Doctoral Thesis

Optimising dairy production systems through supra-regional collaboration between farms in the lowland and mountain regions

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OPTIMISING DAIRY PRODUCTION SYSTEMS THROUGH SUPRA-REGIONAL COLLABORATION BETWEEN FARMS IN THE LOWLAND AND MOUNTAIN REGIONS

A thesis submitted to attain the degree of

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presented by

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Summary

Switzerland features very different agricultural regions, ranging from relatively flat areas in the Central Plateau to mountainous areas in the Alps. Dairy farming is practiced in all geographical regions, but mountain farms are challenged by natural constraints such as steeper slopes and shorter vegetation periods, making farming in these areas less viable. The lower productivity of mountain areas also has another drawback: The environmental impact of products from the mountains is often higher compared to production on lowland farms. This is also the case for milk, as the environmental impact per kg of milk from mountain farms is higher. However, the role of mountain farms goes beyond the mere production of food. They prevent the area from forest encroachment and thus preserve the traditional landscape. Furthermore, extensively managed mountain farming areas have a high nature value, offering very unique habitats for various species.

The aim of this thesis was to test whether the Swiss contract rearing scheme could help to improve the environmental impact of milk production while maintaining the high nature value of mountain farm areas. In this collaboration scheme, dairy farms in the lowlands focus on the actual milk production, and outsource their young stock to a mountain farm specialised in heifer rearing.

The main method to quantify the environmental performance of dairy production systems applied in this thesis was life cycle assessment (LCA). Dairy production systems are multi-output systems, where milk, meat and manure are produced. A comparison of such systems is challenging, as the way inputs and emissions are allocated between the different outputs can influence the results. Therefore, in a first step several allocation procedures were tested to identify the most suitable approach for the purpose of this thesis. For the allocation between milk and meat, a physical causality approach was chosen, while system expansion turned out to be the most holistic approach for dealing with manure exported from the dairy production system.

Based on simulated farms representing average dairy farms from the lowland and mountain region, it was shown that mountain farms had higher environmental impacts for both phases of the dairy production system, the actual milk production and the rearing of heifers. However, this disadvantage was less pronounced for heifer rearing, resulting in a comparative environmental advantage on mountain farms for this activity, while lowland farms had a comparative environmental advantage for milking. Thus, milk produced in the contract rearing scheme had a slightly lower environmental impact compared to a situation where the mountain and lowland farms would both produce milk and rear the restocking animals on their own farm.

The same comparison was then performed with a sample of eight farms from the lowlands and eight farms from the mountains. Half of these farms were collaborating farms, i.e. farms that practiced the contract rearing scheme, the other half were non-collaborating farms, i.e. dairy farms that kept their own restocking animals. With real farms, differences between dairy production with and without collaboration were more pronounced, with the contract rearing system having the lower
The contract rearing system was not only improving the environmental impact of milk, it also led to a lower environmental impact per hectare on mountain farms. In the lowlands, the LCA showed no differences between farms that collaborated with mountain farms and those that were rearing their own heifers, but an additionally performed assessment of the nitrogen balance on farms revealed a lower nitrogen surplus on collaborating lowland farms.

Contract rearing also had an influence on farm income. The collaborating lowland farms from the sample achieved a higher net income per hectare compared to the non-collaborating lowland farms. On the sample mountain farms, there was a trend for higher net incomes per hectare on farms specialised in heifer rearing, but this difference was not significant. Nevertheless, as the workload on heifer rearing farms was half as high as the workload on mountain dairy farms, heifer rearing farms reached a higher income per working hour. They also achieved a higher off-farm income, which indicates that they were able to invest the saved time on farm into alternative off-farm labour. However, there is a drawback of becoming specialised in heifer rearing: Mountain farmers become dependent on the lowland farms’ demand for their service. Once they have invested into a new housing system optimised for heifer rearing, an easy return to dairy production is not possible.

The results from simulated and real farms show the potential of the contract rearing scheme to reduce the environmental impact of dairy production to some extent. In an environment of ongoing pressure on the dairy market and milk prices, a specialisation in heifer rearing can be an attractive production alternative for mountain dairy farmers and prevent them from abandoning their land, while lowland farms could benefit from efficiency gains.
Zusammenfassung

In der Schweiz findet man ganz unterschiedliche landwirtschaftliche Regionen, vom vergleichsweise flachen Mittelland bis hin zu den bergigen Gebieten in den Alpen. Milch wird in allen Regionen produziert, wobei Bergbetriebe aufgrund der natürlichen Produktionsbedingungen vor größeren Herausforderungen stehen: Die steileren Hänge und die kürzere Vegetationszeit sorgen für einen Wettbewerbsnachteile. Hinzu kommt, dass die tiefere Flächenproduktivität in Berggebieten meist auch dazu führt, dass in den Bergen produzierte Produkte im Vergleich zur Produktion im Flachland eine höhere Umweltbelastung je Produkteinheit aufweisen. Dies ist auch bei der Milchproduktion der Fall, was sich in einer höheren Umweltbelastung pro kg Milch widerspiegelt. Andererseits geht die Bedeutung der Bergbetriebe über die rein Nahrungsmittelproduktion hinaus. Bergbetriebe schützen ihre Flächen vor Wald- und Straucheneinwuchs und erhalten so die traditionelle Bergkulturlandschaft. Zudem weisen extensiv bewirtschaftete Flächen im Berggebiet einen hohen Naturwert auf, indem sie einzigartige Habitate für diverse Spezies bieten.

Ziel dieser Arbeit war es herauszufinden, ob durch Vertragsaufzucht im Berggebiet die Umweltwirkungen der Milchproduktion reduziert und gleichzeitig der hohe Naturwert der Flächen auf Bergbetrieben erhalten werden kann. In dieser überregionalen Zusammenarbeitsform fokussieren sich Talbetriebe auf die eigentliche Milchproduktion, und gliedern die Aufzucht des Jungviehs an Bergbetriebe aus.

Die Hauptmethode, die im Rahmen dieser Arbeit zur Bewertung der Umweltwirkungen zum Einsatz kam, war die Ökobilanz. Die Milchproduktion ist ein System welches verschiedene Endprodukte hervorbringt, namentlich Milch, Fleisch und Hofdünger. In Ökobilanzen ist der Vergleich solcher Systeme eine Herausforderung, da die Umweltwirkungen des gesamten Produktionssystems auf die verschiedenen Endprodukte allokiert werden müssen. In einem ersten Schritt wurden daher verschiedene Allokationsmethoden getestet, um die für den Zweck dieser Arbeit beste Methode zu identifizieren. Für die Allokation zwischen Milch und Fleisch wurde der Ansatz der physisalen Kausalität gewählt. Im Falle von Hofdüngern, welcher ausserhalb des Milchproduktionssystems ausgebracht wurde, stellte sich die Systemerweiterung als umfassendste Methode heraus.

Mittels Modellbetrieben, welche durchschnittliche Milchbetriebe im Tal und Berggebiet repräsentierten, konnte gezeigt werden, dass Bergbetriebe sowohl bei der eigentlichen Milchproduktion als auch bei der Aufzucht des Jungviehs höhere Umweltwirkungen aufwiesen. Allerdings war dieser Nachteil in der Jungviehaufzucht weniger deutlich, was zu einem komparativen Umweltvorteil für die Aufzucht im Berggebiet führte, während die Talbetriebe über einen komparativen Umweltvorteil für die Milchproduktion verfügten. Dies führte dazu, dass Milch, welche in einem auf Vertragsaufzucht aufbauenden Produktionssystem produziert wurde, leicht tiefere Umweltwirkungen
Zusammenfassung

aufwies im Vergleich zu einer Situation, in welcher sowohl Bergbetriebe als auch Talbetriebe Milch produzieren und ihr eigenes Jungvieh aufziehen.


Die Vertragsaufzucht hatte auch einen Einfluss auf das Betriebseinkommen. Die zusammenarbeitenden Talbetriebe in der Stichprobe wiesen ein höheres Nettoeinkommen pro Hektare auf als die nicht zusammenarbeitenden Betriebe. Bei den Bergbetrieben gab es eine Tendenz zu höheren Einkommen auf zusammenarbeitenden Betrieben (Aufzuchtbetrieben), allerdings war dieser Unterschied nicht signifikant. Da aber die Arbeitsbelastung bei der Aufzucht im Vergleich zur Milchproduktion deutlich tiefer lag, erreichten diese Betriebe ein höheres Einkommen pro Arbeitsstunde. Die Betriebe verfügten zudem über höhere ausserlandwirtschaftliche Einkommen, was darauf hinweist, dass sie die eingesparte Zeit in andere Aktivitäten investieren konnten. Die Spezialisierung auf Aufzucht bringt aber auch Nachteile mit sich. So sind für eine Umstellung von Milch auf Aufzucht Investitionen in das Stallsystem nötig, so dass eine einfache Rückkehr zur Milchproduktion nicht möglich ist.

Die Resultate der modellierten und realen Betriebe zeigen, dass die Vertragsaufzucht das Potenzial hat die Umweltwirkungen der Milchproduktion leicht zu reduzieren. Mit dem zunehmenden Preisdruck im Milchmarkt kann eine Spezialisierung auf Aufzucht eine attraktive Alternative zur Milchproduktion im Berggebiet darstellen, während Talbetriebe von einer Effizienzsteigerung profitieren.
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1 General introduction

1.1 Different regions – different suitability for agricultural land use

Agricultural production takes place in different topographic and climatic regions of the world, but not all of them are equally suitable for agricultural production. Some areas face natural constraints due to poor soil quality, steep slopes, or climatic conditions, or have poor market access as a result of their remote location. Traditional farming practices in less favoured regions are rather extensive. This means that they use few external inputs, and produce a relatively low amount of outputs. In addition to the provision of agricultural products, these systems also preserve traditional agricultural landscapes appreciated by locals and tourists and provide habitats of high nature value. However, farming itself is often not viable compared to farming in other, more favourable regions or compared to wages from alternative jobs. Therefore these regions are threatened by abandonment (Gellrich and Zimmermann, 2007; MacDonald et al., 2000; Rudow, 2014). On the other hand, a progressing intensification is observed in regions with more favourable conditions for agricultural production, with increased use of mineral fertilisers, pesticides and landscape simplification to facilitate the cultivation with large machinery (Katayama et al., 2015). The reasoning behind intensification is an increased efficiency, and thus a higher profitability of the farms.

Both tendencies, the abandonment of less favourable and the intensification of favourable land influence the environmental impact of agricultural production and the landscapes in the respective regions. Intensification often goes along with environmental problems on a local level, such as an increased eutrophication of water or higher nitrate levels in tap water (Guerci et al., 2013). It is also associated with a loss of biodiversity. Land abandonment, conversely, can have positive effects when it leads to a recovery of a highly biodiverse native habitat, or negative effects in cases where farmland was managed in a way that it offered diverse habitats of high nature value that exceeded the biodiversity of the natural flora and fauna. Positive effects of land abandonment are more common in tropical and subtropical regions, while in temperate regions negative effects predominate (Katayama et al., 2015).

In a European context, many countries have developed schemes to support farmers in order to prevent land abandonment. In the EU, such areas have been classified as less-favoured areas in the past. Over 50 % of the agricultural area in the EU-28 countries fall into this category, and thereof 30 % are classified as mountain areas. Mountain areas are characterized by a short vegetation period and/or steep slopes. Areas above a latitude of 62° north are also considered as mountain areas (Figure 1). The delimitation is currently being revised under a new scheme defining “areas facing natural or specific constraints”, where the definition of the non-mountainous areas with constraints will be harmonized among the different member countries, while the definition of the mountain
area remains unchanged (European Commission, 2015). Active farmers in areas classified as mountain area or less-favoured areas / areas facing natural or specific constraints receive additional payments in order to compensate for the income gap between them and farmers in non-classified areas (Rudow, 2014).

An even more refined system is applied in Switzerland, with the aim of fostering sustainable agricultural practices. There, agricultural area is classified into six different zones, with a lowland zone (the most favourable agricultural zone), a hill zone, and four mountain zones (Figure 2). The lowland zone covers almost half of the total agricultural area, while the four mountain zones cover approximately 40%. Similar as in the less favoured areas in the EU, farms in the hill and mountain zones receive additional financial support, which is highest in mountain zone IV (El Benni and Finger, 2013). The financial support of farms in the mountain zones helps to prevent farms from abandoning their land. The percentage of farmers that quit farming is on a comparable level in all agricultural zones. The average yearly decrease in farm numbers between 2000 and 2015 was 1.9% in the lowland zone, 1.6% in the hill zone, and 1.7, 1.8, 2.2, and 2.0% in the mountain zones I–IV, respectively (Swiss Federal Statistical Office – SFSO, 2016). Land outside of these zones is not accounted as agricultural area, and is either unproductive, or used for alpine summer grazing. Alpine summer pasture farms are operated during summer month only, for approximately 100 days. These farms receive special subsidies if they keep an animal number suitable to maintain these

![Figure 1. Delimitation of the less favoured areas in the EU (European Environment Agency – EEA, 2010)](image)
1.2 Dairy production and its environmental impact

Grasslands open (Schulz, 2015). Nevertheless, summer pasture farms have more and more difficulties to achieve a sufficiently high stocking rate. Therefore, an additional incentive was introduced in the current agricultural policy. In addition to the subsidies paid to alpine summer pasture farms, farms within the agricultural zones sending animals to such summer pasture farms receive further financial contributions (Mack and Flury, 2014).

![Figure 2 - Delimitation of the agricultural production zones in Switzerland, and location of the cantons Thurgau and Grisons (Federal Office for Agriculture – FOAG, 2015; swisstopo, 2016)](image)

Similar tendencies have also been observed in other alpine regions, where farms no longer use the additional feed resources from summer pastures, but instead intensify the production system on their home-farm, for instance with higher yielding dairy cows, and consequently rely on imported feed to sustain the need of their animals. However, an intensification in the mountain zone reduces the nature value of the farm land (Battaglini et al., 2014). In order to maintain the quality of the habitats and landscapes mountain farming provides, agricultural policy should not only prevent mountain farms from abandonment, but also support production systems, that are suitable to this specific and vulnerable environment. For the more favourable production zones, on the other hand, a certain intensity, often denominated as sustainable intensification (Garnett et al., 2013), is reasonable, in order to fulfil agriculture’s main objective, the provision of enough food.

1.2 Dairy production and its environmental impact

For mountainous areas, competitive crop production is not possible due to a rather short vegetation period. Therefore, farming is mostly grassland based, and thus relies on animals that are able to convert grass into valuable products. Dairy and other cattle based production systems therefore
dominate in the mountainous areas in Switzerland, where 80 % of all farms in the mountains keep cattle (Swiss Federal Statistical Office – SFSO, 2016). However, cattle production raises increasing concerns with regard to its environmental impact. Due to its emissions of the greenhouse gasses methane from enteric fermentation and nitrous oxide from manure emissions, it is an important contributor to climate change. In 2014, cattle was responsible for 73 % and 11 % of Switzerland’s methane and nitrous oxide emissions, respectively (Federal Office for the Environment – FOEN, 2016). Cattle production also contributes to acidification due to ammonia emissions both from the storage and application of manure (65 % of total Swiss ammonia emissions in 2010 according to Kupper et al., 2013), and to the eutrophication of water caused by manure application and the loss of nutrients through erosion, runoff, or leakage (Withers et al., 2014). In addition to these direct impacts, further impacts of cattle production are related to the inputs used on the farms, such as purchased concentrates, fertilisers or energy carriers.

Of all cattle production systems, dairy farming is the most abundant in Switzerland, both in lowlands and mountains. Therefore, an improvement of the environmental performance of dairy production could contribute significantly to a reduction of the environmental performance of agriculture in this country. The strategies to reduce impacts are diverse. Strategies can be of technical nature (manure application method, manure storage system; de Vries et al., 2015), focus on the reduction of emissions from enteric fermentation (feed additives, feed composition; Beauchemin and McGinn, 2008), or focus on the management strategy (organic or conventional farming, grassland-based milk production, choice of dual purpose or specialized dairy breeds; CEAS Consultants, 2000). Some of these possible solutions, especially those related to management decisions, can lead to trade-offs between the environmental impact per area and per product. For example, pasture-based milk production without concentrate feed reduces the environmental impact per hectare compared to indoor feeding with silage and concentrates, but due to a lower milk yield achieved in the pasture system, the environmental impact per kg of milk is higher (Sutter et al., 2013). As long as milk consumption is not reduced, systems with lower milk yield will only shift the environmental burden to other regions or systems, e.g. when additional milk has to be imported. Real improvement within the dairy production system can only be achieved when both, the impact per area and the impact per product unit can be reduced.

1.3 The Swiss contract rearing system

There are three different strategies for restocking of dairy herds: (1) rearing the young stock on the own farm, (2) purchasing restocking animals from the market, or (3) contract rearing. In contract rearing, dairy farmers outsource their young stock to another farm, and focus on the productive dairy herd. The advantage of contract rearing compared to purchasing animals from the market lies in the possibility of the dairy farms to bread their own animals, and thus increase the genetic merit
of their herds. The main driver for contract rearing systems is an increase in the size of dairy farms and thus the need for a facilitated management (Olynk and Wolf, 2010).

The particularity of the Swiss contract rearing system lies in its supra-regional character. It has been established in the 1960ies, when farmers from the canton of Thurgau, situated in the lowlands (Figure 2), were seeking for a possibility to increase dairy production. They realised that the quality of the grassland in the lowlands was above the needs of the less demanding young stock, and started to collaborate with farms from the canton of Grisons. The canton of Grisons is situated in the mountain area, and although the grassland in this canton is of lower quality, it is still well suitable for heifer rearing (M. Tanner, 20 October 2015, personal communication). Today, the collaboration between the farms is formalised through standardised contracts. These standardised contracts are a result of an annual renegotiation between representatives from the mountains and lowlands. Through this contract, the lowland farmers sell their calves to the mountain farmers. Calves can either be sold unweaned at an age of approximately 14 days, or weaned at an age of approximately four months. By selling the calves, the whole responsibility for the animals is transferred to the heifer rearing farms, but they have a guarantee that the lowland farms will purchase the animal back in the case of successful rearing. The animals are purchased back when close to calving. Both, the price of the calves and the heifers in calf are defined in the contract, with two pricing systems to choose from: (1) a monthly flat rate based on the achieved age at first calving, or (2) a pricing based on weight gains (Agridea, 2015). During the period of the milk quota system in Switzerland (1977–2009) the contract rearing system was supported through extra quotas awarded for lowland farmers buying heifers from mountain farms, and since 2000 additionally through a regulation that allowed a transfer of milk quota from mountain farms to lowland farms in cases of contract rearing (Federal Office for Agriculture – FOAG, 2001). Since the phase out of milk quotation, the system is no longer supported, still the demand for contract rearing increased slightly (Sutter, 2012).

1.4 Objective and outline

Well adapted cattle production systems in mountainous regions and a sustainable intensification in more favoured regions could be a solution to maintain high nature value areas in the sensitive mountain areas, without compromising the main goal of agriculture: The provision of enough food for society. The aim of this doctoral thesis was to study whether the Swiss contract rearing system is a viable option to address these conflicting interests. The environmental analysis of the system was based on life cycle assessments (LCA), and supplemented with an assessment of farmers’ workload and some economic indicators.

This thesis is structured as follows: Chapter 2 introduces the method of life cycle assessment (LCA) in the context of dairy production. A special emphasis is set on different allocation proce-
dures in dairy production systems. In Chapter 3 different allocation procedures and system boundaries are tested, in order to identify a suitable way to compare farms that produce different outputs, such as milk, meat and in some cases cash crops. In Chapter 4, collaborative milk production, where heifers are reared in the Swiss contract rearing system, is compared to non-collaborative milk production, where heifers are reared on the home farm. Based on simulated farms, this comparison is performed in an environmental, economic and workload context. Chapters 5 and 6 are based on data from eight collaborating and eight non-collaborating farms from the mountain and lowland region. Effects of collaboration on socio-economic and agronomic indicators such as income, workload, nitrogen balance, or feed autonomy are shown in Chapter 5. Results of an LCA of the environmental impact per hectare farm area and per kg of milk are presented in Chapter 6. This thesis ends with a general discussion and conclusion in Chapter 7.
2 Life cycle assessment for quantifying the environmental impact of dairy production

Life cycle assessment (LCA) is a method to quantify the environmental impact of products or processes from “cradle to grave”. By taking into account the full life cycle of products, it allows to identify trade-offs or feedbacks that an optimisation of a single aspect of the production process may have on other aspects (Hellweg and Milà i Canals, 2014). For example, if dairy farmers decide to use more concentrate in their feed ration, in order to reduce methane emissions from enteric fermentation, the beneficial effect within the farm could be at least partially compensated by increased deforestation in another part of the world, especially if more soya meal is used in the feed ration.

The general procedure of LCA is defined by two standards: ISO 14040 and ISO 14044 (ISO, 2006a, b), where four phases of LCA are specified. In the first phase, the definition of goal and scope, the objectives and system boundaries of the study are defined. In LCA of dairy production, a typical goal would be a comparison of different production systems in order to identify the most environmental friendly system, and to identify hot-spots for optimisation (e.g. Thomassen et al., 2008b). The system boundaries in such studies are often defined as “cradle to farm gate”, which means that all upstream processes as well as all activities on the farm are considered, but the transport of the milk to a dairy or the further processing into consumable products, consumption, and disposal are excluded from the study. In most cases it is justifiable to skip the downstream processes, as changes within the farming system will not affect the way milk is handled after it has left the farm. The so called functional unit, i.e. the product or service used as a reference to which all environmental impacts are related, is then commonly defined as 1 kg of milk at farm gate. Another important aspect of the goal and scope definition is the selection of an appropriate allocation procedure. As this decision has the potential to largely influence the results, it is discussed in Chapter 2.1.

The second phase of an LCA, the life cycle inventory (LCI), is the phase where data are compiled. For dairy production systems, primary data are either collected directly on the farm, or taken from existing data bases such as the farm data accountancy networks (FADN) available for most European countries (e.g. Thomassen et al., 2009). Primary data include the number of animals, feed production and purchases, infrastructure, energy inputs, but also data about the amount of sold milk and by-products such as meat or manure. Direct emissions, e.g. from enteric fermentation, fertiliser application or the combustion of fuels, are commonly not measured but modelled. As a last step, these data are related to the functional unit, under consideration of the allocation procedures defined in the goal and scope definition phase.
In the third phase of the LCA, the life cycle impact assessment (LCIA), the inventory data are linked to environmental impact categories, and converted into a common unit for each impact category. This conversion is performed with so called characterisation factors. Taking the example of the impact category “global warming potential”, this is done as follows: All emissions of greenhouse gasses, e.g. carbon dioxide, methane or nitrous oxide, are expressed as CO$_2$ equivalents based on their global warming potential in relation to CO$_2$. For instance, one kg of N$_2$O causes the same warming effect as 265 kg of CO$_2$ (Myhre et al., 2013), and thus the amount of N$_2$O emitted is multiplied by this (characterisation) factor to get the CO$_2$ equivalents. In order to cover the whole life cycle of the analysed products, this is not only done for the emissions that occur directly on the farm, but also for all the emissions that the different inputs have caused. If a farm purchases feed, the emissions caused on the field where the feed was produced, the emissions from inputs used on the feed producing farm, such as fertilisers or fuel, and from transports are included as well. Information about the impacts caused by these inputs are commonly taken from life cycle inventory databases, such as ecoinvent® or GaBi®.

The fourth phase of the LCA is dedicated to the interpretation of the results, in order to answer the questions defined in the goal and scope phase.

2.1 Allocation procedures

In cases where more than one output is produced in a system, inputs and emissions of this system need to be allocated to the different outputs. Dairy production is a typical multi-output system, where milk is considered the main output, with meat from culled cows and surplus calves, and in some cases also manure as the co-products. Therefore, dairy production is used in different studies to test different allocation procedures (e.g. Flysjö et al., 2011; Zehetmeier et al., 2011). The standard ISO 14044:2006 proposes a stepwise procedure to define the suitable allocation method (ISO, 2006b):

a) Step 1: Wherever possible, allocation should be avoided by
   1) dividing the unit process to be allocated into two or more sub-processes and collecting the input and output data related to these sub-processes, or
   2) expanding the product system to include the additional functions related to the co-products (...)

b) Step 2: Where allocation cannot be avoided, the inputs and outputs of the system should be partitioned between its different products or functions in a way that reflects the underlying physical relationships between them; i.e. they should reflect the way in which the inputs and outputs are changed by quantitative changes in the products or functions delivered by the system.
c) **Step 3: Where physical relationship alone cannot be established or used as the basis for allocation, the inputs should be allocated between the products and functions in a way that reflects other relationships between them.** For example, input and output data might be allocated between co-products in proportion to the economic value of the products.

For the allocation between milk and meat, there is no clear consensus in literature on the right procedure to be chosen. A sub-division of the system is not possible, as the systems are too closely interlinked. Thus, following the ISO standard, system expansion is the best procedure. System expansion can be performed either in an additive (basket of benefits) or subtractive way (credits for displaced products). The additive system expansion works as follows: When dairy production system A produces 1000 kg of milk and 10 kg of meat, and dairy production system B produces 1000 kg of milk and 20 kg of meat, an amount of 10 kg of meat from alternative sources is added to system A, in order to compare two systems with the same amount of outputs. The subtractive system expansion works as follows: The environmental impact of the production of 10 and 20 kg alternative (displaced) meat is credited to dairy production system A and B, respectively. The remaining emissions are all attributed to the 1000 kg of milk. Ideally, the alternative meat should be produced in a mono-output system, e.g. from suckler beef, pork or poultry production systems. The challenge with both system expansion approaches is to identify the right alternative meat production system. This is mainly a question of the meat market (i.e. which meat alternatives are available if dairy production systems would reduce their output of meat), the preference of consumers (i.e. are they willing to substitute a T-bone steak with a chicken breast), or religious reasons (pork cannot substitute beef in a kosher or halal diet).

This makes the approach of system expansion challenging, and less suitable for an international standard. In its guideline for LCA in the dairy sector, the International Dairy Federation (IDF, 2015) recommends to use the physical causality approach developed by Thoma et al. (2013). There, the physical causality is based on the net energy available for lactation and growth. As in most cases the exact feed consumption of the animals as well as the energy content of the feed are unknown, they developed a simplified approach based on empirical data from 536 dairy farms in the United States to calculate the allocation factor. The simplified formula only requires information on the quantities of milk and meat produced within the dairy production system.

Although defined as the “last resort” by ISO, economic allocation is so far the most commonly used method for dairy LCA (de Vries and de Boer, 2010). The economic allocation factor for milk is defined as the revenue from milk sales divided by the sum of revenues from milk and meat sales.

For manure exported from the dairy system and used as a fertiliser, the most commonly chosen allocation procedure is the sub-division of the processes related to manure management. The process manure storage (e.g. direct emissions during storage, storing infrastructure) is attributed to the dairy system, while application processes (e.g. direct field emission, machinery) are attributed to the crop where manure is applied. This procedure is recommended by the 2015 version of the LCA
guideline of the International Dairy Federation (IDF, 2015). The previous version of the LCA guideline of the IDF proposed system expansion for exported manure. In this system expansion, the exported manure substituted mineral fertilisers at the crop production, and it was recommended to credit these substituted mineral fertilisers to the dairy production system (IDF, 2010). Other allocation methods, such as physical causality or economic allocation are less common for manure. Physical causality approaches, like the one by the IDF, are commonly focusing on the net energy available for growth and lactation (Thoma et al., 2013). Net energy is defined as the energy after subtraction of energy losses through faeces, urine, methane and heat, and thus an allocation between meat, milk and manure on this level is not possible. Economic allocation is, in the case of manure, also not feasible, as manure has usually no value when it leaves the dairy system (IDF, 2015).

2.2 Impact assessment methods

Comparative LCA studies should, according to ISO 14044:2006, consider a “sufficiently comprehensive set of category indicators” (ISO, 2006b). The impact categories used for at least one of the assessments in Chapters 3, 4 and 6 are the following:

**Acidification** is assessed according to the method EDIP2003 (Hauschild and Potting, 2005). Acidification is caused by the emissions of nitrogen oxides (NO\textsubscript{x}), ammonia (NH\textsubscript{3}), sulphur dioxide (SO\textsubscript{2}) and other acidifying emissions into the air. These emissions are converted and transported over long distances, before they are deposited. The deposition of such acidifying substances leads to increased acidity in both water and soil. In soils for instance, a low pH leads to weathering of minerals, and thus influences the availability of plant nutrients. Furthermore, it can mobilise toxic aluminium, which is harmful for vegetation. The dispersion of the acidifying substances is influenced by the region where they are emitted, and its effect caused on the location where the substances are deposited depends on the capacity of the affected system to compensate the entry of these substances. Therefore, EDIP2003 provides specific characterisation factors for different European countries. In this study, the characterisation factors for Switzerland were used. Acidification is expressed as the area becoming unprotected (acidification above the critical acidification load) in m\textsuperscript{2}.

**Deforestation** corresponds to the net area transformed from forest (e.g. natural or managed, tropical or boreal forest) or shrub land into all other land use types, such as agricultural. These land transformation categories correspond to the land transformation categories from ecoinvent® (Frischknecht et al., 2007a). Deforestation is expressed in m\textsuperscript{2} transformed area.

**Ecotoxicity** is assessed with the CML 2001 method (Guinée et al., 2001), supplemented with characterisation factors for various pesticides that were not covered by the original method (Hayer et al., 2010). The CML method distinguishes between freshwater aquatic, marine and terrestrial ecotoxicity, and evaluates the ecotoxicity potential of the input of different toxic substances into these ecosystems. The ecotoxicity potential is expressed in kg 1,4-dichlorobenzene equivalents (1,4-
2.2 Impact assessment methods

DB-eq), and the characterisation factors are defined by the maximum tolerable concentration of toxic substances in comparison to the maximum tolerable concentration of 1,4-DB. In an agricul-
tural context, emphasis is laid on the impact of pesticide applications. In this thesis, the Swiss Ag-
ricultural LCA (SALCA) method is used to calculate pesticide and heavy metal inputs into the ecosystem. As SALCA only models pesticide and heavy metal inputs into soil, but not into water, the focus of the present thesis is put on terrestrial ecotoxicity.

**Aquatic Eutrophication** is assessed with the method EDIP2003, corresponding to nutrient en-
richment in water. Nutrient enrichment leads to an increased growth of plankton and algae, disturb-
ing the natural balance of the aquatic environment. In severe cases, the subsequent decomposition
of this biomass leads to a reduction of the oxygen content, threatening water fauna. As in the case of acidification, the EDIP method provides specific characterisation factors for the different Euro-
pean countries, taking into account the quality of local waterways, nutrient transports through drain-
age and surface runoff. EDIP also distinguishes between the impacts of the two nutrients respon-
sible for eutrophication: nitrogen and phosphorus. Nitrogen is the generally limiting nutrient in ma-
ine waters, and thus an increase of nitrogen in marine waters is responsible for biomass growth
there, while phosphorus is mostly the limiting nutrient in freshwater and thus responsible for bio-
mass growth in rivers or lakes. Therefore, two different impacts for eutrophication are presented in
this thesis: **aquatic eutrophication due to nitrogen (N)** expressed in kg N input into surface and
groundwater, and **aquatic eutrophication due to phosphorus (P)** expressed in kg P input into
surface and groundwater.

**Global warming potential** is an indicator for the contribution to climate change, and is ex-
pressed as kg CO₂ equivalents (CO₂-eq). For most environmental impact categories, characterisa-
tion is performed based on effects that happen rather shortly after an emission. Not so for global
warming potential, where a distinction is made between gasses with a long lifetime, and gasses
defined as ‘near-term climate forcers’ causing an effect on global warming shortly after their emis-
sions. If global warming potential is analysed for shorter time spans, the near-term climate forcers
have a higher influence compared to an analysis on a longer time span. Thus, the characterisation
factors of the global warming potential of different gasses depend on the time span considered
(Myhre et al., 2013). In this thesis, 100 years are considered, as this is the most commonly used
time span.

**Land competition** is defined as the occupation of an area multiplied by the duration of this
occupation, expressed in square meter-years (m²a). This impact category is based on the different
land occupation categories (e.g. arable, industrial, managed forest, urban) from ecoinvent®
(Frischknecht et al., 2007a). The different categories are not weighted, i.e. no characterisation is
applied. Therefore, this impact category does not quantify the environmental impact of land use
directly, but it gives an information about the use efficiency of the scarce resource land. Possible
environmental impacts of land competition are mainly related to biodiversity, as the anthropogenic
land use not only competes with other anthropogenic land use types but also with the natural vegetation and fauna.

**Non-renewable energy demand** is defined as the cumulative energy demand from fossil and nuclear sources, as implemented in ecoinvent® (Frischknecht et al., 2007a). It is expressed in MJ equivalents (MJ-eq). Like in the case of land competition, non-renewable energy demand does not quantify the environmental impact of energy use itself. It is rather an indicator for the resource use efficiency of a system.

**Ozone depletion potential** refers to the depletion of ozone in the stratospheric ozone layer. This layer acts as a filter for solar UV-B radiation, and its depletion potentially causes damages on ecosystems and human health. In the past, ozone depletion was mainly caused by substances used as refrigerants, and the use of these substances has been phased-out by the Montreal Protocol. As refrigeration is not a major issue in farming, ozone depletion in agricultural production is mainly caused by the upstream processes, such as fuel production. Therefore, it is often not considered as being of importance for agricultural production. However, after the ban of many ozone depleting substances, nitrous oxide (N\textsubscript{2}O) has gained in importance and is now considered as the most important contributor to ozone depletion. Nitrous oxide is so far not considered by the commonly used impact assessment methods like CML 2001, EDIP2003, ReCiPe Midpoint 2008 (Goedkoop et al., 2009), as these methods consider only the substances mentioned in the Montreal Protocol, focussing on chlorofluorocarbons (CFC) and hydrochlorofluorocarbons (HCFC), and thus no solid estimation of the ozone depletion potential of N\textsubscript{2}O was available at the time the above mentioned impact assessment methods were developed. In 2009, Ravishankara et al. (2009) published an ozone depletion potential for N\textsubscript{2}O. As Ravishankara is a member of the scientific steering committee of the World Meteorological Organization’s “Global Ozone Research and Monitoring Project”, this value was considered as solid enough to be used in an impact assessment context. Therefore, in this thesis the EDIP2003 method was expanded with the ozone depletion potential of N\textsubscript{2}O. The ozone depletion potential is expressed in equivalents of CFC-11 (CFC-11-eq).

**Overall species diversity** is an indicator for biodiversity developed by Jeanneret et al. (2014). This model estimated scores for the species diversity of 11 indicator species groups (crop flora i.e. weeds, grassland flora, birds, small mammals, amphibians, snails, spiders, carabid beetles, butterflies, wild bees and grasshoppers). It considers the suitability of different fields on a farm as habitat for these species, as well as information of single events that interfere with these species, such as the date and technology of soil cultivation, fertilisation, cutting/grazing or harvesting. By weighing the scores of the individual indicator species groups according to their total species richness and their position in the food web, all 11 scores are aggregated into one biodiversity score, the overall species diversity (OSD) score. Higher scores indicate higher biodiversity.

**Phosphorus resource use** corresponds to the amount of phosphorus extracted from mineral sources, expressed in kg phosphorus. Phosphorus resource use itself is not an impact category in
the narrow sense, it corresponds to a life cycle inventory indicator based on inputs of mineral phosphorus as implemented in ecoinvent®. However, it is of importance as phosphorus is a relatively scarce and limited resource, and it is expected that this resource will become depleted within the next century (Cordell et al., 2009).

Potassium resource use corresponds to the amount of potassium extracted from mineral sources, expressed in kg potassium. Like phosphorus resource use, this category corresponds to a life cycle inventory indicator. Compared to phosphorus, potassium is less scarce, but the use of potassium can also be considered as an indicator for nutrient efficiency on farms.

Water use is a life cycle inventory indicator and corresponds to the amount of water extracted from groundwater, rivers, lakes or oceans, expressed in m³ (Frischknecht et al., 2007a).
3 Comparing the environmental performance of mixed and specialised dairy farms: The role of the system level analysed

This chapter is based on the same-titled paper written by Silvia M.R.R. Marton, Albert Zimmermann, Michael Kreuzer and Gérard Gaillard, published in Journal of Cleaner Production, 124, 73–83, 2016. doi:10.1016/j.jclepro.2016.02.074

Abstract

Mixed crop-livestock systems are often considered more environmental friendly compared to specialised systems, but due to the interactions between different farming activities, it is not trivial to quantify possible benefits. Using life cycle assessment (LCA), we tested different allocation procedures and system expansion through avoided burden to compare the environmental impact of milk from either specialised or mixed dairy production systems (product level). In a second approach, we compared the whole farming systems with additive system expansion, where the functional unit comprised milk, live animals sold for meat production and crops (farm level). On the product level, milk from the mixed farm had higher non-renewable cumulative energy demand, terrestrial ecotoxicity and phosphorus use, but lower aquatic eutrophication N, independently of the allocation method. For all other impact categories, differences were not significant. On the farm level, results were partially reversed. The mixed system had a lower energy demand and potassium use, while phosphorus use was higher. All other differences were not significant on farm level. The different rankings on product and on farm level were caused by the way manure was attributed to the farming activities. In order to avoid allocation, manure management was sub-divided into storage and application processes. Storage was attributed to dairy production, application to dairy production only if applied on grassland or feed crops, and to cash crops when applied to produce these crops. Manure applied on cash crop areas was thus out of the scope of the product approach, and mineral fertilisers that could be saved within the cash crop production were thus not attributed to milk production. We conclude that only system expansion was able to cope with the complexity of mixed farming systems in LCA. Based on our results with modelled farms, mixed farming showed the potential to reduce environmental impacts compared to specialised farming. Nevertheless, due to the complexity of the system regarding farm management and interactions between cropping and livestock activities, only an assessment with real farm data could reveal the actual benefits of such systems.
3 Comparing the environmental performance of mixed and specialised dairy farms

3.1 Introduction

Mixed farming systems combine cash crop and livestock production on the same farm. Such systems were very common in the past, but in industrialised countries increasingly specialised agricultural systems emerged (Ryschawy et al., 2012). With a rising concern about the environmental effects of agriculture, mixed farms are currently reconsidered, as they are assumed to be more efficient in nutrient cycling and to foster ecosystem services through an enhanced biodiversity (Lemaire et al., 2014). However, it is not evident to which extent these theoretical advantages are translated into effective environmental benefits. In a life cycle assessment (LCA) of Swiss dairy production, Alig et al. (2011b) found no significant differences between specialised and mixed farms per kg of milk. Veysset et al. (2014) even calculated a higher N surplus per ha and higher greenhouse gas emissions on mixed beef and crop farms compared to specialised beef farms in France. Both studies focussed on the livestock product, and did not compare the crop products from the mixed systems to those from specialised crop farms. However, the interactions between crops and livestock have benefits and drawbacks (Bell and Moore, 2012), and thus a focus on just one product category might not reflect the overall effect of mixed farming. For LCA studies, processes with co-products are challenging, as there are different approaches on how to allocate emissions to different outputs. Dairy production is a multi-output process per-se, with the outputs being milk and live animals sold for meat production. Various studies therefore used dairy production to illustrate the influence of different co-product handling methods on LCA results and interpretation (Bartl et al., 2011; Cederberg and Stadig, 2003; Flysjø et al., 2011; Thomassen et al., 2008a). They showed that the choice of the co-product handling method has a significant influence on the absolute results, and some even showed that the ranking between production alternatives can change depending on the method chosen (Flysjø et al., 2012; Zehetmeier et al., 2011). All these studies were based on specialised dairy production systems, i.e. systems that only produced milk and meat. If the dairy production happens on a mixed crop-livestock farm, this adds further complexity to the system. The livestock system provides manure for the cropping system, and part of the cropping system produces feed for the livestock system. These interactions might have an influence on the environmental performance of the different products on the farm and the whole farming system. In order to identify the most suitable method to compare mixed and specialised farming systems in LCA, we therefore analysed the effect of different co-product handling methods as well as different system boundaries when comparing specialised and mixed dairy production systems.

3.2 Methods

In the present study, a specialised and a mixed dairy system were modelled. The LCA was performed on both product and farm level. On the product level, we focussed on milk as the primary product and tested different co-product handling methods between milk and its co-product meat.
On the farm level, we considered all products of the farming systems, i.e. milk, meat and crops. The latter approach was more holistic and aimed at including all possible effects of mixed farming systems compared to specialised ones. The focus was put on the ranking of the different systems and not primarily on the absolute results.

### 3.2.1 Dairy production systems

Our analysis focussed on dairy production in the Swiss lowlands, where both specialised and mixed dairy farms can be found. In order to get representative farms for the two systems, we modelled the farms based on the average specialised and the average mixed dairy farms as obtained from the Swiss Farm Accountancy Data Network (FADN; Mouron and Schmid, 2011). Table 1 gives an overview about the main characteristics of the simulated farms. The average specialised lowland dairy farm kept 33.1 livestock units (LU) and had an agricultural area of 20.3 ha. Thereof 17.7 ha were grassland, 1.1 ha silage maize and the remaining part was used for other crops. The average mixed lowland dairy farm kept 29.9 LU and had an agricultural area of 26.8 ha, thereof 12.3 ha grassland. The cropping area was used for both, cash and feed crop production. On both farms, the LU consisted mainly of dairy cows and young stock, with some minor quantities of other animal categories, like fattening pigs. For the simulated farms, we presumed that the farms only kept dairy cattle, i.e. dairy cows and young stock. In order to cover the full dairy production cycle, i.e. from the birth of a female dairy calf until the end of the productive life of a dairy cow, we attributed the LU on the farms to the two animal categories young stock and dairy cows, based on a restocking rate of 0.29 cows per year and an age at first calving of 30 months (Boessinger et al., 2013). The mixed farm was assumed to produce less meat per kg milk, because the total milk production per cow was higher on this farm type (Mouron and Schmid, 2011). This higher milk yield on mixed farms was achieved with a higher amount of concentrate fed to the cows, which was produced in part on the farm.
3 Comparing the environmental performance of mixed and specialised dairy farms

Table 1. Main characteristics of the simulated specialised and mixed dairy farms.

<table>
<thead>
<tr>
<th></th>
<th>Specialised dairy farm</th>
<th>Mixed dairy farm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total LU</td>
<td>33.1</td>
<td>29.9</td>
</tr>
<tr>
<td>Dairy cows (LU)</td>
<td>25.7</td>
<td>23.2</td>
</tr>
<tr>
<td>Young stock (LU)</td>
<td>7.4</td>
<td>6.7</td>
</tr>
<tr>
<td>Milk yield (kg FPCM sold / cow)</td>
<td>6540</td>
<td>6940</td>
</tr>
<tr>
<td>Usable agricultural area (ha)</td>
<td>20.3</td>
<td>26.8</td>
</tr>
<tr>
<td>Grassland including leys (ha)</td>
<td>17.7</td>
<td>12.3</td>
</tr>
<tr>
<td>Maize, silage and grain (ha)</td>
<td>1.2</td>
<td>3.1</td>
</tr>
<tr>
<td>Cereals (ha)</td>
<td>1.0</td>
<td>7.3</td>
</tr>
<tr>
<td>Beets and potatoes (ha)</td>
<td>0.1</td>
<td>2.4</td>
</tr>
<tr>
<td>Other crops incl. perennials (ha)</td>
<td>0.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Sold products</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Milk (kg FPCM)</td>
<td>168,142</td>
<td>161,009</td>
</tr>
<tr>
<td>Animals for meat production (kg LW)</td>
<td>6,496</td>
<td>5,863</td>
</tr>
<tr>
<td>Cereals (kg DM)</td>
<td>4,547</td>
<td>37,963</td>
</tr>
<tr>
<td>Maize (kg DM)</td>
<td>671</td>
<td>2,421</td>
</tr>
<tr>
<td>Beets and potatoes (kg DM)</td>
<td>1,109</td>
<td>31,893</td>
</tr>
<tr>
<td>Other crops (kg DM)</td>
<td>1,083</td>
<td>4,947</td>
</tr>
</tbody>
</table>

DM: dry matter; FPCM: fat and protein corrected milk; LU: Livestock units; LW: live weight

3.2.2 Life cycle assessment

In order to identify a suitable method to compare crop-livestock systems, two different LCA approaches were tested. These were a product approach and a farm approach. The product approach focussed on milk production, while the farm approach integrated all products obtained from the activities in the entire farming system, i.e. milk, live animals for meat production and cash crops.

3.2.2.1 Goal and scope

The goal of the product approach was to compare the environmental impact of milk production, while the farm approach aimed at comparing the impact of a basket of products generated by the farms. Both, the product and the farm approach, included all environmental impacts from cradle to farm gate. All inputs and outputs of the farm were considered and no cut-off criteria were applied. The farming system itself was sub-divided into two farm enterprises (FE), both with their own system boundaries: dairy and cash crops. The FE dairy produced milk and the co-product meat from culled animals and surplus calves. It included all processes related to the husbandry of dairy cows and young stock, such as direct emissions generated by the animals or the storage of its manure, forage and concentrate feed production on the farm including direct emissions of applied fertilisers and manure, external inputs and infrastructure for keeping the animals. The FE cash crops included
3.2 Methods

all processes related to the production of sold crops, such as external inputs, machinery, and direct emissions from the application of fertilisers and manure (Figure 3). The system boundaries of the product approach were limited to the FE dairy, while the farm approach included all FE on the farm. Both approaches had their own definition of the functional unit and different methods to cope with multiple outputs from the production systems.

![Figure 3. System boundaries of a dairy farm and its farm enterprises (FE)](image)

**Product approach**: The functional unit was 1 kg FPCM at farm gate. As the dairy system had two outputs, milk and live animals for meat production, the environmental impact of the dairy system needed to be allocated between the two products. Previous studies have shown that different allocation methods may influence the results (e.g. Flysjö et al., 2012; Zehetmeier et al., 2011). Therefore, four different co-product handling methods were applied in the present study to evaluate their influence on the result: physical causality allocation, economic allocation, and two system expansion alternatives. We performed physical causality allocation based on the guidelines from the IDF (2010) and economic allocation based on price information from Boessinger et al. (2013). For system expansion, we assumed that the meat derived from the dairy system replaced an equal amount of meat from an alternative production system. The impact of the replaced meat was thus credited to the dairy system (system expansion through avoided burden). As already discussed by Flysjö et al. (2011), quality and price of meat from the dairy system are different from those of suckler beef production systems and it is therefore not evident if consumers will actually replace
meat from dairy systems with suckler beef. We therefore distinguished between two possible meat alternatives: meat from suckler beef systems and pork. Results obtained without allocation, where all impacts were attributed to milk, were used as a reference to which the influence of the different co-product handling methods was compared.

Farm approach: The farm approach considered all outputs generated by the simulated farms. Therefore, the functional unit was a basket of products containing milk, live animals for meat production, and crops. As the specialised and mixed farming systems compared did not produce these products in the same proportion (Table 1), comparability was achieved through system expansion. This means, if one system produced less crops than the other, this difference was balanced with crops produced on specialised crop farms. For meat, differences were balanced with the corresponding number of animals to produce the same amount of beef or pork. The total production amounts of the systems were divided by the amount of milk produced, resulting in a functional unit of 1 kg FPCM plus the respective amounts of co-products live animals and crops, which were thus equal for both systems (Table 2).

Table 2. Total amounts of milk, live animals sold for meat production and crops included in the functional unit and the amounts contributed by the dairy farms and by system expansion farms.

<table>
<thead>
<tr>
<th>Contribution of single farms</th>
<th>Specialised system</th>
<th>Mixed system</th>
<th>Functional unit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dairy farm</td>
<td>System expansion</td>
<td>Dairy farm</td>
</tr>
<tr>
<td>Milk (kg FPCM)</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Live animals (kg LW)¹</td>
<td>0.0364</td>
<td>0.0022</td>
<td>0.0386</td>
</tr>
<tr>
<td>Cereals (kg DM)</td>
<td>0.0270</td>
<td>0.2358</td>
<td>-</td>
</tr>
<tr>
<td>Maize (kg DM)</td>
<td>0.0040</td>
<td>0.0150</td>
<td>-</td>
</tr>
<tr>
<td>Beets and potatoes (kg DM)</td>
<td>0.0066</td>
<td>0.1981</td>
<td>-</td>
</tr>
<tr>
<td>Other cash crops (kg DM)</td>
<td>0.0064</td>
<td>0.0307</td>
<td>-</td>
</tr>
</tbody>
</table>

¹For the substitution with pork, the higher ratio between boneless meat and LW compared to beef was considered.

3.2.2.2 Inventory

For each of our simulated dairy farms, as well as for the specialised crop farm, the suckler beef farm and the pig farm occasionally needed for system expansion, the production within one year was simulated. Economic data and main farm characteristics, such as revenues from sales and production costs, or land use types, were taken from FADN (Mouron and Schmid, 2011), which were complemented with quantitative data on inputs and processes. Accordingly, the livestock system model considered forage requirements of the animals (Flisch et al., 2009), typical compositions of
concentrate mixtures (Boessinger et al., 2013), infrastructure such as animal houses, feed and manure storage containers, manure production and management (Kupper et al., 2013), and requirements for other inputs such as energy (Dux et al., 2009). Simulations of crop and forage production included data on yields (Boessinger et al., 2013; Mack et al., 2013; Mouron and Schmid, 2011), a farm-gate nutrient balance to calculate fertiliser imports, nutrient requirements of the plants and the availability of manure (Flisch et al., 2009), pest management (Federal Office for Agriculture – FOAG, 2012; Nemecek et al., 2005) and machine usage (Boessinger et al., 2013). Wherever required, the models were complemented with inputs from experts or additional sources, e.g. concerning recommendations on crop rotation (Vullioud, 2005).

Out of these models, an inventory of all inputs was extracted and linked to the corresponding processes from ecoinvent v2.2 (ecoinvent Centre, 2010). Direct emissions from farming activities such as storage and spreading of manure, emissions from enteric fermentation of cattle and combustion of fuels were calculated with the method SALCAfarm v3.2 (Swiss Agricultural Life Cycle Assessment for farms; Nemecek et al., 2010). To facilitate a contribution analysis, SALCA assigns the different inputs and direct emissions to eleven input groups (IG): buildings, machinery, energy carriers, fertilisers & field emissions, pesticides, purchased seeds, purchased concentrate, purchased roughage, purchased animals, animal husbandry, and other inputs. The life cycle inventory (LCI) was calculated for both the whole farm, as well as for the different FE.

3.2.2.3 Impact assessment

For comparative LCA, the impact assessment should consider a comprehensive set of impact categories (ISO, 2006b). Accordingly, SALCA provides a broad set of impact categories that are relevant for agricultural systems (Nemecek et al., 2010), which were all calculated. From these we selected cumulative energy demand from fossil and nuclear sources (nrCED; Frischknecht et al., 2007a), global warming potential over 100 years (GWP; IPCC, 2007), aquatic eutrophication N (aqEN) according to EDIP2003 (Hauschild and Potting, 2005), and terrestrial ecotoxicity (terrET) according to CML 2001 (Guinée et al., 2001) for further analysis. Other impact categories like ozone formation and depletion, eutrophication P, acidification, aquatic and human toxicity are not shown. They turned out to be closely related to at least one of the above mentioned categories, like for example the ozone formation potential which was related to non-renewable energy resources, as both are linked to the combustion of fuels. Thus, these other categories provided no additional information. Furthermore, we decided to exclude water use from the set of impact categories. In an initial assessment, more than 90 % of water use was caused on farm, the remaining part was caused by external inputs. However, the on farm water consumption in the farm simulation was based on a very rough estimate, only considering water consumption within animal husbandry, where variability is very high and depending on various factors such as manure management, dilution factor of the slurry, or even the water source (tap water or collected rainwater). Water consumption linked
Comparing the environmental performance of mixed and specialised dairy farms

to crop production, e.g. for irrigation or cleaning, was not simulated. Therefore, the inventory for water consumption was incomplete and too uncertain to provide meaningful results. As a supplement to the basal set of impact categories shown, we show the use of potassium (K use) and phosphorus (P use) from mineral sources based on the LCI. These two categories were added because nutrient use efficiency is often used as an argument in favour of mixed farming systems.

3.2.2.4 Uncertainties

In LCA, there are various sources of uncertainties, which can be categorised into parameter uncertainties, scenario uncertainties and model uncertainties (Huijbregts et al., 2003).

Parameter uncertainties come from the uncertainty of input data of LCI, e.g. uncertainty about the exact amount of slurry spread or energy used or uncertainty due to natural variability in crop yields. As for a majority of the LCI data uncertainty information was lacking, uncertainty was calculated based on the ecoinvent pedigree matrix included in the SALCA tools. This simplified method for quantifying uncertainty presumes a lognormal distribution and uses basic uncertainty factors for different input groups, and further factors for reliability, completeness, temporal, geographic or technological correlation as well as for the sample size to calculate the square of the geometric standard deviation $\sigma_g^2$ (Frischknecht et al., 2007b). The $\sigma_g^2$ calculated from our data varied from 1.07 for diesel combustion, to 1.11 for land occupation and 1.51 for nitrate leaching, and up to 5.00 for heavy metal emissions. Based on this uncertainty data, a Monte Carlo analysis was performed with the software SimaPro 7.3.3 for the main allocation scenario (physical causality according to IDF, 2010) and for all farm level results. In the present article, we only discussed differences in cases where at least 950 out of 1000 runs were in favour of one of the situations studied. All other differences were considered as not significant.

Scenario uncertainties are due to normative choices such as the method of co-product handling, the definition of the system boundaries or the functional unit (Huijbregts et al., 2003). To study the effects caused by such uncertainties was the main goal of the present study, and it was covered by the different ways of allocation in the product approach and by the two possible meat substitutes considered in the farm level approach. On farm level, the system was not only expanded by alternative meat production systems, but also by alternative crop production systems. We assumed that crops that were not produced on dairy farms will be substituted by crops from specialised crop farms in Switzerland. An alternative way of substituting crops would be to import them from abroad, but this scenario was not considered for two reasons: (1) Differences between the same crops produced in different countries (Bystricky et al., 2014) are not as large as differences between beef and pork production (de Vries and de Boer, 2010), and are therefore not expected to cause significant changes. (2) Our farm modelling system was based on Swiss FADN and therefore only operates with Swiss farms. We did not have access to production data of imported crops of the same quality, i.e. with the same system boundaries and the same models for the calculation of direct
emissions. Taking data from another source would therefore have added another level of uncertainty and would not have improved the model.

*Model uncertainties* in the present study are due to two main reasons: (1) The models used to calculate direct emissions, such as those from fertiliser application or enteric fermentation, as well as models to simulate the whole farming systems are simplified versions of the real world. (2) Characterisation factors in impact assessment methods are based on models with their own inherent uncertainties. This can be illustrated by the methane conversion factor for the global warming potential for a time horizon of 100 years, which was changed from 21 to 25 kg CO$_2$eq between the IPCC reports from 2001 to 2007, and was corrected to 28 (without inclusion of climate-carbon feedbacks) or 34 (with inclusion of climate-carbon feedbacks) in the most recent IPCC report (Myhre et al., 2013). Such uncertainties not only affect the metrics behind the global warming potential, they might be even higher for other environmental impact methods such as ecotoxicity (Rosenbaum, 2015). Model uncertainties due to the first reason are partially covered in the present study by the pedigree matrix used for parameter uncertainties, e.g. by attributing higher basic uncertainty factors to direct emissions. Furthermore, some model uncertainties that might not be sufficiently covered by the uncertainty factors were discussed in a qualitative way. Model uncertainties due to the second reason were not addressed here.

3.3 Results

### 3.3.1 Product approach

Compared to dairy production on a specialised farm, milk produced on a mixed farm had significantly higher nrCED, terrET and P use, while aqEN was lower (Figure 4). The different co-product handling methods influenced the absolute values of the impacts. Under allocation, the proportion of impact allocated to milk was the same for all impact categories, i.e. 77.7% for milk from specialised farms and 79.0% for milk from mixed farms in case of physical allocation, and 84.1% and 84.9% in case of economic allocation. Under system expansion, the proportion allocated to milk depended on the impact category. In some cases, namely nrCED, GWP, aqEN, and P use, system expansion with beef resulted in the smallest impacts. For terrET and K use, the situation was different. Here system expansion with pork led to the smallest impacts of milk production. The ranking between dairy production systems was the same under all co-product handling methods studied, except for K use. For this impact category, although not on a significant level, the mixed dairy farm had a lower impact with allocation and system expansion with the avoided burden of beef production, and a slightly higher impact under system expansion with the avoided burden of pork production.
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For nrCED, aqEN, terrET and P use, the impact categories significantly differing between specialised and mixed farms. The contribution of the different IG under physical causality allocation is shown in Figure 5. Compared to milk produced on specialised farms, nrCED was higher for milk from mixed farms. This was mainly caused within IG machinery, IG energy carriers and IG fertilisers & field emissions, all linked to feed production on farm. As the proportion of feed produced on farm was higher in mixed farms, the contribution of the IG purchased concentrates decreased. A similar effect was observed for terrET and P use. Emissions related to on-farm feed production were higher on mixed farms, namely the emissions from IG fertilisers & field emissions, IG pesticides and IG purchased seeds. The contribution of IG purchased concentrates decreased in comparison to the milk production on specialised farms. For the impact category terrET, the differences were caused by the changed feed composition. On mixed farms, a part of the potatoes produced on farm were fed to the animals, and due to the high pesticide usage in potato production, this led to the increase in terrET of dairy production. The aqEN was mainly reduced in IG fertilisers and field emissions, due to different N sources used on mixed farms, with a higher proportion of mineral fertilisers applied on fields designated for feed production.
3.3 Results

Figure 5. Contribution analysis of milk production for milk production on specialised and mixed farms for the impact categories nrCED (cumulative energy demand from fossil and nuclear sources), aqEN (aquatic eutrophication N), terrET (terrestrial ecotoxicity), and P use (phosphorus use) per kg of FPCM (fat and protein corrected milk) when using physical causality allocation in the product approach.

3.3.2 Farm approach

Considering all farm outputs, i.e. milk, meat and cash crops, differences between specialised and mixed dairy systems were significant for nrCED, K use, and P use (Figure 6). The choice of the meat production system for system expansion had no influence on the ranking and only a small influence on the absolute values. For nrCED, GWP, aqEN, and P use, the expansion with suckler beef added more to the mixed production system than the expansion with pork, while the opposite was the case for terrET and K use. Different from the product approach, nrCED was lower on mixed farms and the difference in terrET was no longer significant when applying the farm approach. This was mainly due to reductions within the FE cash crops. These reductions were high enough to more than compensate the increased nrCED of FE dairy and FE suckler beef and compensate terrET from
these two FE (Figure 7). For aqEN there was still a trend for a lower impact from the mixed system that was, due to high uncertainties linked to nitrate leaching, no longer significant. The FE cash crops was also responsible for the significant lower K use within the mixed system compared to the specialised production. Most of the reduction was achieved in IG fertilisers and field emissions. Phosphorus use was also reduced within FE cash crops, but in this case, the reduction was not high enough to compensate for the increased P use within FE dairy cows and the P use from system expansion to compensate the lower meat production on the mixed dairy farm (Figure 8).

![Figure 6. Comparison of the different dairy production systems and the contribution of the dairy farms and the expansion systems for meat and crops using the farm approach. S = specialised farming system, M = mixed farming system; SE beef = system expansion with beef, SE pork = system expansion with pork; nrCED = cumulative energy demand from fossil and nuclear sources, GWP = global warming potential over 100 years, aqEN = aquatic eutrophication N, terrET = terrestrial ecotoxicity, K use = potassium use, P use = phosphorus use. a,b = differing letters indicate significant differences.](image-url)
3.3 Results

Figure 7. Comparison of nrCED (cumulative energy demand from fossil and nuclear sources) and terrET (terrestrial ecotoxicity) found in the mixed system compared to the specialised system within the input groups and farm enterprises under the farm approach. Differences were not significant (ns) in the case of terrET.

Figure 8. Difference in K use (potassium use) and P use (phosphorus use) found in the mixed system compared to the specialised system within the input groups and farm enterprises under the farm approach.
3.4 Discussion

3.4.1 Co-product handling

Physical causality allocation, economic allocation and system expansion through avoided burden with either beef or pork were the investigated co-product handling methods on product level. Although the absolute values were strongly influenced by the different methods, the ranking between milk produced on specialised or mixed farms was not affected for most impact categories. The ranking only changed for K use, but this on an insignificant level. Similarly, no influence of the co-product handling method on the ranking among different production alternatives was observed in a study comparing dairy production in Sweden and New Zealand, where allocation and system expansion led to the same ranking between the two systems (Flysjö et al., 2011). However, there are cases where the choice of co-product handling methods influenced the ranking. Flysjö et al. (2012) compared organic and conventional dairy production, and found that conventional milk production had a lower environmental impact when no allocation was performed, whereas system expansion resulted in a lower impact for organic milk production. This reversed ranking was mainly caused by the higher meat production per kg milk in the organic system and thus a higher avoided burden from beef production. In a study comparing dairy production systems with different milk yields per cow, Zehetmeier et al. (2011) found that performing no allocation and economic allocation resulted in the lowest greenhouse gas emissions for the system with the highest yield, while system expansion led to the opposite conclusion. The latter two studies compared systems with relatively large changes in meat production per unit of milk (17% less meat on the conventional system compared to the organic system; Flysjö et al., 2012; 60 % less meat in the high compared to low milk yield systems; Zehetmeier et al., 2011). In our study, the milk-to-meat ratio was also affected by the production system, as the milk yield per cow on mixed farms was higher. However, the difference was small; the mixed farm produced only 6% less meat per kg FPCM. This change was too small to have a significant effect on the ranking.

Using the farm approach, where all FE were included, instead of the product approach influenced the ranking of the systems. For terrET and aqEN, the difference between specialised and mixed production systems found with the product approach was no longer significant, and for nrCED the ranking was even reversed. For K use, mixed farms had a significant lower impact, a difference not apparent with the product approach. Bell and Moore (2012) stated that many practices in mixed farming systems can have positive or negative effects on other farming activities, which was clearly the case for nrCED, terrET, P use, and K use on the present mixed farm. For these impact categories a reduction was achieved in FE cash crops, and this FE was out of the scope of the product approach. The reason for this lies in our definition of the system boundaries between the FE and the way manure was attributed to the different FE. We sub-divided manure handling
into two processes: storage and application. Storage was fully attributed to the animals that produced the manure, while application was attributed to the crop where it was applied and its distinction (feed crops or forage for livestock vs. cash crops). This is the standard procedure within the SALCA method, and is rather commonly used in agricultural LCA, both in the context of dairy (Cederberg and Flysjö, 2004) and crop production (Nemecek and Kägi, 2007; Willmann et al., 2014). As mixed farms produced more crops, a larger share of the total available manure was used for cash crops, and subsequently this manure was no longer available for feed production. This increased the use of mineral fertilisers within feed production, and thus within the FE dairy. On the other side, the manure applied on the cash crops reduced the use of mineral fertilisers within the FE cash crops.

These results show that the division of processes into sub-processes might mask some environmental effects, although it is stated as the first option in the ISO 14044 standard to avoid allocation (ISO, 2006b). Therefore, it should only be applied if sub-processes are independent and do not cause any rebound effects, like the ones we observed in the case of manure, where manure applied outside of the dairy system led to an import of mineral fertiliser within the dairy system. The second option recommended by ISO 14044 to avoid allocation is system expansion. For manure, this is also the approach recommended by IDF (2010). Yet, other than for the allocation between meat and milk, where IDF (2010) offers a ready-to-use formula, there is no clear recommendation on how to account for the nutrients exported with manure. It is also not trivial to define the effective amount of mineral fertilisers this exported manure can displace. Firstly, not all nutrients in manure, especially nitrogen, are directly available to the plants. Secondly, direct emissions from manure and mineral fertiliser application differ, and they depend on the application time and technique (Flisch et al., 2009). Dalgaard and Halberg (2007) as well as Weiss and Leip (2012) argue that all extra emissions from the application of manure instead of mineral fertilisers should be attributed to the livestock system, while the displaced mineral fertiliser should be credited. However, to define the amount of displaced mineral fertiliser and the amount of extra emissions properly, the crops where the manure is applied and the application technique should be known. For exported manure, this is rarely the case. Alternatively, direct emissions can be approximated based on national standards as done by Dalgaard and Halberg (2007) as well as Mogensen et al. (2014). The third option recommended by the ISO standard 14044 is allocation. Physical causality allocation is no alternative, because the approaches used either by IDF (2010) or by other LCA attempts are based only on the net energy requirements to produce meat and milk (Basset-Mens et al., 2009; Cederberg and Stadig, 2003). The last option would be an economic allocation. LCA using economic allocation approaches usually do not attribute any or only a very small environmental burden to manure because it is, from an economical point of view, rather considered as waste (Bartl et al., 2011; van der Werf et al., 2009). This also applies to Switzerland, where market prices for manure are zero or even negative (Gerwig, 2008). Therefore, this procedure would not change our results if applied to the
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product approach. System expansion is thus the only method suitable to consider the effects of manure application outside of the dairy system appropriately.

3.4.2 **Advantage of the farm approach**

Taking system expansion on product level one step further and including the effects of manure application on the FE cash crops through an avoided burden approach would generate results with the same ranking as the results from the farm approach. Thus, both approaches would be suitable to identify the most environmental friendly production system. However, the goal of LCA is not only to identify the best solution, but also to identify possibilities for optimisation (Hellweg and Milà i Canals, 2014). In this context, the limitation to the product level makes it difficult to identify optimisation potentials outside of the dairy production system even under system expansion with avoided burden. This can be illustrated by the example of manure. System expansion on a product approach credits the displaced mineral fertiliser to the determining product, in our case milk, but it also attributes all extra emissions from manure application (compared to mineral fertilisation) to milk. As the maintenance of the mass balance is a principle that needs to be respected under system expansion (Weidema and Schmidt, 2010), crops produced with manure from the dairy system are thus treated as if they were produced only with the help of mineral fertilisers. In consequence, if emissions from manure application are reduced through better timing and emission reducing application techniques, these reductions will be attributed to the milk and not to the crops. This might be counter-intuitive for the farmer, as he would expect that such reductions were attributed to the crops where the actual reduction happens. The situation becomes even more contradictory in cases where manure is not used on the same farm but is exported. A crop farmer who imports manure from a dairy farm has no incentive to reduce direct emissions from manure application, as his products will be treated as if they were produced with mineral fertiliser anyway, and his efforts to reduce emissions would only reduce the impact of milk. By contrast, in combining all products within one composite functional unit using additive system expansion, all effects are attributed to the whole production system, and thus all involved parties can profit from an optimisation. In addition, the distinction between different farm enterprises within the whole system gives additional information about possible trade-offs and illustrates hot spots for further optimisation.

3.4.3 **Identifying the best meat substitutes**

The scenarios studied did not differ much in the amount of meat produced as a co-product. Thus, the different expansion systems for meat investigated had no significant effect on the ranking in either the product or the farm approach. Nevertheless, in systems with more pronounced changes in the amount of meat produced as a co-product, the choice of the displaced product can be decisive due to the large differences in the environmental impact of different meat production systems. For
meat from the dairy system, beef seems to be the most obvious choice, and many studies use suckler beef systems as a substitute for meat produced in dairy production systems (Cederberg and Stadig, 2003; Flysjø et al., 2012; Zehetmeier et al., 2011). In order to account for the different meat qualities and characteristics, Flysjø et al. (2011) recommended using different meat substitutes for different meat types from the dairy system, such as a mix of pork and suckler beef for meat from culled cows, suckler beef for meat from fattened surplus calves and chicken for meat from bobby calves (slaughtered at an age of four days). Another approach was proposed by Weidema (2003), who recommended using market information for the identification of the most appropriate substitute. For Switzerland, domestic production of pork and beef both increased in the last 10 years but, at the same time, the market demand only increased for beef. Veal, which is one of the meat types closely linked to dairy production, had a decrease in both production and demand (Proviande, 2013). Thus, from the domestic market trends, beef currently seems to be the most appropriate substitute, as both supply and demand are increasing. When including meat import into the considerations, pork is appropriate as a substitute as well. In Switzerland, import is regulated through quotas, and increased imports are currently only possible for pork (Proviande, 2013). To identify the most probable substitute or a ratio between them, a more profound market study or a study on preferences of consumers would be necessary. If this is not possible, at least a scenario analysis as the one performed in the present study is required.

3.4.4 Differences between mixed and specialised farming systems and the limits of farm simulations

In our example of Swiss dairy farms, there was a tendency for lower emissions on mixed farms when using the farm approach. However, for nutrient efficiency, which is one of the presumed advantages of mixed farming (Hendrickson et al., 2008; Ryschawy et al., 2012), results were contradictory. Although there was a trend towards a more efficient use of N on mixed farms, N eutrophication was not significantly lower in mixed farms, with 938 of 1,000 Monte Carlo runs in favour of the mixed system it was just slightly below the threshold of 950 runs. For the other two main nutrients, K and P, the differences between the specialised and the mixed production systems were significant, with lower K use and higher P use on mixed farms. This seemingly contrasting result might have been a result of the way we modelled crop production. Nutrient application per hectare was assumed to be the same for both, specialised and mixed farms, as it was based on fertiliser recommendations (Flisch et al., 2009), while yields were based on data from FADN and thus on effective crop yields. As these yields were higher on the specialised farms, this led to a higher P use efficiency on these farms, and thus to an advantage of the specialised system. This higher efficiency might either be an artefact of our simulation, or the result of a possibly better crop management on specialised farms. If the latter is the case, this result would illustrate one of the
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major challenges of mixed farming systems, namely the skills of the farmer (Bell and Moore, 2012). If managing a mixed dairy farm, the farmer needs to be a generalist, with knowledge about cropping and dairying, while on a specialised farm the farmer can focus on only one activity. Possible benefits from mixed farming systems can therefore only be achieved if the farmer manages to perform livestock and cropping activities on the same level of professionalism as a specialised farmer. The mixed dairy farm in the Swiss lowlands simulated from real data had a slightly lower crop yield than the specialised crop farm, but a higher milk yield per cow compared to the specialised dairy farm. On average, the mixed dairy farms from FADN seem to manage the balancing act between the two activities quite well, but there might be room for improvement within the cropping activity.

Another presumed advantage of mixed farming is a reduced use of pesticides on crops due to improved crop rotation and benefits from ecosystem services (Lemaire et al., 2014). In the present study pesticide use was modelled by crop type independently of the farm type where the crop was grown. Therefore, no difference in application on the two farm types was assumed, which impedes final conclusions about benefits from mixed farming regarding pesticide use. Only an assessment of real farms would reveal the presence or absence of positive and negative side-effects of mixed or specialised farming systems.

3.5 Conclusion

Mixed farms are complex systems, and optimisation within one enterprise can have negative or positive effects on other enterprises. Performing LCA at the product level was not suitable to cover trade-offs to a full extent in the example analysed in the present study due to the way the manure management process was handled. Although being the prime solution according to ISO 14044, the sub-division of processes should be conducted with care. In our product approach, the sub-division of the manure management process into storage and application processes led to the exclusion of side-effects that were caused by manure application onto cash crops. System expansion was thus the only way to integrate the benefits and trade-offs of manure application outside of the dairy system. A system can be expanded in two ways, either through substitution (avoided burden), applied in the product approach, or additive, applied in the farm approach. The latter turned out to be more holistic and suitable for farmers who intend to identify further optimisation potential. Based on our results from the farm approach applied to the modelled farms, we conclude that mixed farming has the potential to reduce environmental impacts. Certain possible benefits of mixed farming, such as a potentially reduced use of pesticides due to ecosystem services, were even not covered by our models. However, due to the complexity of the system the success depends on the individual skills of the farmer. The question whether the theoretical benefits of mixed farming can be translated into a real advantage over specialised farming needs to be tested with real farm data.
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4 Environmental and socioeconomic benefits of a division of labour between lowland and mountain farms in milk production systems

This chapter is based on a revised version of the same-titled manuscript written by Silvia M.R.R. Marton, Albert Zimmermann, Michael Kreuzer and Gérard Gaillard, submitted to Agricultural Systems.

Abstract

Swiss mountains and lowlands feature different climatic and topographic conditions for agricultural production. Thus, farmers developed a collaborative dairy production scheme, where they take advantage of the specific environment of the two regions. In this contract rearing system, the young stock is reared on a mountain farm and the more intensive milk production is performed in the lowlands. This system is an example for the principle of comparative advantage, where each region focuses on the activity where it has the lowest opportunity costs. We hypothesised that the same principle can also be applied in an environmental context, to reduce the environmental impacts of agricultural production. Based on the life cycle assessments of average dairy farms, we could show that the absolute environmental impact was higher on mountain farms for both, the production of one heifer for restocking and the production of one kg milk. However, they had a comparative environmental advantage for rearing, as the young stock was better suitable for their local conditions than the dairy cows. Therefore, milk produced in collaboration between lowland and mountain farms had an up to 4.5 % lower non-renewable energy demand and used up to 30.9 % less potassium and up to 5.2 % less phosphorus resources compared to non-collaborative production. Further consequences of collaboration were a reduced workload and income on mountain farms, and a potentially increased income on lowland farms. We conclude that the principle of comparative environmental advantage is appropriate as a screening method to identify suitable production systems for less favoured regions. However, the total effects of a possible division of labour among regions need to be assessed in a more holistic way where possible side-effects on other aspects are considered as well.
4.1 Introduction

Some agricultural production regions are confronted with constraints that influence both the environmental and economic performance of farming systems. Such constraints can be the result of man-made factors such as the political environment and market conditions, but in many cases they are due to natural factors such as climate, topography, or soil quality. Factors such as the latter cannot be changed easily, which results in disadvantages for certain regions. Farmers in such regions can either use technical solutions, e.g. irrigation in dry regions, or try to identify production systems that are most suitable within their given environment. Life cycle assessments (LCA) could help to identify such systems. However, in LCA studies comparing the environmental impact of production in different regions or countries, the aim is often set at identifying the production region with the lowest impact (Bystricky et al., 2014; Edwards-Jones, 2010). Therefore, classical comparative LCA fails to identify any product that should be optimally produced in regions that are less favoured because nothing can be produced there more efficiently than in other regions. It is tempting to conclude that such regions should not be involved in agricultural production at all. However, Switzerland already has a rather low self-sufficiency rate of 50% in food production (Rossi, 2015), and in a global context the demand for both food and agricultural area are increasing (Brunelle et al., 2014). Thus, the abandonment of less favoured but productive agricultural land would be shortsighted.

The environmental optimisation problem outlined is comparable to the theory of trade in classical economics. Therefore, principles typically applied in economics might be applicable to the environmental context in order to identify environmentally suitable production systems for less favoured regions. The concept of comparative advantage from Ricardo (1817) is still used to explain trade between countries (e.g. Deardorff, 2014) or the spatial distribution of production systems (Rajsic and Fox, 2016). Compared to an absolute advantage, the comparative advantage focuses on opportunity costs. If a favoured and a less favoured region collaborate and each region focuses on the activities where it has lower opportunity costs, the overall costs of production are reduced.

In Switzerland, agricultural land is classified according to its suitability for agricultural production, which is highly influenced by topography, distinguishing between lowland and mountain regions (Landwirtschaftliche Zonen-Verordnung, 1998). The lowlands offer broad possibilities for different farming activities, whilst the mountains are less favoured due to a shorter vegetation period and steeper slopes, both factors impeding competitive crop production. Even for dairy production, which is still performed by many mountain farms, the disadvantage compared to lowland farms is large, which is reflected by the corresponding differences in income (Hoop and Schmid, 2014). Due to the natural constraints in the mountains, production is often more extensive and mountain farms thus have lower environmental impacts on a per hectare basis. However, as a
consequence of the lower productivity, the environmental impacts of their agricultural outputs (per kg product) are higher (Alig et al., 2011b; Bystricky et al., 2014).

The idea of collaboration between lowland and mountainous areas in dairy production originates from the 1960s. At that time, lowland farmers from the Swiss Canton of Thurgau recognised that the high quality forage available would be better invested completely in milk producing animals, as the young stock did not require forage of such high quality. However, the farmers preferred breeding their own animals for creating high genetic merit cows instead of purchasing restocking animals from the market. The result was a collaboration with mountain farmers from the Canton of Grisons for contract rearing, where the lowland farms sold dairy calves to mountain farms and purchased them back when they were close to calving. In this system, the less intensive phase in the life cycle of a dairy cow was shifted to the less favoured mountain region, while the productive phase was maintained in the favoured lowlands. Although rearing heifers on mountain farms was more expensive than on lowland farms, these extra costs were more than compensated by additional milk sales on lowland farms (M. Tanner, son of one of the founders of the system, 20 October 2015, personal communication). The benefits of the system are founded in the comparative advantage of lowland farms in the productive phase of the dairy cow, and the mountain farms’ comparative advantage in rearing the young stock. As this model for collaboration became more popular, it was formalised by a standardised contract between the two parties. Once a year, a delegation of mountain and lowland farmers meets to negotiate the details of their partnership and the prices (Honegger et al., 1977). In addition to the comparative advantage, both profit from a rationalisation through specialisation while reducing market risks due to the contract (Agridea, 2013). Nowadays, the system is rather popular in the eastern part of Switzerland, but it has not made its way to other regions (F. Sutter, personal communication, 18 January 2013). The advantages and disadvantages are not well enough known for this system to be more widespread in Switzerland.

Our first hypothesis is that mountain farms have a comparative advantage for rearing the young stock also in environmental respect, as the forage quality on farm is sufficient for these animals. For productive dairy cows, on the other side, a comparative disadvantage is expected, as higher imports of concentrates are needed in order to cover the nutrient requirements of higher-yielding dairy cows. If this is true, the collaboration between mountain farms and lowland farms has the potential to reduce the environmental impact of dairy production. However, farming systems are complex, and a change within the dairy production might also influence other farming activities. Our second hypothesis is, therefore, that the environmental impact, and thus the success of the collaboration, also depends on the extent and kind of changes in other activities. This could be e.g. through a changed availability or quality of manure. In addition, lowland farms that opt for a collaboration with a mountain farm will free land that would have been used by the young stock. They could use this land either to increase dairy production, which was the original motivation for the farmers who started the collaboration back in the 1960s (M. Tanner, 20 October 2015, personal
communication). Another option would be to increase crop production, as the land in the lowlands would be well suitable for this activity. To test the first hypothesis, we performed an LCA for both phases in the life cycle of a dairy cow, i.e. the rearing of a heifer from the day of birth up to the first calving, and the productive phase. For testing the second hypothesis, we expanded our LCA to the farm level. In addition to the LCA, we also evaluated the effect of such forms of collaboration on farm income and workload.

4.2 Methods

We compared three dairy production systems, a non-collaborative baseline, and two collaborative systems, one with increased specialisation in dairy production and one with increased diversification. The comparison is based on simulated farms. The systems were analysed for their environmental performance as well as their effects on economics and labour.

4.2.1 Farm types considered and simulation

Specialised dairy farms that rear their own young stock were defined as the baseline, with a baseline farm in the lowlands (BaseLow) and one in the mountains (BaseMount). Under collaboration, the mountain farm (ColMount) was assumed to specialise in the rearing of young stock and to quit milk production. The ColMount farm purchased weaned female dairy calves from the collaborating lowland farms and sold the heifers back 1 month before calving. As the collaborating lowland farm outsourced its young stock, it freed land and resources formerly used by the young stock for other activities. This farm could have either used those resources to increase dairy production or crop production. The former corresponds to a situation where the farm remained specialised, hereafter referred to as the collaborative specialised lowland farm (ColSpLow), the latter corresponds to a situation with more diversification, hereafter referred to as the collaborative diversified lowland farm (ColDiLow).

The starting point of the farm simulations were the different restocking strategies of the dairy farms. The restocking was modelled according to Boessinger et al. (2013), with a restocking rate of 0.29, and an age at first calving of 30 months, both for mountain and lowland farms. Only female calves required and designated for restocking were kept, surplus and male calves were sold to a fattening farm a few days after birth. The dairy herd of the BaseLow and BaseMount farms therefore consisted of dairy cows and the respective amount of young stock needed for restocking, from the day of birth up to an age of 30 months. On the collaborative lowland farms (ColSpLow and ColDiLow) the dairy herds consisted of dairy cows, female calves up to the age of 4 months and the heifers close to calving, with an age of 29 to 30 months. The ColMount farm kept the young stock of an age between 4 and 29 months.
In order to simulate representative Swiss dairy farms the average land use, stocking densities and milk yields for specialised dairy farms were taken from the Swiss farm accounting data network (FADN; Mouron and Schmid, 2011). The BaseLow, BaseMount, ColSpLow, and ColMount farms were modelled to have the land use and total livestock units as the average farm from the respective region. The livestock units were composed by animals from the different age categories corresponding to the restocking strategies of the respective farms. For the ColDiLow farm, we modelled a farm with the same number of cows as the BaseLow farm and thus the same milk yield. Due to the outsourced young stock, the total livestock units of this farm were lower, thus less land was needed for forage production (grassland and silage maize). The freed land was used for increased crop production, with a relative increase of the area of all crops that were already grown under the BaseLow scenario. Table 3 shows the main characteristics of the simulated farms. The diet of the animals was modelled combining data from FADN and Boessinger et al. (2013). Forage as well as crop yields on farm were mainly taken from the agent-based agricultural-sector model SWISSland (Mack et al., 2013). In cases where no data from SWISSland were available, data were derived from FADN, Boessinger et al. (2013) or Nemecek et al. (2005). Feed crop production was partially used on farm. The ratio between sold feed crops and internally used ones was based on average FADN data for specialised lowland and mountain dairy farms. Based on the on farm forage and feed crop production and the animals’ need, the amount of purchased feed was calculated. As the ColDiLow farm had a larger cropping area, the amount of home-grown concentrates was thus increased by the same ratio as the cropping area increased. Crop and grassland cultivation was modelled based on nutrient requirements described in Flisch et al. (2009) and cultivation practices described in Nemecek et al. (2005). It was simulated that the manure distributed on the different cultures did not exceed the requirements for N and P, and that any additional nutrient requirements were covered with mineral fertilisers. In the model, none of the farms exported manure, as the total P and N demands of the crops and grassland grown on the farms were always higher than the amount available from manure produced on farm.
Table 3. Simulated farms used for the assessment and their main characteristics, based on the average specialised dairy farm from the lowlands and mountains from the Swiss farm accounting data network (FADN).

<table>
<thead>
<tr>
<th></th>
<th>Lowlands</th>
<th>Mountains</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Baseline lowland dairy farm</td>
<td>Baseline mountain dairy farm</td>
</tr>
<tr>
<td></td>
<td>Collaborating specialised dairy farm</td>
<td>Heifer rearing farm</td>
</tr>
<tr>
<td></td>
<td>Collaborating diversified dairy farm</td>
<td></td>
</tr>
<tr>
<td>Total LU</td>
<td>33.1</td>
<td>20.9</td>
</tr>
<tr>
<td>Dairy cows (LU)</td>
<td>25.7</td>
<td>16.2</td>
</tr>
<tr>
<td>Young stock (LU)</td>
<td>7.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Milk yield (kg FPCM sold / cow)</td>
<td>6540</td>
<td>5500</td>
</tr>
<tr>
<td>Forage area (ha)</td>
<td>18.8</td>
<td>19.5</td>
</tr>
<tr>
<td>- Permanent grassland (%)</td>
<td>73</td>
<td>96</td>
</tr>
<tr>
<td>- Temporary grassland (%)</td>
<td>21</td>
<td>4</td>
</tr>
<tr>
<td>- Silage maize (%)</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td>Cropping area (ha)</td>
<td>1.4</td>
<td>0.2</td>
</tr>
<tr>
<td>- Cereals (%)</td>
<td>82</td>
<td>92</td>
</tr>
<tr>
<td>- Grain maize (%)</td>
<td>7</td>
<td>-</td>
</tr>
<tr>
<td>- Beets &amp; potatoes (%)</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>- Other crops (%)</td>
<td>5</td>
<td>1</td>
</tr>
</tbody>
</table>

FPCM = fat and protein corrected milk; LU = livestock units.

4.2.2 Environmental assessment

Agricultural production causes both, direct and indirect environmental impacts. Nitrate leakage on fields or methane emissions from ruminants are emissions directly produced on farm, indirect impacts are resulting from inputs that caused environmental impacts along their supply chain. As changes within an agricultural production system might influence not only on-farm production but also the amount of external inputs used, the environmental assessment of the farming system should consider both direct and indirect environmental impacts. We therefore performed an LCA, as this method aims at quantifying the environmental impact of products or services along their full value chain. The ISO standards for LCA 14,040 and 14,044 (ISO, 2006a, b) define four phases to be considered: (1) goal and scope, (2) life cycle inventory (LCI), (3) life cycle impact assessment, and (4) life cycle interpretation. In the following, we describe the first three phases, and the way we handle uncertainty within the present study. The interpretation follows in the discussion section.
4.2.2.1 Goal and scope

Our study had two goals: (1) the identification of a possible comparative environmental advantage of the mountain region within the dairy production system, (2) the environmental effect of a production change from non-collaborative to collaborative dairy production on the whole farming system, including crop production. For each of the goals, the system level analysed was different. For the first goal, the assessment was performed on farm enterprise level, for the second on farm level. The farm enterprises were defined as components of the whole farm, designated for the production of one specific output. In this context, we distinguished between the three farm enterprises dairy cows, young stock and cash crops. The farm enterprise dairy cows included all processes related to the husbandry of dairy cows, such as housing, feeding and feed production, the farm enterprise young stock included all processes related to the keeping and feeding of young stock for restocking of the dairy herd, from the day of birth of a calf until the day of first calving of a heifer, and the farm enterprise cash crops included processes linked to the production of crops to be sold. Manure production and storage was attributed to the animal group that produced it, its field application was attributed to the area where it was applied. The agricultural area of the farm was attributed to the farm enterprise that used its products. Thus, the grassland area and all activities on this area like fertiliser application as well as direct field emissions were attributed to the dairy cows and the young stock based on estimated feed requirements of the two animal groups. The cropping area and its related processes and direct field emissions were attributed to cash crops, dairy cows and young stock, based on sales data and estimated feed requirements. External inputs, such as mineral fertilisers, purchased feed or energy carriers, as well as infrastructure, were attributed based on the effective consumption within the different farm enterprises.

Farm enterprise level: For our first goal, the identification of a possible comparative environmental advantage of mountain farms in the dairy production system, we focused on the farm enterprise young stock and the farm enterprise dairy cows from the non-collaborative farms, i.e. BaseLow and BaseMount. The functional unit was defined by the determining product of each farm enterprise. This was kg of fat and protein corrected milk (FPCM) at farm gate for farm enterprise dairy cows and heifer finished to enter the dairy herd for farm enterprise young stock. All environmental impacts were attributed to the determining product, while knowing that both farm enterprises produce meat as a co-product.

Farm level: For the second goal, the environmental effect of a change from non-collaborative to collaborative production on the collaborating farms, we considered the whole farm, including crop and meat production, before and after the system change. The ColSpLow farm needed 9.2 heifers per year for restocking, and the ColDiLow farm 7.5. As the ColMount farm produced 25.5 heifers close to calving per year, it thus produced more heifers than needed by one lowland farm. Therefore, we defined the ratio between lowland and mountain farms based on the demand for heifers of the collaborating lowland farms, which resulted in a ratio of 1:2.7 between ColMount and ColSpLow.
farms and 1:3.3 for ColMount and ColDiLow farms. This ensured that we had a closed restocking cycle on the collaborating farms. The same ratios were also used for milk production in the non-collaborative baselines.

Table 4. Multiple-output functional unit (FU), and the contribution of the farms from the two regions and the system expansion to this FU, for the comparison of non-collaborative and collaborative farming based either on increased specialisation or diversification at farm level.

<table>
<thead>
<tr>
<th></th>
<th>Non-collaborative (baseline)</th>
<th>Collaboration</th>
<th>Total (FU)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lowland farm</td>
<td>Mountain farm</td>
<td>System expansion</td>
</tr>
<tr>
<td></td>
<td>Base Low</td>
<td>(Base Low)</td>
<td>(ColSp Low or ColDi Low)</td>
</tr>
<tr>
<td>Milk (kg FPCM)</td>
<td>0.8338</td>
<td>0.1662</td>
<td>–</td>
</tr>
<tr>
<td>Beef (kg LW)</td>
<td>0.0322</td>
<td>0.0076</td>
<td>–</td>
</tr>
<tr>
<td>Cash crops (kg DM)</td>
<td>0.0367</td>
<td>0.0010</td>
<td>–</td>
</tr>
</tbody>
</table>

DM = dry matter; FPCM = fat and protein corrected milk; LW = live weight.

All farming system scenarios produced milk, meat and crops, and the changes in the production system affected all three product groups, either because their amounts of production were changed or because the production itself was affected by a changed availability of inputs produced on-farm such as feed or manure. In order to make the systems comparable, we applied system expansion and defined a multiple-output functional unit that covered all three product groups at the farm gate. In cases where one system produced less of a single output, this difference was balanced by increased production of the same product or a suitable substitute on another farm type. Table 4 shows the multiple-output functional unit for both comparisons, i.e., baseline vs. collaboration with increased specialisation and baseline vs. collaboration with increased diversification. These values were derived from the total outputs of each production system, and then normalised by dividing all outputs of the systems by the total amount of milk. By the example of the comparison between the non-collaborative baseline and the collaboration with more specialisation, we illustrate how this was done: Without collaboration, the 2.7 BaseLow farms produced 447 tons of FPCM, 17.2 tons of
Methods

beef, and 19.7 tons of cash crops, while 1 BaseMount farm produced 89 tons of FPCM, 4.1 tons of beef and 0.5 tons of cash crops. Together, the BaseLow and Base Mount farms produced 536 tons of FPCM, 21.3 tons of beef and 20.2 tons of cash crops. Under collaboration, 2.7 ColSpLow farms produced 553 tons of FPCM, 20.7 tons of beef and 19.7 tons of cash crops, while 1 ColMount farm produced no milk, 0.7 tons of beef and 0.5 tons of cash crops. Together, the ColSpLow and ColMount farms produced 553 tons of FPCM, 21.3 tons of beef, and 20.2 tons of cash crops. After the normalisation by dividing all outputs of the systems by the total amount of milk, this resulted in 1 kg FPCM, 0.0398 kg of beef and 0.0377 kg of cash crops for the system with no collaboration, and 1 kg FPCM, 0.0374 kg of beef and 0.0366 kg of cash crops for the collaborative system. The collaborative system thus produced 0.0012 kg less beef and 0.0011 kg less cash crops per kg FPCM. This difference was balanced with the same amount of beef and crops produced on specialised beef respectively crop farms, in order to get two systems that produce the exact same amount of outputs.

4.2.2.2 Computation of the life cycle inventory

The LCI was based on the simulation of one year of the different farm types: BaseMount, BaseLow, ColMount, ColSpLow, and ColDiLow. The same was done for a specialised crop farm and a suckler beef farm that were defined based on the same background data as our different dairy farms, i.e. FADN, SWISSland, and Boessinger et al. (2013), and thus represented average farms of these farm types under Swiss conditions. These specialised farms were needed for system expansion. The simulation considered inputs such as feed, seeds, fertilisers, and fuels, infrastructure such as buildings and machinery, as well as on farm processes causing direct emissions, such as combustion of fuels, fertiliser application, enteric fermentation, and manure management. The method Swiss Agricultural LCA for farms version 3.2 (SALCAFarm; Nemecek et al., 2010) was used to calculate direct emissions and link the different inputs to the corresponding processes from ecoinvent v2.2 (ecoinvent Centre, 2010). To facilitate further analyses, the LCI was grouped according to eleven input groups and four farm enterprises. The input groups were: buildings, machinery, energy carriers, fertilisers and field emissions, pesticides, purchased seeds, purchased concentrate, purchased roughage, purchased animals, animal husbandry, and all other inputs. The functional unit included the three farm enterprises of the dairy farms, i.e. dairy cows, young stock, and cash crop, and the additional farm enterprise suckler beef. The latter included all processes related to the production of suckler beef on the respective farm.

4.2.2.3 Impact assessment

From the comprehensive set of impact categories SALCAFarm provides (Nemecek et al., 2010), the following were selected: cumulative energy demand from fossil and nuclear sources (nrCED) (Frischknecht et al., 2007b), global warming potential over 100 years (GWP; Myhre et al., 2013),

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aquatic eutrophication N (aqEN) according to EDIP2003 (Hauschild and Potting, 2005), terrestrial ecotoxicity (terrET) according to CML 2001 (Guinée et al., 2001), potassium (K use) and phosphorus use (P use) from mineral sources, as well as water use, the latter three based on the LCI. This selection was made after a preliminary evaluation, and impact categories found to be strongly correlated with others, like for instance ozone formation potential that correlated with nrCED, were not considered for further analysis.

4.2.2.4 Uncertainties

In order to cope with the uncertainties associated with LCA, we focussed on so-called parameter uncertainties, i.e. uncertainties linked to the data in LCI (Huijbregts et al., 2003). Our inventory was based on various sources, and for most of those sources, data for both uncertainty and natural variability were lacking. Therefore, for each input as well as for direct emissions, we calculated an uncertainty based on the ecoinvent pedigree approach (Frischknecht et al., 2005). This approach considers two sources for uncertainty, the so-called ‘basic’ and ‘additional’ uncertainty (Weidema and Wesnæs, 1996). The basic uncertainty refers to intrinsic variability and to stochastic errors, while the additional uncertainty derives from the use of imperfect data (Muller et al., 2016). The final uncertainty linked to each input or emission is calculated with a basic uncertainty factor (defined for different input or emission categories, based on expert judgements), and additional uncertainty factors based on a rating for data reliability, completeness, temporal correlation, geographic correlation, further technology correlation, and sample size. These additional uncertainty factors are defined with the help of a pedigree matrix, inspired by Funtowicz and Ravetz (1990).

The uncertainty data obtained with this pedigree approach were then used for a Monte Carlo analysis with the LCA software SimaPro. If at least 950 out of 1000 runs were in favour of one of the scenarios, we considered the differences as significant.

4.2.3 Assessment of changes in income and labour

The analysed collaborative systems have an effect on income and workload of the farms. Farm income depends on many factors, including fixed costs such as rents. Such fixed costs depend on the individual situation of the farm and are not, or only to a small extent, influenced by a system change from a non-collaborative to a collaborative dairy farm. In the present study we focused only on the potential income changes induced by a change of the production system, using contribution margin data. The contribution margin is calculated by subtracting variable costs from the revenue (including subsidies). Boessinger et al. (2013) provides contribution margins per ha for grassland and all main crops grown in Switzerland, per restocking animal, and per dairy cow. For the contribution margin per dairy cow, they distinguish between different milk yields per cow, and between production with or without silage. Milk produced with silage serves for various industrial purposes,
hereafter referred to as standard milk, while the latter is demanded by small enterprises for cheese production, hereafter referred to as cheese milk. This cheese milk is awarded with a higher price. Thus, depending on the production system, the contribution margin per cow varies. Out of the various production systems covered by Boessinger et al. (2013), we selected the system with the lowest and the system with the highest contribution margin per dairy cow, in order to cover a broad range of contribution margins possibly achieved on a dairy farm: (a) low yield (7000 kg/cow and year) sold as standard milk, and (b) high yield (8000 kg) sold as cheese milk. Based on the differences in animal numbers and land use between the base line farms (BaseLow and BaseMount) and the collaborative farms (ColSpLow, ColDiLow and ColMount), we calculated the change in income per farm switching from a non-collaborative to a collaborative dairy production system. After calculating the change in income based on the contribution margin, this change in income was put into relation with the average income of dairy farms in 2013 (Hoop and Schmid, 2014).

For estimating changes in the farms’ workload, we used the tool ART-AV 2014, a work budget planning tool for Swiss farms (Stark et al., 2014). The tool distinguishes between different production regions, i.e. lowlands or mountains, and different degrees of mechanisation, and considers economies of scale in its calculations.

4.3 Results

4.3.1 Environmental assessment on farm enterprise level

Lowland farms had lower environmental impacts per kg FPCM for all studied impact categories, and lower impacts per finished heifers for all impact categories except P use (Figure 9). This was mainly due to the higher productivity of the lowland farms. Compared to mountain farms, the milk yield per cow and per hectare was 19 % and 88 % higher, respectively. Also in the heifer sector, mountain farms only produced 1.11 heifers close to calving per ha while lowland farms produced 1.76 (+59 %). The lower productivity on mountain farms led to higher inputs per product unit (kg FPMC or finished heifer) for most input groups, except for fertilisers, purchased pesticides, and purchased seeds. These inputs were mainly linked to silage maize and feed crop production, which were mainly grown on lowland farms while mountain farms had a higher proportion of grassland. In most cases, the savings within these input groups on mountain farms were too low to compensate for the higher impacts linked to the other input groups. Only for P use in heifer production the lower input of P fertilisers was high enough and led to a lower impact per finished heifer (Figure 10).
As the relative difference between mountain and lowland production was generally lower for heifer production, the mountain farm had a comparative environmental advantage in this activity, while the lowland farm had a comparative advantage in milk production. We illustrate how these comparative advantages could reduce the impact of the dairy system using the example of nrCED. The production of 1 kg FPCM in the farm enterprise dairy cows was calculated to require 4.02 MJ nrCED on the BaseLow farm and 5.56 MJ nrCED, i.e. 38% more on the BaseMount farm. The production of one heifer close to calving (farm enterprise young stock) consumed 21.0 and 25.1 GJ (+19%) in the lowlands and mountains, respectively. If the mountain farm would produce one heifer more while keeping its total nrCED on the same level as before, it should reduce milk production by 4513 kg FPCM (25.1 GJ / 5.56 MJ). This amount of milk corresponds to the opportunity costs of the production of one heifer on a mountain farm. The corresponding opportunity costs of heifer production on the lowland farm are 5230 kg FPCM (21.0 GJ / 4.02 MJ). If the two farms now collaborate, and the mountain farm produces one heifer more and the lowland farm one heifer less while both keep their total nrCED constant, they could increase the total milk production by 717 kg FPCM.
Figure 10. Difference between the production on mountain farms relative to the impact of production on lowland farms with the example of cumulative energy demand from fossil and nuclear sources (nrCED), and phosphorus use (P use).

4.3.2 Environmental assessment on farm level

Compared to the non-collaborative situation, the collaboration between lowland and mountain farms was calculated to reduce nrCED, K use and P use by 4.5, 5.2, and 6.4 %, respectively, if the lowland farm opted for an increased milk production (ColSpLow) (Figure 11). In the situation with more diversification, nrCED and K use would be reduced by 2.3 and 30.9 %, respectively. There was no significant difference in all other impact categories.
The reduction of nrCED under collaboration with increased specialisation was mainly achieved through a reduction in the input groups energy carriers and purchased concentrate (Figure 12). In the situation with increased diversification, together with the increased cash crop production home-grown concentrate production was increased. This led to a more pronounced reduction in the input group purchased concentrate. On the other side the reduction was less pronounced in the input group energy carriers on diversified farms, as crop production and thus the production of concentrates on farm was also associated with energy consumption. For the same reason, the contribution from cropping inputs, such as seeds, pesticides and fertilisers increased compared to the non-collaborative scenario.
Figure 12. Changes in the use of cumulative energy demand from fossil and nuclear sources (nrCED), potassium use (K use), and phosphorus use (P use) through collaboration with increased specialisation (Sp) and increased diversification (Di) specified by input groups on farm level. Differences indicated in parentheses were not significant.

For both collaborative scenarios, nrCED was reduced in farm enterprise dairy cows and increased in the farm enterprises young stock and suckler beef (system expansion) (Figure 13). The nrCED was reduced in the farm enterprise cash crop production by collaboration with increased diversification. The reduction of K use on collaborating farms with more diversification, characterised by more home-grown concentrate and cash crops on the lowland farm (ColDiLow), was influenced to a large part by the system expansion. As the baseline farms were calculated to produce fewer crops than the collaborating farms, the gap in crop production had to be filled by specialised crop farms. These farms would rely on mineral fertilisers and thus use more mineral K. This was not the case for the ColDiLow farms, where no mineral K fertiliser was needed in cash crop production. As the baseline farms were calculated to produce fewer crops than the collaborating farms, the gap in crop production had to be filled by specialised crop farms. These farms would rely on mineral fertilisers and thus use more mineral K. This was not the case for the ColDiLow farms, where no mineral K fertiliser was needed in cash crop production. Thus, the reduction in K use by collaboration with more diversification was mainly achieved in the input group fertilisers and field emissions and in the farm enterprise cash crops. For P use there were trade-offs between different input groups and farm enterprises in the scenario with more diversification. The ColDiLow farm was simulated to use more mineral P fertiliser on its forage crops, but less on cash crops compared to the BaseLow farm and the crop farm from system expansion. In total, the reduction was therefore not significant.
4.3.3 Changes in income and workload

For lowland farms, outsourcing young stock was calculated to cause direct and indirect costs. Direct costs comprised the prices they pay to mountain farms when buying the heifers, indirect costs were caused because they would lose subsidy payments that are linked to the number of animals kept on the farm. On the other side, they were calculated to generate additional income from selling more milk or crops and saving the costs that keeping the young stock on the own farm would have caused. The economic benefit from collaboration was found to depend on the enterprise the farmers would choose to expand on their farm (dairy for the scenario with increased specialisation, or crops for the scenario with increased diversification) as well as on milk yield and quality. The scenarios for lowland farms changing from non-collaborative production to collaborative production are displayed in Table 5. For lowland farms with relative low milk yield selling standard milk, collaboration would result in a zero-sum situation, while farms with high milk yield selling cheese milk would increase their income while their workload slightly increased. Lowland farms that increased their crop production (ColDiLow) would have a reduced income, but they could also reduce workload.
### Table 5. Economic and labour effect of a change from non-collaborative dairy production (Base-Low) to collaboration with increased specialisation (ColSpLow) or diversification (ColDiLow) by the lowland farms.

<table>
<thead>
<tr>
<th></th>
<th>ColSpLow</th>
<th>ColDiLow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk yield per cow (kg)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low yield</td>
<td>7,000</td>
<td>-</td>
</tr>
<tr>
<td>High yield</td>
<td>8,000</td>
<td>Not relevant</td>
</tr>
<tr>
<td>Milk used for cheese (silage free production)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Additional costs of outsourcing young stock</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price paid for heifers (CHF)</td>
<td>-21,478</td>
<td>-21,478</td>
</tr>
<tr>
<td>Lost subsidies, animal payments (CHF)</td>
<td>-4,692</td>
<td>-4,692</td>
</tr>
<tr>
<td>Lost subsidies, payment per area (CHF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Saved costs in animal production (CHF)</td>
<td>+2,168</td>
<td>+2,168</td>
</tr>
<tr>
<td>Saved costs in forage production (CHF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Additional income from milk or crop production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sales revenue, milk and meat (CHF)</td>
<td>+26,677</td>
<td>+36,970</td>
</tr>
<tr>
<td>Sales revenue, cash crops (CHF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Subsidies, animal payments (CHF)</td>
<td>+4,184</td>
<td>+4,184</td>
</tr>
<tr>
<td>Subsidies, payments per area (CHF)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Production costs (CHF)</td>
<td>-6,888</td>
<td>-9,480</td>
</tr>
<tr>
<td>Change in income, absolute and relative (CHF)</td>
<td>-28</td>
<td>+7,672</td>
</tr>
<tr>
<td></td>
<td>(-0%)</td>
<td>(+11%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(-12%)</td>
</tr>
<tr>
<td>Change in workload (h)</td>
<td>+67</td>
<td>+67</td>
</tr>
<tr>
<td>Income per additional working hour (CHF)</td>
<td>-0</td>
<td>+115</td>
</tr>
<tr>
<td>Income loss per saved working hour (CHF)</td>
<td>-</td>
<td>-22</td>
</tr>
</tbody>
</table>

1) Relative to the income of an average dairy farm in the lowlands in the year 2013 (Hoop and Schmid, 2014).

For the mountain farms, the switch from dairy production to specialised rearing represents a larger system change than for the lowland farms. Collaborative dairy production would reduce the income of the mountain farms compared to dairy farming. Mountain farms with high yielding cows or those that produce cheese milk would generate a higher income in their baseline situation. Thus, a change to a specialisation in heifer rearing would reduce their income more compared to farms with lower yielding cows selling standard milk. On the other side, the workload of the farms was calculated to be almost halved, going from 3,522 h under dairy production (BaseMount) to 1,783 h per year for the specialised rearing farm (ColMount) (Table 6).
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Table 6. Economic and labour effect of a change from non-collaborative dairy production (BaseMount) to a specialisation in heifer rearing (ColMount) on mountain farms.

<table>
<thead>
<tr>
<th></th>
<th>Low yield</th>
<th>High yield</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milk yield per cow (on BaseMount) (kg)</td>
<td>7,000</td>
<td>8,000</td>
</tr>
<tr>
<td>Milk used for cheese (silage free production)</td>
<td>no</td>
<td>yes</td>
</tr>
<tr>
<td>Lost income from abandoning dairy production</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lost revenue, milk and meat (CHF)</td>
<td>−74,421</td>
<td>−103,134</td>
</tr>
<tr>
<td>Lost subsidies, animal payments (CHF)</td>
<td>−11,673</td>
<td>−11,673</td>
</tr>
<tr>
<td>Saved production costs (CHF)</td>
<td>+19,216</td>
<td>+26,447</td>
</tr>
<tr>
<td>Additional income from heifer rearing</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Revenue from rearing (CHF)</td>
<td>+58,032</td>
<td>+58,032</td>
</tr>
<tr>
<td>Subsidies, animal payments (CHF)</td>
<td>+22,269</td>
<td>+22,269</td>
</tr>
<tr>
<td>Production costs (CHF)</td>
<td>−23,517</td>
<td>−23,517</td>
</tr>
<tr>
<td>Change in income, absolute and relative (CHF)(^1)</td>
<td>−10,513 (-20%)</td>
<td>−31,995 (-60%)</td>
</tr>
<tr>
<td>Change in workload (h)</td>
<td>−1,732</td>
<td>−1,732</td>
</tr>
<tr>
<td>Income loss per saved working hour (CHF)</td>
<td>−6</td>
<td>−18</td>
</tr>
</tbody>
</table>

\(^1\)Relative to the income of an average dairy farm in the mountains in the year 2013 (Hoop and Schmid, 2014).

4.4 Discussion

4.4.1 Comparative environmental advantage

Mountain farms had a lower productivity per ha for farm enterprises young stock and dairy cows. This lower productivity translated into an environmental disadvantage of farms in this region compared to the lowlands, when compared on a per kg product basis. As this disadvantage was less pronounced for the more extensive type of production activity, the farm enterprise young stock, the mountain farm had a comparative environmental advantage in this farm enterprise, while the lowland farm had one for the farm enterprise dairy cows. In order to profit from this comparative advantage, a collaboration between the regions, where mountain farms focus on heifer rearing and lowland farms on milk production, had the potential to reduce the environmental impact of the overall milk production system.

However, the above described situation neglected three important aspects owed to the complexity of the real system: (1) an absolute specialisation in heifer rearing implies that the mountain farm has no longer any dairy cows and thus is not able to produce milk needed in the farm enterprise young stock (feed for calves); (2) changes within the dairy production system might have side-effects on other farm activities, such as cropping or meat production; (3) the farm enterprises dairy cows and young stock are strongly interlinked. The demand for heifers is defined and limited by
the restocking rate practiced in the farm enterprise dairy cows, thus the ratio of lowland and mountain farms involved in production is defined by this demand, and not by the actual number of farms present in the two regions. In the following, we discuss these three aspects to evaluate if the comparative environmental advantage of mountain and lowland farms within dairy production would also translate into environmental advantages on a more holistic level.

4.4.1.1 Specialisation of mountain farms in heifer rearing

When mountain farms specialise in heifer rearing and quit dairy production, they have no milk available to feed calves. For the collaboration between lowland and mountain farms, this requires that the calf has to stay on the lowland farm until weaned. The assessment on farm level therefore considered that in the collaborative scenarios only weaned calves could be outsourced to the mountain farms. Accordingly, the first phase of keeping the young stock still happened on the lowland farm. This could weaken the effect of the comparative advantage. Nevertheless, on the example of nrCED, we could clearly see how the mechanism of comparative advantage works. There was a slight increase of the impact within farm enterprise young stock, which was overcompensated by a decrease of the impact within farm enterprise dairy cows.

For K use, the situation was different. Here both farm enterprises, young stock and dairy cows, had a reduced impact. This indicated that the ColMount farm had an absolute advantage for the heifer rearing phase for animals from an age of 4 to 29 months, although they had an absolute disadvantage for heifer rearing for animals from 0 to 30 months. This disadvantage was rooted in the first 4 months, i.e. the most intensive phase of heifer rearing where the animals are fed with milk, but also with concentrate to foster the development of the rumen (Yanez-Ruiz et al., 2015).

For P use, our analysis on farm enterprise level showed an absolute advantage for mountain farms in heifer rearing, but on farm level P use was increased in the farm enterprise young stock. This was an effect of the specialisation of the mountain farm in heifer rearing. As manure from young stock had a lower level of P than manure from dairy cows, the ColMount farm had less P available from manure than the BaseMount farm, and thus had to import mineral P to cover the plants’ requirements. The conversion from dairy farms to specialised heifer rearing farms thus led to an absolute disadvantage for the ColMount farm in P use. However, like for nrCED, the disadvantage of the mountain farm was overcompensated by the reduced P use on lowland farms, indicating that the ColMount farm still had a comparative advantage in keeping young stock.

4.4.1.2 Side-effects on meat and cash crop production

In addition to the main product milk, the farm level also covered other commodities produced on the farm, i.e. meat and cash crops. It therefore also unveiled side-effects of the collaboration on
other farm enterprises. Accordingly, due to the higher milk yield of the lowland cows and the assumption that both, dairy herds from mountain and lowland farms were restocked at a rate of 0.29, the amount of meat produced per kg of milk decreased in the collaborative systems. As the difference in meat production was balanced with meat from suckler cattle, the environmental benefit from collaboration within the dairy production system (farm enterprises dairy cows and young stock combined) was partially offset with the emissions from beef production.

In case the lowland farm opted for increased crop production when collaborating with a mountain farm, the collaboration also caused side-effects on the farm enterprise cash crops. One of the most prominent arguments used in favour of diversification on farm level is the better use of nutrients and closing of nutrient cycles (Lemaire et al., 2014; Ryschawy et al., 2012). However, this was only partially true for our example. Lowland farms that diversified (ColDiLow) had less manure available on their farm. Thus, these farms had to import mineral N and P fertilisers. In total, these farms did not use less N and P mineral fertilisers compared to the situation where milk was produced on a farms with less cropping (BaseLow) combined with crop production on specialised arable farms (system expansion). Only for K use the diversification strategy proved to be advantageous. As most of the K from feed is excreted by dairy cattle via urine (Leiber et al., 2009), the amount of K imported with concentrate feed plus the cycling of K from home-grown feed and excreted by the animals exceeded the nutrient requirements from the plants grown on the farms. Other than N and P, K is usually not the limiting factor for algae growth in water and thus not considered to be relevant for eutrophication (Talling, 2010) and its application is also not limited by Swiss legislation. As long as N and P limits are not exceeded, farms will not export manure, even if the K balance is positive. Thus both, the BaseLow and the ColDiLow farm, would not export manure. Consequently, the specialised arable farm taken for the system expansion in the baseline situation had to use mineral K for crop production.

4.4.1.3 Lowland farms’ demand for heifers determines the number of collaborating mountain farms

Of the 31,000 farms keeping dairy cows in Switzerland, about half are situated in the mountain region (TSM, 2013). In our collaborative dairy production systems, however, the ratio between lowland and mountain farms was approximately 3:1. This means that even if all dairy farms situated in the lowlands would outsource their young stock, the collaborative system could involve only a part of all current mountain dairy farms. It therefore largely depends on the behaviour of those farms not involved in the collaborative dairy production system whether or not the gains from the comparative advantages of the two regions within dairy production can be translated in a real environmental benefit.

The farms who cannot participate in the collaborative production scheme have different options. They could continue with dairy production, opt for another production system or even give up
farming. The latter option, the abandonment of agricultural land in the mountains is often associated with negative impacts on biodiversity and landscape (MacDonald et al., 2000). Furthermore, due to the worldwide growing food demand and an estimated increase of agricultural land demand in the future (Brunelle et al., 2014), the abandonment of land that is already used for food production is not a reasonable option, even if this land is in a less favoured area. Therefore, those areas should remain productive. As dairy production in the mountains is generally less efficient, a continuation of dairy production on the remaining mountain farms would dilute the gains achieved through collaboration on the other farms, as part of the mountain farms would still focus on a production activity where they have a comparative disadvantage. In a broader context, this means that further agricultural activities should be identified where mountain farms have a comparative environmental advantage. Possible candidates for such considerations include grassland-based beef production systems that would substitute more concentrate-based beef production systems in the lowlands. The usefulness of this approach could be evaluated by linear programming, another concept from economics that was already successfully used in an LCA context for an optimisation of diets in the Netherlands (van Kernebeek et al., 2015). Different from the concept of comparative advantage optimising only two production systems in two different regions, linear programming allows considering more production systems and regions.

4.4.2 Effects on farm income and workload

To what extent collaboration was found beneficial in the simulations depended on the chosen strategy, with either increased specialisation or diversification, and the milk yield and its designation (standard or better priced cheese milk). Lowland farms were calculated to be able to increase their income through collaboration with increased specialisation, but only if they owned cows with a high milk yield or produced milk with an added value. In the scenario with high yielding cows producing cheese milk, the additional working time needed for the increased milk production was valued at CHF 115/h. This can be considered as very good compensation, as the comparable agricultural wage used in Swiss economic calculations is defined as CHF 28/h (Gazzarin and Lips, 2012). In the scenario with a rather low milk yield with the milk sold as standard milk, no additional income was generated according to the simulations and thus the farmer would be inclined to rear his young stock on his own farm.

Alternatively, farms with low milk yield could also opt for more diversification. This reduced the income, but also saved some time, as cropping was calculated to be less labour intensive than milk production or rearing the young stock. The farmer could generate a higher income in a complementary job, or save costs by reducing the degree of employment of an employee. If the wage on the complementary job or the wage of the employee would be higher than CHF 22/h, this would compensate the income loss.
For mountain farms, an income loss through collaboration was calculated. The effective loss depended on the income before becoming a specialised heifer rearing farm. More intensive mountain dairy farms with high milk yields per cow had a higher income compared to more extensive dairy farms. This was also observed for farms in the alpine region of Italy (Penati et al., 2011). Thus, the more intensive the farm was before changing to a collaborative system and specialising in keeping the young stock, the higher the income loss would be. However, due to the significant reduction of the workload, the collaboration could still be beneficial, if wages achieved in complementary jobs were higher than the income loss per hour saved. Drawbacks are that it might not be that easy to find a job that is compatible with farm work as the mountain areas are often remote. An additional hindrance for mountain farms to participate in a collaborative system are the high investment costs when changing from dairy production to heifer rearing, as the barn infrastructure needs to be adapted to the new production system. Such costs were not considered in our assessment, which was based on contribution margins and thus only covered variable costs. Once a mountain farm has invested in a new barn for heifers, there is no easy return to dairy production. On the lowland farm, the changes induced by the collaboration are not as pronounced, and the lowland farm still has a certain flexibility either to return to the old system or to opt for a system where heifers are purchased on a cattle market.

4.5 Conclusion

With the example of collaborative dairy production between lowland farms and mountain farms in Switzerland, we were able to show that Ricardo’s theory of comparable advantage is applicable to identify suitable production systems for less favoured regions not only in an economic but also in an environmental context. However, in a rather complex production system like dairy production, the theory of comparative advantage does not cover possible side effects that a division of labour could cause. In our example, changes in both meat and crop production were induced by the collaboration, and contributed either in a positive or negative way to the environmental and economic impact of the dairy production systems. We therefore recommend using the comparative advantages approach as a screening method to identify possible agricultural systems for less favoured regions. After this first screening, a more profound assessment is required. In the present study, the collaborative production reduced the environmental impact, with no clear preference for one of two collaborative systems investigated. An additional analysis of the socioeconomic effects can support farmers in their decision for the other option with more specialisation or that with more diversification.
Acknowledgements

The authors gratefully acknowledge Franz Sutter for inspiring discussions on the collaborative dairy production systems in Switzerland. This work has been funded under the EU seventh Framework Programme by the CANTOGETHER project No289328: Crops and ANimals TOGETHER. The views expressed in this work are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission.
5  Does the recoupling of dairy and crop production via cooperation between farms generate environmental benefits? A case-study approach in Europe.

This chapter is based on the same-titled revised manuscript written by John T Regan, Silvia Marton, Olivia Barrantes, Eimear Ruane, Marjoleine Hanegraaf, Jérémy Berland, Hein Korevaar, Sylvain Pellerin and Thomas Nesme, submitted to European Journal of Agronomy.

Abstract

The intensification of agriculture in Europe has contributed significantly to the decline of mixed crop-livestock farms in favour of specialised farms. Specialisation, when accompanied by intensive farming practices, leaves farms poorly equipped to sustainably manage by-products of production, capture beneficial ecological interactions, and adapt in a volatile economic climate. An often-proposed solution to overcome these environmental and economic constraints is to recouple crop and livestock production via cooperation between specialised farms. If well-managed, synergies between crop and livestock production have the potential to improve feed and nutrient autonomy, and pest regulation. However, strategies currently used by farmers to recouple dairy livestock and crop production are poorly documented; there is a need to better assess these strategies using empirical farm data. In this paper, we employed a farming system approach to describe, analyse and assess the following strategies: (1) Local exchange of materials among dairy and arable farms; (2) Land leasing between dairy and arable farms; (3) Animal exchanges between lowland and mountainous areas; and (4) Industrially mediated transfers of dehydrated fodder. For each strategy, cooperating farm groups were compared to non-cooperating farm groups using indicators of metabolic performance, ecosystem services provision, and resilience. The results indicate that recoupling of crop and dairy production through farm cooperation gives farmers access to otherwise inaccessible or underutilised local resources such as land, labour, livestock feed or organic nutrients. This in turn leads to additional outlets for by-products (e.g. animal manure). Farmers’ decisions about how to allocate the additional resources accessed via cooperation essentially determine if the farm diversifies, intensifies or expands operations. The key finding is that in three of the four crop-livestock integration strategies assessed, these newly accessed resources facilitated more intensive farming practices (e.g. higher stocking rate or number of milking cows per hectare) on cooperating dairy
farms relative to non-cooperating, specialised dairy farms. As a consequence, cooperation was accompanied by limited environmental benefits but helped to improve resource use efficiency per unit of agricultural product produced. This article provides a critical step toward understanding real-world results of crop-livestock cooperation beyond the farm level relative to within-farm crop-livestock integration. As such, it brings practical knowledge of vital importance for policy making to promote sustainable farming.

5.1 Introduction

Contemporary agriculture through its direct impacts on land use and ecosystems, and on regional and global cycles of carbon, nutrients and water is one of the main drivers of environmental change (Foley et al., 2011). Many negative agricultural impacts are related to intensification and specialisation of farming systems in industrialised countries (Maréchal et al., 2008; O'Sullivan et al., 2015). In Europe, mixed crop-livestock farms have been declining since 1970 (Ryschawy et al., 2013) and by 2010 only 14% of farm holdings were mixed with both crops and livestock, while 52% were specialised in cropping, and 34% were specialised in livestock husbandry (Eurostat, 2013). These specialised farms are often dissociated from land and its natural communities and cycles (Naylor et al., 2005; Peyraud et al., 2014), and as a result generally exhibit low diversity, high-input use, and low resilience in the face of sudden shocks (Oomen et al., 1998).

Given that farmers now have to operate in a context characterised by unprecedented change and high uncertainty, such as ever-more limited and costly production resources, stricter environmental regulations, volatility in agricultural product prices and increasing frequency of extreme climatic events (Lebacq et al., 2015), continuing along a trajectory of specialisation in dairy and arable farming potentially threatens the long-term sustainability of these food production systems. Specialised farms are more vulnerable to increases in the cost of inputs to production than are mixed farms that can source inputs to production from exchanges between the crop and livestock enterprises on the farm (i.e. manure for animal feed). Similarly, a decrease in price received for crop or livestock products is more threatening to a specialised farm producing only one output than it is to a mixed farm with a diversity of outputs. Furthermore, the lower crop diversity and system flexibility generally observed on specialised farms relative to mixed farms leaves the former less prepared to adapt their systems in the face of climate shocks. Diversified systems, such as crop-livestock systems (where local integration of crops and livestock systems occurs), therefore appear to be an interesting alternative and path forward for agricultural development (Lemaire et al., 2014). Recoupling crop and livestock production is often advocated as an approach to improve properties of agricultural systems such as productivity (Herrero et al., 2010; Peyraud et al., 2014; Soussana and Lemaire, 2014), resource use efficiency (de Moraes et al., 2014; Schiere et al., 2002; Sulc and Tracy, 2007; Veysset et al., 2014; Villano et al., 2010), autonomy (Ryschawy et al., 2013) and
resilience (Havet et al., 2014; Peyraud et al., 2014; Salton et al., 2014), and to provide ecosystem services, such as improved soil fertility, pest regulation and carbon sequestration (Bonaudo et al., 2014; Lemaire et al., 2014; Peyraud et al., 2014; Sanderson et al., 2013; Soussana and Lemaire, 2014; Sulc and Franzluebbers, 2014).

Achieving this recoupling at farm-level on specialised dairy and arable farms will be challenging for farmers: resource and infrastructural constraints on individual specialised farms will make it difficult for farmers to evolve their production system to one where recoupling of crops and livestock can easily occur. As an alternative, several authors (Bell and Moore, 2012; Bell et al., 2014; Franzluebbers et al., 2014; Russelle et al., 2007) have proposed that recoupling can be achieved at larger scales than the farm through cooperation, partnerships and contracts between specialised crop and livestock farms. This is an attractive solution in the current climate of high input cost and limited resources as it allows some of the synergies normally provided by within-farm integration to be obtained, but with much smaller increases in farm workload, complexity of rotations, skills and infrastructure on individual farms involved. Integrating crops and livestock beyond the farm scale also has the advantage that a greater quantity and diversity of production resources are accessible compared to those available when integration takes place internally at the farm scale.

Yet, research in this domain remains, except for a few exceptions, largely at a theoretical and conceptual level (Ryschawy et al., 2014; Veysset et al., 2014; Villano et al., 2010), and therefore practical messages for policy makers and farmers are lacking (Franzluebbers et al., 2014; Moraine et al., 2014; Peyraud et al., 2014; Russelle et al., 2007). For example, little is known about the appropriate scale at which to promote integration between crops and livestock or about the difficulties that farmers encounter when cooperating with another farmer to integrate their productions. As a consequence, there are insufficient empirical research studies to assess the performance of integrated crop-livestock systems at scales beyond the farm (Bonaudo et al., 2014; Tanaka et al., 2008). In particular, questions remain as to whether collaboration among specialist farms might achieve the same range of the metabolic (utilizing animal manure to enhance soil tilth, fertility and C sequestration) and ecological (longer crop rotations to enhance pest control and improve biodiversity) synergies as within-farm integration (Peyraud et al., 2014; Russelle et al., 2007).

The objective of this study was to assess the benefits and drawbacks of integrating crops and livestock via cooperation between farms compared to integrating them at the farm scale or keeping them separated on individual specialised crop and livestock farms. Four crop-dairy livestock integration strategies were assessed using empirical farm data from case studies in different biogeographical regions of Europe. The strategies assessed were: (1) Local exchange of straw for manure among dairy and arable farms; (2) Temporary land leasing between dairy and arable farms; (3) Animal exchanges between lowland and mountainous areas; and (4) Industrially mediated transfers of dehydrated fodder. By comparing non-cooperating baseline farms (specialised and mixed) with cooperating, specialised farms in each case study area, it was possible to identify the benefits
and drawbacks, at both farm and beyond farm levels, of the different integration strategies, in particular relating to system metabolism (nutrient use efficiency and autonomy) and ecosystem services provision (such as soil fertility, pest regulation and carbon sequestration). It was hypothesised that cooperation between specialised arable and livestock farms will improve farm level environmental performances due to more optimal management of natural resources and enhanced provision of ecosystem services. More precisely, we first hypothesised that cooperation between farms specialised in crop or dairy livestock production can help close nutrient cycles, increase autonomy and mitigate external inputs of fertiliser and feed beyond the farm level. Second, we hypothesised that the production of ecosystem services will be greater on cooperating farms relative to non-cooperating, specialised farms since it is expected that recoupling crop and livestock production will capture positive ecological interactions, such as a reduced pest pressure through optimised and more diverse crop rotations.

One may want to distinguish between cooperation and integration among specialised farms. In the former, flows of products are generally organised through a marketplace in a pure economic logic where transport of products depends only on costs, with little consideration for the benefits linked to integration, whereas in the latter, there is a collective organisation of the landscape structure such that crop and livestock activities in a collection of farms are considered simultaneously to optimally manage resources and promote ecosystem services (Moraine et al., 2014). However, the difference between these terms can at times be disputed. For example, all the case-studies considered in this paper involved some market mediated cooperation among specialised farms but such cooperation generally took place through two way material exchanges and was designed to improve environmental benefits (such as increased nitrogen fixation, increased carbon sequestration, natural pest regulation, preservation of biodiversity, etc.). Therefore, in the following sections we use cooperation as a general term that encompasses a wide range of interactions among specialised farms.

5.2 Materials and Methods

5.2.1 Case studies

Case studies were chosen to ensure a diversity of forms of cooperation from different biogeographical regions (Atlantic, Alpine and Mediterranean), and were located in different European countries. The four case studies assessed were located in: Ebro River Basin, Aragon, Spain; Winterswijk, The Netherlands; Thurgau and Grisons, Switzerland; and Brittany, France. The strategies to recouple crop and livestock production are illustrated in Supplementary Figure 1.

5.2.1.1 Ebro Basin, Aragon, Spain

The Ebro River Basin of the Aragon region is situated in the northeast of Spain. The climate in the region is mainly Mediterranean semiarid, with precipitation ranging from around 290 to 400
mm/yr (Table 7). Due to a severe hydric deficit in the area, dairy farming systems are linked to the irrigated valley bottoms of the Ebro River and some of its tributaries. The dairy farming system in the Ebro Basin involves permanent housing of cows and zero-grazing with cut irrigated forages fed indoors (Barrantes et al., 2009). Land use involves irrigated lands, sown mainly with maize for silage, Italian ryegrass and alfalfa. The most common land use is double cropping (two crops grown successively during one year) of Italian ryegrass in winter and silage maize in spring-summer. High levels of concentrate feeds are used which consist mainly of locally produced maize and barley, and imported soybean meal (from United States, Brazil and Argentina). As dairy farms in the area don’t generally grow cereals, the straw they require for animal bedding and for feeding to heifers as low quality forage is often obtained through exchange for dairy manure with neighbouring arable farms. On arable farms that cooperate with dairy farms, conventional tillage is predominant as manure has to be incorporated into the soil whereas non-cooperating arable farms practice mostly no-till or min-till and grow mainly cereals, such as barley and wheat. The form of cooperation taking place was the exchange of solid manure produced on dairy farms for barley straw produced on neighbouring arable farms, allowing dairy manure to be spread on crop land (improving soil fertility on arable farms) and providing straw for use as bedding material on dairy farms. Cooperation is not governed by a contractual agreement and so the risk to farmers is not covered from year to year.

5.2.1.2 Winterswijk, The Netherlands

Winterswijk is located in the Eastern part of the Netherlands in the province of Gelderland. The soil type together with good rainfall makes the municipality highly suitable for grass production. Agriculture accounts for 61% of the land use in Winterswijk, with specialised dairy farming the most important agricultural sector in the region (150 farms). Land use in the municipality is dominated by grass and maize for silage (Korevaar and Geerts, 2012) while other crops are cereals and potatoes with about 10 – 15 arable farms specialised in potato production (Table 7). The form of cooperation taking place is the short-term leasing of land between dairy farms and neighbouring arable farms specialised in potato production. This form of cooperation allows the introduction of temporary grassland in potato crop rotations and the spreading of dairy slurry on potato crop fields. The leasing of fields generally takes place when dairy farmers renew their grassland (on average every 5 years). This allows arable farmers to extend their acreage by planting a potato crop on the dairy farmer’s field in spring. The relative small size of these arable farms means that the growing of potatoes on the rented fields of dairy farms is very important to the arable farmer as it allows him to have long potato-based crop rotations to better control soil-borne diseases.
5.2.1.3 Cantons of Thurgau and Grisons, Switzerland

The cantons of Thurgau and Grisons are situated in the northeast and east of Switzerland, respectively. They are representatives of lowland and mountainous areas. Pronounced differences in altitude and climate between the two cantons is the main reason for the vast difference in the productivity of their soils, with those of the lowland Thurgau canton being more productive and therefore more suitable for intensive agriculture than the soils of the mountainous Grisons canton, which are more suitable for extensive agriculture (Table 7). Grassland farming is dominant in both cantons, with dairy cattle being the dominant grazing livestock. Cereal and root crop production (primarily sugar beet and potato) takes place on about one quarter of the utilised agricultural area (UAA) in Thurgau compared to only about 2% of UAA in Grisons (Swiss Federal Statistical Office – SFSO, 2016).

Concentrate feed autonomy (currently around 50% in Switzerland) could be improved through collaboration between the cantons of Thurgau and Grisons, whereby, more cattle with lower feed requirements such as lowland heifers are fed on mountain grassland, and cattle with higher feed requirements such as dairy cows are fed on lowland grass. The form of cooperation taking place is the sale, by lowland farmers, of weaned female dairy calves to mountain farmers. The mountain farmers raise the heifers and then sell them back to the same lowland farmer when they are pregnant and close to calving. Cooperation takes place via a standardised contract with the price being determined by age at first calving.

This form of cooperation allows cooperating lowland and mountain farmers to better exploit available resources. The lowland dairy farmer may use the land (and time) previously used for the raising of young stock, to either grow crops or to increase cattle numbers and produce more milk using highly productive lowland grass. This grassland resource can be grazed to its full potential when stocked with dairy cattle whereas it remained under grazed when stocked with young animals.

5.2.1.4 The Coopédom cooperative (Domagné, Brittany, France)

The climate (temperate oceanic) and soil context in the Brittany region has favoured the development of animal production such that it is France’s leading region for animal production (Table 7). Even though 94% of the regions UAA is allocated to animal production (grazing, and feed and forage crops), the region is highly dependent on protein crop imports (particularly soybean meal). The Coopédom agricultural cooperative, realising the needs of its 700 members (mostly dairy farmers) for high quality forages, adopted the industrial process of dehydrating forages (mainly grass, alfalfa and silage maize) to preserve their quality. The cooperative also harvests and transports forages for its members. The facility to dehydrate alfalfa makes it a viable home-grown protein crop with potential to reduce dairy farmer’s dependency on imported soybean meal. The dehydration process uses a biomass (40% miscanthus and 60% wood from forest or sawmills) furnace and a
coal furnace. Coopédrom currently harvests approximately 400 ha of miscanthus per annum for fueling its biomass furnace, which provides 30% of the energy needs of the cooperative. Some of this miscanthus is produced on dairy farms where it is sown on land normally reserved for annual crops. The form of cooperation taking place is the dehydration and supply of forage crops (primarily alfalfa) through an agricultural cooperative fuelled by miscanthus grown by the cooperative’s members.

5.2.2 Research approach employed and data collection

In order to assess the potential for the different strategies to recouple crop and livestock production, a farm survey design was employed in each case study to compare two existing farming approaches non-cooperating, specialised and/or mixed farms (i.e. the baseline farms) were compared to cooperating, specialised farms. Cooperating farms consisted of both dairy livestock and crop farms that employed one of the four crop-livestock integration strategies already introduced above (see Supplementary Figure 1).

For each case study and its associated crop-livestock integration strategy a number of baseline farms and cooperating farms were sampled. The baselines to be sampled for each case study were defined based on the type of farms cooperating together. In general, the first baseline consisted of non-cooperating, specialised farms and had a sampling density of 4-8 non-cooperating, specialised dairy farms and 5-15 non-cooperating, specialised arable farms located nearby. The second baseline group, which was only relevant or available for some of the case studies, consisted of non-cooperating, mixed farms (farms with interdependent livestock and arable enterprises) and had a sampling density of 3-4 mixed farms. The purpose of this baseline was to allow comparison of the performance of mixing crops and livestock at the farm level (within-farm) versus beyond the farm level (among-farm). The two baseline groups were compared with 6-11 specialised farms that cooperate for mutual benefit. The number of baseline and cooperating farms sampled in each case study is outlined in Table 8. More details of the farm types sampled in each case study are provided in Supplementary Tables 1-4.
<table>
<thead>
<tr>
<th>Study area</th>
<th>Biogeographic region</th>
<th>Study area (km²)</th>
<th>Administrative unit</th>
<th>Maximum distance between sampled farms (km)</th>
<th>Dominant soil type</th>
<th>Climate (average annual temp and average annual rainfall)</th>
<th>Land use in % of total agricultural area</th>
<th>Farm type by % of total farms</th>
<th>Average farm size in ha (for dairy, arable and mixed farms in the study area)</th>
<th>Average stocking rate on dairy and mixed farms (LU ha⁻¹)</th>
<th>Average milk yield of dairy and mixed farms (kg milk/cow/year)</th>
<th>Dominant crop species and average yield (t DM/ha) for arable and mixed farms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ebro Basin, Spain</td>
<td>Mediterranean</td>
<td>2607</td>
<td>Catchment</td>
<td>100</td>
<td>Loam to silty loam</td>
<td>14.2°C; 360 mm</td>
<td>Cereals = 55; Maize = 12; Alfalfa = 15; Ryegrass = 2; Other crops = 5</td>
<td>Dairy = 1; Pig and poultry = 8; Beef = 4; Sheep = 5; Arable = 80</td>
<td>NA</td>
<td>NA</td>
<td>Winter cereals (dryland) = 2.5; Grain maize = 12; Alfalfa = 15.5</td>
<td></td>
</tr>
<tr>
<td>Winterswijk, The Netherlands</td>
<td>Atlantic</td>
<td>139</td>
<td>Municipality</td>
<td>18</td>
<td>Sand</td>
<td>10.3°C; 848 mm</td>
<td>Cereals = 4; Grassland = 65; Silage maize = 22; Potato = 6; Other crops = 3</td>
<td>Mixed = 2; Dairy = 60; Arable = 4; Poultry = 12; Beef = 13; Sheep/goat = 8; Arable = 22; Mixed = 33</td>
<td>Dairy = 29; Arable = 26; Mixed = 31</td>
<td>Dairy: 1.69; Mixed: 1.21</td>
<td>Cereal: 24; Oilseed: 2.5; Grassland: 60; Perennial crops: 5; Others: 15</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>Alpine</td>
<td>991</td>
<td>Canton</td>
<td>36</td>
<td>Loam</td>
<td>8.7°C; 1075 mm</td>
<td>Cereals = 17; Oilseed = 2.5; Grassland = 60; Perennial crops: 5; Others: 15</td>
<td>Dairy = 24; Pig and poultry = 9; Beef = 5; Sheep/goat = 8; Arable = 22; Mixed = 33</td>
<td>Dairy = 59; Arable: 18; Mixed: 56</td>
<td>Dairy: 0.96; Mixed: 1.43</td>
<td>Cereal: 34; Oilseed: 3; Grassland: 63</td>
<td></td>
</tr>
<tr>
<td>Brittany, France</td>
<td>Atlantic</td>
<td>7105</td>
<td>Canton</td>
<td>73</td>
<td>Loam to sandy loam</td>
<td>2-10°C; 860 mm</td>
<td>Cereals = 34; Oilseed = 3; Grassland: 63</td>
<td>Dairy = 33; Pig and poultry = 13; Beef = 10; Sheep/goat = 11; Arable = 16; Mixed = 11; Other: 5</td>
<td>Dairy = 6164; Arable = 7788</td>
<td>Lowland dairy = 6987; Lowland mixed = 7788</td>
<td>Winter cereals (dryland) = 2.5; Grain maize = 12; Alfalfa = 15.5</td>
<td></td>
</tr>
</tbody>
</table>

*These figures are not specific to Thurgau or Grisons, but to the lowland and mountainous areas they represent.*
Table 8. Baseline and cooperating farms surveyed per case study.

<table>
<thead>
<tr>
<th>Farm group</th>
<th>Ebro Basin, Spain</th>
<th>Winterswijk, The Netherlands</th>
<th>Thurgau and Grisons, Switzerland</th>
<th>Brittany, France</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-cooperating, specialised dairy</td>
<td>4</td>
<td>4</td>
<td>8 (4, 4)(^a)</td>
<td>7</td>
</tr>
<tr>
<td>Non-cooperating, specialised arable</td>
<td>5</td>
<td>15(^b)</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Mixed dairy</td>
<td>4</td>
<td>3</td>
<td>NR</td>
<td>NR</td>
</tr>
<tr>
<td>Cooperating, specialised dairy</td>
<td>5</td>
<td>3</td>
<td>8 (4, 4)(^c)</td>
<td>11</td>
</tr>
<tr>
<td>Cooperating, specialised arable</td>
<td>4</td>
<td>3</td>
<td>NR</td>
<td>NR</td>
</tr>
</tbody>
</table>

\(^a\) Four non-cooperating lowland dairy farms and four non-cooperating mountain dairy farms.

\(^b\) Surveyed farms were located approximately 40km from the Winterswijk municipality in the provinces of Gelderland, Overijssel and Drenthe.

\(^c\) Four lowland dairy farms (no heifers) and four mountain heifer rearing farms.

NR, not relevant

A number of baseline and cooperating farms were chosen from each study area based on their representativeness in terms of land use, farm size, stocking rate, milk yield per cow, and dry matter yield per dominant crop type (Table 7). Note that cooperating farms were not selected based on their exact representativeness of dairy and arable farms within the considered case study areas but were selected in order to capture the dominant form of cooperation between farms. Farms were then surveyed to collect data on location (distance between farms), interaction with neighbouring farms (contract based or verbal, quantities exchanged, amount exchanged etc.), farm structure (land use, labour force, output, livestock etc.), farming practices (chemical input, irrigation, tillage etc.), and farm agronomic and economic performances (crop and animal productivity, farm income, etc.). The farms were then grouped according to type (non-cooperating dairy, mixed dairy, cooperating arable etc.) for analysis of each group followed by comparisons between certain groups. The empirical farm data used to calculate indicator values were collected by case study leaders for the year 2013 (in some cases supplemented with data from 2012). Interviews with farmers took place during the winter season 2014.

Appropriate indicators of metabolic performance, ecosystem services provision, and resilience were used to conduct a multi-criteria assessment of each crop-livestock integration strategy. Some general indicators were calculated for all case studies, whereas others were specific to a case study,
5 Recoupling of dairy and crop production via cooperation between farms

depending on the expected benefit of the cooperation. Indicators of metabolic performance included: farm-gate N surplus (after Nevens et al., 2006); N use efficiency; district N autonomy; concentrate feed autonomy; forage autonomy; cropping intensity (FAO, 1997) and stocking rate. Indicators of ecosystem services provision included: crop yield; milk production; number of pesticide applications; and share of UAA under permanent grassland or legumes. Indicators of farm resilience included crop rotation duration; and crop diversity as measured using the Shannon Diversity Index (after Benin et al., 2004). A short list describing the non-self-explanatory indicators is provided in Table 9.

Table 9. Indicators of metabolic performance, ecosystem services provision and resilience.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stocking rate</td>
<td>LU ha⁻¹</td>
<td>Number of livestock units divided by the land area on the farm used to produce feed (forage + grain feed) for livestock</td>
</tr>
<tr>
<td>Farm-gate N surplus</td>
<td>kg ha⁻¹ or kg kg⁻¹</td>
<td>Total N input - total N output. Expressed per hectare of UAA or per kg of N in sold agricultural products*</td>
</tr>
<tr>
<td>Nitrogen use efficiency</td>
<td>kg kg⁻¹</td>
<td>Total N in sold products divided by total N input</td>
</tr>
<tr>
<td>District N autonomy</td>
<td>%</td>
<td>N input via material exchange of straw or manure, biological fixation and deposition divided by total N input to the farm</td>
</tr>
<tr>
<td>Concentrate feed autonomy</td>
<td>%</td>
<td>Home-grown cereal grain fed to livestock divided by total concentrates (protein and energy) fed to livestock</td>
</tr>
<tr>
<td>Forage autonomy</td>
<td>%</td>
<td>Home-grown forages (grazed and cut) fed to livestock divided by the total forages fed to livestock</td>
</tr>
<tr>
<td>Shannon diversity index</td>
<td>SDI = − ∑_i a_i ln a_i where a_i = area share occupied by i-th crop variety within the total planted area.</td>
<td></td>
</tr>
<tr>
<td>Cropping intensity</td>
<td></td>
<td>Ratio between irrigated crop area (where double cropping areas are counted twice respectively) and physical area equipped for irrigation (FAO, 1997)</td>
</tr>
</tbody>
</table>

*Stock changes (e.g., conserved forages, straw, etc.): a stock increase was considered as an output of N and a stock decrease was considered as an input of N to the farm.

Indicators were first calculated at the farm level and then averaged for each farm group. For each indicator and case-study, the comparison between baseline and cooperating groups were performed through simple Anova followed eventually by multiple comparison Tukey tests. All the statistical treatments were performed with R.
5.3 Results

5.3.1 Local exchange of materials among dairy and arable farms (Ebro Basin, Aragon, Spain)

Characteristics of the studied farm groups in the Ebro Basin are presented in Table 10. The cooperating, specialised dairy group had the highest mean milk production per hectare of feeding area producing over 45,000 litres. Milk yield per cow was approximately the same across the three dairy farm groups ranging from 10,405 to 10,510 litres. In terms of tillage system, the non-cooperating, specialised arable group is different from the other groups with only 6% of its UAA under conventional tillage compared to between 70 and 97% for the other groups.

Table 10. Characteristics of the Ebro Basin farm groups; mean values ± standard deviations.

<table>
<thead>
<tr>
<th>Farm characteristic</th>
<th>Non-cooperating, specialised dairy</th>
<th>Mixed dairy</th>
<th>Cooperating, specialised dairy</th>
<th>Cooperating, specialised arable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilised agricultural area (ha)</td>
<td>35 ± 7.2</td>
<td>195 ± 85</td>
<td>306 ± 223</td>
<td>29.6 ± 22.8</td>
</tr>
<tr>
<td>Stocking rate (LU ha⁻¹)</td>
<td>3.5 ± 0.6</td>
<td>-</td>
<td>2.7 ± 1.9</td>
<td>6.8 ± 4.9</td>
</tr>
<tr>
<td>Milk production (m³ ha⁻¹)</td>
<td>25.2 ± 4.3</td>
<td>-</td>
<td>17.7 ± 8.6</td>
<td>45.5 ± 31.3</td>
</tr>
<tr>
<td>Conventional tillage area (%)</td>
<td>73 ± 31</td>
<td>6 ± 9</td>
<td>70 ± 22</td>
<td>90 ± 22</td>
</tr>
<tr>
<td>Irrigated area (%)</td>
<td>100 ± 0</td>
<td>26 ± 37</td>
<td>97 ± 6</td>
<td>82 ± 25</td>
</tr>
<tr>
<td>Forage area (%)</td>
<td>94 ± 7</td>
<td>9 ± 12</td>
<td>51 ± 14</td>
<td>75 ± 35</td>
</tr>
<tr>
<td>Cereals and oilseeds area (%)</td>
<td>6 ± 7</td>
<td>75 ± 21</td>
<td>47 ± 11</td>
<td>22 ± 32</td>
</tr>
</tbody>
</table>

*All tillage, irrigation and land use areas are expressed as a percentage of the total UAA of the farm area.*

Potential benefits of material exchanges between specialised farms were assessed via hypothesis testing. We firstly hypothesised that cooperation would: 1) reduce mineral fertiliser use on cooperating, specialised arable farms relative to their non-cooperating counterparts; and 2) limit over application of manure on cooperating dairy farms thus preventing highly positive farm-gate nutrient budgets. However, the mineral N fertiliser input per hectare on cooperating arable farms was more than double that used on non-cooperating arable farms (Figure 14(b)). Such results were due to intensive arable cropping on cooperating arable farms as revealed by intensive soil tillage and irrigation (Table 10) and the cropping intensity indicator in Figure 14(b). Results also showed that the N surplus per hectare was higher on cooperating dairy farms than on their non-cooperating counterparts (Figure 14(a)). This result may be due to cooperating dairy farms having a much higher stocking rate (Table 10) which makes them more dependent on imported feed than non-cooperating, specialised dairy farms. However, expressing farm-gate N surpluses per unit of agricultural product showed non-cooperating (2.20 kg N surplus/kg N sold in products) and cooperating (2.15 kg N surplus/kg N sold in products) dairy farms to have similar N surpluses.
It was secondly hypothesised that cooperation helps to increase the fraction of the nutrients entering farm gates that comes from within the cooperating group (for both arable and dairy farms), thus improving nutrient autonomy of the cooperating farms. To test this hypothesis, the district N autonomy was calculated as N input via material exchange of straw or manure, biological fixation and deposition divided by total N input for each farm group. However, results showed that cooperating dairy farms exhibited lower district N autonomy (16%) than non-cooperating dairy farms (24%) due primarily to a large amount of imported concentrate feed and forages (Figure 14(a)). The contrary was observed for cooperating arable farms as they had slightly higher N autonomy (44%) than their non-cooperating (38%) counterparts (Figure 14(b)).

Lastly, aside from the expected benefits of this cooperation, a major drawback could be that cooperation between specialised arable and dairy livestock farms would limit the crop species diversification of arable farms compared to mixed farms and may thus result in short, simplified crop rotations. Results showed that cooperating arable farms, when compared to mixed farms, exhibited: 1) much lower land use diversity as measured by the Shannon Diversity Index (Figure 14(b)); 2) shorter crop rotations (Figure 14(b)) with lower species diversity (data not shown); 3) smaller share of UAA alternating spring and winter crops (25% compared to 53%); and 4) greater share of UAA with two or more subsequent cereals (70% compared to 47%). Similarly in Figure 14(a) it can be seen that cooperating and non-cooperating, specialised dairy farms, when compared to mixed farms, have lower land use diversity and shorter crop rotations. These results provide further evidence of the higher intensity of farming taking place on cooperating dairy farms relative to non-cooperating, specialised and mixed dairy farms. The percentage UAA with ≥ 1 pesticide application was the only indicator showing lower intensity of farming on cooperating farms relative to non-cooperating, specialised farms (Figure 14(a) and Figure 14(b)). Comparing mixed farms with cooperating dairy farms in Figure 14(a) shows that the former are more diverse, autonomous, and efficient, and pose a lower pollution risk per hectare of farmed area.

The increase in farming intensity on cooperating dairy farms as indicated by higher stocking rate, and on cooperating arable farms as indicated by the cropping intensity and input use has restricted the benefits that these farming systems would otherwise have realised as a result of cooperation, such as lower N surplus per hectare. As a result of cooperation, dairy farms have access to a greater land area on which to spread excess manure. The result is a doubling of the stocking rate on cooperating dairy farms relative to specialised dairy farms as they take advantage of new outlets for manure acquired through material exchange. As this increase in stocking rate is aligned only with the farming systems ability to manage manure and not with its ability to produce livestock feed, higher volumes of concentrate feed and forages must be imported onto the farm to sustain the
5.3 Results

Figure 14. Comparison between Ebro Basin farm groups: radar chart (a) compares non-cooperating, cooperating and mixed dairy farms; and radar chart (b) compares non-cooperating and cooperating arable farms and mixed dairy farms. Higher indicator values on green axes are indicative of more sustainable systems (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of less sustainable systems (i.e. less self-sufficient in inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for $P<0.1$, ** for $P<0.05$, and ns for non-significant). The min and max value for each indicator’s axis is provided in brackets after the indicator label.
system. Hypotheses pertaining to the expected benefits of material exchanges between farms were proved to be false. This would appear to be a result of the intensification observed on both cooperating dairy and cooperating arable farms.

5.3.2 Land leasing between dairy and arable farms (Winterswijk, The Netherlands)

In Winterswijk, cooperation through land leasing is generally not covered by a contractual agreement. Land is mostly leased on a yearly basis and in many cases the arrangement may also allow the dairy farmer to bring any excess slurry to fertilise the land where the potatoes are grown. On average, surveyed dairy farms cooperated with 1 arable farm leasing them approximately 6 hectares of land for potato production whereas surveyed arable farms cooperated with up to 32 dairy farms renting approximately 144 hectares of land for potato and silage maize production. More details of the land leasing strategy are provided in Supplementary Table 5.

The stocking rate on cooperating dairy farms was similar to that on non-cooperating dairy farms (Table 11). The UAA of cooperating arable farms is three times the size of the area for non-cooperating arable farms but about 85% of the cooperating arable farms’ land area is rented from neighbouring dairy farmers. This has allowed cooperating arable farms to become highly specialised in potato production as they can have very long potato-based crop rotations that would not otherwise be possible. Land use diversity, as estimated using the Shannon Diversity Index, was similar on non-cooperating and cooperating dairy farms but higher on non-cooperating arable and mixed dairy farms than on cooperating arable farms due to these farms having specialised in potato production as a result of cooperation (Table 11).
Table 11. Characteristics of Winterswijk farm groups; mean values ± standard deviations.

<table>
<thead>
<tr>
<th>Farm characteristic</th>
<th>Non-cooperating, specialised dairy</th>
<th>Non-cooperating, specialised arable</th>
<th>Mixed dairy</th>
<th>Cooperating, specialised dairy</th>
<th>Cooperating, specialised arable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilised agricultural area (ha)</td>
<td>67 ± 23</td>
<td>75 ± 0</td>
<td>52 ± 25</td>
<td>72 ± 42</td>
<td>218 ± 150</td>
</tr>
<tr>
<td>Stocking rate (LU ha⁻¹)</td>
<td>2.07 ± 0.37</td>
<td>-</td>
<td>1.31 ± 1.08</td>
<td>2.12 ± 0.62</td>
<td>-</td>
</tr>
<tr>
<td>Milk production per cow (lit)</td>
<td>7991 ±</td>
<td>7072 ±</td>
<td>8833 ± 316</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Permanent grassland (%)</td>
<td>62 ± 19</td>
<td>0 ± 0</td>
<td>58 ± 23</td>
<td>68 ± 10</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Temporary grassland (%)</td>
<td>11 ± 17</td>
<td>3 ± 0</td>
<td>4 ± 8</td>
<td>2 ± 3</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Silage Maize (%)</td>
<td>25 ± 4</td>
<td>0 ± 0</td>
<td>6 ± 6</td>
<td>23 ± 16</td>
<td>21 ± 13</td>
</tr>
<tr>
<td>Potatoes (%)</td>
<td>1 ± 2</td>
<td>38 ± 0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>74 ± 8</td>
</tr>
<tr>
<td>Wheat, barley, sugar beet (%)</td>
<td>2 ± 2</td>
<td>42 ± 0</td>
<td>3 ± 4</td>
<td>6 ± 10</td>
<td>3 ± 5</td>
</tr>
<tr>
<td>Shannon diversity index</td>
<td>0.85 ± 0.37</td>
<td>1.24 ± 0</td>
<td>1.09 ± 0.48</td>
<td>0.98 ± 0.2</td>
<td>0.63 ± 0.14</td>
</tr>
</tbody>
</table>

*Surveyed farms in this group were from outside - but close to - the Winterswijk municipality

Potential benefits of land leasing between specialised farms were assessed via hypothesis testing. We firstly hypothesised that if arable farmers rent land (via a lease agreement) from dairy farmers it will result in: 1) longer crop rotations; and 2) lower cropping frequency of potatoes and hence a lower incidence of soil-borne diseases on sensitive crops such as potatoes (as indicated by lower fungicide or insecticide use on these crops). The results showed that both cooperating arable and dairy farms have longer crop rotations than their non-cooperating counterparts (Figure 15(a) and Figure 15(b)). Cooperation allows arable farms to become more specialised in potato production and expand the area on which they grow potatoes. Results also showed that the cropping frequency of potatoes was lower on both cooperating arable (0.24) and dairy (0.17) farms than on non-cooperating arable (0.29) farms. Cropping frequency of potatoes was calculated by dividing the number of years of potatoes in the crop rotation by the total duration of the rotation. Even though longer crop rotation duration and lower cropping frequency of potatoes was observed on cooperating farms, it did not result in reduced numbers of pesticide applications on potatoes. There were thirteen pesticide applications per year on potatoes in both non-cooperating arable and cooperating dairy farms compared to 13.8 applications per year on cooperating arable farms (this high application frequency is a result of fungicide use against phytophthora on potatoes). It appears that any reduction in the incidence of soil-borne diseases that might occur as a result of the lengthening of crop rotations and lowering of potato cropping frequency have not been accounted for in the pest management plans of cooperating arable farms.
Figure 15. Comparison between Winterswijk farm groups: radar chart (a) compares non-cooperating, cooperating and mixed dairy farms; and radar chart (b) compares non-cooperating and cooperating arable farms and mixed dairy farms. Higher indicator values on green axes are indicative of more sustainable systems (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of less sustainable systems (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for \( P<0.1 \), ** for \( p<0.05 \), *** for \( p<0.01 \) and ns for non-significant). The min and max value for each indicator’s axis is provided in brackets after the indicator label.
We also expected that the inclusion of crops such as potatoes in the grassland based rotations of cooperating dairy farms would: 1) improve weed control as a result of ploughing at time of potato planting; and 2) reduce fuel use on cooperating dairy farms as ploughing is undertaken by arable farmers. Results confirmed that the number of herbicide applications at the time of grassland renewal was lower on cooperating dairy farms (0.06 per year) than on non-cooperating dairy farms (0.3 per year) and that diesel use per hectare was much lower on cooperating dairy farms than it was on non-cooperating dairy farms (Figure 15(a)). The magnitude of the decrease in diesel use suggests that there may be other factors at play that are partly responsible for the lower diesel use on cooperating dairy farms. One such factor is the preference for hiring contractors on cooperating dairy farms which results in more expensive contractor bills but lower on-farm consumption of diesel.

It was lastly hypothesised that the renting of dairy fields by arable farmers for potato growing would reduce mineral fertiliser use on cooperating arable farms as they can rely instead on slurry applied by dairy farmers and on legacy effects of historical applications of slurry on grasslands (e.g., high soil organic matter on ploughed grassland). Results indeed showed that mineral N fertiliser use was lower on cooperating arable farms than on specialised arable farms (Figure 15(b)).

Overall, mixed farms performed better in terms of sustainability indicators and intensity indicators than all other farm groups while the differences between cooperating and non-cooperating dairy farms were small.

5.3.3 Animal exchanges between lowland and mountainous areas (Thurgau and Grisons, Switzerland)

The stocking rate is similar in the two lowland dairy groups and higher than in the mountain farm groups (Table 12). The two lowland dairy farm groups have roughly the same land area dedicated to cropping activities but the cooperating farms dedicate a greater land area to more profitable root crops (potatoes and sugar beet). Land use diversity, as estimated using the Shannon Diversity Index, is higher on cooperating than on non-cooperating lowland dairy farms due to the different crop species being grown on similar size areas (as opposed to some crop species being grown on a very large area).
5 Recoupling of dairy and crop production via cooperation between farms

Table 12. Characteristics of the Swiss farm groups; mean values ± standard deviations.

<table>
<thead>
<tr>
<th>Farm characteristic</th>
<th>Non-cooperating lowland dairy (baseline)</th>
<th>Non-cooperating mountain dairy (baseline)</th>
<th>Cooperating lowland dairy (no heifers)</th>
<th>Cooperating mountain heifer rearing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural Area (ha)</td>
<td>50 ± 19</td>
<td>38 ± 13</td>
<td>40 ± 14</td>
<td>39 ± 11</td>
</tr>
<tr>
<td>Stocking rate (LU ha⁻¹)</td>
<td>2.63 ± 0.76</td>
<td>1.66 ± 0.50</td>
<td>2.68 ± 0.57</td>
<td>1.48 ± 0.24</td>
</tr>
<tr>
<td>Milk production (L ha⁻¹)</td>
<td>12435 ± 2859</td>
<td>7337 ± 3831</td>
<td>14427 ± 1920</td>
<td>-</td>
</tr>
<tr>
<td>Permanent grassland (%)</td>
<td>52 ± 23</td>
<td>79 ± 30</td>
<td>42 ± 12</td>
<td>89 ± 17</td>
</tr>
<tr>
<td>Temporary grassland (%)</td>
<td>10 ± 12</td>
<td>13 ± 19</td>
<td>22 ± 7</td>
<td>3 ± 3</td>
</tr>
<tr>
<td>Silage Maize (%)</td>
<td>10 ± 10</td>
<td>8 ± 11</td>
<td>11 ± 11</td>
<td>4 ± 7</td>
</tr>
<tr>
<td>Wheat and barley (%)</td>
<td>13 ± 9</td>
<td>0 ± 0</td>
<td>11 ± 7</td>
<td>5 ± 8</td>
</tr>
<tr>
<td>Sugar beet and potatoes (%)</td>
<td>2 ± 4</td>
<td>0 ± 0</td>
<td>9 ± 8</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Corn maize (%)</td>
<td>4 ± 6</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
</tr>
<tr>
<td>Shannon diversity index</td>
<td>1.22 ± 0.36</td>
<td>0.43 ± 0.53</td>
<td>1.38 ± 0.15</td>
<td>0.37 ± 0.54</td>
</tr>
</tbody>
</table>

Potential benefits of animal exchanges between lowland and mountainous farms were assessed via hypothesis testing. In the case of cooperating lowland dairy farms, it was hypothesised that if the freed up land previously occupied by heifers is used for cash cropping then farm income will increase, or, if the land is used for feed crops; then concentrate feed autonomy will improve; and nutrient cycles may become more closed. Contrary to the hypothesis, it appears that cooperating lowland dairy farms have opted not to increase the area on which they grow crops (Table 12), but instead have opted to use the land formerly occupied by heifers to increase the number of milking cows on the farm. This is evidenced by an increase in number of milking cows per hectare of forage area in the cooperating lowland dairy group relative to the non-cooperating lowland dairy group (Figure 16). Therefore, instead of the expected increase in crop production area, there is an increase in milk production per hectare on cooperating lowland dairy farms (Table 12). Consequently, net income per hectare is higher on these farms (Figure 16) due to 1) increased milk production per hectare; and 2) increased production of more lucrative cash crops, such as sugar beet and potatoes. Milk production per cow was the same in non-cooperating and cooperating lowland dairy farms.

Contrary to expectations, concentrate feed autonomy was lower in the cooperating dairy farms (Figure 16). This was due to an increase in land area under labour intensive cash crops, such as potatoes and sugar beet at the expense of feed crops, such as barley and grain maize. The absence of heifers from cooperating dairy farms appears to have afforded farmers not only the time and land to increase milk production but also the time to grow more labour intensive cash crops. Even though concentrate feed autonomy was lower on cooperating lowland dairy farms compared to non-cooperating lowland dairy farms, the amount of imported concentrates consumed per livestock unit (LU)
was lower on the cooperating lowland farms (Figure 16). It would appear that cooperation has allowed lowland dairy farms to substitute expensive imported concentrates in the feed ration with home-grown forage.

Finally, results showed that cooperation resulted in better closing of nutrient cycles, as is evidenced by a lower N surplus per hectare on cooperating lowland dairy farms than on non-cooperating lowland dairy farms (Figure 16). The N surplus on a product output basis was also lower on cooperating lowland dairy farms (1.12 compared to 2.18 kg N/kg N in sold products). The probable reasons for the observed lower N surpluses on cooperating lowland dairy farms are differences in the operational management of N (i.e. lower amount of N imported in concentrate feeds), removal of (unproductive) heifers from the herd and increased export of N through milk and cash crop sales. This is in line with the findings of Nevens et al. (2006), who showed that lower N surpluses on progressive specialised dairy farms (where progressive farms were defined as the 10 % of the farm group set with the lowest N surplus in relation to their production intensity) were due to considerably lower use of concentrate feed N and fertiliser N and, to a lesser extent, in a lower share of heifers in the herd. Nitrogen use efficiency was considerably higher on cooperating lowland dairy farms than on non-cooperating lowland dairy farms (Figure 16) due to cooperating lowland dairy farms having greater temporary grassland area in the crop rotation (Table 12), lower concentrate feed consumption per livestock unit (Figure 16), and greater export of N via the sale of cash crops.

By comparing the grazing regime and the amount of cut forages consumed per LU in cooperating and non-cooperating lowland dairy farms it becomes apparent why cooperating lowland farms feed less imported concentrates per LU. Cooperating lowland dairy farms have a larger pasture area for dairy cows (18.2 ha compared to 8.2 ha), and this area does not have to be shared with heifers. As a result, milking cattle on cooperating lowland dairy farms can spend more time grazing (approximately 4.3 hrs per day compared to 3.3 hrs per day). The total plant material fed per livestock unit (including grazed pasture and home-grown and imported plant materials) is higher in the cooperating lowland dairy group than in the non-cooperating lowland dairy group, thus allowing the former to import less concentrate feed. The key point to be taken from this type of cooperation is that animal exchange allows farms to optimise the use of grasslands. This is further evidence of the potential for improved efficiency via among-farm cooperation that allows individual farms to specialise in either dairy production or heifer rearing.
Recoupling of dairy and crop production via cooperation between farms

Figure 16. Comparison between non-cooperating lowland dairy farms and cooperating lowland dairy farms in Canton Thurgau, Switzerland. Higher indicator values on green axes are indicative of more sustainable systems (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of less sustainable systems (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1 and ns for non-significant). The min and max value for each indicator’s axis is provided in brackets after the indicator label.

For mountain farms, we hypothesised that a switch from dairying to heifer rearing will reduce workload thus allowing farmers to: 1) increase their off-farm income; 2) optimise the use of home-grown feed resources; and 3) reduce external inputs of concentrate feed. Results confirmed all these expectations (Figure 17): the mountain heifer rearing farms have lower on-farm labour per hectare which allows them to take up employment outside the farm; and lower imported concentrates consumed per LU. These findings are probably because cooperation allowed mountain farmers to access additional resources or to better exploit their natural resource base. For instance, rearing of heifers was far less time consuming than producing milk and the stocking rate of heifers was well matched to the mountain farms natural capacity to produce forages. Specialising in heifer rearing via animal exchange allows mountain farmers to reduce their intensity of production to a level that is more in line with the resources they have at their disposal. The result is a more profitable enterprise and free time to take up work outside of the farm.
5.3 Results

Figure 17. Comparison between non-cooperating mountain dairy farms and cooperating mountain heifer rearing farms in Canton Grisons, Switzerland. Higher indicator values on green axes are indicative of more sustainable systems (i.e. more diverse, autonomous and efficient) whereas higher indicator values on red axes are indicative of less sustainable systems (i.e. less self-sufficient in agricultural inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1, ** for p<0.05, *** for p<0.01 and ns for non-significant). The min and max value for each indicator’s axis is provided in brackets after the indicator label.

5.3.4 Industrially mediated transfers of dehydrated fodder (Brittany, France)

Cooperation via the dehydration facility provides high quality forages for milking cows and aims to improve forage autonomy and protein feed autonomy when alfalfa is grown. Farmers sign a 5-yr contract with the cooperative in which they agree to provide land at the disposition of the cooperative for production of forage and/or miscanthus. Dehydrated forages are usually returned to the same farm on which they were grown. The planting and harvesting of the perennial crop, miscanthus, is carried out by the cooperative and generally displaces the annual crops - silage maize and wheat. The average transport distance by road between the cooperative dehydration facility and cooperating farms was approximately 15 km. The cooperating farms had approximately 10% of their UAA growing crops dehydrated by the cooperative. More descriptors of the cooperation strategy are provided in Supplementary Table 6.

The stocking rate and number of milking cows per hectare was significantly higher in the cooperating farm groups than in the baseline group (Table 13). Feed concentrates fed per livestock unit were lowest in the baseline group: baseline dairy farms were generally less intensive and had a higher share of UAA under permanent grassland (Table 13). The lower milk production per hectare
in the baseline group may be a result of these farms practicing less intensive livestock production,
feeding lower amounts of concentrates per livestock unit (Table 13).

<table>
<thead>
<tr>
<th>Farm characteristic</th>
<th>Baseline Dairy(^a)</th>
<th>Cooperating dairy farms growing alfalfa and miscanthus(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utilised agricultural area (ha)</td>
<td>76 ± 19</td>
<td>100 ± 44</td>
</tr>
<tr>
<td>Bovine stocking rate (LU ha(^{-1}))</td>
<td>1.57 ± 0.30</td>
<td>1.77 ± 0.42</td>
</tr>
<tr>
<td>Milk production (lit ha(^{-1}))</td>
<td>5508 ± 1352</td>
<td>6625 ± 1138</td>
</tr>
<tr>
<td>Feed concentrates (kg LU(^{-1}) year(^{-1}))</td>
<td>680 ± 216</td>
<td>860 ± 361</td>
</tr>
<tr>
<td>Permanent grassland (%)</td>
<td>47 ± 4</td>
<td>29 ± 10</td>
</tr>
<tr>
<td>Silage maize (%)</td>
<td>28 ± 5</td>
<td>31 ± 6</td>
</tr>
<tr>
<td>Wheat (%)</td>
<td>21 ± 5</td>
<td>24 ± 5</td>
</tr>
<tr>
<td>Alfalfa (%)</td>
<td>1 ± 2</td>
<td>7 ± 4</td>
</tr>
<tr>
<td>Miscanthus (%)</td>
<td>0</td>
<td>1.4 ± 2.1</td>
</tr>
</tbody>
</table>

\(^a\) Two farms in this group also stocked pigs and one farm had a small poultry enterprise.
\(^b\) One farm in this group also stocked pigs.

Potential benefits of industrially mediated transfers of dehydrated fodder were assessed via hy-
pothesis testing. We firstly expected that cooperation would: 1) help to increase milk yield and
forage autonomy on cooperating dairy farms relative to their non-cooperating counterparts; and 2)
improve the ratio of grass/alfalfa to silage maize, thus lowering input use. Results showed that the
milk yield per cow in the cooperating farm group was slightly higher than in the non-cooperating
baseline farm group but the difference was not statistically significant (Figure 18). In terms of for-
age autonomy both groups were 100 % autonomous and this precluded any improvement in forage
autonomy as a result of cooperation. The second part of the hypothesis was proved false in that the
cooperating farm group did not have a higher ratio of grass/alfalfa to silage maize compared to the
non-cooperating baseline group (Figure 18). Therefore, cooperation did not have the effect of low-
ering input use: no. of pesticide applications on silage maize (4.8 compared to 3.7), mineral N
fertiliser use per hectare (Figure 18) and on-farm labour per hectare (Figure 18) were all higher in
the cooperating farm group relative to the baseline group, suggesting more intensive operations in
cooperating farms.
Figure 18. Comparison between the non-cooperating baseline farm group and the cooperating farm group in Brittany, France. Higher indicator values on green axes are indicative of more sustainable systems (i.e. more diverse, productive, autonomous and efficient) whereas higher indicator values on red axes are indicative of less sustainable systems (i.e. less self-sufficient in inputs, greater pollution risk and higher intensity). Different indicator values adjacent to different letters are significantly different. Significance levels are shown next to indicator labels (* for P<0.1, ** for p<0.05, *** for p<0.01, **** for p<0.001 and ns for non-significant). The min and max value for each indicator’s axis is provided in brackets after the indicator label.

It was secondly hypothesised that the introduction of alfalfa in crop rotations would: 1) help to reduce the need for external feed inputs such as soybean meal imported from abroad; and 2) reduce farm workload. However, results showed that livestock on cooperating farms consumed more imported concentrates (Figure 18) and soybean (0.35 t/LU compared to 0.27 t/LU). These results illustrate the higher intensity of farming on cooperating farms relative to non-cooperating farms. Results also showed that total labour per hectare (Figure 18) and per LU (data not shown) was higher in the cooperating farm group than in the non-cooperating baseline group. It would appear that the expected decreases in external input use and labour input on cooperating dairy farms were not realised because of higher numbers of milking cows per hectare in the cooperating farm group (Table 13).

It was lastly hypothesised that the increase in area growing alfalfa and miscanthus in the cooperating group would: 1) help to improve land use diversity; and 2) increase the potential for carbon sequestration. The Shannon Diversity Index was indeed higher for cooperating farms growing alfalfa (and sometimes miscanthus) than for the non-cooperating baseline farms (Figure 18). However, the potential to sequester carbon in soil (estimated using the share of UAA under perennials...
as a proxy) was not higher in cooperating farm group relative to the baseline group (Figure 18). The higher share of UAA under arable-arable rotation in the cooperating farm group (37 %) is further evidence of the lower potential for carbon sequestration in this group compared to the baseline group (17 %).

Aside from these poor environmental benefits, cooperation helped to improve resource efficiency. Nitrogen surplus did not vary significantly between farm groups (106 kg N /ha in the baseline group compared to 107 kg N /ha on the cooperating farms) but was lower on cooperating farms than on the baseline farms when expressed per unit of agricultural product (Figure 18). This implies a lower risk of N loss per unit of agricultural product from these farms.

The overall trend is one of intensification on cooperating dairy farms: it would appear that the facility to have forage crops dehydrated by Coopédom incentivises farmers to replace lower intensity permanent grassland area with forage crops that are more input intensive. This increases the livestock carrying capacity of their land allowing them to increase their stocking rate (Table 13). As a result these farms import more concentrate feed per LU and have a reduced area under permanent grassland relative to baseline farms.

5.4 Discussion and conclusion

5.4.1 Summary of the main findings and consequences for dairy and arable farming systems

Cooperation between specialised farms via the four crop-livestock integration strategies assessed, generally allowed farmers to access additional local resources, such as land, labour, organic nutrients or livestock feed. The farmers’ decisions about how to manage or deploy these extra resources largely determined the consequences for the farms: basically, farmers could opt to either diversify their farming system - therefore tending toward greater farm autonomy and resilience - or intensify their farming system via increased specialisation. Table 14 summarises the resources made available through each crop-livestock integration strategy as well as how the farmers deployed those resources. In three of the four crop-livestock integration strategies assessed (namely: material exchange, animal exchange and industrially mediated transfer of dehydrated forages) there was a marked increase in farming intensity on cooperating farms relative to non-cooperating farms, as indicated by farmers opting to use newly accessed resources to increase: 1) the number of milking cows per hectare on dairy farms; and 2) the cropping intensity on arable farms. Two of the integration strategies (namely: animal exchange and land leasing) facilitated increased specialisation in milk production, heifer rearing or potato production. As a result of farmers opting to use the local resources, made available via cooperation, to intensify and specialise as opposed to diversifying their operations, some of the expected benefits of recoupling crop and livestock production via farm cooperation were not realised, such as, lower external input use and improved nutrient autonomy.
Indeed, specialisation usually leads to lower costs per unit product (due to economies of scale) but could potentially increase the vulnerability of individual farms and their capacity to handle sudden price fluctuations, which are expected to become more frequent in the future. Specialisation also creates technical efficiencies that can reduce labour input thereby freeing up labour resources to be utilised elsewhere on or off the farm – increasing net income.

This study provides first empirical evidence that recoupling crop and livestock production via cooperation among specialised farms doesn't lead to many environmental benefits but instead helps specialised dairy and arable farmers to further intensify and specialise their farming systems through more intensive use of available local resources. With the exception of the food provisioning service, cooperation didn’t result in improved ecosystem services. Cooperation did however help improve resource use efficiency by enabling farmers to access previously untapped on-farm resources (such as, Alpine grassland) and optimally exploit nutrients in by-products of production such as manure. Intensification and specialisation that is facilitated by optimised use of home-grown feed resources and available land and labour resources can be considered more sustainable than intensification that relies primarily on increasing inputs from outside. Indeed, benefits of cooperation were generally observed on those farms that used cooperation to replace some external inputs to production with some locally sourced inputs.

Beyond the general conclusion that cooperation among specialised farms doesn't lead to many environmental benefits, we found that the level of benefits were specific to the crop-livestock integration strategy employed: for animal exchange and industrially mediated transfer of dehydrated forages, the benefits of cooperation included increased productivity, increased N use efficiency and lower N surplus per unit of agricultural output. Cooperation via these strategies allowed farms to increase production without an increase in N surplus per hectare relative to non-cooperating farms (Table 14). In contrast, benefits of cooperation through material exchange were restricted to arable farms that exhibited increased productivity. Except for reduced use of pesticides, there were no obvious environmental benefits of material exchange observed on dairy farms. This was due to cooperation being strongly orientated towards the handling of increased outputs of manure from an enlarged dairy system without attempting to increase the local forage input. Implementing the material exchange strategy with the aim of meeting the manure management needs of the dairy farm while neglecting the potential for cooperating arable farms to provide forages resulted in a number of drawbacks for the farming system (Table 14). Material exchange could be improved if manure were to be exchanged for alfalfa instead of straw, as this would help ensure easy access to sufficient livestock feed, while also improving the nutrient exchange equality between cooperating farms.
<table>
<thead>
<tr>
<th>Crop-livestock integration strategy</th>
<th>Local resources accessed through among-farm cooperation, their deployment by the farmer and subsequent consequences for the farming system.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dairy Farm</td>
<td>Material exchange</td>
</tr>
<tr>
<td>Land (outlet for manure)</td>
<td>Export excess manure to land located off-farm</td>
</tr>
<tr>
<td></td>
<td>Increased stocking rate; increased milk production</td>
</tr>
<tr>
<td></td>
<td>Higher input use per ha (concentrate feed, forages); increased N surplus per ha</td>
</tr>
<tr>
<td>Arable Farm</td>
<td>Manure</td>
</tr>
<tr>
<td>Land (inlet for manure)</td>
<td>Incorporated in soil to supply crops</td>
</tr>
<tr>
<td></td>
<td>Increased milking herd size and productivity</td>
</tr>
<tr>
<td></td>
<td>Increased specialisation in dairy production; Increased milk yield per cow</td>
</tr>
<tr>
<td></td>
<td>Reduced % UAA under permanent grassland; reduced N surplus per unit product produced</td>
</tr>
<tr>
<td></td>
<td><strong>Table 14</strong>. Local resources accessed through among-farm cooperation, their deployment by the farmer and subsequent consequences for the farming system.</td>
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</tr>
<tr>
<td>Land</td>
<td>Increased milking herd size and productivity</td>
</tr>
<tr>
<td></td>
<td>Increased specialisation in dairy production; Increased milk yield per cow</td>
</tr>
<tr>
<td></td>
<td>Higher overall feed autonomy through optimized use of the grassland resource; lower N surplus per ha</td>
</tr>
<tr>
<td>Arable Farm</td>
<td>Labour and machinery (lowland)</td>
</tr>
<tr>
<td>Land</td>
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<tr>
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</table>

**Table 14**. Table containing data on the consequences of resource integration for the farming system.
This research has shown that if agricultural production can be reoriented towards the local resource base via cooperation between specialised farms, then farmers will be better positioned to optimally exploit underutilised natural resources and improved ecosystem services, thus reducing their reliance on external inputs of synthetic fertilisers, pesticides and concentrate feeds. Although cooperation was accompanied by intensification and specialisation that limited farm diversification, it did lead to some environmental benefits by improving resource use efficiency per unit of agricultural product produced. Cooperation ensured that a greater part of the inputs required for intensification were locally sourced. This may be why cooperation sometimes led to metabolic benefits for the farming systems concerned. Although it is not clear if cooperation helped farmers to intensify their system, or if cooperation is required to sustain already intensive systems, and if cooperating farms were more prone to innovative practices, these results provide a platform to discuss integration strategies between crop and livestock and to design resource efficient farming systems at different spatial scales.

5.4.2 Possible implications for the period after the milk quota abolition in Europe

Simulation results from a number of studies (Chantreuil et al., 2008; Kempen et al., 2011; Réquillart et al., 2008; Witzke and Tonini, 2009) indicate that the abolition of the milk quota regime will have the effect of increasing milk production in the EU by between 3 and 5% and reducing raw milk prices by between 7 and 10% on average. This fall in milk prices in the wake of the abolition of the milk quota regime will put pressure on farmers to either increase milk production (while reducing unit cost, in an economy of scale perspective, in competitive regions) or to diversify their systems by growing cash crops (in an economy of scope perspective, in less competitive regions). In this context, cooperation with arable farmers can provide dairy farmers with the resources and sometimes infrastructure they require to either intensify operations (e.g. increase milk production) or diversify income streams (e.g. introduce cash crops). So, by cooperating with neighbouring arable farmers, specialised dairy farmers should have greater flexibility to adjust their system in response to changing prices and regulations without greatly increasing direct production costs. The forms of cooperation assessed in this study revealed that cooperating farms tend to be more intensive and less diversified than non-cooperating farms but further studies are required to see if this finding applies to other forms of among-farm cooperation and if it applies evenly in competitive and less competitive regions.

In the absence of the milk quota regime, land will likely be the most scarce production factor as farmers seek to increase their milk output. Dairy farmers need enough land for feeding the animals with forages but also to comply with the EU nitrate regulatory limits, expressed per hectare of land (Boere et al., 2015). It follows then that with the abolition of milk quotas, nitrate regulations, may become the limiting factor for milk production (Boere et al., 2015). Therefore, options that help
farmers to increase their production while limiting their N surplus per hectare will likely be adopted by farmers (Gaigné et al., 2012). As such, the crop-livestock integration strategies of animal exchange, and to a lesser extent, industrially mediated transfers of dehydrated forage show potential as a way of sustainably intensifying production as they allowed farms to increase their product output per hectare (Table 12 and Table 13) without increasing their N surplus per hectare (Figure 16 and Figure 18). In both strategies, the N surplus per unit of agricultural product was lower on cooperating farms than on non-cooperating baseline farms thus helping to protect water quality.

To conclude, these results provide key elements from farming system analysis to anticipate the potential consequences of milk quota abolition in Europe. They show that farmers' decisions about how to face the widened competitive gap between producing regions and how to utilise the resources freed up by the milk market liberalisation will be key in future environmental performances of European agriculture. This study provides timely knowledge about the appropriate scale to promote integration between crops and livestock and about the difficulties that farmers encounter when cooperating with other farmers to integrate their productions. As such, these results are likely to play a critical role in farming system design operations and public policy elaboration to overcome these difficulties.

**Acknowledgements**

This work has been funded under the EU seventh Framework Programme by the CANTOGETHER project N°289328: Crops and ANimals TOGETHER. The views expressed in this work are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission. We thank the farmers who answered the surveys as well as two anonymous reviewers for their comments.
Supplementary Material

Additional information about case studies and crop livestock integration strategies:

**Ebro Basin: local cooperation through material exchange**

The terms of exchange require only that the quantities of, and transport of, exchanged materials are agreed and as such no money changes hands. Even though no contractual agreements are in place the cooperation is quite stable over time. This is evidenced by farms cooperating for 11.2 years on average, with only one incidence of breakdown in cooperation during that period. Cooperation is facilitated by a short average road distance of only 5 km between cooperating farms. The carrying of the economic burden associated with transport of straw/manure and spreading of manure varied from partnership to partnership. Sometimes it was taken on wholly by one or other party and sometimes it was split between the two. The material exchange ratio of manure for straw (by weight) is approximately 5 to 1.

On average, the surveyed dairy farms cooperated with 2.7 arable farms while arable farms only cooperated with 1 dairy farm. Farm surveys showed that both farm types are heavily invested in the partnership such that cooperating dairy farms export (for exchange) approximately 61% of their total manure production, while cooperating arable farms export (for exchange) approximately 81% of their total straw production.

**Winterswijk: land leasing between dairy and arable farms**

A minimum break period of 3 years is normally required between potato crops for disease prevention which means that small farms cannot produce enough potatoes on their own land to offset the high costs associated with potato production. By leasing land from neighbouring dairy farms, arable farmers can include their potato crop in the longer crop rotation of the dairy farm while either leaving their own fields to rest or growing an alternative crop to potatoes. The dairy farmers benefit from reduced ploughing costs and an outlet for excess slurry, which they use to fertilise the potato crop. The arable farmer benefits from extended crop rotations and mineralised Nitrogen that is released in the soil at the time of ploughing up grasslands for reseeding. The arable farmer leases the land from the dairy farmer at a cost of approximately 750 €/ha. After the potatoes are harvested in August/September the field is returned to the dairy farmer at which time it is reseeded with grass by the dairy farmer.
Switzerland: animal exchanges between lowland and mountain farms

On average, lowland dairy farmers cooperate with 3 mountain rearing farms whereas mountain rearing farms cooperate with 10 lowland dairy farms. The average transport distance by road between lowland and mountain farms was approximately 125 km. Cooperating lowland farms sent 17 calves and bought back 14 pregnant heifers on average.

Domagné: industrially mediated transfers of dehydrated fodder

The Coopédom cooperative society was created to dehydrate forages. This facility allowed dairy farmers to introduce the legume crop, alfalfa, in crop rotations. Growing alfalfa is not viable in this area of France without a facility to quickly dry the harvested crop. In summary, the legume crop alfalfa cannot be grown for feeding to dairy livestock without the Coopédom cooperative society, which is owned and run by its farmer members. This is a form of industrial integration beyond the farm scale.
Supplementary Figure 1. Crop-livestock integration strategies under study
**5 Recoupling of dairy and crop production via cooperation between farms**

*Supplementary Table 1. Summary of the baseline and cooperating farm groups studied in the Ebro Basin case study.*

<table>
<thead>
<tr>
<th>Situation</th>
<th>Farm type</th>
<th>No. of farms assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline dairy 1: Non-cooperating dairy</td>
<td>Dairy farms with only a small area dedicated to crop production, use their manure on their own land and buy in straw, grains and some fodder.</td>
<td>4 farms</td>
</tr>
<tr>
<td>Baseline 2: Non-cooperating arable</td>
<td>Arable farms with no organic fertiliser input</td>
<td>5 farms</td>
</tr>
<tr>
<td>Baseline 3: Within-farm mixing</td>
<td>Farms with both dairy animals and cereal crops, on which a significant amount of the feed and/or straw for livestock is home produced and with a significant fraction of income comes from grain sales.</td>
<td>4 farms</td>
</tr>
<tr>
<td>Mixing Strategy: Exchange of solid manure for straw</td>
<td>Specialised dairy farms that exchange solid manure for straw with specialised arable farms</td>
<td>5 dairy and 4 arable farms</td>
</tr>
</tbody>
</table>

*Supplementary Table 2. Summary of the baseline and cooperating farm groups studied in the Winterwijk case study.*

<table>
<thead>
<tr>
<th>Situation</th>
<th>Farm type</th>
<th>No. of farms assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline dairy 1: Non-cooperating dairy</td>
<td>Specialised dairy farms with grass/maize rotations, using the majority of their manure on their own land, buying in concentrates and not exchanging fields</td>
<td>4 farms</td>
</tr>
<tr>
<td>Baseline 2: Mixed dairy farms</td>
<td>Mixed farms (i.e. dairy farms growing cereals on their own land)</td>
<td>3 farms</td>
</tr>
<tr>
<td>Baseline 3: Non-cooperating arable</td>
<td>Specialised arable farms from outside the zone of influence that do not rent land</td>
<td>15 arable farms on sandy soils in eastern part of the Netherlands were used</td>
</tr>
<tr>
<td>Mixing strategy: Land sharing between dairy farms and arable farms</td>
<td>Specialised dairy farms that lease some fields to arable farms specialised in potato production</td>
<td>3 dairy farms and 3 arable farms</td>
</tr>
</tbody>
</table>

*Supplementary Table 3. Summary of the baseline and cooperating farm groups studied in the Swiss case study.*

<table>
<thead>
<tr>
<th>Situation</th>
<th>Farm type</th>
<th>No. of farms assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline 1: Non-cooperating lowland dairy</td>
<td>Lowland dairy farms that raise their own heifers.</td>
<td>4 farms</td>
</tr>
<tr>
<td>Baseline 2: Non-cooperating mountain dairy</td>
<td>Mountain dairy farms that raise only their own heifers.</td>
<td>4 farms</td>
</tr>
<tr>
<td>Mixing strategy: sale, by lowland farmers, of heifers to mountain farmers specialised in heifer rearing</td>
<td>Lowland dairy farmers that sell their weaned female pure bred dairy calves to mountain farmers specialised in heifer rearing, who later sell them back when pregnant and close to calving.</td>
<td>4 lowland dairy farms and 4 heifer rearing mountain farms</td>
</tr>
</tbody>
</table>
Supplementary Table 4. Summary of the baseline and cooperating farm groups studied in the Coopédém case study.

<table>
<thead>
<tr>
<th>Situation</th>
<th>Farm type</th>
<th>No. of farms assessed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline: Non-cooperating dairy farms</td>
<td>Dairy farms located outside the area where Coopédém operates</td>
<td>7 farms</td>
</tr>
<tr>
<td>Mixing strategy: dehydration of forages and production of miscanthus for use as a biomass fuel</td>
<td>Dairy farms growing alfalfa for dehydration, with some farms also having silage maize and ryegrass dehydrated, and growing miscanthus</td>
<td>11 farms (of which, all 11 dehydrate alfalfa, 5 grow miscanthus, 6 dehydrate ryegrass and 2 dehydrate silage maize)</td>
</tr>
</tbody>
</table>

Supplementary Table 5. Descriptors of cooperation for Winterswijk farm groups; mean values ± standard deviationsa

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specialised Dairy</th>
<th>Specialised Arable</th>
<th>Mixed Dairy</th>
<th>Cooperating Dairy</th>
<th>Cooperating Arable</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of farms cooperated with</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>0 ± 0</td>
<td>1 ± 0</td>
<td>32 ± 22</td>
</tr>
<tr>
<td>Utilised agricultural area (ha)</td>
<td>67 ± 23</td>
<td>75 ± 0</td>
<td>52 ± 25</td>
<td>72 ± 42</td>
<td>218 ± 150</td>
</tr>
<tr>
<td>Land leased from yr to yr (ha)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6 ± 3</td>
<td>-</td>
</tr>
<tr>
<td>Land rented from yr to yr (ha)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>6 ± 8</td>
<td>144 ± 116</td>
</tr>
<tr>
<td>Land ownership (ha)</td>
<td>67 ± 23</td>
<td>75 ± 0</td>
<td>52 ± 25</td>
<td>73 ± 36</td>
<td>74 ± 50</td>
</tr>
</tbody>
</table>

a The mean UAA shown includes only the land that was farmed during the survey year (i.e. the land a farmer leased was excluded and the land a farmer rented was included).

Supplementary Table 6. Descriptors of cooperation for Coopédém farm groups; mean values ± standard deviations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Farms outside Coopédém</th>
<th>Farms cooperating with Coopédém</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average road distance between farms and Coopédém (km)</td>
<td>37.5 ± 12.5</td>
<td>14.6 ± 7</td>
</tr>
<tr>
<td>Forage area dehydrated (% of UAA)</td>
<td>0</td>
<td>10 ± 6</td>
</tr>
<tr>
<td>Forages dehydrated (tons)</td>
<td>0</td>
<td>92 ± 55</td>
</tr>
<tr>
<td>Agricultural area harvested by Coopédém (% of UAA)</td>
<td>0</td>
<td>12 ± 7</td>
</tr>
</tbody>
</table>
6 Cooperation of mountain and lowland farms improves the environmental performance of dairy production

This chapter is based on the same-titled manuscript written by Silvia M.R.R. Marton, Gisela Lüscher, Michael S. Corson, Michael Kreuzer and Gérard Gaillard, submitted to Frontiers in Environmental Sciences.

Abstract

Mountain farming areas are associated with high nature value and offer attractive landscapes, but farming in these areas is less viable than farming in more favorable regions. Consequently, there is a threat of land abandonment. Additionally, due to a lower productivity, products from mountain farms often bear a higher environmental burden than those from other areas. An optimal division of labor between mountain farms and farms in more favorable regions based on comparative advantages could help maintain attractive landscapes and reduce environmental impacts of agricultural production. An established Swiss contract rearing system, in which dairy farms from the agronomically favorable lowlands collaborate with heifer rearing farms in the mountains, represents a promising approach for such a division of labor. In this system, the intensive phase of dairy production is performed in the lowlands, while the less intensive phase is performed in the mountains. Here, we analyzed a sample of 16 farms to compare the contract rearing system to a situation in which both, mountain and lowland farms produce milk and rear their own restocking animals. In a life cycle assessment we found that collaboration reduced environmental impacts per kg of milk. Collaboration also reduced environmental impacts per hectare agricultural area on mountain farms, but not on lowland farms. In addition, we analyzed farm workload, since increased work efficiency is one reason for farmers to engage in contract rearing. Specialization in heifer rearing reduced the workload of mountain farms significantly, while on lowland farms no effect was observed. This led to a reduction in overall workload per kg of milk produced in the collaborative system compared to non-collaborative production. This example of a contract rearing system thus illustrates for future collaborative production systems how they might profit from the benefits of focusing on activities with comparative advantages.
6 Cooperation of mountain and lowland farms improves the environmental performance

6.1 Introduction

Farming activities in mountainous regions face natural constraints that inhibit high productivity. Instead, such areas are often of high nature value, provide an attractive landscape and are extensively managed (Rudow, 2014). To address for the reduced economic viability and to prevent land abandonment, the European Union’s Common Agricultural Policy (CAP) and agricultural policies in European countries outside the EU, such as Switzerland or Norway, have defined plans to support farming activities in these areas (Gellrich and Zimmermann, 2007; MacDonald et al., 2000; Marriott et al., 2004). Since environmental conditions do not allow intensive agricultural production and specific policy measures may limit high-input farming, environmental impacts per hectare are often lower in areas with natural constraints (Rudow, 2014). On the other hand, because of the lower productivity of the land, products from such areas usually have higher environmental impacts per unit (Hörtenthal et al., 2010; Ripoll-Bosch et al., 2013). This results in a trade-off between maintaining agricultural production to preserve scenic landscapes with high-value semi-natural habitats, and providing environmentally sound agricultural products.

To address this conflict, the most suitable production systems for such areas have to be identified and, in parallel, environmental impacts of products from these systems must be optimized. An approach focusing only on comparing absolute results of production systems from favorable and less favorable regions could be too narrow, since the chances of identifying a product that is produced more efficiently in areas with natural constraints are rather low. A more promising approach is inspired by the classical economic theory of trade and comparative advantage (Deardorff, 2014). It focuses on possibilities for division of labor between regions with different natural conditions. By considering the environmental impacts of a set of products, it is possible to identify products or activities, where the disadvantage of the region with natural constraints is less pronounced compared to other products or activities from this set, i.e. where the mountain farms have a comparative advantage. In consequence, more favorable regions will have a comparative advantage for production activities where the disadvantages of the region with natural constraints are more pronounced. An example of division of labor between two regions with different climatic and topographic conditions can be found in Switzerland. Swiss lowland farms generally have favorable conditions and invest in grassland-based animal production and crop production. In contrast, mountain farms are mainly restricted to grassland based systems due to steep slopes and a shorter vegetation period. Although dairy farming is practiced in both regions, mountain farms do not compete well with lowland farms. Compared to lowland farms, mountain farms have lower income (Roesch, 2012) and milk with higher environmental impacts per kg (Alig et al., 2011a). One reason for the lower performance of mountain farms is the lower nutritive quality of home-grown feed, which, when given alone, is not sufficient for today’s high-genetic-merit dairy cows (Horn et al., 2013). In contrast, lowland farmers often perceive their forage quality as being too high for their young stock.
Introduction

(M. Tanner, 20 October 2015, personal communication). Already in the 1960ies farmers from the cantons of Thurgau and Grisons, Switzerland, developed a contract rearing plan that took advantage of the different production conditions on mountain and lowland farms. In this plan, dairy farmers from the lowlands sell their female dairy calves to mountain farmers, who then rear them and sell them back to the lowland farmers shortly before calving. Accordingly, the animals spend the less intensive phase of their life on mountain farms, and the more intensive phase, i.e. the productive phase, on lowland farms, which can offer feed of higher quality. The system has spread to other regions as well, but it is still most popular in these two cantons. In a previous assessment based on simulated farms, this collaborative production system had environmental advantages but decreased mountain farms’ income and workload compared to a system without collaboration, in which all dairy farms rear their own young stock (Marton et al., 2016b). However, this assessment assumed that yields and production efficiency per hectare and per cow were the same on collaborating and non-collaborating farms within each region; it thus considered only the benefits due to the comparative advantage of each region. For the present study, using data from real farms, we assumed that the specialization due to collaboration creates further efficiency gains and reduces the environmental impacts of milk production even more. Furthermore, specialization was also expected to affect environmental impacts directly on farms. For instance, by outsourcing the less-intensive young stock and keeping only the more-intensive dairy cows, lowland farms might increase environmental impacts per hectare of usable agricultural area (UAA). On mountain farms, specialization in heifer rearing could have the opposite effect, i.e. reduce environmental impacts per hectare of UAA. Furthermore, it is expected that division of labor has an impact on farmers’ workload, since labor constraints are considered an incentive for contract rearing (Olynk and Wolf, 2010). In the present study, we therefore compared environmental impacts and workload of collaborative and non-collaborative dairy production using data from real commercial farms. Specifically, we tested the following hypotheses:

1. Collaboration leads (a) to intensification and thus to higher environmental impacts per hectare of UAA on lowland farms and (b) to extensification and thus to lower environmental impacts per hectare of UAA on mountain farms. Intensification in this context is defined as an increase in inputs per ha, while extensification corresponds to a reduction in inputs per ha.

2. Environmental impacts per kg of fat- and protein-corrected milk (FPCM) produced in the overall system is reduced through collaboration.

3. Workload is lower on collaborating farms than on non-collaborating farms.
6.2 Materials and methods

6.2.1 Farming systems and study region

We compared two farming systems: collaborative (contract rearing) and non-collaborative. Both systems consisted of dairy farms in the lowlands and the mountains. In the collaborative system, lowland farms concentrated on milk production; female dairy calves designated for restocking were sold to mountain farms when weaned. Mountain farms reared the animals and sold them back to lowland farms when the heifers were close to calving. In the non-collaborative system, dairy cows spent their entire lives on the same farm, i.e. both lowland and mountain farms kept productive dairy cows and young stock for restocking.

The farms analyzed were located in the cantons of Thurgau and Grisons, the two cantons that first adopted the contract-rearing plan. Both cantons still have many farms that do not participate in contract rearing, which allowed comparison of the collaborative and non-collaborative systems under similar climatic and topographic conditions. Thurgau is a relatively small canton, with approximately 50% of its area as UAA, mostly in the lowlands, which corresponds to 4.8% of the UAA of Switzerland. Thurgau contains 6.6% of Swiss dairy cows, which produce 7.7% of the milk sold in Switzerland. Grisons is the largest Swiss canton. Due to its location in the center of the Alps, only 8% of its area is used for agriculture, corresponding to 5.2% of the UAA of Switzerland. In addition, 23% of the area of Grisons is considered alpine agricultural area. By law, this area may only be used as pasture during the summer (alpine summer-pasture). Grisons contains 2.9% of Swiss dairy cows, which produce 2.1% of the milk sold in Switzerland (Swiss Federal Statistical Office – SFSO, 2016; TSM, 2013).

6.2.2 Farm data and characteristics

Sixteen dairy farms from the two cantons were assessed; Thurgau represented the lowland and Grisons the mountain region. In each region, four farms were collaborating in contract rearing (hereafter “collaborating farms”), and four farms were not participating in contract rearing (hereafter “non-collaborating farms”). Data on farm characteristics and agricultural practices were collected during farm visits or provided directly by the farmers. Data collection was based on two datasets developed within the EU FP7 project CANTOGETHER. One set contained data needed for life cycle assessment (LCA) (Teuscher et al., 2014), and the other contained supplementary agronomic and economic data (Regan et al., 2016).

Collaborating and non-collaborating dairy farms were randomly selected from those that offer apprenticeship positions. Since authorization to do so requires additional training for the farmer, we assumed that the farms in the sample were more advanced farms, i.e. farms that apply good management practices and are well informed about new technical developments. Most farms in the sample were conventional farms, except for three collaborating mountain farms that were managed...
organically. Farms in the sample were larger and had more animals than the average dairy farm in Switzerland, which had (in 2012) 24 ha UAA and 23 dairy cows. Except for one mountain farm, milk yield per cow also lay above the Swiss average of 6000 kg of milk (TSM, 2013). On lowland farms, most forage was home-grown, mainly grass and whole-crop maize (silage or dried pellets). In addition to the home-grown forages, some farms also relied on forage imports. Two collaborating and two non-collaborating farms purchased either hay or grass silage. One of the collaborating and two of the non-collaborating farms purchased whole-crop maize silage or pellets, one of the collaborating and two of the non-collaborating farms purchased sugar beet pulp, and two of the collaborating and one of the non-collaborating farms used waste potatoes (from the potato-processing industry). Most concentrate was purchased; only a small percentage home-grown. In addition to producing feed, five lowland farms also grew cash crops. Mountain farms were grassland-based, produced mostly home-grown forage, and purchased all concentrate. Only one collaborating mountain farm purchased hay. Two collaborating mountain farms produced cash crops (Table 15).

All mountain farms, and one collaborating and one non-collaborating lowland farm, sent animals to alpine summer-pasture. To represent this phase (approximately 100 days), we collected data from two alpine summer-pasture farms in Grisons and averaged these data for further calculations.

Since all farms were selected randomly, there was no effective link between collaborating lowland and mountain farms. Most farms collaborated with more than one farm from the other region: mountain farms collaborated with 3-15 lowland farms, which collaborated with 1-5 mountain farms. To simulate collaborative dairy production among the farms in the sample, we combined each collaborating lowland farm with each collaborating mountain farm, resulting in a set of 16 combinations. Farms were combined based on the lowland farm’s need for heifers and the mountain farm’s production of heifers. For example, if the lowland farm needed four heifers per year and the mountain farm produced 12 heifers per year, then one-third of the mountain farm’s heifer rearing enterprise was added to the lowland farm to include the outsourced restocking phase in collaborative dairy production. To compare this collaborative system to non-collaborative dairy production, we combined the non-collaborating dairy farms from the two regions so that the ratio of lowland to mountain UAA corresponded to the median land-use ratio of the two regions in the collaborative system (3.5:1). See Supplementary Tables 7 and 8 for details about these combinations. Each non-collaborating lowland farm was combined with each non-collaborating mountain farm, resulting in a set of 16 combinations, which created an equal basis for comparison.
Cooperation of mountain and lowland farms improves the environmental performance

Table 15. Farm characteristics: median and mean deviation of the median per farm group.

<table>
<thead>
<tr>
<th></th>
<th>Lowland farms</th>
<th>Mountain farms</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Collaborating</td>
<td>Non-collabor-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collaborating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rating</td>
</tr>
<tr>
<td>Dairy enterprise</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Livestock units (LU)</td>
<td>66.0 ± 9.2</td>
<td>90.1 ± 30.0</td>
</tr>
<tr>
<td>of which dairy cows</td>
<td>58.8 ± 8.3</td>
<td>70.8 ± 25.4</td>
</tr>
<tr>
<td>LU per ha / UAA dairy enterprise</td>
<td>2.33 ± 0.33</td>
<td>2.24 ± 0.45</td>
</tr>
<tr>
<td>FPCM sold per dairy cow (kg/a)</td>
<td>8844 ± 818</td>
<td>8608 ± 900</td>
</tr>
<tr>
<td>Concentrate per cow (kg/a)</td>
<td>922 ± 582</td>
<td>1931 ± 532</td>
</tr>
<tr>
<td>of which home-grown (kg/a)</td>
<td>102 ± 164</td>
<td>273 ± 310</td>
</tr>
<tr>
<td>Farm area characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total agricultural area (ha)</td>
<td>36.5 ± 9.6</td>
<td>43.3 ± 11.0</td>
</tr>
<tr>
<td>of which Grassland</td>
<td>24.6 ± 1.5</td>
<td>24.6 ± 14.0</td>
</tr>
<tr>
<td>Maize (whole crop forage)</td>
<td>3.8 ± 2.6</td>
<td>4.3 ± 2.8</td>
</tr>
<tr>
<td>Fodder beets</td>
<td>-</td>
<td>0 ± 0.15</td>
</tr>
<tr>
<td>Cereals</td>
<td>3.1 ± 3.1</td>
<td>5.3 ± 2.4</td>
</tr>
<tr>
<td>Grain maize</td>
<td>-</td>
<td>1.0 ± 1.6</td>
</tr>
<tr>
<td>Oil seeds</td>
<td>0 ± 0.5</td>
<td>0 ± 0.5</td>
</tr>
<tr>
<td>Sugar beets and potatoes</td>
<td>3.8 ± 2.3</td>
<td>0 ± 0.9</td>
</tr>
<tr>
<td>Orchards and other crops</td>
<td>0 ± 2.8</td>
<td>0.3 ± 2.2</td>
</tr>
<tr>
<td>Elevation (m.a.s.l.)</td>
<td>471 ± 66</td>
<td>533 ± 40</td>
</tr>
<tr>
<td>Percentage of area with slopes &gt; 18 %</td>
<td>0 ± 2</td>
<td>2.5 ± 3</td>
</tr>
</tbody>
</table>

FPCM = fat- and protein-corrected milk; m.a.s.l. = meters above sea level; UAA = usable agricultural area

6.2.3 Environmental assessment

We used LCA to compare environmental impacts of (1) farms within the two regions and (2) milk produced in collaborative and non-collaborative dairy production systems.

6.2.3.1 Goal and scope definition

To compare environmental impacts within mountain and lowland regions, the functional unit was one hectare of UAA used for the dairy enterprise during one year. This functional unit relates to the farm’s function as a provider of environmental services, like the maintenance of water quality (van der Werf et al., 2009). The dairy enterprise comprised all farm activities linked to dairy production, e.g. management of dairy cows and restocking animals, production of feed for these animals, and use of buildings and machinery. System boundaries were defined as “cradle to farm gate”, including all environmental impacts caused by the dairy enterprise itself and by all upstream processes linked to production and supply of inputs (e.g. fertilizers, purchased feed), infrastructure and
machinery (Figure 19). Seven farms in the sample grew cash crops, which connected the cash-crop and dairy enterprises, since the by-product straw from the former was used as bedding in the latter, and some manure produced in the latter was used as fertilizer in the former. For straw, we performed economic allocation between straw and cash crops to allocate part of the cash-crop area to the dairy enterprise. To account for manure spread on areas allocated to the cash-crop enterprise, we used system expansion, since this method has previously been compared to other approaches and was identified as the most suitable to account for interactions between cash-crop and dairy enterprises (Marton et al., 2016a). All emissions related to application of manure to cash crops were attributed to the dairy enterprise, while emissions that a mineral fertilizer would have caused, as well as emissions from producing it, were credited to the dairy system. The amounts of nutrients replaced by manure applied within the cash crop enterprise were calculated based on crop requirements and the nutrient availabilities of manure and mineral fertilizers. The amount of nitrogen (N) replaced was calculated based on the total ammonium N (TAN) in the applied manure (Flisch et al., 2009) and the ammonia-loss rates of manure and the mineral fertilizer replaced (Hutchings et al., 2009; Hutchings et al., 2013). When more N was applied to a crop than its theoretical N requirements, only the amount of N required minus the amount of N provided by other fertilizers was credited (Equation 1). We assumed that manure replaced ammonium nitrate, the mineral N fertilizer most commonly used on farms in our sample.

$$N_{\text{min,sub}} = \text{Min} \left( \frac{\text{TAN}_{\text{appl}} \times (1 - r_{\text{org}})}{1 - r_{\text{min,sub}}} ; \frac{N_{\text{need}} - N_{\text{min,appl}} \times (1 - r_{\text{min,appl}})}{1 - r_{\text{min,sub}}} \right) \quad (1)$$

- $N_{\text{min,appl}}$: Amount of N from mineral fertilizers applied to crops
- $N_{\text{min,sub}}$: Amount of N from mineral fertilizers replaced with manure
- $N_{\text{need}}$: Amount of N required by the crop
- $r_{\text{min,appl}}$: Ammonia loss rate of mineral fertilizers applied to crops
- $r_{\text{min,sub}}$: Ammonia loss rate of mineral fertilizers replaced with manure
- $r_{\text{org}}$: Ammonia loss rate of manure applied to crops
- $\text{TAN}_{\text{appl}}$: Total ammonium N in manure applied to crops

For phosphorus (P) and potassium (K), the amount of each contained in manure was calculated to replace the same amount from mineral fertilizers, as long as it did not exceed plant requirements. If the latter was the case, only the amount of nutrients needed by the plant and not covered by other fertilizers was credited. The mineral fertilizers assumed to be replaced were triple-superphosphate and potassium chloride (KCl), respectively.
6 Cooperation of mountain and lowland farms improves the environmental performance

Farming systems are multifunctional, but their main goal is the provision of food. Therefore, the collaborative and non-collaborative dairy production system were compared based on their main output, using the functional unit of one kg of FPCM. System boundaries were defined in the same way as for the assessment of the impact per hectare of UAA, i.e. considering all upstream processes and activities on the farm, up to the farm gate. Milk production is a multi-output process, and besides the manure that can be exported from the dairy enterprise (accounted for as described above), meat is also produced from culled animals and surplus calves. We followed the guidelines of the International Dairy Federation, using physical causality to allocate environmental impacts to milk and meat (IDF, 2015).

6.2.3.2 Life cycle inventory

The farmers provided the main data used to calculate the life cycle inventory (LCI), which included data about yields, animal numbers, purchased inputs such as feed or energy carriers, housing infrastructure and manure management, machinery, and detailed information about field-management practices such as date, type, quantity applied and application method for each fertilization or crop-protection event. The LCI itself was then calculated with a tool developed for the CANTOGETHER project (CANCale, Teuscher et al., 2014). For the calculation of direct emissions the final version of CANCalc combined the following tools and models:

1. a dataset of organic and mineral fertilizers, with their nutrient contents and availability to plants, based on data from Flisch et al. (2009), Nemecek and Kägi (2007) and fertilizer producers

Figure 19. System boundaries of the dairy enterprise. Upstream processes and infrastructure are not illustrated.
6.2 Materials and methods

(2) a tool developed by project partner SP Technical Research Institute of Sweden (formerly SIK) to predict emissions from enteric fermentation, manure management and application (Berglund and Cederberg, 2014)

(3) the SPACSYS (soil-plant-atmosphere continuum system) model, version 5.1 (Wu et al., 2015), to predict N leaching and runoff, and nitrous oxide (N₂O) emissions,

(4) the Universal Soil Loss Equation (Renard et al., 2010) for soil erosion

(5) elements of the Swiss agricultural LCA method for farms – SALCAfarm (Nemecek et al., 2010) to predict heavy-metal entry into soil and ammonia emissions from mineral fertilizers

As a final step, CANCalc aggregated results from the individual tools into an LCI with links to upstream processes from ecoinvent v2.2 (ecoinvent Centre, 2010) and the SALCA database.

The LCI was calculated for the entire farm and for its individual farm enterprises, according to the system boundaries defined. To facilitate contribution analysis, inputs and emissions were grouped into 12 categories: buildings and equipment, machinery, energy carriers, fertilizers and field emissions, pesticides, purchased seeds, purchased concentrate, purchased roughage, purchased animals, animal husbandry, other inputs, and summer pasture. The last category is special, since it comprises all inputs and emissions that occur during the summer-pasture phase, without distinguishing their exact sources. These emissions are mainly caused by the animals, either due to enteric fermentation (corresponding to the category ‘animal husbandry’) or due to excretion directly on the area (corresponding to the category ‘fertilizers and field emissions’).

For the credits related to manure application within the cash-crop enterprise, two LCI were calculated, one with manure application and one in which the mineral fertilizers that had been replaced were applied instead of manure (equation 1). This was necessary because direct emissions linked to N fertilization, such as nitrate leaching into water or ammonia emissions to the air, are influenced by the type of N source applied. For example, manure has higher ammonia emissions than ammonium nitrate (Hutchings et al., 2009; Hutchings et al., 2013). If the inventory with manure application had higher direct emissions, the difference was attributed to the dairy enterprise, but if it had lower direct emissions, the difference was credited to the dairy enterprise.

6.2.3.3 Life cycle impact assessment

We considered impact categories related to three aspects: (1) emissions into the ecosphere, i.e. into the air, soil or water, (2) land use, and (3) resource use. The impact categories related to emissions into the ecosphere are linked to specific environmental challenges, such as climate change, and thus cover rather narrow topics. Impact categories related to land use are linked to the scarcity of land as a resource, but also to the impact that use of this land could have on biodiversity. The resource-related impact categories, as used in this study, are indicators of both depletion of scarce
resources and efficiency of production systems. From these three impact category groups, the following categories were assessed:

- **Categories related to impacts caused by emissions into the ecosphere**
  - Acidification (EDIP2003, Hauschild and Potting, 2005)
  - Ecotoxicity, terrestrial (CML 2001, Guinée et al., 2001)
  - Eutrophication due to N (EDIP2003, Hauschild and Potting, 2005)
  - Eutrophication due to P (EDIP2003, Hauschild and Potting, 2005)
  - Global warming potential over 100 years (IPCC2013, Myhre et al., 2013)
  - Ozone depletion (EDIP2003, Hauschild and Potting, 2005), with the addition of the ozone depletion potential of N₂O according to Ravishankara et al. (2009)

- **Categories related to land use**
  - Deforestation (Frischknecht et al., 2007a)
  - Land competition (Frischknecht et al., 2007a), excluding alpine summer-pasture land use
  - Alpine summer-pasture land use
  - Biodiversity on the farm area (Jeanneret et al., 2014)

- **Categories related to resource use**
  - Non-renewable energy demand, fossil and nuclear (Frischknecht et al., 2007a)
  - Resource use, P extraction (based on elementary flow from ecoinvent 2.2, Frischknecht et al., 2007b)
  - Resource use, K extraction (based on elementary flow from ecoinvent 2.2, Frischknecht et al., 2007b)
  - Water use (Frischknecht et al., 2007a)

The impact category ‘ozone depletion potential’ was adapted for this study, since currently available life cycle impact assessment methods do not consider the ozone depletion potential of N₂O, although it is currently considered the most important ozone-layer-depleting substance (UNEP, 2013). Ravishankara et al. (2009) were the first to publish an ozone depletion potential for N₂O: 0.017 kg CFC-11 equivalents per kg N₂O. This ozone depletion potential is valid at present, but future change in gas composition in the stratosphere, namely chlorine, CO₂ and CH₄, may increase the ozone depletion potential of N₂O (Revell et al., 2015). We therefore considered the factor of 0.017 as robust enough to be used in our context. For comparison of results with and without consideration of N₂O, see Supplementary Figure 2.

In addition, the impact category of land competition was adapted. Alpine summer-pasture land use was treated separately, since it does not compete with other anthropogenic land-use types. The area is not suitable for other agricultural practices and is too remote for other land-use purposes such as urban or industrial use. It does, however, compete with the natural vegetation that would be
found on these areas if they were not used as summer pastures. In Europe, alpine summer-pasture areas have declined, and if abandoned, shrubs and forests encroach on them (Anthelme et al., 2001). Although LCA studies usually recommend minimizing land use, many indicate that conservation and use of summer pasture is beneficial, especially for biodiversity (Koch et al., 2015; Pornaro et al., 2013). In the present study, more alpine summer-pasture land use was thus considered as beneficial. Similar to land competition, alpine summer-pasture land use is expressed as the area occupied multiplied by the duration of the occupation (square meter years - $m^2a$).

Compared to the other impact assessment methods used, the method to assess biodiversity is a special case. It relies on estimations of the effects of various agricultural land use types (arable crops, grasslands, and semi-natural habitats) and agricultural practices (e.g. plowing, pesticide application, or date of first cut in grasslands) on local biodiversity. This local biodiversity is reflected in overall species diversity (OSD) scores for eleven indicator species groups related to farmland. High OSD scores indicate that a system is beneficial for biodiversity. Because the method focuses on a farm’s agricultural area, its system boundaries exclude upstream processes. Also, since it uses scores instead of quantitative units, its OSD scores cannot be attributed to single products. Thus, its system boundaries differ from those of the other impact categories, and possible interactions between dairy and crop enterprises, especially for manure applied outside of the dairy enterprise, cannot be considered using the system-expansion approach used for the other impact categories. Therefore, we estimated two different OSD scores for the study farms. In one, only the area and agricultural practices related to the dairy enterprise were considered. In the other, the entire farm including the cash-crop enterprise was considered, to include possible interactions between the two enterprises.

6.2.4 Workload assessment

Workload related to dairy production was calculated for each farm with the workload budgeting tool ART-AV 2014 (Stark et al., 2014). The tool considers the different crop and grassland fields on the farm, and animal numbers of several livestock categories, such as calves, heifers, dairy cows, fattening cattle or pigs. It also considers economies of scale, for instance assuming lower workloads per hectare for larger areas of the same crop produced on one a given farm. Using the same allocation rules as for the LCA, we calculated the workload for the dairy enterprise, expressed as hours per hectare of UAA, as well as the hours needed to produce 1 kg of FPCM.

6.2.5 Statistical tests and sensitivity analyses

Differences between collaborative and non-collaborative dairy production systems and between collaborative and non-collaborative farms within each region for the environmental impact categories and workload indicators were tested for significance with a one-sided Mann-Whitney U test.
Comparison of the dairy production systems considered two groups with 16 data points each, a number of observations that is large enough to provide meaningful results. Comparison of the farms within a given region, however, had only two groups with 4 data points each. A one-sided test with such a small sample size will result in a p-value < 0.05 only if one group contains the first four ranks or the first three and the fifth rank. As these cases are rare, we therefore also considered tendencies, defined as p ≤ 0.10, when comparing farms within one region. A value of p = 0.10 would correspond to a situation in which the three best-performing farms are in one group and the worst-performing farm is in the other group, i.e. one group contains ranks 1,2,3, and 7, and the other 4,5,6, and 8.

Given the sample size, the sample farms do not necessarily represent the entire population of collaborative and non-collaborative dairy farms in Switzerland. For example, while more than 50% of all farms in Grisons are organic (Swiss Federal Statistical Office – SFSO, 2016), none of the non-collaborating farms in the Grisons sample was organic. Two of them, however, used no mineral fertilizers or pesticides, and thus differed from organic farms only in the type of concentrate purchased. We therefore performed a sensitivity analysis in the comparison of farms, in which these two farms were virtually converted into organic farms by replacing purchased conventional concentrate with organic concentrate. Another sensitivity analysis was performed for credits for mineral fertilizer replaced by manure applied to cash crops. In it, we applied an allocation procedure based on a cut-off principle: all emissions from manure storage were allocated to the dairy enterprise, while those from manure application outside of the dairy enterprise were allocated to the cash-crop enterprise. This allocation procedure corresponds to that in ecoinvent v2.2 (Nemecek and Kägi, 2007) and is also recommended in the IDF’s current LCA guidelines, while in the previous version the IDF recommended crediting mineral fertilizers that are replaced (IDF, 2010, 2015).

6.3 Results

6.3.1 Environmental impacts

On lowland farms, environmental impacts per hectare of UAA of collaborating and non-collaborating farms did not differ significantly, not even in tendency (Figures 20-22). In the mountains, collaborating farms had significantly lower environmental impacts for terrestrial ecotoxicity, eutrophication due to N, deforestation, land competition, non-renewable energy demand, P and K resource use, and a tendency for lower emissions for acidification and water use. In addition, there was a tendency for higher alpine summer-pasture land use and higher OSD on collaborative mountain farms than on non-collaborative mountain farms.

In both regions, variability in environmental impacts within a group of farms was often higher than differences between the groups. This was most prominent for ecotoxicity of collaborating lowland farms (Figure 20B), one of which had much higher emissions than non-collaborating lowland
farms. The high ecotoxicity on this farm was due to a relatively large amount of potatoes in the feed ration, and potato production was linked to high pesticide use. Two further impact categories with high variability were P and K resource use (Figure 22B and C), which both depended highly on the fertilizer strategy and the crops grown on individual farms. Negative impacts (i.e. a positive effect on the environment) resulted from credits due to manure applied to cash crops. Two of the collaborating lowland farms grew sugar beets, a crop with high K demand. Application of manure on this crop led to high credits, which in one case were much higher than the K resource use linked to the inputs of the farm’s dairy enterprise. In contrast, one collaborating lowland farm had relatively high K resource use, since it was the only lowland farm that applied KCl to grassland. The same was true for one non-collaborating mountain farm, which applied KCl to both grassland and maize.

Figure 20. Environmental impact per hectare usable agricultural area (ha UAA) for impact categories related to emissions into the ecosphere: (A) acidification, (B) terrestrial ecotoxicity, (C) eutrophication due to N, (D) eutrophication due to P, (E) global warming potential, (F) ozone depletion potential. Bars indicate the median performance of the respective farm group (CL = collaborating lowland farms, NCL = non-collaborating lowland farms, CM = collaborating mountain farms, NCM = non-collaborating mountain farms) and the sources of the impacts. Whiskers indicate the minimum and maximum impact within each group, * indicate significant differences between farm groups within one region (p < 0.05), ° indicate tendencies (p ≤ 0.1).
Figure 21. Environmental impacts per hectare usable agricultural area (ha UAA) for impact categories related to land use. Top: (A) deforestation, (B) land competition, (C) alpine summer-pasture land use. Bars indicate median performance of each farm group and sources of impacts. Whiskers indicate minimum and maximum impacts within each group (CL = collaborating lowland farms, NCL = non-collaborating lowland farms, CM = collaborating mountain farms, NCM = non-collaborating mountain farms). Bottom: Biodiversity of the UAA of (D) the dairy enterprise and (E) the entire farm, including the cash-crop enterprise. Biodiversity is expressed as overall species diversity scores for three selected indicator-species groups (crop flora, birds, and spiders) and as aggregated species diversity scores for all 11 indicator-species groups. * indicates significant differences between farm groups within the same region (p < 0.05), and ° indicates tendencies (p ≤ 0.1).
Per kg of FPCM, collaborative production caused lower or equal environmental impacts compared to non-collaborative production (Figures 23-25), except for alpine summer-pasture land use, for which collaborative production used more area. Differences were significant for terrestrial ecotoxicity, eutrophication due to P, ozone depletion, deforestation, alpine summer-pasture land use, non-renewable energy demand, P resource use, and water use. As for individual farms, variability among farm combinations was high. For some farm combinations, the credits attributed to the dairy enterprise due to manure applied to cash crops led to negative K resource use, especially when two farms were combined that both had a negative K resource use.
Cooperation of mountain and lowland farms improves the environmental performance

Figure 23. Environmental impacts per kg of fat- and protein-corrected milk (FPCM) from collaborative (C; n=16) and non-collaborative (NC; n=16) production systems for impact categories related to emissions into the ecosphere: (A) acidification, (B) terrestrial ecotoxicity, (C) eutrophication due to N, (D) eutrophication due to P, (E) global warming potential, and (F) ozone depletion potential. Whiskers indicate 1.5 times the standard deviation, and asterisks indicate significance level (*: p < 0.05, **: p < 0.01, ***: p < 0.001).

Figure 24. Environmental impacts per kg of fat- and protein-corrected milk (FPCM) from collaborative (C; n=16) and non-collaborative (NC; n=16) production systems for the impact categories related to land use (A) deforestation, (B) land competition, (C) alpine summer-pasture land use. Whiskers indicate 1.5 times the standard deviation, and asterisks indicate significance level (**: p < 0.01, ***: p < 0.001).
6.3.1.1 Sensitivity analyses

In the first sensitivity analysis (two non-collaborating mountain farms virtually converted to organic farms), impacts for terrestrial ecotoxicity, deforestation, and P and K resource use decreased (Table 16). Nonetheless, non-collaborating mountain farms still had significantly higher impacts for eutrophication due to N, land competition, non-renewable energy demand, and a tendency for higher impacts for acidification, ecotoxicity and water use. In contrast, deforestation was no longer significantly higher on non-collaborating farms. For P and K resource use, the formerly significant differences were reduced, but a tendency for higher use of these elements on non-collaborating mountain farms remained. Per kg of FPCM, the conversion had no substantial influences. Differences between collaborative and non-collaborative production remained significant for terrestrial ecotoxicity, eutrophication due to P, ozone depletion, deforestation, alpine summer-pasture land use, non-renewable energy demand, P resource use, and water use.

Figure 25. Environmental impacts per kg of fat- and protein-corrected milk (FPCM) from collaborative (C; n=16) and non-collaborative (NC; n=16) production systems for impact categories related to resource use: (A) non-renewable energy demand, (B) resource use, P extraction, (C) resource use, P extraction, and (D) water use. Whiskers indicate 1.5 times the standard deviation, and asterisks indicate significance level (*: p < 0.05, ***: p < 0.001).
6 Cooperation of mountain and lowland farms improves the environmental performance

Table 16. Sensitivity analysis: Conversion of two non-collaborative mountain farms into organic farms (50% organic scenario) compared to the original scenario, in which all non-collaborative mountain farms were conventional farms (main scenario) for the impact categories affected the most by this change (terrestrial ecotoxicity, deforestation, P resource use, K resource use).

<table>
<thead>
<tr>
<th></th>
<th>Terr. ecotoxicity</th>
<th>Deforestation</th>
<th>P resource use</th>
<th>K resource use</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(kg 1,4-DB eq)</td>
<td>(m²)</td>
<td>(kg P)</td>
<td>(kg K)</td>
</tr>
<tr>
<td>Median non-collaborating mountain farms (per ha UAA dairy enterprise)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>9.58</td>
<td>9.21</td>
<td>5.31</td>
<td>6.06</td>
</tr>
<tr>
<td>50% organic scenario</td>
<td>7.94</td>
<td>5.00</td>
<td>3.79</td>
<td>3.88</td>
</tr>
<tr>
<td>Change</td>
<td>-17.1%</td>
<td>-45.7%</td>
<td>-28.5%</td>
<td>-36.0%</td>
</tr>
<tr>
<td>Median non-collaborative dairy production system, mountain and lowland farms combined (per kg of FPCM)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>1.57E-03</td>
<td>2.66E-03</td>
<td>8.71E-04</td>
<td>8.05E-04</td>
</tr>
<tr>
<td>50% organic scenario</td>
<td>1.57E-03</td>
<td>2.57E-03</td>
<td>8.57E-04</td>
<td>7.73E-04</td>
</tr>
<tr>
<td>Change</td>
<td>-0.09%</td>
<td>-3.30%</td>
<td>-1.60%</td>
<td>-3.95%</td>
</tr>
</tbody>
</table>

UAA = usable agricultural area; FPCM = fat- and protein-corrected milk

The second sensitivity analysis (cut-off applied instead of a credit for manure applied outside of the dairy enterprise) influenced mainly P and K resource use (Table 17). On all farms that applied manure outside of the dairy enterprise, P and K resource use increased if no credits had been given for these fertilizers. In the lowlands, differences between collaborating and non-collaborating farms remained insignificant, although the absolute difference for K resource increased slightly. In the mountains, collaborating farms still had significantly lower P and K resource use than non-collaborating farms. When collaborating, lower K resource use per ha on mountain and lowland farms (significant and non-significant, respectively) led to significantly lower K resource use per kg of FPCM in the collaborative production system. For the other impact categories, differences between collaborative and non-collaborative production remained significant for terrestrial ecotoxicity, eutrophication due to P, ozone depletion, deforestation, alpine summer-pasture land use, non-renewable energy demand, P resource use, and water use.
Table 17. Sensitivity analysis: Cut-off approach for manure applied outside of the dairy enterprise, in which emissions from manure application lay outside of the scope of the dairy enterprise (cut-off for manure), compared to the original scenario, in which credits for mineral fertilizers replaced by manure were applied (main scenario) for the impact categories affected the most by this change (P resource use, K resource use).

<table>
<thead>
<tr>
<th></th>
<th>P resource use (kg P)</th>
<th>K resource use (kg K)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Median collaborating mountain farms (per ha UAA dairy enterprise)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>0.66</td>
<td>-0.09</td>
</tr>
<tr>
<td>Cut-off for manure</td>
<td>1.48</td>
<td>1.44</td>
</tr>
<tr>
<td>Change</td>
<td>+124.8%</td>
<td>n/a</td>
</tr>
<tr>
<td><strong>Median non-collaborating mountain farms (per ha UAA dairy enterprise)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>5.31</td>
<td>6.06</td>
</tr>
<tr>
<td>Cut-off for manure</td>
<td>5.31</td>
<td>6.06</td>
</tr>
<tr>
<td>Change</td>
<td>0.00%</td>
<td>0.00%</td>
</tr>
<tr>
<td><strong>Median collaborating lowland farms (per ha UAA dairy enterprise)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>7.04</td>
<td>5.73</td>
</tr>
<tr>
<td>Cut-off for manure</td>
<td>7.81</td>
<td>9.81</td>
</tr>
<tr>
<td>Change</td>
<td>+11.0%</td>
<td>+71.1%</td>
</tr>
<tr>
<td><strong>Median non-collaborating lowland farms (per ha UAA dairy enterprise)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>15.04</td>
<td>12.56</td>
</tr>
<tr>
<td>Cut-off for manure</td>
<td>15.36</td>
<td>13.90</td>
</tr>
<tr>
<td>Change</td>
<td>+2.1%</td>
<td>+10.7%</td>
</tr>
<tr>
<td><strong>Median collaborative dairy production system, mountain and lowland farms combined (per kg FPCM)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>3.96E-04</td>
<td>2.63E-04</td>
</tr>
<tr>
<td>Conversion of two conventional farms into organic</td>
<td>4.21E-04</td>
<td>5.12E-04</td>
</tr>
<tr>
<td>Change</td>
<td>+6.5%</td>
<td>+94.3%</td>
</tr>
<tr>
<td><strong>Median non-collaborative dairy production system, mountain and lowland farms combined (per kg FPCM)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Main scenario</td>
<td>8.71E-04</td>
<td>8.05E-04</td>
</tr>
<tr>
<td>Conversion of two conventional farms into organic</td>
<td>8.82E-04</td>
<td>9.77E-04</td>
</tr>
<tr>
<td>Change</td>
<td>+1.3%</td>
<td>+21.4%</td>
</tr>
</tbody>
</table>

UAA = usable agricultural area; FPCM = fat- and protein-corrected milk

### 6.3.2 Workload

In the lowlands, collaborating farms had slightly higher (but not significantly so) median workload per hectare of UAA than non-collaborating farms. In the mountains, however, collaborating farms had significantly lower median workload per hectare of UAA (64 h/ha UAA) than non-collaborating farms (134 h/ha UAA). Workload per kg of FPCM was significantly lower for collaborating farms (Figure 26).
Figure 26. Comparison of workload (A) per hectare usable agricultural area (ha UAA) of the dairy enterprise on collaborating lowland (CL, n=4), non-collaborating lowland (NCL, n=4), collaborating mountain (CM, n=4) and non-collaborating mountain (NCM, n=4) farms; and (B) per kg fat- and protein-corrected milk (FPCM) in collaborative (C, n=16) and non-collaborative (NC, n=16) dairy production systems. Whiskers indicate 1.5 times the standard deviation, and * indicates significant differences between farm groups (p < 0.05).

6.4 Discussion

6.4.1 Effects of collaboration on environmental performance of lowland farms

We hypothesized that collaborative production would lead to intensification of lowland farms due to outsourcing of the less-intensive heifer rearing activity and an increase in environmental impacts per hectare of UAA. Overall, this hypothesis was not confirmed. Livestock density (expressed as livestock units/ha UAA) was similar for both collaborating and non-collaborating farms, but most animals on collaborating farms were dairy cows, which usually depend more on external inputs such as concentrate. Therefore, higher environmental impacts per ha UAA were expected, but no significant differences between collaborating and non-collaborating farms were observed. For most environmental impacts, the median for collaborating lowland farms was slightly lower or equal to that for non-collaborating lowland farms. Only for acidification and eutrophication due to N did collaborating farms tend to have higher median impacts, although differences were not high enough to be considered as tendencies. Both impact categories are strongly linked to N fertilization and the amount of N excreted by animals, and these data are among the most uncertain data in our inventory. They were estimated with data from Flisch et al. (2009) and represent average or standard data for Switzerland. Based on these data, high-yielding dairy cows excreted more N per livestock unit than young stock and thus the N per ha and in stored manure was higher on collaborating lowland farms. However, by using such standard data, effects of the total N balance of farms and especially effects of feeding on N excretion were not considered. Analyzing the same farm sample, Regan et al. (2016) found significantly lower N surplus per hectare on collaborating lowland farms than on non-collaborating farms, which was caused by lower N input from concentrate and higher
N output due to producing more milk per hectare. If this lower N surplus correlated with lower N content in feed, cows would have excreted less N (Castillo et al., 2000), possibly changing results in favor of collaborative farms.

Concentrate use explains most of the reason why collaborating farms did not have higher impacts than non-collaborating farms. For most impact categories, differences between individual farms were strongly influenced by the concentrate purchased, although concentrate was not always the main contributor to the environmental impact in absolute terms. For example, enteric fermentation from animals (animal husbandry) contributed most to global warming potential, but it varied little among farms. Concentrate contributed only moderately to global warming potential but had high variability, and was thus responsible for differences among farms. One of the four collaborating lowland farms used more concentrate than any other farm in the sample, and it had the highest impacts per hectare of UAA for most of the impact categories studied. The other three collaborating lowland farms depended less on external inputs. They used less purchased concentrate per cow and per hectare of UAA than any of the four non-collaborating lowland farms, and average milk yield per cow was similar for both farm groups. Collaborating lowland farms were able to produce more milk with home-grown feed, which indicated higher quality or more efficient use of home-grown forages. Our findings disprove the hypothesis of increased intensity and consequently higher environmental impacts per hectare of UAA on collaborating lowland farms. Collaborative farms managed to keep environmental impacts at levels similar to those of non-collaborative farms, although their herds consisted almost exclusively of dairy cows. We presume that this was an effect of farm specialization, which reduces complexity of farm management, often increasing efficiency (Kingwell, 2011). More efficient use of farm resources may thus decrease environmental impacts. In the present case, efficient use of home-grown forages led to equal environmental impacts per ha UAA in the collaborative system, even though it produced more milk per ha UAA.

6.4.2 Effects of collaboration on environmental performance of mountain farms

For mountain farms, we hypothesized that due to reduced intensity, collaborating farms would have lower environmental impacts per hectare of UAA than non-collaborating farms. Our results supported this hypothesis and are also consistent with the study of Regan et al. (2016), in which collaborating mountain farms had significantly lower concentrate and mineral fertilizer inputs. Lower intensity is also reflected in a higher OSD for collaborating mountain farms, mainly a result of less intensive use of grasslands, with fewer cuts and less fertilization. Only spiders were not affected, since they depend more on agricultural practices on arable land rather than grassland-management practices. All other species groups benefited from the extensive grassland use.

Besides lower intensity of land use, organic farming also improved environmental performance of collaborating farms. Organic production is relatively common for collaborating mountain farms,
6 Cooperation of mountain and lowland farms improves the environmental performance

since a special exception in the directive for organic production allows them to purchase animals from conventional farms in the case of contract rearing (Bio Suisse, 2016). Since collaborating farms rely on relatively low amounts of external inputs, conversion to an organic farm has relatively low cost. In addition, organic farms receive higher subsidies, making organic farming more attractive. Organic farming was well represented in the sample of collaborating mountain farms but underrepresented in the sample of non-collaborating mountain farms. The sensitivity analysis showed that organic farming practices influenced impacts of mountain farms, especially those related to mineral fertilization (P and K resource use), pesticide application (terrestrial ecotoxicity) and concentrate use (deforestation). Accordingly, for these impact categories, net differences between the population of collaborating and non-collaborating mountain farms in Switzerland may be smaller than apparent from the sample of farms investigated. For deforestation, virtual conversion of the two conventional non-collaborating farms into organic farms reduced impact to the point that non-collaborating farms no longer differed from collaborating farms. This was due to only one feed ingredient: soybean meal. Soybean meal from Brazil is considered to be the main source for deforestation in conventional concentrate. The organic concentrate used in this study from the SALCA database (Nemecek et al., 2010) contained no soybean meal from deforested areas. In contrast, the conventional concentrate included soybean meal from the global market and thus also from Brazil. Consequently, use of organic concentrate led to much lower deforestation. However, this result is valid only as long as indirect land-use change is excluded from the assessment (Meyfroidt et al., 2013), since land competition itself did not decrease in the scenario with more organic farms.

6.4.2.1 Alpine summer-pastures

Mountain farms generally practice more alpine summer-grazing, but due to the steep slopes and relatively poor feed quality on these pastures and the higher feed requirements of today’s dairy cows, the traditional practice of summer pasture is becoming less attractive to dairy farmers (Penati et al., 2011). It is therefore not surprising that collaborating mountain farms used more summer pastures than non-collaborating mountain farms, since it is still convenient to use these pastures for less demanding animals. In this study, we considered greater use of these areas as a benefit, especially for biodiversity. Still, the effective biodiversity value of summer pasture also depends on its management. The biodiversity assessment method used in the present study (Jeanneret et al., 2014), considers management practices at the farm level, but so far it is not applicable to summer pasture. Therefore, we can discuss effects of possible changes in summer-pasture management only qualitatively. Alpine summer-pasture land use by non-collaborating and collaborating mountain farms differs in the type of animals they send to summer pasture, the former sending both dairy cows and heifers, the latter sending almost only heifers. Since cows and heifers may differ in their grazing patterns, the question arises whether dairy cows or heifers are best suited to maintain optimal sum-
mer-pasture vegetation. In the study of Homburger et al. (2015), dairy cows showed different grazing and land-use patterns than suckler beef cows. Dairy cows tended to avoid steeper slopes more than suckler beef cows did. During the night, dairy cows were housed either in a shed or on a small paddock near the farm buildings where animals were milked, while suckler beef cows were kept on the same paddocks as during the day. Homburger et al. (2015) did not study heifers, but we expect that they behave more like suckler beef cows than dairy cows. Since suckler beef cows and heifers are not milked, they can be sent to summer pastures without the need to keep them close to farm buildings. Because they weigh less, heifers are also more suited to steeper slopes and cause less treading damage than heavier animals (Greenwood and McKenzie, 2001). We therefore expect that heifers are better suited to management that optimizes and maintains high biodiversity on summer pasture; thus, collaborative mountain farms have not only greater, but potentially more beneficial, use of summer pastures.

6.4.3 Effect of collaboration on environmental impacts per kg of fat- and protein-corrected milk

We hypothesized that collaborative production would reduce environmental impacts per kg of FPCM. This was supported by the LCA results and confirmed the trends already observed at the farm level. Our results were also consistent with those of a previous assessment based only on simulated farms, for which collaborative production was calculated to have lower non-renewable energy demand and lower resource use both for P and K (Marton et al., 2016b). Compared to those of the simulated farms, the differences found in the present assessment of real farms were larger. We assume that the real farms not only benefited from effects of the principle of comparative advantage observed under farm simulations but were also able to improve the system further by increasing efficiency gains via specialization, as observed for the collaborating lowland farms.

Still, our assessment is based on a small and possibly biased sample. We identified two possible causes for bias. First, none of the non-collaborating mountain farms was organic. At the farm level, virtually converting half of them into organic farms reduced certain impacts of the group, but not enough to influence results per kg of FPCM. This was because mountain farms in the non-collaborative system contributed only 11% of total milk production, due to two reasons: the ratio of lowland to mountain land use was set to 3.5:1 (the median ratio in the collaborative system), and mountain farms produced less milk per ha than lowland farms. The second possible bias came from sampling only dairy farms that offered apprenticeship positions. To hire apprentices, farmers need to have additional training. We assume that most farmers who are willing to help train the next generation are more motivated to keep themselves updated about agricultural developments. If so, their farms may have above-average environmental performance. In any case, direct comparison with other LCA studies is always challenging, since system boundaries and allocation procedures vary, as do
as the methods used to calculate direct emissions (de Vries and de Boer, 2010). Therefore, we have no evidence for the magnitude of bias in the samples. If bias does exist, it is reasonable to assume that it affects all samples equally and thus does not change the conclusions drawn.

6.4.4 Effects of collaboration on workload

Our hypothesis that collaboration would reduce workload was partially confirmed. The reduction in workload on collaborating mountain farms was the most distinct, since heifers require less labor to care for than dairy cows. On lowland farms, the most important influences on workload were economies of scale, which were considered by the workload estimation tool. By outsourcing heifers, collaborating lowland farms increased the number of their dairy cows, obtaining economies of scale. However, non-collaborating dairy farms increased their number of dairy cows to the larger. Consequently, they kept more dairy cows than collaborating dairy farms and thus could also profit from economies of scale. The effect of larger size was at least as beneficial to non-collaborating farms as the effect of having fewer animal categories was to collaborating farms. Our results confirm those of Regan et al. (2016) who analyzed workload based on self-declaration by farmers in the same farm sample. Their approach considered all farming activities combined (i.e. dairy and cash-crop enterprises), since it was not possible for farmers to indicate workload for each enterprise on the farm, but this likely had no major influence on the results.

Combining workloads of farms from the two regions, collaboration decreased workload per kg of FPCM. This was caused mainly by lower workload on mountain farms under collaboration, but also by higher output of milk per ha UAA on lowland farms under collaboration. Similar as for environmental impacts, higher work efficiency in the collaborative production system was assumed to be a combination of benefits from focusing on an activity with comparative advantage and from specialization.

The goal of financially supporting mountain farmers in agricultural policies is not only to prevent abandonment of mountain areas, but also to offer mountain farmers the possibility of a sufficient family income (El Benni and Finger, 2013). Reduced workload when specializing in heifer rearing, however, might decrease income on farms, since heifer rearing is less profitable than dairy farming (Marton et al., 2016b). In the sample, however, most collaborating mountain farms gained a large percentage of their family income from off-farm labor. Thus, the reduced workload is positive not only because it indicates efficiency gains, but also because it allows farmers to increase their income, since off-farm labor usually pays better than on-farm labor (Hoop and Schmid, 2014; Swiss Federal Statistical Office – SFSO, 2015).
6.4.5 Effects of collaboration outside of the dairy enterprise

Our assessments were restricted mainly to the dairy enterprise, although seven of the 16 farms also produced cash crops. For biodiversity impact, we assessed both the dairy enterprise alone and the entire farm. Including other farm enterprises did not influence results of mountain farms, but doing so for lowland farms had some non-significant influence. The slightly lower OSD score on collaborating lowland farms than on non-collaborating lowland farms was caused mainly by the kind of cash crops grown. Collaborating farms grew more potatoes and sugar beets, while non-collaborating farms grew more cereals, which provide more suitable habitat for crop flora. In cereals, farm interventions tend to suppress weeds less than in potatoes or sugar beets. As Regan et al. (2016) noted, the cash-crop and dairy production enterprises may be interrelated. It is unknown whether the collaboration and corresponding specialization motivated farmers to grow more labor-intensive crops, such as potatoes or sugar beets.

For environmental impacts, we did not consider cash crops directly, but rather links between the dairy and cash-crop enterprises. Most farms growing cash crops used at least some of the manure produced in the dairy enterprise to fertilize these cash crops. In the present study, possible benefits due to less use of mineral fertilizers and drawbacks due to higher emissions (especially of ammonia) from manure within the cash-crop enterprise were incorporated into the dairy enterprise by crediting the mineral N, P, and K fertilizers replaced by manure. In most cases, credits for manure helped to decrease the nutrient surplus of the dairy enterprise. In some cases, credits more than compensated resource use of the dairy system, especially of K. This was most pronounced on farms on which sugar beets, a crop with high K demand, were cultivated. One could argue that these farms were risking a K deficit in their dairy enterprise; however, their effective K input via imported feed was higher than their K resource use linked to these imports. This was an effect of the inventories used for concentrate. The inventories for feed-crop production were taken from ecoinvent v2.2, and these crops were fertilized with both mineral and organic fertilizers. Thus, there was a certain inconsistency in our approach between credits for manure applied to cash crops produced on farm (system expansion) and allocation or cut-off criteria used in concentrate inventories from the ecoinvent database (Nemecek and Kägi, 2007). In the sensitivity analysis, we applied the cut-off approach to the manure applied outside of the dairy enterprise, i.e. used the same approach for cash crops as that used for concentrate. Results showed that, except for K resource use, only absolute values were affected, not the differences between scenarios.

Another possibility to eliminate this inconsistency between manure applied to cash crops exported from the farm and to concentrate imported to the farm would have been to apply system expansion to concentrate inventories. In this approach, all manure applied in concentrate inventories would be replaced by mineral fertilizers, which would affect not only resource use but also direct emissions of concentrate production. Since direct emissions in ecoinvent were calculated with other models, this approach would have required a much deeper adaptation, one that lay outside of the
6 Cooperation of mountain and lowland farms improves the environmental performance

scope of this study. Nonetheless, it is possible to qualitatively estimate the effects that adaptation of the background inventories might have caused. Because non-collaborating lowland farms imported more concentrate, we expect that their P and K resource use would increase more than that of collaborating lowland farms. Thus, the difference between collaborative and non-collaborative production would be more pronounced. For acidification, we expect a decrease within the background inventories, because ammonia emissions from manure application are higher than those from mineral fertilizers (Hutchings et al., 2009; Hutchings et al., 2013). This would decrease acidification per ha UAA of the farms, and this decrease would be larger for non-collaborating lowland farms because they imported more concentrate. According to SPACSYS (Wu et al., 2015), the model that predicted N leaching and runoff in the present study, N losses to water were usually higher when N was applied as ammonium nitrate than after manure application. Thus, we expect concentrate inventories to have a small increase in N leaching and runoff; consequently, eutrophication due to N would increase more on non-collaborating lowland farms.

6.5 Conclusion

Using the example of a contract-rearing system between farms in a favorable region and a region with natural constraints, we demonstrated how collaboration can help decrease environmental impacts of agricultural production while keeping the areas with natural constraints productive. We identified two effects responsible for the improvement. The first was associated with comparative advantages, in which each collaboration partner focused on an activity with lower opportunity costs. The collaborative system allowed both mountain and lowland farms to concentrate on the phase within the life of a dairy cow that corresponded best to the resources available on their land. The steeper land and lower energy content of mountain grass can fulfill the needs of young stock, while lowland farms can produce high-quality grass, other forages such as maize, and the concentrate needed to meet the higher energy requirements of lactating dairy cows. The second effect responsible for lower impacts under collaboration was specialization. Specialization can reduce management complexity of farms, and focusing on fewer activities helps to increase the skills necessary to perform them. Limitations of our study included the relatively small sample size and the potential overrepresentation of more advanced dairy farms. Further research is needed to test whether the effects also apply to average dairy farms. We are confident, however, that reduction in management complexity will be especially beneficial for more average collaborating farms. Furthermore, we believe that this example of contract rearing involving favorable and less favorable regions could encourage development of other collaborative production systems. It would be of great interest to study the applicability of this principle to other agricultural production systems with a regional division of labor or to other geographic and climatic regions.
Acknowledgments

We wish to express our gratitude to the farmers who provided the data for our assessment. We also thank Rémy Teuscher, Peter Koch, Hisko Baas and Jens Lansche for the development of the CANTOGETHER LCA tools, and Lianhai Wu for his support with SPACSYS. We would also like to thank Daniel U. Baumgartner for his support and proof reading of the manuscript, and Thomas Nemecek for his methodological advicees during the project. This work was funded under the EU Seventh Framework Program by the CANTOGETHER project (no. 289328): Crops and ANimals TOGETHER. The views expressed in this work are the sole responsibility of the authors and do not necessarily reflect the views of the European Commission.
Supplementary Material

Supplementary Figure 2. Ozone depletion potential per ha of utilized agricultural area (UAA), (A) calculated with EDIP2003, and (B) calculated with EDIP 2003 including the characterization factor of nitrous oxide. The inclusion of N₂O increased the ozone depletion potential by more than two orders of magnitude, and the formerly relevant contributors buildings, machinery, and energy carriers are now of negligible importance, while direct field emissions (directly on the farm and related to concentrates and roughages purchases) and the emissions from animal husbandry gained in importance.
Supplementary Table 7. Combination of each collaborating lowland farm (CL) and each collaborating mountain farm (CM) under consideration of the heifers demanded by the lowland farm, the heifers produced by the mountain farms and the areas from the respective farm types. Each two farms are combined in a way that the demand in heifers of the lowland farm is covered.

<table>
<thead>
<tr>
<th>Farm combinations</th>
<th>Area lowland farm</th>
<th>Heifers demanded by lowland farm</th>
<th>Area mountain farm</th>
<th>Heifers produced by mountain farm</th>
<th>Area from mountain farm needed to cover lowland farm heifer demand</th>
<th>Ratio lowland area : mountain area</th>
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<tbody>
<tr>
<td>CL1xCM1</td>
<td>32.14</td>
<td>9</td>
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<td>85</td>
<td>5.25</td>
<td>6.12 : 1</td>
</tr>
<tr>
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<td>24.13</td>
<td>28</td>
<td>7.76</td>
<td>4.14 : 1</td>
</tr>
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<td>44</td>
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<td>4.47 : 1</td>
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<td>44</td>
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<td>3.20 : 1</td>
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<td>2.90 : 1</td>
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<td>1.96 : 1</td>
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<td>16</td>
<td>24.13</td>
<td>28</td>
<td>13.79</td>
<td>2.54 : 1</td>
</tr>
</tbody>
</table>

Median 3.50 : 1
Supplementary Table 8. Combination of each non-collaborating lowland farm (NCL) and each non-collaborating mountain farm (NCM) in a way that the land use ratio within the two regions corresponds to the median land use ratio in the collaborative dairy production system

<table>
<thead>
<tr>
<th>Farm combinations</th>
<th>Area lowland farm</th>
<th>Area mountain farm</th>
<th>Area mountain farm needed for non-collaborative dairy production system (area ratio 3.50 : 1)</th>
<th>Share of lowland farm added to non-collaborative dairy production system</th>
<th>Share of mountain farm added to non-collaborative dairy production system</th>
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<td>NCL1xNCM1</td>
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<td>21.60</td>
<td>1</td>
<td>0.44</td>
</tr>
<tr>
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<td>36.76</td>
<td>9.07</td>
<td>1</td>
<td>0.25</td>
</tr>
<tr>
<td>NCL2xNCM2</td>
<td>31.77</td>
<td>26.17</td>
<td>9.07</td>
<td>1</td>
<td>0.35</td>
</tr>
<tr>
<td>NCL2xNCM3</td>
<td>31.77</td>
<td>19.49</td>
<td>9.07</td>
<td>1</td>
<td>0.47</td>
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<tr>
<td>NCL2xNCM4</td>
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<td>48.68</td>
<td>9.07</td>
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<td>0.19</td>
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<tr>
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<td>7.47</td>
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<td>0.20</td>
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<td>26.17</td>
<td>7.47</td>
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<tr>
<td>NCL4xNCM1</td>
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<td>NCL4xNCM2</td>
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<td>NCL4xNCM4</td>
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7 General discussion and conclusion

Agriculture is presumed to be the economic sector that is the most dependent on external conditions, such as climate, soil quality or slopes. Due to its geographical location in the Alps, Switzerland is a good study region offering both very favourable farming conditions in the lowlands and less favourable farming conditions in the mountains. Dairy production is practiced in both regions, and allows a direct comparison of the production within the two regions. The aim of the present doctoral thesis was to analyse whether the regionally established Swiss contract rearing system is suitable to address two conflicting interests: the maintenance of high nature value areas in the mountains and the efficient as well as environmentally sound production of food.

7.1 Absolute and comparative advantage of lowland and mountain farms

The shorter vegetation period and steep slopes both impede a competitive crop production in the mountain region. Farming in the Swiss mountains is therefore mostly grassland based, with ruminants converting the grass into products for human consumption. Cattle production systems such as dairy or beef are the most abundant farming systems in the mountains (Swiss Federal Statistical Office – SFSO, 2016). But even if ruminants are well suitable to convert mountain grassland into products for human consumption, the production of the same foods in the lowlands is more efficient and thus also linked to lower environmental impacts. In Chapter 4 it was shown that lowland farms had indeed an environmental advantage for the production of milk, but also for the rearing of heifers. However, according to the theory of comparative advantages from classical economics (Ricardo, 1817), even in such situations a division of labour can be beneficial, as long as the two parties have different opportunity costs. As environmental impacts can be considered as costs of production activities, the same principle is also applicable to optimise environmental impacts through collaboration. The contract rearing system was originally developed due to economic reasons, but it turned out that the comparative advantage of mountain farms for heifer rearing is both, an economic and an environmental one.

7.2 Farm specialisation

The contract rearing system implies that farms become more specialised, with lowland farms focussing on the activities linked to the actual milk production, and mountain farms focussing on heifer rearing. Specialisation in farming is a rather controversial topic in environmental respect. On one hand, specialisation commonly leads to efficiency gains, which often go hand in hand with environmental benefits. On the other hand, specialisation can lead to local environmental problems, such as eutrophication in regions with high animal density, like for instance in Brittany, France (Acosta-Alba et al., 2012). In the case of the Swiss contract rearing system, there is a certain risk
for an increased intensity on lowland farms. Due to the higher nutrient requirements of dairy cows compared to young stock, the keeping of these animals is more intensive. The outsourcing of the young stock thus could lead to a higher environmental impact on the lowland farm’s agricultural area. However, this was not the case with the analysed farm sample. On average, the environmental impacts of the lowland farms that were collaborating with mountain farms in a contract rearing system were not higher than those of the lowland farms that kept their own young stock (Chapter 6). The collaborating farms even had a lower N surplus, and a higher N use efficiency (Chapter 5). The main reason for the good environmental performance of the collaborating farms were linked to the concentrate imports. These farms used less concentrate per cow, although the milk yield was on a similar level as on the non-collaborating farms. This implies that they were able to produce a higher amount of milk with their home-grown forages. Although this might have been a coincidence due to the small sample size, it is also well possible that the higher quality of their forage was an effect of the specialisation. Specialisation reduces the management complexity on the farm, allowing farmers to professionalise the remaining activities to a higher extend than on more diversified farms. On crop farms for example, it has been observed that a focus on fewer crops is beneficial as long as the farm does not get overly specialised (Tiedemann and Latacz-Lohmann, 2013). The same might be true for the specialisation within the dairy enterprise. It would therefore be of interest to analyse a larger farm sample to test whether collaborating farms are effectively able to produce more or better forage than non-collaborating farms. On mountain farms, the specialisation in heifer rearing led to a more extensive farm management compared to dairy farming, with corresponding benefits for the environment.

The controversy concerning specialisation of farms goes beyond specialisation within one farming enterprise. The major concerns raised with respect to specialisation in farming systems are related to the loss of the link between cropping and livestock activities. In Chapter 3, a tendency for lower emissions on mixed dairy farms compared to specialised production systems was identified, which were related to on-farm concentrate production and efficient nutrient cycles. Lemaire et al. (2014) also stressed the benefits of ecosystem services which are fostered through improved crop rotation patterns on mixed farms. In the beginning of the present project it was assumed that contract rearing could allow lowland dairy farmers to increase their cropping activities as this would free land and labour resources through outsourcing the young stock. As discussed in Chapter 5, this was not the case, as the share of land dedicated to cropping did not differ between collaborating and non-collaborating lowland farms. The freed resources were rather invested into increasing milk production. An explanation for this behaviour might be the agricultural policy during the period of milk quotation in Switzerland. Due to high milk prices during this period, it was attractive to increase the milk output, and it was possible for lowland farms to obtain the quota of mountain farms in the case of a collaboration in the contract rearing system (Federal Office for Agriculture – FOAG, 2001). Many of the contract rearing partnerships are long term partnerships and were established
during this phase. Although milk prices have decreased since the abolishment of the milk quotation in 2009 (Haller, 2014), farmers still earn more per hectare with milk production than with cropping (Chapter 4). With a further decrease in milk prices, cropping might become a more attractive alternative, and in this case contract rearing could lead to an extension of the cropping area on lowland dairy farms.

7.3 Is contract rearing attractive for lowland farmers?

Each of the non-collaborating farms had its reasons why they did not opt for the contract rearing system. Some of the non-collaborating farms had, although being in the lowlands, some plots that were less suitable for dairy cows, e.g. remote or steep areas. It was thus reasonable for them to keep the young stock to graze these plots. Most farmers presumed that contract rearing would be more expensive than rearing the animals on the own farm. One farmer has made bad experiences with animals purchased from the market and preferred to have everything under his own control (personal information given by the farmers during data collection).

The perception of farmers that costs for contract rearing are higher than costs for rearing the animals on the own farm might be due to a neglect of opportunity costs. If comparing the costs of rearing heifers on the own farm with the price to be paid to a contract rearing farm, the costs of rearing the animal on the own farm are certainly lower. However, while keeping the animals on the own farm, the farmer uses resources that he could have invested in more profitable activities. The sample farms that collaborated with mountain farms all opted to increase the number of dairy cows, an activity with a high return per hectare. They also grew more profitable root crops than the farms that kept their own heifers (Chapter 5). Both aspects indicate that on these farms the opportunity costs for keeping the heifers would be rather high, and an outsourcing was thus profitable.

Outsourcing heifers to a contract rearer is a matter of trust, as the rearer might not take care of the animal in an appropriate way. There is also a certain risk for the transmission of diseases, as the animals could be infected when grouped with animals from other farms (Künzler et al., 2014). However, none of the sample farms that were sending their heifers to a mountain farm had reported problems with the heifers they got back or with the partnership in general. Moritz Tanner, who was member of the contract rearing price commission for many years, stated that problems are rare, but also emphasised the importance to sign a contract for every single animal to avoid possible conflicts (personal communication, 20 October 2015).

The attractiveness of contract rearing for lowland farmers thus depends on the natural conditions on their own land, the possibilities to expand a more profitable activity when outsourcing the young stock, and the identification of a reliable partner farm in the mountains. To address the last aspect, an online platform was developed, which was launched earlier this year (German: vieh.agff.ch,
French: betails.adcf.ch, Italian: animale.agff.ch). This online platform shall work like an online
dating agency, helping farmers to find their perfect match for contract rearing.

7.4  Is heifer rearing an attractive solution for mountain farmers?

Dairy farming is, compared to any other cattle production activity in the mountains, still the
most profitable production system per hectare (Hoop and Schmid, 2014; Schmid, 2012). Although
mountain farms face natural constraints, they have one advantage over their competitors in the low-
lands: The possibility to promote their products with labels indicating their provenience from moun-
tainous regions. If the milk can be sold to local dairies, and is used to produce traditional cheese,
farmers receive an additional price benefit (Finger et al., 2015). This can help to compensate for the
higher production costs, and keep dairy farming in mountain regions attractive. However, the mar-
ket for such products is limited, and therefore many mountain farms sell their milk as a commodity
that is used for any industrial purposes, including milk powder production. None of the dairy farms
from the farm sample used in this project were selling their milk to a local dairy, and thus the milk
was sold without any additional mountain value. The net income per hectare of these farms did not
differ significantly from the net income of the heifer rearing farms, and there was even a tendency
for higher net incomes for the latter (Chapter 5). This contradicts the findings from Schmid (2012),
and might be the result of the small and possibly biased sample, because the mountain dairy farm
group used in the study of Schmid (2012) included farms that sell their milk for traditional cheese
production, and farms that sell milk without any price premium. For a more profound comparison
of the different production alternatives in the mountain region, it would be important to distinguish
between these different dairy farm types. While the production of cheese milk is likely to stay the
most profitable alternative for mountain farms, it is well possible that heifer rearing is a viable
alternative to standard milk production based on the results from our heifer rearing farms.

A specialisation in contract rearing also leads to a reduced workload, and allows farmers to have
a more flexible planning of their day, as they are not bound to fixed milking times. If there are
attractive off-farm job opportunities within the region, heifer rearing farms have the possibility to
generate a higher family income from off-farm labour. At least for the sample heifer rearing farms
this was the case; they generated a higher off-farm income compared to the mountain dairy farm
sample (Chapter 5).

The other side of the coin is that mountain farmers need to invest into new infrastructure when
specialising in heifer rearing. As they cannot easily return to dairy farming after such a conversion,
they depend on the demand of lowland farmers for their services. One of the farmers from the
sample thus decided to already consider possible alternatives to heifer rearing when he constructed
a new stable, opting for a housing system that could be used for suckler beef production as well. A
second aspect that could reduce the attractiveness of heifer rearing for mountain farmers is the
availability of off-farm labour. If no suitable off-farm labour is available in their region, heifer rearing alone might not be profitable enough to make a living.

### 7.5 Outlook

Since the abolishment of the milk quota system in 2009, Swiss milk production increased and prices decreased (Haller, 2014). If this trend continues, this would be especially challenging for mountain farms, and might force them to seek for production alternatives like contract rearing. For lowland farms, lower prices would make it even more important to optimise the efficiency of dairy production, and thus outsourcing the heifers could become more attractive. On the other hand, decreasing prices would also push some lowland farms to abandon milk production, and if they would continue with their farming business, they were very likely to seek for an activity that is closely related to their former business. Thus, lowland farms quitting dairy farming could start to offer contract rearing as well. With the more favourable conditions in the lowlands, they could offer the same service at a lower price and outcompete mountain farms.

As the prevention of land abandonment in the mountains in one of the goals of the Swiss agricultural policy, such a development should be anticipated through policy measures. Such measures could consist of additional payments to mountain farmers, outbalancing their higher costs and allowing them to offer their heifer rearing services at competitive prices. In addition, lowland farmers could receive subsidies when collaborating with mountain farmers. A similar scheme was developed to foster alpine summer grazing, where summer pasture farms and the farms that send their animals to these summer pasture farms both receive subsidies (Mack and Flury, 2014). Another alternative would be to support those lowland farmers willing to quit dairy production to switch to activities where they have a comparative environmental advantage compared to mountain farmers, in order to prevent them from becoming direct competitors to the heifer rearing farms in the mountains. Although cropping or horticulture were not assessed in this project, these are probably activities with such an advantage. The support could be either financial, or through consulting services, as the switching from a livestock system to a cropping or horticulture system requires a different knowhow of farmers.

### 7.6 General conclusion

The Swiss contract rearing system has been practiced over many years, but remained restricted to very few regions and so far very few studies have been conducted to analyse the benefits of this collaboration between mountain and lowland farms. The present project was the first to assess the environmental performance of contract rearing, and results from simulated and from real farms showed that the system has the potential to reduce the environmental impact of milk production. As an alternative to mountain dairy farming, it also helps to prevent abandonment of mountain
farms and summer pasture areas, and thus preserves high nature value areas. With the ongoing pressure on the dairy market, further research would be desirable, not only on contract rearing itself, but also on other farming activities where mountain farms could have a comparative economic and environmental advantage over lowland farms.
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List of abbreviations

1,4-DB 1,4 dichlorobenzene
1,4-DB-eq 1,4 dichlorobenzene equivalents
aqEN Aquatic eutrophication N
BaseLow Baseline farm in the lowlands (dairy farm with no contract rearing)
BaseMount Baseline farm in the mountains (dairy farm with no contract rearing)
CFC Chlorofluorocarbon
CFC-11 Trichlorofluoromethane
CML 2001 Impact assessment methodology developed at the Institute of Environmental Sciences of the Leiden University (Centrum voor Milieuwetenschappen Leiden)
CO₂ Carbon dioxide
CO₂-eq Carbon dioxide equivalents
ColDiLow Collaborating lowland farm, with increased crop production (diversification)
ColMount Collaborating mountain farm, specialised in heifer rearing
ColSpLow Collaborating lowland farm, with increased dairy production (specialisation)
DM Dry matter
EDIP2003 Environmental Development of Industrial Products, impact assessment methodology developed by the Institute for Product Development (IPU) at the Technical University of Denmark
EEA European Environment Agency
EU European Union
FADN Farm accountancy data network
FAO Food and Agriculture Organization
FE Farm enterprise
FOAG Federal Office for Agriculture (Switzerland)
FOEN Federal Office for the Environment (Switzerland)
FPCM Fat and protein corrected milk
GWP Global warming potential
GWP100 Global warming potential over 100 years
HCFC Hydrochlorofluorocarbons
IDF International Dairy Federation
IG Input group
ISO International Organization for Standardization
K Potassium
K use Potassium use from mineral sources
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>LCA</td>
<td>Life cycle assessment</td>
</tr>
<tr>
<td>LCI</td>
<td>Life cycle inventory</td>
</tr>
<tr>
<td>LCIA</td>
<td>Life cycle impact assessment</td>
</tr>
<tr>
<td>LU</td>
<td>Livestock unit</td>
</tr>
<tr>
<td>LW</td>
<td>Live weight</td>
</tr>
<tr>
<td>MJ-eq</td>
<td>Megajoule equivalents</td>
</tr>
<tr>
<td>N</td>
<td>Nitrogen</td>
</tr>
<tr>
<td>NA</td>
<td>Not available</td>
</tr>
<tr>
<td>NH$_3$</td>
<td>Ammonia</td>
</tr>
<tr>
<td>N$_2$O</td>
<td>Nitrous oxide</td>
</tr>
<tr>
<td>NO$_x$</td>
<td>Nitrogen oxides</td>
</tr>
<tr>
<td>NR</td>
<td>Not relevant</td>
</tr>
<tr>
<td>nrCED</td>
<td>Cumulative energy demand from fossil and nuclear sources</td>
</tr>
<tr>
<td>OSD</td>
<td>Overall species diversity</td>
</tr>
<tr>
<td>P</td>
<td>Phosphorus</td>
</tr>
<tr>
<td>P use</td>
<td>Phosphorus use from mineral sources</td>
</tr>
<tr>
<td>ReCiPe</td>
<td>Impact assessment method developed by RIVM and Radboud University, CML, and PRé Consultants</td>
</tr>
<tr>
<td>SALCA</td>
<td>Swiss Agricultural LCA</td>
</tr>
<tr>
<td>SE</td>
<td>System expansion</td>
</tr>
<tr>
<td>SFSO</td>
<td>Swiss Federal Statistical Office</td>
</tr>
<tr>
<td>SO$_2$</td>
<td>Sulphur dioxide</td>
</tr>
<tr>
<td>SPACSYS</td>
<td>Soil-plant-atmosphere continuum system</td>
</tr>
<tr>
<td>SWISSland</td>
<td>StrukturWandel InformationsSystem Schweiz (Swiss Structural Change Information System)</td>
</tr>
<tr>
<td>TAN</td>
<td>Total ammonia nitrogen</td>
</tr>
<tr>
<td>terrET</td>
<td>Terrestrial ecotoxicity</td>
</tr>
<tr>
<td>UAA</td>
<td>Usable agricultural area</td>
</tr>
</tbody>
</table>
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