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Farm diversity impacts on food production, income generation and environmental preservation: The Swiss case

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ABSTRACT

A sample of 239 farm year observations of Swiss farms was assessed at the product group level for analyzing the relationship between environmental and economic performance and correlations between product groups (Milk, Cattle, Cereal, Beets, and Potatoes). The farms cover the production regions valley, hill and mountains and practice organic production or proof of ecological performance (PEP), the Swiss standard production.

The environmental dimension was covered by nine impact categories calculated by the Swiss Agricultural Life Cycle Assessment method (SALCA). The impacts were aggregated using a data envelopment analysis (DEA). The economic dimension is assessed by the family workforce income per product group calculated from a full cost data set from the Swiss farm accountancy data network (FADN). Hereby, all indirect costs, which cannot be directly attributed to the product groups, were allocated using standard costs.

We also included productivity as a third dimension in our analysis, quantified as output per area for crop products and output per animal livestock unit for the animal product groups.

No trade-offs between the environmental efficiency and the economic performance were identified. On the contrary, for Cattle and Milk we found significant synergies (1.5 times more observations show synergies than no effect or trade-offs).

Furthermore we found that productivity correlated positively with environmental efficiency for Milk (coefficient = 0.27), Cattle (coefficient = 0.38) and Cereals (coefficient = 0.30), but only for Cattle (coefficient = 0.17) and Potatoes (coefficient = 0.47) it correlated with economic performance.

For all product groups except Cereals, the organic farming system had 5% to 10 higher environmental efficiency and 5%–26% higher economic performance than the PEP farms. Although the differences were not significant, a consistent decrease up to −20% in environmental performance and productivity was observed between the valley/hill and the mountain region.

Our results show no indication that farmers maximize their productivity or economic performance at the cost of environmental efficiency. However, the large variability suggests that there is a) room for improvement in several dimension simultaneously, and b) that maximizing productivity does not seem to be a necessity for these improvements.

1. Introduction

Beyond its primary function of producing food, agriculture should fulfill several different functions (Adam, 2013; Knickel et al., 2004; Lankoski, 2000), such as the preservation of natural resources (for instance soil fertility conservation), the maintenance of an attractive landscape and the provision of an adequate income for farm families. As an activity strongly relying on the use of natural resources, food production accounts for a substantial share of the environmental impacts of humanity (Kuempel et al., 2020; Rees et al., 2004; Tukker et al., 2010). Considering the environmental impacts caused by agricultural intensification (Repar et al., 2017) and given the fact that humanity has already

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exceeded the planet boundaries for several environmental categories (Rockström et al., 2009), there is an need to reduce the environmental impacts of agriculture (Kuempel et al., 2020; Sala et al., 2017). Agricultural production and its related processes are responsible for 25% of anthropogenic GHG emissions, more than 30% of global terrestrial acidification and more than 75% of eutrophication. These emissions can fundamentally reduce the species composition of natural ecosystems, reducing biodiversity and ecological resilience. As Poore and Nemecek (2018) show, on-farm production dominates, representing 61% of food's GHG emissions (81% including deforestation), 79% of acidification, and 95% of eutrophication. This is all the more urgent as a growing global population with more wealth is expected to lead to a higher demand for food. Combined with an increasing consumption of animal products with relatively high environmental impacts this is expected to result in an increase of environmental impacts from agriculture (Dijkman et al., 2018; Gerbens-Leenes et al., 2010; Godfray et al., 2010; Kuempel et al., 2020).

Reconciling food production, income generation, and environmental preservation is therefore needed to ensure the future sustainability of agri-food chains. However, simultaneously fulfilling these three objectives (food production, income generation and preservation of environment) presents a challenge for the farmers (Cassman et al., 2003; Godfray et al., 2010; Jan et al., 2019; Lee et al., 2015; Mondelaers et al., 2009; Muller et al., 2017).

Assessing and better understanding farm performance with respect to these multidimensional objectives is therefore of importance. In order to accurately represent the environmental performance, the analysis should account for the environmental impacts of the whole supply chain of agricultural production. Life Cycle Assessment (LCA) methodology provides a method to calculate these cradle to farm gate impacts (Dijkman et al., 2018; Notarnicola et al., 2017; Pickel and Eigner, 2012). LCA includes impacts from upstream processes, performs a comprehensive environmental assessment, and is widely used to describe environmental impacts of products.

In the last two decades, several analyses using LCA have empirically investigated the relationship between economic and environmental performance in agriculture for single products (i.e. dairy) or at the farm level.

An experimental study on durum wheat production in Italy (Falcone et al., 2019) compared four production systems combinations (conventional vs. conservative and continuous cropping vs. crop rotation with green manure (vetch). The study calculated 18 LCA impact categories and a cumulative as well as the economic performances (e.g. gross margin). They found the least environmental impacts for almost all categories and best economic performance for the conventional + crop rotation system. The experimental design did not include multiple output groups and did not calculate an integrated measure of environmental efficiency.

Flaten et al. (2019) assessed 18 Norway organic and conventional dairy farms regarding GHG emissions, nitrogen surplus and energy intensity as well as profitability. The environmental impacts were assessed individually and results showed that "higher profitability tended to be associated with improved performance of the environmental indicators examined". The study did not include farms with multiple output groups.

Assessing diary production in Austrian Alps, Grassauer et al. (2022) found no systematic trade of between the size of environmental impacts and income generation when assessing eco-efficiency of 21 Austrian dairy farms. They also highlight the high variability as well as the importance of concentrated feed as a driver for higher costs and environmental impacts. The measure of eco-efficiency integrates (multiple) environmental impacts and economic performance in a single measure (similar to the aim of the present study). However, the study only considered whole dairy farms and not product groups.

Using a sample of 56 Swiss dairy farms in the moutain production region, Jan et al. (2012) identified a positive relationship between a farms economic and environmental performance. Similar to this study, the study used DEA methodology to aggregate the environmental impacts, but did not assess individual output groups but rather specialized farms.

To the best of our knowledge, no LCA-based study analyzed the farm performance diversity at the level of multiple simultaneously present product groups (PG) in terms of income generation, environmental preservation, and productivity. As stated above, improving the sustainability of the agri-food chain requires a better understanding of farm performance in its multidimensionality and over the whole supply chain (Dalgaard et al., 2003). The aim of the present study was to capture the diversity of Swiss farms' performance with respect to the objectives of food production, income generation and environmental preservation, considering thereby a wide range of environmental impact categories.

Our work focused on cattle and arable farming and, more precisely, on a selection of production groups (Milk, Cattle, Cereals, Beets, and Potatoes)[1] that are of significant importance for Swiss agriculture. The data used in this study consist of 239 farm-year observations of Swiss farms. The farms cover the production regions valley, hill and mountains and practice organic production or proof of ecological performance (PEP). PEP is the Swiss standard of an integrated production, required to be eligible for direct payments. The PEP standard enforces amongst others regulations regarding balanced nutrient budgets, crop rotation, biodiversity zones, soil protection, and animal welfare. Differently than the organic production label, PEP allows for targeted application of plant protection products (with some restrictions) and mineral fertilizers. Organic production uses farmyard manure and a few plant protection products (mostly inorganic compounds like copper or sulfur).

The goal of our study was to gain better insights into the sustainable performance of Swiss farms at PG level by answering the following questions.

1. What is the distribution of the performance indicators in terms of environment impacts, income, and productivity within each PG?
2. What is the relationship between these three performance dimensions? Are there synergies, trade-offs or no relationship between them?
3. Do farms with multiple PGs perform similarly in all their outputs with respect to the three dimensions considered? In particular, are there any correlations between the PGs in terms of performance regarding agricultural production, income generation and environmental preservation?

The present study contributes to an improved understanding of the relationship between environmental efficiency, economic performance, and productivity using the Swiss case. Furthermore we show how DEA methodology can be used to aggregate Life Cycle Impacts in order to calculate environmental efficiency scores without having to rely on prior weightings.

2. Data and methods

The data stem from the FADN-LCA project (Hersener et al., 2011), which is the most comprehensive and detailed dataset combining LCA and economic assessment for Swiss farms. It includes a non-random sample of 113 farms for the period 2006–2008 covering dairy farms, beef cattle farms, arable crop farms, pig fattening and combinations thereof. The sample was stratified with regard to production region (valley, hill, and mountain) and farm type (organic and proof of ecological performance PEP). The data combine both, detailed production inventories, and economic data at the farm and PG level (Hersener et al., 2011). The sampling design was made to deliver a representative

[1] We use capitalized names in order to distinguish the allocated PGs from the generic products.

datasets of Swiss farms. However, due to too low response, it was not possible to implement the original sampling design fully. Therefore, the final dataset is a non-random sample of Swiss farms.

Subsets of the data were previously used in studies on dairy farms (Jan et al., 2012; Jan et al., 2019; Repar, 2018; Repar et al., 2016, 2017, 2018). To date no comprehensive and systematic analysis on the whole data, including all farms and product groups has been conducted.

The current study analyses the relationship between economic performance, environmental efficiency and productivity within PGs which does not require an extensive random sample to describe the entire sector. The advantage of this very comprehensive and detailed environmental data outweighs the interpretation limitations resulting from the fact that the sample was not drawn at random.

Our empirical investigation was conducted at product group (PG) level, which enabled us to circumvent the issue of the farm diversity met when carrying out investigations at whole farm level (Pedolin et al., 2021). A PG is made exclusively of products of homogeneous nature. For instance, in the case of dairying, the PG Milk encompasses solely the main product milk from dairying and not the related by-product beef from culled dairy cows, this latter being allocated to the PG Cattle. Out of the eight individual PGs originally analyzed for their environmental impacts (Pedolin et al., 2021) we considered only the five PGs Milk, Cattle, Cereals, Beets, and Potatoes for the subsequent analysis. We excluded the two PGs Vegetables and Fruits, because they were both: too few observations and too inhomogeneous (many disparate products like berries, orchards, salads, cucumbers etc.) for a consistent (environmental and economic) analysis. The PG “Pig fattening” was also excluded due to too few observations. The final sample used in the following analysis consisted of 239 farm-year observations resulting in 33–211 farm-year PG observations (subsequently called observations) (Table 1).

The output of the PG Milk is raw milk, measured in liters. For Cattle the output is the quantity of sold animals (for slaughter or breeding) in kg live weight. Dairying is usually associated with the production of surplus animals (calves or cows), which are sold either for breeding or slaughtering. This was taken into account when allocating the farm level environmental impacts from dairying to its two related PGs, namely Milk and Cattle. The allocation occurred proportionally to the net energy needed to produce milk and body mass, respectively, according to the procedure proposed by Nemecek and Thoma (2020). The output for the three crop PGs Cereals, Beets, Potatoes was quantified in kg dry matter.

2.1. Environmental data

The environmental impacts of agricultural production were calculated using the Swiss Agriculture Life Cycle Assessment tool SALCA version 3.6 (Gaillard and Nemecek, 2009) as described in Pedolin et al. (2021).

2.1.1. Goal and scope

The goal of the PG approach was to calculate the environmental impact of production of 1 L or kg of product. The system boundary was cradle to farm gate. All inputs and outputs related to the PGs were considered. For the two animal PGs Milk and Cattle this included all impacts from animal husbandry, such as direct emissions from animals and pastures, storage or application of manure, production of feedstuffs on farm, etc. as well as impacts from purchased feedstuffs and animals.

Table 1
Number of observations per product group.

Product group	N
Milk	160
Cattle	211
Cereals	136
Beets	33
Potatoes	42

For the crop products (Cereals, Beets, Potatoes) this included impacts from production and application of fertilizers, plant protection products and seed production. The functional unit is produced output as liter (Milk) or kg live weight (Cattle) or kg dry matter (Cereal, Beets, Potatoes). Wherever possible we used physical allocation. If this was not applicable, economic allocation was used (Pedolin et al., 2021).

For the allocation between Milk and Cattle, biophysical allocation using the ratio of the required net energy for the produced amount of milk and life weight, respectively (net energy for pregnancy and growth) was used (Nemecek and Thoma, 2020).

2.1.2. Inventory data

The raw data for the life cycle assessment consist of production inventories collected on farm. The production inventories contain detailed information on inputs (e.g. fertilizer, fuel, seeds, plant protection products) and outputs (produced goods that are leaving the farm) as well as information on processes (tillage, application of plant protection products or manure etc.). For the impacts of upstream processes (i.e. machinery, infrastructure, fuel, fertilizer, purchased feedstuffs, etc.) we used the SALCA database and the ecoinvent V3.6 database (Wernet et al., 2016).

2.1.3. Impact assessment

The nine impacts considered in this study cover the five domains soil (land competition, deforestation), water (aquatic ecotoxicity, water use, eutrophication, acidification), air (global warming potential), energy use (non-renewables) and human health (human toxicity). For a detailed description of the used methods see (Pedolin et al., 2021).

2.1.4. Interpretation

The environmental impacts were aggregated using Data Envelopment Analysis (DEA). DEA relates the impacts to the output by benchmarking each producer against its peers. The resulting score is a relative measure of environmental efficiency.

2.2. Economic data

The economic data set originates from the Swiss farm accountancy data network (FADN). FADN data provides very detailed economic information at both the whole farm level (revenues, costs, income) and the PG level (market revenues, direct costs, gross margin). Market revenues and direct costs (costs that are directly connected to an output, e.g. seeds, feed, fertilizer, as opposed to indirect costs like buildings, machines etc.) were allocated to the PGs by the farm bookkeeper in consultation with the farm manager. However, indirect costs, for which the allocation to PGs is often less straightforward, were allocated using the full cost methodology. This method allocates all common costs from infrastructure, labor, machinery etc., as well as revenues to the individual PGs using proportional allocation. The allocation relies on standard costs, from which cost shares are estimated for each output group (Hersener et al., 2011; Lips et al., 2018).

The costs for surplus animals (calves or cows) that are sold for breeding or slaughtering were not accounted for separately in the original full cost data. To ensure the comparability between the economic and environmental data in terms of system boundaries definition, we reallocated these costs to the PG Cattle. This occurred using a proportional allocation relying on the economic output (total revenues including direct payments). Direct payments were included in the revenues since their contribution to the farmers’ income is crucial. The difference between the revenues (including direct payments) and full costs (including salaries for non-family workforce and the costs for the remuneration of equity capital) is the available family labor income.

2.3. Performance indicators

As mentioned in the introduction, the aim of our research was to analyze the heterogeneity of Swiss farms' performance in terms of environment preservation, income generation, and productivity. For that purpose, we defined indicators assessing the farms' performance at product level with respect to each of these three objectives.

2.3.1. Environmental performance indicator

Environmental performance was measured using a biophysical indicator of environmental efficiency, also called environmental productivity (Huppes and Ishikawa, 2005). It is defined as the ratio between the produced output in biophysical terms (liter, kg) and the environmental impact generation. In the present work, we estimated an aggregate environmental efficiency score for each observation using data envelopment analysis (DEA). The environmental efficiency scores are the average values from 2000 bootstrap DEA replications using sampling with replacement (Pedolin et al., 2021). The DEA scores are per definition normalized for each PG, with the best observed producers having a value of 1 and less efficient producers having a value between 0 and 1. By using data envelopment analysis instead of weighted sums like in distance to target approaches or endpoint impacts we avoid normative assumptions on the relative relevance of each impact category or their effect on the areas of protection (Finnveden et al., 2009). Instead, DEA uses linear programming to calculate the "maximal" efficiency for each producer by allowing any weightings of the individual impacts under the constraint that no other observed producer would achieve better efficiency using the same weights. The weights are thus generated endogenously from the observed data and not fixed a priori (Charnes et al., 1978).

2.3.2. Economic performance indicator

For the present analysis, the family labor income per working hour was used as economic performance indicator at PG level. The indicator family labor income per working hour was chosen for two reasons: First, it enables a comprehensive assessment of farm economic performance because it takes all production factors into account. Second, it is a common farm's economic performance measure, which has a very intuitive interpretation and is used in many comparable studies (Andersen et al., 2007; BFS, 2017; Breitschuh et al., 2008; Bystricky et al., 2020; Dux et al., 2017; Hersener et al., 2011; Jan et al., 2012; Mouron et al., 2006; Picazo-Tadeo et al., 2011; Repar et al., 2017; Zorn et al., 2018). Additionally, labor income shows high correlation with other economic key performance indicators (Supplementary Information S4). The family labor income was normalized by dividing each observation's family labor income per working hour by the highest observed value for each PG, the best performer of each PG showing thus a normalized economic performance of 1.

2.3.3. Agricultural production performance indicator

The measure of farm's performance in terms of agricultural/food production relied on a relative biophysical productivity indicator. It was calculated by dividing the output of each PG expressed in physical units (liter, kg) by either the utilized agricultural area for crop products (Cereals, Beets, and Potatoes) or the number of livestock units for animal products (Milk and Cattle). This value was then normalized on a 0 to 1 scale by dividing each observation by the largest value for each PG.

2.4. Statistical analysis

2.4.1. Variance of environmental, economic and productivity measures

The analysis of the distribution of the environmental, economic and productivity measures relied first on statistical measures of central tendency (mean and median value) and dispersion (coefficient of variation CV, 10% and 90% percentiles). In a second step, we conducted a two-way analysis of variance (ANOVA) to estimate the effects of farming system and production region on the three performance dimensions. With regard to research question one, we used two-way ANOVA to estimate the effects of farming system (proof of ecological performance, versus organic farming) and agricultural production region[2] on the three dimensions environmental efficiency, economic performance and productivity.

Table 2
Classification of the observations based on their joint economic and environmental performance at product group level.

Type	Economic performance	Environmental performance
Both-efficient	≥ Median	≥ Median
Both-inefficient	< Median	< Median
Environmentally efficient	< Median	≥ Median
Economically efficient	≥ Median	< Median

2.4.2. Synergies and trade-offs between the dimensions

To examine the relationship between environmental performance, economic performance, and productivity (research question two), we first carried out a Pearson's correlation analysis. In a second step, we investigated more in depth the relationship between economic and environmental performance within each PG. For that purpose, we classified the observations into four types based on their joint economic and environmental performance as described in Table 2.The number of observations in each of these four classes was then tested for significant deviation from the null hypothesis (H0 = all frequencies are equal) using a Chi-squared test.

2.4.3. Performance of simultaneously produced product groups

To explore the existence of correlations between the PGs in terms of performance regarding agricultural production, income generation and environmental preservation (research question three), we considered all pairwise combinations of simultaneously produced PGs and calculated the correlation coefficient using Pearson's product-moment correlation.

2.5. Pooling of observations

For the calculation of the performance indicators, the observations were pooled over the years. This pooling was necessary in order to have a sample large enough for the DEA calculation and for the analysis of the effects of the farming system and production region. To make sure that this pooling was valid, we carried out additional investigations, which are presented in Supplementary Information (Fig. S1).

3. Results

3.1. Variance of environmental, economic and productivity measures

The distributions of the normalized indicators for the three performance dimensions vary considerably within as well as between PGs (Fig. 1). We found some very low and negative economic performance scores for the animal PGs. While there were not many farm-year observations with negative income (28 for Cattle, 11 for Milk, 7 for Potatoes and 3 for Cereals), their family labor income per hour could reach strongly negative values, especially for the animal PGs. These findings are similar to the results of the report of Swiss Farm Accountancy Data Network on economic heterogeneity at the enterprise level (Lips et al., 2017), showing that there is a large variability, including negative incomes from animal PGs, most notably so for beef production.

All five PGs displayed in Fig. 1 showed high variance in the economic

[2] The definition of the agricultural production regions in Switzerland is based on three groups of criteria: the climatic conditions, the accessibility in terms of transport and the topography.

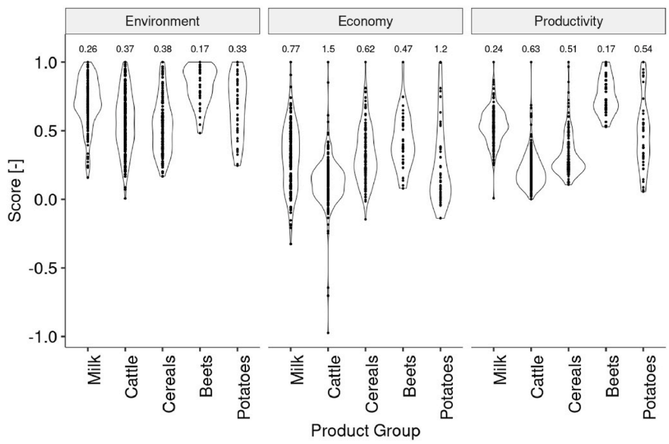

Fig. 1. Distribution of the environmental, economic and productivity performance scores. Dots mark the individual observations, the width of the violin plot is proportional to the density. (Numbers above the plots describe the coefficients of variation CV).

performance score, which is similar to findings from other studies for crop products (Alem et al., 2018) and for animal products (Lips et al., 2017).The CV ranged between 1.47 for Cattle and 0.47 for beets. The environmental efficiency and productivity scores cannot be negative by definition. The CV for the environmental efficiency was the lowest ranging from 0.37 (Cereals, Cattle) to 0.17 (Beets), while the productivity score CV varied between 0.63 (Cattle) and 0.17 (Beets) (Fig. 1 and Supplementary Information Table S2).

The range between the 10% and 90% percentiles for the performance indicators varied between the PGs, with Potatoes and Milk and Cereals having the largest and Cattle and Beets the smallest ranges (Fig. 2). The highest values for all three dimensions resulted for the PG Beets, followed by Milk. For Cereals, Cattle and Potatoes the ranking depends on the dimension, with Cattle having third highest median environmental efficiency, but only fourth for economic performance, and last for productivity. Across all PGs, we found the lowest mean, median and 10% percentile values for the economic performance indicator. Conversely, the highest mean, median and 10% percentile values were observed for the environmental performance indicator (Supplementary Information Table S3).

Assessing the effect of the farming system on the three dimensions (Fig. 3 left), we found no significant effects on the environmental efficiency, but a trend towards higher environmental efficiency for the organic farming system. A notable exception was the PG Cereals, where

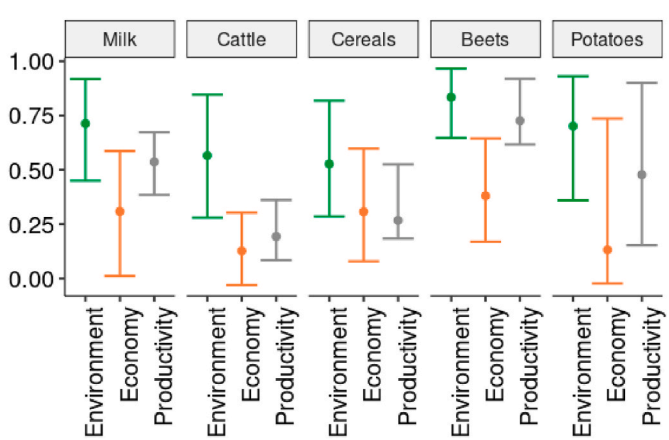

Fig. 2. Median values and 10% and 90% percentiles of the performance indicators for the three dimensions environment, economy and productivity for each product group.

we found a trend towards higher average environmental efficiency for the PEP farming system. The economic performance was significantly higher for the organic farming system for Milk and Cereals and the productivity significantly lower for Cattle and Cereals (Supplementary Information Table S4). However, these effects on economic performance and productivity were not significant, if we also accounted for the production region (Supplementary Information Fig. S6 -S9). For Potatoes and Beets, the effect of the farming system could not be investigated, as there were not enough observations for organic production.

We also investigated the effect of the agricultural production region (valley, hill and mountain) on the environmental and economic performances as well as on the productivity (Fig. 3 right). For Milk and Cattle, which are the only two PGs present in all regions, we found a decrease in environmental performance and productivity from the plains to the mountain region. In contrast, the economic performance did not differ between the three regions. This absent impact on economic performance is likely related to the direct payments for production under unfavorable natural conditions ("Direktzahlungen zum Ausgleich der erschwerten Produktionsbedingungen"). For Cereals and Potatoes there were only observations available for the production region valley and hill. The differences between these two regions were less pronounced.

3.2. Synergies and trade-offs between the dimensions

The performance indicators regarding the three considered dimensions (environment, economy, and productivity, research question two) showed some correlations between each other, depending on the PG (Table 3). All significant correlations were positive and the highest correlation appeared between economic performance and productivity for Potatoes.

Environmental performance correlated positively with productivity for Milk, Cattle and Cereals. Economic performance was positively related with productivity for Cattle and Potatoes. Only for the PG Cattle resulted a significant positive correlation between environmental and economic performance.

This relationship between environmental efficiency and economic performance was assessed using a more robust method by grouping each observation into one of four categories. For each PG, observations were considered as environmentally efficient, if their environmental efficiency score was above the median value, or as inefficient if the value was below the median. The separation into economically efficient and economically inefficient was made accordingly. In Fig. 4 the four resulting sectors are labelled Both-efficient if both dimensions showed above median scores, Both-inefficient if the scores for both dimensions were below median, environmentally efficient and economically efficient, respectively, if only one of the dimensions was above median.

The number of observations in each group was counted and checked for unequal distribution between groups using a chi-square test (Table 4). If there were more observations in the Both-inefficient and Both-efficient sector than in the two other sectors, then there were synergies between economic performance and environmental efficiency. Conversely, a higher number of observations in the other two groups ("economically efficient" and "environmentally efficient") points to the existence of trade-offs between the economic and environmental performance. The results of the Chi-squared test show that the observations were not equally distributed across the four joint performance types for the two animal PGs Milk and Cattle. Here the two categories Both-efficient and Both-inefficient show significantly more observations than the two mixed efficiency categories, highlighting thus the existence of a synergy between economic and environmental performance for Milk and Cattle. Conversely, for the plant PGs (Cereals, Beets, and Potatoes), the observations were equally distributed between the four joint performance types, implying thus that were neither synergies not trade-offs between the two performance dimensions considered. We have to keep in mind that Milk and Cattle were the PGs with the highest number of

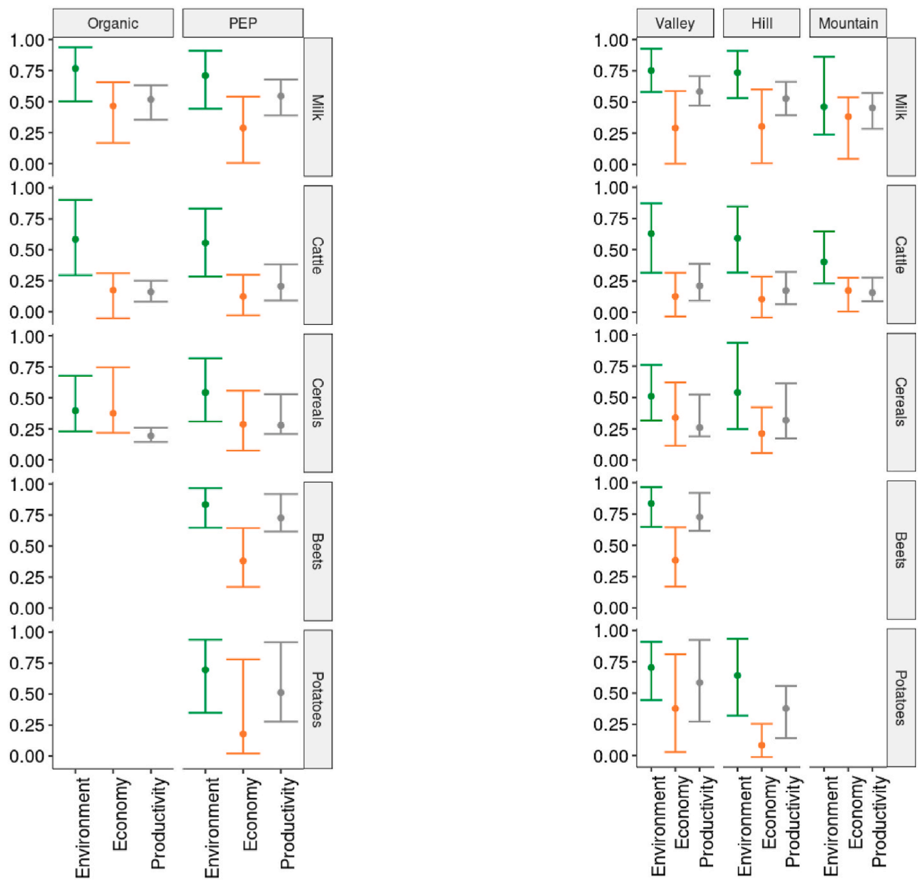

Fig. 3. Median values and 10% and 90% percentiles of the three performance indicators according to the farming system (left) and production region (right). Only groups with at least 10 observations were included.

Table 3
Correlation between the performance indicators regarding the three dimensions considered (environment, economy and productivity) for each product group. Shown are Pearson correlation coefficients and p-value (in parenthesis).

Product Group	Dimension	Environment	Economy	Productivity
Milk	Environment	1 (0)	0.124 (0.119)	**0.273 (< 0.001)**
Milk	Economy		1 (0)	−0.0318 (0.689)
Milk	Productivity			1 (0)
Cattle	Environment	1 (0)	**0.278 (< 0.001)**	**0.38 (< 0.001)**
Cattle	Economy		1 (0)	**0.169 (< 0.05)**
Cattle	Productivity			1 (0)
Cereals	Environment	1 (0)	0.048 (0.579)	**0.296 (< 0.001)**
Cereals	Economy		1 (0)	−0.031 (0.721)
Cereals	Productivity			1 (0)
Beets	Environment	1 (0)	0.162 (0.369)	0.197 (0.272)
Beets	Economy		1 (0)	0.209 (0.243)
Beets	Productivity			1 (0)
Potatoes	Environment	1 (0)	0.118 (0.456)	0.284 (0.068)
Potatoes	Economy		1 (0)	**0.465 (< 0.01)**
Potatoes	Productivity			1 (0)

observations, present in all three production regions and with both farming systems. It is possible that with a larger sample, more effects could be detected also in the crop PGs.

3.3. *Performance of simultaneously produced product groups*

The within farm relationship between simultaneously produced PGs (research question three) was assessed for each combination of PGs (Supplementary Information Table S6). For the environmental dimension, significant correlations were detected between the performance of the two animal PGs Milk and Cattle (coefficient of correlation = 0.67) and between Cereals and Beets (0.49). For the economic dimension we found three significant correlations for joint production with Milk or Cereals, two for Cattle and one for Beets or Potatoes. The fact that we found more than twice as many significant effects for the economic dimension than for the environment, is probably related to differences in farm manager's economic capabilities and direct payment structures. With respect to the productivity dimension, we found no significant correlation between the performances of simultaneously produced PGs (Table 5).

Most importantly, none of the significant correlations are negative – we couldn't find any signs that the performance in one PG is systematically reduced at the expense of another. Nonetheless, the lack of positive correlations for productivity is somewhat surprising since we found systematic (albeit not always significant) effects of production region and farming system for all PGs (Figs. 2 and 3). Apparently, the variability within a production region or farming system is so great that differences between regions and farming systems could be masked.

4. Discussion

4.1. *Variance of environmental, economic and productivity measures*

With regard to the first research question, we found the largest

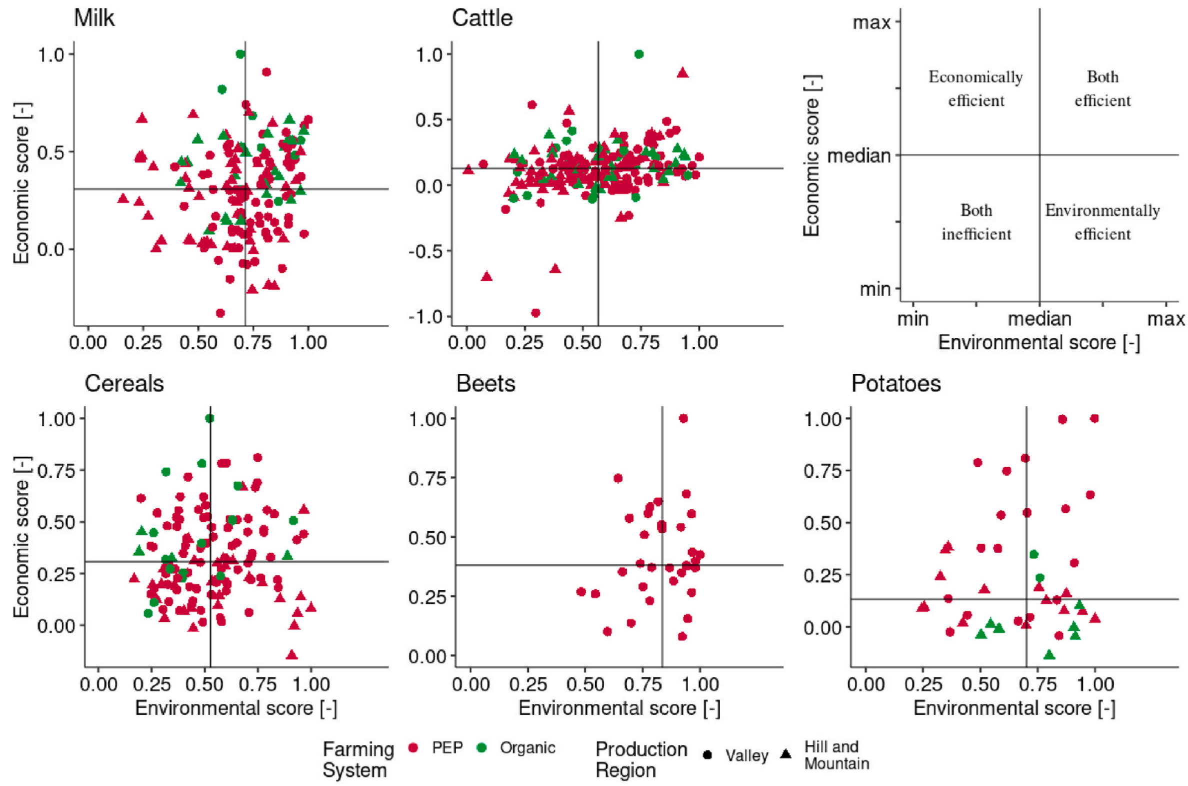

Fig. 4. Classification of the observations into one of the four combined environmental-economic efficiency groups.

Table 4
Chi squared test for environmental and economic performance categories. Chi squared tests whether there is a significant difference between the expected frequencies (H0 = all categories have same frequency) and observed frequencies.

Product Group	p-value	Both efficient	Both inefficient	Economically efficient	Environmentally efficient
Cereals	0.573	26%	26%	24%	24%
Milk	0.024	30%	30%	20%	20%
Cattle	0.016	30%	29%	20%	20%
Beets	0.623	27%	24%	24%	24%
Potatoes	0.584	24%	24%	26%	26%

Table 5
Correlation between the performances of simultaneously produced product groups. Only significant correlations are shown (see Supplementary Information Table S7 for all tested correlations).

Dimension	N	PG1	PG2	Correlation coefficients	p-value
Environment	160	Milk	Cattle	0.67	<0.001
Environment	28	Cereals	Beets	0.49	<0.01
Economy	160	Milk	Cattle	0.42	<0.001
Economy	78	Milk	Cereals	0.34	<0.01
Economy	28	Milk	Potatoes	0.59	<0.001
Economy	104	Cattle	Cereals	0.37	<0.001
Economy	28	Cereals	Beets	0.78	<0.001

variability in performance scores amongst the three measures for the economic dimension (mean CV over all PGs: 0.90), followed by productivity (CV = 0.42), and environmental efficiency (CV = 0.30). The very high variability in economic performance for Cattle (CV = 1.5) is closely related to the relatively large negative values we found for this PG (Fig. 1). This poor economic performance is consistent with the observations from Lips et al. (2017) who also found very low incomes for Cattle farming, especially for the suckler cow husbandry (average hourly wages of CHF 11.50 for PEP and CHF 10.30 for organic farming systems, compared to the median income of the employees of the secondary and tertiary sectors between CHF 22.60 in the mountain region and CHF 26.50 in the valley region).

For the environmental efficiency we found the highest average performance and lowest coefficient of variation for Beets (mean = 0.83, CV = 0.17), which could be explained by two reasons: First, the production of beets in the analyzed sample takes place only in the valley region and under the PEP farming system. It occurs thus under quite homogeneous natural and production system conditions. Second, beet production is relatively highly standardized and mechanized, which may also account for the lower variability observed for the environmental efficiency. The lowest average performance for environmental efficiency was found for Cereals (mean = 0.53, CV = 0.38) and Cattle (mean = 0.57, CV = 0.37), indicating a high improvement potential. As in the previous study relying on the same data set (Pedolin et al., 2021), we found only relatively small and non-significant differences in terms of environmental efficiency of Cereals production between the two farming systems investigated. The average environmental efficiency tends to be higher for Cereals produced under the PEP farming system than under the organic one. The fact that 25% of the PEP farms produce their Cereals under the Extenso agri-environmental scheme contributes to reducing the differences in terms of environmental efficiency between the two farming systems investigated (Böcker and Finger, 2018). The Extenso program compensates farmers for lower yields if they forego the application of fungicides, insecticides, and plant growth regulators, while herbicides and slug granules are still permitted. A study on the economic and environmental effects of Extenso on Swiss wheat production by Böcker et al. (2019) found that the program is able to lower the risks for the environment and human health due to pesticide use. Since this program still allows for mineral fertilizers use, which contributes to higher yields than in the organic system, it leads in the end to a better environmental efficiency.

The mean productivity scores are lowest for Cattle (mean = 0.22, CV = 0.63) and highest for Beets (mean = 0.75, CV = 0.17), again reflecting the standardized production circumstances and standardized production technique for Beets. Additionally in both 2007 and 2008 we observed above average sugar beet yields, while 2006 had below average yields (Arnold and Fankhauser, 2007; Pfauntsch and Fankhauser, 2008, 2009). Productivity for Milk (mean = 0.54, CV = 0.24) showed an almost normal distribution. This was expected because Milk producers were distributed across all production regions and farming systems, which are two factors responsible of large differences between farms in terms of mechanization and automation. This result of high variability in productivity falls in line with the findings of a study on dairy farms in the alpine region by Sturaro et al. (2013). In their sample, "halve of the observed farms belong to the very traditional dairy farming system, while, on the opposite, only 19% of the farms seem to have completed the transformation into intensive units" (Sturaro et al., 2013). The substantial variability of the productivity of Potatoes may result (i) from large differences in mechanization and (ii) from the fact that this production occurs in two different production regions (valley and hill), which show heterogeneous natural production conditions and suitability for this production, and (iii) from both farming systems (PEP and organic). Similar to the findings in a study by Cassman et al. (2003), we found that for Cereals productivity is for most producers relatively low. Accordingly Cereals showed amongst all product groups the second lowest mean value (mean = 0.32, CV = 0.51) and the second largest skew (1.7).

Many studies assessed the environmental benefits of organic production and show that it can contribute to lowering the environmental impacts from agricultural production if it is implemented correctly and part of an overall transition of the food value chain to more sustainable consumption and production (de Ponti et al., 2012; Muller et al., 2017; Reganold and Wachter, 2016). Similar to studies by Clark and Tilman (2017) and Tuomisto et al. (2012) on the effects of organic vs. conventional farming systems on the environmental performance, we found higher albeit not significant environmental efficiency for Milk and Cattle in the organic farming systems. Repar (2018) came for dairy to similar results as in our investigation. They showed that for alpine (mountain) dairy farms, both environmental efficiency and economic performance are better in the organic farming system than for PEP farms. We also observed that for the PG Cereals the lower yields in organic farming reduces the benefits from reduced environmental impacts per area, since we relate the impacts to the output.

4.2. Synergies and trade-offs between the dimensions

No trade-offs between the economic and environmental dimension were identified for any of the assessed PGs. Over all farming systems we found significant positive correlations between environmental efficiency and productivity for Milk, Cattle and Cereals. Including the farming system, we found stronger, albeit not significant correlations between environmental efficiency and productivity in the PEP than in the organic farming system for Milk, Cattle and Potatoes (Supplementary Information Table S5). This indicates that the integrated farming required by PEP allows for a better balance between productivity and environmental efficiency. Nemecek et al. (2011) also identified the lower yields in organic farming as the main driver for inefficient use of production factors when compared to integrated farming. The effect of the higher productivity on (better) economic performance for PEP farms was less pronounced than for environmental efficiency.

For the product group Milk we could identify a significant correlation between environmental efficiency and economic performance. Similarly, a study by Repar et al. (2016) on Swiss mountain dairy farms also identified positive correlations between farm's environmental and economic performance.

In the case of Cattle we found a strong correlation between environmental and economic performance for PEP production (Supplementary Information Table S5).

A study assessing the economic and environmental performance of Brazil beef farming systems of varying intensities found synergies between both performance dimensions for medium intensity production (improved pastures) and a reduction in economic performance for the most intensive system (feedlot finishing) (Pashaei Kamali et al., 2016). In addition, similarly to our study, they observed a relatively poor economic performance of beef production: For farms with combined soy bean and beef production 88% of the profits were derived from soybean production.

For Potatoes we found a relatively strong correlation (correlation coefficient = 0.46) between productivity and economic performance (but no significant relationship between these performance dimensions and the environmental one). The lack of translation from productivity gains to better environmental performance indicates that these productivity gains are achieved by implementing measures and inputs with (dis)proportionally large environmental impacts (as fungicides and pesticides and mineral fertilizers).

For these production systems an improved direct payment scheme, which incentivizes farmers to implement environmentally friendly practices while maintaining the productivity could allow farmers to improve their environmental efficiency and economic performance simultaneously.

Since we assessed agricultural production for different climatic and topographic conditions and two farming systems (PEP and organic), we expect differences in productivity. In fact, for Milk and Cattle, the lower productivity has an effect on environmental efficiency but almost no effect on the economic performance. This finding is closely related to direct payments for production under disadvantageous circumstances which are paid for production in mountain regions. These payments, which aim at compensating the lower productivity resulting from the disadvantageous natural production conditions, are an important source of income for these farms (El Benni and Finger, 2013). However, animal production in the mountains can deliver non-market goods and can free productive arable land for direct food production. This overall positive effect on environment and economic performance of transhumance (seasonal movement of livestock) and share of labor (crop production in valley regions, animal husbandry in mountain region) has been shown by Marton et al. (2016), Marton et al. (2016b) and Repar (2018).

In general we find that there is a relation between the three dimensions environmental and economic performance as well as productivity. Higher productivity results in higher outputs and higher returns. On the other hand also the costs for inputs increase, both in financial and environmental terms. Productivity showed relatively low or no correlation with the environmental or economic dimension. Nemecek et al. (2005) presented a framework to conceptualize the relationship between productivity and environmental performance. Depending on the PG, farming system and production region, an increase in productivity can lead to better environmental and economic performance, if the marginal economic cost or environmental burden is lower than the increase in productivity (Fig. 5). If the marginal economic cost or environmental burden is larger than the additional productivity, an increase in productivity leads to lower economic or environmental efficiency. This can be the case if large inputs of (mineral) fertilizer, plant protection products or machinery is required to increase productivity. On the other hand, if a measure leads to less environmental impacts at the price of lower productivity, this decrease in output can nullify or overcompensate for the better environmental impacts. An example of this is found in organic farming where yield losses can lead to lower environmental efficiency (per unit of output). Additionally, all production has some constant costs and emissions that are independent of the output. For these (fixed) impacts, an increase in output leads always to better efficiency (all other being equal). Inversely, a decrease in productivity leads to a decrease in efficiency, because there is less output to take a share of the fix cost/burden. Since the organic farming system mainly aims at lowering impacts (lower fixed base emissions, lower marginal emissions) an increase in productivity is more likely to result in a better overall performance. For the PEP

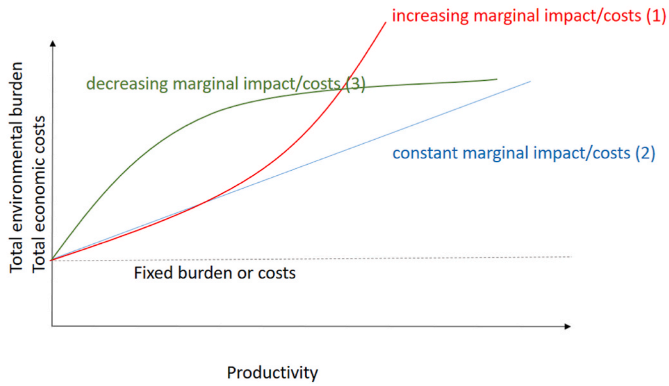

Fig. 5. Schematic depiction of the relationship between productivity, environmental and economic performance. Depending on the variable impacts an increase in productivity can lead to better or worse environmental and economic performance (Nemecek et al. (2005) adapted).

farming system, which compared to the organic systems is more reliant on inputs, an increase in productivity can sometimes only be achieved by an even larger increase in inputs, therefore negating an overall improvement (except lower shares of the fixed costs/impacts).

The more a farming system relies on inputs, the more likely is its productivity – performance function between 1 and 2. The more extensive a farming system is, the more the function is between 2 and 3. Typical examples for decreasing marginal effects or linear relationship between productivity and environmental burden or economic cost are: Low-input agriculture, extensive animal husbandry (suckler cows), and organic crop production. In these cases, an increase in productivity can lead to better overall environmental efficiency and economic performance. Typical examples for increasing marginal: High input agriculture, horticultural crops requiring intensive plant protection, and large scale animal husbandry. Here, increasing productivity will lead to lower overall environmental efficiency or economic performance. In practice this means that there is no single strategy on how to improve the joint environmental and economic performance: Depending on how input intensive a production system is, one should either aim to improve productivity or to reduce inputs.

4.3. Performance of simultaneously produced product groups

Regarding research question three, we found only for a few pairs of simultaneously produced PGs a positive correlation between their performance and no significant negative correlations. There was no significant correlation between any PGs for productivity. For Milk and Cattle, a highly significant correlation between the simultaneous performance of these two PGs was observed for both environmental ($R = 0.42$) and economic dimension ($R = 0.67$). Some of this relative strong correlation can be attributed to imputed allocation between Milk and Cattle. This was necessary because in the case of the FADN data there was no separation between Cattle from surplus calves and culled animals. A second significant correlation for the environmental efficiency was found between the two crop products Beets and Cereals ($R = 0.49$). For these two PGs we also found the highest correlation in the sample for the economic performance ($R = 0.78$). The lack of correlation between these two PGs for the productivity dimension indicates that the environmental and economic performance is not so much dependent on the output but rather on the avoidance of costly or environmentally problematic inputs. Additionally the direct payments for extensive crop production (Böcker and Finger, 2018) and area dependent direct payments for sugar beets play an important role for the economic performance and are independent from the productivity.

We found synergies for mixed dairy and crop production for the economic dimension in the case of Cattle combined with Cereals ($R = 0.37$) as well as Milk combined with Cereals ($R = 0.34$) or Potatoes ($R = 0.59$). However, there was no correlation between the environmental efficiencies of these PGs. This finding of no clear effect of simultaneous production on the PGs performance for mixed farms is somewhat different to the results of a study by Marton et al. (2016a). Their analysis of mixed and specialized dairy farms found lower emissions on mixed farms (synergies) but overall lower yields for crop PGs in presence of Milk production (trade-offs). However, a recent study of Czech farms reported synergies for combined milk and crop production and no indication for trade-offs (Špička et al., 2020). These somewhat contradicting findings are most likely related to how and which direct payments are included and which environmental impacts were considered.

4.4. Suitability of the underlying data

The data used in this study was collected during the period 2006–2008. In order to check the validity of the data for the current time period we assessed the development of the family labor income (Supplementary Information Fig. S2), farm size (utilized agricultural area, Appendix Fig. 3) and selected environmental impacts (Supplementary Information Fig. S5) for which long-term data was available. For the assessment of the income situation and farm size development we used the FADN data. Since all farms participating in this study were also part of the FADN network we could identify a subset where we had observations for the whole period of 2006–2014 (after 2014 the FADN methodology changed). While the farms participating in this study had ca. 10% lower family workforce incomes and were ca. 10% smaller than the other farms in the FADN sample, their development since 2008 did not differ significantly from the FADN sample. For the assessment of the environmental performance over the time period 2009–2019, no corresponding data exist. We used data from the agronomy environmental monitoring program of Agroscope (Gilgen et al., 2023) instead. Their long term study collects data on selected environmental impacts. We used four of these impacts: nitrogen balance, ammonia emissions, biodiversity index and greenhouse gas emissions, each for the four farm types: cattle, suckler cows, crop and milk and (representing PGs Cattle, Beets, Potatoes and Cereals, and Milk). For the period from 2009 to 2019, there were no significant trends regarding any of the four assessed environmental impacts (Supplementary Information Fig. S5). This analysis showed no evidence of a fundamental change over time, so the relationships identified in the current study can still be considered valid.

The Swiss integrated farming system standard PEP can be used as a model for other integrated production systems. Similar standards regarding cross-compliance with environmental legislation and compulsory measures exist in the European Union (Isoni, 2015).

4.5. Uncertainty

There are multiple sources of uncertainty regarding the results. We can distinguish between data uncertainty, model uncertainty, and scenario uncertainty. Various measures have been taken to ensure the quality of the underlying data.

4.5.1. FADN data

The FADN data used in this study were extensively checked for plausibility by the Business Management and Value Creation research group. Any observation that did not pass the assessment was omitted from the sample.

4.5.2. LCA results

For the LCA part of this study we identified three different sources of uncertainties parameter uncertainties, scenario uncertainties and model uncertainties (Huijbregts, 2002).

Part of parameter uncertainty is related to inaccurate or missing data. This component can be reduced by comprehensive plausibility tests of the production inventory data.

Scenario uncertainty due to allocation was minimized by using allocation by farm managers and physical allocation wherever applicable.

Model uncertainty resulting from uncertainty in the emission models or characterization factors are of lesser concern for this study, because any introduced errors would apply to all observations in the PG. The production inventories were carefully assembled by the farmer in cooperation with a representative from the fiduciary office which was employed by the FADN for data collection. Allocation of machines, infrastructure and outputs was also done by the farmer and trustee. Additionally we increased the data quality by conducting additional plausibility tests.

Model uncertainty is of a lesser concern because we are only assessing within PG variability. Thus any inaccuracies in the calculation of emissions would have a similar impact on all observations. Due to the large sample size and limitations of the toolchain a comprehensive uncertainty analysis using Monte Carlo simulation was not feasible.

4.5.3. *Calculation of environmental efficiency*

In order to get robust estimates for the environmental efficiency, we used bootstrapping to calculate the scores (Pedolin et al., 2021). For each PG the DEA was performed 2000 times, each time with another combination of the observations (sampling with replacement). The reported efficiency scores are the mean value of these 2000 replications. Additionally we assessed the scores sensitivity of the included or excluded impact categories. This analysis showed that all impact categories had a similar effect on the aggregated environmental efficiency score (Pedolin et al., 2021).

4.6. *Suitability of the methods*

For this study we focused on the family labor income as measure to quantify economic performance. This indicator shows positive correlation with other indicators, especially those reflecting the liquidity and income generation (Supplementary Information Table S1). However, for a fully economic analysis also other indicators, reflecting more long-term economic sustainability, should be included.

For the environmental impact assessment, impacts on biodiversity and other hard to quantify measures were not considered. Additionally, we did not include outputs of non-market goods like provisioning of ecosystem services or landscape aesthetics, etc. These measures, while important contributions of agriculture in Switzerland were not included in the initial assessment and would require more information than was available for this study.

The combination of DEA and life cycle impacts methodology in order to aggregate the impacts and outputs is a promising approach with increasing usage in the LCA community (Vásquez-Ibarra et al., 2020). The weights are not determined a priori, implying that no subjective judgment about the weights is required. In lieu thereof, the weights are determined endogenously within the model to maximize efficiency (Kuosmanen and Kortelainen, 2005). . Given the efficiency score is a relative measure, comparing each observation to the best observed producer, we can compare observed performance to a benchmark without relying on a hypothetical best case scenario. On the other hand, the scores do not objectively quantify good or bad performances in absolute terms but only in relative terms. In other words, we are not sure, whether the best observation is good enough to meet certain absolute sustainability objectives. The DEA environmental efficiency scores used in this study show no super-efficiency (Coelli et al., 2005). The bootstrapped scores are robust with regard to outliers and all included impacts contribute to the final score (Pedolin et al., 2021).

5. Conclusions

With regard to research question one: “What is the distribution of the performance indicators in terms of environment impacts, income, and productivity within each PG?” we found a large variability in economic performance for the PGs Cattle, Milk, and Cereals. This high variability in income was partially explained by low productivity due to the production region. However, we found low incomes for all three production regions. In particular, we showed that the role of productivity as a driver for both environmental and economic performance is not straightforward: While the productivity is lower for organic farming systems, the lower inputs, higher prices and direct payments result in better environmental efficiency and economic performance of the organic system for all PGs except Cereals. Depending on the intensity of the production, increases in productivity can lead to both, better or worse environmental efficiency and/or economic performance.

Regarding research question two: “What is the relationship between these three performance dimensions? Are there synergies, trade-offs or no relationship between them?” we found that there is only little correlation between the environmental efficiency and economic performance. Nevertheless, in the case of Milk and Cattle, the PGs with the largest and most diverse samples, significant synergies were detected. We did not find any signs of a trade-off between environmental efficiency and economic performance for any of the assessed PGs. Especially in the case of PEP farming system we found signs for a well-balanced compromise between productivity and environmental efficiency. This is a new finding insofar as there has been no study assessing joint economic and environmental performance of the simultaneous production of multiple PGs for these farming systems.

For research question three: “Do farms with multiple PGs perform similarly in all their outputs with respect to the three dimensions considered? In particular, are there any correlations between the PGs in terms of performance regarding agricultural production, income generation and environmental preservation?“, we found an inconclusive signal, with some positive correlations between PGs for the environmental dimension and to a larger extend for the economic dimension, but no significant correlations for productivity. The fact that we did not find any significant negative correlations indicates that there are no systematic performance trade-offs between PGs for diversified farms.

Regarding the PG based approach we conclude that such an aggregation level allows for a more differentiated assessment of farm performance. We also showed in the present study that there are multiple structural differences between the PGs.

Conclusions were limited by the lack of significant effects. A larger sample size could lead to more differentiated results. A more automated toolchain for LCA calculation would allow for improved uncertainty analysis and enable for more detailed description of the sources of impacts. Future work should include observations from other countries and other farming systems as well as more detailed information on the farmers training and management practices.

In general we conclude that, there is no indication that farmers maximize their productivity or economic performance at the cost of environmental efficiency. Judging from the large variability of the observed scores we suggest that there is a) room for improvement in both the environmental and economic dimension simultaneously, and b) that maximizing productivity, measured as output of agricultural products (i.e. market-goods) does not seem to be a necessity for this improvements.

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CRediT authorship contribution statement

Dario Pedolin: Conceptualization, Methodology, Writing – original draft, Visualization, Writing – review & editing. **Pierrick Jan:**

Methodology, Writing – review & editing. **Andreas Roesch:** Writing – review & editing, Visualization. **Johan Six:** Supervision, Writing – review & editing. **Thomas Nemecek:** Supervision, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The authors do not have permission to share data.

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Appendix A. Supplementary data

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References

Adam, E., 2013. Multifunctionality of agriculture and international trade. In: Thompson, P.B., Kaplan, D.M. (Eds.), Encyclopedia of Food and Agricultural Ethics. Springer Netherlands, pp. 1–11. https://doi.org/10.1007/978-94-007-6167-4_364-3.

Alem, H., Lien, G., Hardaker, J.B., 2018. Economic performance and efficiency determinants of crop-producing farms in Norway. Int. J. Prod. Perform. Manag. 67 (9), 1418–1434. https://doi.org/10.1108/IJPPM-01-2018-0026.

Andersen, E., Elbersen, B., Godeschalk, F., Verhoog, D., 2007. Farm management indicators and farm typologies as a basis for assessments in a changing policy environment. J. Environ. Manag. 82 (3), 353–362. https://doi.org/10.1016/j.jenvman.2006.04.021.

Arnold, J., Fankhauser, H.R., 2007. The 2006 campaign in Switzerland [Article]. Zuckerindustrie 132 (5), 366–371. https://www.scopus.com/inward/record.uri?eid=2-s2.0-34249888746&partnerID=40&md5=39eaf2bee9f200f680c80358d52464f6.

BFS, 2017. *Schweizerische Lohnstrukturerhebung 2016* Bundesamt für Statistik Schweiz (BFS).

Böcker, T., Finger, R., 2018. Implications of Herbicide-free Extenso Wheat Cultivation in Switzerland. Recherche Agronomique Suisse, pp. 296–305, 9.

Böcker, T., Möhring, N., Finger, R., 2019. Herbicide free agriculture? A bio-economic modelling application to Swiss wheat production [Article]. Agric. Syst. 173, 378–392. https://doi.org/10.1016/j.agsy.2019.03.001.

Breitschuh, G., Eckert, H., Matthes, I., Strümpfel, J., 2008. Kriteriensystem nachhaltige Landwirtschaft (KSNL) : ein Verfahren zur Nachhaltigkeitsanalyse und Bewertung von Landwirtschaftsbetrieben, vol. 466. KTBL.

Bystricky, M., Nemecek, T., Krause, S., Gaillard, G., 2020. Potenzielle Umweltfolgen einer Umsetzung der Trinkwasserinitiative. Agroscope Science, Issue.

Cassman, K.G., Dobermann, A., Walters, D.T., Yang, H., 2003. Meeting cereal demand while protecting natural resources and improving environmental quality. Annu. Rev. Environ. Resour. 28 (1), 315–358. https://doi.org/10.1146/annurev.energy.28.040202.122858.

Charnes, A., Cooper, W.W., Rhodes, E., 1978. Measuring the efficiency of decision making units. Eur. J. Oper. Res. 2 (6), 429–444. https://doi.org/10.1016/0377-2217(78)90138-8.

Clark, M., Tilman, D., 2017. Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice. Environ. Res. Lett. 12 (6), 064016 https://doi.org/10.1088/1748-9326/aa6cd5.

Coelli, T.J., Rao, D.S.P., O'Donnell, C.J., Battese, G.E., 2005. An Introduction to Efficiency and Productivity Analysis, 2 ed. Springer.

Dalgaard, T., Hutchings, N.J., Porter, J.R., 2003. Agroecology, scaling and interdisciplinarity. Agric. Ecosyst. Environ. 100 (1), 39–51. https://doi.org/10.1016/S0167-8809(03)00152-X.

de Ponti, T., Rijk, B., van Ittersum, M.K., 2012. The crop yield gap between organic and conventional agriculture. Agric. Syst. 108, 1–9. https://doi.org/10.1016/j.agsy.2011.12.004.

Dijkman, T.J., Basset-Mens, C., Antón, A., Núñez, M., 2018. LCA of food and agriculture. In: Hauschild, M.Z., Rosenbaum, R.K., Olsen, S.I. (Eds.), Life Cycle Assessment: Theory and Practice. Springer International Publishing, pp. 723–754. https://doi.org/10.1007/978-3-319-56475-3_29.

Dux, D., Jan, P., Renner, S., Hoop, D., Schmid, D., Pfefferli, S., 2017. Die wirtschaftliche Entwicklung der schweizerischen Landwirtschaft 2016. Agroscope Transfer 196, 12.

El Benni, N., Finger, R., 2013. The effect of agricultural policy reforms on income inequality in Swiss agriculture - an analysis for valley, hill and mountain regions. J. Pol. Model. 35 (4), 638–651. https://doi.org/10.1016/j.jpolmod.2012.03.005.

Falcone, G., Stillitano, T., Montemurro, F., De Luca, A.I., Gulisano, G., Strano, A., 2019. Environmental and economic assessment of sustainability in mediterranean wheat production [Article]. Agron. Res. 17 (1), 60–76. https://doi.org/10.15159/AR.19.011.

Finnveden, G., Hauschild, M.Z., Ekvall, T., Guinée, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., Suh, S., 2009. Recent developments in life cycle assessment. J. Environ. Manag. 91 (1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018.

Flaten, O., Koesling, M., Hansen, S., Veidal, A., 2019. Links between profitability, nitrogen surplus, greenhouse gas emissions, and energy intensity on organic and conventional dairy farms. Agroecol. Sustain. Food Sys. 43 (9), 957–983. https://doi.org/10.1080/21683565.2018.1544960.

Gaillard, G., Nemecek, T., 2009. Swiss Agricultural Life Cycle Assessment (SALCA): an Integrated Environmental Assessment Concept for Agriculture. International Conference on «Integrated Assessment of Agriculture and Sustainable Development, Setting the Agenda for Science and Policy». Egmond aan Zee.

Gerbens-Leenes, P.W., Nonhebel, S., Krol, M.S., 2010. Food consumption patterns and economic growth. Increasing affluence and the use of natural resources. Appetite 55 (3), 597–608. https://doi.org/10.1016/j.appet.2010.09.013.

Gilgen, A., Blaser, S., Schneuwly, J., Liebisch, F., Merbold, L., 2023. The Swiss agri-environmental data network (SAEDN): Description and critical review of the dataset. Agric. Syst. 205, 103576. https://doi.org/10.1016/j.agsy.2022.103576.

Godfray, H.C.J., Beddington John, R., Crute Ian, R., Haddad, L., Lawrence, D., Muir James, F., Pretty, J., Robinson, S., Thomas Sandy, M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327 (5967), 812–818. https://doi.org/10.1126/science.1185383.

Grassauer, F., Herndl, M., Iten, L., Gaillard, G., 2022. Environmental assessment of Austrian organic dairy farms with closed regional production cycles in a less favorable production area [article]. Front. Sustain. Food Syst. 6 https://doi.org/10.3389/fsufs.2022.817671. Article 817671.

Hersener, J.-L., Baumgartner, D., Dux, D., Aeschbacher, U., Alig, M., Blaser, S., Gaillard, G., Glodé, M., Jan, P., Jenni, M., Mieleitner, J., Müller, G., Nemecek, T., Rötheli, E., Schmid, D., 2011. *Zentrale Auswertung von Ökobilanzen landwirtschaftlicher Betriebe (ZA-ÖB) : Schlussbericht.* Agroscope Reckenholzstrasse 191 8046 Zürich.

Huijbregts, M., 2002. Uncertainty and variability in environmental life-cycle assessment. Int. J. Life Cycle Assess. 7 (3) https://doi.org/10.1007/BF02994052, 173-173.

Huppes, G., Ishikawa, M., 2005. Eco-efficiency and its terminology. J. Ind. Ecol. 9 (4), 43–46. https://doi.org/10.1162/108819805775247891.

Isoni, A., 2015. The common agriculture policy (CAP): achievements and future prospects. In: Monteduro, M., Buongiorno, P., Di Benedetto, S., Isoni, A. (Eds.), Law and Agroecology: A Transdisciplinary Dialogue. Springer Berlin Heidelberg, pp. 185–206. https://doi.org/10.1007/978-3-662-46617-9_9.

Jan, P., Dux, D., Lips, M., Alig, M., Dumondel, M., 2012. On the link between economic and environmental performance of Swiss dairy farms of the alpine area [journal article]. Int. J. Life Cycle Assess. 17 (6), 706–719. https://doi.org/10.1007/s11367-012-0405-z.

Jan, P., Repar, N., Nemecek, T., Dux, D., 2019. Production intensity in dairy farming and its relationship with farm environmental performance: empirical evidence from the Swiss alpine area. Livest. Sci. 224, 10–19. https://doi.org/10.1016/j.livsci.2019.03.019.

Knickel, K., Renting, H., Van der Ploeg, J.D., 2004. Multifunctionality in European Agriculture. *Sustaining Agriculture and the Rural Economy: Governance, Policy and Multifunctionality.* Edward Elgar Publishing Inc, pp. 81–103.

Kuempel, C.D., Frazier, M., Nash, K.L., Jacobsen, N.S., Williams, D.R., Blanchard, J.L., Cottrell, R.S., McIntyre, P.B., Moran, D., Bouwman, L., Froehlich, H.E., Gephart, J.A., Metian, M., Többen, J., Halpern, B.S., 2020. Integrating life cycle and impact assessments to map food's cumulative environmental footprint. One Earth 3 (1), 65–78. https://doi.org/10.1016/j.oneear.2020.06.014.

Kuosmanen, T., Kortelainen, M., 2005. Measuring eco-efficiency of production with data envelopment analysis. J. Ind. Ecol. 9 (4), 59–72. https://doi.org/10.1162/108819805775247846.

Lankoski, J., 2000. Multifunctional Character of Agriculture. Maatalouden taloudellinen tutkimuslaitos.

Lee, K.S., Choe, Y.C., Park, S.H., 2015. Measuring the environmental effects of organic farming: a meta-analysis of structural variables in empirical research. J. Environ. Manag. 162, 263–274. https://doi.org/10.1016/j.jenvman.2015.07.021.

Lips, M., Hoop, D., Zorn, A., Gazzarin, C., 2018. Methodische Grundlagen der Kosten-/Leistungsrechnung auf der Betriebszweig-Ebene. Agroscope Sci. 69, 55.

Lips, M., Rordorf, T., Zorn, A., Renner, S., Schorr, A., Hoop, D., Spörri, M., Gazzarin, C., 2017. Wirtschaftliche Heterogenität auf Stufe Betrieb und Betriebszweig, vol. 53. Agroscope.

Marton, S.M.R.R., Lüscher, G., Corson, M.S., Kreuzer, M., Gaillard, G., 2016. Collaboration between mountain and lowland farms decreases environmental impacts of dairy production: the case of Swiss contract rearing [original research]. Front. Environ. Sci. 4 (74) https://doi.org/10.3389/fenvs.2016.00074.

Marton, S.M.R.R., Zimmermann, A., Kreuzer, M., Gaillard, G., 2016a. Comparing the environmental performance of mixed and specialised dairy farms: the role of the system level analysed. J. Clean. Prod. 124, 73–83. https://doi.org/10.1016/j.jclepro.2016.02.074.

Marton, S.M.R.R., Zimmermann, A., Kreuzer, M., Gaillard, G., 2016b. Environmental and socioeconomic benefits of a division of labour between lowland and mountain farms in milk production systems. Agric. Syst. 149, 1–10. https://doi.org/10.1016/j.agsy.2016.07.015.

Mondelaers, K., Aertsens, J., Van Huylenbroeck, G., 2009. A meta-analysis of the differences in environmental impacts between organic and conventional farming. Br. Food J. 111 (10), 1098–1119. https://doi.org/10.1108/00070700910992925.

Mouron, P., Nemecek, T., Scholz, R.W., Weber, O., 2006. Management influence on environmental impacts in an apple production system on Swiss fruit farms: combining life cycle assessment with statistical risk assessment. Agric. Ecosyst. Environ. 114 (2), 311–322. https://doi.org/10.1016/j.agee.2005.11.020.

Muller, A., Schader, C., El-Hage Scialabba, N., Brüggemann, J., Isensee, A., Erb, K.H., Smith, P., Klocke, P., Leiber, F., Stolze, M., Niggli, U., 2017. Strategies for feeding the world more sustainably with organic agriculture [Article]. Nat. Commun. 8 (1) https://doi.org/10.1038/s41467-017-01410-w. Article 1290.

Nemecek, T., Dubois, D., Huguenin-Elie, O., Gaillard, G., 2011. Life cycle assessment of Swiss farming systems: I. Integrated and organic farming. Agric. Syst. 104 (3), 217–232. https://doi.org/10.1016/j.agsy.2010.10.002.

Nemecek, T., Huguenin-Elie, O., Dubois, D., Gaillard, G., 2005. ÖKOBILANZIERUNG VON ANBAUSYSTEMEN IM SCHWEIZERISCHEN ACKER- UND FUTTERBAU. Agroscope FAL.

Nemecek, T., Thoma, G., 2020. Allocation between milk and meat in dairy LCA: critical discussion of the IDF's standard methodology. In: 12th International Conference on Life Cycle Assessment of Food LCAFood2020, Berlin Virtually, Germany.

Notarnicola, B., Sala, S., Anton, A., McLaren, S.J., Saouter, E., Sonesson, U., 2017. The role of life cycle assessment in supporting sustainable agri-food systems: a review of the challenges. J. Clean. Prod. 140, 399–409. https://doi.org/10.1016/j.jclepro.2016.06.071.

Pashaei Kamali, F., van der Linden, A., Meuwissen, M.P.M., Malafaia, G.C., Oude Lansink, A.G.J.M., de Boer, I.J.M., 2016. Environmental and economic performance of beef farming systems with different feeding strategies in southern Brazil. Agric. Syst. 146, 70–79. https://doi.org/10.1016/j.agsy.2016.04.003.

Pedolin, D., Six, J., Nemecek, T., 2021. Assessing between and within product group variance of environmental efficiency of Swiss agriculture using life cycle assessment and data envelopment analysis. Agronomy 11 (9), 1862. https://www.mdpi.com/2073-4395/11/9/1862.

Pfauntsch, J., Fankhauser, H.R., 2008. The 2007 beet campaign - Switzerland [Article]. Zuckerindustrie 133 (4), 252–257. https://www.scopus.com/inward/record.uri?eid=2-s2.0-44449087468&partnerID=40&md5=48299b4312e5e181a7d3c935f468d01b.

Pfauntsch, J., Fankhauser, H.R., 2009. The 2008 beet campaign - Switzerland [Article]. Zuckerindustrie 134 (5), 349–354. https://www.scopus.com/inward/record.uri?eid=2-s2.0-67649920818&partnerID=40&md5=be3c52ae2cf364b08a20bc04e9756910.

Picazo-Tadeo, A.J., Gómez-Limón, J.A., Reig-Martínez, E., 2011. Assessing farming eco-efficiency: a data envelopment analysis approach. J. Environ. Manag. 92 (4), 1154–1164. https://doi.org/10.1016/j.jenvman.2010.11.025.

Pickel, P., Eigner, M., 2012. Life Cycle Assessment (LCA) and its Importance for the Agricultural Sector. Club of Bologna -XXIII, Members' Meeting Bologna, Italy.

Poore, J., Nemecek, T., 2018. Reducing food's environmental impacts through producers and consumers. Science 360 (6392), 987–992. https://doi.org/10.1126/science.aaq0216.

Rees, W.E., Eaglesham, A.R.J., Wildeman, A.G., Hardy, R.W.F., 2004. The Eco-Footprint of Agriculture: a Far-From-(thermodynamic)-Equilibrium Interpretation.

Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nature Plants 2 (2), 15221. https://doi.org/10.1038/nplants.2015.221.

Repar, N., 2018. *On the interplay of local versus global environmental and economic performance of Swiss alpine dairy farms* Kommunikations-, Informations- und Medienzentrum der Universität Hohenheim]. Hohenheim. http://opus.uni-hohenheim.de/volltexte/2018/1470.

Repar, N., Jan, P., Dux, D., Nemecek, T., Doluschitz, R., 2017. Implementing farm-level environmental sustainability in environmental performance indicators: a combined global-local approach. J. Clean. Prod. 140, 692–704. https://doi.org/10.1016/j.jclepro.2016.07.022.

Repar, N., Jan, P., Nemecek, T., Dux, D., Alig Ceesay, M., Doluschitz, R., 2016. Local versus global environmental performance of dairying and their link to economic performance: a case study of Swiss mountain farms. Sustainability 8 (12), 1294. https://www.mdpi.com/2071-1050/8/12/1294.

Repar, N., Jan, P., Nemecek, T., Dux, D., Doluschitz, R., 2018. Factors affecting global versus local environmental and economic performance of dairying: a case study of Swiss mountain farms. Sustainability 10 (8), 2940. https://www.mdpi.com/2071-1050/10/8/2940.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T. M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461 (7263), 472–475. https://doi.org/10.1038/461472a.

Sala, S., Anton, A., McLaren, S.J., Notarnicola, B., Saouter, E., Sonesson, U., 2017. In quest of reducing the environmental impacts of food production and consumption. J. Clean. Prod. 140, 387–398. https://doi.org/10.1016/j.jclepro.2016.09.054.

Špička, J., Vintr, T., Aulová, R., Macháčková, J., 2020. Trade-off between the economic and environmental sustainability in Czech dual farm structure. Agric. Econ. 66, 243–250. https://doi.org/10.17221/390/2019-AGRICECON.

Sturaro, E., Marchiori, E., Cocca, G., Penasa, M., Ramanzin, M., Bittante, G., 2013. Dairy systems in mountainous areas: farm animal biodiversity, milk production and destination, and land use. Livest. Sci. 158 (1), 157–168. https://doi.org/10.1016/j.livsci.2013.09.011.

Tukker, A., Cohen, M.J., Hubacek, K., Mont, O., 2010. The impacts of household consumption and options for change. J. Ind. Ecol. 14 (1), 13–30. https://doi.org/10.1111/j.1530-9290.2009.00208.x.

Tuomisto, H.L., Hodge, I.D., Riordan, P., Macdonald, D.W., 2012. Does organic farming reduce environmental impacts? – a meta-analysis of European research. J. Environ. Manag. 112, 309–320. https://doi.org/10.1016/j.jenvman.2012.08.018.

Vásquez-Ibarra, L., Rebolledo-Leiva, R., Angulo-Meza, L., González-Araya, M.C., Iriarte, A., 2020. The joint use of life cycle assessment and data envelopment analysis methodologies for eco-efficiency assessment: a critical review, taxonomy and future research. Sci. Total Environ. 738, 139538 https://doi.org/10.1016/j.scitotenv.2020.139538.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., Weidema, B., 2016. The ecoinvent database version 3 (part I): overview and methodology. Int. J. Life Cycle Assess. 21 (9), 1218–1230. https://doi.org/10.1007/s11367-016-1087-8.

Zorn, A., Esteves, M., Baur, I., Lips, M., 2018. Financial ratios as indicators of economic sustainability: a quantitative analysis for Swiss dairy farms. Sustainability 10 (8), 2942. https://www.mdpi.com/2071-1050/10/8/2942.