role as economic decision makers, further modeling work would benefit from the consideration of such additional parameters.

The whole-farm model developed in AGWAM provides a good basis for the development of a future agent-based modeling approach. Interactions between different agents are important to better capture management options in agricultural systems, in particular for models of agricultural land use. Furthermore, agent-based models are able to consider heterogeneity amongst farms and land and to model decision making using a bottom-up strategy (i.e., taking into account locally interacting farms competing for land) that allows analyzing the properties of a particular system at a regional level.

The assessments conducted in AGWAM focused on farm- and regional-scale management. However, the scenarios assessed imply changes in productivity, which imply further changes in other components of the system not addressed in detail here, such as changes in import and export amounts or changes in consumption requirements. Consideration of such effects using national and international market models and consequential LCA, for example, could provide a more exhaustive perspective on the overall environmental implications of the scenarios, reaching beyond the local implications and supporting strategy formulation at a national level.

Finally, the involvement of stakeholders in the process of developing suitable adaptation strategies, as it was part of AGWAM, is essential. Research can provide options for climate change adaptation to the farming community and administrations, but these options must be balanced against stakeholder expectations and socioeconomic and political constraints. In the light of an uncertain path of climate change, such an interdisciplinary approach ensures that adaptation strategies are robust and that excessive budgetary expenditures can be avoided.

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ART-Schriftenreihe 19

Water Demand in Swiss Agriculture – Sustainable Adaptive Options for Land and Water Management to Mitigate Impacts of Climate Change (AGWAM)

Agriculture will in future be strongly affected by climate change. As temperatures increase and summer precipitation decreases, the quantity and quality of harvests is likely to decline. Farmers must therefore consider measures for adapting their plant and livestock production, e.g. in terms of crop rotation, irrigation or choice of livestock. Such adaptations, however, can have negative impacts on the environment, possibly causing nutrients to wash out of the soil more readily, or erosion to increase. A growing need for water in agriculture could also create conflicts with other water users. To minimize such impacts and conflicts, policy measures that promote adaptation strategies at both single-farm and landscape-planning level are needed.

As part of the National Research Programme "Sustainable water management" (NRP 61), Agroscope and ETH Zurich research groups devised options for adaptation at both regional and farm level by considering basic economic and policy conditions as well as possible negative repercussions on the environment. Taking Broye and Greifensee catchments as a basis, the interdisciplinary team developed and applied biophysical and economic models, spatial optimization routines and life-cycle assessment tools in order to identify and evaluate different adaptive strategies for coping with conditions projected by two climate scenarios for 2050. Farmers as well as stakeholders from the planning and policy sectors were involved in the project. The experts agreed that the recommended adaptive strategy should be something of a compromise solution, i.e. stable productivity accompanied by low environmental impact, which should at least be theoretically possible according to the research results.

The present report summarizes the background, approach and methodology of the AGWAM project, provides an overview of key results, and concludes with recommendations serving as a basis for decision-making with respect to sustainable water management in Swiss agriculture under changing climatic, economic and policy conditions.

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