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ON THE INTERPLAY OF LOCAL VERSUS GLOBAL ENVIRONMENTAL AND ECONOMIC PERFORMANCE OF SWISS ALPINE DAIRY FARMS

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EXECUTIVE SUMMARY

Several studies have revealed that the cradle-to-farm gate link of the food chain is an important contributor to the environmental impacts generation of the entire food chain. Therefore, appropriately monitoring, assessing and enhancing farm environmental performance is a key issue in order to improve the environmental sustainability of agro-food systems. In scientific practice, a plethora of indicators have been used to measure environmental performance at farm level. The definition of many of these indicators is often driven mostly by considerations regarding data availability or data collection feasibility, without conceptually considering which indicators are actually required for the assessment of farm environmental performance. As a result, several indicators show a questionable appropriateness for the task at hand. To ensure real improvements in the environmental sustainability of the agri-food sector, it is essential for farm environmental performance indicators to be consistent with the meaning and principles of the macro-level environmental sustainability concept. The aim of the present thesis was (i) to develop a theoretically sound and consistent framework on how to measure environmental performance at farm level and (ii) to implement this framework for the Swiss alpine dairy sector. Within this empirical application, the aim was to better understand farm environmental performance, its determinants and its link to farm economic performance. The final objective was to derive conclusions on how to simultaneously promote the economic and environmental sustainability of Swiss alpine dairy farming.

This cumulative dissertation consists of a general introduction (Chapter 1), three scientific papers (Chapters 2, 3 and 4) and a general conclusion (Chapter 5).

The introductory chapter (Chapter 1) provides background information on the sustainability concept. It furthermore presents the key issues of the agricultural sustainability challenge, highlights the role of farms in promoting sustainability and addresses the challenge of defining and measuring farm environmental performance. It concludes with the objectives, research questions and outline of this dissertation.

The first peer-reviewed paper presented in Chapter 2 is of a conceptual nature. Based on a comprehensive and systematic review of the farm-level environmental performance indicators found in scientific literature, it shows that several of these indicators are inconsistently defined

and inappropriate for the purpose of farm environmental performance assessment. This is due to the lack of conceptual considerations behind their definition. In the second step, starting from the environmental sustainability concept at macro level, the paper develops conceptual considerations on how to implement this concept at farm level into theoretically sound and consistent indicators of farm environmental performance. Based on the environmental sustainability concept viewed from an ecological perspective and on the associated ecosystem's carrying capacity (constraint) concept, it distinguishes between the carrying capacity of the global ecosystem and that of the local ecosystem. Relying on this distinction, it proposes to differentiate between the global and local environmental performance of a farm. Whereas farm global environmental performance relates the cradle-to-farm gate (i.e. off- and on-farm) environmental impacts to the biophysical farm output, farm local environmental performance focuses on local on-farm environmental impact generation and relates it to the local on-farm area. The paper concludes with highlighting the vital need to account for both global and local farm environmental performance dimensions in any farm environmental performance assessment to avoid any environmental problem shifting from global to local scale and vice versa.

The second peer-reviewed paper (Chapter 3) consists in an empirical application of the framework developed in Chapter 2. This application was carried out for a sample of 56 Swiss dairy farms, for which very detailed and comprehensive cradle-to-farm gate life cycle assessments (LCAs) were conducted. Farm global environmental performance was assessed as the farm digestible energy output for humans per unit of cradle-to-farm gate environmental impact. Farm local environmental performance was measured by the on-farm land area per unit of on-farm environmental impact. The paper investigates the relationships within the environmental performance dimension (i.e. between farm global and local environmental performance), and between the environmental and economic performance dimensions. The results showed the complexity of the relationships between farm global and local environmental performance. Depending on the environmental issues (impact categories) considered, either no significant relationships, or trade-offs or synergies were observed. Trade-offs occurred more frequently than synergies, implying that an improvement in farm global environmental performance regarding one environmental issue will likely lead to a deterioration in farm local environmental performance regarding at least one other issue, and vice versa. These trade-offs highlight the challenging and complex nature of the improvement of the environmental sustainability of farming and provide clear evidence that farm environmental performance cannot and should not be reduced to a single "one size fits all" indicator. Our work furthermore showed the existence of synergies between farm global environmental and economic performance. This implies that an improvement in 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 in farm economic performance and vice versa.

The third peer-reviewed paper (Chapter 4) relies on the same dataset as used in Chapter 3. It investigates different structural, farm management, socio-demographic, technological and natural-environment-related determinants of the economic and environmental performance of dairying. It aims to identify the factors with the potential to simultaneously improve farm global environmental, local environmental and economic performance. The results revealed the existence of some factors presenting synergies and several factors showing trade-offs in the enhancement of these three dimensions of the sustainable performance of a farm. Organic farming, higher agricultural education level of the farm manager, the production of silage-free milk, and also, however to a weaker extent, full-time farming, larger farm size and a lower intensity of cattle concentrates use were identified as factors that allow global environmental, local environmental and economic performance to be improved simultaneously. More generally, the promotion of farm global environmental performance and farm economic performance was shown to be synergetic whereas the enhancement of farm global and local environmental performance turned out to be mostly antinomic.

The last section (Chapter 5) recapitulates the main findings of this dissertation, discusses their implications, makes recommendations for stakeholders, especially policy-makers and LCA practitioners, and discusses the outlook of this thesis.

The core implications and related recommendations derived from the findings of this work are twofold. First, the conceptually correct measurement of farm environmental performance imperatively requires (i) the separate implementation of global and local environmental performance indicators as proposed in the framework and (ii) the consideration of both global and local dimensions to avoid environmental problem shifting from local to global scale and vice versa. This is especially necessary as the empirical application for Swiss alpine dairy farming found several trade-offs between farm global and local environmental performance. This empirical finding has far-reaching implications, especially if it is to be confirmed for other types of farms and other countries. When dealing with the environmental sustainability of farming, scientists and policy-makers have indeed tended to adopt a rather one-sided focus up to now. For example, LCA practitioners have – due to their LCA perspective – mainly focused solely on global environmental performance. Contrariwise, 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 (e.g. nitrogen surplus per ha). Through this one-sided focus, scientists and policy-makers implicitly assumed that local and global environmental performance go hand in hand and do not need to be considered separately. The 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, this work indirectly questions whether these one-sided perspectives, which have been widely used for years, have always been able to achieve real improvements in terms of environmental sustainability.

The second core finding of this dissertation relates to the possibilities for improving the environmental and economic sustainability of Swiss alpine dairy farming. This work showed that there are some factors, namely organic farming, higher agricultural education level of the farm manager, the production of silage-free milk, and also, however to a weaker extent, lower intensity of concentrates use, larger farm size and full-time farming, which allow farm global environmental, local environmental and economic performance to be improved simultaneously. Swiss policy-makers should thus consider promoting these factors, two of which, namely organic farming and lower concentrates use intensity, are already supported within the current Swiss agricultural policy in force since 2014.

ZUSAMMENFASSUNG

Mehrere Studien haben gezeigt, dass der Produktionsteil der Nahrungsmittelkette bis zum Verlassen des Landwirtschaftsbetriebs (von der Wiege bis zum Hoftor) wesentlich zu den Umweltwirkungen der gesamten Nahrungsmittelkette beiträgt. Im Hinblick auf eine Verbesserung der ökologischen Nachhaltigkeit von Agrar- und Lebensmittelsystemen ist es deshalb wichtig, die ökologische Performance (d.h. Umweltperformance) der Landwirtschaftsbetriebe zu überwachen, zu bewerten und zu verbessern. In der wissenschaftlichen Praxis wird eine Fülle von Indikatoren eingesetzt, um die ökologische Performance auf der Ebene der Landwirtschaftsbetriebe zu messen. Viele dieser Indikatoren wurden hauptsächlich aufgrund des Kriteriums festgelegt, ob bereits entsprechende Daten zur Verfügung stehen oder wie gut sich diese beschaffen lassen, ohne jedoch konzeptionell zu prüfen, welche Indikatoren für die Bewertung der ökologischen Performance eines Landwirtschaftsbetriebs wirklich erforderlich sind. Als Folge davon sind etliche Indikatoren nur bedingt für diesen Zweck geeignet. Um in der ökologischen Nachhaltigkeit des Agrar- und Lebensmittelsektors echte Fortschritte zu erzielen, braucht es Indikatoren zur ökologischen Performance der Landwirtschaftsbetriebe, die mit der Bedeutung und den Grundsätzen des Nachhaltigkeitskonzepts auf Makroebene in Einklang stehen. Ziel der vorliegenden Dissertation war es, (i) einen theoretisch fundierten und konsistenten Rahmen für die Messung der ökologischen Performance auf Ebene Landwirtschaftsbetrieb zu entwickeln und (ii) diesen Rahmen auf Schweizer Berg-Milchviehbetriebe anzuwenden. Innerhalb dieser empirischen Anwendung auf Landwirtschaftsbetriebe sollte die ökologische Performance, deren Einflussfaktoren und deren Verbindung zur ökonomischen Performance besser verstanden werden. Das letzte Ziel waren Schlussfolgerungen zur Frage, wie sich ökologische und ökonomische Nachhaltigkeit der Milchviehbetriebe in den Schweizer Alpen gleichzeitig fördern lassen.

Diese kumulative Dissertation besteht aus einer allgemeinen Einführung (Kapitel 1), drei Veröffentlichungen in wissenschaftlichen Zeitschriften (Kapitel 2, 3 und 4) sowie einer allgemeinen Schlussfolgerung (Kapitel 5).

Die Einführung (Kapitel 1) gibt Hintergrundinformationen zum Konzept der Nachhaltigkeit. Ausserdem werden die Schlüsselpunkte für Nachhaltigkeit in der Landwirtschaft, die Rolle der

Landwirtschaftsbetriebe bei der Nachhaltigkeitsförderung und die Herausforderung einer geeigneten Definition und Messung der ökologischen Performance von Landwirtschaftsbetrieben beschrieben. Das Kapitel schliesst mit den Zielen und Forschungsfragen, sowie einem Überblick über diese Dissertation.

Der in Kapitel 2 vorgestellte erste peer-revidierte Artikel ist konzeptioneller Art. Er bietet einen umfassenden und systematischen Überblick über die in der Literatur beschriebenen Indikatoren zur ökologischen Performance auf Ebene Landwirtschaftsbetrieb. Es wird gezeigt, dass einige dieser Indikatoren inkonsequent festgelegt und für die Bewertung der ökologischen Performance von Landwirtschaftsbetrieben ungeeignet sind. Grund dafür sind fehlende konzeptionelle Überlegungen bei der Definition dieser Indikatoren. Ausgehend vom Konzept der ökologischen Nachhaltigkeit auf Makroebene werden im Artikel in einem zweiten Schritt konzeptionelle Überlegungen dazu angestellt, wie dieses Konzept auf der Ebene des Landwirtschaftsbetriebs in theoretisch fundierte und konsistente Indikatoren zur ökologischen Performance von Landwirtschaftsbetrieben umgesetzt werden könnte. Basierend auf dem Konzept der ökologischen Nachhaltigkeit und auf dem dazugehörigen Tragfähigkeitskonzept des Ökosystems, wird zwischen der Tragfähigkeit des globalen Ökosystems und jener des lokalen Ökosystems unterschieden. Auf der Grundlage dieser Unterscheidung wird vorgeschlagen, auch zwischen der globalen und lokalen ökologischen Performance eines Landwirtschaftsbetriebs zu unterscheiden. Während die globale ökologische Performance die Umweltwirkungen des Produktionsteils von der Wiege bis zum Hoftor (d.h. die Umweltwirkungen auf dem Betrieb und ausserhalb des Betriebs) mit dem biophysikalischen Output des Betriebs in Beziehung setzt, konzentriert sich die lokale ökologische Performance auf die lokale Entstehung von Umweltwirkungen auf dem Betrieb und setzt diese in Beziehung zur lokalen Betriebsfläche. Der Artikel kommt zum Schluss, dass es bei jeder Bewertung der ökologischen Performance eines Landwirtschaftsbetriebs unerlässlich ist, sowohl die globale als auch die lokale Dimension der ökologischen Performance zu berücksichtigen, um zu vermeiden, dass ein Umweltproblem von der globalen auf die lokale Ebene oder umgekehrt verlagert wird.

Der zweite peer-revidierte Artikel (Kapitel 3) besteht aus einer empirischen Anwendung des in Kapitel 2 entwickelten Rahmens. Diese Anwendung wurde auf eine Auswahl von 56 Milchviehbetrieben in der Schweiz übertragen, für die detaillierte und umfassende Ökobilanzen «von der Wiege bis zum Hoftor » berechnet wurden. Die globale ökologische Performance eines Betriebs wurde anhand des Outputs des Betriebs in Form von für den Menschen verdaulicher Energie pro globale Umweltwirkungen bewertet. Die lokale ökologische Performance eines Betriebs wurde als Betriebsfläche pro Umweltwirkungen auf dem Betrieb berechnet. Im Artikel werden die Beziehungen zwischen den zwei Dimensionen der ökologischen Performance (d.h. zwischen der globalen und lokalen ökologischen Performance) und zwischen den ökologischen und ökonomischen Performancedimensionen untersucht. Die Ergebnisse zeigten die Komplexität der Beziehungen zwischen der globalen und der lokalen ökologischen Performance eines Landwirtschaftsbetriebs. Je nach dem betrachteten Umweltproblem (Umweltwirkung) wurden Synergien, Zielkonflikte oder keine signifikanten Zusammenhänge beobachtet. Zielkonflikte waren häufiger als Synergien, was den Schluss nahelegt, dass eine Verbesserung der globalen ökologischen Performance bezüglich eines Umweltproblems mit einer Verschlechterung der lokalen ökologischen Performance bei mindestens einem anderen Umweltproblem einhergeht und umgekehrt. Diese Zielkonflikte unterstreichen die herausfordernde und komplexe Natur der Verbesserung der ökologischen Nachhaltigkeit von Landwirtschaftsbetrieben und liefern klare Hinweise, dass die ökologische Performance von Landwirtschaftsbetrieben nicht auf einen einzelnen allgemeingültigen Indikator reduziert werden kann. In unserer Arbeit wurden aber auch Synergien zwischen der globalen ökologischen Performance und der ökonomischen Performance eines Landwirtschaftsbetriebs nachgewiesen. Dies bedeutet, dass eine Verbesserung der Ökoeffizienz der Lebensmittelproduktion im Produktionsteil der Nahrungsmittelkette mit grosser Wahrscheinlichkeit zu einer Verbesserung der ökonomischen Performance des Betriebs führt und umgekehrt.

Der dritte peer-revidierte Artikel (Kapitel 4) baut auf demselben Datensatz, wie in Kapitel 3 beschrieben, auf. Er untersucht verschiedene strukturelle, technologische und soziodemographische Faktoren sowie Determinanten im Zusammenhang mit Betriebsmanagement und natürlicher Umwelt, die Einfluss auf die ökologische und ökonomische Performance eines Milchviehbetriebes haben. Ziel war es, Faktoren zu identifizieren, die das Potenzial haben, gleichzeitig die globale ökologische Performance, die lokale ökologische Performance und die ökonomische Performance zu verbessern. Die Ergebnisse zeigten, dass es bei der Verbesserung dieser drei Dimensionen der Nachhaltigkeitsperformance eines Landwirtschaftsbetriebs einige Faktoren mit Synergien und einige Faktoren mit Zielkonflikten gibt. Der Biolandbau, ein höheres Ausbildungsniveau des Betriebsleiters und die Produktion von silofreier Milch wurden als jene Faktoren identifiziert, die eine gleichzeitige Verbesserung der lokalen ökologischen Performance, der globalen ökologischen Performance und der ökonomischen Performance ermöglichen. Ferner haben sich eine niedrigere Kraftfutterintensität, grössere Betriebsgrösse und Vollerwerbslandwirtschaft auch als günstig für die untersuchten Performancedimensionen erwiesen. Allgemein kann zusammengefasst werden: Es bestehen Synergien in der Förderung der globalen ökologischen Performance und der ökonomischen Performance von Landwirtschaftsbetrieben. Die Verbesserung der lokalen und globalen ökologischen Performance hat sich im Gegenteil häufig als antagonistisch erwiesen.

Im letzten Teil (Kapitel 5) werden die wichtigsten Erkenntnisse dieser Dissertation zusammengefasst, ihre Implikationen diskutiert, Empfehlungen für die Akteure (namentlich die politischen Entscheidungsträger und die Ökobilanzierer) formuliert und ein Ausblick dieser Arbeit dargestellt.

Aus dieser Arbeit lassen sich zwei zentrale Erkenntnisse und daraus resultierende Empfehlungen ableiten. Erstens erfordert die konzeptionell korrekte Beurteilung der ökologischen Performance eines Landwirtschaftsbetriebs zwingend (i) die getrennte Implementierung der globalen und lokalen ökologischen Performance, wie in dem Rahmenwerk vorgeschlagen und (ii) die Berücksichtigung sowohl der globalen als auch der lokalen Dimension, um zu vermeiden, dass eine Verlagerung der Umweltprobleme von der lokalen auf die globale Ebene oder umgekehrt stattfindet. Dies ist umso wichtiger, als die empirische Anwendung auf Milchviehbetrieben in den Schweizer Alpen mehrere Zielkonflikte zwischen der lokalen und der globalen ökologischen Performance feststellte. Diese empirisch gewonnene Erkenntnis hat weitreichende Konsequenzen, insbesondere wenn sie für andere Typen von Landwirtschaftsbetrieben und andere Länder bestätigt wird. Wissenschaftler und politische Entscheidungsträger haben sich bisher im Umgang mit der ökologischen Nachhaltigkeit der Landwirtschaft hauptsächlich auf relativ einseitige Indikatoren gestützt. Bei der Ökobilanzierung lag der Fokus beispielsweise in erster Linie auf der globalen ökologischen Performance. Im Gegensatz dazu fokussieren in der Schweiz, wie in vielen anderen Ländern, bestehende politische Umweltmassnahmen und -instrumente auf Stufe Landwirtschaftsbetrieb ausschliesslich auf die lokale Dimension der ökologischen Performance (z.B.

Stickstoffüberschuss pro ha). Aufgrund dieser einseitigen Sicht gingen die Wissenschaftler und Entscheidungsträger implizit davon aus, dass die lokale und globale ökologische Performance des Betriebs Hand in Hand gehen und nicht separat berücksichtigt werden müssen. Die Feststellung, dass zwischen lokaler und globaler ökologischen Performance Zielkonflikte bestehen, widerspricht dieser weitläufigen Ansicht – zumindest im Kontext der Milchviehbetriebe in der Schweiz. In diesem Sinn stellt diese Arbeit indirekt in Frage, ob mit diesen über Jahre breit angewendeten einseitigen Perspektiven immer wirkliche Verbesserungen im Hinblick auf die ökologische Nachhaltigkeit erzielt werden konnten.

Die zweite wichtige Erkenntnis dieser Dissertation bezieht sich auf die Möglichkeiten, die ökologische und ökonomische Nachhaltigkeit in der Milchviehhaltung der Schweizer Alpen zu verbessern. Diese Arbeit zeigte, dass einige Faktoren eine gleichzeitige Verbesserung der globalen ökologischen Performance, der lokalen ökologischen Performance und der ökonomischen Performance ermöglichen, nämlich Biolandbau, höheres Ausbildungsniveau des Betriebsleiters und die Produktion von silofreier Milch. Ferner haben sich niedrigere Kraftfutterintensität, grössere Betriebsgrösse und Vollerwerbslandwirtschaft auch als günstig für die untersuchten Performancedimensionen erwiesen. Die politischen Entscheidungsträger in der Schweiz sollten diesen Faktoren Beachtung schenken, wobei zwei von denen, nämlich Biolandbau und niedrigere Kraftfutterintensität, bereits in der seit 2014 geltenden Schweizer Agrarpolitik gefördert werden.

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1 GENERAL INTRODUCTION

“Whoever says he knows what ‘sustainability’ is, in all probability does not. In a certain sense, a sustainable world is a fiction.” (Martens, 2006)

This chapter begins with a general overview of the concept of sustainability, with a special focus on agriculture and the challenges it faces in sustainability terms. Next, we highlight the role of farms in achieving sustainable food chains and address the challenge of environmental performance assessment at farm level. We then present the main objectives, research questions, and the outline of this dissertation.

1.1 SUSTAINABILITY: FROM THE CONCEPT TO THE CHALLENGE OF IMPLEMENTATION AT FARM LEVEL

1.1.1 Sustainability concept

1.1.1.1 Historical emergence

Sustainable development is one of the most important challenges for the planet in today’s globalised world; tackling it requires increased mobilisation of interdisciplinary scientific research and a strong integration of different disciplines with public policy (Sachs, 2005). The sustainability challenge faced by humanity today is on an unprecedented scale, as human activities are threatening to irreversibly damage the Earth systems crucial for the development and preservation of life (Rockström et al., 2009). At present, the planetary boundaries have already been exceeded for some environmental issues (e.g. climate change, biodiversity) and are most likely being approached for various other issues (e.g. freshwater use, ocean acidification) (Rockström et al., 2009).

In recent decades, the concept of sustainability has become widely used by various actors – governments, businesses, NGOs and academia all seem eager to comprehend and improve it but often have (i) very different understandings of what sustainability actually means and (ii) quite different goals in mind while dealing with it (Crane and Matten, 2016). The term itself has been used in various fields and contexts and holds different meanings depending on whether it is understood from an environmental, social or economic perspective (Brown et al., 1987).

Although the term sustainability has been widely popularised in recent decades, the issue of sustainability is by no means young. Factors related to ecological sustainability were indeed a decisive element in the rise and fall of ancient civilisations, as well as in the most important agricultural and industrial transformations of society (Mebratu, 1998).

The term 'sustainability' is considered to have appeared for the first time in scientific literature in the 18th century. In the handbook entitled "Sylvicultura oeconomica", Carl von Carlowitz tackled the sustainable use of forests (Pufé, 2012a). As a mining director in then Saxony, he realised the negative effects of deforestation on natural resources and economy (Pufé, 2012a) and called for "*a continuous, steady and sustained use of timber*" and for intergenerational timber resources management (Grober, 2007).

In eighteenth and nineteenth century England, the classical economists Thomas Robert Malthus and David Ricardo theorised the "environmental limits to growth" in terms of the limits on the supply of good-quality agricultural land, which will lead to diminishing returns in agricultural production (Pearce & Turner, 1990). In his "law of population", Malthus asserted that population when left unchecked increases geometrically, while agricultural production increases arithmetically at most (Oser & Blanchfield, 1975). Malthus predicted that the fixed amount of land (absolute scarcity limit) in combination with population growth would lead to diminishing returns in agriculture, ultimately reducing the per capita food supply, lowering living standards and curbing population growth (Pearce & Turner, 1990). Ricardo's model also foresaw the appearance of diminishing returns due to the scarcity of natural resources (Pearce & Turner, 1990). In his model, the limiting factor was not so much the absolute scarcity of land but rather its quality, which varies, and as the population increases it is forced to move to successively less fertile lands (Pearce & Turner, 1990). Neither Malthus's nor Ricardo's model accounted for technological progress, which has allowed agricultural productivity to be increased up to a certain level, thereby offsetting but not entirely eliminating the diminishing returns (Pearce & Turner, 1990).

1 GENERAL INTRODUCTION

The cause of the current sustainability crisis can be traced back to the industrialisation which followed the industrial revolution, accelerated economic growth and resulted in a dramatic increase in the consumption of fossil fuels and other non-renewable resources, which caused the 20th century to be regarded by some as the "century of explosive expansion" (Komiyama & Takeuchi, 2006). It was also a century of the emergence of modern scientific sustainability examination, marked by the publication of a study conducted by scientists from the Massachusetts Institute of Technology (MIT) and published in the report "The Limits to Growth" in 1972 (Pufé, 2012b). The scientific team considered five basic factors to be determining and therefore limiting for economic growth on this planet, namely world population, food production, natural resource depletion, industrialisation, and pollution (Meadows et al., 1972). The study modelled the global outcome of five major global trends: accelerating industrialisation, rapid population growth, widespread malnutrition, depletion of non-renewable resources, and a deteriorating environment, all of which combined showed distressing results (Meadows et al., 1972). If these major global trends remain unchanged in the future ("business as usual" scenario), the model showed that "*the limits to growth on this planet will be reached sometime within the next one hundred years*", resulting in great declines in population and industrial capacity (Meadows et al., 1972). Although "The Limits to Growth" study was criticised on different accounts, recent empirical analysis based on historical data concerning the changes occurring from 1970-2000 on the five global issues mentioned above closely matches that study's "business as usual" scenario, which predicted a collapse of the global system before the mid-21st century (Turner, 2007).

In 1983, the United Nations (UN) assembled an independent expert commission – also known as the World Commission on Environment and Development (WCED) – with the goal of drafting a report that would set out a vision of long-term, viable and environment-friendly development (Pufé, 2012a). This report, entitled "Our Common Future", was the conceptual foundation of the political discussions and actions in the area of sustainability under UN guidance, such as the Rio Summit and the Agenda 21 in 1992, the 2000-2015 Millennium Development Goals and the Durban Climate change conference in 2011 (Pufé, 2012a).

"Our Common Future" contains the most-quoted definition of sustainable development (Pufé, 2012a), namely "*development that meets the needs of the present without compromising the ability of the future generations to meet their own needs*" (WCED, 1987). "Our Common

Future" also conceived the foundations of the three-pillar sustainability approach, calling for "*economic growth that is forceful and at the same time socially and environmentally sustainable"* (WCED, 1987). Although sustainability and sustainable development are intertwined, they are not synonymous terms. While sustainability refers to a static state and durability, sustainable development is a more dynamic, process-oriented approach (Pufé, 2012a). The concept of sustainability as defined in WCED (1987) comprises the notion of intragenerational (within a generation) and intergenerational (between different generations) equity (Goodland & Daly, 1996). It also encompasses the goals of equity to nature, survival in terms of durability and resilience, and welfare improvement (Pearce, 1988). Although all of these goals may be complementary up to a certain point, it is highly likely that there are also trade-offs between them (Pearce, 1988).

1.1.1.2 The economists' approach to sustainability

From a general perspective, the economic theory of sustainability implies that certain indicators of welfare or development are not declining over a very long-term timeframe (Pezzey, 1989). Sustainable development can therefore be viewed as a transformative process of change in an economy which does not breach this criterion (Stern, 1997). More specifically, economists' views on sustainable development revolve predominantly around the "capital theory approach" (Stern, 1997). The capital theory approach (CTA) sees maintenance of capital (the constant capital rule) as a prerequisite for sustainable development and generally distinguishes between natural and artificial capital (i.e. manufactured, human, and institutional capital) (Stern, 1997). The main advantage of the CTA is that it proposes relatively simple rules and indicators for ensuring and measuring sustainability, thereby clearing away the vagueness inherit in previous discussions of sustainable development (Stern, 1997).

Within the CTA, there are two different schools of thought regarding the degree of substitutability of different capital types, one represented by the proponents of weak sustainability and the other by the proponents of strong sustainability (Stern, 1997). Although it may seem that the two schools of thought have differing ideas on what sustainability is, in fact they agree on that issue (Stern, 1997). Their disagreement stems from applying the constant capital rule to different levels of capital stock and, therefore, holding different opinions on the degree of substitutability believed to be possible between natural and artificial capital (Stern, 1997).

The weak sustainability paradigm focuses on the preservation of the total capital stock regardless of its form, therefore assuming no restrictions on substitutability between natural and artificial capital (Gutés, 1996). The elasticity of the substitution between natural and artificial capital is assumed to be equal to one and, therefore, there are no natural resources that cannot be replaced by other forms of capital in the weak sustainability school of thought (Stern, 1997). In theory, technological progress and increased efficiency could be used as possible pathways to achieve sustainability even with reduced natural capital stock, as long as they compensate for the reduction in natural capital by increasing the stock of artificial capital (Pearce & Turner, 1990). This could be achieved through improved efficiency of the use of existing resources or an invention of a new "backstop technology" with the capacity of powering itself solely by some indefinitely renewable resource once the limited resource has been exhausted (Pearce & Turner, 1990). However, reservations have been expressed regarding the certainty of timely discovery of such technologies and their ability to resolve increasingly serious sustainability issues (Schumacher, 1978; Daily & Ehrlich, 1992; Sachs, 2005). Furthermore, weak sustainability is intrinsically not concordant with the established laws of biological and physical science (Ayers et al., 1998).

In contrast to weak sustainability, the strong sustainability paradigm regards natural capital as not being substitutable by artificial capital due to its special functions (Gutés, 1996). Its proponents define sustainable development in terms of constant or non-declining total natural capital and call for the maintenance of separate stocks of aggregate natural capital and aggregate artificial capital (Stern, 1997). Somewhere in the middle of these two extreme paradigms is the concept of critical natural capital (Stern, 1997). This concept allows for some degree of substitutability between natural and artificial capital, but stresses the importance of maintaining the levels of critical natural capital, which is non-substitutable because it "*performs important and irreplaceable environmental functions, i.e. ecosystem services*" (Brand, 2009).

1.1.1.3 The ecologists' approach to sustainability

The ecologists took a more ecologically oriented stand on sustainability and criticised the idea of limitless growth as the neglect of the ecological (biophysical) carrying capacity constraint of the Earth's ecosystem(s) (Rees, 1996). They therefore shared Schumacher's (1978) view that "*There can be growth towards a limited objective, but there cannot be unlimited, generalised growth*". Indeed, biophysical reality renders it simply "*impossible to grow into sustainability*" due to limitations of the source and sink capacities of the environment (Goodland, 1995).

By implementing an ecological focus and taking into account the biophysical carrying capacity constraint of the earth's ecosystems, a new definition could be coined, one that considers the objective of sustainability as "*meeting the resource and services needs of current and future generations without compromising the health of the ecosystems that provide them*" (Morelli, 2011). More precisely, sustainability appraised from an ecological perspective can be defined as a "*condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting ecosystems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity*" (Morelli, 2011). Environmental sustainability is composed of a set of constraints on the use of renewable and non-renewable resources on the source side, and pollution and waste assimilation on the sink side (Goodland, 1995). Its ultimate goal is the perpetual maintenance of global life-support systems through sustaining the environmental sink and source capacities (Goodland, 1995).

Sustainability is invariably connected with and dependent on the carrying capacity of the ecosystems as it requires humanity to remain within the biophysical carrying capacity of the planet (Robinson, 2004). In other words, "*sustainability depends on the size and spatiotemporal characteristics of humanity's footprint relative to Earth's carrying capacity*" (Hoekstra & Wiedmann, 2014). More precisely, "*human population and activity should not surpass the carrying capacity of the biosphere, its renewing, resource, and sink capacities*" (Károly, 2011).

Some streams of thinking adopt a radical view of carrying capacity and assume that humans can perpetually increase the carrying capacity of their habitat through import, technology advancement, and elimination of other competing species (Rees, 1996). However, ecologists do not share the belief in technological breakthrough as a potential solution for accommodating billions more people on earth, and they argue that this view is not grounded in reality, especially when the current poor living conditions in some parts of the world are taken into account (Daily & Ehrlich, 1992). Moreover, they see this concept of perpetually expanding the carrying capacity by human intervention as an "*ironic error*", as shrinking carrying capacity may soon become the single most important issue for human survival on this planet (Rees, 1996). The biophysical reality does indeed suggest that the carrying capacity of this planet is of a finite nature (Arrow et al., 1995; Goodland, 1995; Rees, 1996) and, moreover, has already been exceeded for various environmental issues (Goodland, 1995; Rockström et al., 2009).

1.1.2 Agriculture and the sustainability challenge

1.1.2.1 Importance of agriculture for humanity and challenges it faces in the context of world population growth and dietary pattern shifts

Though the agricultural sector today accounts for only a small part of the world economy and the proportion of people working in agriculture is decreasing (e.g. according to Timmer (2009), in the USA there are more lawyers than farmers), agriculture is still of crucial importance for the livelihoods of many people (Alston & Pardey, 2014). In 2012, agriculture represented under 3 percent of overall global income, however an estimated 19 percent of the world population was engaged in farming (Alston & Pardey, 2014). Agriculture is an important supplier for the fulfilment of basic human needs: it produces food for human consumption, feed for animal production, fuel for transportation and energy production, fibre for clothing, and agricultural biomass for industrial use in material production (Alston & Pardey, 2014).

The overarching importance of agriculture was the reason why UN embedded it in Goal 2 of its Sustainable Development Goals (SDGs). SDG 2 aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture (UN, 2016). According to the FAO (2015), around 793 million people are still undernourished globally, which is 167 million fewer than in the previous decade. The decline in undernourishment is more pronounced in the developing regions, although they also experienced population growth (FAO, 2015).

Despite these somewhat encouraging present trends regarding global undernutrition, agriculture still faces an enormous challenge of feeding the growing world population, as continuing population and consumption growth indicate that global food demand will have to increase for at least another 40 years (Godfray et al., 2010). This implies, for instance, that the cereals yield increase rate in the next 40 years will have to be 37% higher than the historical yield increase rate observed since 1961 (Tester & Langridge, 2010). The surge in food demand is caused not only by population growth, but also by income growth, urbanisation and the resulting change in food preferences in developing countries towards higher consumption of processed food, meat, dairy and fish (von Braun, 2007; Godfray et al., 2010). By 2050 these dietary shifts, if left unchecked, are likely to become a major contributor to the predicted 80 percent increase in global agricultural greenhouse gas emissions from food production and are also likely to contribute greatly to global land clearing (Tilman & Clark, 2014). Moreover, these dietary changes are also causing adverse health effects, as they are greatly increasing the prevalence of cardiovascular diseases, type II diabetes and other chronic illnesses, and thereby lowering global life expectancies (Tilman & Clark, 2014).

Feeding a growing population and servicing this fast nutritional transition in developing countries requires, as already mentioned, a rapid increase in global agricultural production, which in turn will put even greater pressure on scarce natural resources (Gerbens-Leenes et al., 2010). Our ability to produce food will be affected both by growing competition for land, water and energy and by the growing urgency to reduce the impact of the food system on the environment (Godfray et al., 2010). Short-term gains in terms of food production will be offset by long-term losses if the rise in agricultural production leads to degradation of ecosystems, threatening future abilities to maintain the present production levels (De Schutter, 2010). If sustainability is to be achieved in agricultural terms, agriculture has to find a way to produce sufficient amounts of food without compromising the ability to meet future needs (De Schutter, 2010). However, how to feed the increasing world population in a sustainable way is a question on which little consensus has been reached (Tilman et al., 2002).

1.1.2.2 The green revolution and its environmental consequences

1.1.2.2.1 General overview

In the second half of the 20th century, the green revolution introduced high-yielding plant varieties that led to an unprecedented increase in agricultural productivity (Gomiero et al., 2011). This increase was further stimulated by the availability of cheap fossil fuels, which enabled chemical production of fertilisers and pesticides and the mechanisation of agricultural production (Gomiero et al., 2011). The green revolution is acclaimed to have jumpstarted economies, alleviated poverty, saved large areas of natural land from conversion into agricultural land and helped to avoid the Malthusian outcome of population growth (Rai et al., 2011). However, the "green revolution" technologies and the associated decades of agricultural intensification have also caused extensive environmental damage at the local, regional and global levels of the Earth ecosystem (Matson et al., 1997; Vitousek et al., 1997; Foley et al., 2005). The green revolution was accompanied by globalisation of agri-food supply chains, which have become increasingly complex. From an environmental perspective, one effect of the increase in global international agri-food trade is that it has ultimately caused the "globalisation of environmental issues" that were originally chiefly of local relevance (Bare, 2014).

The list of negative externalities caused by today's food production systems is long and includes greenhouse gas emissions, pollution due to nutrient run-off, water shortages, soil degradation, loss of biodiversity, and disruption of aquatic ecosystems (Godfray et al., 2010). Humanity has reached the point where "*its rapidly growing reliance on fossil fuels and industrialized forms of agriculture could damage the systems*" that have kept the Earth in a state suitable for the development of human life, as it may be approaching planetary boundaries for global freshwater use, change in land use, ocean acidification, and interference with the global phosphorus cycle, whereas climate change, biodiversity loss, and nitrogen cycles have already exceeded these boundaries (Rockström et al., 2009).

1.1.2.2.2 Overview for different environmental issues

More specifically, agriculture is a major contributor to global climate change as it alone contributes about 13 percent to global human induced GHG emissions or up to 32 percent if indirect emissions such as fertiliser production, distribution and land conversion to agriculture are taken into account (Paoletti, 2010). The relationship between agriculture and climate change is a mutually dependent one, as agricultural productivity is also primarily determined by the climate (Adams et al., 1998). Projections of climate change effects predict possible risks for global agricultural yields, drastic weather events, sea level rise and loss of sensitive ecosystems

(Van Vuuren & Faber, 2009). The effects of climate change on the global food supply are likely to be negative, threatening food security, especially in the developing countries (Nelson et al., 2009).

Furthermore, the increasing human food demand has already depleted many of the natural terrestrial and aquatic resources and continues to put heavy pressure on the remaining biodiversity (Van Vuuren & Faber, 2009). In view of future population growth pressures, humanity is facing a global challenge of achieving efficient and productive land use while at the same time conserving biodiversity (Tscharntke et al., 2012). Deforestation due to increased land use for agricultural production and wood demand is a further cause for concern and may severely reduce the ecosystem's capacity to provide ecosystem services (Van Vuuren & Faber, 2009). In addition, phosphorus depletion may soon become a serious agricultural global issue, as this resource has no substitutes (Van Vuuren & Faber, 2009).

In addition, agricultural production is also a major contributor to water scarcity, as irrigated agriculture accounts for around 70% of the world's freshwater withdrawals (Rosegrant et al., 2009). Agriculture is projected to continue to be the largest user of freshwater resources and, at the same time, a sector that will be heavily affected by growing water scarcity (Rosegrant et al., 2009).

Agricultural production is also responsible for the greatest part of the marine and freshwater eutrophication of surface waters (Withers et al., 2014). This nutrient-related environmental issue has become an endemic problem all over the world (Withers et al., 2014). It causes the formation of low oxygen areas, also known as "dead zones", which have spread significantly in coastal oceans during recent decades, causing severe harm to the biodiversity of marine ecosystems (Rabalais et al., 2010).

1.1.2.2.3 The role of livestock farming

Livestock farming is an especially important contributor to the aforementioned environmental issues, as well as to some other environmental problems. Globally speaking, the livestock sector is a major stressor on many ecosystems (Steinfeld et al., 2007). Livestock activities influence the environment either directly (e.g. through grazing) or indirectly (e.g. through soybean production for animal feed, which could be causing deforestation in South America) (Steinfeld et al., 2007).

Livestock are known to be a very important source of anthropogenic climate change pressures, responsible for 80 percent of agricultural methane emissions, 35-40 percent of total anthropogenic methane emissions, and 18 percent of total anthropogenic greenhouse gas emissions (Steinfeld et al., 2007). The livestock sector is also one of the leading causes of biodiversity loss (Steinfeld et al., 2007). The negative impact of livestock on biodiversity takes place through many channels, some of which are heavy grazing, soil compaction, forest loss due to accommodation of new pastures and cropland for livestock farming in the tropics, GHG emissions causing climate change and in turn negatively affecting biodiversity, diseases spreading from livestock to wildlife, and pollution of watercourses causing negative effects on aquatic biodiversity (Herrero et al., 2009). Furthermore, livestock systems are the biggest land-occupying activity, appropriating 45 percent of global surface area (Thornton et al., 2011).

As modern livestock systems have become largely industrialised and globalised, with confinement-based systems overtaking traditional production forms, overall livestock production has experienced a great decoupling from its supporting natural resource base and its land use has changed substantially from grazing to the consumption of feed crops (Naylor et al., 2005). Major pollution forms of these intensive livestock systems are related to manure management and include eutrophication of surface water, leaching of nitrates into groundwater, build-ups of excess nutrients and heavy metals in the soil, contamination of soil and water resources with pathogens, release of ammonia, methane and other gases into the air and destruction of fragile ecosystems such as wetlands, mangroves and coral reefs (FAO, 2005). Regrettably, environmental and resource costs of industrial livestock systems remain mostly ignored and further obscured by the expanding trade in livestock products (Naylor et al., 2005). For example, increased soybean production in the Brazilian grassland and rainforest areas supplies cattle feed to the growing cattle industry of Brazil, China and India and other parts of the world, with great and often irreversible negative effects on biodiversity, climate, soil and water quality (Naylor et al., 2005).

1.1.3 The role of farms in the promotion of agricultural sustainability

The importance of farms in achieving sustainable food chains is essential for several reasons. First, they are the place where everyday decisions related to the use of economic and environmental resources are made, which – combined together – result in the production of agricultural commodities and services but also cause negative environmental externalities. The use of environmental resources in agriculture is in many ways very specific because of the particular role of land in the agricultural production process. Agriculture relies on land as the central production factor, unlike other man-made production systems, which use land merely as locations for economic activity infrastructures and not as a production factor in a narrow sense. The result of this agricultural particularity is that land, an integral element of natural ecosystems, enters into farms' production function as an essential economic input. However, despite it becoming farms' essential economic input, land can never really be excluded from the natural ecosystem.

Secondly, the importance of farms in achieving sustainable food chains becomes even more evident once their role as major environmental impact generators in the food chain has been recognised. Different studies have shown that, especially for the environmental impacts related to nutrient management, toxicity, phosphorus, and land use, the cradle-to-farm-gate link is responsible for a large share of the impacts generated over the entire food supply chain (e.g. for the dairy chain: Eide, 2002, Hospido et al., 2003, Gerber et al., 2010, Thoma et al., 2013, Bystricky et al., 2014a; or for the bread supply chain: Korsaeth et al., 2012, Bystricky et al., 2014a, Kulak et al., 2014). Monitoring, assessing, and enhancing farm environmental performance is therefore an issue of utmost importance for improving the environmental sustainability of the entire food chain. Environmental performance is generally defined here as the ability of a farm to comply with the biophysical restrictions in terms of natural resource use and polluting emission generation imposed by the natural ecosystem it operates in to ensure the short- and long-term provision of the supporting, regulating and provisioning services this natural ecosystem renders to humanity.

Measuring farm sustainable performance, and more precisely its environmental and social dimension, is challenging. We will focus in the present work on the economic and environmental dimension of sustainability. Whereas the indicators for the measurement of farm economic performance are quite well-known and widespread in their use, the measurement of environmental performance is highly challenging and the indicators used for this purpose vary greatly in their goal and scope, as will be explained in the following section.

1.1.4 The challenge of defining and measuring farm environmental performance

In scientific practice, a plethora of different indicators have been used for the purpose of measuring environmental performance at farm level. In many studies, the definition of the environmental indicators is driven mainly (and sometimes even solely) by considerations regarding data availability or data collection feasibility, without conceptually considering how to implement the environmental sustainability concept, which is originally a biophysical concept, into indicators of farm environmental performance that are theoretically sound and consistent.

Lack of conceptual considerations behind the indicators may result in questionable appropriateness and usefulness of the indicators obtained in this manner. For example, the use of monetary variables as functional units in environmental performance indicators is conceptually highly debatable, as it relates two intrinsically different dimensions – biophysical and monetary – and creates indicators that are biased by market prices. Evidence indeed suggests that, in the case of natural resources, prices are often far from reflecting true scarcities, due to the occurrence of market failures (Gutés, 1996; Farley, 2008; Turner & Daily, 2008), such as the inability of market price formation to account for future scarcities (Browne, 2012) and especially to integrate future generations' demand (Bromley, 1989).

To ensure real sustainable development of the agri-food sector, it is essential that farm environmental performance indicators are consistent with the meaning and principles of the sustainability concept, originally coming from the macro level.

1.2 THE SWISS DAIRY SECTOR AND THE SUSTAINABILITY CHALLENGE

According to the Swiss Federal Office for Agriculture (FOAG), over 70% of Swiss farmland consists of meadows and pastureland, which explains why dairy and beef farming are of crucial importance for Swiss agriculture (FOAG, 2004a). Dairy farming alone constitutes in economic terms the most important subsector in Swiss agriculture, accounting for 21% of the sector's total monetary market output in 2012 (FSO, 2012). An economically viable and environmentally friendly sustainable dairy farming sector is thus essential when it comes to guaranteeing the sustainable development of the Swiss agro-food chain.

Since the early 1990s, agricultural sustainability has gained increasing importance on the level of Swiss agricultural policy. The promotion of a sustainable agriculture as a principle is even formally anchored in the Swiss Federal Constitution (SR 101, Article 104). In a 1996 federal referendum, Swiss citizens opted to fully embrace the multifunctional approach to sustainable agriculture and the resulting "agricultural article" can be seen as "*an explicit contract between agriculture and society to ensure the sustainability of agriculture*" (Aerni, 2009). Despite the progress made in political and citizens' awareness of the importance of agricultural sustainability, there are still many important environmental, economic and social sustainability issues of farming waiting to be tackled. In the following subsections, we will present some selected important sustainability issues faced by Swiss agriculture with a particular focus on the livestock and dairy sector.

1.2.1 Environmental challenges

Several of the environmental challenges faced by Swiss agriculture[1] are related to livestock farming and, especially, to dairy and beef farming. Many of these challenges are connected to the very high stocking rates (FOEN, 2016a). According to the Swiss Federal Office for Environment (FOEN), in 2010 Switzerland showed stocking rates that were 60-122% higher than those of its neighbouring countries (FOEN, 2016a). Related to this issue, it comes as no surprise that Switzerland is, after the Netherlands, Europe's second highest emitter of ammonia from agricultural sources per ha farmland area (FOAG, 2016). Total Swiss ammonia emissions from agricultural sources are still almost two times higher than the target values (FOEN, 2016a). Livestock farming contributes approximately 80% of agricultural emissions, which alone account for 92% of total Swiss ammonia emissions (FOAG, 2004b). Ammonia emissions and

[1] A detailed overview of all environmental issues at stake in Swiss agriculture is available in Jan (2012).

other nitrogen compound losses into the soil, air and water contribute to several environmental problems such as eutrophication, acidification, climate change and biodiversity loss (FOAG, 2016). Ammonia emissions furthermore play a role in the formation of particulate matter, which has been shown to have adverse effects on human health (FOAG, 2016).

Beyond the nitrogen-related issue, climate change is also a key environmental issue of Swiss agriculture, which in 2014 accounted for 12.7% of total national Swiss greenhouse gas (GHG) emissions. Livestock was the most important contributor to agricultural GHG emissions, with enteric fermentation being responsible for 55% of total Swiss agricultural GHG emissions (FOEN, 2016b).

The environmental impacts caused by Swiss dairy farming are not confined to the geographical boundaries of Switzerland. Due to the purchase of farming inputs originating from other countries, Swiss dairy farms also indirectly cause environmental impacts in various other parts of the world. This is the case, for instance, for imports of feedstuffs for the Swiss livestock sector. These imports increased fourfold between 1990 and 2013. Soybean imports in particular have increased strongly in recent years. 41% of soybean imports are used for cattle feed, primarily for dairy cows (FOEN, 2016).

1.2.2 Economic challenges

In general, the profitability of Swiss farming lags behind that of other sectors. In 2015, the median work income per family work unit in the agricultural sector was significantly lower than the comparable salary[2] of employees in the secondary and tertiary sectors of the Swiss economy (Dux et al., 2016). For example, in the mountain region, the median work income per family work unit reached 48% of the comparable salary in the mountain area. In comparison to other farm types, dairy farms showed a particularly low profitability, with their work income per family work unit being around CHF 37,600, 15% lower than the average work income per family work unit in Swiss agriculture for 2015 (Dux et al., 2016).

[2] The comparable salary is defined as the median gross salary of the employees in the secondary and tertiary sector. The comparable salary statistics are provided by the Swiss Federal Statistical Office.

In international terms, the costs of milk production in Switzerland are among the highest in the world. According to the International Farm Comparison Network (IFCN), when compared to the typical dairy farms of 59 other countries that participated in the IFCN survey in 2015, the costs of milk production of an average-sized typical Swiss dairy farm (in USD/100 kg ECM) were the highest. The same was true for a typical large Swiss dairy farm (IFCN, 2016). Compared with its immediate neighbours, namely Austria, Italy, France and Germany, Switzerland also showed substantially higher milk production costs in 2015. For an average-sized typical dairy farm, the full costs of milk production in Switzerland were 1.4-2.7 times higher than in neighbouring countries (IFCN, 2016).

1.2.3 Social challenges

Although our work does not focus on the social sustainability dimension of farming, it is worthwhile at this point to highlight some of the important social sustainability issues faced by Swiss agriculture.

Firstly, gender equality in farming is still a long way off. Although women’s employment and their importance to the Swiss agricultural sector has risen in the last ten years, they are rarely owners or independent business managers of Swiss farms (FOAG, 2012). Their work on the farm is often neither remunerated nor registered and, therefore, not covered by the social security system, making them more dependent and vulnerable in the event of health issues, financial problems or changes in family circumstances (FOAG, 2012). Women farmers also tend to have a lower level of education than the men engaged in farming (FOAG, 2011).

Secondly, according to the study conducted by the Swiss Federal Statistical Office, the general satisfaction of Swiss farmers with their financial situation, working conditions and available leisure time is lower than for non-farming households in sparsely populated areas (FOAG, 2016). Affording sufficient heating and living in housing that is considered too dark or too damp is also more often a problem encountered by farmers than by non-farming rural people (FOAG, 2016).

A further important social issue is the conservation of the quality and quantity of arable land. This requires attention, as Switzerland is estimated to be losing 3,400 hectares of arable land each year, despite existing government interventions (FOAG, 2016).

Comprehensive investigations of these and other sustainability-related issues with appropriate indicators, and for different farms, production systems and regions, are crucial for deepening the understanding of sustainability and finding solutions to improve the sustainability of the Swiss agricultural sector.

1.3 OBJECTIVES AND RESEARCH QUESTIONS

Promoting the economic and environmental performance of Swiss dairy farming requires improved know-how at farm level as regards (i) the respective determinants of farm economic and environmental performance and (ii) the relationship between these two dimensions of the sustainable performance of a farm.

Based on a unique and innovative dataset combining precise and comprehensive economic and environmental data collected on-farm for a sample of 56 Swiss alpine dairy farms (Jan et al., 2012a) the present dissertation aims to:

(1) Further develop the thoughts of Jan et al. (2012a) on the conceptualisation and measurement of farm environmental performance into a comprehensive framework;
(2) Comprehensively investigate the synergies and trade-offs involved in the promotion of the economic and environmental performance of the Swiss dairy farms in the mountain region;
(3) Identify at farm level the determinants of economic and environmental performance.

These three main objectives and their corresponding research questions are detailed below.

Objective 1: Starting from the environmental sustainability concept at macro level and based on the initial work of Halberg et al. (2005a) and Jan et al. (2012a), we aim to develop conceptual considerations on how to implement the environmental sustainability concept at farm level into theoretically sound and consistent indicators of farm environmental performance. Building on these conceptual considerations, we then aim to propose a theoretically sound and operational framework for defining and measuring environmental performance at farm level.

Question 1: How has farm environmental performance been defined and measured in the existing scientific literature? Are there any major differences in the approaches to measuring farm environmental performance depending on the scientific research field and, if so, what are they? What are the strengths and weaknesses of the different approaches?

Question 2: What does the macro-level environmental sustainability concept mean, and what does this meaning imply in terms of defining and measuring environmental performance at farm level?

Question 3: How should farm environmental performance be concretely defined and measured, and how not?

Objective 2: Based on the example of Swiss mountain dairy farms and the framework proposed to measure farm environmental performance, we aim to investigate the relationships between (i) farm global and local environmental performance and (ii) farm environmental and economic performance.

Question 1: What is the relationship between farm global and local environmental performance? Are there prevailingly synergies or trade-offs between these two dimensions?

Question 2: What is the relationship between farm global environmental and economic performance? Are the synergies between these two sustainable performance dimensions found by Jan et al. (2012a) for the same dataset robust to the update of the emissions and life cycle impact assessment models and to the choice of the economic performance indicator?

Question 3: What is the relationship between farm local environmental and economic performance? Do synergies or trade-offs prevail between these two dimensions?

Objective 3: Our third objective is (i) to investigate the relationship between different farm characteristics and the global versus local environmental performance and economic performance of Swiss alpine dairy farms and (ii) to identify the characteristics with the potential of simultaneously improving all three performance dimensions.

Question 1: What is the relationship between different structural, technological, managerial, socio-demographic and natural environment characteristics related to the farms and their global versus local environmental and economic performance?

Question 2: Which are the factors that simultaneously improve *versus* worsen all three investigated performance dimensions, i.e. that present a synergy (either positive or negative) in the enhancement of farm environmental and economic performance. Which are the factors that influence at least two performance dimensions in a different direction, i.e. that show a trade-off in terms of promotion of the sustainable performance dimensions considered?

1.4 OUTLINE

This cumulative dissertation is divided into five chapters. Chapters 2 to 4 each focus on one of the objectives and their associated research questions presented previously. Each of these three chapters consists of a scientific article. Two of these three articles (Chapters 2 and 3) have already been published and one of them (Chapter 4) has recently been submitted for publication in a peer-reviewed journal. The last chapter (Chapter 5) provides a summary of the main findings of this dissertation, discusses them and their policy implications, and addresses the limitations of this thesis as well as future research needs. Further details on the papers contained in Chapters 2 to 4 are provided below.

Chapter 2 – Title of the paper: *Implementing farm-level environmental sustainability in environmental performance indicators: A combined global-local approach*

Status:	Published on 1 January 2017
Journal:	Journal of Cleaner Production, 140, 692–704
Authors:	Nina Repar, Pierrick Jan, Dunja Dux, Thomas Nemecek and Reiner Doluschitz

Chapter 3 – Title of the paper: *Local versus Global Environmental Performance of Dairying and Their Link to Economic Performance: A Case Study of Swiss Mountain Farms*

Status:	Published on 10 December 2016
Journal:	Sustainability, 8, 1294
Authors:	Nina Repar, Pierrick Jan, Thomas Nemecek, Dunja Dux, Martina Alig Ceesay and Reiner Doluschitz

Chapter 4 – Title of the paper: *Determinants of global versus local environmental performance and economic performance of dairying: A case study of Swiss mountain farms*

Status: Submitted on 21 April 2017

Journal: Sustainability

Authors: Nina Repar, Pierrick Jan, Thomas Nemecek, Dunja Dux and Reiner Doluschitz

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2 IMPLEMENTING FARM-LEVEL ENVIRONMENTAL SUSTAINABILITY IN ENVIRONMENTAL PERFORMANCE INDICATORS: A COMBINED GLOBAL-LOCAL APPROACH

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Abstract
As major generators of environmental impacts, farms play a crucial role in enhancing the environmental sustainability of food-supply chains. However, appropriately assessing farm environmental performance poses a challenge; a plethora of different indicators have been used for this purpose, sometimes in the absence of conceptual considerations. This paper develops a broadly implementable framework for defining and measuring farm environmental performance which complies with the environmental sustainability concept viewed from an

ecological perspective. After providing a critical review of existing indicators in the literature for measuring farm environmental performance and identifying their strengths and above all their weaknesses, it proceeds to develop ideas on how to implement the environmental sustainability concept at farm level. Starting at the macro level, these ideas are based on the central concept of ecosystem carrying capacity (constraints) referring to biophysical threshold thinking. The implementation of this concept at farm level results in the framework that we propose for measuring farm environmental performance. Environmental sustainability requires compliance with the carrying-capacity constraints imposed by the natural ecosystem within which a farm operates. Compliance with carrying capacity must occur at both local and global ecosystem levels, requiring a distinction between local and global farm environmental performance. The global environmental performance of a farm is defined as its relative contribution to compliance with the carrying capacity of the global ecosystem, and is measured by means of an indicator of environmental intensity over the entire production chain up to the farm gate. The local carrying-capacity constraint can be understood as the maximum environmental impact per unit of farmland area that can be sustained by the local ecosystem. Local environmental performance is therefore measured by means of an area-based indicator. Whereas all environmental issues must be considered at a global level, for some of them local level consideration is also required. Implementing separate local and global environmental performance indicators, as opposed to using only global or local indicators without distinguishing between them in conceptual terms, provides a more appropriate assessment of the environmental performance of farms, as well as a better basis for comparison between farms. Furthermore, it eliminates the risk of shifting environmental problems from the local to the global scale or vice-versa. The framework highlights the complexity of the environmental sustainability concept, which cannot be reduced to a single “one size fits all” indicator.

2.1 INTRODUCTION AND OBJECTIVES

Agricultural activity has always shared a close bond with the surrounding natural ecosystem as a result of the complex network of interactions occurring between this human activity (technosphere) and the natural environment in which it operates (biosphere) (Schau & Fet, 2008). These interactions have allowed agriculture to use many natural ecosystem services in its production processes (Zhang et al., 2007). At the same time, agriculture has generated negative environmental externalities influencing the health and wellbeing of the ecosystem that provides these vital services (Dale & Polasky, 2007; Power, 2010). The list of these externalities is long, and includes greenhouse-gas emissions, pollution due to nutrient run-off, water shortages, soil degradation, loss of biodiversity, and disruption of aquatic ecosystems (Godfray et al., 2010).

Nowadays, the link between agriculture and the ecosystem is of increasing concern, given that "green revolution" technologies and the associated decades of agricultural intensification, which have succeeded in increasing food production, have also caused extensive environmental damage at the local, regional and global levels of the Earth ecosystem (Matson et al., 1997; Vitousek et al., 1997; Foley et al., 2005). Humanity has reached the point where "*its rapidly growing reliance on fossil fuels and industrialized forms of agriculture could damage the systems*" that have kept the Earth in the state suitable for the development of human life, as it may be approaching planetary boundaries for global freshwater use, change in land use, ocean acidification, and interference with the global phosphorus cycle, whereas climate change, biodiversity loss, and nitrogen cycles have already exceeded these boundaries (Rockström et al., 2009). At the same time, at a global level, rising populations and the economic growth of developing countries are leading to a major increase in the demand for food and to changes in food consumption patterns marked by an increase in the proportion of fats and animal proteins in the human diet (Gerbens-Leenes et al., 2010; Godfray et al., 2010). This in turn calls for further increases in agricultural production, putting even greater pressure on scarce natural resources (Gerbens-Leenes et al., 2010). These global trends underscore the importance and urgency of effectively addressing environmental issues in agri-food systems, and demand further exploration of innovative solutions and approaches for successfully dealing with the problems in question.

There are several reasons why farms play such an important role in creating sustainable food chains. First of all, farms are the place where day-to-day decisions regarding the use of economic and environmental resources are made. Taken as a whole, these decisions result in the production of agricultural commodities and services, but also cause negative environmental externalities. Owing to the particular role played in the agricultural production process by land, environmental resource use in agriculture is in many respects highly specific.

Secondly, once we recognise the role of farms as major environmental impact generators in the food chain, their importance in achieving sustainable food chains becomes even more evident. For the environmental impacts related to nutrient management, toxicity, phosphorus, and land use in particular, the cradle-to-farm- gate link is responsible for a large share of the impacts generated over the entire food supply chain (e.g. Eide, 2002; Hospido et al., 2003; Gerber et al., 2010; Thoma et al., 2013; Bystricky et al., 2014a for the dairy chain; Korsaeth et al., 2012; Bystricky et al., 2014a; Kulak et al., 2014 for the bread supply chain). The monitoring, assessment and enhancement of farm environmental performance is therefore an issue of the utmost importance for improving the environmental sustainability of the entire food chain. Environmental performance is generally defined here as the ability of a farm to comply with the biophysical restrictions (in terms of the use of natural resources and generation of polluting emissions) imposed by the natural ecosystem in which it operates to ensure the short- and long-term provision of the support, regulatory and provisioning services rendered by said natural ecosystem to humanity.

In scientific practice, a plethora of different indicators have been used to measure environmental performance at farm level. In many studies, the definition of these environmental indicators is mainly driven by considerations regarding data availability or data-collection feasibility, without conceptually considering which indicators are actually required for the assessment of farm environmental performance. An absence of conceptual considerations behind the indicators may result in the questionable relevance and usefulness of the indicators thus obtained.

To ensure truly sustainable development in the agri-food sector, it is essential for farm environmental performance indicators to be consistent with the meaning and principles of the sustainability concept originally derived from the macro level. Such indicators aim to compare farms in terms of their relative contribution to environmental sustainability, and ultimately to improve environmental performance. Taking the macro-level environmental sustainability concept as its point of departure, this paper therefore aims (i) to develop ideas on how to implement the environmental sustainability concept at farm level, and (ii) to build on these ideas in order to propose a sound framework for defining and measuring environmental performance at farm level.

Our research makes a threefold contribution to the discussion on farm environmental performance assessment. Firstly, our work focuses exclusively on defining and measuring environmental performance at farm (i.e. micro-) level. Secondly, the development of environmental performance indicators starts with and is based on consideration of the importance and implications of the macro-level environmental sustainability concept for the definition and measurement of environmental performance at farm level, which to the best of our knowledge is the main uniqueness of our work. The development of indicators is thus rooted in a more general context ensuring that the developed indicators are consistent with the macro-level environmental sustainability concept as viewed from an ecological perspective. Thirdly, our considerations attempt to reconcile different perspectives, namely the macro- vs. the micro-perspective, and the economists' vs. the natural scientists' view.

The present paper is organised as follows: Section 2.2 provides a literature review of the typologies of indicators designed to measure farm-level environmental performance. This section does not purport to provide an exhaustive, in-depth review of all existing indicators. Rather, its main general objective is to classify the existing range of indicators into different types and – based on selected examples of types of farm environmental performance indicators – to show how limited some indicators may be, and why it is essential to consider the meaning behind farm environmental performance if we wish to move towards greater sustainability in agricultural production. Section 2.3 deals with the theoretical underpinnings of our work, focusing on the concepts of environmental sustainability and carrying capacity. The aim of this section is to provide a sound basis for implementing the macro-level environmental sustainability concept in farm environmental performance indicators. In Section 2.4, we propose the framework for defining and measuring environmental performance at farm level, followed by a discussion in Section 2.5 and conclusions in Section 2.6.

2.2 MEASURING ENVIRONMENTAL PERFORMANCE AT FARM LEVEL: A LITERATURE-BASED REVIEW OF THE EXISTING TYPES OF INDICATORS AND APPROACHES USED IN THE ASSESSMENT OF FARM ENVIRONMENTAL PERFORMANCE

A review and analysis of the literature reveals a wide variety of indicators that have been used to measure environmental performance at farm level. This section aims to classify the range of indicators found in the literature, to discuss the main types of indicators, and to draw initial conclusions regarding their suitability for assessing farm environmental performance. Defining a farm environmental performance indicator involves two steps: (i) the choice of the variable to be used to assess the environmental impact of the investigated farming system (said variable being hereafter also referred to as the "environmental indicator"); and (ii) the definition of the environmental performance indicator (hereafter also referred to as the "performance indicator"), which is based on the environmental variable of the first step. In a first subsection, we present different typologies found in the literature for classifying the different types of variables used to assess the environmental impact of a farming system. The strengths and weaknesses of the main types of environmental indicator are then discussed. In a second subsection, we describe the three main streams of approach for defining the performance indicator, followed by a critical review of these three streams of approach. The last subsection summarises the lessons to be learned from this review.

2.2.1 Typologies of existing farm-level environmental indicators and related terminologies

The present subsection is primarily based on Van Der Werf & Petit (2002), Schröder et al. (2003), and Payraudeau & Van Der Werf (2005), who propose typologies of different possible variables that can be used to assess the environmental impact of farming systems. These variables are indicators which are alternative or indirect measures that provide information on the farming system's impact on the environment in terms of the issue of concern (Van Der Werf & Petit, 2002; Payraudeau & Van Der Werf, 2005). The use of environmental indicators is motivated by the difficulty of making direct measurements owing to e.g. methodological problems or practical reasons of cost and time (Bockstaller & Girardin, 2003).

2.2.1.1 Indicator position in the environmental impact pathway

In their review of methods for the environmental impact assessment for a farming region, Payraudeau & Van Der Werf (2005) distinguish between four environmental indicator classifications (and associated terminologies) depending on the part of the cause-effect chain, also called impact pathway (linking the agricultural production practices to environmental impact), covered by the classification and on the position of the indicators in this chain. These are (i) pressure and state indicators, (ii) means-based and effect-based indicators, (iii) emission and impact indicators, and (iv) midpoint and endpoint indicators. As is obvious from Payraudeau &Van Der Werf (2005), indicator classifications i-iv are not mutually exclusive, but rather interconnected.

There is a trade-off between the feasibility and environmental relevance (i.e. the effectiveness of the environmental assessment) of environmental indicators (Payraudeau & Van Der Werf, 2005). Basically, indicators at the beginning of the cause-effect chain (e.g. the nitrogen fertiliser applied) are easier to quantify than indicators at the end of this chain (e.g. potential disappeared fraction of species due to eutrophication). However, the indicators at the beginning of the chain are poorly related to the environmental objective and thus do not allow an actual evaluation of the environmental effect of farming practices (Van Der Werf & Petit, 2002). On the other hand, end-chain indicators have a higher relevance in environmental terms than those at the beginning of the chain, because they are much closer to showing the actual influence on the state of the environment (Payraudeau & Van Der Werf, 2005). Nevertheless, the assessment of end-chain indicators remains a highly challenging undertaking. The assessment of environmental impacts often requires a very comprehensive data collection and highly complex impact-assessment models, which in turn increases the costs and uncertainty of the assessment, often leading in practice to the use of means-based indicators that are easier to measure (Bare et al., 2000; Van Der Werf & Petit, 2002; Jolliet et al., 2004; Payraudeau & Van Der Werf, 2005).

Considerations in the literature confirm that preference should be given to indicators at the end of the cause-effect chain (Van Der Werf & Petit, 2002; Payraudeau & Van Der Werf, 2005) or, if this is not possible, to indicators with an intermediate position on the means- and effects-based spectrum. The use of means-based indicators is not recommendable because evaluations based on this type of indicators "*will not contribute to recognising errors and improving practices*" (Van Der Werf & Petit, 2002).

Whether midpoint or endpoint impact indicators are to be preferred is a question that has been discussed in the life cycle assessment (LCA) literature (e.g. Bare et al., 2000; Payraudeau & Van Der Werf, 2005). Due to the complexity and uncertainties associated with endpoint modelling (Jolliet et al., 2004), the use of midpoint indicators is often deemed to be a more pragmatic solution offering the best compromise between environmental relevance and indicator accuracy (Bare et al., 2000; Payraudeau & Van Der Werf, 2005).

2.2.1.2 Spatial system boundaries of the environmental assessment

Environmental indicators differ not only in terms of their position in the cause-effect chain, but also with respect to the spatial system boundaries of the underlying environmental assessment, i.e. to the part (links) of the food (or value) chain covered by this assessment. Whereas conventional, non-LCA-based farm environmental assessments cover just the farm itself ("on-farm assessment"), LCA-based farm environmental performance assessments adopt a production-chain perspective, and hence encompass both on-farm and off-farm links (upstream stages) of the production chain. LCA is a methodological framework for assessing the environmental impacts of a product throughout its whole life cycle (i.e. from "cradle to grave") (Rebitzer et al., 2004). Despite this, most LCA applications conducted at whole-farm level which aim to assess farm environmental performance do not cover the entire life cycle of the products, but focus on the cradle-to-farm-gate link of the food chain. This exclusion of the farm-gate-to-grave link is explained by the fact that the farmer has very little (if any) influence on what happens in the downstream stages (processing, retail, and consumption) of the food chain. The focus on the cradle-to- farm-gate link assumes that the nature of the activities occurring at farm level is homogeneous among the farms investigated, and, above all, that no processing or any other downstream-stage activities occur at farm level, or – if they do – that they should be excluded from the LCIA. This cradle-to-farm-gate-chain perspective prevents the shifting of any environmental impacts from the on- farm to the upstream stage of the agricultural production process, and is therefore preferable to an assessment that focuses exclusively on the on-farm level.

2.2.2 Moving from environmental variables to farm-level performance indicators: three main groups of approaches

Once the environmental indicator is defined and assessed, the second step of any farm environmental performance assessment is to define the performance indicator deriving from the environmental indicator that will enable a comparative judgement of farms in terms of their compliance with the environmental sustainability objectives. This section reviews the three main groups of approaches to defining the environmental performance indicator that are found in the literature.

2.2.2.1 Productive-efficiency-based approaches

Agricultural economists from the productive efficiency field have generally followed one of four different types of approaches for assessing environmental performance at micro-level. The first stream of approach, labelled environmentally adjusted production efficiency (EAPE) by Lauwers (2009), involves integrating environmental issues – especially the undesirable environmental output – into traditional approaches to assessing (economic) productive efficiency, and "*treating the environment as merely one criterion among others in a technically oriented efficiency assessment*" (Kuosmanen & Kortelainen, 2005). As emphasised by Lauwers (2009), the manner in which the undesirable outputs are included in the model (i.e. the specification of the model used to measure efficiency) influences not only the results but also their interpretation. For example, Reinhard et al. (1999) define environmental efficiency as the "*ratio of minimum feasible to observed use of an environmentally detrimental input [nitrogen surplus], conditional on observed levels of the desirable output [monetary farm output] and the conventional inputs [conventional economic inputs: labour, capital, and variable inputs]*".

Over the past decade, alternative productive-efficiency-based approaches have been proposed to measure environmental performance. One of these alternative approaches tackles the issue from the perspective of ecological economics or industrial ecology. Instead of including environmental issues in conventional models for measuring productive efficiency, this alternative approach, also referred to by Lauwers (2009) as the frontier eco-efficiency (FEE) model, assesses eco-efficiency separately by considering the economic outcome as an output and the environmental outcome (e.g. emissions or environmental impacts) as an input in the production model (Lauwers, 2009).

Coelli et al. (2007) and Hoang & Coelli (2011) have shown that a number of the EAPE models mentioned previously are inconsistent with the materials balance condition, also referred to by Lauwers (2009) as the materials balance principle (MBP). Also known as the first law of thermodynamics or law of conservation of mass/energy (Hoang & Rao, 2010) and applicable to all materials (such as nutrients) and energy flows, this principle is "*an essential biophysical* *condition stating that flows from and into the environment are equal*" (Lauwers, 2009). To overcome the MBP inconsistency problem of EAPE methods, Coelli et al. (2007) propose an approach that treats the nutrient content of inputs and outputs in the same way as input and output prices are treated in cost-, revenue-, or profit-efficiency assessments. Termed the MBP-adjusted approach by Lauwers (2009), this third stream of approach can be implemented for all nutrients (e.g. nitrogen, phosphorus). The environmental efficiency of a farm – defined as "*the ratio of minimum nutrients over observed nutrients*" (Coelli et al., 2007) – can be broken down into its two component parts, namely technical efficiency and environmental allocative efficiency.

Hoang & Rao (2010) argue that environmental efficiency measures based on the MBP-adjusted approach are faced with two main limitations. The first is the ambiguous treatment of non-material inputs such as labour, capital, and services, for which no universally accepted weights (materials content) are available (Hoang & Rao, 2010). The second limitation derives from the problem of choosing weights when more than one material is involved in the production process (Hoang & Rao, 2010; Hoang & Alauddin, 2012).

These two limitations can be overcome by making use of the cumulative exergy balance instead of the material balance (Hoang & Rao, 2010). The cumulative exergy balance is calculated as the difference between the cumulative exergy in inputs and exergy in outputs (Hoang & Rao, 2010; Hoang & Alauddin, 2012) and thus implies the adoption of an LCA perspective. The cumulative exergy balance is incorporated into frontier-based methods for the assessment of environmental performance in much the same manner as the materials balance. The sustainable efficiency derived from the cumulative exergy balance (CEB) approach is defined "*as the ratio of feasible minimum total amount of cumulative exergy to the aggregate cumulative exergy in the observed input vector*" (Hoang & Rao, 2010), and can be broken down into the components of technical efficiency and exergy allocative efficiency (Hoang & Rao, 2010).

As outlined by Hoang & Alauddin (2012), the CEB approach does not render the MBP-adjusted approach redundant. Whereas the CEB approach is better suited to capturing the aggregate effects of cumulative resources use and pollution, the MBP-adjusted approach is particularly suitable for the analysis of more-specific types of pollution, provided that a proper science-based quantification of the weights of various materials is possible (Hoang & Alauddin, 2012).

2.2.2.2 LCA-based approaches

In an LCA-based approach, the environmental performance indicator is defined via the definition/choice of functional unit (FU) that occurs according to ISO (2006) in the "goal and scope definition" phase of an LCA. Environmental performance is expressed as the amount of environmental impacts generated per FU. Each agricultural system investigated fulfils one or more functions. The FU quantifies the function of a product system (adapted from ISO, 2006) or, put differently, assesses the services provided by the system investigated in terms of the function under consideration. For example, the function of providing food by delivering energy to the human body can be quantified using the FU "digestible energy output". The environmental performance of a farm is quantified by relating the environmental impact of the farm to the FU in question. The choice of FU is highly dependent on the aim of the investigation (De Boer, 2003; Schau & Fet, 2008; Hokazono & Hayashi, 2015; Van Der Werf & Salou, 2015). Basically, three main groups of FUs can be distinguished: product-based, area-based, and financial FUs. The classification proposed below is derived from the considerations of Nemecek et al. (2008), Schau & Fet (2008), and Van Der Werf et al. (2014), supplemented by a literature review of the FUs used in farm-level LCAs. The product-based FUs refer to the productive function of agriculture (the production of food, feed, and biomass), and include (i) mass or volume FUs, (ii) nutritional FUs quantifying the nutritional value (e.g. energy or protein content) of the food produced, and (iii) monetary FUs reflecting the monetary value of the food, or more generally, outputs, produced. The area-based FUs (i.e. the surface area of the land used) relate to the land-use/land-occupation function of agriculture, while the financial FUs refer to the function of farm income/profit generation, and include FUs such as farm gross margin and farm net income.

Farm-level LCA applications found in the literature either use one FU only (mainly product-based, viz., mass, volume, or energy FUs – e.g. Cederberg & Mattsson, 2000; Casey & Holden, 2005, 2006; Thomassen et al., 2008; Mu et al., 2014) or multiple FUs. In the latter case, either product-based and area-based FUs are both applied for all impact categories (e.g. Basset-Mens & Van Der Werf, 2005; Hokazono & Hayashi, 2015), or, in some investigations, product-based FUs are applied for all impact categories combined with area-based FUs for selected impact categories (such as eutrophication and acidification e e.g. De Boer, 2003; Thomassen et al., 2009). A few applications also implement three types of FUs for all impact categories considered, (e.g. Van Der Werf et al., 2009; Van Der Werf & Salou, 2015).

The choice of FU is particularly crucial when comparing products in the agricultural sector, since the results of the comparison of farming systems (e.g. intensive vs. organic farming) will vary substantially depending on the FU chosen (see for instance Halberg et al., 2005a; Van Der Werf & Salou, 2015).

2.2.2.3 Approaches outside the LCA and productive-efficiency field

To create a farm environmental performance indicator, most environmental scientists foreign to the LCA field as well as agricultural economists outside of the productive-efficiency field take a somewhat similar approach to that of environmental scientists from the LCA field. The performance indicator is also expressed as the ratio between the environmental indicator and a specific FU (e.g. ha of land area). The environmental variables used are either means-based (e.g. nitrogen fertiliser applied) or have an intermediate position on the means- and effect-based spectrum (e.g. nitrogen surplus). The two most common groups of FUs are the product-based ones (e.g. kg of output; cf. e.g. Nevens et al., 2006; Beukes et al., 2012) and the area-based ones (land area, e.g. Oenema & Pietrzak, 2002; Nielsen & Kristensen, 2005; Groot et al., 2006; Nevens et al., 2006; Jan et al., 2015; Micha & Heanue, 2015). Detailed examples of such indicators can be found in Van Der Werf & Petit (2002), Schröder et al. (2003), and Halberg et al. (2005b).

2.2.3 Critical review of existing farm-level environmental performance indicators

This subsection provides a critical review of the three main groups of approaches for defining and measuring farm environmental performance presented in Section 2.2.2, with a special focus on (i) the productive efficiency measures adapted for use as environmental-performance measurement tools, and (ii) the discussion of FUs from an LCA perspective.

2.2.3.1 Approaches from the productive efficiency field: moving from approach-driven to problem-driven

The first type of approach (EAPE models) proposed in the productive-efficiency field to assess environmental performance at micro-level was more approach-driven than problem-driven.

Essentially, the question originally addressed during development of the EAPE models was not how to define environmental performance at micro-level in a manner consistent with the (biophysical) environmental sustainability concept, but rather how to incorporate environmental issues in the existing approaches or, put differently, how to accommodate the existing models to take into account environmental pollutants or, more generally, environmental "bads". With the emergence of the FEE approach, and later, of the MBP-adjusted and CEB approaches, environmental performance development became less approach- and more problem-oriented. Basic biophysical laws underlying ecosystem functioning, and hence a more biophysical concept of environmental sustainability, gradually came to the fore. Despite this new and highly valuable perspective, a thorough consideration of how to implement the environmental sustainability concept at farm level – or, more generally, at micro-level – in environmental performance indicators is still absent. This may be because the primary focus of work done in this field is still the methodological development of productive-efficiency measurement tools.

2.2.3.2 "Functional units" approach from the LCA field

The FU-based approach used in the LCA field is – compared with the approaches coming from the productive efficiency field – less methodologically driven and more focused on the issue of environmental sustainability. Even so, farm-level applications of this approach also suffer from shortcomings. Firstly, some performance indicators originating in this field suffer from a system-boundaries inconsistency between the environmental impact variable and the chosen FU. This is seen to be the case when we analyse the environmental performance in terms of its landscape maintenance[3] function. The performance indicator created for this purpose relates the environmental impacts generated throughout the entire chain up to the farm gate to the farm's usable agricultural area, the latter representing only the on-farm part of the production chain. The estimated cradle-to-farm-gate environmental impacts are however also very often associated with landscape maintenance in the off-farm upstream stages of the life cycle.[4] This

[3] "Landscape maintenance" is used here as a generic term for the function of land use, or more precisely, for the maintenance of a cultivated/open landscape.

[4] This is e.g. the case when the farm investigated purchases forage (such as hay) from another farm.

off-farm land- scape maintenance is not taken into account in the on-farm area. From a life-cycle perspective, in order to keep the spatial system boundaries consistent, the off-farm landscape maintenance (i.e. the corresponding off-farm area) associated with the activity of the farm investigated should also be included in the area-based environmental performance indicator. The particular treatment of landscape maintenance results from the non-market good/positive externality nature of this output. This example shows how important it is to keep the spatial boundaries of the system clearly defined and consistent when creating the performance indicator.

Secondly, the use of monetary FUs in LCA environmental performance indicators is highly problematic; because prices are very often biased and do not reflect the real scarcity of goods and resources, the use of monetary FUs may yield biased environmental performance indicators. However, assuming perfectly competitive and efficient markets, and hence unbiased prices, monetary FUs possess two decisive advantages. Firstly, prices enable the aggregation of different biophysical outputs expressed in the same or different units to a single monetary output. Secondly, the monetary FU (also referred to as the "economic value FU") is able to take account of the quality of a product based on the latter's price (Van Der Werf & Salou, 2015). This second advantage, however, is not supported by empirical evidence. Several studies have in fact shown that price and quality are only weakly correlated, especially in the food and beverages sector, "*making price a poor signal to infer quality from*" (Kirchler et al., 2010). In the German food sector, the price-quality correlation has even been found to be negative (Schulze et al., 2008).

Thirdly, and more generally, the choice of FU(s) for deriving the environmental performance indicator(s) should stem from consideration of the significance of the farm environmental performance concept, and not, as is the case in several contributions, from a simple consideration of all functions that agriculture can potentially fulfil. We would argue that when defining FUs for the purpose of measuring environmental performance, the focus should be on the primary functions of agriculture from a biophysical environmental perspective, viz., the production of food, feed, and biomass, as well as land use. The financial function is not one of agriculture's main biophysical environmental functions, and is therefore not of interest in an environmental performance assessment.

We are aware that monetary FUs associated with the financial function are used with the aim of obtaining a sort of "all-in-one" combined economic/environmental performance indicator. This demonstrates that the performance indicators derived from the LCA-based FU approach follow one of two different (conceptual) objectives – to measure environmental performance, or to assess combined environmental/economic performance. It is unlikely that all LCA practitioners are aware of this (conceptual) distinction, which might make the correct interpretation of the indicators difficult.

2.2.3.3 Approaches outside of the LCA and productive-efficiency field

Because this approach category does not apply a life-cycle perspective to the process of quantifying environmental performance, it risks shifting environmental problems from one part of the life cycle to another. To give an example, if a dairy farm that depends heavily on concentrates and whose production generates environmental impacts in the upstream stages has performance indicators that focus on on-farm impacts, the existence of these upstream impacts will be ignored, causing the farm's environmental performance to appear better than it actually is, owing to the shifting of the environmental problems from the farm to the upstream stages. Furthermore, a boundary problem may occur if the environmental variable is associated with an FU taking into account the cradle-to-farm-gate link of the life cycle (as is the case with most product-related FUs). Moreover, the use of performance indicators that rely on means-based environmental variables can be contested for the reasons set out in Section 2.2.1. Last but not least, just as with any other environmental performance assessment, the use of monetary FUs is deemed inappropriate in this context as well.

2.2.4 Summary of the lessons learned

The aim of this review was not to provide an exhaustive examination of all existing indicators for measuring environmental performance at farm level, but rather to furnish a systematic overview of the main types of farm environmental performance indicators found in the literature together with a number of critical considerations, and to discuss the strengths and weaknesses of these indicators.

The review clearly highlights the existence of numerous approaches or indicators used to measure farm environmental performance, to a large extent owing to the different academic backgrounds of these publications (i.e. natural sciences as opposed to agricultural economics). Whereas natural scientists seem to focus more on a wide range of individual performance indicators when assessing environmental performance, agricultural economists tend to refine existing approaches from the sphere of productive (economic) efficiency measurement for use as environmental performance measurement tools.

Furthermore, the review shows that existing approaches vary greatly in terms of (i) the environmental indicator's position in the environmental impact pathway, (ii) spatial boundaries of the system underlying the environmental assessment, and (iii) definition of the performance indicator.

Although explicit definitions of farm environmental performance are rarely found in the literature, an implicit definition can be derived primarily from the type of variable(s) chosen to represent environmental performance. The different groups of approaches for determining environmental performance reflect different understandings of the concept, shaped primarily by the outlook of the scientific field in question. Ideally, however, the definition of environmental sustainability should not depend on the researcher's discipline.

Several problems relating to the assessment of farm environmental performance addressed in this review indirectly highlight the lack of attention paid to the implementation of the environmental sustainability concept at farm level. This might result in indicators that are not appropriate for decision-making. The following section therefore explores the theoretical foundations on which the farm environmental performance concept must be based if meaningful measures and definitions are to be developed.

2.3 THEORETICAL UNDERPINNINGS: FROM ENVIRONMENTAL SUSTAINABILITY TO FARM ENVIRONMENTAL PERFORMANCE

Starting from the macro-level (environmental) sustainability concept, the aim of this section is to develop ideas on how (and how not) to implement this concept in farm- (i.e. micro-) level environmental performance indicators.

2.3.1 Environmental sustainability: a biophysical concept

Sustainable development and concepts relating to sustainability were widely popularised by the report "Our Common Future", published in 1987 by the World Commission on Environment and Development (WCED). In this report, sustainable development is basically defined as development "*that meets the needs of the present without compromising the ability of the future generations to meet their own needs*" (WCED, 1987). The approach to sustainability advocated by the WCED (1987) has been criticised on various accounts, ranging from the scientific appropriateness of the concept of human-needs satisfaction (Karoly, 2011), to the very idea of limitless growth (Goodland, 1995), to its non-consideration of the ecological (biophysical) carrying-capacity constraint of the Earth's ecosystem(s) (Rees, 1996). A focus on the ecological perspective of the ecological (biophysical) carrying-capacity constraint considered here creates a general definition of environmental sustainability similar to the WCED's oft-quoted definition of sustainable development, but which adds the crucial component of ecosystem health – namely, "*meeting the resource and services needs of current and future generations without compromising the health of the eco-systems that provide them*" (Morelli, 2011). More precisely, environmental sustainability can be defined as a "*condition of balance, resilience, and interconnectedness that allows human society to satisfy its needs while neither exceeding the capacity of its supporting eco-systems to continue to regenerate the services necessary to meet those needs nor by our actions diminishing biological diversity*" (Morelli, 2011). Similarly, Goodland (1995) defines the ultimate goal of environmental sustainability as the perpetual maintenance of global life-support systems through sustaining the environmental sink and source capacities. He considers environmental sustainability to be composed of a set of constraints on the four major activities in the human economic subsystem: the use of renewable and non-renewable resources on the source side, and pollution and waste assimilation on the sink side.

Owing to the complexity of the issue, measuring environmental sustainability remains a challenging problem. Monetary evaluations in particular are fraught with serious difficulties owing to the biased nature of price information, which in turn stems from the fact that prices very often fail to reflect the real scarcity of goods and resources, since "*standard monetary analyses are blind to ecological structure and function and are therefore incapable of indicating either ecologically meaningful scarcity or incipient systems destabilization*" (Rees, 1996). Evidence suggests that in the case of natural resources, prices are often far from reflecting true scarcities, due to the occurrence of market failures (Cabeza Gutés, 1996; Farley, 2008; Turner & Daily, 2008) such as the inability of market-price formation to take into account future scarcities (Browne, 2012) and, above all, to integrate the demand of future generations (Bromley, 1989). For this reason, the use of "*environmentally myopic market signals*" when performing biophysical evaluations (Pelletier & Tyedmers, 2011) is strongly discouraged. It is important to bear in mind that environmental sustainability is a natural-science concept governed by biophysical laws that cannot be ignored (Goodland, 1995). In choosing the indicators for environmental evaluations or performance assessments, therefore, biophysical indicators should take precedence over monetary indicators. In agriculture, biophysical variables are associated with the primary functions of agriculture as viewed from a biophysical environmental perspective, namely the production of food, feed, and biomass, and in some cases land use.

2.3.2 Carrying-capacity compliance as a precondition for environmental sustainability

Environmental sustainability requires humanity to remain within the biophysical carrying capacity of the planet (Robinson, 2004). More precisely, this straightforward precondition for environmental sustainability means that "*human population and activity should not surpass the carrying capacity of the biosphere, its renewing, resource, and sink capacities*" (Karoly, 2011), or, in other words, "sustainability depends on the size and spatiotemporal characteristics of humanity's footprint relative to Earth's carrying capacity" (Hoekstra & Wiedmann, 2014). As with Lowe & Evans (1995), the concept of ecosystem carrying capacity is central to our conceptual considerations with respect to the implementation of the environmental sustainability concept at farm level. Carrying capacity is understood as the "*maximum load that can be safely imposed on the environment by people*", or more precisely, as the "*maximum rates of resource harvesting and waste generation (the maximum load) that can be sustained indefinitely without progressively impairing the productivity and functional integrity of relevant ecosystems wherever the latter may be located*" (Rees, 1996). This carrying capacity is closely related to the input-output rule for environmental sustainability (e.g. keep wastes within assimilative capacities, harvest within regenerative capacities of renewable resources, deplete non-renewable ones at the rate at which renewable substitutes are developed) proposed by

Goodland & Daly (1996). Carrying capacity refers to area-based biophysical threshold thinking (maximum sustainable environmental impact per unit area).

While conceptualising the carrying capacity is in itself a challenge, measuring the amount of pressure that the Earth can sustain is an even more difficult undertaking because of the various uncertainties, ambiguities and subjectivities surrounding this issue (Hoekstra & Wiedmann, 2014). In presenting their approach to quantifying and measuring planetary boundaries, Rockström et al. (2009) employ a concept akin to carrying capacity, that of planetary boundaries. These boundaries "*define the safe operating space for humanity with respect to the Earth system and are associated with the planet's biophysical subsystems and processes*" (Rockström et al., 2009). Faced with vast knowledge gaps and quantification challenges, the attempt to define the exact planetary boundaries for various Earth-system processes is plagued by a high degree of uncertainty (Rockström et al., 2009).

2.3.3 Implementing carrying capacity at farm level

In the case of agriculture, the exceeding of the carrying capacity limit is becoming particularly evident and is a cause for concern (Rees & Wackernagel, 2013) – a fact that highlights the crucial importance of bearing in mind this issue when assessing environmental sustainability at farm level. The challenge when developing farm environmental performance indicators is therefore how to relate carrying-capacity considerations originating at planet (i.e. macro-) level and, more specifically, the associated absolute global biophysical thresholds, with the farm (i.e. micro-) level.

Basically, we can distinguish two levels at which the carrying capacity constraint applies for ensuring sustainable development: that of the global ecosystem (planet Earth), and that of the local ecosystem underpinning the farm area (sub-ecosystem of the global ecosystem) (Lowe & Evans, 1995). The local ecosystem has a more or less narrowly defined local dimension. Depending on the environmental-issue/impact category considered, this ranges from a very local to a more regional level, and can also encompass a homogeneous ecosystem area inside a region or country (cf. also the issue of local carrying-capacity entitlement in the Discussion section). Both local and global carrying capacities are intrinsic characteristics of the ecosphere's closed system, and limiting factors for the economic activity in the technosphere (Wackernagel

& Rees, 1997).

Complying with the carrying capacity constraints at both global and local ecosystem level is a prerequisite for achieving a sustainable state with no possibilities for compensation or substitution available between these two levels. Based on this distinction, and as proposed by Jan et al. (2012a), we differentiate between the local and global environmental performance of a farm. Farm local and global environmental performances measure the extent to which a farm complies, respectively, with the local and global carrying-capacity constraints. The local environmental performance of a farm also possesses a regional character. The link with the regional scale occurs when the local carrying-capacity entitlement of the farm is quantified as explained in the Discussion.

2.4 DEFINING AND MEASURING THE GLOBAL VS. LOCAL ENVIRONMENTAL PERFORMANCE OF A FARM

Implementing global and local carrying-capacity constraints at farm level is the challenge posed by the development of farm environmental performance indicators. This section precisely defines and specifies the measures to be used when assessing the local and global dimension of a farm's environmental performance. As explained in Section 2.2.1, we propose the use of environmental performance indicators based on environmental variables that best represent the potential damage to the environment. The closer the environmental assessment is to the ultimate environmental impact, the more relatable the impact will be to environmental sustainability and carrying-capacity constraints. Despite this, unless the endpoint modelling is associated with a high level of certainty, the midpoint impact indicators will provide a more feasible solution, for the reasons already set out in Section 2.2.1.1.

2.4.1 Local vs. global environmental performance of a farm

At local ecosystem level, the use of an indicator termed “local environmental performance” and defined as the local environmental impact generation per unit of (local) farm area enables us to assess the intensity of the farm's environmental impact generation on its local ecosystem, and thus – when this is compared to the carrying capacity of the local ecosystem – its compliance with the said local-ecosystem carrying capacity. If the local environmental impact per unit area is greater than the carrying capacity of the local ecosystem, then the situation is unsustainable. While it is fairly easy to establish the link between carrying-capacity constraint and farm unit at local ecosystem level, this is not the case at global ecosystem level. Indeed, direct implementation of the global carrying-capacity constraint at farm level is a highly challenging if not impossible undertaking, requiring as it does an allocation of the planetary carrying capacity to each polluting unit (companies, households, etc.) of planet Earth. Such an allocation could not be implemented on an exclusively scientific basis, but would also need to bear in mind the preferences of society and interspatial equity, a fact which highlights the extreme complexity of such an allocation. Using a farm environmental intensity indicator (defined as the inverse of eco-efficiency) over the entire production chain up to the farm gate in order to measure global environmental performance enables us to tackle this problem and to indirectly link global-ecosystem carrying capacity with the farm unit. In point of fact, even if a low environmental intensity level does not guarantee that the absolute carrying-capacity thresholds at global ecosystem level will not be exceeded, a relative comparison among farms of the value of this indicator allows us to measure the relative contribution of each farm and its production chain to the reduction of environmental impact generation at global ecosystem level, and thus its contribution to compliance with carrying capacity at this level.

Whether a local or global carrying-capacity constraint, or indeed both types of constraint, apply for a given environmental issue depends on the scale (local or global) of environmental relevance of the impacts associated with the issue, i.e. the (local or global) level at which the environmental impacts ultimately affect carrying capacity. For some environmental issues, both local and global carrying-capacity constraints may be of relevance, while for others only one or the other may apply, as will be shown below.

The global/local farm environmental performance distinction proposed here on the basis of our theoretical considerations has already been suggested in the literature; in fact, various authors point out that environmental problems of a local and global nature must be considered separately with different indicator types when assessing a farm's environmental performance (Haas et al., 2000; Van Der Werf & Petit, 2002; De Boer, 2003; Halberg et al., 2005a; Payraudeau & Van Der Werf, 2005; Blonk et al., 2010; Jan et al., 2012a).

Halberg et al. (2005a) make a substantial contribution in this respect, proposing the use of area-based indicators for environmental issues with a local dimension, and product-based indicators for those of a global nature. They also recommend that only those environmental impacts occurring at local farm level be included in the area-based indicator of local environmental performance. The product-based indicator of global environmental performance should for its part encompass the environmental impacts generated both at farm level and in the upstream stages of farm-input production, i.e. over the entire production chain up to the farm gate.

2.4.2 Global environmental performance

As mentioned previously, a farm's global environmental performance is measured by means of an indicator of environmental intensity over the entire production chain up to the farm gate. As Formula 2.1 below shows, environmental intensity is thus defined as the overall level of environmental impact generated throughout the entire production chain up to the farm gate per (bio-)physical unit of output produced by the farm.

Formula 2.1

$$Global\ environmental\ performance = \frac{EI_{glob}}{farm\ physical\ output}$$

EI_{glob}: global environmental impact

It is important to emphasise here that, for the reasons exposed in Section 2.3.1, it is necessary to use a biophysical output variable related to the basic functions of agriculture from a biophysical environmental perspective to avoid any biases induced by the use of monetary variables. A farm is conceptualized here as a biophysical transformation process of natural resources into biophysical outputs. Basically, three major categories of biophysical outputs or functions fulfilled by a farm can be distinguished: (i) food and feed production, (ii) biomass production, and (iii) maintenance of an open/cultivated landscape or any other environmental amenity. This latter function concerns only areas (such as mountain regions) where the natural conditions are particularly unfavourable for the production of agricultural commodities, and where society – for mainly social and environmental reasons - has an interest in maintaining an open cultivated landscape. An overview of possible biophysical output variables that can be used for different basic agricultural functions is provided in Table 2.1.

The majority of farms typically produce several outputs associated with one or more primary functions of agriculture. This raises the question of how best to deal with these multiple heterogeneous outputs. If the outputs produced contribute to the same single function, then a common biophysical unit (e.g. digestible energy output in the case of the food provision function) may be found to aggregate the different outputs. If no common unit can be found, then the entire range of outputs should be addressed, either by allocating the environmental impacts to each output/function, thereby switching to an environmental-intensity calculation at product/function level (instead of at whole-farm level), or by using an approach such as data envelopment analysis (see Coelli et al., 2005), which allows for an objective aggregation of these multiple outputs expressed in different units.

As is obvious from the definition of farm global environmental performance, we take a production-chain – more specifically, a cradle-to-farm-gate – approach. We therefore take account not only of those environmental impacts generated on-farm, but also of those generated off-farm in the farm upstream stages, during the manufacture and transport of farm inputs. This ensures that no environmental impact goes unnoticed. The LCA method is therefore particularly well suited to assessing those environmental impacts considered in the global environmental performance indicator.

Table 2.1: Possible biophysical output variables for different basic agricultural functions.

Primary agricultural function	Food & feed production	Biomass production	Maintenance of an open/cultivated landscape[5]
Biophysical output variable	*Product-based FU:* - Mass or volume FU, such as kg or litre of a particular agricultural output *Nutrition-based FU:* For food: - Digestible energy content in MJ or kilocalories - Protein content - Nutrient-score FUs For feed: - Digestible energy/protein output available to the animal species consuming the feed	*Product-based FU:* - Mass or volume of biomass *Energy-based FU:* - Caloric output in MJ *Transport function-based FU:* - Kilometres or miles of distance travelled with biomass-produced fuel	*Area-based FU:* - Hectares of landscape under cultivation

Source: Own representation.

[5] Both on- and off-farm landscape maintenance must be taken into account in order to ensure spatial system boundary consistency (for further details, see Section 2.2.3.2).

2.4.3 Local environmental performance

Local environmental performance focuses exclusively on the environmental impacts generated on-farm at local-ecosystem level (Halberg et al., 2005a). Here, the focus is on environmental impacts arising from emissions generated locally by the activities of the farm in question, and resulting in environmental impacts at the immediate local/regional ecosystem level (e.g. watershed) of the farm in question. Although other farms or polluters may also generate environmental impacts in the area of the farm investigated, they are not taken into account in the local environmental performance of the farm itself. Moreover, although emissions generated elsewhere in the farm's supply chain are not to be taken into account when determining the farm's local environmental performance, they could be used for separate assessment of the local environmental performance of other actors in the chain. Indeed, any farm purchasing inputs (e.g. mineral fertilisers or feed) off- farm, or moving part of its livestock to another background farm, is contributing to the creation of local environmental impacts elsewhere in the production chain. To give an example, if a farm uses commercial mineral fertilisers, the environmental impacts associated with the production and transport of this input should not be included in the farm's local environmental performance assessment, because the emissions from the production of the fertilizer are generated elsewhere than on the farm itself; however, the local environmental impacts arising from the emissions associated with the farm-level application of the fertilizer must be taken into account when evaluating the farm's local environmental performance. Ideally, it would be possible to estimate the local environmental performance in all links of the chain, from cradle to farm gate. Such an assessment, however, would pose quite a challenge, and would very likely fail owing to (i) its complexity, especially in terms of defining system boundaries and quantifying environmental impacts that are local and those that are not, (ii) the heterogeneous nature of the activities in the upstream stages of farm production, and (iii) the associated limited data available for such a quantification.

The local carrying-capacity constraint can be understood as the maximum environmental impact per unit of farmland area that the local ecosystem is capable of sustaining. Local environmental performance is measured by means of an area-based indicator quantifying the level of environmental impacts generated by the farm at local (i.e. farm) level per unit of local farm area, as shown in Formula 2.2.

Formula 2.2

$$Local\ environmental\ performance = \frac{EI_{loc}}{farmland\ area}$$

EI_{loc}: local environmental impact

Environmental impact per hectare of area should be less than the carrying capacity of the local ecosystem. For the reasons outlined in Sections 2.4.1 and 2.4.6, determining the local carrying capacity is not a precondition for implementing the local environmental performance indicator proposed by us.

2.4.4 Environmental issues to be considered at global vs. local level

Generally speaking, environmental issues constituting global-level concerns are those connected with the depletion of the Earth's non-renewable resources as well as emissions that spread from farms to the global ecosystem, causing global-scale problems once a certain global threshold for environmental-impact generation has been exceeded (e.g. fossil energy use and greenhouse-gas emissions) (Haas et al., 2000; Van Der Werf & Petit, 2002; Halberg et al., 2005a; Payraudeau & Van Der Werf, 2005). In our framework, the following issues will therefore be considered exclusively at global level: non-renewable-energy use, global-warming potential, ozone depletion, abiotic resource depletion (e.g. mined resources such as phosphorus or potassium), and land use (land competition). The environmental issues to be borne in mind when quantifying local environmental performance are those for which farm environmental impacts exert an impact chiefly on the local ecosystem scale, namely eutrophication, acidification, terrestrial and aquatic ecotoxicity, human toxicity, photo-oxidant formation, biodiversity, water use, and soil quality. For these issues, minimising local environmental-impact generation per unit of farm area is key for ensuring a sustainable state.

In the globalised economy of the 21st century, however, international trade may ultimately cause the globalisation of environmental issues that were originally chiefly of local relevance (Bare, 2014). Furthermore, through the complex interconnectedness of natural processes, what were originally local environmental issues can spread far and wide, thereby also putting pressure on the global carrying capacity of the planet. Acidification and eutrophication phenomena, for example, primarily influence the environment close to the source of nutrient emission, but may also affect the environment at several hundred kilometres' distance (Payraudeau & Van Der Werf, 2005). To ensure the taking into account of (i) any issues that might be important at both local and global ecosystem level as well as (ii) off-farm impacts created by environmental issues of a primarily local nature, the latter types of environmental issues should also be considered from a global perspective. This will prevent the potential shifting of environmental impacts from the farm stage to the off-farm upstream stages of the life cycle, allowing us to form a complete picture of farm environmental performance. Global consideration of the environmental issues that are primarily of local relevance would not be necessary if we also measured local environmental performance in each upstream link of the production chain. As already mentioned in Section 2.4.3, however, such an assessment would be very challenging, as well as highly unlikely to succeed.

2.4.5 Practical implementation

The actual implementation of our framework for measuring farm environmental performance involves several steps. In the first step, a classic cradle-to-farm-gate LCA is conducted. As an environmental impact assessment method that can be used to comprehensively determine impacts across the entire cradle-to-farm-gate link of the food chain, LCA is the most appropriate method for measuring farm global environmental performance, given that it holistically quantifies the generation of overall environmental impacts associated with farm activity. Since the local environmental impacts can be derived from the global ones by their on-farm and off-farm breakdown, LCA results can also be used for the assessment of local environmental performance. Before conducting the LCA, the environmental issues to be considered should be selected. In order to provide a complete environmental performance profile, all relevant environmental issues at global as well as local scale must be taken into account. We are, however, aware that in most empirical applications of our framework, the choice of environmental issues will depend on data availability or data-collection feasibility. Nevertheless, because of potential trade-offs between environmental issues, the assessment should be as complete as possible. In the second step, once the cradle-to-farm-gate impacts have been assessed, they are decomposed to their on- and off-farm parts. Next, farm global environmental performance is quantified by dividing the cradle-to-farm-gate environmental impacts by the farm's biophysical output(s). In step four, the farm's local environmental performance is estimated by dividing on-farm environmental impact generation by the farm's area. Finally, global and local environmental performance indicators are compared among the farms studied, with the goal of learning from the best performers.

2.4.6 A benchmarking, and, hence relative, approach

The concept of an ecosystem carrying-capacity constraint is associated with the physical threshold thinking. The problem posed by the impossibility of defining a physical threshold (carrying capacity) for the global ecosystem that would apply at farm level (for further thoughts on this subject, cf. also Section 2.4.1) can be circumvented by using an environmental intensity indicator over the entire production chain up to the farm gate, combined with a benchmarking approach. Proceeding in this manner means adopting a relative approach for the assessment of global environmental performance. The said approach consists in benchmarking farms against one another in terms of their environmental intensity over the entire production chain up to the farm gate, and explaining why some farms perform better than others.

Even if it were possible to define physical thresholds for the carrying capacity of the local ecosystem that should not be exceeded, due to the uncertainties and difficulties associated with determining such thresholds (e.g. Steffen et al., 2015), here, too, we prefer to adopt a relative approach consisting in a comparison of the farms in terms of environmental-impact generation at local farm level per unit of area, and an analysis of the causes of the observed heterogeneity. Our choice of a relative approach for measuring global and local environmental performance does not call into question the appropriateness and usefulness of the carrying-capacity concept for the definition and measurement of environmental performance. In this paper, however, the carrying-capacity concept represents just the starting point of our theoretical considerations regarding the development of a framework for measuring farm environmental performance, especially for the local/global distinction we propose. The indicators developed do not directly incorporate the carrying capacities, however.

Through the use of a benchmarking-based, and hence relative, approach for assessing farm environmental performance, sustainability comes to be viewed "*as a dynamic process in which the targets have to be continuously checked and improved, or as a philosophy that permanently* *tends towards improvement*" (Callens & Tyteca, 1999).

2.5 DISCUSSION

The framework that we propose for defining and measuring farm environmental performance is based on the environmental sustainability concept, approached from an ecological perspective. More precisely, it builds on the intrinsically related concept of ecosystem carrying capacity, thereby making a substantial contribution to the assessment of farm environmental sustainability. The framework outlines and specifies the appropriate indicators for assessing the environmental performance of a farm. By distinguishing between the carrying capacity of the local vs. global ecosystem and proposing relevant environmental performance indicators measuring the relative compliance of a farm with these two carrying-capacity constraints, it avoids the short-sighted focusing of attention on just one ecosystem level at the expense of the other. In addition, the framework identifies environmental issues that should be considered at a global and/or local level, and contributes to the discussion of FUs from an LCA perspective. Last but not least, the framework is universally implementable, regardless of farm type/activities or location. Despite the strengths of this framework, several limitations can be identified with respect to its implementation.

The first major limitation of our framework is the relative nature of the approach used to assess the global and local environmental performance of the farm. By relying on environmental intensity – the inverse of eco-efficiency – for the measurement of global environmental performance, we assess relative rather than absolute environmental sustainability (Bjørn & Hauschild, 2013). This implies that there is no guarantee of reaching an absolute sustainable state, for the following reasons: Firstly, scientific evidence shows that the anthropogenic perturbation levels for a number of environmental issues are higher than the carrying capacity of planet Earth, thus implying that an unsustainable state of the environment has already been reached (Steffen et al., 2015). According to Bjørn & Hauschild (2013), eco-efficiency improvement factors ranging from 4 to as high as 50 have been proposed in the literature in order to keep the environmental impacts generated globally by human activity within the carrying capacity. The scale of these eco-efficiency improvement factors shows how unlikely they are to be achieved. Secondly, growth in population and per capita material affluence lead to a rise in global environmental impacts (Bjørn & Hauschild, 2013, 2015), which wipes out the positive effects of eco-efficiency improvements in terms of a reduction in environmental impacts. Last but not least, eco-efficiency improvements have also been shown to lead to direct and indirect rebound effects which offset the reduction in environmental impacts resulting from the higher degree of eco-efficiency (Hueseman & Hueseman, 2007). For these reasons, the eco-efficiency approach cannot be considered a panacea for reducing environmental impacts below the carrying capacity.

Although the local environmental performance indicator – defined as the local environmental impact generation per hectare of area – does not rely on eco-efficiency, like eco-efficiency it still belongs to the group of indicators termed "*relative environmental sustainability indicators (RESI)"* by Bjørn et al. (2016), and that do not enable to draw conclusions in terms of sustainability on an absolute scale. Furthermore, our local environmental performance indicator has another limitation, in that it fails to take account of the differences in vulnerability between different local ecosystems, ignoring the fact that carrying capacity may vary substantially from one local ecosystem to another. This issue should be borne in mind when comparing the local environmental performance of different farms.

Recently, LCA-based works were conducted with the aim of incorporating carrying capacities in environmental performance indicators, and thus of switching from relative to absolute environmental sustainability indicators (cf. e.g. Bjørn & Hauschild, 2015; Bjørn et al., 2015a, 2016). Bjørn & Hauschild (2015) developed carrying-capacity-based normalisation references that can be used in LCAs to aggregate environmental impact scores across impact categories. The said normalisation references (NRs) are defined as the carrying capacity per year for a given impact category in a given region, divided by the population of this region (e.g. kg CO_2-eq per person and year; Bjørn & Hauschild, 2015). They allow us to convert the LCA midpoint indicator scores for each impact category into person equivalents. One "person equivalent" can be interpreted as "*an environmental impact generation equivalent to the annual personal share of the carrying capacity for impact category i*" (adapted from Bjørn & Hauschild, 2015). These person equivalents can then be aggregated across all impact categories (Bjørn & Hauschild, 2015). Bjørn et al. (2016) included carrying capacity as a sustainable reference value in spatially resolved characterisation factors used for environmental impacts assessment. The indicator derived by multiplying the characterisation factor by emission or resource use then expresses "*the area equivalent of fully occupied capacity*" (Bjørn et al., 2016). This area can be compared to "*the actual area of the ecosystem affected*" (Bjørn et al., 2016).

From a purely conceptual perspective, carrying capacities could easily be integrated in the farm environmental performance indicators of our framework, albeit in a different manner from that proposed in Bjørn & Hauschild (2015) or Bjørn et al. (2016). Global carrying capacities specific to each impact category would first need to be allocated to various human needs (e.g. food, housing, clothing, mobility). This entitlement would imply valuation that is normative in nature, given that "*it inherently involves value judgement of anthropogenic systems that are competing for the occupation of the same finite carrying capacity*" (Bjørn et al., 2015b). Based on the carrying capacity entitlement for each need, as well as on the global biophysical output (e.g. MJ digestible energy) that must be produced in order to satisfy global human needs, it would be possible to estimate for each need a maximum global environmental intensity (termed a "global environmental intensity entitlement") that, in order to comply with the global ecosystem's carrying capacity, must not be exceeded. The global environmental intensity of a farm in the cradle-to-farm-gate link of the food chain could then be divided by the global environmental intensity entitlement for food production in this link. This would result in a performance variable indicating whether or not the maximum permissible global environmental intensity has been exceeded, and if so, by how much the farm's global environmental intensity should be reduced in order to comply with the carrying-capacity entitlement. The approach to integrating carrying capacity in the local performance indicator would be similar. The local carrying capacity entitlement would be estimated by allocating the carrying capacity of the local/regional ecosystem to the different anthropogenic systems competing for this carrying capacity. This allocation would be based on the relative perceived value of each competing system (Bjørn et al., 2015b). The farm's local environmental impact generation per hectare would be divided by the local carrying-capacity entitlement (defined as the maximum permissible environmental impact generation per hectare). The indicator thus derived would measure the degree to which a farm complies with its local carrying-capacity entitlement.

As is obvious from these initial considerations, it is conceptually possible to incorporate carrying capacities in the performance indicators proposed by us. Quantifying the carrying-capacity entitlement for the different impact categories and on the two different scales (global vs. local) considered is expected to be a highly challenging process that is fraught with uncertainties, especially given the dynamic nature of carrying capacities (Bjørn & Hauschild, 2015). The practical implementation of these conceptual considerations should be the subject of future research.

The second restriction of our framework is its reliance on the LCA approach, which suffers from some limitations. For one thing, assessments for some categories of impact are still in the research and development phase (Pashaei Kamali et al., 2014; Bare, 2014). Moreover, LCAs can suffer from high levels of uncertainty owing to the simplified modelling of complex cause-effect chains and the large quantities of measured and simulated data involved (Hellweg & Canals, 2014). Furthermore, since LCA is developed as a global-impact assessment tool, its use at local-impact level poses a challenge, due primarily to the absence of spatial differentiation in characterisation modelling in commonly used LCIA approaches (Potting & Hauschild, 2006; Blonk et al., 2010). Spatial differentiation would be especially useful for environmental issues of local relevance, since it would increase the accuracy and discriminating power of LCIA by introducing a site-dependent or site-specific impact assessment (Potting & Hauschild, 2006).

The third limitation of our framework concerns the challenges associated with the practical implementation of the measurement of local environmental performance. The on- and off-farm breakdown is not available as such, and must be performed in great detail at the process level, which takes time and requires a very good understanding of the processes involved. Moreover, because this type of consideration of local environmental performance is new, there is no possibility to compare it with values found in the literature.

The final limitation of the framework is that the proposed farm environmental performance assessment focuses exclusively on the cradle-to-farm-gate link, without extending the scope of the environmental assessment beyond the farm gate. It therefore provides no insights into the impacts resulting from the processing, distribution, consumption, and waste phases of the food life cycle. We excluded the farm-gate-to-grave link of the food chain because the farmer has very little (if any) influence on what happens in the downstream stages (processing, retail, and consumption) of the food chain. Although a majority of the food chain's environmental impact creation occurs at farm level, we should be aware that in the globalised world, food is produced, traded, consumed, and disposed of at different localities that may be geographically very distant from one other. In order to gain a comprehensive picture of the environmental impact of the entire food chain, the cradle-to- farm-gate assessment should be supplemented by a detailed quantification of the impacts occurring in the post-farm life-cycle stages.

2.6 CONCLUSIONS

Environmental sustainability is an ecological concept closely connected with the ecosystem carrying capacity (constraint), which is a biophysical concept relating to the maximum damage that an ecosystem can sustain. Indicators used to assess farm environmental performance must therefore (i) be biophysical in nature and (ii) best represent the damage to the environment. The carrying-capacity constraint applies at two levels: that of the global ecosystem, and that of the local ecosystem (sub-ecosystem of the global ecosystem). Compliance with the carrying-capacity constraints at both levels is a prerequisite for sustainable development, with no possibility of compensation or substitution between these two levels. Implementation of the global and local carrying-capacity constraints at farm level results in the differentiation between two different types of farm environmental performance (global vs. local) and related indicators. These two indicator types directly or indirectly measure the relative extent to which a farm complies with the carrying-capacity constraints of the global vs. local ecosystem, and differ from one another not only in terms of their definition, but also with respect to the spatial system boundaries of the underlying environmental assessment and the environmental issues considered. Whereas farm global environmental performance is measured by the environmental intensity of the farm across the entire production chain up to the farm gate, farm local environmental performance is defined as the environmental impact generated at local (i.e. farm) level per unit of (local) farm area.

The implementation of separate local and global environmental performance indicators should above all prevent the shifting of environmental problems from the local to the global scale and vice versa. Last but not least, this framework allows us to analyse potential synergies and trade-offs between the various dimensions of the environmental performance of a farm, and in this sense highlights the complexity of the environmental sustainability concept, which cannot be reduced to a single “one size fits all” indicator.

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(Tscharntke et al., 2007), rather than the “first-last-author emphasis” norm.

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3 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)

3.1 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. Gerber et al., 2010; Garnett, 2011; Korsaeth et al., 2012; Thoma et al., 2013; Bystricky et al., 2014a; Kulak et al., 2015). Complying with the carrying capacity of both local and global ecosystems is a prerequisite to ensure sustainability (Repar et al., 2017). Based on theoretical considerations and using the local versus global carrying capacity distinction as a starting point, Repar et al. (2017) 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 (Repar et al., 2017). 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) (Repar et al., 2017). Local environmental performance is measured by the on-farm environmental impact generation per unit of farm usable agricultural area (Repar et al., 2017).

The distinction between global and local environmental performance proposed by Repar et al. (2017) builds upon previous considerations made by several authors in this field (Haas et al., 2000; Van Der Werf & Petit, 2002; De Boer, 2003; Halberg et al., 2005a; Payraudeau & Van Der Werf, 2005; Jan et al., 2012a). 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 (Van Der Werf & Petit, 2002; Payraudeau & Van Der Werf, 2005; Repar et al., 2017). The approach proposed by Repar et al. (2017) 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 Brouwer, 1998; Oenema et al., 1998; Herzog & Richner, 2005; Nevens et al., 2006; Hoang & Alauddin, 2010; Jan et al., 2015). 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 (Mouron et al., 2006; Thomassen et al., 2009; Jan et al., 2012a; Fenollosa et al., 2014). With the exception of Jan et al. (2012a) who explicitly focused on farm global environmental performance as specified in Repar et al. (2017), 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. (2017) and its relationship to farm economic performance. Furthermore, also with the exception of Jan et al. (2012a), 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. (2012a), 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. (2012a) 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.

3.2 MATERIALS AND METHODS

3.2.1 Data source and sample

The present work relied on the same dataset as the one used in Jan et al. (2012a), which was originally collected as part of the Life Cycle Assessment Farm Accountancy Data Network

(LCA-FADN) Project in the years 2006–2008 (Hersener et al., 2011). 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 (Gaillard & Nemecek, 2009; Baumgartner et al., 2011). 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. (2012a). A very detailed and comprehensive description of the Swiss FADN's accounting approach is available in (Hausheer Schnider, 2008).

3.2.2 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 (Hersener et al., 2011). 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 Alig et al., 2015). 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 (Hischier et al., 2010).

3.2.2.1 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. (2014b) (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 (HAFL, 2013 a; 2013b). Emissions from mineral N fertilisers were estimated with emission factors according to EEA (2013). For some types of N fertilisers, different factors for pH above and below 7 applied. For a detailed description see Bystricky et al. (2014b) (Chapter 2.6);
- Emissions of nitrogen oxides (NO_x) were modelled according to EEA (2013). A detailed description is available in Bystricky et al. (2014b) (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 (IPCC, 2006). 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. (2014b) (Chapter 2.8);
- Methane (CH_4) emissions from enteric fermentation and manure management were calculated by using emission factors from IPCC (2006) 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. (1996). Further details on the approach used to estimate these emissions can be found in Bystricky et al. (2014b) (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 (2006) 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 (2006). 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 (Richner et al., 2014). 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 (Freiermuth, 2006).

3.2.2.2 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 (Hauschild et al., 2006) and CML01 (Guinée et al., 2001). 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. (2004);

- Global warming potential over 100 years (in kg CO_2 eq.), according to IPCC (2007);
- Ozone formation potential (in m^2.ppm.h) (so-called "summer smog"), according to the EDIP2003 method (Hauschild & Potting, 2005);
- Ozone depletion (in kg CFC11 eq.) as the impact of stratospheric ozone-depleting emissions, according to the EDIP2003 method (Hauschild & Potting, 2005);
- 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 (Hauschild & Potting, 2005);
- N aquatic eutrophication potential (in N equivalents) as the impact of losses of N to the aquatic ecosystems according to the EDIP2003 method (Hauschild & Potting, 2005);
- P aquatic eutrophication potential (in P equivalents) as the impact of losses of P to the aquatic ecosystems according to the EDIP2003 method (Hauschild & Potting, 2005);
- 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 (Hauschild & Potting, 2005);
- Terrestrial and aquatic ecotoxicity potentials (in kg 1,4-DB eq.) estimated according to the CML01 method (Guinée et al, 2001);
- Human toxicity potential (in kg 1,4-DB eq.) as the impact of toxic pollutants on human health, quantified according to the CML01 method (Guinée et al, 2001);
- Land competition (in m^2a) was assessed using the CML01 method (Guinée et al, 2001). 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 (Goedkoop et al., 2009) 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. (2009). 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*" (Pfister et al. 2009).

3.2.3 Off-farm and on-farm environmental impacts' decomposition

To assess farm local environmental performance as defined by Repar et al. (2017), 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. (2017), 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 (PRé Consultants, 2012). 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.

3.2.4 Farm global environmental performance indicators

Repar et al. (2017) 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 (Huppes & Ishikawa, 2005). 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. (2017). 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.

3.2.5 Farm local environmental performance indicators

Local environmental performance is defined by Repar et al. (2017) 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 3.2.3. 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 (Repar et al., 2017). These categories were the ones for which farm environmental impacts are primarily influential on the local ecosystem scale (Repar et al., 2017). 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.

3.2.6 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 & Weidema, 2015). 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., 2009). 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., 2012a). 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 3.1). 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 3.1: 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

Source: Own representation.

3.2.7 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 (Jan et al., 2012a). Spearman's correlation is furthermore more appropriate for a small sample size (Blalock, 1979) 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.

3.3 RESULTS

3.3.1 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 (Table 3.2 and Table 3.3). 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 (1996).

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 3.2: 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. Source: Own calculations.

Table 3.3: 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. Source: Own calculations.

3.3.2 Analysis of the link between farm environmental and farm economic performance

3.3.2.1 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. (2012a). In the present work, we re-conducted the analysis with the updated LCA data (see Section 3.2.2) and—to test the robustness of the results—broadened it by considering two additional economic performance indicators. The results in Table 3.4 and Table 3.5 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).

3.3.2.2 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 3.6). 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 3.4: 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. Source: Own calculations.

Table 3.5: 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. Source: Own calculations.

Table 3.6: 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. Source: Own calculations.

3.4 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.

3.4.1 Main findings

In the present work, we applied—within a case study for Swiss alpine dairy farms—the approach proposed by Repar et al. (2017) 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.

3.4.2 Discussion of the main findings

This work represents the first implementation of the framework proposed by Repar et al. (2017) 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, Thomassen et al., 2009; Jan et al., 2012a). However, these studies focused solely on what Repar et al. (2017) 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. (2012a), who also found a synergy between these two dimensions of the sustainable performance of a farm. Jan et al. (2012a) 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. (2012a), three other contributions (De Koeijer et al., 2002; Mouron et al., 2006; Thomassen et al., 2009) 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 (Repar et al., 2017). 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 3.2.4. Nevertheless, some results regarding this link can be found in Thomassen et al. (2009) 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. (2009) 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. (2009) 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.

3.4.3 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., Haas et al., 2001; Charles et al., 2006; Nemecek et al., 2011). 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*" (Loos et al., 2014). 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., 2016). The sustainable intensification discussion has thus mostly targeted improvements in agricultural sustainability at the global level (see e.g., Godfray et al., 2010; Tilman et al., 2011; Mueller et al., 2012; Rockström et al., 2016), 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.

3.4.4 Limitations and future research need

Although the framework established by Repar et al. (2017) 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. (2012a), because the sample used for this study was quite small and not selected at random, there are limitations regarding its representativeness. These limitations should be considered when interpreting the results of this work.

As discussed in Repar et al. (2017), 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., 2011) or the change in diets (see, for example, Tukker et al., 2011).

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 (Repar et al., 2017). Such indicators enable a relative improvement in terms of sustainability but are still no guarantee for the achievement of an absolute sustainable state (Repar et al., 2017). As identified by Sala et al. (2013), 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., Bjørn, & Hauschild, 2015; Bjørn et al., 2015; Bjørn et al., 2016). Also, Repar et al. (2017) 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.

3.5 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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3.7 APPENDIX

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 3.1. 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 farms.

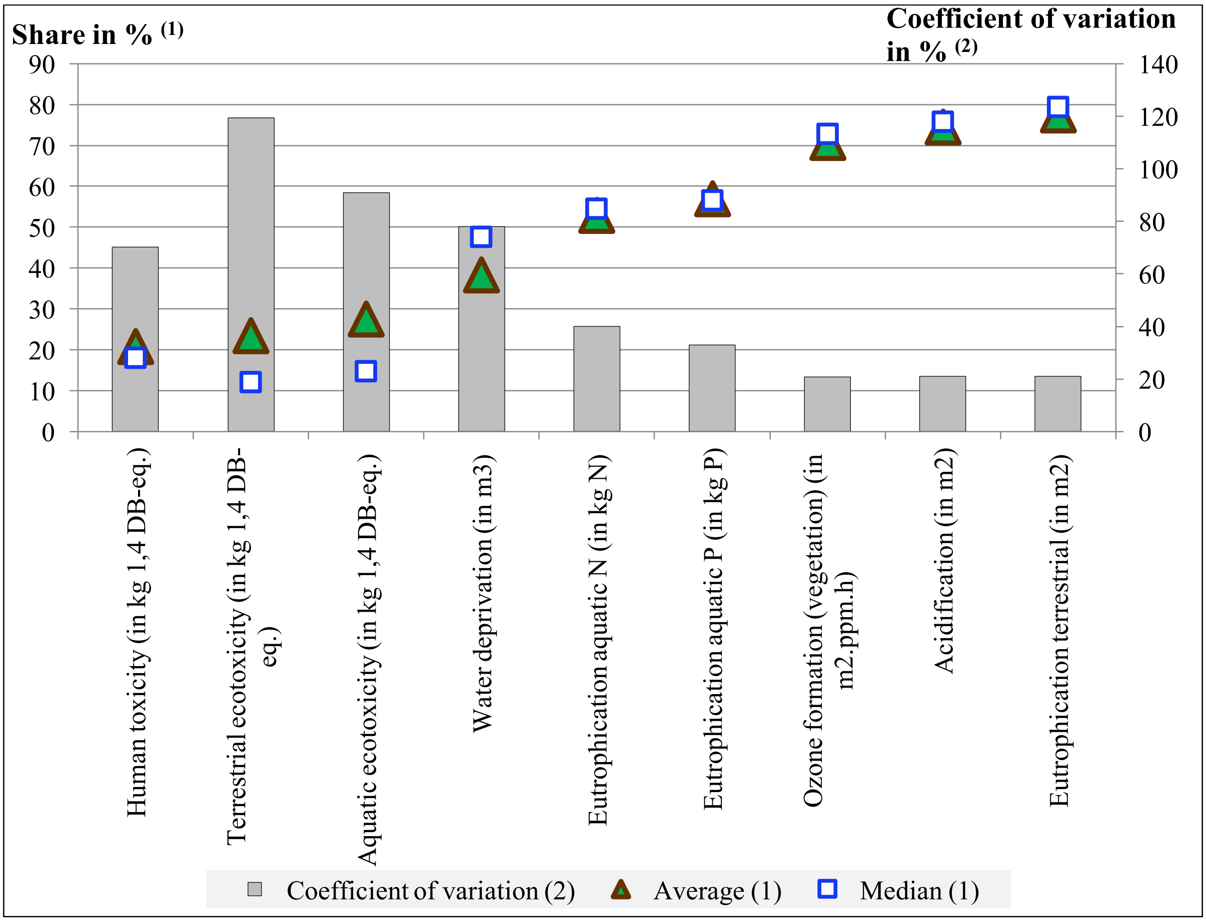

Figure 3.1: Average, median and coefficient of variation of the on-farm share of the cradle-to-farm gate environmental impact for impact categories considered both at global and local level, listed from left to right in ascending order of average on-farm share. Source: Own calculations.

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4 DETERMINANTS OF GLOBAL VERSUS LOCAL ENVIRONMENTAL PERFORMANCE AND ECONOMIC PERFORMANCE OF DAIRYING: A CASE STUDY OF SWISS MOUNTAIN FARMS

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Abstract

Improving the sustainability of the dairy food chain requires a simultaneous improvement in the global and local environmental performance as well as in the economic performance of dairy farms. We investigated different structural, farm management, socio-demographic, technological and natural-environment-related potential determinants of the economic and environmental performance of dairying. Our analysis relied on a case study of 56 Swiss alpine dairy farm observations, for which life cycle assessments and farm accountancy data were combined. The effect of the selected factors on farms' economic and environmental performance was analysed by means of non-parametric statistical approaches. The results revealed the existence of some factors presenting synergies and several factors showing trade-offs in the enhancement of farm global environmental, local environmental and economic performance. More generally, the promotion of farm global environmental performance and farm economic performance was shown to be synergetic whereas the enhancement of farm global and local environmental performance turned out to be mostly antinomic. However, some factors, namely organic farming, higher agricultural education, silage-free milk production, and also, to a weaker extent, full-time farming, larger farm size and lower intensity of cattle concentrates use, showed a potential to bring simultaneous improvements in the global and local environmental performance as well as the economic performance of dairy farming. Policy-makers should be aware of the complexity of the joint improvement of farm economic and environmental performance and only promote factors capable of holistically enhancing the environmental and economic performance of dairy farming.

Key words: sustainable agriculture, dairy farming, environmental performance, economic performance, Switzerland

4.1 INTRODUCTION

Dairy products are of high relevance in terms of environmental sustainability of final consumption. According to a study conducted for the EU-25 by Tukker et al. (2006), dairy products were – within the food and drink consumption area – the second highest contributors[6] to the environmental impact of final consumption by private households and the public sector. Only a few studies have assessed the relative contribution of each phase in the life cycle of milk to milk's total environmental impact over its whole life cycle from production through consumption to disposal. Focusing on the milk production and processing phases, Hospido et al. (2003) showed for the Galician dairy sector that, of these two phases, the production phase (farming) was – for the impact categories (i) global warming potential, (ii) eutrophication potential and (iii) acidification potential – the main contributor to the total environmental impact (contributing 80%, 74% and 58% respectively to the total impact). Performing a comprehensive life cycle assessment encompassing the farming, processing and consumption phases, Eide (2002) showed for Norwegian dairies that the agricultural "cradle-to-farm gate" phase was – for (i) energy consumption, (ii) acidification potential, (iii) eutrophication potential and (iv) global warming potential – the greatest contributor to the total environmental impact

[6] The most important contributor is meat and meat products.

of the whole dairy supply chain. Assessing a very large sample of dairy farm operators from the United States and considering all phases in the dairy supply chain, Thoma et al. (2013) found that 72% of greenhouse gas emissions associated with the consumption of fluid milk in the United States was accrued by the dairy farm gate. Analysing – within a comparative study between Switzerland, Germany, France and Italy – the life cycle of cheese up to its point of sale, Bystricky et al (2014a) found that the farming stage was responsible – in all environmental impact categories considered (demand for non-renewable energy resources, global warming potential, ozone formation potential, land use, eutrophication potential, acidification potential, terrestrial and aquatic ecotoxicity, and human toxicity) – for more than 70% of the environmental impacts generated from the "cradle to the point of sale". These four studies provide evidence that, within the dairy supply chain, the "cradle-to-farm gate" link is for most environmental impact categories the main contributor to the environmental impact of the full chain. A thorough understanding of the factors affecting the environmental impact of farming is therefore a prerequisite if we wish to improve the environmental sustainability of the dairy food chain and thus reduce its contribution to environmental impacts related to the final consumption of products by private households and the public sector.

Farm environmental sustainability requires complying with the ecosystem's carrying capacity constraints at both local and global ecosystem level (Repar et al., 2017). In terms of farm environmental performance assessment, this implies the separate implementation of local and global environmental performance indicators (Repar et al., 2017). Holistic improvement of farm environmental sustainability requires improvement of both global and local environmental performance dimensions (Repar et al., 2017). The empirical implementation of both global and local environmental performance indicators in a case study of Swiss dairy farms revealed – depending on the environmental impact category considered – both synergies and trade-offs between the two environmental performance dimensions, with trade-offs predominating over synergies (Repar et al., 2016). This study highlighted the need to investigate the factors affecting both global and local environmental performance with the objective of identifying those factors that allow a simultaneous improvement in both environmental performance dimensions (Repar et al., 2016). To avoid an improvement in both environmental performance dimensions happening at the expense of farm economic performance, the factors influencing farm environmental performance should also be investigated for their effects on farm economic performance.

Until now, most LCA-based studies investigating the potential determinants of environmental performance in dairy farming have focused on the analysis of the effect of production form (organic vs. conventional, e.g. Cederberg & Mattsson, 2000; Haas et al., 2001; Grönroos et al., 2006; Thomassen et al., 2008) or of production intensity (see, for example, Haas et al., 2001; Basset-Mens et al., 2009; Bava et al., 2014; Battini et al., 2016; Salou et al., 2017) on farm environmental performance. When investigating the effects of different determinants on farm environmental performance, none of these studies distinguished between the global and local environmental performance of a farm as defined by Repar et al. (2017). With a few exceptions, the environmental focus of these studies was – due to their LCA perspective – mostly on what Repar et al. (2017) defined as farm global environmental performance, since the LCA approach by definition does not separately assess the farm local environmental performance dimension as defined by Repar et al. (2017). Holistic investigations simultaneously analysing the potential determinants of the global and local environmental, as well as economic performance of dairying are still lacking.

The present article aims to extend the LCA-approach and related farm global environmental performance perspective by complementing it with the local dimension of farm environmental performance in order to gain a more comprehensive picture of environmental sustainability. For Swiss dairy farms located in the hill and mountain region, it analyses the link between selected farm characteristics and the (i) global environmental performance, (ii) local environmental performance and (iii) economic performance. Structural, managerial, socio-demographic, natural-environment and production-technology-related characteristics are thereby considered. The analysis relies on a unique dataset combining life cycle assessments (LCAs) and farm accountancy data. The final purpose of this analysis is to highlight the factors that have the potential to simultaneously improve versus worsen all three investigated performance dimensions, i.e. that present a synergy (either positive or negative) in the enhancement of farm environmental and economic performance. At the same time, we are interested in identifying the factors that influence at least two performance dimensions in a different direction, i.e. that show a trade-off in terms of promotion of the sustainable performance dimensions considered.

4.2 MATERIALS AND METHODS

The present work is based on the same data as those used in Repar et al. (2016). Hence, we limit the description of the dataset to essential aspects and refer the reader to that publication for detailed information on the data, especially on the environmental impact assessment carried out.

4.2.1 Data source and sample

The investigation relied on a pooled sample of specialised dairy farms located in the hill and mountain regions of Switzerland from the years 2006, 2007 and 2008. The sample encompassed 56 farm observations. The hill and mountain regions included the hill zone as well as mountain zones 1 to 4 as defined in FOAG (2008). The hill and mountain regions, also called alpine area in the present paper, can be defined roughly as the agricultural production area located between 500 and 1,500 meters above sea level. A specialised dairy farm was defined as a farm whose revenues from dairying generated at least 60% of total farm agricultural revenues without any direct payments. Farms with a proportion of revenues from para-agricultural activities above 20% of total farm revenues, as well as farms whose revenues from forestry activities generated more than 10% of total farm agricultural revenues, were excluded from the analysis to ensure that the observations were homogeneous in terms of production activities.

The data were collected within the framework of a broader project called the LCA-FADN (Life Cycle Assessment–Farm Accountancy Data Network) project, which conducted a joint economic and environmental assessment of Swiss agriculture at farm level (see Hersener et al., 2011). The farms in the sample were not selected according to a random procedure. Participation in the project was voluntary due to the complexity and comprehensiveness of the environmental data collection.

4.2.2 Environmental impact assessment using the SALCA approach

For each farm, a comprehensive environmental impact assessment was conducted using the SALCA (Swiss Agricultural Life Cycle Assessment) approach (see Gaillard & Nemecek, 2009;

Baumgartner et al., 2011). The system investigated was made up of the agricultural production system defined in a narrow sense, i.e. without any forestry and para-agricultural activities (see Jan et al., 2012a). The assessment covered the agricultural stage, i.e. the “cradle-to-farm gate” link, of the milk life cycle. All agricultural inputs, production processes and outputs were taken into account. The environmental impacts were quantified based on detailed production inventories collected at farm level. Due to the update of the SALCA approach since the original data collection, the life cycle impact assessments (LCIAs) for the sample farms were reassessed (see Repar et al., 2016).

The cradle-to-farm gate environmental impacts were quantified for the following environmental impact categories: 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, terrestrial eutrophication, aquatic N-eutrophication and aquatic P-eutrophication. In the second step, due to the requirements of the quantification of farm local environmental performance indicators, the quantified cradle-to-farm-gate environmental impacts were decomposed into their off- and on-farm parts (Repar et al., 2016). Only the on-farm environmental impacts were considered for quantification of farm local environmental performance, whereas both on-farm and off-farm impacts were accounted for when quantifying farm global environmental performance (Repar et al., 2016; Repar et al., 2017). For a list of the models used for (i) the estimation of direct field and farm emissions and (ii) the environmental impact assessment, refer to Repar et al. (2016).

4.2.3 Farm global environmental performance

As in Repar et al. (2016), we quantified global environmental performance by means of an eco-efficiency indicator, this indicator being the inverse of environmental intensity (Huppes & Ishikawa, 2005). Global environmental performance is defined as the MJ digestible energy available 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 (Repar et al., 2016; Repar et al., 2017). Specifically, a global environmental performance indicator was calculated for each of the fifteen environmental impact categories assessed.

4.2.4 Farm local environmental performance

Local environmental performance was calculated as farm usable agricultural area (UAA) in hectares divided by the local (i.e. on-farm) environmental impacts (Repar et al., 2016; Repar et al., 2017). A local environmental performance indicator was quantified for each of the following eight environmental impact categories of local relevance: human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity, ozone formation, acidification, terrestrial eutrophication, aquatic N-eutrophication and aquatic P-eutrophication.

4.2.5 Farm economic performance

Many possible indicators exist to assess the economic performance of a farm. Basically, these indicators can be divided into two sub-groups: (i) efficiency measures from the field of productive efficiency measurement and (ii) classical profitability indicators commonly used in practice within the field of farm management. However, productive efficiency measures were shown to be inappropriate to assess the overall economic performance of an enterprise (Musshof et al., 2009). Hence, we proceeded similarly to Repar et al. (2016) and investigated three profitability indicators from the field of farm management, namely work income per full-time family work unit, return on equity and output/input ratio. All three indicators enable a comprehensive assessment of farm economic performance because they take all production factors into account. However, these three indicators differ regarding the procedure (opportunity cost versus residual value) followed for the remuneration of own production factors (equity capital and unpaid family labour) (for further details refer to Repar et al., 2016). All three economic performance indicators were derived from the accountancy data of the investigated farms.

4.2.6 Determinants of global environmental, local environmental and economic performance

As mentioned in the introduction, the objective of the present contribution was to analyse the determinants affecting the global and local environmental performance as well as the economic performance of Swiss dairy farms located in the alpine area. Numerous factors[7] can impact farm environmental and economic performance. These factors can be classified into two groups: factors pertaining to the general environment of the farm, and those related to the farm itself as an economic agent (Jan et al., 2011). The first group can be split up into three major sub-groups: the legal/regulatory environment, the socio-economic environment and the natural environment. The second group encompasses four sub-groups: structural factors, farm management factors, technological factors and socio-demographic factors.

Taking into account the variable availability, limited sample size and the fact that the investigated farms operate under the same socio-economic and regulatory environment, present work focused mostly on the factors belonging to the aforementioned second group. In total, seventeen factors, which may potentially affect farm environmental and economic performance were considered. These factors are listed, defined and categorised in Table 4.1. Five of the investigated factors were categorical in nature, while twelve of them were numeric. An overview of descriptive statistics for the investigated determinants is available in Table 4.2 for the categorical determinants and in Table 4.3 for the numeric determinants.

[7] The terms “factor,” and “determinant” are used here as synonyms.

Table 4.1: Overview and specification of investigated determinants of farm global and local environmental and economic performance

Determinant group	Determinant	Determinant type	Determinant specification	Measurement unit
ENVIRONMENT	Agricultural production zone	Categorical, ordinal	The natural production conditions were represented by the ordinal variable "agricultural production zone", this variable consisting of three modalities: (1) hill zone, (2) mountain zones 1&2 and (3) mountain zones 3&4. The agricultural zone classification is based on criteria regarding (i) climatic conditions and especially vegetation period length, (ii) accessibility in terms of transport and (iii) topography (FOAG, 2008). Within the mountain region, the favourableness of the natural production conditions decreases from mountain zone 1 to 4.	n.a.
STRUCTURE	Farm size	Numeric, interval scaled	Farm size was measured in terms of usable agricultural area (UAA).	ha UAA
STRUCTURE	Farming type	Categorical, ordinal	Farming type encompassed two modalities: (1) part-time farming and (2) full-time farming. Full-time farms were defined as farms whose household income originated from at least 90% agricultural income. Part-time farms were farms with at least 10% of their household income originating from non-agricultural activities.	n.a.
OUTPUT COMPOSITION	Share of crops in the farm digestible energy output	Numeric, ratio scaled	Share of digestible energy (DE) from crops in the total digestible energy output of the farm (both in MJ).	%
OUTPUT COMPOSITION	Share of non-dairy cattle in the farm digestible energy output	Numeric, ratio scaled	Share of DE from other cattle (cattle not used for dairy production) in the total digestible energy output of the farm (both in MJ).	%

DAIRY PRODUCTION TECHNOLOGY	Production form	Categorical, nominal	The production form encompasses two modalities: (1) proof of ecological performance (PEP) versus (2) organic farming. The PEP requirements are equivalent to those of the former Swiss integrated production label, which was in force until 1998. Since farms have to comply with the PEP requirements to receive direct payments, conventional farming (i.e. farming without PEP) hardly exists any more (OECD, 2015).	n.a.
DAIRY PRODUCTION TECHNOLOGY	Milk utilisation and associated feeding system	Categorical, nominal	In Switzerland, farms producing milk used to make raw-milk cheese are not allowed to feed silage to their cows. For this reason, we differentiate between the following two dairy production systems: (1) dairy production with silage, called here "silage milk" (the milk is used to produce dairy products other than raw-milk cheese and silage is fed to the cows) versus (2) dairy production without silage, referred to here as "silage-free milk" (the milk is used for raw-milk cheese production and no silage is fed to the cows).	n.a.
MILK PRODUCTION, GRASSLAND MANAGEMENT AND FERTILISATION INTENSITY	Milk production intensity	Numeric, interval scaled	Milk production intensity was defined as the farm annual milk production output (in kg) per unit (ha) forage area.	kg milk/ha forage area
MILK PRODUCTION, GRASSLAND MANAGEMENT AND FERTILISATION INTENSITY	Stocking rate	Numeric, interval scaled	Defined as the total number of livestock units (LUs) present on the farm per unit farm UAA.	LU/ha UAA
MILK PRODUCTION, GRASSLAND MANAGEMENT AND FERTILISATION INTENSITY	Grassland share	Numeric, ratio scaled	Share of grassland area in the total farm UAA.	%
MILK PRODUCTION, GRASSLAND MANAGEMENT AND	Grassland yield	Numeric, interval scaled	Farm grassland yield (in dT dry matter) divided by the farm UAA (in ha).	decitonne dry matter /ha UAA

FERTILISATION INTENSITY				
MILK PRODUCTION, GRASSLAND MANAGEMENT AND FERTILISATION INTENSITY	N-fertiliser applied	Numeric, interval scaled	Total quantity of nitrogen (N) fertiliser applied on the farm in a year per unit farm UAA. It encompassed the nitrogen from manure, other organic fertiliser and mineral fertiliser.	kg N/ha UAA
MILK PRODUCTION, GRASSLAND MANAGEMENT AND FERTILISATION INTENSITY	P-fertiliser applied	Numeric, interval scaled	Total quantity of phosphorus (P) fertiliser applied on the farm in a year per unit farm UAA. It encompassed the phosphorus from manure, other organic fertiliser and mineral fertiliser.	kg P/ha UAA
HERD MANAGEMENT	Milk yield per cow	Numeric, interval scaled	Expressed as the farm yearly milk production in kg per dairy cow and year.	kg milk/cow/year
HERD MANAGEMENT	Concentrates use intensity	Numeric, ratio scaled	Concentrates use intensity was defined as the share of concentrates in the total cattle feed, this share being estimated on a dry matter basis.	%
SOCIO-DEMOGRAPHIC CHARACTERISTICS OF FARM MANAGER	Age	Numeric, interval scaled	Expressed as the age of farm manager in years.	years
SOCIO-DEMOGRAPHIC CHARACTERISTICS OF FARM MANAGER	Agricultural education level	Categorical, ordinal	The agricultural education level of the farm manager comprises of two categories: (1) completed apprenticeship or lower agricultural education level, (2) agricultural education level higher than a completed apprenticeship (e.g. master craftsman diploma or university degree).	n.a.

Source: Own representation.

Table 4.2: Descriptive statistics of the investigated categorical determinants of farm global environmental, local environmental and economic performance

Categorical determinant	Percentage of farms in the sample (%)
Agricultural production zone	
Hill zones	37.5
Mountain zones 1 and 2	30.4
Mountain zones 3 and 4	32.1
Farming type	
Full-time farming	41.1
Part-time farming	58.9
Production form	
Organic farming	23.2
Proof of ecological performance	76.8
Milk utilisation and associated feeding system	
Silage-free milk	33.9
Silage milk	66.1
Agricultural education level of the farm manager	
Higher than an apprenticeship	37.5
Completed apprenticeship or lower agricultural education level	62.5

Source: Own calculations.

Table 4.3: Descriptive statistics of the investigated numeric determinants of farm global environmental, local environmental and economic performance (DE= digestible energy)

Determinant [unit in square brackets]	Minimum	Maximum	Mean	Std. deviation	Coefficient of variation (%)
Farm size [ha]	7.98	40.60	22.49	9.06	40.28
DE share crops [in %]	0.00	58.20	8.18	13.96	170.66
DE share other cattle [in %]	0.08	65.80	8.49	12.21	143.82
Milk production intensity [in kg milk per ha forage area]	1,943.09	14,661.59	5,382.88	2,568.69	47.72
Stocking rate [in Livestock Units per ha]	0.45	2.00	1.18	0.34	28.81
Grassland share [%]	54.55	100.00	91.22	11.92	13.07
Grassland yield [dT/ha]	35.30	113.48	65.08	15.45	23.74
N-fertiliser applied [kg N/ha]	11.02	208.02	100.38	41.99	41.83
P-fertiliser applied [kg P /ha]	2.17	25.02	9.13	4.03	44.14
Milk yield per cow [in kg per cow and year]	2,858	12,167	6,027	1,524	25
Share of concentrates [%]	0.75	17.28	8.12	4.32	53.20
Age of the farm manager [years]	24	65	44.38	9.76	21.99

Source: Own calculations.

4.2.7 Analysis of the determinants of global environmental, local environmental and economic performance

Taking into account the limited sample size as well as the number of independent variables analysed and considering the requirements in terms of number of observations for performing a multiple linear regression analysis[8], we had to reject this multivariate approach, which would have best suited for the purpose of the present work. Instead, we investigated separately the effect of each factor on each performance indicator considered. Because of the limited sample size and the fact that the assumptions (*inter alia* normal distribution assumption) required for performing parametric tests were not fulfilled, this effect was investigated by means of non-parametric statistical tools. If the determinant was interval-scaled, we used the non-parametric Spearman's rank correlation to assess the relationship between this determinant and the performance indicator considered. In the case of a categorical determinant, its effect on the performance indicator was analysed with the Mann-Whitney U test if the factor in question had two categories, or the Kruskal-Wallis test if the factor considered had more than two categories.

4.3 RESULTS

The results of the Spearman's rank correlation analysis between the numeric determinants and the performance indicators are presented in Table 4.4.

The results show that, for most impact categories considered, farm size showed no significant effect on the global environmental performance (GEP). For two impact categories (demand for non-renewable energy and human toxicity), however, farm size was slightly positively correlated with GEP. The effect of farm size on the local environmental performance (LEP) was positive for four issues (human toxicity, ozone formation, acidification and terrestrial eutrophication) and not significant for the remaining issues. Farm size was also positively

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[8] Harrell (2001, p. 61) stated, as a rule of thumb, that at least 10 to 20 observations should be available per determinant to obtain a reliable fitted-regression model. Applied to the present investigation, this rule would imply that at least 170 to 340 observations would be needed since the model encompassed 17 determinants.

correlated with two of the three economic performance indicators considered (return on equity and output/input ratio) and had no significant effect on the third (work income per family work unit).

The share of crops in the farm's digestible energy (DE) output was positively correlated with the GEP regarding several impact categories except for K-resources demand, deforestation, aquatic ecotoxicity, terrestrial ecotoxicity and aquatic N-eutrophication, for which no significant correlation was observed. Conversely, the crop share in the farm DE output was negatively related to the LEP regarding three impact categories (aquatic ecotoxicity, terrestrial ecotoxicity and aquatic N-eutrophication). Regarding the other impact categories, we found no significant correlation between the crop share in the farm DE output and LEP. Also, none of the three economic performance indicators was significantly correlated with farm DE crop share.

The share of non-dairy cattle in the farm DE output was negatively correlated with all GEP indicators except terrestrial ecotoxicity, for which no signification relationship was observed. Conversely, the non-dairy cattle share in the farm DE output tended to have no significant effect on farm LEP, with the exception of the impact categories aquatic ecotoxicity, terrestrial ecotoxicity and ozone formation, for which a positive effect was observed. The non-dairy cattle share in the farm DE was slightly negatively correlated with one of the three economic performance indicators (return on equity) and had no significant relationship with the other two.

Milk production intensity, defined as the annual quantity of milk produced per ha forage area, was positively correlated with most GEP indicators, with the exception of those related to the impact categories K-resources demand, aquatic ecotoxicity and terrestrial ecotoxicity. Conversely, milk production intensity showed a negative relationship with the LEP regarding aquatic ecotoxicity, terrestrial ecotoxicity, ozone formation, acidification, terrestrial eutrophication and aquatic N-eutrophication. For a few environmental categories, either no significant relationship (for human toxicity) or a slightly positive correlation (for aquatic P-eutrophication) was observed between milk production intensity and LEP. Milk production intensity was furthermore positively related to two of the economic indicators investigated (work income per family work unit and output/input ratio) and had no effect on the third (return on equity).

The correlation between the stocking rate and the GEP indicators was not significant, the only exception being the GEP regarding ozone depletion for which a very weak positive correlation was observed. Contrariwise, the stocking rate turned out to be negatively correlated with six LEP indicators (human toxicity, ozone formation, acidification, terrestrial eutrophication, aquatic N- and P-eutrophication). For the remaining LEP indicators as well as for the economic performance indicators, no significant relationships were observed between the stocking rate and the performance indicators.

The grassland share was negatively correlated with almost all GEP indicators, with the exception of those related to K-resources demand, aquatic and terrestrial ecotoxicity. The significance and direction of the relationship between grassland share and LEP depended on the environmental impact category considered. A positive correlation was observed for the impact categories aquatic ecotoxicity, terrestrial ecotoxicity, ozone formation and aquatic N-eutrophication. Contrariwise, a negative relationship was observed for LEP regarding aquatic P-eutrophication. No significant relationships were observed between the grassland share and LEP for the impact categories human toxicity, acidification and terrestrial eutrophication. With respect to economic performance, the grassland share was shown to correlate slightly negatively with the output/input ratio whereas it exhibited no significant relationship with the other two economic performance indicators.

The grassland yield was shown to be positively correlated with eleven of the fifteen GEP indicators and to negatively influence the LEP indicators regarding ozone formation, acidification and terrestrial eutrophication. It had no significant effect on the remaining GEP and LEP indicators, or on the economic performance indicators considered.

The two determinants N- and P-fertiliser applied per ha behaved – in terms of their effect on farm GEP, LEP and economic performance – quite similarly. They were positively correlated with most of the GEP indicators, showed a negative relationship with most LEP indicators and had no significant effect on farm economic performance.

The milk yield per cow positively influenced most of the GEP indicators and one LEP indicator (aquatic P-eutrophication). At the same time, the milk yield also correlated negatively with one GEP indicator (terrestrial ecotoxicity) and with two LEP indicators (aquatic and terrestrial ecotoxicity). Furthermore, it was slightly positively correlated with two of the three economic performance indicators considered (work income per family work unit and output/input ratio).

Concentrates use intensity had a negative effect on the GEP regarding six environmental impact categories, namely P-resources demand, K-resources demand, deforestation, aquatic ecotoxicity, terrestrial ecotoxicity and aquatic N-eutrophication. It furthermore negatively correlated with the LEP with respect to aquatic ecotoxicity, terrestrial ecotoxicity and aquatic N-eutrophication. Concentrates use intensity also showed a weak negative correlation with one of the three economic performance indicators investigated, namely return on equity.

Farm manager's age correlated positively and weakly with the GEP regarding K-resources demand, human toxicity, terrestrial ecotoxicity and aquatic N-eutrophication as well as with the LEP regarding human toxicity. Conversely, it showed a negative correlation with the LEP regarding acidification, terrestrial eutrophication and aquatic P-eutrophication. No significant relationship was observed between farm manager's age and farm economic performance.

Table 4.5 provides the results of the non-parametric tests (Kruskal-Wallis test / Mann-Whitney U test) investigating the relationship between the categorical determinants and the performance indicators. The median and average values of each performance indicator for each determinant category/group are available in Appendix.

The unfavourableness of the natural production conditions was shown to negatively affect almost all the GEP indicators with the exception of terrestrical ecotoxicity, for which no significant effect could be observed. On the other hand, unfavourable natural production conditions had a prevailingly positive effect on LEP, except for the impact categories human toxicity and aquatic P-eutrophication for which the impact of the unfavourable natural production conditions was negative and non-significant. Unfavourable natural production conditions were furthermore shown to negatively impact two out of three investigated economic performance indicators (work income per family work unit and output/input ratio).

Part-time farming showed – compared to full-time farming – a lower GEP regarding two environmental impact categories (demand for non-renewable energy resources and human toxicity). For most impact categories considered, however, no significant GEP differences could be observed between part-time and full-time farming. In terms of LEP, part-time farms did not differ significantly from full-time farms for all environmental impact categories considered except human toxicity, for which part-time farms exhibited a lower LEP compared to full-time farms. With respect to economic performance, part-time farms showed for all three indicators investigated a significantly lower economic performance than full-time farms.

Farms whose managers had an agricultural education level higher than an apprenticeship showed a higher GEP regarding almost all environmental impact categories considered than farms whose manager had an agricultural education level equivalent to or lower than an apprenticeship, with the exception of P-resources demand and terrestrial ecotoxicity. For these two environmental impact categories, no significant difference in GEP was exhibited between the higher and lower education level of the farm manager. A higher agricultural education level of the farm manager was also associated with a better LEP regarding human toxicity, acidification and terrestrial eutrophication. The higher agricultural education also resulted in a better economic performance for all three economic performance indicators considered.

Compared to proof of ecological performance farming (PEP), organic farming showed a higher GEP for all impact categories considered except land competition and ozone formation, for which no significant differences could be observed between the two production forms. A positive effect of organic farming was also observed for the LEP regarding human toxicity, aquatic ecotoxicity, terrestrial ecotoxicity and aquatic N-eutrophication. For the other environmental impact categories, no significant LEP differences were observed between PEP and organic farming. Organic farming furthermore yielded a higher economic performance than PEP farming for all three economic performance indicators considered.

Compared to the milk produced by using silage in the feed, silage-free milk was associated with a higher GEP regarding P-resources demand, K-resources demand, deforestation, human toxicity, aquatic ecotoxicity, aquatic N- and P-eutrophication. With respect to the other environmental categories, no significant differences were found between silage milk and silage-free milk. Silage-free milk production influenced LEP mostly non-significantly. However, in the case of two impact categories (human toxicity and aquatic N-eutrophication) it exhibited a positive effect on the LEP. Silage-free milk furthermore showed a higher economic performance than silage milk for all three observed indicators.

Table 4.4: Spearman's rank correlation analysis between the numeric determinants and the performance indicators

	Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy (DE) for Humans/On- and Off-Farm Environmental Impact)															**Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)**								**Farm Economic Performance**		
Determinant	Demand for non-renewable energy	Ozone depletion	P-resources demand	K-resources demand	Deforestation	Global warming potential	Land competition	Human toxicity	Aquatic ecotoxicity	Terrestrial ecotoxicity	Ozone formation	Acidification	Terrestrial eutrophication	Aquatic N-eutrophication	Aquatic P-eutrophication	Human toxicity	Aquatic ecotoxicity	Terrestrial ecotoxicity	Ozone formation	Acidification	Terrestrial eutrophication	Aquatic N-eutrophication	Aquatic P-eutrophication	Work Income per Family Work Unit	Return on Equity	Output/Input Ratio
Farm size	+0.23 *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+0.25 *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	+0.30 *	n.s.	n.s.	+0.38 **	+0.37 **	+0.36 **	n.s.	n.s.	n.s.	+0.30 *	+0.33 *
Share of crops in the farm DE output	+0.51 ***	+0.44 ***	+0.24 *	n.s.	n.s.	+0.51 ***	+0.49 ***	+0.42 **	n.s.	n.s.	+0.48 ***	+0.52 ***	+0.50 ***	n.s.	+0.38 **	n.s.	-0.47 ***	-0.45 ***	n.s.	n.s.	n.s.	-0.54 ***	n.s.	n.s.	n.s.	n.s.
Share of non-dairy cattle in the farm DE output	-0.53 ***	-0.54 ***	-0.44 ***	-0.33 *	-0.52 ***	-0.59 ***	-0.60 ***	-0.51 ***	-0.31 *	n.s.	-0.59 ***	-0.57 ***	-0.56 ***	-0.53 ***	-0.52 ***	n.s.	+0.25 *	+0.28 *	+0.23 *	n.s.	n.s.	n.s.	n.s.	n.s.	-0.24 *	n.s.
Milk production intensity	+0.52 ***	+0.52 ***	+0.30 *	n.s.	+0.24 *	+0.62 ***	+0.80 ***	+0.60 ***	n.s.	n.s.	+0.65 ***	+0.55 ***	+0.55 ***	+0.44 ***	+0.69 ***	n.s.	-0.34 **	-0.49 ***	-0.50 ***	-0.38 **	-0.38 **	-0.31 *	+0.27 *	+0.33 *	n.s.	+0.33 *
Stocking rate	n.s.	+0.24 *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.32 *	n.s.	n.s.	-0.69 ***	-0.62 ***	-0.61 ***	-0.23 *	-0.25 *	n.s.	n.s.	n.s.
Grassland share	-0.70 ***	-0.63 ***	-0.37 **	n.s.	-0.32 *	-0.71 ***	-0.72 ***	-0.61 ***	n.s.	n.s.	-0.68 ***	-0.72 ***	-0.71 ***	-0.33 *	-0.66 ***	n.s.	+0.53 ***	+0.58 ***	+0.26 *	n.s.	n.s.	+0.54 ***	-0.31 *	n.s.	n.s.	-0.25 *
Grassland yield	+0.24 *	+0.28 *	+0.32 *	+0.30 *	+0.39 **	n.s.	+0.38 **	+0.36 **	+0.37 **	+0.25 *	n.s.	n.s.	n.s.	+0.52 ***	+0.43 **	n.s.	n.s.	n.s.	-0.61 ***	-0.56 ***	-0.56 ***	n.s.	n.s.	n.s.	n.s.	n.s.
N-fertiliser applied	+0.41 **	+0.43 ***	n.s.	n.s.	n.s.	+0.51 ***	+0.57 ***	+0.27 *	n.s.	n.s.	+0.51 ***	+0.44 ***	+0.43 ***	+0.25 *	+0.46 ***	-0.30 *	-0.42 **	-0.62 ***	-0.74 ***	-0.59 ***	-0.58 ***	-0.53 ***	n.s.	n.s.	n.s.	n.s.
P-fertiliser applied	+0.32 *	+0.37 **	n.s.	n.s.	n.s.	+0.37 **	+0.43 **	n.s.	n.s.	n.s.	+0.39 **	+0.28 *	+0.28 *	+0.30 *	+0.29 *	-0.29 *	-0.24 *	-0.42 **	-0.74 ***	-0.68 ***	-0.68 ***	-0.35 **	n.s.	n.s.	n.s.	n.s.
Milk yield per cow	+0.27 *	n.s.	n.s.	n.s.	n.s.	+0.43 **	+0.47 ***	+0.38 **	n.s.	-0.23 *	+0.46 ***	+0.50 ***	+0.51 ***	n.s.	+0.47 ***	n.s.	-0.33 *	-0.47 ***	n.s.	n.s.	n.s.	n.s.	+0.42 **	+0.29 *	n.s.	+0.32 *
Concentrates use intensity	n.s.	n.s.	-0.42 **	-0.48 ***	-0.50 ***	n.s.	n.s.	n.s.	-0.51 ***	-0.54 ***	n.s.	n.s.	n.s.	-0.33 *	n.s.	n.s.	-0.58 ***	-0.63 ***	n.s.	n.s.	n.s.	-0.46 ***	n.s.	n.s.	-0.27 *	n.s.
Age	n.s.	n.s.	n.s.	+0.27 *	n.s.	n.s.	n.s.	+0.24 *	n.s.	+0.24 *	n.s.	n.s.	n.s.	+0.23 *	n.s.	+0.35 **	n.s.	n.s.	n.s.	-0.23 *	-0.23 *	n.s.	-0.30 *	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. Source: Own calculations.

Table 4.5: Results of the non-parametric tests (Kruskal-Wallis test and Mann-Whitney U test) investigating the relationship between the categorical determinants and performance indicators

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)															Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)								Farm Economic Performance		
		Demand for non-renewable energy	Ozone depletion	P-resources demand	K-resources demand	Deforestation	Global warming potential	Land competition	Human toxicity	Aquatic ecotoxicity	Terrestrial ecotoxicity	Ozone formation	Acidification	Terrestrial eutrophication	Aquatic N-eutrophication	Aquatic P-eutrophication	Human toxicity	Aquatic ecotoxicity	Terrestrial ecotoxicity	Ozone formation	Acidification	Terrestrial eutrophication	Aquatic N-eutrophication	Aquatic P-eutrophication	Work Income per Family Work Unit	Return on Equity	Output/Input Ratio
Determinants	Unfavourable natural production conditions	- ***	- ***	- **	- *	- **	- ***	- ***	- ***	- *	n.s.	- ***	- ***	- ***	- ***	- ***	- **	+ **	+ **	+ ***	+ *	+ *	+ ***	n.s.	- *	n.s.	- *
	Part-time farming	- *	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	- **	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	- **	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	- ***	- ***	- ***
	Higher agricultural education level of farm manager	+ **	+ **	n.s.	+ **	+ ***	+ **	+ *	+ ***	+ *	n.s.	+ **	+ ***	+ ***	+ *	+ *	+ *	n.s.	n.s.	n.s.	+ *	+ *	n.s.	n.s.	+ *	+ **	+ *
	Organic farming	+ *	+ *	+ ***	+ ***	+ ***	+ *	n.s.	+ ***	+ ***	+ ***	n.s.	+ *	+ *	+ **	+ *	+ **	+ *	+ **	n.s.	n.s.	n.s.	+ *	n.s.	+ *	+ **	+ **
	Silage-free milk	n.s.	n.s.	+ **	+ **	+ **	n.s.	n.s.	+ **	+ *	n.s.	n.s.	n.s.	n.s.	+ *	+ *	+ **	n.s.	n.s.	n.s.	n.s.	n.s.	+ *	n.s.	+ ***	+ **	+ ***

Notes: Results of non-parametric tests 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. Source: Own calculations.

4.4 DISCUSSION

In the present section, we firstly summarise the main findings of our investigation and then relate them to those of other studies found in the literature. Lastly, we address the limitations of our work and highlight future research needs.

4.4.1 Main findings

In the present work, we investigated – for a sample of Swiss dairy farms from the alpine area – the relationship between the characteristics of these farms and their global environmental, local environmental and economic performance. The characteristics investigated related to the farm's natural environment, structure, production technology, management and farm manager considered from a socio-demographic perspective.

Based on the results of the analysis conducted, we can classify the determinants into different groups/types depending on their relationship with farm global environmental, local environmental and economic performance.

Organic farming, higher agricultural education level, silage-free milk production, farm size, concentrates use intensity and part-time farming belong to the first group of determinants defined as those that simultaneously influenced all three performance dimensions in the same direction. Depending on the direction (positive versus negative) of the effect, we can distinguish two subgroups within this first group. Organic farming, higher agricultural education level and silage-free milk synergistically positively influenced farm global and local environmental as well as economic performance. They had a clear positive correlation with many global environmental performance indicators, some local environmental performance indicators and all economic performance indicators investigated. Farm size also belongs to this subgroup of determinants that synergistically positively influenced farm global and local environmental as well as economic performance. However, the positive effect of larger farm size on global environmental performance was quite weak and only concerned very few indicators, i.e., environmental impact categories.

Conversely, the share of concentrates in the cattle feed was negatively correlated with several global and local environmental performance indicators and with one economic performance indicator, revealing the existence of a negative synergetic effect of this determinant on global and local environmental performance and also, but to a lesser extent, on economic performance. Part-time farming also belongs to the determinants that synergistically negatively influenced farm global and local environmental as well as economic performance. Its negative effect on farm environmental performance is, however, limited to a very few global and local environmental performance indicators.

Ten further determinants affected two of the performance dimensions considered in different directions. A first subgroup that can be distinguished within this group consists of the determinants that prevailingly positively influenced farm global environmental performance and negatively affected farm local environmental performance. This first subgroup encompasses the following seven determinants: crop share in the farm digestible energy output, milk production intensity, grassland yield, N-fertiliser applied per ha, P-fertiliser applied per ha, milk yield per cow and year, and age of the farm manager. Most of the determinants in this first subgroup did not show any significant relationship with farm economic performance, with the exception of milk production intensity and milk yield per cow, both of which positively correlated with two farm economic performance indicators (work-income per family work unit and output/input ratio). The second subgroup consists of the determinants that correlated prevailingly negatively with farm global environmental performance and correlated positively with farm local environmental performance. This second subgroup consists of three determinants, namely unfavourable natural production conditions, non-dairy cattle share in the farm digestible energy output, and grassland share. These three determinants correlated negatively with at least one economic performance indicator.

The stocking rate represents the last type of determinant. It significantly influenced only one of the three dimensions considered. More precisely, it correlated negatively with farm local environmental performance.

More generally, we observed that most factors analysed influenced global environmental performance and economic performance in the same direction, which highlights the synergies that exist in the promotion of these two dimensions of the sustainability performance of a farm. Contrariwise, for the majority of determinants, the enhancement of local environmental performance frequently presented trade-offs with the improvement in global environmental performance.

4.4.2 Discussion of the main findings

The present work embodies the first comprehensive analysis of the relationship between various farm characteristics (related to the farm's natural environment, structure, production technology, management and also the farm manager) and the local and global dimensions of farm environmental performance that were proposed by Repar et al. (2017). It also investigates the relationship between these characteristics and farm economic performance. Existing studies looking into the determinants of sustainable performance of dairy farming have so far mostly focused on analysing (i) the effect of production form and (ii) the effect of production intensity on what Repar et al. (2017) referred to as global environmental performance. No study to date has simultaneously investigated the determinants of global and local environmental performance as defined in Repar et al. (2017). The following subsection discusses two out of six determinants that synergistically influenced all performance dimensions investigated, namely organic farming and concentrates use intensity, by comparing our results with those of similar studies found in the literature. For the other four determinants (farm manager's agricultural education, silage-free milk, farm size and part-time farming), no similar LCA-based studies could be found in the literature.

Regarding dairy production technology, organic farming was shown in a review conducted by Tuomisto et al. (2012) to be associated with – compared to conventional farming – higher eco-efficiencies (i.e. global environmental performance) for one impact category (energy use) and lower ones for a couple of others (land use, eutrophication potential and acidification potential). In terms of local environmental performance, Thomassen et al. (2008) found for Dutch dairy farms a lower N and P_2O_5 surplus per ha for organic farming. Jan et al. (2015) also reported for Swiss farms a lower nitrogen surplus per ha for organic farming. Regarding farm economic performance, organic farming was shown to have a positive effect on work income per family work unit of the Swiss mountain farms (Jan et al., 2011). In the present work, organic farming was associated not only with higher local environmental performance regarding all impact categories considered, but also with higher global environmental performance for all impact categories, and higher economic performance regardless of the chosen profitability indicator. This finding implies that – under the natural production conditions of the alpine area and the associated production restrictions and low forage yield potential – organic farming is likely to be, from both an environmental and an economic perspective, a more appropriate technology than conventional farming for dairy activity. Thus, a process of conversion from conventional to organic farming is likely to lead to overall environmental and economic benefits and consequentially to a substantial improvement in the sustainability of the dairy food chain in this region. This probably explains why the share of organic farms in Switzerland increases with the unfavourableness of the natural production conditions (e.g. in 2012, according to Bio Suisse (2013), the proportion of the usable agricultural area cultivated under organic farming in the mountain and in the plain region was 19.6% and 6.5% respectively).

Concerning the effect of concentrates use intensity on the environmental performance of dairying, LCA-based studies have shown that decreasing the use of concentrates in the feed may lead to improvement in farm global and local environmental performance. Thomassen et al. (2008) have shown for Dutch dairy farms that decreasing the use of concentrates per kg of milk has the potential to improve farm global environmental performance, for both organic and conventional dairy farming. They furthermore showed that the N and P_2O_5 surplus per ha was higher for conventional than for organic farms. This finding had to do with higher concentrates input on conventional farms, showing the negative effect of concentrates use intensity on local environmental performance (Thomassen et al., 2008). The results found by Arsenault at al. (2009) for Canadian dairy farms in Nova Scotia province also suggested that a decrease in the use of concentrates had the potential to improve the global environmental performance of dairy farming. The present study confirmed these findings in the context of Swiss mountain dairy farming as it showed that a lower share of concentrates in cattle feed has the potential to produce positive effects on both global and local environmental performance. Furthermore, it also revealed the existence of positive effects of a lower concentrates use intensity on farm economic performance. Similar findings regarding the positive influence of decreased concentrates use intensity on farm profitability (measured as work income per family work unit) have already been revealed for the Swiss alpine dairy farms in the study by Jan et al. (2011).

Using the same dataset as in the present work and based on a correlation analysis, Repar et al. (2016) found that farm global environmental performance goes hand in hand with farm economic performance, while it is often negatively correlated with farm local environmental performance. The present analysis of the factors affecting farm global and local environmental performance came to a similar finding. Specifically, it showed that several factors affect farm global environmental and farm economic performance in the same direction and several other factors influence farm global and local environmental performance in the opposite direction. In that sense, our work highlights (i) the synergies that exist in the promotion of farm global environmental and economic performance and (ii) the trade-offs that are present in the enhancement of farm global and local environmental performance. Our findings regarding the trade-offs between local and global environmental performance are in line with those of Guerci et al. (2013) and Battini et al. (2016), who stressed for Italian dairy farms the potential trade-offs that may exist between global and local environmental impacts.

As identified in the present work, six factors have a synergetic effect on all three performance dimensions investigated, and can therefore be used as a lever for the simultaneous improvement of the environmental and economic sustainability of dairy farming in the alpine region. Nevertheless, for most of the determinants investigated in this work, the direction of their effect on the three investigated performance dimensions diverged, which highlights the high complexity of the farm sustainable performance maximisation.

4.4.3 Limits of the study and future research needs

For an interpretation and discussion of the results of the present investigation as well as their implications, attention should be paid to the following issues.

Firstly, the sample was not selected at random due to the comprehensiveness and complexity of the data collection. This may have introduced a positive bias in the representativeness of the sample as it has to be expected that farm managers interested in environmental issues were more likely to participate in the project than those who did not feel concerned by such issues.

Secondly, as already discussed by Repar et al. (2017) and Repar et al. (2016), the indicators implemented in this work for the measurement of farm environmental performance present through their definition a major limitation, namely that they assess relative rather than absolute environmental sustainability (Bjørn & Hauschild, 2013). This implies that there is no guarantee of achieving an absolute sustainable state at global and local ecosystem level (Repar et al., 2017). Implementing the absolute environmental sustainability concept in the farm environmental performance indicators would imply the highly challenging introduction of the ecosystem carrying capacity constraint into each environmental performance indicator as conceptually exposed in the discussion by Repar et al. (2017).

Thirdly, an additional sample-related limitation of the investigation lies in the approach used to assess the effect of the selected factors on farm environmental and economic performance. As mentioned in the methodological part, due to the limited sample size we had to refrain from applying multiple linear regression analysis. Consequently, the measured relationship between one factor and one performance indicator is not a *ceteris paribus* effect and may capture the effects of other factors correlated with the one investigated.

An additional limitation of our investigation was that it did not cover the social dimension of sustainability. Further investigations on the effect of different determinants on the social sustainability performance of alpine dairy farms are required, especially when considering the important socio-economic relevance of dairy farming for the local economies of the mountainous regions, which are less populated and not easily accessible (Jan et al., 2012b).

Finally, the complexity of the relationships found between the determinants and performance indicators investigated and especially the numerous trade-offs observed in this study reveal that a holistic improvement in the environmental performance of the cradle-to-farm gate link of the food chain is highly challenging. In that sense, our work indirectly suggests that improving the environmental sustainability of food chains may require more than an environmental performance improvement in the cradle-to-farm gate link of the food chain. Without questioning and changing consumption patterns towards goods and services with a much lower environmental impact, the challenge of reducing the ecological footprints of humanity within the planet's boundaries will very likely be difficult to meet. This was also argued by Godfray & Garnett (2014), who called for action throughout the food system on multiple fronts and especially for a moderation of demand, a reduction in waste, an improvement in governance and the production of more food with less environmental impacts.

4.5 CONCLUSIONS

The present work provides evidence that the promotion of an economically viable Swiss alpine dairy farming sector, as well as the enhancement of one with high global and local environmental performance, is a complex and highly challenging undertaking. Whereas some factors allow simultaneous improvements in global environmental, local environmental and economic performance, several determinants are shown to influence the sustainability dimensions considered in different directions and thus to present trade-offs in terms of sustainable performance enhancement. Organic farming, higher agricultural education level of the farm manager and the production of silage-free milk were identified as factors that allow global environmental, local environmental and economic performance to be improved simultaneously. Lower intensity of concentrates use, larger farm size and full-time farming were also revealed to be beneficial for all the investigated performance dimensions, but to a weaker extent. Our work furthermore provides initial evidence that the promotion of an economically viable alpine dairy farming sector, as well as the enhancement of one with a high global environmental performance, are not antinomic but synergetic. Contrariwise, the enhancement of farm local and global environmental performance turns out to be in many cases antinomic. Policy-makers should be aware of the trade-offs that exist in the enhancement of farm sustainable performance and stimulate only those factors that are capable of holistically enhancing the global environmental, local environmental and economic performance of farming. Last but not least, our work demonstrates the value of combined micro-level economic and environmental data. Such data enable us to gain a better insight into the relationship between different dimensions of sustainability, which is a pre-requisite if we wish to improve sustainability.

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4.7 APPENDIX

Table 4.6: Median and average values of farm global environmental performance indicators for the investigated categorical determinants: Part 1

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)													
		Demand for non-renewable energy[1]		Ozone depletion[2]		P-resources demand[3]		K-resources demand[4]		Deforestation[5]		Global warming potential[6]		Land competetion[7]	
		Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average
Natural production conditions	Hill	0.51	0.53	8.43e+07	8.69e+07	4825	17102	3400	9083	2054	17608	1.80	1.82	1.44	1.41
	Mountain 1&2	0.38	0.37	5.95e+07	6.06e+07	2837	10547	1777	7013	1767	15928	1.55	1.51	1.09	1.08
	Mountain 3&4	0.24	0.23	3.37e+07	3.65e+07	2073	2704	1707	2344	574	978	0.76	0.82	0.49	0.45
Farm type	Part-time	0.34	0.35	5.57e+07	5.58e+07	3022	7407	1798	5283	956	8857	1.33	1.34	0.92	0.93
	Full-time	0.48	0.44	7.30e+07	7.27e+07	3800	14899	2951	7730	2054	15908	1.58	1.50	1.34	1.10
Agricultural education level	Lower	0.34	0.32	5.21e+07	5.24e+07	2645	5039	1692	4151	846	5658	1.23	1.21	0.87	0.87
	Higher	0.48	0.48	7.56e+07	7.99e+07	6483	19559	5391	9850	2189	21911	1.77	1.72	1.33	1.22
Production form	PEP	0.36	0.35	5.57e+07	5.57e+07	2668	3502	1657	2372	890	3138	1.37	1.33	1.02	0.95
	Organic	0.44	0.49	7.91e+07	8.61e+07	24618	33578	18773	19242	13697	40249	1.73	1.66	1.34	1.16
Feeding system	Silage	0.39	0.37	5.89e+07	5.82e+07	2800	7721	1777	4311	890	9339	1.31	1.32	0.92	0.92
	Silage-free	0.35	0.42	5.50e+07	7.15e+07	5405	15865	4023	10138	2158	16453	1.52	1.57	1.31	1.15

Source: Own calculations.

1 : in MJ DE per MJ eq. 2: in MJ DE per kg CFC11 eq. 3: in MJ DE per kg P 4: in MJ DE per kg K 5: in MJ DE per m^2 6: in MJ DE per kg CO_2 eq. 7: in MJ DE per m^2a.

Table 4.7: Median and average values of farm global environmental performance indicators for the investigated categorical determinants: Part 2

		Farm Global Environmental Performance: Eco-Efficiency (MJ Digestible Energy for Humans/On- and Off-Farm Environmental Impact)															
		Human toxicity[8]		Aquatic ecotoxicity[9]		Terrestrial ecotoxicity[10]		Ozone formation[11]		Acidification[12]		Terrestrial eutrophication[13]		Aquatic N-eutrophication[14]		Aquatic P-eutrophication[15]	
		Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average
Natural production conditions	Hill	10.79	10.91	94	233	2598	4768	0.21	0.21	7.95	8.54	0.87	0.94	567	662	18772	18567
	Mountain 1&2	6.14	6.46	118	221	3375	4557	0.18	0.18	6.93	6.71	0.77	0.74	654	852	13322	13762
	Mountain 3&4	4.17	4.20	78	84	2479	2453	0.09	0.10	3.44	3.58	0.37	0.39	344	329	3961	5919
Farm type	Part-time	5.84	6.17	99	160	2598	3483	0.15	0.15	5.83	5.97	0.63	0.66	496	622	12478	11859
	Full-time	8.33	9.17	108	213	3117	4644	0.19	0.17	7.46	7.00	0.81	0.77	567	599	13502	14741
Agricultural education level	Lower	5.15	5.85	94	135	2372	2954	0.14	0.14	5.16	5.33	0.57	0.59	484	537	11689	11233
	Higher	8.33	9.99	135	259	3355	5637	0.19	0.19	7.95	8.16	0.86	0.90	627	738	14573	16059
Production form	PEP	6.08	6.28	85	102	2145	2422	0.16	0.15	5.83	6.06	0.64	0.67	496	510	12784	11979
	Organic	10.95	11.10	435	445	9622	9046	0.19	0.19	6.31	7.48	0.69	0.82	828	952	17211	16561
Feeding system	Silage	5.84	6.54	94	144	2592	3348	0.14	0.15	5.83	5.90	0.63	0.65	496	545	12322	11486
	Silage-free	8.11	9.07	167	254	3355	5152	0.18	0.18	6.93	7.35	0.76	0.81	595	746	16941	16075

Source: Own calculations.

8: in MJ DE per kg 1,4-DB eq. 9: in MJ DE per kg 1,4-DB eq. 10: in MJ DE per kg 1,4-DB eq. 11: in MJ DE per m^2.ppm.h 12: in MJ DE per m^2 13: in MJ DE per m^2 14: in MJ DE per kg N 15: in MJ DE per kg P

Table 4.8: Median and average values of farm local environmental performance indicators for the investigated categorical determinants

		Farm Local Environmental Performance (ha Farm Usable Agricultural Area/On-Farm Environmental Impact)															
		Human toxicity[1]		Aquatic ecotoxicity[2]		Terrestrial ecotoxicity[3]		Ozone formation[4]		Acidification[5]		Terrestrial eutrophication[6]		Aquatic N-eutrophication[7]		Aquatic P-eutrophication[8]	
		Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average	Median	Average
Natural production conditions	Hill	7.63e-03	8.77e-03	0.03	0.05	0.28	8.82	1.38e-05	1.37e-05	5.55e-04	5.36e-04	5.90e-05	5.68e-05	0.06	0.05	1.96	1.84
	Mountain 1&2	1.18e-03	2.16e-03	0.08	0.12	2.02	4.67	1.42e-05	1.45e-05	4.43e-04	5.38e-04	4.67e-05	5.69e-05	0.11	0.11	1.38	1.54
	Mountain 3&4	2.76e-03	7.24e-03	0.09	0.10	4.78	23.89	1.87e-05	1.91e-05	6.83e-04	6.85e-04	7.22e-05	7.23e-05	0.13	0.12	1.42	1.56
Farm type	Part-time	1.49e-03	5.61e-03	0.08	0.09	2.29	13.94	1.43e-05	1.54e-05	5.29e-04	5.72e-04	5.61e-05	6.05e-05	0.10	0.10	1.39	1.60
	Full-time	5.43e-03	7.21e-03	0.06	0.08	2.08	10.20	1.49e-05	1.60e-05	6.07e-04	6.02e-04	6.38e-05	6.37e-05	0.07	0.08	1.62	1.74
Agricultural education level	Lower	1.90e-03	5.55e-03	0.08	0.09	2.29	13.38	1.42e-05	1.52e-05	5.35e-04	5.35e-04	5.61e-05	5.65e-05	0.08	0.10	1.39	1.66
	Higher	6.22e-03	7.43e-03	0.04	0.09	2.08	10.78	1.49e-05	1.64e-05	6.29e-04	6.66e-04	6.65e-05	7.06e-05	0.07	0.09	1.52	1.66
Production form	PEP	1.79e-03	5.64e-03	0.06	0.07	1.64	10.75	1.43e-05	1.52e-05	5.35e-04	5.55e-04	5.61e-05	5.88e-05	0.08	0.09	1.49	1.69
	Organic	6.30e-03	8.35e-03	0.15	0.15	4.95	17.88	1.49e-05	1.73e-05	6.29e-04	6.79e-04	6.65e-05	7.19e-05	0.13	0.12	1.48	1.56
Feeding system	Silage	1.79e-03	6.45e-03	0.06	0.08	2.02	15.96	1.43e-05	1.55e-05	5.29e-04	5.66e-04	5.61e-05	5.99e-05	0.07	0.09	1.49	1.67
	Silage-free	6.09e-03	5.91e-03	0.07	0.10	2.40	5.47	1.49e-05	1.61e-05	6.07e-04	6.19e-04	6.38e-05	6.55e-05	0.08	0.10	1.48	1.65

Source: Own calculations.

1: in ha per kg 1,4-DB eq.   2: in ha per kg 1,4-DB eq.   3: in ha per kg 1,4-DB eq.   4: in ha per m^2.ppm.h   5: in ha per m^2 6: in ha per m^2 7: in ha per kg N   8: in ha per kg P

Table 4.9: Median and average values of farm economic performance indicators for the investigated categorical determinants

		Farm Economic Performance					
		Work Income per Family Work Unit (in Swiss Francs)		Return on Equity (in %)		Output/Input Ratio	
		Median	Average	Median	Average	Median	Average
Natural production conditions	Hill	50272	46315	-4.54	-14.14	0.93	0.92
	Mountain 1&2	28872	29930	-6.56	-6.66	0.84	0.83
	Mountain 3&4	30309	34549	-8.50	-18.18	0.84	0.85
Farm type	Part-time	25951	27764	-11.87	-16.10	0.84	0.82
	Full-time	54213	51614	-0.42	-8.95	0.93	0.93
Agricultural education level	Lower	29914	33432	-11.87	-19.07	0.84	0.84
	Higher	43018	44437	0.75	-3.33	0.92	0.92
Production form	PEP	28872	32676	-10.24	-16.93	0.84	0.85
	Organic	52270	53712	0.76	-0.74	0.94	0.94
Milk production	Silage	25382	28677	-12.29	-16.55	0.83	0.83
	Silage-free	52270	54855	0.75	-6.58	0.94	0.96

Source: Own calculations.

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5 GENERAL CONCLUSIONS AND OUTLOOK

In the present thesis, we developed a theoretically sound and consistent framework on how to measure environmental performance at farm level and we implemented this framework empirically for the Swiss alpine dairy sector. Within this empirical application, we investigated the relationship between farm economic and environmental performance and analysed their respective determinants. The aims of this empirical application were to better understand these two dimensions of the sustainable performance of Swiss alpine dairy farms and to find out whether it is possible to improve them simultaneously. The main results and conclusions of the dissertation are summarised and discussed below.

5.1 HOW TO MEASURE FARM ENVIRONMENTAL PERFORMANCE IN A THEORETICALLY SOUND AND CONSISTENT WAY?

Defining a farm environmental performance indicator involves two steps: (i) choosing the variable to be used to assess the environmental impact of the investigated farming system (also referred to as the "environmental indicator"); and (ii) defining the environmental performance indicator (referred to as the "performance indicator"), which is based on the environmental variable from the first step. Several types of environmental indicators and different approaches to defining performance indicators were found in the scientific literature on the measurement of farm environmental performance. Quite often, the definition of farm environmental performance indicators was driven mostly by considerations regarding data availability or data collection feasibility, without conceptually considering which indicators were actually required for the assessment of farm environmental performance. The lack of attention paid to how to implement the environmental sustainability concept in farm environmental performance indicators often led to environmental performance indicators that were inconsistently defined and inappropriate. For example, some indicators showed spatial system boundaries inconsistencies in their definition. Others relied on monetary variables, which are poorly suited for the purpose of environmental performance assessment due to the biased nature of price information. To ensure real sustainable development in the agri-food sector, it is essential for farm environmental performance indicators to be consistent with the meaning and principles of the sustainability concept originally derived from the macro level. Environmental sustainability is an ecological concept closely connected with the ecosystem carrying capacity (constraint), which is a biophysical concept relating to the maximum damage that an ecosystem can sustain. Basically, we distinguished between two levels at which the carrying capacity constraint for ensuring sustainable development applies: that of the global ecosystem (planet Earth), and that of the local ecosystem underpinning the farm area. Complying with the carrying capacity constraints at both global and local ecosystem level is a prerequisite for achieving a sustainable state with no possibilities for compensation or substitution between these two levels. Based on these considerations and on this distinction, we differentiated between the local and global environmental performance of a farm. Farm local and global environmental performances measure the relative contribution of a farm to compliance with the local and global carrying-capacity constraints.

When operationalising the concept of local and global environmental performance, we paid particular attention to three major issues that we considered of utmost importance for the definition of farm environmental performance indicators. First, the spatial system boundaries underlying the defined environmental performance indicators should be perfectly consistent. Second, the farm environmental performance indicators should be of a purely biophysical nature (i.e. should not rely on price information). Third, the environmental indicator underlying the defined environmental performance indicator should best represent the potential damage caused by farming to the environment, i.e. should be as close as possible to the end of the cause-effect chain, also called impact pathway, linking the agricultural production practices to the environmental impacts. This is the reason why we opted for the use of midpoint indicators, which show the best compromise between environmental relevance and indicator accuracy. Specifically, we proposed to measure farm global environmental performance by the farm environmental intensity across the entire production chain up to the farm gate. Environmental intensity, which is the inverse of eco-efficiency, was defined as the cradle-to-farm gate (i.e. on- and off-farm) environmental impact generation per biophysical unit of output produced by the farm. We defined farm local environmental performance as the environmental impact generated at local (i.e. on-farm) level per unit of local farm area. Whereas all environmental issues must be considered at a global level, only those that are primarily of local relevance (i.e. those for which farm environmental impacts are primarily influential on the local ecosystem scale) have to be considered at local level. The assessment of farm environmental performance according to our framework requires the carrying out of a cradle-to-farm gate LCA (Life Cycle

Assessment) with a decomposition of the cradle-to-farm gate environmental impacts into their off- and on-farm parts. To ensure an easier and more intuitive interpretation (i.e. to ensure that a high versus low indicator value implies good versus poor performance), we recommend – when implementing local and global environmental performance indicators in empirical applications – to build them reversely like we did in our empirical application for Swiss dairy farms[9].

The implementation of separate local and global environmental performance indicators, as proposed in our framework, prevents the shifting of environmental problems from on-farm to off-farm scale and vice versa.

Our framework highlights the complexity of the agricultural environmental sustainability concept, which conceptually cannot and practically should not be reduced to a single 'one size fits all' indicator. The framework we developed is not only theoretically sound but also universally implementable regardless of farm type/activities or location. From a more general perspective, our work on the definition of farm environmental performance makes a substantial contribution to the field of agricultural environmental sustainability. Beyond the framework for farm environmental performance assessment, we also provide a comprehensive and systematic overview of the farm-level environmental performance indicators found in scientific literature and we address their weaknesses especially from a theoretical/conceptual perspective. In that sense, our work shows not only how farm environmental performance should be measured but also how it should *not* be measured, and therefore eliminates the lack of clarity existing in this field. This should prevent the further use and uncontrolled growth of inappropriate indicators claiming to measure farm environmental sustainability.

[9] We did not implement this recommendation when developing our proposed framework, as it would have made it more difficult to understand the rationale behind our indicators if they had been reversely defined from the beginning.

5.2 LOCAL VERSUS GLOBAL FARM ENVIRONMENTAL PERFORMANCE AND THEIR LINK TO ECONOMIC PERFORMANCE IN SWISS ALPINE DAIRY FARMING

The analysis of the relationships between farm local environmental performance, measured as the farm area per unit of local (i.e. on-farm) environmental impact, and farm global environmental performance, measured as the farm digestible energy output for humans per unit of global (i.e. on- and off-farm) environmental impact, in Swiss alpine dairy farming revealed complex relationships. Depending on the environmental issues (impact categories) considered, either no significant relationships, or trade-offs or synergies were observed. Trade-offs occurred more frequently than synergies. These complex relationships between farm local and global environmental performance empirically show the complexity of improving the environmental sustainability of farming. The several trade-offs observed between farm local and global environmental performance imply that an improvement in farm global environmental performance regarding one environmental issue will likely lead to a deterioration in farm local environmental performance regarding at least one other issue. Therefore, to avoid any improvement in one dimension of environmental performance happening at the expense of another, both local and global performance dimensions must be considered simultaneously.

Our work also showed that the often raised and feared possible trade-off between environmental and economic performance could not be confirmed empirically, either for the local or for the global dimension of environmental performance. Contrariwise, we even found synergies between farm global environmental and economic performance. This finding implies that improving 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 in farm economic performance and vice versa.

5.3 HOW TO SIMULTANEOUSLY IMPROVE FARM GLOBAL VERSUS LOCAL ENVIRONMENTAL PERFORMANCE AND FARM ECONOMIC PERFORMANCE IN SWISS ALPINE DAIRY FARMING?

Our analysis of the potential determinants of farm environmental and economic performance showed that some factors, namely organic farming, higher agricultural education level of the farm manager and the production of silage-free milk allowed global environmental, local environmental and economic performance to be improved simultaneously. Lower intensity of concentrates use, larger farm size and full-time farming were also revealed to be beneficial for all the investigated performance dimensions, but to a weaker extent. Several factors were shown to influence the sustainability dimensions considered in different directions and thus to present trade-offs in terms of sustainable performance enhancement. These results thus provided evidence that the promotion of an economically viable Swiss alpine dairy sector, as well as the enhancement of one with high global and local environmental performance, is a complex and highly challenging undertaking. Our work furthermore provided evidence that the promotion of farm global environmental performance and the enhancement of its economic performance are not antinomic but synergetic. Contrariwise, the enhancement of farm local and global environmental performance turned out to be in many cases antinomic. In that sense, these results confirm the findings of our analysis of the relationship between global versus local environmental performance and economic performance.

5.4 IMPLICATIONS AND RECOMMENDATIONS FOR STAKEHOLDERS

Several implications and recommendations intended for stakeholders, especially for policy-makers and all stakeholders involved to a greater or lesser extent in the assessment and improvement of farm environmental sustainability (for instance, LCA practitioners), can be derived from this work. These recommendations are listed below:

- Several of the numerous existing indicators used to assess farm environmental performance are inconsistent and inappropriate for this purpose. We therefore strongly recommend refraining from the use of such indicators, which could lead to no improvement in farm environmental sustainability or even to a deterioration.

- When measuring farm environmental performance, we recommend adopting a biophysical approach as well as accounting for both local and global ecosystems. This leads to the distinction between farm global and local environmental performance. All stakeholders should be aware that considering both farm global and local environmental performances is imperative if we wish to achieve real rather than spurious improvements in environmental sustainability. We strongly advise against a unilateral focus on either of these two dimensions of farm environmental performance to avoid any environmental problem shifting from one scale to the other.
- The previous recommendation to account for both the local and global dimension of farm environmental performance becomes of acute relevance given that several trade-offs were found between these two dimensions of farm environmental performance in the empirical application conducted for Swiss alpine dairy farms. This finding has far-reaching implications, especially if it is confirmed for other types of farms and other countries. When dealing with the environmental sustainability of farming, scientists and policy-makers have until now mostly adopted a rather one-sided focus. For example, LCA practitioners have mainly focused solely on global environmental performance. Contrariwise, 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 (e.g. by focusing on nitrogen surplus per ha). Due to this one-sided focus, scientists and policy-makers 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 this widespread assumption – at least for Swiss dairy farming. In that sense, our work indirectly questions whether these one-sided perspectives, which have been widely used for years, have always been able to achieve real improvements in terms of environmental sustainability. This leads to the following three recommendations:

  (i) Life cycle assessment (LCA) practitioners should be aware of the potential prejudicial side effects of a one-sided focus on global environmental performance, as is mainly currently practised in the LCA field. A holistic farm environmental performance assessment encompassing both local and global environmental performance dimensions calls for a standard decomposition of cradle-to-farm gate impacts into their on- and off-farm parts. This decomposition should be implemented in the LCIA tools.

(ii) Agricultural policy-makers should be aware that most existing farm-level agri-environmental policy instruments are likely to lead – due to their single focus on farm local environmental performance – to a deterioration in farm global environmental performance. We therefore strongly recommend policy-makers to use LCA and to account for the local and global dimension of farm environmental performance when designing agri-environmental policies.

(iii) The necessity of considering the two dimensions of environmental performance also applies more generally to all stakeholders, and especially agricultural scientists, when developing and assessing new agricultural technologies intended to improve the environmental sustainability of farming.

- Our finding of the existence of trade-offs between farm global and local environmental performance also has indirect implications for the sustainable intensification debate, which has been targeting improvements in farm global environmental performance. Due to its unilateral focus on global environmental performance, the sustainable intensification debate will most likely not lead to holistic environmental sustainability improvements 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)."
- The environmental sustainability challenges faced by agriculture are such that they urgently require action at farm level. Action can only be effective in reaching the sustainability goals if it relies on facts, i.e. on accurate data from a comprehensive and representative sample of farms. The implementation of our proposed framework requires the conducting of cradle-to-farm gate life cycle assessments. The latter are – due to their very comprehensive and detailed data requirements – highly time consuming, which impedes the broad

implementation of our proposed local/global framework. Current developments in the information and communications technology field, especially those related to big data and smart farming, offer a unique opportunity in this regard. Indeed, they should make it possible (i) to substantially improve the efficiency and quality of LCA data collection, (ii) to reduce the "data collection burden" for farmers and LCA practitioners, and (iii) thus ultimately to promote the use of the LCA technique, which is a prerequisite for a broad implementation of the global/local farm environmental performance indicators we propose. This calls for a coordinated action plan at national level aiming to provide the legal, technical, organisational and financial framework conditions to encourage dissemination of the LCA technique in the agricultural sector. Policy-makers should consider this as a priority in their political agenda and especially in future agricultural policy reforms.

- When looking at the options for improving the environmental and economic sustainability of Swiss alpine dairy farms, policy-makers should consider promoting organic farming, higher agricultural education level of the farm manager, the production of silage-free milk, lower intensity of concentrates use, larger farm size and full-time farming, as these factors were shown to simultaneously positively affect farm local environmental, global environmental and economic performance to some extent. Interestingly, two of these factors are already being promoted by means of financial incentives (direct payments) within the current Swiss agricultural policy, which has been in force since 2014. Organic farming is supported with specific production system contributions. A decrease in the intensity of concentrates use is fostered through the contributions for grassland-based cattle farming, which aim to promote the production of milk and meat from grassland with reduced concentrates use.
- Finally, the complexity of the relationships found between the determinants and the environmental and economic performance indicators investigated in the empirical application for Swiss alpine dairy farms, and especially the numerous trade-offs observed in this regard, revealed that a holistic improvement in the environmental performance of the cradle-to-farm gate link of the food chain is highly challenging. In that sense, our work indirectly suggests that improving the environmental sustainability of food chains may require more than an environmental performance improvement in the cradle-to-farm gate link of the food chain. Without questioning and changing consumption patterns towards goods and services with a much lower environmental impact, the challenge of reducing the

ecological footprint of humanity within the planet's boundaries will very likely be difficult to meet. From this perspective, similarly to Godfray and Garnett (2014), we call for action throughout the food system on multiple fronts and especially for a moderation of demand through a shift in diets, a reduction in waste along the whole chain and especially at the end-consumer stage, an improvement in governance and production of more food with less environmental impact.

5.5 OUTLOOK

In this section we address the future research needs related to the field of the assessment and improvement of the sustainability of farming or, more generally, of the whole agri-food chain, which we identified based on the findings and limitations of this dissertation.

- The *global-local* farm environmental performance framework we developed is universally implementable regardless of farm type/activities and location. It would be highly valuable to apply it to other farm types and countries in order to test the robustness of our findings, i.e. to analyse whether the relationship patterns that we observed between farm global environmental, local environmental and economic performance for Swiss alpine dairy farms also hold for other farm types and countries or if these relationship patterns in fact differ.
- The carrying capacity concept represents the starting point of our theoretical considerations underlying the development of the framework for farm environmental performance assessment, and especially the local/global distinction we proposed. However, the farm global and local environmental performance indicators we developed do not directly incorporate the carrying capacities of the local and global ecosystems. This is a major limitation of our framework and a field where future research is needed. In this dissertation, we conceptually paved the way for integrating these carrying capacities into the indicators we proposed. Quantifying the carrying-capacity entitlement for food production for the different impact categories and for the two different scales (global vs. local) considered is however expected to be a highly challenging undertaking fraught with uncertainties, especially given the dynamic nature of carrying capacities. Future research work should thus address this question and the practical implementation of our conceptual considerations on how to incorporate carrying capacities into the farm global and local environmental

performance indicators we defined. This would enable us to move from relative to absolute environmental sustainability.

- One major limitation of the present work is that it does not reflect the three-pillared sustainability approach but focuses only on the environmental and economic pillar. The reasons for this are (i) the especially deep focus that we wanted to take on the farm environmental sustainability dimension, and (ii) the data availability constraints that did not allow for the social dimension to be explored within the limited resources that we had at our disposal. Operating on the premise that less can be more, we wished to explore the environmental sustainability of farming in a deeper and innovative way. Nevertheless, considering the important socio-economic relevance of farming in rural communities and the fragile social situation of farmers and their families, we consider it indispensable to extend our framework by including farm social sustainability indicators in order to conduct a holistic three-pillared sustainability assessment of farming.
- A further limitation of this dissertation relates to our focus on the agricultural production side of the agri-food chain or, more precisely, on the cradle-to-farm gate link of this chain. Although the lion's share of environmental impacts of food takes place in the cradle-to-farm gate link of the food chain, the downstream stages of processing, transportation, consumption and waste disposal also play an important role. Ultimately, the impact and role of every actor in the food chain need to be considered if the overall sustainability of agri-food chains is to be improved. Consumers thereby play a central role "*in the way food chains are developing*" and "*in making food chains more sustainable*" (Grunert, 2011). By making more sustainable food choices, they have the power of prompting producers and retailers to change their product portfolios and production/retail processes towards more sustainable ones (Grunert, 2011). We therefore call for a comprehensive cradle-to-grave investigation of the sustainable performance of the food chain and of its determinants, thereby acknowledging the particular role that consumers play in this chain as a driving force.

We would like to end this section with a recommendation of a more general – and even, to some extent, philosophical – nature. The environmental sustainability challenge faced by humanity is such that the move of our societies towards a sustainable state will very likely require more than a simple environmental optimisation of current production and consumption systems. As stressed by Schumacher as long ago as 1978, "*we must thoroughly understand the problem and* *begin to see the possibility of new life-styles, with new methods of production and new patterns of consumption: a life-style designed for permanence*" (Schumacher, 1978). This questions the effectiveness of current mainstream research approaches, which tend to focus exclusively on the relative optimisation of existing production/consumption systems without asking whether these systems are the right or wrong ones in absolute sustainability terms. The development of sustainable and healthy agri-food chains calls for out-of-the-box interdisciplinary research involving many different scientific fields (natural, agricultural, social, health and economic sciences) and relying on participatory approaches involving citizens in the design of these chains. Policy-makers should more strongly support this type of research, which would benefit society as a whole.

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LIST OF PUBLICATIONS

Peer-reviewed scientific journals

Determinants of global versus local environmental performance and economic performance of dairying: a case study of Swiss mountain farms

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University Education

2015-2017 **University of Hohenheim, Stuttgart, Germany**
Institute of Farm Management
Computer Applications and Business Management in Agriculture
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2011–2013 **Hochschule Pforzheim, Pforzheim, Germany**
Master of Business Administration in International Management

2004-2009 **University of Zagreb, Zagreb, Croatia**
Faculty of Economics and Business
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Work experience

2014-2017 **Agroscope, Ettenhausen, Switzerland**
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2013-2014 **Institute for Market Ecology, Konstanz, Germany**
Finance Manager

2009-2011 **Repro Eko, Jastrebarsko, Croatia**
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