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Local versus Global Environmental Performance of Dairying and Their Link to Economic Performance: A Case Study of Swiss Mountain Farms

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Abstract: Complying with the carrying capacity of local and global ecosystems is a prerequisite to ensure environmental sustainability. Based on the example of Swiss mountain dairy farms, the goal of our research was firstly to investigate the relationship between farm global and local environmental performance. Secondly, we aimed to analyse the relationship between farm environmental and economic performance. The analysis relied on a sample of 56 Swiss alpine dairy farms. For each farm, the cradle-to-farm-gate life cycle assessment was calculated, and the quantified environmental impacts were decomposed into their on- and off-farm parts. We measured global environmental performance as the digestible energy produced by the farm per unit of global environmental impact generated from cradle-to-farm-gate. We assessed local environmental performance by dividing farm-usable agricultural area by on-farm environmental impact generation. Farm economic performance was measured by work income per family work unit, return on equity and output/input ratio. Spearman's correlation analysis revealed no significant relationship, trade-offs or synergies between global and local environmental performance indicators. Interestingly, trade-offs were observed far more frequently than synergies. Furthermore, we found synergies between global environmental and economic performance and mostly no significant relationship between local environmental and economic performance. The observed trade-offs between global and local environmental performance mean that, for several environmental issues, any improvement in global environmental performance will result in deterioration of local environmental performance and vice versa. This finding calls for systematic consideration of both dimensions when carrying out farm environmental performance assessments.

Keywords: sustainable agriculture; environmental sustainability; farm local environmental performance; farm global environmental performance; farm economic performance; life cycle assessment (LCA)

1. Introduction

Assessing and improving the sustainability of farming is an issue of growing importance, especially because farms, and, more precisely, the cradle-to-farm-gate link of the food chain, play a major role in the environmental impact generation of the entire chain (see e.g., [1–6]). Complying with the carrying capacity of both local and global ecosystems is a prerequisite to ensure sustainability [7]. Based on theoretical considerations and using the local versus global carrying capacity distinction as a starting point, Repar et al. [7] developed a framework for the assessment of environmental performance at farm level and thereby distinguished between the local and global environmental performance of a farm. Farm global environmental performance is defined as the environmental intensity of agricultural production in the cradle-to-farm-gate link of the food chain [7]. Environmental intensity is measured as the global (i.e., on- and off-farm) environmental impact generation per unit of biophysical farm output (e.g., digestible energy produced for humans by the farm) [7]. Local environmental performance is measured by the on-farm environmental impact generation per unit of farm usable agricultural area [7].

The distinction between global and local environmental performance proposed by Repar et al. [7] builds upon previous considerations made by several authors in this field [8–13]. All these previous contributions acknowledged the need to distinguish between two major types of environmental issues (local/regional versus global) depending on the scale of environmental relevance of the impacts associated with each issue. They also advocated the use of different types of environmental performance indicators depending on that scale. Both local and global environmental scales should be considered simultaneously to avoid problem shifting from one scale to another [7,12,13]. The approach proposed by Repar et al. [7] for farm environmental performance assessment further developed the existing considerations available in the literature on this topic. It also embedded them in a theoretical framework relying on the ecosystem's carrying capacity concept, which is a central pillar of the environmental sustainability concept.

Better understanding of the relationship between local and global environmental performance and between environmental and economic performance at farm level is highly relevant for improving the sustainability of farming. This is particularly important from the agricultural policy perspective. The promotion of sustainable agriculture requires implementation of appropriate policy instruments that enhance both local and global farm environmental performance. However, up to now, farm-level agricultural policy instruments have mostly focused on screening and improvement of what could be referred to as local environmental performance, e.g., nitrogen surplus per ha (see for instance [14–19]). The relationship between the local and global dimension of farm environmental performance has not been investigated in the literature and is therefore unknown. Consequently, we have no guarantee that these agri-environmental policy measures intended to improve the local environmental performance of farms also lead to an improved global environmental performance.

Simultaneously with the improvements in farm environmental performance, achieving agricultural sustainability also requires improvements in the economic performance of farming. The relationship between farm environmental and economic performance has already been investigated in a few studies relying on life cycle assessment [11,20–22]. With the exception of Jan et al. [11] who explicitly focused on farm global environmental performance as specified in Repar et al. [7], none of these contributions explicitly differentiated between the local and global environmental performance of a farm. However, given the type of environmental performance indicators used, these three contributions implicitly all addressed—to a more or less narrow extent—the global environmental performance of a farm as defined in Repar et al. [7] and its relationship to farm economic performance. Furthermore, also with the exception of Jan et al. [11], none of these studies used complete economic performance indicators that would consider all production factors. Despite differences regarding the economic performance indicators used and the types of farms investigated, these four investigations all found a positive relationship between global environmental and economic performance of farming. Thus they all highlighted the existence of a synergy between these two dimensions of sustainable performance of a farm. However, as is obvious from this overview, a study of the relationship between local environmental performance and economic performance of a farm is lacking.

The objective of our research, which assessed Swiss dairy farms in the alpine area building upon the work of Jan et al. [11], was twofold. Firstly, it aimed to investigate the relationship between the local and global environmental performance of these farms and to highlight possible synergies or trade-offs in the promotion of these two dimensions of farm environmental performance. The second objective was to comprehensively analyse the link between the environmental and economic performance of these farms. We divided this second objective into two sub-objectives. The first one consisted of broadening the analysis carried out by Jan et al. [11] on the relationship between farm global environmental and economic performance. The second sub-objective was to examine the link between the local environmental and economic performance of the sample farms.

2. Materials and Methods

2.1. Data Source and Sample

The present work relied on the same dataset as the one used in Jan et al. [11], which was originally collected as part of the Life Cycle Assessment Farm Accountancy Data Network (LCA-FADN) Project in the years 2006–2008 [23]. This dataset consisted of an unbalanced pooled sample of Swiss dairy farms in the hill or mountain region observed in either 2006, 2007 or 2008. In total, 56 observations were available over a three-year period. For each observation, very detailed environmental and economic data were available.

The environmental data encompassed life cycle assessments (LCAs) estimated using the Swiss Agricultural Life Cycle Assessment (SALCA) approach based on very detailed and comprehensive production inventories collected for each farm [24,25]. In terms of spatial system boundaries, the LCAs of the sample farms covered the cradle-to-farm-gate link of the dairy chain, thus implying that the post-farm links of the dairy chain were excluded from the assessment. The LCAs focused on the agricultural production system defined in a narrow sense, i.e., without any forestry or para-agricultural activities. In terms of temporal system boundaries, the LCAs covered—with the exception of arable crops, which are almost irrelevant for the hill and mountain region–one calendar year from 1 January until 31 December.

The economic data available encompassed detailed accountancy data and originated from the Swiss Farm Accountancy Data Network (FADN). Further details on the data source can be found in Jan et al. [11]. A very detailed and comprehensive description of the Swiss FADN's accounting approach is available in [26].

2.2. Reassessment of the Environmental Impacts by Using the Updated Swiss Agricultural Life Cycle Assessment (SALCA) Approach

Due to the continuous development and improvement of the emission and impact assessment models within SALCA, this approach has undergone several updates since the original data collection and life cycle impact assessments (LCIAs) that took place within the LCA-FADN Project [23]. For this reason, it was necessary to reassess the LCIAs of the sample farms with the newest SALCA version (SALCAfarm V3.5), which encompasses new and revised models for the estimation of (i) field and farmyard emissions and (ii) environmental impacts (see also [27]). This step included recoding of some variables as well as reformatting in order to meet the requirements of the most recent SALCA version. The ecoinvent life cycle inventory database also experienced changes as it was updated to version 2.2 [28].

2.2.1. Models for the Estimation of Direct Field and Farm Emissions

Direct field and farm emissions were estimated by SALCA emission models presented hereinafter. Flows of the nutrients N, P and K in animal husbandry were calculated by a nutrient balance model of a herd. It takes into account the specific feed intake and quality, the export of animal products, changes in live weight, and the emissions. The effects of feed intake, feed quality, and different levels of production on emissions and environmental impacts could thus be represented. For a detailed description see Bystricky et al. [29] (Chapter 2.5):

- The losses of ammonia (NH_3) from animal husbandry, manure management including manure application, and grazing were calculated according to the Agrammon model [30,31]. Emissions from mineral N fertilisers were estimated with emission factors according to EEA [32]. For some types of N fertilisers, different factors for pH above and below 7 applied. For a detailed description see Bystricky et al. [29] (Chapter 2.6);
- Emissions of nitrogen oxides (NO_x) were modelled according to EEA [32]. A detailed description is available in Bystricky et al. [29] (Chapter 2.7);
- Direct and induced emissions of nitrous oxide (N_2O) were considered according to the Intergovernmental Panel on Climate Change (IPCC) method, version 2006 [33]. Direct emissions came from the application of N fertiliser (factor 1% of N released as N_2O) and incorporation of crop residues (1% of the N released as N_2O). In addition to the direct emissions, induced emissions from ammonia and nitrate losses were considered. The respective factors were 1% for ammonia-N and 0.75% for nitrate-N. Emissions from manure storage were 0.5% of the N in slurry and liquid manure and 2% of the N in solid manure. A detailed description is provided in Bystricky et al. [29] (Chapter 2.8);
- Methane (CH_4) emissions from enteric fermentation and manure management were calculated by using emission factors from IPCC [33] and considering the amount and quality of the feed and the manure management system. Methane emissions from dairy cows were calculated by the model of Kirchgessner et al. [34]. Further details on the approach used to estimate these emissions can be found in Bystricky et al. [29] (Chapter 2.9);
- Direct on-farm (fossil) carbon dioxide (CO_2) emissions emerged as a consequence of the application of urea, lime and dolomite. For their calculation, the emission factors of IPCC [33] were used. CO_2 emissions from fuel combustion like diesel or fuel oil were included in the respective life cycle inventories;
- Phosphorus (P) emissions were quantified using the approach developed by Prasuhn [35]. Three paths of P emissions to water were thereby included, namely run-off as phosphate and erosion as P to rivers, as well as leaching to ground water as phosphate. The land use category, the type of fertiliser, the quantity of P spread, and the characteristics and duration of soil cover (for erosion) were considered in the assessment;
- Nitrate (NO_3^-) leaching was estimated on a monthly basis by accounting for N mineralisation in the soil and N uptake by the vegetation, specific to each crop by the updated SALCA nitrate model [36]. If mineralisation exceeds uptake, nitrate leaching can potentially occur. In addition, the risk of nitrate leaching from fertiliser application during unfavourable periods was included in the assessment, considering the crop, month of application and the potential rooting depth;
- Heavy metal (Cd, Cr, Cu, Hg, Ni, Pb, Zn) emissions were assessed by an input–output balance [37].

2.2.2. Impact Assessment Models

Within the SALCA framework, impact categories and impact assessment methods relevant to agricultural systems were selected. The selection was based on mid-point categories, mainly from the methods EDIP2003 [38] and CML01 [39]. Regionalised characterisation factors for Switzerland were used for the impact categories: ozone formation, acidification and eutrophication. An overview of the environmental impact categories considered and the method used for their assessment is provided hereinafter:

- Demand for non-renewable energy resources (in MJ eq.) (oil, coal and lignite, natural gas and uranium), using the upper heating or gross calorific value for fossil fuels according to Frischknecht et al. [40];

- Global warming potential over 100 years (in kg CO_2 eq.), according to IPCC [41];
- Ozone formation potential (in m^2.ppm.h) (so-called "summer smog"), according to the EDIP2003 method [42];
- Ozone depletion (in kg CFC11 eq.) as the impact of stratospheric ozone-depleting emissions, according to the EDIP2003 method [42];
- Terrestrial eutrophication potential (in m^2) as the impact of the N losses to terrestrial ecosystems expressing the area of terrestrial ecosystem potentially damaged, according to the EDIP2003 method [42];
- N aquatic eutrophication potential (in N equivalents) as the impact of losses of N to the aquatic ecosystems according to the EDIP2003 method [42];
- P aquatic eutrophication potential (in P equivalents) as the impact of losses of P to the aquatic ecosystems according to the EDIP2003 method [42];
- Acidification potential (in m^2) as the impact of acidifying substances released into ecosystems expressing the area of ecosystem potentially damaged, according to the EDIP2003 method [42];
- Terrestrial and aquatic ecotoxicity potentials (in kg 1,4-DB eq.) estimated according to the CML01 method [39];
- Human toxicity potential (in kg 1,4-DB eq.) as the impact of toxic pollutants on human health, quantified according to the CML01 method [39];
- Land competition (in m^2a) was assessed using the CML01 method [39]. It was defined as the unweighted sum of all land areas occupied multiplied by their respective occupation time;
- Deforestation (in m^2) was assessed by the balance of the areas transformed from and into forest and shrubland areas. It corresponds with the impact category natural land transformation in the ReCiPe method [43], but in addition to ReCiPe, shrubland was also considered;
- The use of phosphorus and potassium resources (in kg) was assessed at the inventory level, without applying a characterisation factor;
- Water deprivation was assessed as the sum of blue water withdrawal (ground and surface water in m^3) corrected by the water stress index for Switzerland according to Pfister et al. [44]. The water stress index is derived from the ratio of annual water withdrawals and water availability and it reflects the "portion of consumptive water use that deprives other users of freshwater" [44] (p. 4099).

2.3. Off-farm and On-farm Environmental Impacts' Decomposition

To assess farm local environmental performance as defined by Repar et al. [7], we broke down the estimated cradle-to-farm-gate environmental impacts into their on- and off-farm (upstream stages) parts. As explained by Repar et al. [7], only the on-farm parts are relevant for the measurement of farm local environmental performance, whereas both the on-farm and off-farm (upstream) stages are included in the measurement of farm global environmental performance. Therefore, for the calculation of local environmental performance, the spatial system boundary was reduced to the on-farm level. The on-farm environmental impacts resulted from emissions generated at the local on-farm level by the activity of the investigated farm. The emissions that were released elsewhere in the farm's supply chain were excluded from the calculation of local environmental performance. However, these emissions and their associated impacts were relevant for the measurement of global environmental performance. Therefore, we decomposed the cradle-to-farm-gate environmental impacts into on-farm and off-farm impacts. The decomposition was conducted based on a detailed analysis of the processes/sub-processes underlying the different input groups and by allocating these processes/sub-processes on the basis of their location in the supply chain. We estimated the off- and on-farm environmental impacts at input group and total farm levels by using the SimaPro software version 7.3.3 [45]. Descriptive statistics related to the on-/off-farm cradle-to-farm-gate environmental impact decomposition and, more precisely, to the on-farm environmental impact share for the impact categories considered at both the global and the local level are provided in the Appendix A.

2.4. Farm Global Environmental Performance Indicators

Repar et al. [7] define farm global environmental performance as the environmental intensity of food production in the cradle-to-farm-gate link of the food chain, environmental intensity being the inverse of eco-efficiency [46]. For an easier and more intuitive interpretation of the performance indicators, we decided in this investigation to build the global environmental performance indicator reversely as in Repar et al. [7]. More particularly, this was done to ensure that a high or low value of both economic and environmental indicators can be interpreted as "good" or "bad", respectively. Global environmental performance was thus defined as the eco-efficiency of food production in the cradle-to-farm-gate link of the food chain. We defined eco-efficiency as the MJ digestible energy for humans produced by the farm divided by the global (i.e., on- and off-farm) environmental impacts generated in the cradle-to-farm-gate link of the food chain. We built a global environmental performance indicator for each of the 16 environmental impact categories considered in the LCA, namely demand for non-renewable energy, ozone depletion, P-resource demand, K-resource demand, deforestation, global warming potential, land competition, human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, ozone formation, acidification, eutrophication terrestrial, eutrophication aquatic N, eutrophication aquatic P and water deprivation.

2.5. Farm Local Environmental Performance Indicators

Local environmental performance is defined by Repar et al. [7] as the on-farm environmental impact generation per unit of usable agricultural area, thus considering only the on-farm impact generation as already mentioned in Section 2.3. Analogous to the global environmental performance and for the same reasons, here too we built the indicator reversely. Whereas global environmental performance was assessed for all environmental impact categories considered, local environmental performance was measured only for a subset of the impact categories [7]. These categories were the ones for which farm environmental impacts are primarily influential on the local ecosystem scale [7].

We built local environmental performance indicators for the following nine impact categories: human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, ozone formation, acidification, eutrophication terrestrial, eutrophication aquatic N, eutrophication aquatic P and water deprivation.

2.6. Farm Economic Performance Indicators

Economic performance was defined here from a profitability perspective as the ability of a farm to maximise returns while minimising economic input usage. We thus adopted a classical farm management view for the economic performance assessment. We did not implement the environmental life cycle costing (LCC) approach, which accounts for cost shifting, i.e., economic externalities (for more details on this approach, refer to Moreau and Weidema [47]). In the farm management literature, several indicators have been proposed or used to measure the economic performance of a farm. Some of these indicators consider only the external factor costs (for instance gross value added per unit of labour, see also Thomassen et al. [21]). Others take all production factors, including the own factors equity and unpaid family labour, into account (for instance work income per family work unit, see also Jan et al. [11]). To get a complete economic performance picture of a farm and especially to account for the substitution possibilities existing between the different inputs, we decided to use performance indicators considering all production factors. The three following indicators were selected: (i) work income per family work unit (full-time equivalent); (ii) return on equity and (iii) output/input ratio. These three indicators differ from each other regarding the approach followed to remunerate the own production factors, namely equity and unpaid family labour (see Table 1). As none of these three indicators can be considered as better suited than the others, we decided to consider all of them.

This enabled us to test the robustness of our results to the definition of the economic performance indicator and, more precisely, to the approach used to remunerate these production factors.

Table 1. Definitions of economic performance indicators selected and their differences in terms of the approach followed to remunerate the own production factors (equity and unpaid family labour).

Indicator	Indicator Definition	Approach Followed to Remunerate Equity	Approach Followed to Remunerate Unpaid Family Labour Force
Work income per family work unit (full-time equivalent) (in Swiss francs)	Income available per full-time equivalent family work unit after deduction of all external factor costs and after remuneration of equity capital at its opportunity cost	Opportunity cost: interest rate on a 10-year Swiss government bond	Residual value: income left for the remuneration of the unpaid family labour force after deduction of the external factor costs and after remuneration of equity to its opportunity cost
Return on equity (in %)	The income that remains available for the remuneration of equity capital as a percentage of equity capital, after deduction of all external factor costs and after remuneration of the unpaid family labour force at its opportunity cost	Residual value: income left for the remuneration of equity after deduction of the external factor costs and after remuneration of the unpaid family labour force to its opportunity cost	Opportunity cost: median salary of the employees of the secondary and tertiary sector of the Swiss economy
Output/input ratio (in %)	The ratio between the farm outputs (gross profit) and all farm inputs, i.e., external factor costs as well as the costs for the own production factors (equity and unpaid family labour) remunerated at their respective opportunity costs	Opportunity cost: interest rate on a 10-year Swiss government bond	Opportunity cost: median salary of the employees of the secondary and tertiary sector of the Swiss economy

2.7. Statistical Approach for the Analysis of the Relationship between Farm Global Environmental Performance, Farm Local Environmental Performance and Farm Economic Performance

We analysed the relationships between farm global environmental performance, farm local environmental performance and farm economic performance by means of Spearman's rank correlation analysis (Spearman's rho). The non-parametric Spearman's correlation was preferred to Pearson's correlation because we are primarily interested in the monotonicity of the relationships between the observed variables, not in their linearity [11]. Spearman's correlation is furthermore more appropriate for a small sample size [48] as is the case in the present work.

We analysed the correlations between:

(i) Farm global environmental performance indicators and farm local environmental performance indicators;
(ii) Farm global environmental performance indicators and farm economic performance indicators;
(iii) Farm local environmental performance indicators and farm economic performance indicators.

A negative correlation between two performance indicators implies the existence of a trade-off between these two indicators. This means that an improvement of the performance measured by the first indicator will be accompanied by a deterioration of the performance assessed by the second indicator and vice versa. This negative relationship implies that the two objectives underlying these indicators are conflictual. A positive correlation conveys a synergy between the two indicators, meaning that these two indicators or, more precisely, their related performances can be improved at the same time. This relationship implies that the two objectives underlying these indicators are synergetic. A non-significant correlation between two indicators reveals the absence of a significant relationship between them, implying that the two environmental objectives underlying them are neither conflictual nor synergetic.

3. Results

3.1. Analysis of the Link between Farm Local and Global Environmental Performance

The results of Spearman's rank correlation analysis between the global and local environmental performance indicators show a complex picture (Tables 2 and 3). Overall, depending on the environmental impact categories considered, we found no significant relationships, trade-offs and synergies between farm local and global environmental performance indicators. Out of 144 correlations investigated, 90 (63%) were not significant, 39 (27%) were negative and significant, and 15 (10%) were positive and significant.

As is obvious from these figures, it can be noted that when the relationship between local and global environmental performance indicators was statistically significant, negative correlations (trade-offs) predominated. For example, farm local environmental performances regarding ozone formation and aquatic eutrophication N were both negatively correlated with several global environmental performance indicators. Similarly, local environmental performances regarding aquatic ecotoxicity and terrestrial ecotoxicity showed negative correlations with most global environmental performance indicators. Furthermore, global environmental performances regarding demand for non-renewable energy resources, ozone depletion, global warming potential, land competition, human toxicity, ozone formation, acidification, terrestrial eutrophication, aquatic eutrophication P and water deprivation were negatively correlated with several local environmental performance indicators. The strength of the negative correlation varied from low (−0.23) to moderate (−0.50). For the interpretation of the strength of the correlation, we refer here onwards to Evans [49].

Despite the overall prevalence of negative over positive correlations, for some impact categories the relationship between the local and global environmental performance was predominantly positive. This was the case for the local environmental performances regarding human toxicity and aquatic eutrophication P, which were correlated positively with several global environmental performance indicators. For the aquatic and terrestrial ecotoxicity, we found a positive correlation between their local and global environmental performances. We also detected a positive correlation between the local environmental performance regarding aquatic ecotoxicity and the global environmental performance with respect to terrestrial ecotoxicity and vice versa. The local environmental performance regarding terrestrial ecotoxicity was furthermore positively correlated with the global environmental performance regarding K-resource demand. The strength of the positive correlation varied from low (+0.23) to strong (+0.60).

Table 2. Spearman's rank correlation analysis between farm global and local environmental performance indicators: Part 1.

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)							
		Demand for Non-Renewable Energy	Ozone Depletion	P-Resource Demand	K-Resource Demand	Deforestation	Global Warming Potential	Land Competition	Human Toxicity
Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)	Human toxicity	+0.25 *	n.s.	+0.36 **	+0.39 **	+0.24 *	n.s.	n.s.	+0.60 ***
	Aquatic Ecotoxicity	−0.39 **	−0.31 *	n.s.	n.s.	n.s.	−0.45 ***	−0.40 **	−0.28 *
	Terrestrial Ecotoxicity	−0.26 *	n.s.	n.s.	+0.27 *	n.s.	−0.39 **	−0.42 **	n.s.
	Ozone Formation	−0.26 *	−0.25 *	n.s.	n.s.	n.s.	−0.25 *	−0.40 **	−0.28 *
	Acidification	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	−0.25 *	n.s.
	Eutrophication Terrestrial	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	−0.25 *	n.s.
	Eutrophication Aquatic N	−0.39 **	−0.31 *	n.s.	n.s.	n.s.	−0.39 **	−0.36 **	−0.30 *
	Eutrophication Aquatic P	n.s.	n.s.	n.s.	n.s.	+0.23 *	n.s.	n.s.	n.s.
	Water Deprivation	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.

Notes: significant Spearman's rhos are given in the table; statistical significance level: * $p < 0.1$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; Shading in red indicates significant negative correlation; Shading in green indicates significant positive correlation.

Table 3. Spearman's rank correlation analysis between farm global and local environmental performance indicators: Part 2.

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)							
		Aquatic Ecotoxicity	Terrestrial Ecotoxicity	Ozone Formation	Acidification	Eutrophication Terrestrial	Eutrophication Aquatic N	Eutrophication Aquatic P	Water Deprivation
Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)	Human toxicity	n.s.	+0.30 *	n.s.	n.s.	n.s.	n.s.	n.s.	+0.27 *
	Aquatic Ecotoxicity	+0.34 *	+0.32 *	−0.49 ***	−0.46 ***	−0.46 ***	n.s.	n.s.	−0.50 ***
	Terrestrial Ecotoxicity	+0.30 *	+0.47 ***	−0.42 **	−0.44 ***	−0.44 ***	n.s.	−0.31 *	−0.37 **
	Ozone Formation	n.s.	n.s.	−0.26 *	n.s.	n.s.	−0.23 *	−0.30 *	−0.24 *
	Acidification	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Eutrophication Terrestrial	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Eutrophication Aquatic N	n.s.	n.s.	−0.38 **	−0.40 **	−0.39 **	n.s.	−0.23 *	−0.39 **
	Eutrophication Aquatic P	n.s.	n.s.	n.s.	n.s.	+0.24 *	n.s.	+0.49 ***	n.s.
	Water Deprivation	n.s.	n.s.	−0.24 *	n.s.	n.s.	n.s.	n.s.	n.s.

Notes: Significant Spearman's rhos are given in the table; statistical significance level: * $p < 0.1$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; Shading in red indicates significant negative correlation; Shading in green indicates significant positive correlation.

3.2. Analysis of the Link between Farm Environmental and Farm Economic Performance

3.2.1. Relationship between Farm Global Environmental Performance and Farm Economic Performance

The link between global environmental performance and economic performance was previously investigated in Jan et al. [11]. In the present work, we re-conducted the analysis with the updated LCA data (see Section 2.2) and—to test the robustness of the results—broadened it by considering two additional economic performance indicators. The results in Tables 4 and 5 show that global environmental performance and economic performance were positively correlated for all environmental impact categories considered. This was true regardless of which of the three economic performance indicators was observed. The only exception was the global environmental performance regarding terrestrial ecotoxicity, which was positively correlated only with return on equity. The strength of the positive correlation varied from weak (+0.24) to moderate (+0.54).

3.2.2. Relationship between Farm Local Environmental Performance and Farm Economic Performance

The relationship between economic performance and local environmental performance was for most environmental impact categories not statistically significant (Table 6). However, a few exceptions with a weak positive correlation between farm economic and local environmental performance existed. Higher local environmental performance regarding eutrophication aquatic P and human toxicity tends to be associated with a higher work income per family work unit and a higher output/input ratio. On the other hand, a negative correlation existed between local environmental performance regarding terrestrial and aquatic ecotoxicity, and the output/input ratio.

Table 4. Spearman's rank correlation analysis between farm global environmental performance indicators and farm economic performance indicators: Part 1.

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)							
		Demand for Non-Renewable Energy	Ozone Depletion	P-Resource Demand	K-Resource Demand	Deforestation	Global Warming Potential	Land Competition	Human Toxicity
Farm Economic Performance	Work Income Per Family Work Unit	+0.24 *	+0.26 *	+0.31 *	+0.35 **	+0.40 **	+0.33 *	+0.37 **	+0.40 **
	Return on Equity	+0.24 *	+0.32 *	+0.38 **	+0.41 **	+0.54 ***	+0.30 *	+0.31 *	+0.25 *
	Output/Input Ratio	+ 0.28 *	+0.30 *	+0.34 *	+0.37 **	+0.42 **	+0.39 **	+0.38 **	+0.43 **

Notes: Significant Spearman's rhos are given in the table; statistical significance level: * $p < 0.1$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; Shading in green indicates significant positive correlation.

Table 5. Spearman's rank correlation analysis between farm global environmental performance indicators and farm economic performance indicators: Part 2.

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)							
		Aquatic Ecotoxicity	Terrestrial Ecotoxicity	Ozone Formation	Acidification	Eutrophication Terrestrial	Eutrophication Aquatic N	Eutrophication Aquatic P	Water Deprivation
Farm Economic Performance	Work Income Per Family Work Unit	+0.30 *	n.s.	+0.37 **	+0.39 **	+0.41 **	+0.29 *	+0.45 ***	+0.49 ***
	Return on Equity	+0.43 ***	+0.27 *	+0.31 *	+0.28 *	+0.28 *	+0.41 **	+0.30 *	+0.34 **
	Output/Input Ratio	+0.30 *	n.s.	+ 0.41 **	+0.47 ***	+0.48 ***	+ 0.26 *	+0.44 ***	+0.54 ***

Notes: Significant Spearman's rhos are given in the table; statistical significance level: * $p < 0.1$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; Shading in green indicates significant positive correlation.

Table 6. Spearman's rank correlation analysis between farm local environmental and farm economic performance indicators.

		Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)								
		Human Toxicity	Aquatic Ecotoxicity	Terrestrial Ecotoxicity	Ozone Formation	Acidification	Eutrophication Terrestrial	Eutrophication Aquatic N	Eutrophication Aquatic P	Water Deprivation
Farm Economic Performance	Work Income Per Family Work Unit	+0.26 *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+0.28 *	n.s.
	Return on Equity	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
	Output/Input Ratio	+0.24 *	−0.23 *	−0.26 *	n.s.	n.s.	n.s.	n.s.	+0.23 *	n.s.

Notes: Significant Spearman's rhos are given in the table; statistical significance level: * $p < 0.1$; ** $p < 0.01$; *** $p < 0.001$; n.s. = not significant; Shading in red indicates significant negative correlation; Shading in green indicates significant positive correlation.

4. Discussion

This section discusses the main findings of our investigation, firstly summarizing them and then relating them to other studies in the field. We finish this section by addressing the limitations of our work.

4.1. Main Findings

In the present work, we applied—within a case study for Swiss alpine dairy farms—the approach proposed by Repar et al. [7] to assess farm environmental performance with a differentiation between farm local and global environmental performance. To assess the local environmental performance of a farm, we decomposed the cradle-to-farm-gate impacts assessed by means of LCAs into their on- and off-farm parts. We considered a very broad set of environmental impact categories to provide the fullest possible environmental performance picture.

The analysis of the link between farm local and global environmental performance revealed complex relationships. Depending on the environmental impact categories considered, no significant relationships, trade-offs and synergies were observed. However, trade-offs were more frequent than synergies. Furthermore, we found synergies between farm global environmental performance and farm economic performance, regardless of the environmental impact category observed or the indicator of economic performance chosen. For most impact categories considered, the analysis showed no significant relationship between local environmental performance and economic performance, with very few exceptions, where a weak synergy or trade-off existed.

4.2. Discussion of the Main Findings

This work represents the first implementation of the framework proposed by Repar et al. [7] to assess environmental performance at farm level. To the best of our knowledge, this is therefore the first study that distinguishes between the local and global dimensions of the environmental performance of a farm and comprehensively analyses their mutual link as well as their relationship with farm economic performance. Very few studies analysing the relationship between economic and environmental performance at farm level can be found in the literature (see, for instance, [11,21]). However, these studies focused solely on what Repar et al. [7] called “farm global environmental performance” and analysed its link to farm economic performance.

Our finding of a positive relationship between farm global environmental and economic performance is similar to that of Jan et al. [11], who also found a synergy between these two dimensions of the sustainable performance of a farm. Jan et al. [11] used the same original dataset but relied (i) on an older SALCA version for the environmental impact assessment and (ii) on only one economic performance indicator, namely work income per family work unit. As discussed in Jan et al. [11], three other contributions [20,21,50] also reported a positive relationship between global environmental performance and economic performance.

No study explicitly analysed the link between farm local environmental and economic performance, which likely has two major reasons. First, the distinction between local and global environmental performance has only recently been introduced [7]. Second, almost all empirical LCA applications have up to now—due to the life cycle perspective inherent to LCA—exclusively dealt with global environmental impacts as defined in Section 2.4. Nevertheless, some results regarding this link can be found in Thomassen et al. [21] for Dutch dairy farms. However, this link was not the focus of their investigation, and the two indicators we can identify as “local environmental performance indicators” were not even referred to as such in the publication. Moreover, Thomassen et al. [21] used partial economic performance indicators that did not consider all production factors and therefore did not reflect the overall economic performance of a farm. Despite this methodological difference to our study, it is interesting that Thomassen et al. [21] found no correlation between the farm local environmental performance indicators (on-farm eutrophication per ha, on-farm acidification per ha) and the economic performance indicators (gross value added per kg milk, gross value added per unit of labour). Their finding is therefore similar to ours that also reveals mostly no significant correlation between the local environmental performance indicators and three different (complete) indicators of economic performance. Our findings regarding the relationship between farm global and local environmental performance cannot be compared with those of similar studies because such studies do not exist for the reasons mentioned at the beginning of this section.

4.3. Implications of Our Findings for the Sustainable Intensification Debate

There exists an extensive body of scientific literature dedicated to the comparison of environmental impacts of intensive and extensive agricultural systems (see e.g., [51–53]). In the last decade, the sustainable intensification concept came to the forefront of the debate on the future of agriculture. This debate is especially focused on the degree of agricultural intensity and the future challenge of feeding a growing and increasingly wealthy human population. The sustainable intensification concept actually "originates from sub-Saharan agriculture in the 1990s and originally focussed on building adaptable farming systems that support the livelihood of the rural poor" [54]. In the last decade, its meaning has shifted towards the "enhancement of agricultural productivity while reducing environmental impacts" or, in more operationalised terms, "the production of more food with less resources" (adapted from Rockström et al. [55]). The sustainable intensification discussion has thus mostly targeted improvements in agricultural sustainability at the global level (see e.g., [55–58]), or what we call the global environmental performance (or eco-efficiency) of farming.

Our work does not primarily aim at comparing the environmental performance of dairy farming systems with different production intensities. However, it indirectly has substantial implications for the debate on the sustainable intensification of farming. The local environmental performance defined and assessed in our work is strongly connected to the farming intensity because it measures the extent of the local environmental impact generation per hectare usable agricultural area. It is thus an indicator of the "local environmental burdens" resulting from the farming intensity. Our findings of the existence of negative correlations between local and global environmental performance imply, at least for the Swiss dairy farms of the mountain area, that an improvement of the global environmental performance will likely lead to a deterioration of the local environmental performance. This means that the sustainable intensification debate, due to its unilateral focus on global environmental performance, will most likely not lead to a holistic environmental sustainability improvement in agriculture but to food chains that are globally more eco-efficient but locally worse off in environmental terms.

We therefore advocate the following redefinition of sustainable intensification: "Sustainable intensification aims at improving the biophysical eco-efficiency of food production over the whole food chain (global environmental performance) while at the same time ensuring that the environmental impacts generated at the local level do not exceed the carrying capacities of the local ecosystems (local environmental performance)". Due to the existence of the aforementioned trade-offs between the global and local dimension of farm environmental performance, the challenge for sustainable intensification is to find technologies that enable simultaneous improvement in both dimensions.

4.4. Limitations and Future Research Need

Although the framework established by Repar et al. [7] and used here can be implemented to various farms, irrespective of their type or location, it is important to emphasise that the findings of the present empirical study apply only to Swiss dairy farming in the alpine area. Furthermore, as pointed out by Jan et al. [11], because the sample used for this study was quite small and not selected at random, there are limitations regarding its representativeness [11]. These limitations should be considered when interpreting the results of this work.

As discussed in Repar et al. [7], some issues of conceptual nature also arise when using the framework for farm environmental performance assessment implemented in the present paper. Firstly, because we focused on the cradle-to-farm-gate analysis, the subsequent parts of the chain, which are important for painting the wholesome sustainability picture, were ignored. Although focusing on the production perspective provides an important view, there are also other strategies to improve the sustainability of the food chain that have to be considered on the consumption side. The examples of such strategies are the reduction of food waste (see, for example, Gentil et al. [59]) or the change in diets (see, for example, Tukker et al. [60]).

Secondly, as mentioned in the introduction, in our framework, the local versus global carrying capacity distinction was used only as a starting point for the differentiation between local and global environmental performance. However, the indicators proposed did not directly integrate the carrying capacity constraints and are therefore of a relative nature [7]. Such indicators enable a relative improvement in terms of sustainability but are still no guarantee for the achievement of an absolute sustainable state [7]. As identified by Sala et al. [61], further research and development of the methods in the LCA field are needed in order for the indicators to better reflect the carrying capacity and planetary boundaries. First LCA-based approaches that integrate carrying capacities into environmental performance indicators and enable analyses to move from relative to absolute environmental sustainability were recently developed (e.g., [62–64]). Also, Repar et al. [7] developed conceptual considerations on how to integrate carrying capacities into the indicators of the local and global environmental performance they proposed. The practical implementation of these carrying capacities should be the subject of future research work.

Finally, our work did not account for the third dimension of sustainability, namely the social one. Future work should therefore assess the link between (i) local environmental performance and social performance; (ii) global environmental performance and social performance; and (iii) economic performance and social performance, in order to provide a complete sustainability overview. Such assessment requires the implementation of the social sustainability concept into farm-level indicators of social performance. This implementation is probably as challenging as the development of theoretically sound farm-level environmental performance indicators.

Analysing the relationship between different performance dimensions is a first important contribution to a deeper understanding of farm sustainability. However, what is ultimately necessary for practical improvements is to understand the mechanisms behind these relationships. Furthermore, farm management strategies and production technologies that enable simultaneous improvements in global and local environmental and economic performance of farming need to be identified. This calls for very detailed investigations of the factors affecting farm environmental and economic performance.

5. Conclusions

Our analysis provides evidence that the improvement of the environmental sustainability of dairy farming in the mountain region of Switzerland is a highly complex endeavour. Both synergies and trade-offs exist between the local and global environmental performance of a farm, depending on the environmental issue considered. Interestingly, the often raised and feared possible trade-off between environmental and economic performance could not be confirmed empirically, neither for the local nor for the global dimension of environmental performance. Contrariwise, we found synergies between farm global environmental and economic performance. This implies that the improvement of the eco-efficiency of food production in the cradle-to-farm-gate link of the food chain is very likely to lead to an improvement of the economic performance and vice versa.

The complex relationships between farm local and global environmental performance imply that no one-size-fits-all solution may exist for the improvement of farm environmental sustainability. The results suggest that exclusively focusing on the global environmental performance, i.e., on the eco-efficiency of food production in the cradle-to-farm-gate link of the food chain could negatively affect the local environmental performance. To avoid that any improvement in one dimension of environmental performance happens at the expense of the other, both local and global performance dimensions have to be considered. Life cycle assessment (LCA) practitioners should therefore be aware of the potential prejudicial side effects of a unilateral focus on global environmental performance. A holistic farm environmental performance assessment encompassing both local and global environmental performance dimensions calls for a standard decomposition into on- and off-farm impacts in LCIA tools.

Furthermore, our findings have implications for policy makers. Existing farm-level agri-environmental policy measures and instruments in Switzerland, as in many other countries, tend to focus exclusively on the local dimension of farm environmental performance. Due to the negative correlations that were found between local and global environmental performance, these instruments may lead to a deterioration of farm global environmental performance. Hence, a clear definition of the objectives of environmental policy measures, the consideration of both local and global aspects of environmental performance and the use of LCAs in policy making are indispensable. These actions are required if we wish to prevent problem shifting between the local and global ecosystems and reach real improvements in terms of environmental sustainability. The necessity of considering the two dimensions of environmental performance also applies for the development and assessment of new agricultural technologies intended to improve the environmental sustainability of farming.

Finally, from a more general perspective, our findings have potentially far-reaching implications, especially if these findings should be confirmed for other types of farms and countries. As mentioned previously, when dealing with the environmental sustainability of farming, scientists and policy makers have until now been adopting a one-sided focus on either global environmental performance (for instance, LCA practitioners) or on local environmental performance (for instance, most farm-level agri-environmental policy makers). Through this one-sided focus, they implicitly assumed that local and global environmental performance go hand in hand and do not need to be considered separately. Our finding of the existence of trade-offs between farm local and global environmental performance refutes—at least for Swiss dairy farming—this widespread assumption. In that sense, our work indirectly questions whether these one-sided perspectives, which have been used widely for years, have always been able to reach real improvements in terms of environmental sustainability.

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Appendix A

For the impact categories considered at both the global and the local level, the average, median and coefficient of variation of the on-farm share of the cradle-to-farm-gate environmental impact are shown in Figure A1. The average share of the impacts generated on- versus off-farm varied substantially according to the impact category considered.

Within the impact categories for which farm environmental performance was assessed not only from a global but also from a local perspective, we distinguished two groups. The first group consisted of the impact categories for which on-farm impact share was below 50%. It represented all toxicity impact categories (human toxicity, terrestrial and aquatic ecotoxicity) and water deprivation. The second group represented the impact categories for which on-farm impact share was above 50%. It contained the impact categories N and P aquatic eutrophication, ozone formation, acidification and terrestrial eutrophication.

The coefficient of variation of the on-farm impact share showed that the proportion of on-farm impacts varied between farms. Highest relative heterogeneity existed for the toxicity impact categories and for water deprivation (predominately off-farm impact categories), whereas the predominately on-farm impact categories were characterized by smaller variations of on-farm impact share between the investigated farms.

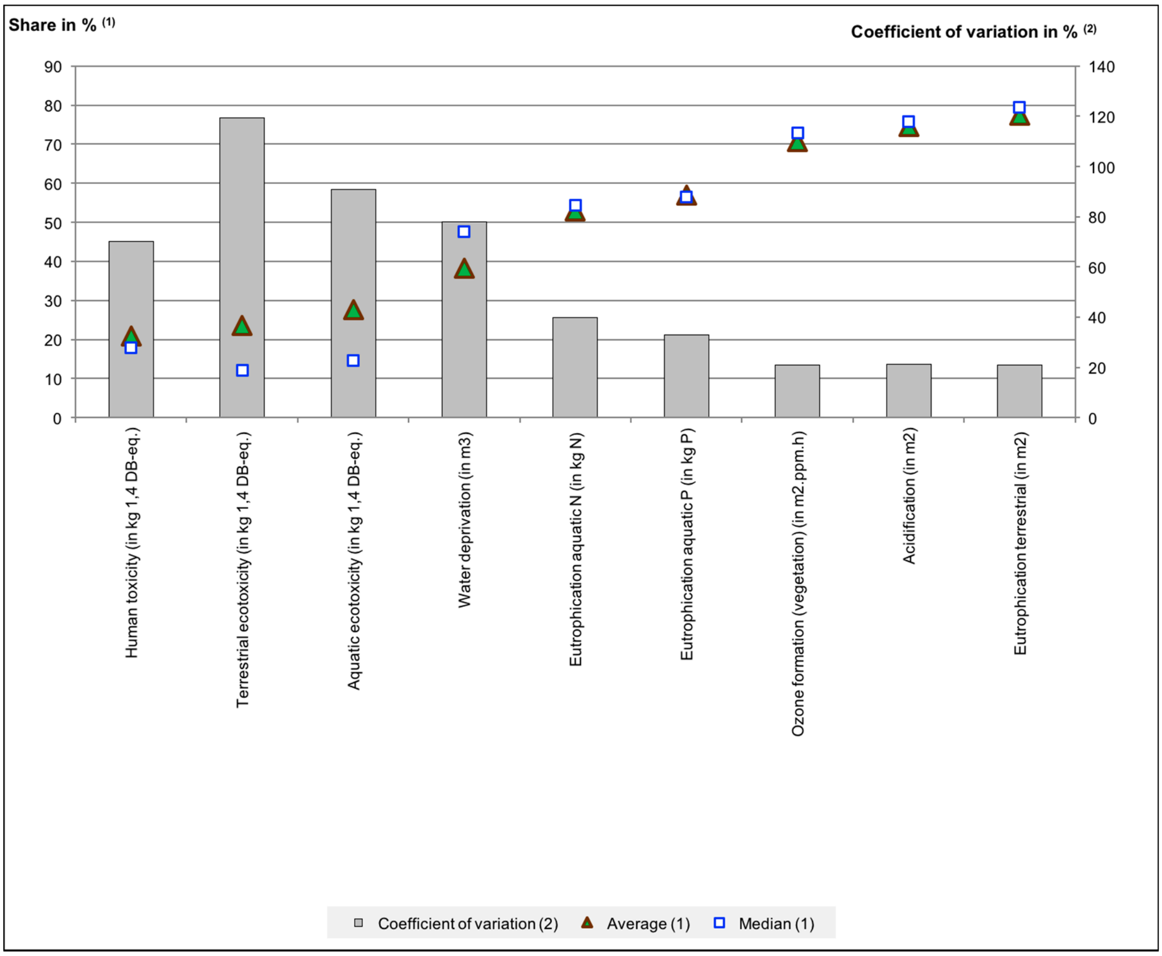

Figure A1. Average, median and coefficient of variation of the on-farm share of the cradle-to-farm-gate environmental impact for impact categories considered both at global and local level, listed from left to right in ascending order of average on-farm share.

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