Universität für Bodenkultur Wien
University of Natural Resources
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Doctoral Dissertation

Eco-efficiency of Austrian farms considering multiple functions of agriculture

submitted by

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in partial fulfillment of the requirements for the academic degree

Doktor der Bodenkultur (Dr.nat.techn.)

Vienna, April 2022

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Affidavit

I hereby declare that I have authored this dissertation independently, and that I have not used any assistance other than that which is permitted. The work contained herein is my own except where explicitly stated otherwise. All ideas taken in wording or in basic content from unpublished sources or from published literature are duly identified and cited, and the precise references included. Any contribution from colleagues is explicitly stated in the authorship statement of the published papers.

I further declare that this dissertation has not been submitted, in whole or in part, in the same or a similar form, to any other educational institution as part of the requirements for an academic degree.

Finally, I confirm that I am familiar with the standards of Scientific Integrity and with the guidelines of Good Scientific Practice, and that this work fully complies with these standards and guidelines.

Vienna, 07th April 2022 Florian GRASSAUER *(manu propria)*

Dedicated to my parents, Ulrike and Manfred

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Table of contents

List of publications

Paper I

Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms

Citation

Grassauer, F., Herndl, M., Nemecek, T., Guggenberger, T., Fritz, C., Steinwidder, A., Zollitsch, W., 2021. Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms. Journal of Cleaner Production 297, 126662.

Link

https://www.sciencedirect.com/science/article/abs/pii/S0959652621008829

Paper II

Assessing and improving eco-efficiency of multifunctional dairy farming: The need to address farms' diversity

Citation

Grassauer, F., Herndl, M., Nemecek, T., Fritz, C., Guggenberger, T., Steinwidder, A., Zollitsch, W., 2022. Assessing and improving eco-efficiency of multifunctional dairy farming: The need to address farms' diversity. Journal of Cleaner Production 338, 130627.

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Additional journal contribution

Environmental Assessment of Austrian Organic Dairy Farms With Closed Regional Production Cycles in a Less Favorable Production Area

Citation

Grassauer, F., Herndl, M., Iten, L., Gaillard, G., 2022. Environmental Assessment of Austrian Organic Dairy Farms With Closed Regional Production Cycles in a Less Favorable Production Area. Frontiers in Sustainable Food Systems 6, 817671.

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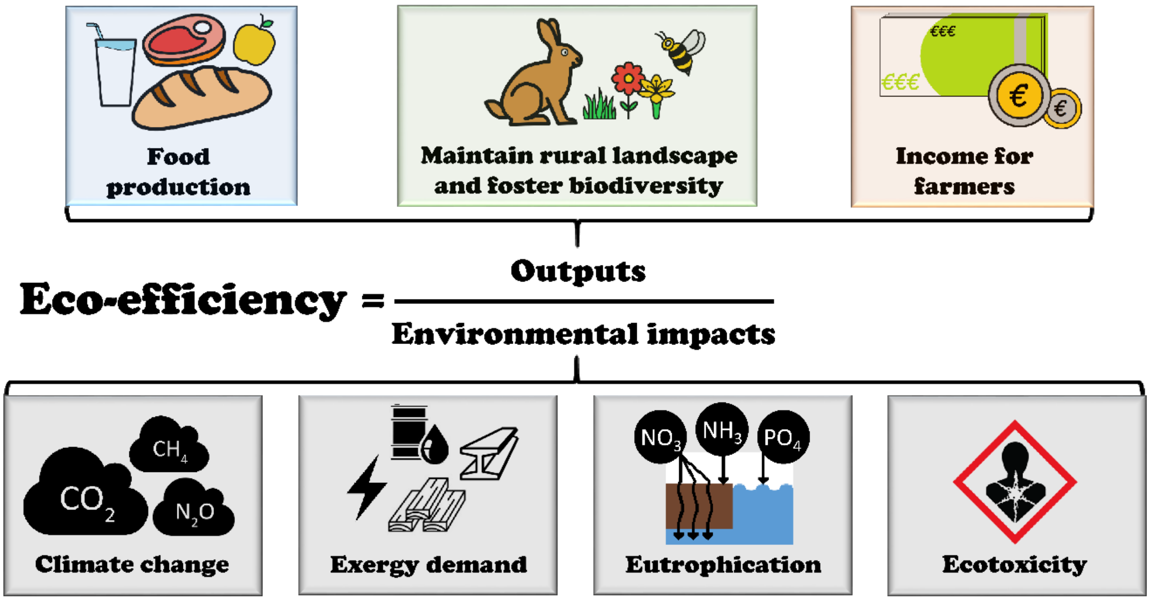
Graphical abstract



Abstract

A growing world population and food demand spurred the intensification of agricultural production over the last decades. However, with the concept of sustainability, certain social groups were sensitized to the consequences of humanity's perturbation of the Earth system and nowadays seek eco-efficient agricultural production practices that produce sufficient food without increasing environmental pressure. Besides food production, agriculture also provides other functions to society, such as generating an income for farmers, preserving attractive rural areas, and specific agricultural systems may also contribute to maintaining or even enhancing biodiversity. Therefore, this thesis aims to develop a novel concept of farm-level eco-efficiency assessment that simultaneously considers multiple functions of agriculture and comprises two scientific papers. Paper I describes this novel concept and implements it on 47 Austrian farms from four different farm types. The results revealed high diversity in eco-efficiency among the farms, and a comparison of the farm types showed a slightly higher eco-efficiency of the crop- and wine-producing farms than livestock keeping farms. Paper II deals with the eco-efficiency assessment and its improvement on 44 specialized dairy farms. The results revealed organic farms to score a significantly higher mean eco-efficiency than conventional farms. Moreover, specific management options to promote eco-efficiency could be pointed out. The purchased concentrate was identified as a central source that diminishes eco-efficiency, thus highlighting site-adapted agriculture. Ultimately, the thesis shows that eco-efficient livestock farming states a major challenge in the future, and especially the considerable impact of the purchased concentrate in livestock keeping farms is tempting one to amend Ludwig Feuerbach's well-known quote from "you are what you eat" into "you are what you feed."

Kurzfassung

Der steigende Lebensmittelbedarf hat in den letzten Jahrzehnten zu einer Intensivierung der Landwirtschaft geführt. Mit dem Konzept der Nachhaltigkeit wurden spezifische gesellschaftliche Gruppierungen für die Folgen dieser Intensivierung sensibilisiert und streben nun ökoeffiziente Landwirtschaft an, die ausreichend Lebensmittel produziert, ohne die Umwelt weiter zu belasten. Neben der Lebensmittelproduktion erfüllt die Landwirtschaft auch andere gesellschaftliche Funktionen, wie z. B. die Erzielung eines Einkommens für LandwirtInnen. Manche Agrarsysteme leisten auch einen Beitrag zur Sicherung bzw. Verbesserung der Biodiversität. Ziel dieser Arbeit ist es daher, ein neuartiges Konzept zur Bewertung der Ökoeffizienz zu entwickeln, das gleichzeitig mehrere Funktionen der Landwirtschaft berücksichtigt. Paper I beschreibt dieses neuartige Konzept und wendet es auf 47 Betriebe an. Die Ergebnisse zeigen, dass die Ökoeffizienz der Betriebe sehr unterschiedlich ist, und ein Vergleich der Betriebstypen zeigt, dass die Ökoeffizienz der Ackerbau- und Weinbaubetriebe etwas höher ist als jene der viehhaltenden Betriebe. Paper II bewertet die Ökoeffizienz von 44 Milchviehbetrieben und sucht Potentiale für deren Verbesserung. Die Ergebnisse zeigen, dass biologisch wirtschaftende Betriebe eine signifikant höhere mittlere Ökoeffizienz aufweisen als konventionelle Betriebe. Zudem konnten spezifische Managementoptionen zur Verbesserung der Ökoeffizienz aufgezeigt werden. Das zugekaufte Kraftfutter wurde als eine zentrale Quelle identifiziert, die die Ökoeffizienz mindert und damit die Wichtigkeit der standortangepassten Landwirtschaft hervorhebt. Letztlich zeigt die Arbeit, dass die ökoeffiziente Tierhaltung in Zukunft eine große Herausforderung darstellt und insbesondere der erhebliche Einfluss des zugekauften Kraftfutters in viehhaltenden Betrieben verleitet dazu, Ludwig Feuerbachs bekanntes Zitat von "Du bist, was du isst" in "Du bist, was du fütterst" abzuwandeln.

1. General introduction

As the first chapter of this thesis, the General introduction outlines the emergence of the concept of sustainability, its changing perceptions over time, and the current state of the art. Subsequently, the readers are introduced to the origins of the concept of eco-efficiency and its close relation to sustainability. After explaining the general definition of eco-efficiency as a quotient of the value of a product or service and its environmental impacts, the following subchapter covers the implementation of eco-efficiency in agricultural research. It highlights crucial environmental impacts that agriculture contributes to and elaborates on how the value of agricultural products or services is accounted for in eco-efficiency studies.

Derived from the conceptional shortcomings detected in the previous subchapter, the thesis' aims are presented in chapter 2.

The main part of this thesis comprises two scientific papers, which are presented in chapter 3:

- Paper I, published in 2021 in the Journal of Cleaner Production, describes an innovative approach to assess farms' eco-efficiency and implements it on a set of 47 Austrian farms of four different types.
- Paper II, published in 2022 in the Journal of Cleaner Production, deals with the eco-efficiency assessment and its improvement on 44 specialized dairy farms. By linking the determining components of eco-efficiency to farm-related parameters, specific management options to promote the eco-efficiency of a farm could be pointed out.

The journal contributions are followed by a General discussion elaborating on methodological aspects of the thesis that were not or only partially discussed in the papers, chapter 5 draws conclusions, and after the list of references used in the General introduction and General discussion, an additional journal contribution is presented. Finally, the lists of figures and tables that are not part of the scientific publications are given, and the academic curriculum vitae of the author completes the thesis.

1.1. A brief history of sustainability

Early mentions of the concept of sustainability date back to the German cameralist Hans Carl von Carlowitz, who criticized the overexploitation of forests for short-term profits and stressed respect- and careful treatment of nature (von Carlowitz, 1713). His "Sylvicultura Oeconomica" was henceforth received and implemented throughout Europe and is considered a seminal work of sustainability.

In his book titled "A Sand County Almanac," the American ecologist Aldo Leopold stated that the environment has an intrinsic value and should not just be considered as an object for human exploitation or enjoyment (Leopold, 1949). By declaring this intrinsic value to be clearly distinguishable from the classical economic value, Leopold dissociated himself from the general conception of anthropocentric utilitarianism (Armstrong, 2006) and provided a literary concept of sustainability.

In the 1970s, Donella Meadows and her team from the Massachusetts Institute of Technology utilized the first global model to integrate the world economy with the environment (Costanza et al., 2007) to analyze the "world problematique" as formulated by the Club of Rome. In their published study report "The Limits to Growth," Meadows et al. (1972) predicted that continued growth of the global economy would lead to a collapse of the population and economic system sometime in the 21st century (Turner, 2008). However, this collapse could eventually be avoided by early changes in policy, technology, and behavior (Turner, 2008), thus establishing "a condition of ecological and economic stability that is sustainable far into the future" (Meadows et al., 1972).

The first worldwide noticed articulation of the idea of sustainable development occurred with the so-called Brundtland report in 1987. The report with the title "Our Common Future" was published by the World Commission on Environment and Development (WCED) of the United Nations and named after Mrs. Gro Harlem Brundtland, then chair of the commission and former Prime Minister of Norway. The WCED (1987) defined sustainable development as "… development that meets the needs of the present without compromising the ability of future generations to meet their own needs," which became a widely used dictum in scientific and policy-making communities (Yunlong and Smit, 1994).

In subsequent years, issues regarding sustainable development began to predominate academic and political debates (Scoones, 2007). This upsurge in globally recognizing the sustainability term culminated in the United Nations Conference on Environment and Development (UNCED) held in 1992 in Rio de Janeiro. A major outcome of this conference was the AGENDA 21, a comprehensive action program setting guidelines towards sustainable development in the 21st century (UNCED, 1992).

In 1997, John Elkington further popularized sustainable development in terms of the Triple Bottom Line (TBL) (Adams et al., 2016). The TBL, as presented in Figure 1, is an approach to human well-being and emphasizes sustainability as the outcome of societies simultaneously striving for environmental quality, economic prosperity, and social justice (Elkington, 1997; Raworth, 2018). Although the prioritization of the specific objectives varies globally, between, and within societies, the shared focus on environmental, economic, and social targets states a hallmark of sustainable development and a broad consensus on which the world can build (Sachs, 2012).

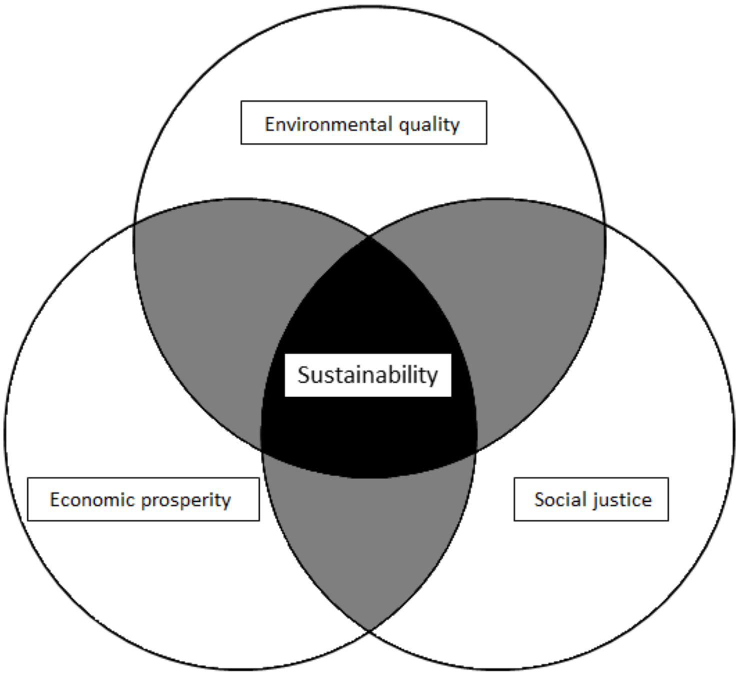


Figure 1. The Triple Bottom Line. Adapted from Elkington (1997).

Targeting a global mobilization towards achieving environmental quality, economic prosperity, and social justice (i.e., sustainability), the United Nations convened the

Millennium Summit in 2000 in New York, where 189 nations ratified the Millennium Declaration that pointed out eight Millennium Development Goals (MDGs) to be reached by 2015 (UN, 2000). In 2016, the MDGs were substituted by 17 Sustainable Development Goals (SDGs) adopted within the 2030 Agenda of the United Nations (UN, 2015). The SDGs are further split up into 169 targets and 330 indicators (Hák et al., 2016), should be achieved by 2030, and are the current state of the art regarding the implementation of sustainability into our society.

1.2. Eco-efficiency and its relation to sustainability

Somewhat coevolving besides the perception of sustainability since the last decade of the 20th century, the concept of eco-efficiency was considered the solution for getting the emerging sustainability agenda aboard global businesses. Elkington (1997) drew parallels to the ancient Trojans, as incorporating sustainability in businesses was feared by many to be a treacherous concept, with success ending in disaster, just like dragging the vast wooden horse through a gap in the walls of the long-besieged city of Troy.

Introduced by the World Business Council for Sustainable Development (WBCSD) chaired by Stephan Schmidheiny in 1992, eco-efficiency is defined as "the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle, to a level at least in line with the Earth's estimated carrying capacity" (Schmidheiny, 1992). Following this definition and according to Figure 2, eco-efficiency forms the interface between two of the three bottom lines of sustainability, namely environmental quality and economic prosperity (Dyllick and Hockerts, 2002; Ehrenfeld, 2005).

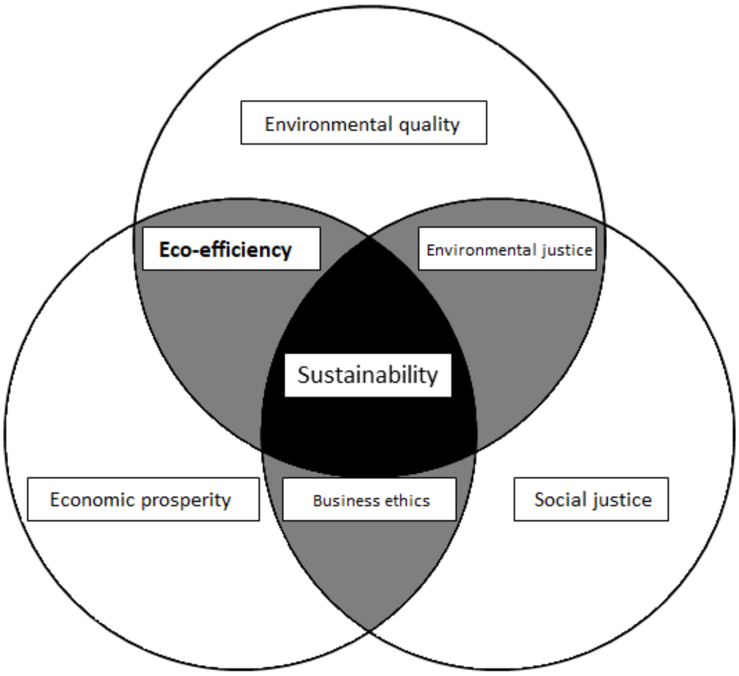


Figure 2. Eco-efficiency as the intersection between the environmental and economic agendas. Adapted from Elkington (1997).

However, the challenge of implementing the concept of eco-efficiency in businesses is inherent in the second part of the abovementioned definition as "progressively reducing ecological impacts and resource intensity throughout the life cycle" requires detailed knowledge of the numerous environmental impacts (EIs) and the resource use of specific goods and services. One appropriate methodology for assessing different EIs and the resource use of a product or service in a numeric manner is life cycle assessment (LCA) (ISO, 2006a, b; Klöpffer and Grahl, 2009; Rebitzer et al., 2004). The typical form of a LCA is a balance sheet focusing on the entire life cycle of a product or service, from raw material extraction, production, use, and disposal, including all transports (i.e., from the cradle to the grave) (Frischknecht and Büsser Knöpfel, 2013).

The last part of the definition of eco-efficiency requires reducing EIs and resource use "to a level at least in line with the Earth's estimated carrying capacity," which also states a major hindrance to adapting eco-efficient production practices successfully. The question of Earth's estimated carrying capacity has gained increasing interest since the early 2000s, as academia stressed the urgency of solving humanity's grand future challenges, e.g., climate change, energy and food security, health, and industrial reconstruction (Bugge et al., 2016; Ollikainen, 2014; Pülzl et al., 2014; Richardson, 2012). On a global scale, the framework of planetary boundaries proposed by Rockström et al. (2009a) and Rockström et al. (2009b) addressed this question by integrating the development of human societies and the maintenance of the Earth system and defined a safe operating space concerning nine planetary systems. Raworth (2012) refined the framework by defining 11 critical human deprivations, which serve as the social foundation, and combined them with the planetary boundaries, thus presenting a safe and just space for humanity to thrive in. A status update on the framework by Steffen et al. (2015) revealed that four planetary systems already exceeded their respective planetary boundary. However, the planetary boundaries framework is associated with significant uncertainties and crossing one of the boundaries does not necessarily lead to a catastrophic outcome directly but rather increases the risk of system destabilization and decreases resilience (van Vuuren et al., 2016).

Upon the extensive definition of eco-efficiency proposed by Schmidheiny (1992), there is also an operationalized periphrasis, defining eco-efficiency as the ratio between the output, i.e., the value of a product or service and its environmental impacts (DeSimone and Popoff, 1997; Thanawong et al., 2014; Van Passel et al., 2007).

1.3. Eco-efficiency in agriculture

As described in the previous subchapter, eco-efficiency is a quotient like any other efficiency term. A quotient is defined as the ratio of two variables to each other (i.e., the result of a division), thus requiring a denominator and a numerator. Regarding eco-efficiency, the environmental impacts serve as the denominator, whereas the product or service value functions as the numerator (Jan et al., 2012; Verfaillie and Bidwell, 2000). Especially regarding agricultural applications, the following two sections are intended to elaborate on the various manifestations of the two mentioned variables below and above the fraction line of eco-efficiency's defining equation.

1.3.1. Environmental impacts: the denominator

According to Foley et al. (2011), agriculture is considered the major force behind several environmental threats, thus pushing the environment to the brink of the planetary boundaries defined by Rockström et al. (2009a). These environmental threats are manifold but most prominently include climate change, biodiversity loss, and the perturbation of global nitrogen and phosphorus cycles (FAO, 2016, 2018b; Foley et al., 2005; Power, 2010; Steinfeld et al., 2006).

1.3.1.1. Climate change

As the agricultural sector currently contributes around 24 % of the global greenhouse gas (GHG) emissions, it inheres substantial potential to tackle climate change, either by absolute reductions, by becoming more efficient, or by providing carbon sinks (FAO, 2018a). Although several greenhouse gases are contributing to climate change, the three most prominent gases regarding the agricultural sector are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). These three gases have different origins in agricultural production systems and highly vary in their radiative forcing (i.e., their ability to trap heat in the Earth's atmosphere). Therefore, to quantify these gases' contribution to climate change, they are assigned individual characterization factors representing their radiative efficiencies relative to the reference gas CO_2 (IPCC, 2013). CO_2 emissions from the agricultural sector mainly stem from land-use changes (e.g., deforestation for pasture and arable land for crop production) (Steinfeld et al., 2006), fuel combustion, and electricity generation (Casey and Holden, 2005). Emissions of CH_4 primarily occur at the enteric fermentation in the digestive tracts of ruminants (Place and Mitloehner, 2010), from manure storage (O'Brien et al., 2012), and from flooded rice cultivation (Cai et al., 2003). N_2O is highly volatile and is formed during denitrification (Place and Mitloehner, 2010). Typical sources of N_2O are manure and slurry pits and the application of nitrogen fertilizers (de Boer, 2003).

1.3.1.2. Biodiversity loss

As stressed by Rockström et al. (2009a) and Steffen et al. (2015), biodiversity loss has already exceeded its planetary boundaries. According to IPBES (2019), approximately 75 and 66 % of the land surface and ocean area, respectively, are significantly altered by anthropogenic influences. Moreover, 32 million hectares (roughly the size of Germany) of highly biodiverse primary forests were lost between 2010 and 2015, and about one million species from the plant and animal kingdoms are currently facing extinction, many of them within decades (IPBES, 2019). The Millennium Ecosystem Assessment (MEA) identified land-use change via destructing natural habitats to expand agricultural areas as the leading cause of biodiversity loss (MEA, 2005). Although this form of land-use change usually does not occur in OECD countries, it is a common, though mostly illegal, practice in large parts of tropical Latin America, Southeast Asia, and sub-Saharan Africa (Steinfeld et al., 2006). The newly established agricultural land is often utilized to cultivate feed crops (e.g., soybean) or for extensive grazing. However, the destruction of natural habitats not only leads to the loss of unique plant and animal species, but the removal of the vegetation cover also fuels climate change through carbon release in the atmosphere (Steinfeld et al., 2006). Another significant driver of biodiversity loss is the intensification of agricultural production (Haaland et al., 2011), which decreases habitat heterogeneity at the farm level and increases the application of fertilizers and pesticides at the field level (Hendrickx et al., 2007), whereas Geiger et al. (2010) specifically identified insecticides and fungicides as having the most consistent negative effects on the species diversity of plants, carabids, and ground-nesting farmland birds. Unfortunately, biodiversity loss has many more far-reaching effects on vital ecosystem services such as water purification and crop pollination. Therefore, Ceballos et al. (2015) may rightly argued that biodiversity loss is the most severe aspect of the current environmental crisis.

1.3.1.3. The perturbation of global nitrogen and phosphorus cycles

As a building block of proteins, nitrogen is essential for the growth of organic tissue, and despite being an abundant chemical element, making up approximately 78 % of Earth's atmosphere, nitrogen most often limits plant growth (Bouwman et al., 2009). According to Galloway et al. (2004), the rate of biologically available atmospheric nitrogen entering the terrestrial biosphere has more than doubled compared to preindustrial levels. This increase is mainly related to human activities such as fossil fuel consumption, cultivation of legumes, and fertilizer production, with the latter two converting around 120 million tons of atmospheric N_2 into reactive, plant-available forms globally (Rockström et al., 2009a).

Conversely, phosphorus (P) only occurs in small amounts in Earth's lithosphere, hydrosphere, and biosphere (Bouwman et al., 2009). It is mined from phosphate rock and further processed for various technical uses, from fertilizer to toothpaste (Rockström et al., 2009a). Currently, phosphate rock is on the European Union's (EU) list of critical raw materials as it is a finite, non-renewable resource with deposits forecasted to last approximately 50 years at the current extraction rates (Nenov et al., 2020). The annual global mining volume of phosphorus is estimated at around 20 million tons, whereas 8.5 to 9.5 million tons are expected to be translocated into the oceans through soil erosion (Bennett et al., 2001; Mackenzie et al., 2002). Moreover, current P supply chains are predominately linear systems comprising P extraction, processing, and application, ultimately leading to tremendous P losses through municipal waste streams. Therefore, recycling P from such municipal waste streams to counteract over-exploitation states a core objective of the EU's proposed transition toward a circular economy (Nenov et al., 2020).

1.3.1.4. The environmental management triangle in agriculture

As mentioned in section 1.2, the environmental impacts can be numerically assessed by LCA. As a result of LCA, the environmental impacts are expressed as different impact categories (e.g., global warming potential) with different implications on management and mitigation (EC, 2010; Owens, 1998). Due to the high variation of impact categories in agricultural LCA, Nemecek et al. (2011) introduced the environmental management triangle, as depicted in Figure 3.

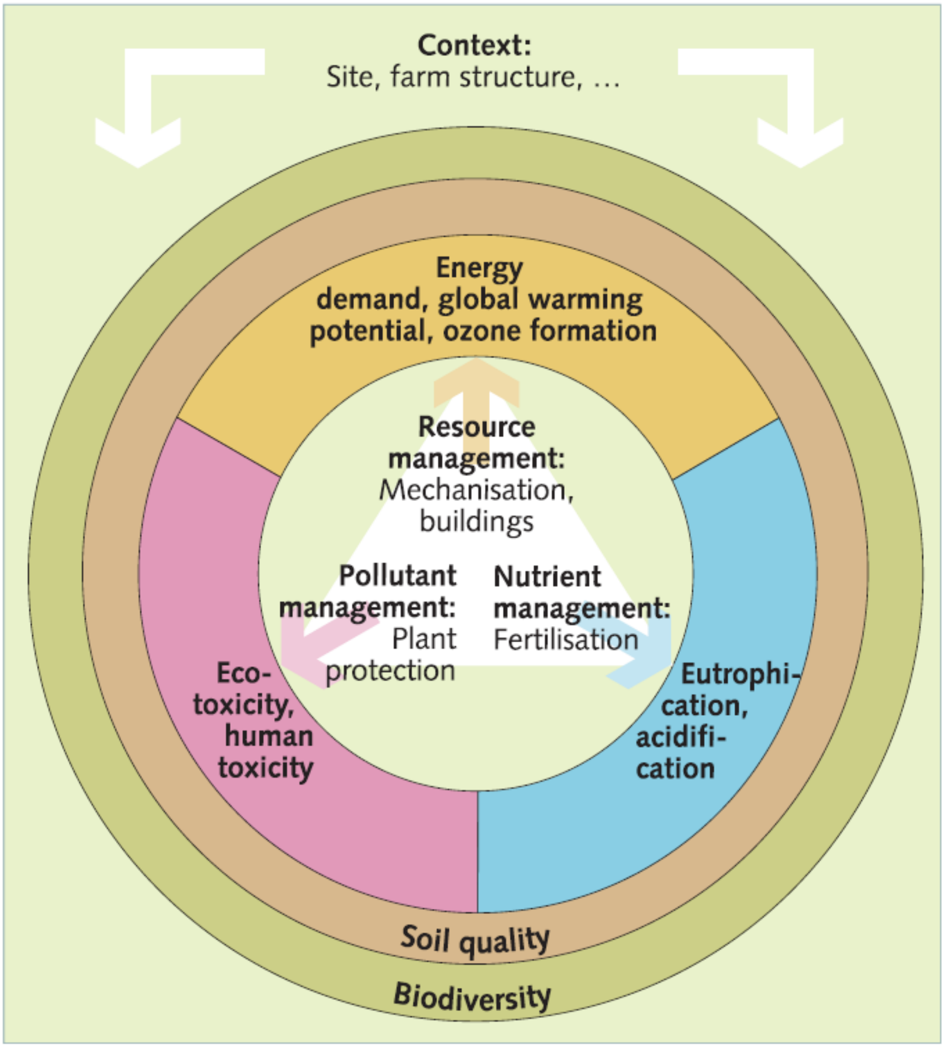


Figure 3. The environmental management triangle of farming systems. Adapted from Nemecek et al. (2011).

According to this triangle, the numerous impact categories can be divided into three groups with different management options and time horizons (Nemecek et al., 2011):

1. Resource management

This group comprises impact categories related to the use of resources and their corresponding emissions (e.g., energy demand, global warming potential, and ozone formation). Since the infrastructure (e.g., mechanization and buildings) and livestock dominate this group's emissions, adaptions and improvements in resource management can only be achieved in the long term (years to decades).

2. Nutrient management

Nutrient management is mainly related to fertilization and comprises impact categories such as eutrophication and acidification. As amendments in fertilization are applicable throughout the growing season, nutrient management refers to mid-term decisions (months to years).

3. Pollutant management

The effects of plant protection and the accumulation of heavy metals on humans and the environment are subsumed by pollutant management. Therefore, this group incorporates impact categories dealing with ecotoxicity (i.e., terrestrial, aquatic, and human ecotoxicity). Regarding the timescale, decisions in pollutant management are considered short-term (days to weeks).

All three groups of the environmental management triangle further affect soil quality and biodiversity.

1.3.2. Product or service value: the numerator

Reminiscing on the simplified definition of eco-efficiency by DeSimone and Popoff (1997), Thanawong et al. (2014), and Van Passel et al. (2007) (i.e., the ratio between the output, i.e., the value of a product or service and its environmental impacts), one may put the question on what to consider as the output of agricultural farms, or, more specific: "What products or services do farms deliver and how to evaluate them?" The OECD (2001) highlighted that agriculture and agricultural farms provide multiple commodity and non-commodity outputs and thus introduced the concept of multifunctionality of agriculture. By fulfilling different functions, agriculture contributes to multiple ecosystem services crucial for human well-being. As shown in Figure 4, these ecosystem services can be assigned to the following groups (MEA, 2003): (1) provisioning services, (2) regulating services, (3) cultural services, and (4) supporting services.

Depending on their respective specialization, agricultural farms simultaneously generate products (provisioning services), deliver benefits (regulating and cultural services), and provide necessary services to maintain themselves (supporting services).

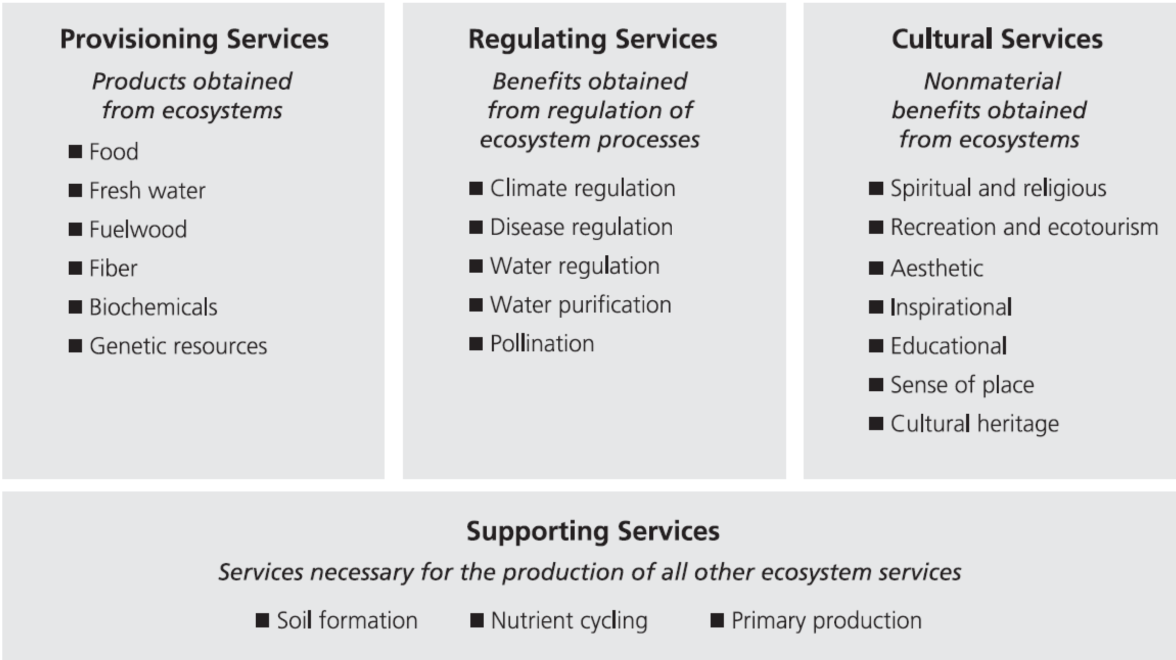


Figure 4. The classification of ecosystem services. Source: (MEA, 2003).

However, despite contributing to different ecosystem services by fulfilling multiple functions, scientists that assessed the eco-efficiency of farming systems only considered one function, i.e., output, in most cases. Table 1 shows examples of agricultural eco-efficiency studies from different farming systems and their respective units to measure the considered output (i.e., functional units). Compared to Figure 4, it becomes evident that most studies included in Table 1 consider the function of food production (i.e., provision services) for their eco-efficiency assessment. Functions related to other groups of ecosystem services are not part of the analysis, which is a common methodological limitation of agricultural eco-efficiency assessment.

Table 1. Examples of agricultural eco-efficiency studies from different farming systems and their respective functional units.

Farming system	**Functional unit**	**Study**
Milk production	kg FPCM[a]	Cortés et al. (2021)
	l raw milk	Iribarren et al. (2011)
	Work income per FWU[b]	Jan et al. (2012)
Crop production	ha cultivated wheat	Masuda (2016)
	kg soybean	Mohammadi et al. (2013)

Note.
[a] FPCM = fat and protein corrected milk.
[b] FWU = family work unit.

2. Thesis aims

Given the incongruity of agricultural farms being multifunctional systems and the usual unidimensional evaluation of their output, this thesis aims to contribute a novel concept of eco-efficiency of farms that simultaneously considers multiple functions of agriculture.

Paper I develops this concept that, besides food production, also considers the generation of income for farmers and the provision of other environmental services. This concept is further applied to a set of 47 Austrian farms from four different farm types (i.e., 22 dairy farms, 11 crop-producing farms, eight beef-producing farms, and six wine-producing farms) to show the farm types' specific strengths and weaknesses regarding the considered functions of agriculture.

Paper II implements the concept on 44 specialized Austrian dairy farms from a specific study area, covering a broad spectrum of site conditions. Besides shedding light on the eco-efficiency of multifunctional milk production in this region, the paper also aimed at an equal share of organic and conventional farms in its farm selection procedure to facilitate a comparison of these production systems. Additionally, the improvement of eco-efficiency is addressed by pointing out specific management options that increase the eco-efficiency of dairy farms.

3. Journal contributions

3.1. Paper I

Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms

Journal of Cleaner Production 297, 126662

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Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms

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Beef production

ABSTRACT

Besides producing food for humanity's nutrition, agriculture also fulfills other functions such as providing a livelihood for farmers and preserving an attractive and biodiverse landscape. These functions of agriculture were considered in a novel eco-efficiency assessment concept applied to Austrian farms within this study. The joint application of life cycle assessment (LCA) and data envelopment analysis (DEA) was used to evaluate Austrian farms' eco-efficiency. Data from 47 farms from different farm types (crop production, milk production, beef production, and wine production) were used to implement the concept. Cumulative exergy demand (CExD), global warming potential (GWP), normalized eutrophication potential (EP), and aquatic ecotoxicity potential (AE) were included as environmental impacts in an LCA and were consequently used as input values for the DEA. Considering multiple functions of agriculture, the farm net income (FNI), the net food production of crude protein and human-edible energy, and High Nature Value farmland (HNVf) were selected as output variables for the DEA. Results show that the purchase of resources causes a substantial share of environmental impacts, highlighting the importance of efficient utilization of on-farm resources. The results further revealed the use of high amounts of human-edible energy and protein as animal feed to cause lower eco-efficiency scores of livestock keeping farms (i.e., milk production and beef production). Overall, the eco-efficiency of farms depends on the fulfillment of different functions of agriculture, and individual strategies for improvement could be identified.

1. Introduction

The concept of eco-efficiency was introduced by the World Business Council for Sustainable Development (Schmidheiny, 1992) and defined as the output (product or service value) per environmental impact (Thanawong et al., 2014; Van Passel et al., 2007). DeSimone and Popoff (1997) further refined the concept by defining eco-efficiency as the ability to produce competitively-priced goods and services while progressively reducing environmental impacts and resource use throughout the life cycle. However, eco-efficiency is only one part of corporate sustainability. It only describes the relationship between ecology and economy (Dyllick and Hockerts, 2002) and disregards sustainability's social pillar (UN, 2015).

Agriculture and especially livestock production appears to have a significant impact on the environment and therefore gained increasing attention over the last years (Steinfeld et al., 2006). Therefore, promoting the trade-off between ecological and economic performance is one of the European Union's common agricultural policy's (CAP) primary objectives (Rybaczewska-Błażejowska and Gierulski, 2018). Accordingly, the assessment of eco-efficiency in agriculture has been conducted for various types of agricultural production, such as crop production (Masuda, 2016, 2019; Mohammadi et al., 2013, 2015; Ullah et al., 2016), milk

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production (Iribarren et al., 2011; Jan et al., 2012; Soteriades et al., 2016a, 2016b), and wine production (Mohseni et al., 2018; Vázquez-Rowe et al., 2012).

For measuring efficiency, Jayamaha and Mula (2011) differentiate between two approaches: the production frontier approach (PFA) and the index number approach. Due to the index number approach's assumption that all entities (e.g., firms, industries, farms, or even countries) under study operating fully efficient, the PFA is more prevalent in empirical efficiency studies (Jayamaha and Mula, 2011) since this assumption cannot be expected in reality (Rogers, 1998). According to Chen et al. (2015), the two principal methodologies following the PFA are data envelopment analysis (DEA) and the stochastic frontier approach (SFA), both approaches to determine an efficiency frontier and estimate entity-specific efficiencies by measuring the distance from the respective entities performance to the efficiency frontier (Chen et al., 2015).

In recent years, the combined application of life cycle assessment (LCA) and DEA has proven its value in presenting the eco-efficiency of comparable multi-input and multi-output entities, so-called decision-making units (DMUs), which are performing the task of converting inputs to outputs (Cooper et al., 2007). LCA constitutes a suitable instrument to describe and evaluate various environmental impacts or the resource use of production processes (Klöpffer and Grahl, 2009; Rebitzer et al., 2004). Thus, several environmental assessment methods according to the specific agricultural activity have been developed, for example, KUL (Eckert et al., 1999), REPRO (Hülsbergen, 2003), or SALCA (Gaillard and Nemecek, 2009). With the combination of LCA and DEA, it is possible to integrate several environmental impacts and output indicators into one aggregated eco-efficiency-score (Rybaczewska-Błażejowska and Gierulski, 2018).

The joint production of multiple commodity and non-commodity outputs is typical in agriculture. This joint production is reflected in the concept of multifunctionality of agriculture (OECD, 2001). Despite being open to diverse interpretations and definitions, agriculture's multifunctionality is gaining an increasingly important role in policy and scientific debates regarding agriculture's future (Cairol et al., 2009; Carmona-Torres et al., 2014; Renting et al., 2009). By compensating for ecosystem services and public goods beyond food production and a change in the traditional policy of price support (Jongeneel et al., 2008), agriculture's multiple functions are also reflected in the European Union's CAP. These ecosystem services can be divided into provisioning, supporting, regulating, and cultural services (Alcamo and Bennett, 2003).

Nemecek et al. (2005) and Hayashi et al. (2005) derived four functions of agriculture: (i) the function of generating an adequate income, (ii) the production of food, (iii) the agricultural use of land to maintain its production potential and the use of ecologically valuable land to preserve an attractive landscape, and (iv) the ecological function which includes the preservation of the natural basis of life. This study's objective was to provide a novel concept of eco-efficiency assessment by incorporating these four functions to assess a set of Austrian farms' eco-efficiency using the combined LCA and DEA approach.

1.1. A novel concept of eco-efficiency assessment of farms

Recent studies assessing the eco-efficiency of farms by combining LCA and DEA mainly focus on one output parameter (e.g., kg ECM) and therefore disregard the multiple functions of agriculture. The novel concept of assessing farms' eco-efficiency presented in this study aims to consider multiple functions of agriculture by incorporating four different output parameters that depict different functions of agriculture. Besides the performance in relation to eco-efficiency, the results also reveal to what extent an individual farm is fulfilling these different functions of agriculture. In this way, the specific strengths and weaknesses of different farm types can be reflected. Although the concept considers multiple functions of agriculture, some critical aspects of the multifunctionality of agriculture (OECD, 2001) remain left aside (e.g., food security).

2. Material and methods

2.1. Farm data

A set of 51 agricultural farms was considered for this study. The farms were divided into six different farm types according to Meier (2000): (i) crop production (11 farms), (ii) milk production (22 farms), (iii) suckler cow husbandry (4 farms), (iv) cattle growing-fattening (4 farms), (v) pig growing-fattening (4 farms), and (vi) wine production (6 farms). The set can further be divided into 30 organic and 21 conventional farms. To get a minimum quantity of five farms per farm type, we excluded the pig growing-fattening farms from the analysis. Accordingly, due to their common objective of producing beef, the farm types suckler cow husbandry and cattle growing-fattening were combined to form the farm type beef production, thus reducing the set to 47 farms (i.e., 28 organic and 19 conventional farms). The set consequently consists of 11 crop-producing farms (7 organic and 4 conventional), 22 dairy farms (12 organic and 10 conventional), 8 beef-producing farms (5 organic and 3 conventional), and 6 wine-producing farms (4 organic and 2 conventional). For a detailed description of the farms, see Appendix A.

2.2. Methodological approach

Rybaczewska-Błażejowska and Masternak-Janus (2018) consider the joint application of LCA + DEA to be a powerful tool for strategic decision making. The methodology is usually applied in two different forms: Either a five-step LCA + DEA approach or a three-step LCA + DEA approach. In this study, we applied the three-step approach, according to Iribarren et al. (2015). The three-step approach uses a set of selected impact categories derived from the LCA as input values for the DEA, whereas the five-step approach uses life cycle inventory tables of resources and emissions as input values (Rajabi Hamedani et al., 2019). An advantage of the three-step approach is the higher discriminatory power of the eco-efficiency analysis (Jan et al., 2012). Further, Masuda (2019) considers the quantification of eco-efficiency based on environmental impact categories instead of input-output life cycle inventory tables to be more appropriate.

2.2.1. Life cycle assessment

As a methodology to assess environmental impacts, LCA follows ISO 14040 (ISO, 2006a) and ISO 14044 standards (ISO, 2006b). According to these standards, an LCA typically consists of four steps: (1) goal and scope definition, (2) life cycle inventory (LCI), (3) life cycle impact assessment (LCIA), and (4) interpretation of results.

Regarding step (1), LCA's goal in this study is to evaluate farms' environmental impacts from cradle to farm gate. Therefore, the study covers inputs into the farm and off-farm processes and emissions within the scope of the entire agricultural area of a farm. System boundaries of the four farm types are presented in Fig. 1. From the different functions of agriculture mentioned by Nemecek et al. (2005) and Hayashi et al. (2005), we derived four different farm outputs and, therefore, four different functional units we consider in this study. Functions (i) and (ii) are considered as

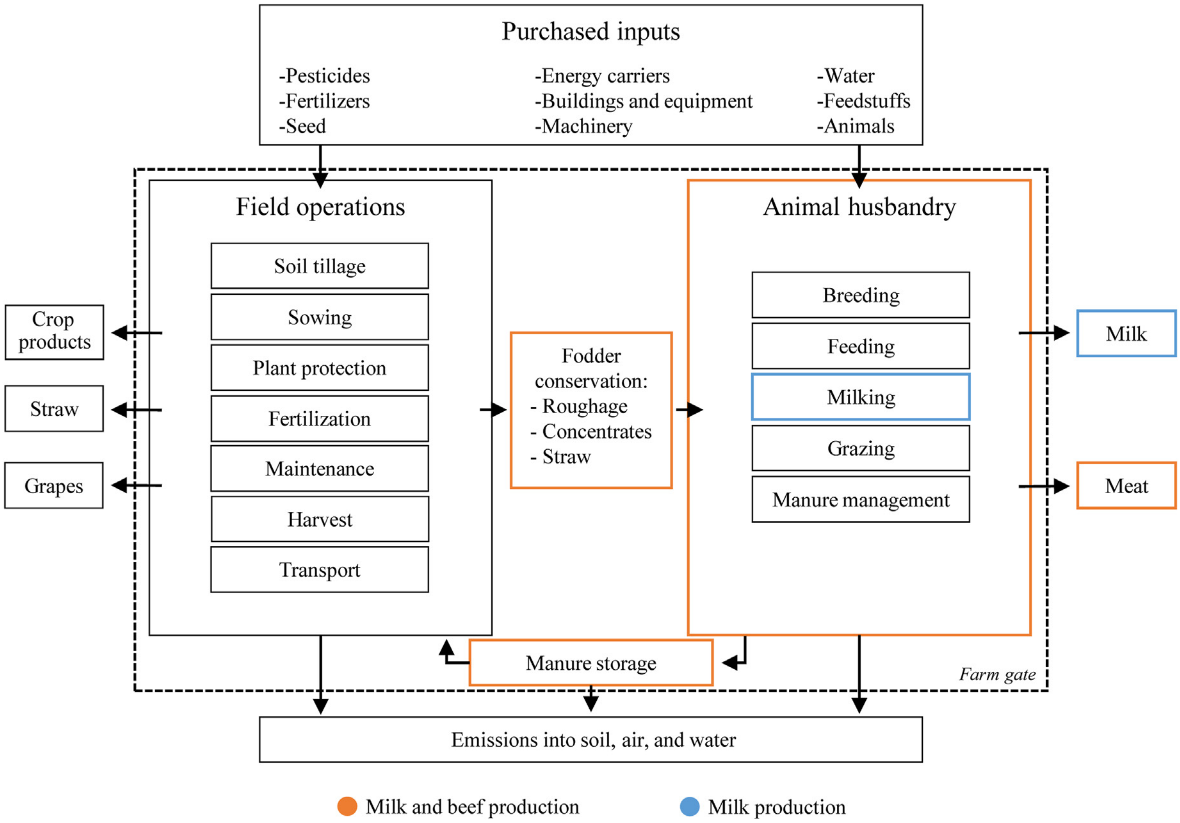

Fig. 1. System boundaries of the four farm types. Colors indicate processes only accounted for within the respective farm type(s).

provisioning ecosystem services, whereas function (iii) delivers supporting, regulating, and cultural ecosystem services. These three functions can be regarded as functional units in an LCA (Table 1). On the other hand, function (iv) delivers supporting and regulating ecosystem services that are not covered by the other functions and, therefore, can be promoted or impaired by the respective production system's environmental impacts.

To depict the function of income generation and for economic evaluation, we selected farm net income (FNI) as an indicator following the Farm Accountancy Data Network (FADN) of the European Commission. FNI is a profitability measure and denotes the difference between the value of production (output, subsidies) and the cost of production (intermediate consumption, depreciation, external factors) (EC, 2018; Edwards and Duffy, 2014). FNI is frequently used to depict a farms' economic viability, comprising remuneration of capital, land, and labor (Odonoghue et al., 2016).

Regarding the food production function, we distinguish between energy and protein output. To calculate the net food production for both outputs for each farm, we subtracted the potential human-edible inputs through feedstuffs and seeds as MJ human-edible energy (hee) and g human-edible crude protein (heCP) from the human-edible outputs through animal products (milk, beef) and plant products (crops, wine), depending on the respective farm type and according to Ertl et al. (2015). Further, we characterize the heCP, using the digestible indispensable amino acid score (DIAAS), introduced by the FAO (2013), to additionally integrate the quality of the different animal and plant-based proteins produced by the different farm types (Ertl et al., 2016).

Due to the link between food production and agricultural area, we assume that the agricultural area mainly utilized for food production is already included in the eco-efficiency assessment by the food production function. Therefore another parameter is needed to represent the function of ecologically valuable land use. High Nature Value farmland (HNVf) is chosen for this purpose. First introduced by Baldock et al. (1993) and Beaufoy et al. (1994), HNVf serves as a condition indicator for ecosystems within the mapping and assessing of ecosystems and their services in the EU (Maes et al., 2018). HNVf is characterized by a high species richness and biological biodiversity and provides several ecosystem services (Matin et al., 2020). Andersen et al. (2003) defined three types of HNVf. HNVf Type 1 is characterized by a high proportion of semi-natural vegetation (Paracchini et al., 2008). In the present study, we calculated the share of HNVf Type 1 for each farm according to the scheme proposed by Bartel et al. (2011), which allows grass- and arable land managed at a low and medium intensity to be accounted for as HNVf Type 1.

Table 1
Considered functions of agriculture, resulting farm outputs, and corresponding functional units.

Function	Output	Functional unit
Generation of income	Farm net income (FNI)	1 € FNI
Food production	Net food production-protein	1 g human-edible crude protein
	Net food production-energy	1 MJ human-edible energy
Use of ecologically valuable land	High Nature Value farmland – Type 1 (HNVf)	1 ha HNVf

The data for step (2), the LCI, were derived from a national research project in which a life cycle assessment of Austrian farms was performed (Herndl et al., 2015). For general information on farm inputs and farm outputs, see Table A1 and Table A2 in Appendix A.

The LCIA (3) transforms different emissions, raw materials, and inputs from the LCI into several impact categories (EC, 2010). In the present study, SALCA 1.12 was used as the impact assessment method because of its specific reflection of the agricultural sector (Gaillard and Nemecek, 2009) and its integration of several LCIA methods. For this study, we have selected a limited number of indicators according to the following criteria: On the one hand, the indicators need to include as many environmental aspects as possible. On the other hand, we can consider only a few indicators in order not to limit the DEA's discriminatory power (Cooper et al., 2006). Therefore, we have given priority to indicators summarizing different aspects, like exergy, which aggregates different types of resources (e.g., land use, water, fossil energy), or the normalized eutrophication potential, which aggregates three eutrophication indicators into one. Furthermore, the indicators have been selected to reduce redundancy. Nemecek et al. (2011) defined three main groups of environmental impacts: (i) resource-related impacts, (ii) nutrient-related impacts, and (iii) pollutant-related impacts, each representing an environmental dimension and different management options. Based on these criteria, the following indicators were selected: (i) Cumulative exergy demand (CExD), (ii) normalized eutrophication potential (EP), and (iii) aquatic ecotoxicity potential (AE). In addition, the global warming potential (GWP) was included due to its relevance and the great attention it receives (Table 2).

Unlike cumulative energy demand (CED), which is used to assess the energy demand from primary energy sources, CExD also takes the quality of energy into account. Therefore, Bösch et al. (2007) state CExD to be a more comprehensive energy-based indicator for resource demand than CED, since it allows to aggregate ten different kinds of energy resources ((i) non-renewables: fossil, nuclear, primary forest, metals, minerals; (ii) renewables: wind, solar, hydro, water; (iii) land resources), into a single indicator. The different types of exergy can also be viewed individually (Hosseini-Fashami et al., 2019).

The EP, calculated with the EDIP 2003 method (Hauschild and Potting, 2005), comprises indicators for (i) aquatic N eutrophication through NO_3, NH_3, and NO_x, (ii) aquatic P eutrophication through all emissions of P to water, and (iii) terrestrial N eutrophication through NH_3 and NO_x. Through normalization, these three categories were aggregated and measured in person year^{-1}, using average European emissions for the year 2004 (Laurent et al., 2011).

The LCIA was computed with SimaPro 9 Developer software (Pré Consultants, 2019).

For the interpretation (4), the results of the LCA were expressed per MJ human-edible energy (MJ hee) output (before subtracting the human-edible inputs through feedstuffs and seeds) and broken down to eleven different sources (i.e., buildings and equipment; machinery; energy carriers; land use, fertilizers, and field emissions; pesticides; seeds; concentrate purchased; roughage purchased; animals purchased; animal husbandry; other inputs).

2.2.2. Data envelopment analysis

First introduced by Charnes et al. (1978), DEA serves as a non-parametric data analysis method to measure the efficiency of DMUs with multiple inputs and outputs. The efficiency is measured by a scalar measure ranging from zero (the worst) to one (the best) (Tone, 2001). For the measurement of efficiency, DEA forms an efficiency frontier against which all DMUs are benchmarked (Soteriades et al., 2016a). In the present study, each farm was considered as one DMU (1 farm = 1 DMU). According to the scope of the study, a meta-frontier input-oriented slacks-based-measure (SBM) model with variable returns to scale (VRS) was selected for the efficiency assessment (Cooper et al., 2007). Rajabi Hamedani et al. (2019) justify the model's input orientation with the producer in a farming system having more control over inputs than outputs. The VRS specification ensures that a DMU is only compared to a DMU of similar size, which is desirable as absolute values rather than ratios are used for the DEA in this study (Soteriades et al., 2016a). Furthermore, Bournaris et al. (2019) also highlighted the use of VRS to be more appropriate in agriculture because one cannot assume perfect competition and, therefore, no variations in returns to scale among farms. According to Toma et al. (2017), constant returns to scale in agriculture would lead to a measure of efficiency distorted by scale efficiencies. The VRS specification prevents this effect. The selected model also calculates input and output slacks, showing the possible reduction of excess inputs and the possible increase of deficient outputs to gain eco-efficiency. The DEA matrix, consisting of each DMU's inputs and outputs, is shown in Table 3. The model was applied using MaxDEA 8 Ultra software and was formulated as follows (Tone, 2001):

$$\rho_o = \min(\lambda,\ s^-, s^+)\frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s}\sum_{r=1}^{s}\frac{s_r^+}{y_{ro}}}$$

subject to :

$$x_o - s^- = X\lambda$$

$$y_o - s^+ = Y\lambda$$

$$\lambda, s^-, s^+ \geq 0$$

$$\sum_{j=1}^{n}\lambda_j = 1$$

Where n = number of DMUs, j = index of the DMUs, m = number of inputs, s = number of outputs, i = index of the inputs, r = index of outputs, o = index of the DMU under assessment, x_{io} = amount of input i demanded by DMUo, y_{ro} = amount of output r produced by DMUo, ρ_o = efficiency score of DMUo, and λ = a non-negative scalar assigned to an individual DMU so that $\sum_{j=1}^{n}\lambda_j = 1$. The variables s^+

Table 2
Selected environmental impacts, corresponding LCIA methods, and units.

Environmental impact	LCIA method	Unit	Reference
Cumulative exergy demand (CExD)	Cumulative Exergy demand	MJ	Alvarenga et al. (2013); Bösch et al. (2007)
Global warming potential (GWP)	IPCC GWP 100a	kg CO_2-eq	IPCC (2013)
Normalized eutrophication potential (EP)	EDIP 2003	person year^{-1}	Hauschild and Potting (2005)
Aquatic ecotoxicity potential (AE)	CML01	kg 1,4 DB-eq	Guinée et al. (2001); Hayer et al. (2010); Kägi et al. (2008)

Table 3
DEA matrix of the 47 farms under study.

	Input				Output			
	CExD	GWP	EP	AE	FNI	Net food production-protein	Net food production-energy	HNVf
Farm	*GJ*	*t CO_2-eq*	*person year^{-1}*	*kg 1,4 DB-eq*	*€*	*kg net heCP*	*GJ net hee*	*ha*
Cr_1_o	9468	26	33	343	43832	2595	560	13
Cr_11_o	10310	152	123	1436	46236	3980	921	3
Cr_12_o	4586	11	44	104	19339	509	111	8
Cr_16_o	9858	30	48	6115	49666	2836	781	19
Cr_19_o	9695	31	68	266	59541	2860	689	10
Cr_29_o	31315	226	244	1930	198355	10055	2819	41
Cr_38_o	4566	14	49	109	12143	844	128	1
Cr_8_c	41187	248	421	6607	124761	19070	5889	5
Cr_15_c	5429	23	52	5069	8988	1318	367	5
Cr_27_c	8775	41	92	3336	58375	5900	552	1
Cr_37_c	7958	44	141	1065	16823	2173	203	1
Mi_2_o	12518	509	536	793	109770	6941	619	14
Mi_3_o	3532	88	142	163	13569	1224	72	14
Mi_4_o	7449	178	319	233	57930	−194	33	5
Mi_18_o	12036	269	479	479	113297	5427	359	4
Mi_21_o	13200	336	424	1010	95771	5850	386	1
Mi_22_o	7931	197	230	374	39535	3356	255	13
Mi_26_o	12489	363	401	876	47403	−3292	264	9
Mi_28_o	14777	369	435	619	85567	6601	415	16
Mi_42_o	14919	352	430	680	83547	7585	491	1
Mi_45_o	13156	364	371	1144	23423	5440	372	3
Mi_46_o	5279	150	116	372	16971	1894	107	1
Mi_47_o	3409	99	81	229	−2139	978	58	5
Mi_5_c	9766	261	547	4500	37687	5676	77	1
Mi_9_c	24637	533	685	6240	33373	5450	293	13
Mi_13_c	10104	356	545	3671	83738	8432	364	1
Mi_23_c	12259	260	347	10479	51281	2381	123	10
Mi_24_c	20530	686	1225	32229	76638	9006	850	3
Mi_25_c	15001	579	765	4156	160348	5184	−427	1
Mi_30_c	5747	182	197	1959	43463	3235	153	1
Mi_32_c	4926	154	167	1220	19700	2350	105	2
Mi_34_c	13235	395	614	9695	52380	9593	422	1
Mi_44_c	4217	123	169	3601	7269	1279	52	17
Be_s_17_o	6175	136	60	221	34850	522	−19	26
Be_s_20_o	17243	118	217	1325	25117	3021	240	17
Be_s_31_o	4743	100	47	141	24255	311	38	1
Be_s_6_c	4441	85	89	1295	5903	228	−5	8
Be_f_39_o	2382	35	19	68	11745	344	11	1
Be_f_43_o	2798	39	32	165	9142	429	14	6
Be_f_14_c	3699	86	75	722	1176	67	−98	1
Be_f_41_c	10332	211	190	4316	19180	770	−38	6
Wi_7_o	3934	74	35	1426	117397	0	143	1
Wi_33_o	1523	7	30	664	36185	0	61	1
Wi_35_o	3358	15	81	1068	94313	0	105	1
Wi_36_o	3217	15	54	116	66615	0	82	1
Wi_10_c	1913	9	11	356	17093	0	121	1
Wi_40_c	1581	6	22	91	66868	0	60	1

Note. Cr = crop production; Mi = milk production; Be = beef production; Wi = wine production; s = suckler cow husbandry; f = cattle growing-fattening; o = organic; c = conventional.

and s^- measure the distance of inputs $X\lambda$ and outputs $Y\lambda$ of a virtual DMU from those of the DMU evaluated (X_o) (Alfiero et al., 2018), thus indicating the input excesses and output shortfalls (i.e., slacks), respectively. The numerator and the denominator of the function provide the measurement of the average distance of inputs and outputs, respectively, from the efficiency frontier (Vincova, 2005).

The meta-frontier specification was introduced by Rao et al. (2003) and allows for consideration of heterogeneous production technology (Long et al., 2018), which is given by the different farm types in this study. By calculating the efficiency of DMUs within different group-frontiers (Yu et al., 2019), this model makes heterogeneous production technology more comparable (Li and Lin, 2015). Furthermore, the model calculates a technology gap ratio (TGR), which allows for comparison of the eco-efficiency under group-frontier and the usual efficiency frontier (meta frontier) (Wang et al., 2013; Yu et al., 2019). The TGR is defined as follows (Long et al., 2018):

$$TGR_i = \frac{ME}{GE_i}$$

Where GE_i = eco-efficiency under production technology of group i and ME = eco-efficiency under meta-frontier. TGR measures the distance between production technology in a certain group-frontier and the production technology of the meta-frontier (Yu et al., 2019). Since ME never exceeds GE, TGR ranges from zero to one. A TGR close to one indicates a specific group's production technology to approach optimal meta-frontier production technology and vice versa (Long et al., 2018). In this study, we assigned the farms to different groups according to their farm type, resulting in four groups.

3. Results

3.1. Life cycle assessment

The environmental impacts (CExD, GWP, EP, AE) per MJ of human-edible energy (MJ hee), including the contribution from eleven different sources, are depicted in Fig. 2 (CExD, GWP) and Fig. 3 (EP, AE) for each of the 47 farms. The CExD per MJ hee of the studied farms ranges from 7 to 337 MJ. Across all farm types, land use, fertilizers, and field emissions are the sources with the highest contribution to the CExD. For three of the beef-producing farms, purchased animals also constitute a leading contributor to the CExD. The highest impacting energy resource is land resources, accounting for approximately 90% of the CExD of all farms. Within this energy resource, the contributions of the sources differ between the different farm types. For the crop and wine-producing farms, a share of 96% of land resources is coming from land use, fertilizers, and field emissions (comprising the use of the farm area, off-farm emissions from the production of commercial fertilizer as well as direct emissions resulting from the application of commercial fertilizer and farm manure, e.g., N_2O, NO_x). By contrast, this share is around 77% for the milk and beef producing farms. The purchase of concentrates (7%), roughage (4%), and animals (4%) make up for most of the remaining share. With a mean share of 7% among all 47 farms, fossil energy has turned out as the energy resource with the next largest contribution to CExD. Energy carriers, machinery as well as land use, fertilizers, and field emissions make up for a large share in crop and wine-producing farms with 36, 34, and 16%, respectively. In contrast, the primary sources in milk and beef-producing farms contributing to this energy resource were energy carriers (29%), buildings and equipment (25%), machinery (19%), and purchased concentrate (12%).

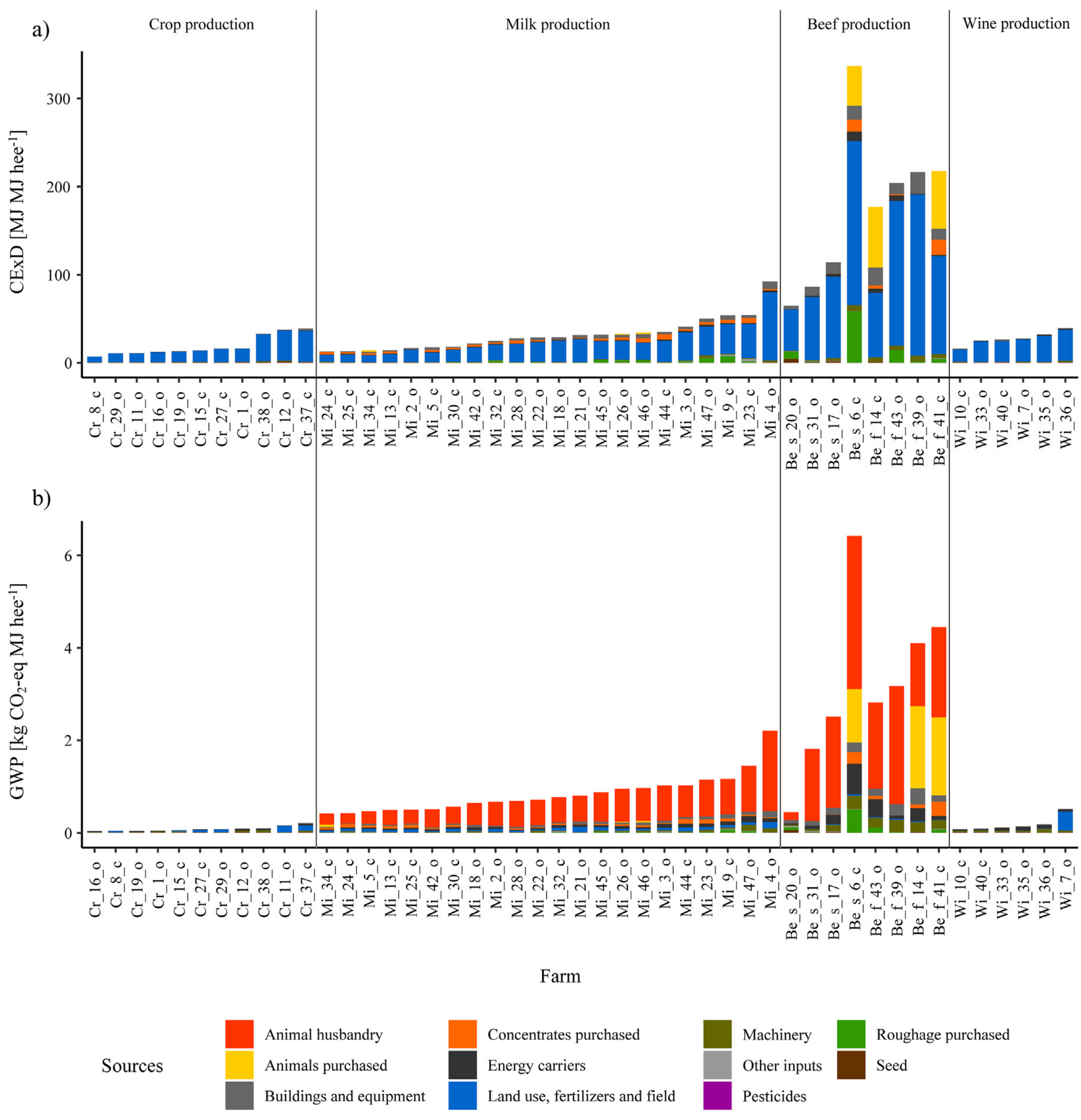

Fig. 2. a) Cumulative exergy demand (CExD) and b) global warming potential (GWP) per MJ of human-edible energy (MJ hee) of each farm (Cr = crop production; Mi = milk production; Be = beef production; Wi = wine production; s = suckler cow husbandry; f = cattle growing-fattening; o = organic; c = conventional) broken down to eleven sources.

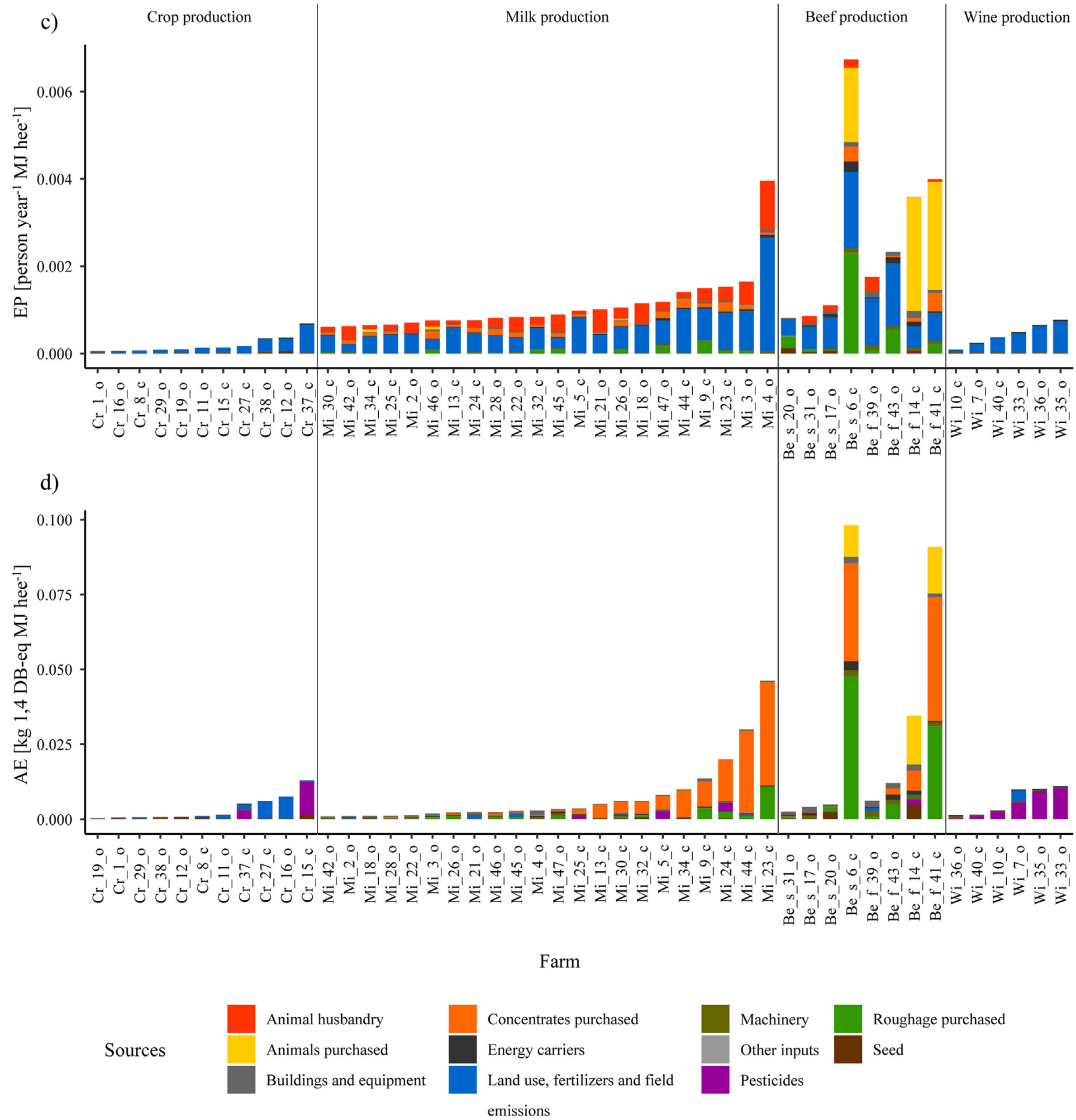

Fig. 3. c) Normalized eutrophication potential (EP) and d) aquatic ecotoxicity potential (AE) per MJ of human-edible energy (MJ hee) of each farm (Cr = crop production; Mi = milk production; Be = beef production; Wi = wine production; s = suckler cow husbandry; f = cattle growing-fattening; o = organic; c = conventional) broken down to eleven sources.

The GWP per MJ hee ranges from 0.04 to 6.42 kg CO_2-eq. In milk and beef production, direct emissions from animal husbandry account for most of the GWP (enteric fermentation and manure management). Another source with a high contribution are the purchased animals, especially in three of the beef-producing farms. Regarding the EP, the 47 studied farms produce one MJ hee within a range of 0.52–59.04 person hour^{-1}. The main contributors to the EP are land use, fertilizers, and field emissions (across all farm types), as well as animal husbandry (milk production) and purchased roughage and animals (beef production). The AE ranges from 0.4 to 98 g 1,4 DB-eq per MJ hee. In livestock keeping farm types (milk- and beef production), purchasing concentrate, roughage, and animals contributed the largest shares to AE. For stockless farm types (crop- and wine production), land use, fertilizers, field emissions, and pesticides (plant protection products and heavy metals) were identified as AE's leading drivers.

Among the different farm types, the eleven crop-producing and six wine-producing farms have a CExD, ranging from 7 to 39 and 16–39 MJ/MJ hee. Crop and wine producers cause a GWP with ranges of 0.04–0.22 and 0.08–0.52 kg CO_2-eq/MJ hee. Regarding EP and AE, crop and wine producers cause values ranging from 0.52 to 6.04 (crop production) and 0.79 to 6.75 person hour^{-1} per MJ hee (wine production) for EP and 0.4 to 13 (crop production) and 0.14–11 g 1,4 DB-eq per MJ hee (wine production) for AE. The highest difference between the eleven crop-producing farms can be seen for AE (Fig. 3). The farm with an AE of 0.4 g 1,4 DB-eq per MJ hee (Cr_19_o) uses no plant protection agents for crop production, whereas another farm (Cr_15_c) uses 6.42 kg of Isoproturon, a plant protection agent not permitted in the European Union since 1st June 2016 (EC, 2016), and therefore causing 11 g 1,4 DB-eq per MJ hee. Within the farm type wine production, the three farms with the highest AE (Wi_7_o, Wi_35_o; Wi_33_o) operate organically and use copper for plant protection in high quantities, i.e., 1.07, 1.68 and, 2.67 kg/ha, respectively.

The 22 dairy farms cause environmental impacts per MJ hee with values ranging from 13 to 92 MJ for CExD, 0.42–2.21 kg CO_2-eq for GWP, 5.34 to 34.16 person hour^{-1} for EP, and 1–46 g 1,4 DB-eq for AE. Fig. 2 shows that the values for CExD and GWP increase with direct emissions from land use, fertilizers, field emissions, and animal husbandry, respectively. The dairy farm with the highest values for CExD (Mi_4_o) produces a low amount of hee. With a stocking rate of 2.3 livestock units (LU) per ha, this farm emits high amounts of CH_4 through enteric fermentation and N_2O through manure storage per MJ hee, leading to the highest GWP amongst all dairy farms as well. As an indicator of production intensity, the stocking rate affects animal-born greenhouse gas emissions at the farm level (Howden et al., 1994). The highest EP is also found for this farm, with NH_3 emissions from animal husbandry and NO_x and P emissions from manure application accounting for the largest contribution. Regarding AE, the results show that the organic dairy farms have low values and hardly differ, whereas the AE of the conventional dairy farms increases with the extent of purchased concentrate and roughage (Fig. 3).

The environmental impacts per MJ hee of the eight beef-producing farms range from 65 to 337 MJ for CExD, 0.45–6.42 kg CO_2-eq for GWP (Figs. 2), 7.18 to 59.04 person hour^{-1} for EP, and 3–98 g 1,4 DB-eq for AE (Fig. 3). The highest values for all four environmental impacts are found for one farm (Be_s_6_c), which produces low levels of human-edible energy and protein. Simultaneously, the farm purchases high amounts of roughage (18884 kg dry matter (DM)), concentrates (5032 kg DM), and animals (1020 kg live weight), which lead to high values for CExD, EP, and through the accumulation of pesticides and heavy metals also to a high AE. Better environmental performance is obtained by an organic farm (Be_s_20_o) with a low stocking rate of 0.5 LU ha^{-1}, thus clearly reducing animal husbandry's impact on the GWP. Simultaneously, the farm demands a high extent of purchased roughage (40282 kg DM) and seeds (28548 kg), resulting in higher contributions to EP and AE, respectively.

3.2. Data envelopment analysis

Based on the DEA matrix presented in Table 3, the selected DEA model calculates input and output slacks for each farm, showing the possible reduction of excess inputs and the possible increase of deficient outputs to reach eco-efficiency (i.e., a score of one). Additionally, the model calculates the eco-efficiency score for each of the 47 farms under group-frontier (GE) and meta-frontier (ME) ranging from zero to one, with a score of one highlighting a farm as eco-efficient and a score of less than one indicating a non-eco-efficient farm. By relating ME and GE, the model also computes the technology gap ratio (TGR). Table 4 shows the input and output slacks, eco-efficiency scores, and the TGR of the non-eco-efficient farms under meta-frontier. Eco-efficient farms under meta-frontier (i.e., farms with a score of one under meta-frontier) were excluded from Table 4.

25 of the 47 farms (53%) under study were found to operate eco-efficient under meta-frontier (ME), whereas the remaining 22 farms (47%) are operating more or less non-eco-efficient. As Fig. 3 shows, the farm Cr_15_c has the highest AE per MJ hee among all crop-producing farms. Consequently, the farm has the highest input slack (91%) for this environmental impact, followed by EP (51%) and GWP (18%). On the other hand, the farm has a high output slack for FNI (227%), resulting from a low FNI of 8988 €. Cr_37_c has the highest values per MJ hee of the remaining three environmental impacts amongst the crop-producing farms with input slacks of 77% for EP, 66% for AE, and 48% for GWP. On the output side, the highest slack comes from HNVf, which should be increased by 635%. Simultaneously, to reach eco-efficiency, the FNI and the net food energy production would have to be increased by 188 and 129%, respectively. Among the dairy farms, Mi_4_o shows the highest values per hee for CExD, GWP, and EP. Accordingly, the farm has to reduce these environmental impacts by 91% (EP), 87% (GWP), and 67% (CExD). To reach eco-efficiency, also the net energy output has to be raised by 73%. Another dairy farm (Mi_21_o) reaches an eco-efficiency score of 0.79 under meta-frontier, with the highest input slack being 36% (AE), whereas the highest output slack is detected for HNVf with 278%. The beef-producing farm Be_s_6_c shows the highest values per MJ hee for all four environmental impacts. Due to a negative net energy output, this output has the highest slack with −1208%. Additionally, the low FNI (5903 €) has to be increased by 731%. To become eco-efficient, the reduction of the CExD by 27%, the GWP and EP by 60%, and the AE by 91% would simultaneously be necessary for this farm.

Further, DEA revealed 11 of the 22 non-eco-efficient farms under meta-frontier to be eco-efficient under group-frontier (GE). With the eco-efficiency score under meta-frontier and group-frontier, the model also calculated the TGR, which resulted in mean values of 0.95 (SEM = 0.04) for crop-producing farms, 0.78 (SEM = 0.05) for dairy farms, 0.76 (SEM = 0.09) for beef-producing farms, and 0.93 (SEM = 0.07) for wine-producing farms.

4. Discussion

4.1. Life cycle assessment

The LCIA of the 47 farms revealed land use, fertilizers, and field emissions to be the dominant drivers for CExD across all farm types (Fig. 2). Land resources were revealed as the energy resource with the highest contribution to the CExD, accounting for approximately 90% of the CExD. Comparing different crops from different countries, Alvarenga et al. (2013) found a similarly high contribution of land resources to the CExD.

Regarding GWP, the source animal husbandry accounted for the maximum contribution within dairy and beef-producing farms (Fig. 2). This can be explained by CH_4 emissions from enteric fermentation and is in accordance with results from other studies (Dick et al., 2015; Doltra et al., 2018; Gislon et al., 2020; O'Brien et al., 2012; Ogino et al., 2007). Also, the purchased animals have a major impact on the GWP in three of eight beef-producing farms. The main contribution to GWP of crop and wine-producing farms comes from land use, fertilizers, and field emissions. According to Brentrup et al. (2004), especially N_2O emissions, which correspond strongly with the amount of N used, are the main drivers of GWP in crop production. Balafoutis et al. (2017) also determined fertilizer production and application to be the primary source for GWP in wine production.

Regarding EP, land use, fertilizers, and field emissions are the highest contributing sources throughout all farm types (Fig. 3). By conducting LCA on seasonal grass-based and confinement dairy farms, O'Brien et al. (2012) also came to this result, further identifying nitrate leaching and manure application as the leading causes for EP. However, in three of the eight beef-producing farms, the purchased animals and purchased roughage also contribute a high share to the farms' total EP per MJ hee.

Fig. 3 shows that the main drivers for AE differ, depending on whether a farm is practicing animal husbandry or not. Regarding stockless farm types, pesticides and land use, fertilizers, and field emissions are the highest contributing sources. This result corresponds with the findings of Nemecek et al. (2001), who related the high contributions of land use, fertilizers, and field emissions to heavy metals contained in manure. Farms with animal husbandry

Table 4
Input and output slacks, eco-efficiency scores, and TGR of all non-eco-efficient farms under meta-frontier.

Farm	Input slacks				Output slacks				Eco-efficiency scores		
	CExD	GWP	EP	AE	FNI	Net food production-protein	Net food production-energy	HNVf	ME	GE	TGR
Cr_11_o	0%	71%	39%	8%	28%	0%	0%	168%	0.70	0.77	0.92
Cr_15_c	0%	18%	51%	91%	227%	0%	0%	28%	0.60	1.00	0.60
Cr_37_c	0%	48%	77%	66%	188%	0%	129%	635%	0.52	0.54	0.97
Mi_4_o	67%	87%	91%	53%	0%	−1%	73%	0%	0.26	1.00	0.26
Mi_21_o	0%	25%	22%	36%	0%	0%	58%	278%	0.79	1.00	0.79
Mi_22_o	0%	6%	0%	1%	14%	0%	19%	0%	0.98	1.00	0.98
Mi_26_o	55%	93%	92%	76%	0%	−36%	0%	0%	0.21	0.58	0.37
Mi_45_o	5%	43%	28%	57%	210%	0%	56%	42%	0.67	0.74	0.90
Mi_46_o	0%	37%	14%	47%	69%	0%	41%	33%	0.76	1.00	0.76
Mi_47_o	0%	34%	7%	44%	−762%	0%	4%	0%	0.79	1.00	0.79
Mi_5_c	13%	85%	84%	29%	56%	0%	588%	20%	0.47	0.74	0.64
Mi_9_c	39%	87%	85%	78%	81%	0%	405%	0%	0.28	0.41	0.67
Mi_23_c	35%	90%	89%	95%	0%	0%	288%	0%	0.23	0.49	0.46
Mi_24_c	19%	87%	86%	87%	0%	0%	115%	11%	0.30	1.00	0.30
Mi_30_c	4%	86%	69%	5%	43%	0%	115%	11%	0.59	1.00	0.59
Mi_32_c	0%	83%	70%	0%	167%	0%	162%	20%	0.62	0.91	0.68
Be_s_20_o	36%	53%	75%	65%	124%	0%	190%	0%	0.43	1.00	0.43
Be_s_31_o	51%	73%	55%	45%	11%	0%	0%	39%	0.44	1.00	0.44
Be_s_6_c	27%	60%	60%	91%	731%	0%	−1208%	0%	0.40	0.44	0.91
Be_f_14_c	52%	93%	70%	86%	5535%	0%	−74%	12%	0.25	0.35	0.71
Be_f_41_c	58%	94%	84%	96%	153%	0%	−519%	0%	0.17	0.31	0.55
Wi_36_o	42%	56%	56%	16%	0%	n.a.	0%	30%	0.57	1.00	0.57

Note. Cr = crop production; Mi = milk production; Be = beef production; Wi = wine production; s = suckler cow husbandry; f = cattle growing-fattening; o = organic; c = conventional; ME = eco-efficiency under meta-frontier; GE = eco-efficiency under group-frontier; TGR = technology gap ratio; n.a. = not available due to wine-producing farms have no protein output.

generate most of their AE through the purchase of concentrate, roughage, and animals.

4.2. Data envelopment analysis

Besides the eco-efficiency scores (ME and GE) and the TGR, the main results of the DEA are the input and output slacks, showing the possible reduction of excess inputs and the possible increase of deficient outputs, to reach eco-efficiency, thus revealing the farm's improvement potential. For nine farms practicing animal husbandry (Mi_22_o; Mi_26_o; Mi_5_c; Mi_9_c; Mi_24_c; Mi_30_c; Mi_32_c; Be_s_31_o; B_f_14_c), DEA revealed the highest input slack for GWP. GWP is mainly driven by CH_4 emissions from ruminants' enteric fermentation (Pinares-Patiño et al., 2007). There are many strategies to mitigate CH_4 emissions of ruminants, e.g., different feeding regimes, animal productivity improvement, or manipulation of the rumen fermentation (Boadi et al., 2004).

EP was determined to be the environmental impact with the highest excess for another four farms (Cr_37_c; Mi_4_o; Be_s_20_o; Wi_36_o). Therefore, these farms should aim to reduce the EP, which is linked to NO_3 losses via leaching, airborne emissions (e.g., NH_3, NO_x), and direct effluents of P (Brentrup et al., 2004).

For nine of the 22 non-eco-efficient farms (Cr_15_c; Mi_21_o; Mi_45_o; Mi_46_o; Mi_47_o; Mi_23_c; Mi_24_c; Be_s_6_c; Be_f_41_c), the reduction of the AE should be striven for. AE is closely related to the application of plant production agents (Nemecek et al., 2011) and heavy metals contained in manure. Another mitigation strategy for AE is reducing the purchase of resources like roughage, concentrates, and animals, thus reducing the accumulation of heavy metals that damage the environment and can be passed into the human food chain (Elliott et al., 2017).

Regarding output slacks, DEA calculated the highest values for FNI of six farms (Cr_15_c; Mi_45_o; Mi_46_o; Mi_47_o; Mi_32_c; Be_f_14_c). In conventional farms, low FNI can be related to lower product prices for their products, which probably outweigh the advantage of higher yields (Kulshreshtha and Klemmer, 2011). Especially for organic farms with livestock, a low FNI can be caused by higher depreciation of investments into barn infrastructure, related to the greater space requirements (EC, 2008).

The net production of food (i.e., protein and energy) caused the highest output slacks for 11 of the 22 non-eco-efficient farms. All of these farms are keeping livestock. In addition, the milk and beef-producing farms showed average TGR values of 0.78 and 0.76, respectively. This can be explained by the different amounts of human-edible energy and protein used to feed animals (Ertl et al., 2015). In some cases, the net food production of energy and protein can also become negative (Table 3), resulting in a net drain of potential human food as dairy and beef production sometimes require more human-edible energy and protein than they yield (Le Cotty and Dorin, 2012; Rask and Rask, 2011). This is especially the case if crops that could be primarily consumed directly by humans are used to feed animals (Cassidy et al., 2013). In this context, grassland-based cattle farming and mixed crop-livestock systems were highlighted as feasible approaches to achieve a positive net production of energy and protein (Ertl et al., 2015; Foley et al., 2011). By converting energy and protein from plant biomass into dairy and beef products, grassland-based cattle production systems can utilize resources that otherwise could not be directly consumed by humans (Steinfeld et al., 2006). Furthermore, in contrast to plants, dairy and beef products have high contents of nutritionally valuable protein, which contains all essential amino acids in ratios appropriate for humans (Cassidy et al., 2013).

For three farms (Cr_11_0; Cr_37_c; Mi_21_o), DEA revealed the increase of HNVf as having the highest potential of optimization towards eco-efficiency (Table 4). The farm Cr_37_c, which only cultivates grain maize and oil pumpkin, causes the highest slack in terms of HNVf (635%), followed by the dairy farm Mi_21_o (278%), which cultivates grassland with three or more cuts per year and therefore has a low biodiversity on its agricultural area. Ceballos et al. (2015) identified the loss of biodiversity as the most severe environmental crisis aspect, affecting vital ecosystem services and human well-being. Moreover, although the global ecosystem may tolerate a high level of biodiversity loss for a certain time, it is unknown which levels or types of biodiversity loss may cause irreversible changes to the ecosystem earth (Steffen et al., 2015). IPBES (2019) highlighted that around one million species are already facing global extinction unless immediate action is taken to mitigate drivers of biodiversity loss. By causing a severe reduction of biodiversity on agricultural land, the intensification of agriculture is one of those drivers (Haaland et al., 2011). This highlights the importance of integrating an additional land use parameter (such as HNVf) as output, emphasizing the use of low and medium intensive grass and arable land with high species and habitat diversity (Andersen et al., 2003; Bartel et al., 2011).

The LCA results in Figs. 2 and 3 have shown that three different organic wine-producing farms have the highest environmental impacts per MJ hee within their farm type. The organic dairy farm Mi_4_o reaches the highest values for CExD, GWP, and EP per MJ hee within its respective farm type. Further, the dairy farms' DEA results in Table 4 showed seven out of twelve organic farms (58%) and six out of ten conventional farms (60%) to be non-eco-efficient. The mean eco-efficiency score of these farms is 0.64 for organic farms and 0.41 for conventional farms. This shows that organic farms should not be a priori considered as being generally more eco-efficient. Instead, it should be noted that measures to reduce environmental impacts need to be implemented in both farming systems (Cederberg and Mattsson, 2000).

4.3. Limitations of the used methods

Regarding LCA, the most recognized limitation is the robustness of results due to data uncertainties, bias, and value judgments (Hofstetter et al., 2000; Huijbregts, 1998; Macombe et al., 2018). Additionally, Dreyer et al. (2003) and Pant et al. (2004) pointed out that at least for specific local environmental impacts, the use of different LCA-tools yields different results. Hellweg and Milà i Canals (2014) and Macombe et al. (2018) therefore consider LCA to be a method not to provide numeric results with the greatest possible accuracy but instead presenting a comprehensive overview of a problem and its possible solutions. On the other hand, DEA needs some degree of homogeneity of technology across the DMUs under study. Otherwise, the fiction of one efficiency frontier underlying the data would be difficult to maintain (Stolp, 1990). To cope with heterogeneous technology, we applied the meta-frontier specification (Rao et al., 2003) on the DEA-analysis, which computes different efficiency frontiers according to different groups of technology (Yu et al., 2019).

5. Conclusions

The joint application of LCA with DEA was used to evaluate the eco-efficiency of 47 Austrian farms of four different farm types. As a novel concept, multiple functions of agriculture were taken into account by implementing four different outputs in the DEA. The purchase of resources like fertilizers, concentrates, roughage, or animals was shown to cause a substantial share of environmental impacts, thus highlighting the importance of efficient utilization of these resources on farms. It could further be shown that the use of high amounts of human-edible energy and protein as animal feed leads to lower eco-efficiency scores of cattle farms. Most likely caused by low product prices or high depreciation of investments, a weak profitability was also shown to diminish eco-efficiency. Overall, the eco-efficiency of a farm depends on how the considered functions of agriculture can be fulfilled by making the best possible use of the local production potential, while the management system applied (i.e., organic vs. conventional) is less relevant.

CRediT authorship contribution statement

Florian Grassauer: Conceptualization, Software, Visualization, Writing – original draft. **Markus Herndl:** Conceptualization, Methodology, Writing – review & editing. **Thomas Nemecek:** Methodology, Writing – review & editing. **Thomas Guggenberger:** Data curation. **Christian Fritz:** Methodology, Writing – review & editing. **Andreas Steinwidder:** Conceptualization, Writing – review & editing. **Werner Zollitsch:** Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A

Table A1
Farm characteristics, purchased inputs, and fertilization of the 47 farms under study.

	Farm characteristics		Purchased inputs				Fertilization[d]		
	Farm size	Stocking rate	Animals	Concentrates	Roughage	Seed	N	P	K
Farm	*ha*	*LU[a] ha^{-1}*	*kg LW[b]*	*kg DM[c]*	*kg DM*	*kg*	*kg*	*kg*	*kg*
Cr_1_o	39.5	0.0	0	0	0	4257	53	42	70
Cr_11_o	33.2	0.0	0	0	0	3766	273	264	581
Cr_12_o	13.8	0.0	0	0	0	3561	0	0	0
Cr_16_o	37.7	0.0	0	0	0	3118	1259	725	2231
Cr_19_o	43.9	0.0	0	0	0	5860	23	23	90
Cr_29_o	132.3	0.0	0	0	0	11152	1757	1513	9434
Cr_38_o	16.5	0.0	0	0	0	1453	79	79	316

Table A1 (*continued*)

	Farm characteristics		Purchased inputs				Fertilization[d]		
	Farm size	Stocking rate	Animals	Concentrates	Roughage	Seed	N	P	K
Farm	*ha*	*LU[a] ha*$^{-1}$	*kg LW[b]*	*kg DM[c]*	*kg DM*	*kg*	*kg*	*kg*	*kg*
Cr_8_c	156.2	0.0	0	0	0	15260	21092	5981	8063
Cr_15_c	20.2	0.0	0	0	0	3248	1773	464	696
Cr_27_c	34.7	0.0	0	0	0	625	4318	2004	3462
Cr_37_c	27.5	0.0	0	0	0	387	3273	1929	2337
Mi_2_o	50.4	2.6	524	0	0	2093	6876	3091	13737
Mi_3_o	13.2	2.1	22	4990	4642	0	1206	591	1512
Mi_4_o	28.1	2.3	85	6486	0	454	2850	1339	5084
Mi_18_o	42.1	1.4	0	0	0	687	2903	1503	5040
Mi_21_o	37.6	2.2	240	7559	0	0	4988	2262	9115
Mi_22_o	29.3	1.2	0	8569	0	0	2068	945	3669
Mi_26_o	37.3	3.0	400	10645	22336	407	5116	2985	8054
Mi_28_o	52.8	1.2	50	34722	0	0	4250	1913	7629
Mi_42_o	45.2	1.2	0	31673	0	1998	4469	2389	8575
Mi_45_o	37.4	1.4	0	14848	15895	0	4123	1935	7231
Mi_46_o	12.7	1.8	450	12767	8376	0	1531	860	2454
Mi_47_o	10.6	1.5	0	3445	5806	0	949	293	2017
Mi_5_c	23.2	1.7	0	39270	0	70	4027	2097	5373
Mi_9_c	74.7	1.4	0	45050	70605	0	6474	3286	11106
Mi_13_c	27.1	3.7	0	48314	0	267	6736	3260	10621
Mi_23_c	39.5	0.7	0	31680	8014	0	1975	1146	3057
Mi_24_c	51.3	3.4	0	105258	18550	2957	14186	7048	20447
Mi_25_c	42.4	2.2	0	55632	0	2774	8228	4010	12914
Mi_30_c	17.0	1.5	0	14074	3483	589	2636	1382	3444
Mi_32_c	14.2	2.6	124	10462	11881	503	2054	1107	3246
Mi_34_c	30.0	1.7	3150	57879	0	1587	5431	3929	8486
Mi_44_c	20.3	1.8	0	18470	0	130	1548	795	2900
Be_s_17_o	23.8	1.5	0	0	0	1165	1997	926	3481
Be_s_20_o	39.1	0.5	0	0	40282	28548	249	195	327
Be_s_31_o	15.9	1.6	0	0	0	1076	1408	666	2412
Be_s_6_c	12.0	1.3	1020	5032	18884	0	549	313	896
Be_f_39_o	6.5	1.3	1500	0	0	0	596	409	918
Be_f_43_o	7.4	1.4	2850	0	2943	0	713	369	1075
Be_f_14_c	6.4	1.6	2524	2551	0	419	724	450	1246
Be_f_41_c	18.5	4.2	5390	22824	31606	0	3214	1684	5260
Wi_7_o	14.8	0.0	0	0	0	149	133	127	279
Wi_33_o	6.0	0.0	0	0	0	0	0	0	0
Wi_35_o	14.4	0.0	0	0	0	0	0	0	0
Wi_36_o	12.5	0.0	0	0	0	0	0	0	0
Wi_10_c	7.1	0.0	0	0	0	169	0	0	0
Wi_40_c	6.0	0.0	0	0	0	0	0	0	0

Note.
[a] LU = livestock unit.
[b] LW = live weight.
[c] DM = dry matter.
[d] Containing purchased fertilizer as well as manure from animal husbandry.

Table A2
Sold outputs and contribution margin of the 47 farms under study.

	Sold outputs						Contribution margin
	Bread grain	Feed grain	Grain maize	Grapes	Milk	Meat	
Farm	*kg DM[a]*	*kg DM*	*kg DM*	*kg DM*	*kg ECM[b]*	*kg LW[c]*	€
Cr_1_o	40427	0	26932	0	0	0	17359
Cr_11_o	58448	0	44303	0	0	0	45997
Cr_12_o	907	0	0	0	0	0	12550
Cr_16_o	53772	0	25038	0	0	0	29887
Cr_19_o	77380	0	0	2835	0	0	53680
Cr_29_o	208864	0	160225	0	0	0	132853
Cr_38_o	13494	0	0	0	0	0	6826
Cr_8_c	282383	136908	101897	3842	0	0	108011
Cr_15_c	37316	5243	0	0	0	0	5375
Cr_27_c	0	0	295249	0	0	0	49075
Cr_37_c	0	0	77320	0	0	0	28588
Mi_2_o	306570	0	0	0	204836	8591	97136
Mi_3_o	0	0	0	0	40484	3282	16960
Mi_4_o	0	0	0	0	108776	3270	52572
Mi_18_o	3467	3079	0	0	148153	7290	128520

(continued on next page)

Table A2 (*continued*)

	Sold outputs						Contribution margin
	Bread grain	Feed grain	Grain maize	Grapes	Milk	Meat	
Farm	*kg DM*[a]	*kg DM*	*kg DM*	*kg DM*	*kg ECM*[b]	*kg LW*[c]	€
Mi_21_o	0	0	0	0	158484	7960	76290
Mi_22_o	0	0	0	0	112245	4420	44911
Mi_26_o	0	0	0	0	163565	9030	50614
Mi_28_o	0	0	0	0	222103	8251	73118
Mi_42_o	0	0	0	0	253958	5890	87203
Mi_45_o	0	0	0	0	163090	5262	53133
Mi_46_o	0	0	0	0	61841	4707	17706
Mi_47_o	0	0	0	0	24974	2456	11151
Mi_5_c	0	0	0	0	198159	9700	68896
Mi_9_c	0	0	0	0	166320	15150	39240
Mi_13_c	0	0	0	0	280059	12429	103305
Mi_23_c	0	0	0	0	83160	6112	41115
Mi_24_c	31570	11744	0	0	467745	12120	114979
Mi_25_c	0	0	0	0	350060	10383	182415
Mi_30_c	0	0	0	0	115396	5068	46297
Mi_32_c	0	0	0	0	71346	5839	29293
Mi_34_c	0	0	0	0	347655	6173	83301
Mi_44_c	0	0	0	0	46789	4086	17503
Be_s_17_o	3205	0	0	0	0	11835	33117
Be_s_20_o	31798	0	0	0	0	7573	29630
Be_s_31_o	4155	1320	0	0	0	4816	16325
Be_s_6_c	0	0	0	0	0	6140	9113
Be_f_39_o	0	0	0	0	0	4887	6642
Be_f_43_o	0	0	0	0	0	6082	−775
Be_f_14_c	0	0	0	0	0	8396	6814
Be_f_41_c	0	0	0	0	0	19375	6091
Wi_7_o	0	0	0	10319	0	0	116424
Wi_33_o	0	0	0	1890	0	0	33502
Wi_35_o	0	0	0	7560	0	0	89919
Wi_36_o	0	0	0	5885	0	0	63701
Wi_10_c	0	0	0	8732	0	0	21839
Wi_40_c	0	0	0	4334	0	0	63702

Note.
[a] DM = dry matter.
[b] ECM = energy corrected milk.
[c] LW = live weight.

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3.2. Paper II

Assessing and improving eco-efficiency of multifunctional dairy farming: The need to address farms' diversity

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Assessing and improving eco-efficiency of multifunctional dairy farming: The need to address farms' diversity

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ABSTRACT

Agriculture and especially dairy production cause considerable environmental impacts. Therefore, the growing world population and food demand long for sustainable agricultural practices which aim at producing more food without intensifying the pressure on limited resources and the environment. At the same time, agriculture also provides several other benefits to society, which should not be neglected. In this study, we combined life cycle assessment (LCA) and data envelopment analysis (DEA) to assess the eco-efficiency of 44 dairy farms and simultaneously considered multiple functions of agriculture. Additionally, we addressed the improvement of non-eco-efficient farms by pointing out specific management options which promote the farms' eco-efficiency. The results revealed a high diversity in fulfilling the different functions of agriculture among the 44 dairy farms. We found that the 21 organic dairy farms scored a higher mean eco-efficiency than the 23 conventionally operated dairy farms. The improvement of eco-efficiency showed a high diversity since it can be accomplished by either increasing the outputs or decreasing the inputs. A central source, which affects all inputs and outputs, is the purchased concentrate. However, we conclude that there is no "one-size-fits-all" concept of improving the eco-efficiency of multifunctional dairy farming. Instead, there is always a farm-individual path of increasing eco-efficiency, which depends on the farm's status quo, the efficiency of managing resources, nutrients, and other inputs, and the farmer's choice to position the farm along the trajectory between input minimizing and output maximizing.

1. Introduction

According to the medium-variant projection, the UN (2017) forecasts the growth of the world population to 9.7 billion people by 2050. This growth is accompanied by an increased demand for food of about 70% compared to the 2005–2007 level (FAO, 2012) and drives intensification of production, which conversely fosters public concern about agriculture's environmental impacts (Foley et al., 2011). Thus, agricultural producers face the challenge of producing more food without intensifying the pressure on limited resources and the environment (Sutton et al., 2013). This challenge is reflected by the concept of eco-efficiency (Schmidheiny, 1992). Eco-efficiency is defined as the ratio between the value of a product or service and its environmental impacts (DeSimone and Popoff, 1997; Jan et al., 2012; Thanawong et al., 2014; Van Passel et al., 2007).

Currently, agriculture has a substantial impact on the environment, as it accounts for approximately 24% of the global anthropogenic greenhouse gas (GHG) emissions and is therefore considered a significant contributor to climate change (FAO, 2018a). Furthermore, a large part of agricultural GHG emissions originates from livestock production (IPCC, 2019), contributing about 14.5% to the global anthropogenic GHG emissions (FAO, 2018a).

The dairy sector plays an essential role within livestock production, as global milk production contributes about 27% to the added value of

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livestock production (FAO, 2018b). However, it also causes considerable amounts of environmental impacts such as GHG emissions, nutrient losses, and land use (FAO, 2016, 2018c; Steinfeld et al., 2006).

For assessing environmental impacts and the resource use over the whole life cycle of products or services, life cycle assessment (LCA) presents a suitable instrument (Frischknecht and Büsser Knöpfel, 2013; Klöpffer and Grahl, 2009; Rebitzer et al., 2004) which is internationally standardized (ISO, 2006a, b). Consequently, the assessment of environmental impacts and the resource use of dairy farms via LCA has been conducted in numerous studies (Baldini et al., 2017).

For eco-efficiency assessment, the combination of LCA with data envelopment analysis (DEA) is an increasingly used framework. DEA is a linear programming methodology that measures the relative efficiency of comparable decision-making units (DMUs), which convert inputs into outputs (Cooper et al., 2007). The main benefit of combining LCA + DEA is the enrichment of the relative efficiency measurement with environmental performance indicators (Avadí et al., 2014). The eco-efficiency of dairy farms has been assessed with an integrated LCA + DEA framework in a variety of studies, e.g., Cortés et al. (2021), Iribarren et al. (2011), Jan et al. (2012), Soteriades et al. (2016a), Soteriades et al. (2016b), or Soteriades et al. (2020).

Besides its central function of meeting the increasing demand for food, agriculture provides several other services to society, such as generating income for farmers, preserving attractive rural areas, and - if managed at low or moderate-intensity - maintaining or enhancing biodiversity (Martinsson and Hansson, 2021). This joint production of multiple commodity and non-commodity outputs is reflected in the concept of multifunctionality of agriculture (OECD, 2001). Considering this concept, Grassauer et al. (2021) presented an innovative approach of eco-efficiency assessment of farms that includes multiple functions of agriculture. Based on this assessment approach, we evaluate the eco-efficiency of a set of Austrian dairy farms by simultaneously considering multiple functions of agriculture. Further, we address the improvement of Austrian dairy farms' eco-efficiency by pointing out specific management options which promote the farms' performance. Thus, this study (i) allows for a comprehensive depiction of dairy farms' eco-efficiency and identifies farm-individual strengths and weaknesses in fulfilling the different considered functions of agriculture, and (ii) aims to contribute evidence on options for improving dairy farms' eco-efficiency and allows for a better understanding of the complexity of factors determining the overall performance of multifunctional dairy farms.

2. Material and methods

2.1. Farm data and study area

Potential farms were selected in collaboration with a local dairy factory, but we only considered farms classified as dairy farms according to the Austrian classification system for agricultural and silvicultural farms (Binder et al., 2015). Further, to cover a wide spectrum of farm settings in our sample, we selected farms with different site conditions (i.e., a wide range of shares of arable land and grassland) and aimed at an equal share of organic and conventional farms to allow for comparison between these production systems. The procedure yielded a set of 44 dairy farms, 21 managed organically and 23 conventionally. A brief description of key production parameters of the farms is given in Table 1. A more detailed description of the farms is provided in Table S1 in the supplementary material.

The dairy farms are located in the Mur- and Mürz valley in the federal province of Styria (Fig. 1). The study area is characterized as favorable for agricultural production within alpine areas (Weber and Seher, 2007), and the appearance of highly fertile soils allows for arable farming, mainly for the production of silage maize and clover grass for forage production, and the cultivation of cereals for concentrate feed or as cash crops.

Table 1
Key production parameters of the 44 dairy farms under study.

Parameter	Unit	Median	Min	Max	SD
Farm area	ha	26	4	60	12
Share of grassland	%	95	36	100	18
Share of arable land	%	5	0	64	18
Dairy cows	heads	21	4	59	14
Stocking rate	LU[a] ha^{-1}	1.31	0.66	3.60	0.55
Milk production	kg ECM[b] cow^{-1} a^{-1}	6843	2828	11368	1512
	kg ECM ha farm $area^{-1}$ a^{-1}	6097	1582	16983	3427
	kg ECM a^{-1}	155252	16970	533085	127067

Note.
[a] LU = livestock unit.
[b] ECM = energy corrected milk.

2.2. Methodological approach

For the assessment of eco-efficiency, a three-step LCA + DEA approach, according to Iribarren et al. (2015), was applied. As proposed by Grassauer et al. (2021), the assessment also considers the four different functions of agriculture defined by Nemecek et al. (2005) and Hayashi et al. (2005): (i) generating income for the farmers, (ii) providing energy and protein as food, (iii) preserving an attractive landscape by utilizing ecologically valuable land, and (iv) providing further ecosystem services.

After assessing the farms' eco-efficiency, the potential for improvement of non-eco-efficient farms is addressed by pointing out specific management options that seek to reduce inputs or increase outputs, thus increasing the farms' eco-efficiency.

2.2.1. Life cycle assessment

LCA is used to assess the resource use and environmental impacts of products or services throughout their respective life cycle, i.e., from cradle to grave (Klöpffer and Grahl, 2009; Rebitzer et al., 2004). As a standardized methodology, LCA follows the guidelines of ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) and is arranged in the following four phases: (1) the definition of goal and scope of the study, (2) the compilation of the life cycle inventory (LCI), (3) the life cycle impact assessment (LCIA), and (4) the interpretation of results.

The goal and scope of the LCA in this study (1) is to assess the resource use and environmental impacts of 44 Austrian dairy farms from a cradle to farm gate perspective. The according system boundaries of the dairy farms are presented in Fig. 2. The system includes the whole farm area (physical limit) and covers one calendar year (temporal limit). The temporal limit of growing arable crops deviates thereof and is set from the harvest of the previous main crop to the harvest of this year's main crop. Purchased inputs were considered through their respective upstream processes (e.g., production, processing, and transportation) and their associated emissions. Due to a lack of data, we could not account for the production and application of veterinary drugs, cleaning-, and disinfection agents. The allocation procedure to assign the resource use and environmental impacts to the sold outputs (i.e., milk, beef, and crop products) consists of a hierarchical process and uses physical and monetary criteria. Please see Pedolin et al. (2021) for a detailed description. We consider four different outputs and corresponding functional units within this study (Table 2). By incorporating these functional units, the fulfillment of three of the mentioned functions of agriculture can be evaluated. In addition, the fourth function of providing further ecosystem services is depicted by the LCA itself (Grassauer et al., 2021).

As a proxy to measure the fulfillment of the function of income generation, we calculated the farm net income (FNI), as defined by the Farm Accountancy Data Network (FADN) of the European Commission.

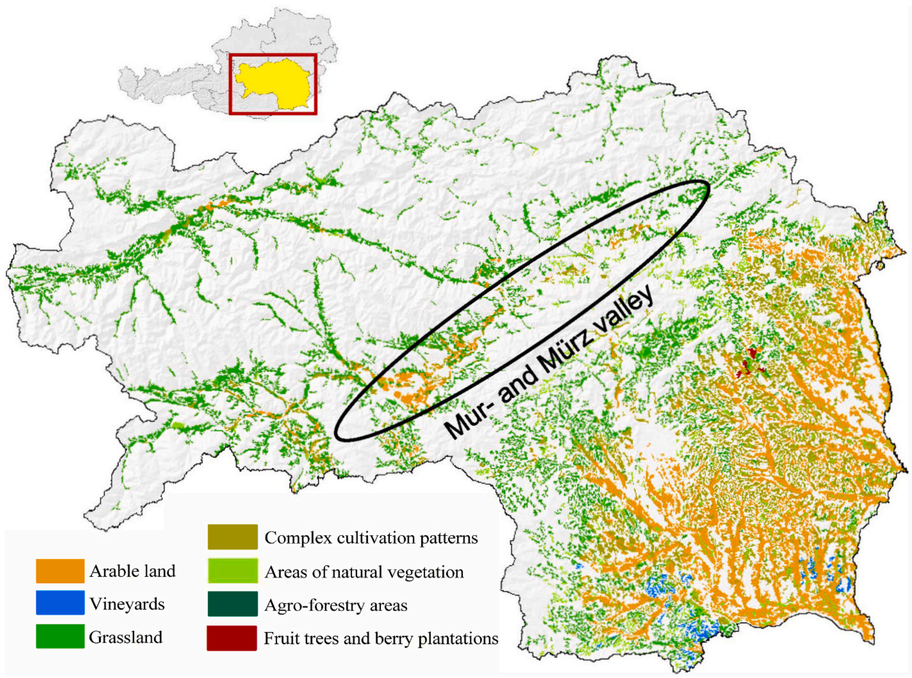

Fig. 1. Agricultural land use in the federal province of Styria based on CORINE land cover data (CLC, 2020) and the location of the study area (Mur- and Mürz valley).

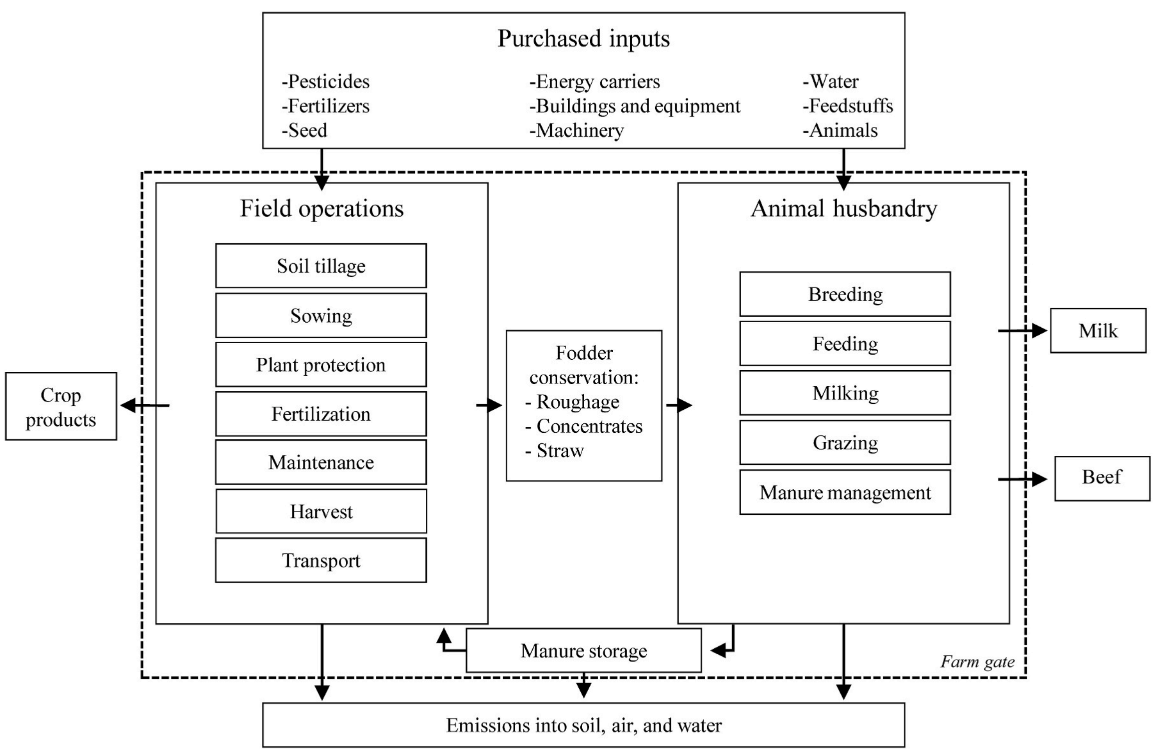

Fig. 2. System boundaries of the dairy farms under study.

As a profitability measure, FNI is defined as the difference between the value of production (sales + subsidies) and the cost of production (intermediate consumption + depreciation + external factors) (EC, 2021; Edwards and Duffy, 2014) and comprises the remuneration of capital, labor, and land.

The function of food production is differentiated into the production of energy and protein. Therefore, the function is depicted as the net production of human-edible energy (heE) and human-edible crude protein (heCP). The net production of heE and heCP on the farm level was calculated by subtracting the human-edible inputs via feedstuffs and seeds from the human-edible outputs through milk, beef, and crop products (Ertl et al., 2015). The human-edible inputs and outputs of heCP were further multiplied with the digestible indispensable amino acid score (DIAAS) (FAO, 2013) to integrate the protein quality,

Table 2
Considered functions of agriculture, resulting farm outputs, and corresponding functional units. Adapted from Grassauer et al. (2021).

Function	Output	Functional unit
Income generation	Farm net income (FNI)	1 € FNI
Food production	Net production of human-edible energy	1 MJ heE
	Net production of human-edible protein	1 g heCP
Utilizing ecologically valuable land	High Nature Value farmland (HNVf)	1 ha HNVf

depending on its source. DIAAS scores of different protein sources were derived from Ertl et al. (2016) and are given in Table S3 in the supplementary material.

High Nature Value farmland (HNVf) was chosen to represent the function of utilizing ecologically valuable land. HNVf provides several ecosystem services and is characterized by a high biological diversity and species richness (Matin et al., 2020). Among three different types of HNVf, defined by Andersen et al. (2003), we calculated HNVf – Type 1 according to Bartel et al. (2011) as an indicator at farm level, which comprises low and moderate intensively managed grass- and arable land.

The compilation and quantification of all inputs and outputs of a product or service throughout its life cycle are computed within the LCI phase (2) of an LCA (ISO, 2006a; Suh and Huppes, 2005). Direct field and animal emissions were estimated based on the sources described in Table 3, which were adapted to Austrian conditions by Herndl et al. (2015). Indirect emissions related to upstream processes were estimated based on eco-inventories from the ecoinvent v.3.5 (Weidema et al., 2013) and SALCA (Gaillard and Nemecek, 2009) databases. Table S1 and Table S2 in the supplementary material provide information on the dairy farms' key production parameters, inputs, and outputs.

Table 3
Considered direct field and animal emissions with their respective source.

Compartment	Emission	Description	Source
Field	PO_4	PO_4 deposits in surface- and groundwater.	Prasuhn (2006)
	NO_3	Leaching of NO_3.	Richner et al. (2014)
	Heavy metals	Accumulation of heavy metals in soil and water.	Freiermuth (2006)
	N_2O[a], NH_3, NO_x	Emissions from applying manure and commercial fertilizer.	Dong et al. (2006); Menzi et al. (1997); Nemecek and Kägi (2007)
Animal	NH_3	Emissions from animals, manure storage, and pasture.	Menzi et al. (1997)
	NO_x	Emissions from manure management and –application.	Nemecek and Kägi (2007)
	N_2O[b]	Emissions from manure storage and pasture.	Dong et al. (2006)
	CH_4[b,c]	Emissions from enteric fermentation and manure storage.	Dong et al. (2006)

Note.
[a] IPCC Tier 1.
[b] IPCC Tier 2.
[c] The daily gross energy (GE) intake for assessing the CH_4 emissions from enteric fermentation is calculated based on the net energy requirement of an animal and the digestible energy as a percentage of GE content of a diet as described in the IPCC guidelines (Dong et al., 2006). The total feed intake was calculated according to the yields of different grassland types and crops and the purchased feedstuffs. The farm-individual values of feed intake, average GE content of the feed, and the resulting GE intake of the dairy cows and the remaining cattle stock are depicted in Table S4 in the supplementary material.

The LCIA (3) is the technical process of transforming all emissions and resource uses from the LCI into environmental burdens (i.e., impact categories) (EC, 2010; Owens, 1998). The LCIA was computed with SimaPro version 9.0.0.49 Developer (Pré Consultants, 2019). As impact assessment method, we selected SALCA (Gaillard and Nemecek, 2009) version 1.12 and considered the following four impact categories: (i) cumulative exergy demand (CExD) (Alvarenga et al., 2013; Bösch et al., 2007), (ii) global warming potential (GWP) (IPCC, 2013), (iii) normalized eutrophication potential (EP) (Hauschild and Potting, 2005), and (iv) aquatic ecotoxicity (AE) (Guinée et al., 2001; Hayer et al., 2010; Kägi et al., 2008). For the rationale behind selecting these impact categories and a more detailed description of them, see Grassauer et al. (2021).

For interpretation (4), the impact categories were broken down to eleven sources (i.e., animal husbandry; animals purchased; roughage purchased; concentrate purchased; land use, fertilizers, and field emissions; pesticides; machinery; energy carriers; buildings and equipment; seed; other inputs). Land use, fertilizers, and field emissions only account for on-farm land use. The off-farm land use is considered within the respective other sources. Consequently, the impact categories were integrated as input parameters in the subsequent data envelopment analysis (DEA).

2.2.2. Data envelopment analysis

DEA is used to assess the relative efficiency of similar multi-input, multi-output entities, so-called decision-making units (DMUs) (Charnes et al., 1978). In the present study, each dairy farm was considered as one DMU. DEA conducts a balanced estimation of weights of the selected inputs and outputs of the DMUs. The resulting linear maximization problems find the best (i.e., maximal) weighting for each DMU's inputs and outputs under the constraint that, using the same weights, no other DMU would achieve a better ratio of outputs to inputs (Pedolin et al., 2021). The calculation of the DEA requires a DEA matrix (Table 4), which comprises all DMUs, including their considered inputs (CExD, GWP, EP, and AE) and outputs (FNI, heE, heCP, and HNVf). Based on the study's aims, we applied a slacks-based-measure (SBM) DEA model with input orientation and variable returns to scale (SBM-I-V) that allows for the calculation of input and output slacks. Slacks show the possible reduction of excess inputs and the desired increase of deficient outputs to reach eco-efficiency for each DMU. The model further calculates an eco-efficiency score ranging from one to zero, where a score of one indicates a DMU as being eco-efficient (resulting in input and output slacks of zero), and a score ≤ 1 denotes a DMU as non-eco-efficient (resulting in input and output slacks ≥ 0) (Tone, 2001). DEA was conducted with MaxDEA 8 Ultra software (MaxDEA, 2021).

2.2.3. Management options to improve eco-efficiency

In order to improve the eco-efficiency of non-eco-efficient dairy farms, we point out specific management options, which reduce the inputs (CExD, GWP, EP, and AE) or increase the outputs (FNI, heE, heCP, and HNVf). Accordingly, we define a management option as a set of changes in inputs and outputs on a farm to improve eco-efficiency. To provide multiple fields of action, we broke down the inputs into eleven sources (see 2.2.1). Further, we also subdivided the outputs into their respective sources: (i) FNI into costs (intermediate consumption; depreciation; external factors) and revenues (sales; subsidies), (ii) heE and heCP into inputs (feedstuffs; seed) and outputs (milk; beef; crop products), and (iii) HNVf into rough pasture; meadow-2 cuts; meadow-1 cut; alpine pasture; temporary grassland; winter wheat and winter rye on marginal arable land. Subsequently, based on the median and its standard error, we ordered the sources of the different inputs and outputs according to their potential for improvement and selected the top three sources that should be focused on when attempting to improve eco-efficiency (fields of action). Finally, we related specific management options of the non-eco-efficient dairy farms to each field of action by

Table 4
DEA matrix of 44 farms under study.

	Inputs				Outputs			
	CExD	GWP	EP	AE	FNI	heE	heCP	HNVf
Farm	*GJ a^−1^*	*t CO_2-eq a^−1^*	*person year^−1^*	*kg 1,4 DB-eq a^−1^*	*€ a^−1^*	*GJ a^−1^*	*kg a^−1^*	*ha*
1_o	4589	120	101	203	27181	162	2588	1
2_o	9337	246	254	487	42919	285	4995	5
3_o	7722	214	304	546	63360	433	6774	2
4_o	11137	274	451	617	52530	367	6267	12
5_o	11005	256	406	541	57900	485	7298	8
6_o	6721	196	186	323	22263	193	3279	4
7_o	4823	152	129	265	41838	150	2379	10
8_o	1699	56	46	127	1634	60	956	1
9_o	9468	243	197	483	34792	282	4451	9
10_o	3199	96	74	179	27584	136	2003	4
11_o	15622	884	772	4354	89090	604	8323	13
12_o	10803	438	464	2194	30954	315	5341	32
13_o	8328	188	224	287	42882	182	2884	30
14_o	4040	79	99	109	13283	68	1042	20
15_o	6259	113	248	290	7230	106	1969	24
16_o	6150	105	202	176	38411	95	−10681	17
17_o	5018	152	185	207	26194	197	2768	16
18_o	5802	211	232	848	16528	222	3454	5
19_o	10485	172	121	247	26291	254	3357	26
20_o	7834	178	258	311	30044	172	2804	11
21_o	4709	147	128	204	37200	164	2666	11
22_c	4805	162	135	2703	23886	89	3549	4
23_c	9133	257	297	6385	64805	335	5934	5
24_c	5999	173	155	1404	14720	221	3548	2
25_c	12815	401	451	6618	35221	45	8527	4
26_c	7414	226	188	2570	10073	299	3929	2
27_c	6966	171	187	3787	−6230	114	3578	10
28_c	12571	490	359	1148	82468	364	9758	13
29_c	19690	819	1053	14,271	104607	910	15308	12
30_c	11229	417	392	7784	21825	418	9138	6
31_c	14536	653	796	13,731	83674	412	11816	4
32_c	9047	290	284	4230	23994	140	5143	6
33_c	9157	273	371	5742	25950	246	5483	12
34_c	10555	402	417	5248	49527	577	8932	3
35_c	16940	514	529	5248	46185	424	10015	11
36_c	10482	331	487	8038	80179	527	9016	1
37_c	9551	352	296	2587	61979	252	4285	28
38_c	8411	163	117	4604	72707	285	5558	6
39_c	14043	398	650	6880	96700	653	10714	10
40_c	1800	64	60	951	−1667	15	290	5
41_c	14370	526	596	14,031	111142	728	14940	7
42_c	10626	336	754	6070	35067	422	8559	4
43_c	8220	272	297	5004	49866	266	6471	9
44_c	8660	360	346	7645	27698	283	7801	2

Note. o = organic; c = conventional.
CExD = cumulative exergy demand; GWP = global warming potential; EP = normalized eutrophication potential; AE = aquatic ecotoxicity; FNI = farm net income; heE = net production of human-edible energy; heCP = net production of human-edible crude protein; HNVf = High Nature Value farmland.

calculating Pearson's correlation coefficient to identify the three most promising management options to improve eco-efficiency (e.g., number of dairy cows ~ GWP from animal husbandry).

3. Results

3.1. Data envelopment analysis

The applied SBM-I-V model calculates input and output slacks and an eco-efficiency score ranging from zero to one, where a score of one indicates a farm to be eco-efficient and a score of zero represents poor eco-efficiency. The input and output slacks show the necessary reduction of inputs and the necessary increase of outputs, respectively, to reach a score of one. Note that the reference basis of reducing the inputs and increasing the outputs is different to interpret (i.e., input slacks can get no higher than 100%, whereas output slacks may, theoretically, approach infinity). Slacks and eco-efficiency scores of the non-eco-efficient dairy farms are presented in Table 5. The 23 eco-efficient farms (i.e., farms with a score of one and therefore input and output slacks of zero) were excluded from Table 5.

The 23 eco-efficient dairy farms can be divided into 15 organic and eight conventional operations, whereas the 21 non-eco-efficient dairy farms consist of 6 organic and 15 conventional operations. The mean eco-efficiency scores are 0.92 (SEM = 0.03) and 0.81 (SEM = 0.03) for the 21 organic and the 23 conventional farms, respectively. According to a Mann-Whitney-U-Test conducted, the mean eco-efficiency score of the organic farms is significantly higher than the mean eco-efficiency score of the conventional farms (p-value = 0.017).

Among the non-eco-efficient dairy operations, farm 25_c has the highest slack for heE (767%), originating from a net production of 45 GJ heE (Table 4). To tackle this slack, the heE of this farm would have to be increased to approximately 345 GJ. Simultaneously, this farm needs to increase the FNI and the HNVf by 112 and 100% to reach eco-efficiency, respectively. Farm 26_c cultivates only two of its 22.3 ha (9%) as HNVf (meadow-2 cuts (Fig. 5)). This low share of HNVf leads to a slack of 379% for this output parameter. Additionally, the farm has output slacks of 327% for FNI and 14% for heCP. Due to a negative FNI of −6230 €, the farm 27_c has its highest output slack (−684%) for this trait.

Table 5
Input and output slacks and eco-efficiency score of the 21 non-eco-efficient farms under study.

	Input slacks (%)				Output slacks (%)				Eco-efficiency score
Farm	CExD	GWP	EP	AE	FNI	heE	heCP	HNVf	
2_o	28	29	15	17	13	14	0	0	0.78
4_o	8	10	35	16	0	7	0	0	0.83
6_o	33	34	27	14	66	12	0	0	0.73
9_o	26	31	5	26	24	5	0	0	0.78
18_o	18	37	35	66	128	1	0	0	0.61
20_o	38	33	43	22	0	6	0	0	0.66
22_c	0	4	0	65	62	127	0	0	0.83
23_c	13	28	30	63	0	4	0	0	0.66
24_c	25	25	0	78	131	4	0	26	0.68
25_c	18	6	25	86	112	767	0	100	0.66
26_c	3	25	0	86	327	0	14	379	0.71
27_c	22	19	4	92	−684	103	0	0	0.66
30_c	2	5	8	75	258	0	0	45	0.78
31_c	19	38	39	35	11	49	0	7	0.67
32_c	27	40	15	90	106	136	0	0	0.57
33_c	1	24	38	92	88	45	0	0	0.61
35_c	28	11	27	48	80	0	0	0	0.72
36_c	0	7	12	43	0	0	0	377	0.84
42_c	6	0	53	66	112	4	0	42	0.69
43_c	0	1	3	77	15	32	0	0	0.80
44_c	1	30	1	71	150	66	0	36	0.74

Note. o = organic; c = conventional.
CExD = cumulative exergy demand; GWP = global warming potential; EP = normalized eutrophication potential; AE = aquatic ecotoxicity; FNI = farm net income; heE = net production of human-edible energy; heCP = net production of human-edible crude protein; HNVf = High Nature Value farmland.

3.2. Management options to improve eco-efficiency

Fig. 3 shows the inputs (CExD, GWP, EP, and AE) subdivided into eleven different sources for each of the 21 non-eco-efficient farms. Land use, fertilizers, and field emissions dominate CExD, whereas animal husbandry accounts for large parts of GWP, and concentrate purchased causes most AE emissions. Within EP, Fig. 3 shows major contributions from land use, fertilizers, and field emissions, animal husbandry, and

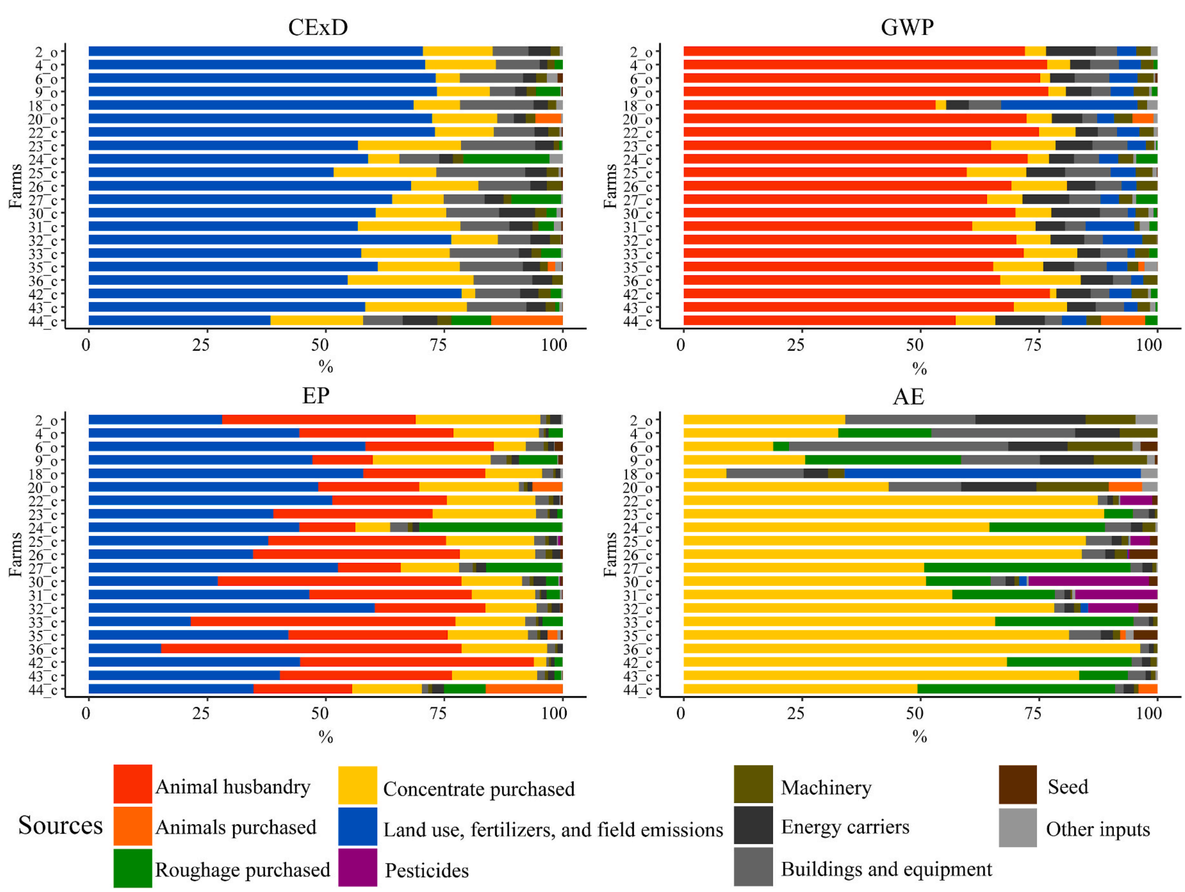

Fig. 3. Contribution of the eleven sources to the cumulative exergy demand (CExD), the global warming potential (GWP), the normalized eutrophication potential (EP), and the aquatic ecotoxicity (AE) of the 21 non-eco-efficient farms.

concentrate purchased.

In order to identify the three most promising sources which should be addressed in attempts to improve eco-efficiency (i.e., the fields of action), we arranged the sources in the order of the median and its standard error for each input (Fig. 4). Accordingly, we identified land use, fertilizers, and field emissions (L_f_f), concentrate purchased (C_p), and buildings and equipment (B) as the three fields of action to improve CExD. The fields of action for GWP are animal husbandry (A), concentrate purchased (C_p), and energy carriers (E). Furthermore, we identified land use, fertilizers, and field emissions (L_f_f), animal husbandry (A), and concentrate purchased (C_p) as fields of action for EP and concentrate purchased (C_p), buildings and equipment (B), and roughage purchased (R_p) as fields of action for AE.

Figs. 3 and 4 indicate C_p to be a central source that affects all considered inputs (i.e., impact categories).

Regarding the outputs (FNI, heE, and HNVf), Fig. 5 shows them subdivided into their respective sources. The output heCP was neglected because a slack for this parameter was found for only one farm (26_c). The sources of FNI were summarized as costs (intermediate consumption; depreciation; external factors) and revenues (sales; subsidies) with different directions of action (i.e., in order to gain eco-efficiency, one can either reduce costs or increase revenues). The dominating sources of costs were intermediate consumption and depreciation, whereas sales account for a significant part of revenues. The sources of heE were also summarized in two categories with different directions of action, i.e., inputs (feedstuffs; seed) and outputs (milk; beef; crop products), with feedstuffs and milk being the dominant sources, respectively. Regarding HNVf, the composition is heterogeneous among the 21 non-eco-efficient dairy farms. Most farms cultivate parts of their grassland as rough pasture and meadows with two cuts. However, winter wheat and winter rye on marginal arable land, temporary grassland, and meadows with one cut occur only once.

Fig. 6 shows the sources of the different output parameters arranged in the order of their median and its standard error, with the fields of action printed in red and bold font. For HNVf, we defined only two fields of action due to the heterogeneity of the HNVf's composition among the farms, which leads to median values of zero for five of seven HNVf sources.

In the next step, we related specific management options to each field of action for every input and output (e.g., number of dairy cows (heads) ~ GWP resulting from animal husbandry (kg CO_2-eq)). For this purpose, we calculated Pearson's correlation coefficient (r) to identify the three most promising management options to improve eco-efficiency. The management options for the fields of action for the inputs are given in Table 6. By modulating the factors presented here, farm eco-efficiency can be improved substantially.

Accordingly, in Table 7, the management options are presented for each field of action for every output with corresponding units, correlation coefficients (r), and asterisks showing the significance level. We excluded the output parameter HNVf from the table due to the heterogeneous composition of HNVf, which did not allow us to identify specific management options to gain eco-efficiency, but would imply an overall increase in HNVf on the farms.

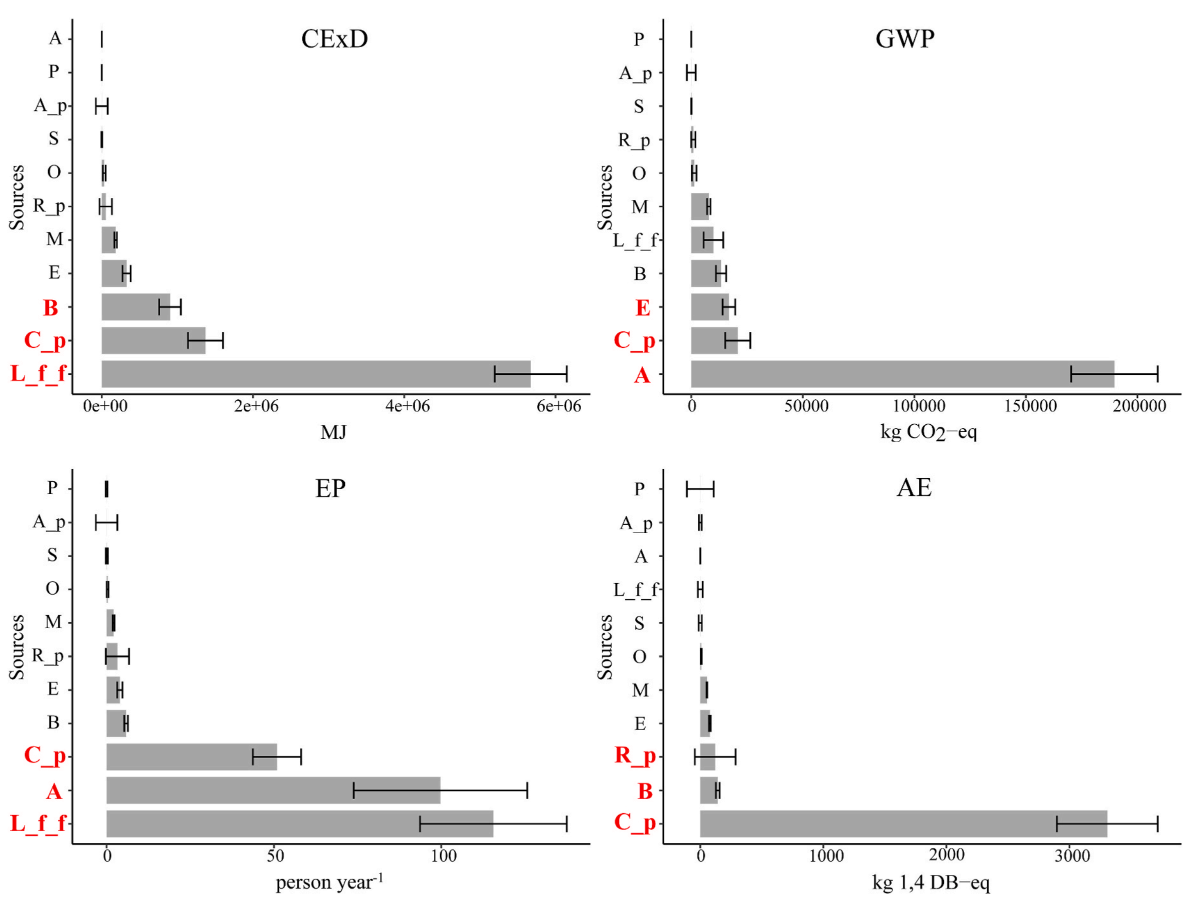

Fig. 4. Eleven sources contributing to cumulative exergy demand (CExD), global warming potential (GWP), normalized eutrophication potential (EP), and aquatic ecotoxicity (AE) of the 21 non-eco-efficient farms (Median ± SE_{Median}), with the three fields of action for each input in red and bold font. A = animal husbandry; A_p = animals purchased; B = buildings and equipment; C_p = concentrate purchased; E = energy carriers; L_f_f = land use, fertilizers, and field emissions; M = machinery; O = other inputs; P = pesticides; R_p = roughage purchased; S = seed.

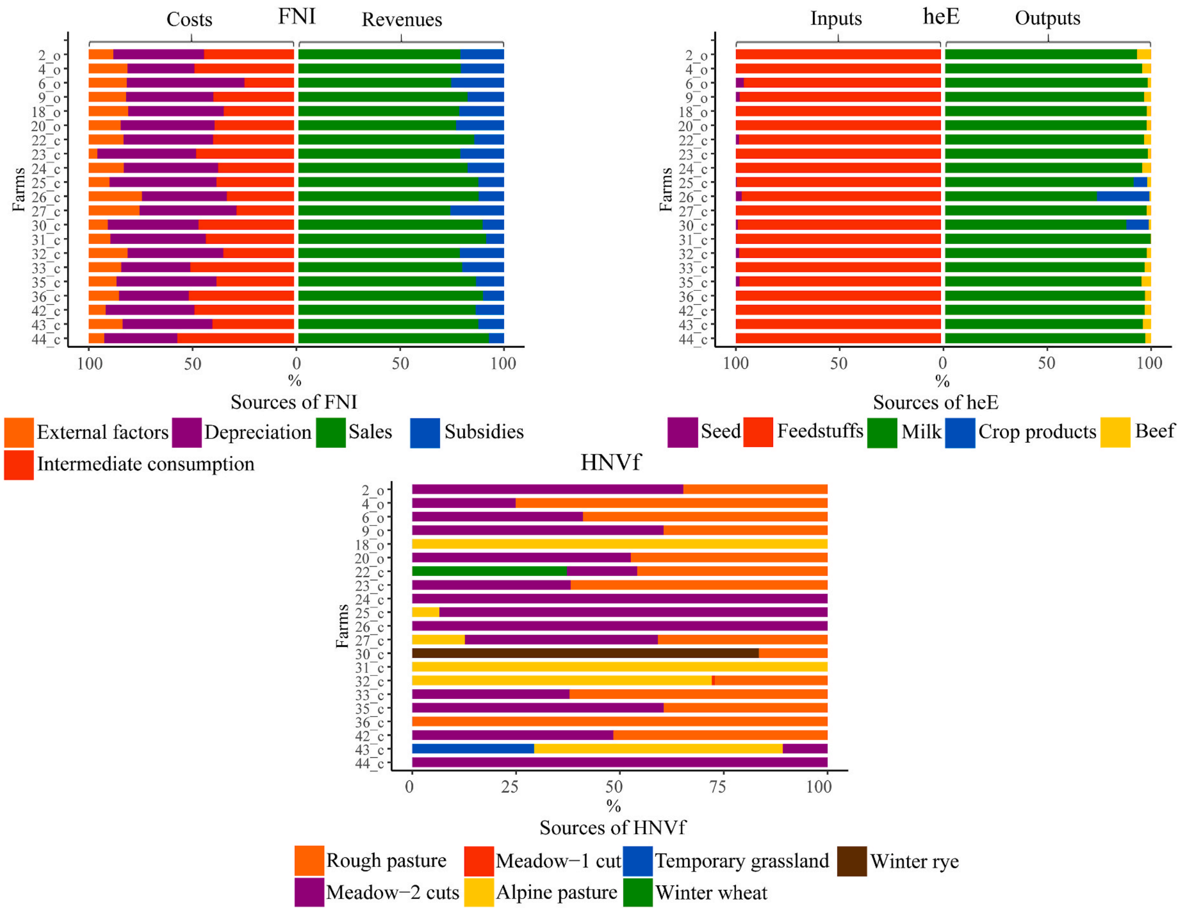

Fig. 5. Contribution of different sources to the farm net income (FNI), the net production of human-edible energy (heE), and the High Nature Value farmland (HNVf) of the 21 non-eco-efficient farms.

4. Discussion

We started from a combination of LCA and DEA and implemented an approach for considering multiple functions of agriculture. This methodological approach allows for a comprehensive assessment of farms and a condensation of the assessment's results in one eco-efficiency score. Furthermore, we elaborated the potential fields of action at the farm level for the 21 non-eco-efficient farms and derived management options to increase the eco-efficiency. In contrast to other studies which combine LCA and DEA (e.g., Cortés et al. (2021), Jan et al. (2012), or Iribarren et al. (2011)), our approach is innovative, as the eco-efficiency score includes multiple functions of agriculture. This allows for a statistically balanced representation and assessment of otherwise often conflicting targets, e.g., milk yield and product-related greenhouse gas emissions versus concentrate production and utilization of ecologically valuable land. On the other hand, there is still room for improvement, e.g., correcting the results for site-effects as proposed by Soteriades et al. (2016a).

4.1. Data envelopment analysis

With an eco-efficiency score below 1, DEA revealed 21 (48%) of the 44 dairy farms as non-eco-efficient. 15 of these non-eco-efficient farms operate conventionally, whereas 15 of the 23 eco-efficient farms are organic operations. The organic dairy farms scored a significantly higher mean eco-efficiency than the conventional dairy farms. A slightly higher eco-efficiency of organic dairy farms was also reported by Grassauer et al. (2021) and is mainly based on the environmental benefits of organic milk production, e.g., the disuse of pesticides (Cederberg and Mattsson, 2000). Further, the selected SBM-I-V model calculated input and output slacks, showing the necessary reduction of inputs and the necessary increase of outputs, respectively. In particular, the output slacks show the extent to which each farm ensures the different functions of agriculture considered in this study.

FNI measures the fulfillment of the income generation function and, therefore, the economic performance of a farm, which is influenced by the levels of revenues and costs. Due to its high prices, the purchased concentrate has a substantial effect on the costs in dairy production (Ertl et al., 2014), and high amounts thereof weaken farms' economic performance. A weak economic performance consequently leads to high slacks for FNI. For example, farm 26_c has a considerable output slack for FNI (327%), resulting from a low FNI of 10073 € (Table 5). However, the highest slack for FNI is assigned to farm 27_c. In order to reach eco-efficiency, this farm would have to increase its negative FNI (−6230 €) by −684%, resulting in an FNI of 42613 €.

The function of food production is measured as the net production of heE and heCP. Despite a considerable output of heE and heCP through milk, beef, and crop products, the purchase of high amounts of human-edible feedstuffs can cause high slacks for these parameters as the human-edible fraction of the feedstuffs gets subtracted from the output through milk, beef, and crop products (Ertl et al., 2015). The highest slack for heE is caused by farm 25_c (767%; Table 5). This farm produces only 45 GJ of net heE, despite a comparatively high milk yield of 307083 kg ECM. The low net production of heE is caused by the purchase of 69.7 tons of concentrate, of which 61 tons are energy-rich concentrate with an energy content of 7.3 MJ NEL and a human-edible fraction of about 80% (Wilkinson, 2011).

High slacks for HNVf indicate a high potential for improvement

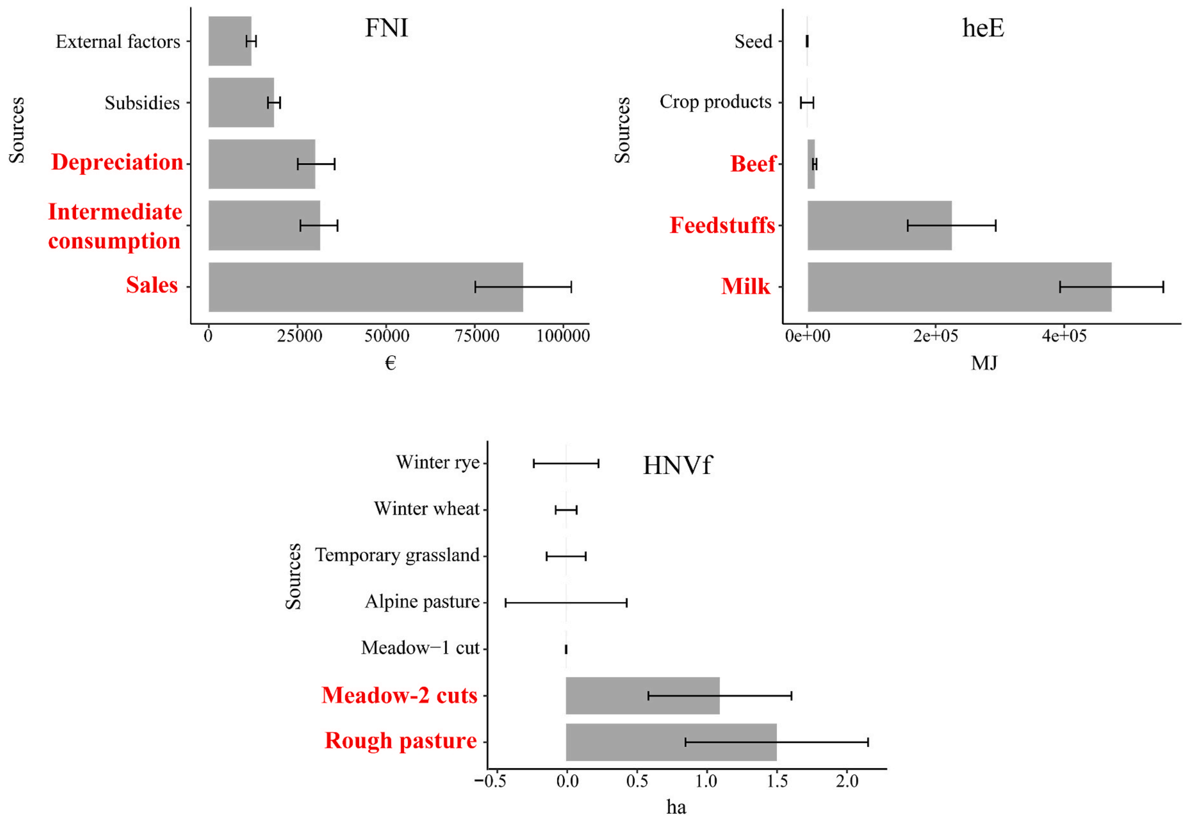

Fig. 6. Different sources contributing to farm net income (FNI), net food production of human-edible energy (heE), and High Nature Value farmland (HNVf) of the 21 non-eco-efficient farms (Median ± SE_{Median}), with the three fields of action for each input in red and bold font.

Table 6
The three most promising management options per field of action and input indicator (CExD, GWP, EP, and AE) with corresponding units in brackets, correlation coefficients (r), and asterisks showing the level of significance (**, *** significant at P < 0.01 and < 0.001, respectively).

Input	Field of action	Management option 1		Management option 2		Management option 3	
		Description	r	Description	r	Description	r
CExD (MJ)	L_f_f	Reduction of farm area (ha)	0.95***	Reduction of total cattle stock (LU[a])	0.78***	Reduction of total yield on farm area (kg DM[b])	0.77***
	C_p	Reduction of dairy cows (heads)	0.77***	Reduction of energy concentrate (kg DM)	0.76***	Reduction of purchased concentrate (kg DM)	0.60**
	B	Reduction of enclosed space (m^3)	0.85***	Reduction of total cattle stock (LU)	0.79***	Reduction of slurry storage (m^3)	0.62**
GWP (kg CO_2-eq)	A	Reduction of dairy cows (heads)	0.93***	Reduction of total cattle stock (LU)	0.87***	Reduction of purchased concentrate (kg DM)	0.87***
	C_p	Reduction of energy concentrate (kg DM)	0.85***	Reduction of purchased concentrate (kg DM)	0.76***	Reduction of dairy cows (heads)	0.74***
	E	Reduction of fuel consumption (kg)	0.84***	Reduction of dairy cows (heads)	0.83***	Reduction of electricity consumption (kWh)	0.77***
EP (person $year^{-1}$)	L_f_f	Reduction of total protein intake (kg)	0.78***	Reduction of purchased concentrate (kg DM)	0.74***	Reduction of nitrogen fertilization (kg)	0.59 ***
	A	Reduction of purchased concentrate (kg DM)	0.77***	Reduction of total protein intake (kg)	0.72**	Reduction of energy concentrate (kg DM)	0.67***
	C_p	Reduction of dairy cows (heads)	0.70***	Reduction of energy concentrate (kg DM)	0.68**	Reduction of total cattle stock (LU)	0.65**
AE (kg 1,4 DB-eq)	C_p	Reduction of energy concentrate (kg DM)	0.79***	Reduction of purchased concentrate (kg DM)	0.74***	Reduction of total protein intake (kg)	0.68***
	R_p	Reduction of purchased roughage (kg DM)	0.93***	n.a.		n.a.	
	B	Reduction of total cattle stock (LU)	0.83***	Reduction of enclosed space (m^3)	0.80***	Reduction of slurry storage (m^3)	0.74***

Note. CExD = cumulative exergy demand; GWP = global warming potential; EP = normalized eutrophication potential; AE = aquatic ecotoxicity; A = animal husbandry; B = buildings and equipment; C_p = concentrate purchased; E = energy carriers; L_f_f = land use, fertilizers, and field emissions; R_p = roughage purchased.
[a] LU = livestock unit.
[b] DM = dry matter.

Table 7
The three most promising management options per field of action and output indicator (FNI and heE) with corresponding units in brackets, correlation coefficients (r), and asterisks showing the level of significance (*** significant at P < 0.001).

Output	Field of action	Management option 1		Management option 2		Management option 3	
		Description	R	Description	r	Description	r
FNI (€)	Sales	Increase of sold milk (€)	0.99***	Increase of sold animals (€)	0.66***	n.a.	
	Intermediate consumption	Reduction of costs for purchased feed (€)	0.95***	Reduction of costs for seed, fertilizer, and plant protection (€)	0.90***	Reduction of veterinary costs (€)	0.76***
	Depreciation	Reduction of costs for energy carriers (€)	0.78***	Reduction of costs for repair and maintenance (€)	0.76***	Reduction of depreciation of buildings (€)	0.74***
heE (MJ)	Milk	Increase of total protein intake (kg)	0.96***	Increase of purchased concentrate (kg DM[a])	0.92***	Increase of dairy cows (heads)	0.91***
	Feedstuffs	Reduction of energy-rich concentrate feed (kg DM)	0.90***	Reduction of dairy cows (heads)	0.84***	Reduction of purchased concentrate (kg DM)	0.81***
	Beef	Increase of total cattle stock (LU[b])	0.70***	n.a.		n.a.	

Note. FNI = farm net income; heE = net production of human-edible energy.
[a] DM = dry matter.
[b] LU = livestock unit.

concerning the function of utilizing ecologically valuable land. The highest slack for HNVf is caused by farm 26_c (379%). This farm comprises 22.3 ha of farm area, of which a comparatively low share of 9% is cultivated as meadow-2 cuts. The rest of the farm's area is cultivated as arable land (silage maize) and meadow-3 or more cuts, which is not considered as HNVf (Bartel et al., 2011).

4.2. Management options to improve eco-efficiency

As a comprehensive energy-based indicator, CExD aggregates the demand and quality of different energy resources (Bösch et al., 2007). Especially for products with a high degree of renewability, like agricultural products, land use can have a high share of CExD among the eleven considered exergy resources (Dewulf et al., 2005), and therefore play an essential role in the resource footprint of products (Alvarenga et al., 2013). Accordingly, we found land use, fertilizer, and field emissions (L_f_f) to be the dominating field of action regarding CExD (Fig. 3; Table 6). Therefore, the most promising management options to mitigate CExD related to L_f_f are reducing the farm area (r = 0.95***) or the total cattle stock (r = 0.78***), as an increasing stocking rate leads to higher dependence on external energy sources (Giambalvo et al., 2009). The CExD from L_f_f attributed to land use and its share on the total CExD of the 21 non-eco-efficient farms is shown in Table S5 in the supplementary material.

The dominating field of action for GWP is animal husbandry, which accounts for emissions from enteric fermentation (CH_4) and manure management (CH_4, N_2O). The majority of these emissions originates from the enteric fermentation of ruminants (Dick et al., 2015; Doltra et al., 2018; Gislon et al., 2020; Ogino et al., 2007). Therefore, the two most promising management options to mitigate GWP emissions from animal husbandry are directly related to reducing livestock. Accordingly, reducing the stock of dairy cows is the most effective management option (r = 0.93***) as about 6% of the gross energy intake of dairy cows is converted into enteric CH_4 (Gavrilona et al., 2019), depending on their milk yield. Another option is to reduce the total cattle stock (r = 0.87***) by outsourcing cattle rearing, potentially leading to a higher farm-level feed efficiency on dairy operations (Vellinga et al., 2011). However, it should be noted that the outsourcing of cattle rearing is simply a displacement of the environmental impacts elsewhere and therefore has no effect on improving the overall eco-efficiency of milk production.

The EP comprises terrestrial (NH_3, NO_x) and aquatic (NO_3, NH_3, NO_x) N eutrophication as well as aquatic P eutrophication (Hauschild and Potting, 2005). Large parts of the EP originate from the application of manure and the leaching of nitrate included in the L_f_f source. This is also supported by Bava et al. (2014), who identified nitrate leaching and volatilized NH_3 from manure application as major contributors to EP. Therefore, to reduce EP emissions from L_f_f, farms should reduce the cattle stock's total protein intake (r = 0.78***), which decreases N excretion via urine and feces (Külling et al., 2001).

Another considerable source of emissions related to eutrophication is animal husbandry (A), with manure storage as the driving contributor, leading to the volatilization of NH_3 (O'Brien et al., 2012). Thus, to reduce the total and urinary N excreted from dairy cows, lowering the protein content of the cows' diet is effective (Colin-Schoellen et al., 2000; Sajeev et al., 2018; Wu and Satter, 2000; Zumwald et al., 2018). Accordingly, we found the highest correlations within A for the amount of purchased concentrate (r = 0.77***) and the total protein intake (r = 0.72**) of the cattle stock.

The dominating field of action related to AE is the purchased concentrate (C_p). Emissions from this source are related to the production and delivery of concentrate feeds, which Arsenault et al. (2009) identified as the most significant driver of freshwater ecotoxicity. Therefore, the environmental impact related to this field of action can be tackled by reducing the amount of energy-rich concentrate (r = 0.79***) or purchased concentrate feeds (r = 0.74**).

Unsurprisingly, the revenues from sold milk are the predominant source of income and economic output on dairy farms (Chamberlain, 2012). Accordingly, we found a high correlation between the sold milk and the sales (r = 0.99***). Another part of dairy farms' sales is the revenues through sold animals (i.e., calves and cull cows) (Chamberlain, 2012). However, due to the farm-individual strategy of cattle rearing, different longevity of dairy cows, different returns for cattle of different breeds, and different culling rates, sold animals show a weaker correlation with the sales (r = 0.66***). Another field of action to increase the FNI is to reduce the costs. Usually, purchased feed costs have the highest share in the costs of milk production (Alqaisi Shawabkeh et al., 2011), leading to a high correlation of r = 0.95*** (Table 7).

The fields of action to increase heE are to raise the output of either milk or beef or to decrease the input of human-edible feedstuffs. Besides energy supply, metabolizable protein is considered a limiting factor in dairy production (Kolver, 2003). Therefore, we found the increase of the cattle stock's total protein intake (r = 0.96***) to be the most promising management option to increase milk output. An increased beef output can be achieved by enlarging the total cattle stock (r = 0.70***) by integrating the rearing and fattening of offspring. Reducing the input of human-edible feedstuffs can be accomplished by lowering the amount of energy-rich concentrate (r = 0.90***) or the amount of purchased concentrate (r = 0.81***). These measures, which lead to higher milk production from grassland, were also proposed by Ertl et al. (2015).

Due to its high site-specific heterogeneity, we could not relate specific management options to the improvement of HNVf. However, to increase this output and fulfill the function of maintaining ecologically valuable land through its utilization, farmers should aim at the extensification of some of their grassland (Bartel et al., 2011). Nevertheless, it should be noted that an extensification of potentially high-yielding grassland results in lower yields and, therefore, lower outputs of heE and heCP. Moreover, substituting lower outputs through the purchase of feedstuffs (concentrate or roughage) could lead to higher environmental impacts and lower economic performance.

Represented as a field of action for every input (Fig. 4) and affecting the outputs as presented in Table 7, the purchased concentrate (C_p) was found to be a central source of environmental impacts, simultaneously diminishing the outputs and, thus, reducing the eco-efficiency of farms. Soteriades et al. (2016b) also concluded that purchased concentrate is an essential factor influencing dairy farms' eco-efficiency. However, the reduction of purchased concentrate also affects the farms' milk yield. Maintaining a certain milk output would consequently require the purchased concentrate to be either substituted by self-produced concentrate or increased roughage quality. Increased roughage quality can be obtained by increasing pasturage, which leads to higher intakes of crude protein and energy (Steinwidder et al., 2018) and causes higher N_2O emissions on the field (Styles et al., 2017). Thus, it becomes evident that the amendment of one management option always causes further effects and that there is always a farm-individual path of improving eco-efficiency where conflicting goals may arise.

4.3. Limitations and uncertainty

Besides bias and value judgments (Hofstetter et al., 2000; Macombe et al., 2018), data uncertainty and robustness of results pose considerable limitations to LCA studies (Huijbregts, 1998). Hauschild et al. (2013) pointed out that the choice of the LCIA method is crucial for the obtained results of an LCA. Therefore, Guo and Murphy (2012) suggest uncertainty analysis of LCA results to improve their robustness and transparency. Accordingly, we conducted uncertainty analyses of the considered environmental impacts for the 44 dairy farms under study, taking the statistical distribution of all upstream processes into account. Based on a Monte Carlo simulation with 1000 iterations, the results of the uncertainty analyses are shown in Fig. S1 in the supplementary material. The highest uncertainties were found for AE, which is explained by a considerable degree of uncertainty regarding the emission of heavy metals (Pizzol et al., 2011a, b). The other impact categories (CExD, GWP, and EP) show considerably lower uncertainty, which is also confirmed by Niero et al. (2014), who attest a high degree of confidence in LCA results related to climate change and resource related impact categories.

5. Conclusions

The novel approach of eco-efficiency assessment revealed a high diversity in fulfilling the different functions of agriculture, which was presented via the slacks from the DEA. Further, we found that organic dairy farms score a higher mean eco-efficiency than conventionally operated dairy farms within the study area. The eco-efficiency improvement through specific management options showed a high variability since it can be accomplished by either increasing one of the four considered outputs (FNI, heE, heCP, and HNVf) or decreasing one of the four inputs (CExD, GWP, EP, and AE). A central source, which affects all of the inputs and outputs, is the purchased concentrate. Generally, outputs and inputs can be increased or decreased by different management options so that conflicting goals may occur. Thus, the individual path of a farm to increase eco-efficiency depends on its status quo and the efficiency of managing resources, nutrients, and other inputs. Therefore, we conclude that even in a specific study region with similar production conditions, there is no "one-size-fits-all" concept of improving the eco-efficiency of multifunctional dairy farming. Instead, there is always a farm-individual path of increasing eco-efficiency, which depends on the occurring input and output slacks and the farmer's choice to position the farm along the trajectory between input minimizing and output maximizing. Future research on eco-efficiency considering multiple functions of agriculture should also focus on other farm types, such as beef, pork, or poultry production, to analyze the contribution of these farm types to other functions besides their livestock production.

CRediT authorship contribution statement

Florian Grassauer: Conceptualization, Software, Visualization, Writing – original draft. **Markus Herndl:** Conceptualization, Methodology, Writing – review & editing. **Thomas Nemecek:** Methodology, Writing – review & editing. **Christian Fritz:** Writing – review & editing. **Thomas Guggenberger:** Data curation. **Andreas Steinwidder:** Conceptualization, Writing – review & editing. **Werner Zollitsch:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.130627.

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4. General discussion

The following subsections cover methodological aspects of the thesis that were not or only partially discussed in the journal contributions.

4.1. Farm selection and sample sizes

Participating farms managed by motivated farmers are the fundamental prerequisite for a successful data collection that yields high-quality primary data, which served as the basis of all analyses conducted within this thesis. The farms analyzed within the two presented papers were selected through the following two approaches:

Data of the 47 farms analyzed in Paper I were derived from Herndl et al. (2015). In order to obtain a high variation of farm settings and to depict multiple site conditions, the authors selected farms from different farm types and site conditions and differentiated between organic and conventional farms. The assignment of farms to a specific farm type was done based on the methodology proposed by Meier (2000), which implies the ratio of arable- to grassland area, the share and stocking density of different livestock species, and the presence of special cultures (e.g., vines). Further, to depict different site conditions within the considered farm types, the farms were classified according to their altitudinal gradient into three groups, i.e., mountain, hill, and lowland. This approach seems common when analyzing different, highly heterogeneous agricultural production systems in the alpine region and was, for example, also found in the studies of Hörtenhuber et al. (2010) and Ertl et al. (2015). However, merely selecting the farms based on their farm type and spatial distribution combined with a comprehensive data collection procedure (which is described in the following subsection) resulted in a high drop-out rate of 49 % (i.e., 47 of 92 pursued farms participated) (Herndl et al., 2015).

In contrast, the 44 dairy farms assessed in Paper II were selected in collaboration with an Austrian dairy factory located in the study region (i.e., Mur- and Mürz valley). Based on a preselection of 93 possible farms conducted by the dairy factory, 57 farms volunteered to participate and started their data collection. In addition, the 57 farms were also examined according to the Austrian classification system for agricultural and silvicultural farms (Binder et al., 2015). This step ensured that only specialized dairy farms were considered for the study. The procedure ultimately yielded 44 dairy farms, which means an even higher drop-out rate of 53 %. Moreover, the spatial distribution of the farms was more or less random, and although the set of 44 farms could depict a wide variety of different site conditions, it cannot be considered representative for the study region. Conversely, the 44 dairy farms could be divided into 21 organic and 23 conventional farms. This nearly equal distribution allowed for a sound comparison of the two different farm management systems and can be considered a strength of the dataset.

4.2. Data collection and -quality

As mentioned by Weidema and Meeusen (2000), data collection is the most time-consuming and costly part of a LCA. Regarding agricultural LCAs, the foreground data (i.e., data related to the on-farm stage of LCA) can be collected or derived from (i) primary data from real farms, (ii) average data from national inventories and repositories, or referring to modeled farms, and (iii) literature data (Baldini et al., 2017). In contrast to studies that modeled agricultural production systems based on average data from different national inventories and repositories (e.g., Hörtenhuber et al. (2010)) or based on a synthesis of literature data from previous studies (e.g., Casey and Holden (2005) and O'Brien et al. (2012)), the foreground data analyzed in this thesis was mainly collected as primary data on real farms. The applied data collection comprises a multi-step process proposed and introduced by Herndl et al. (2015):

In the first step, participating farmers are invited to a kick-off workshop, usually scheduled in the first months of the survey year (i.e., before the growing season). At this workshop, the staff of AREC Raumberg-Gumpenstein explains the goals of the data sampling and provides an overview of the requested data. At the end of the meeting, the farmers know which data they have to provide and are equipped with a manual survey where most parts of the requested data can be entered by hand.

The next step comprises the actual data collection through the farmers. Throughout the entire growing season, the farmers complete the manual survey and collect chronological data regarding the purchase of inputs (e.g., energy carriers, concentrates, fertilizers, plant protection products, or animals), the various field operations on their arable- and grassland (i.e., tillage, sowing, plant protection, fertilization, maintenance, harvest, grazing of livestock, and transport), and the sale of outputs (e.g., milk, beef, or crop products).

After this time-consuming contribution of the farmers, another workshop is arranged in the last months of the survey year (i.e., after the growing season has ended and all field operations are concluded). This workshop aims to enter the collected data in the online data collection tool FarmLife (https://www.farmlife.at/), facilitating the subsequent LCA calculation steps. Under the supervision of the staff of AREC Raumberg-Gumpenstein, the farmers transfer their manually collected data into a user-friendly structure of prefabricated input masks. Through the individual farm identification number and provided the written consent of the farmer, the FarmLife tool is also able to derive additional necessary data from the national Integrated Administration and Control System (IACS) (i.e., the different field sections with their exact area and the grown crops or applied grassland management systems, respectively and the mean annual amount of livestock divided into different categories). The data demand is completed with information on the existing buildings and used machinery, which are also entered into prepared input masks.

Finally, to ensure appropriate data quality, AREC Raumberg-Gumpenstein performs plausibility checks on the entered data and, according to the iterative nature of LCA (Klöpffer and Grahl, 2009), may place further queries on missing or insufficient data to be addressed by the farmers.

Necessary inventory data that cannot be obtained as primary data within the described data collection process (i.e., upstream processes like production, processing, and transport of purchased inputs) was derived from the LCA databases ecoinvent (Weidema et al., 2013) and SALCA (Gaillard and Nemecek, 2009). However, although these databases are commonly used and enjoy a good reputation within the LCA community, a general concern on data quality may nevertheless be justified as most of the derived inventory data was computed based on primary data either from specific countries (in the case of SALCA) or the whole world (in the case of ecoinvent). Although Herndl et al. (2015) already adapted several inventory data to Austrian circumstances, further computing inventory data based on primary data from Austrian farms remains imperative to overcome the data quality issue of upstream processes (Finnveden, 2000).

4.3. Limitations of life cycle assessment

Besides the challenges of farm selection and data collection, which cause a high drop-out rate of farms regardless of the applied farm selection procedure, LCA comes with further limitations worth mentioning here. A highly recognized limitation in LCA literature is the robustness of results due to data uncertainties and value judgments (Huijbregts, 1998). As LCA depends on many input parameters, and many of those parameters are subject to a variable degree of uncertainty (Groen et al., 2014), ISO 14040 and ISO 14044 stipulate multiple procedures to overcome these issues (Curran, 2014).

A commonly suggested procedure to improve the robustness and transparency of LCA results is uncertainty analysis (Guo and Murphy, 2012). The uncertainty analysis aims to determine the variability of the data and the impact on the LCA results, which can be attributed to normal fluctuation or errors in the data (Curran, 2014). According to Baldini et al. (2017), Monte Carlo simulation (MCS) is the preferred approach to utilize uncertainty analysis of LCA results. MCS uses the probability distribution of inventory data and generates thousands of random samples (Firestone et al., 1997). In that way, LCA results (i.e., environmental impacts) can be expressed as probability ranges instead of numerical values, thus highlighting the magnitude of uncertainty (Sonnemann et al., 2003). An according MCS was applied to the LCA results of Paper II.

A further procedure that was not applied in the presented journal contributions is sensitivity analysis. Sensitivity analysis is used to examine how changes in the basic conditions (i.e., assumptions, methods, or data) affect the results of a LCA. The study results are compared with results obtained with modified assumptions, methods, or data (Frischknecht and Büsser Knöpfel, 2013) in order to identify input parameters that considerably influence the results (Baker and Lepech, 2009; Groen et al., 2014). Sensitivity analysis is critical in the case of uncertain data, strongly varying data, or different modeling approaches (Frischknecht and Büsser Knöpfel, 2013) and even mandatory if subjective assumptions are applied within the LCA study (Curran, 2014).

Despite the necessity of uncertainty and sensitivity analysis within the interpretation phase of LCA, they are only conducted in a minority of studies. For example, in their review article on the recent evolution of LCA applied to milk production, Baldini et al. (2017) found that only

9 of the 44 assessed studies (20 %) conducted either uncertainty or sensitivity analysis and thus highlighted the need for standardization and systematic inclusion of these procedures in future LCA studies.

In contrast to the described limitations, it must be noted that LCA also has many strengths establishing it as a powerful tool in decision making related to sustainability's environmental pillar (Curran, 2013). Besides being a comprehensive assessment tool that utilizes life cycle thinking as the highest maxim and highlights potential environmental tradeoffs, Curran (2014) also highlighted the regulation of LCA by ISO 14040 and 14044 standards (ISO, 2006a, b), which provides a clear structure to an environmental investigation. Further, by incorporating life cycle thinking, LCA can also challenge conventional assumptions on what is environmentally preferable, therefore advancing the knowledge base and fostering communication and discourse (Curran, 2014; Ngo, 2012).

4.4. Limitations of data envelopment analysis

As a non-parametric data analysis method that measures the relative efficiency of similar decision-making units (DMUs) with multiple performance measures that are classified as inputs and outputs (Charles et al., 2019; Charnes et al., 1978), data envelopment analysis (DEA) served as the integrating methodological building block in this thesis. It allows for the integration of all considered inputs (i.e., environmental impacts) and outputs (i.e., functions of agriculture) as depicted in Table 2 into one single score, reaching from zero (worst) to one (best) (Tone, 2001). In that way, DEA enabled multiple functions of agriculture to be considered in the eco-efficiency assessments of the presented journal contributions.

It should be noted that the technical computation of the DEA requires a distinction of the considered performance measures into inputs and outputs. When looking at a farming system, it seems contradictory to declare environmental impacts as inputs as they are clearly generated within the agricultural production process (Soteriades et al., 2016) and can therefore also be considered as (undesirable) outputs of the system. However, in order to comply with the technical requirements of DEA, the environmental impacts are presented as inputs in Table 2.

The general assumption of similar DMUs (i.e., farms) could not be met in Paper I due to the highly heterogeneous sample of farms from four different farm types. Therefore, it was necessary to include the meta-frontier specification in the computation of the DEA (Rao et al., 2003) to overcome this limitation. This specification allows for the consideration of different production technologies (Long et al., 2018) and makes them comparable (Li and Lin, 2015). The inclusion of the meta-frontier specification states the only methodological difference between the two papers, as only specialized dairy farms were considered in Paper II, which meet the requirement of similar DMUs.

Table 2. Considered inputs and outputs for the eco-efficiency assessment. Adapted from Grassauer et al. (2021).

Considered inputs and outputs	**Description**	**Unit of measurement**
Inputs (i.e., environmental impacts)	Cumulative exergy demand	MJ
	Global warming potential	kg CO_2-eq
	Normalized eutrophication potential	person $year^{-1}$
	Aquatic ecotoxicity potential	kg 1,4 DB-eq
Outputs (i.e., functions of agriculture)	Generation of income	€
	Food production	MJ heE[a] kg heCP[b]
	Use of ecologically valuable land	ha HNVf[c]

Note.
[a] heE = human-edible energy.
[b] heCP = human-edible crude protein.
[c] HNVf = High Nature Value farmland.

Another limitation of DEA is its discriminatory power. In particular, the discrimination between the performances of individual DMUs is constrained when there is a relatively large number of performance measures (i.e., inputs and outputs) compared to the number of DMUs (Charles et al., 2019). Therefore, it is generally accepted that a higher number of DMUs is always beneficial for DEA's discriminatory power. Conversely, an empirical rule provides guidance for the minimum number of DMUs related to the considered performance measures. It was introduced by Cooper et al. (2006) and is formulated as follows:

$$n \geq \max\{m \times s, 3(m + s)\}$$

Where n= number of DMUs, m= number of inputs, and s= number of outputs.

Looking at Table 2, the eco-efficiency assessment considers eight performance measures (i.e., four inputs and four outputs). Therefore, the minimum number of DMUs is 24. As the sample sizes meet this requirement in both papers (47 farms in Paper I and 44 farms in Paper II), the discriminatory power of DEA is considered sufficient.

5. Conclusions

Against the backdrop of a growing world population and a growing demand for food, agricultural production has always intensified over the last decades. However, with the emergence of sustainability, which is already influencing all areas of life, certain social groups were sensitized to the consequences of the anthropogenic perturbation of the Earth system. This also led to a rethinking of the perpetual intensification of agricultural production and aspirations towards more sustainable agricultural practices that produce sufficient amounts of food without increasing the environmental pressure on the Earth system. This paradoxical challenge is addressed by the concept of eco-efficiency, which is defined as the ratio between the output, i.e., the value of a product or service and its environmental impacts. According to this definition, eco-efficiency forms the overlapping area of sustainability's environmental and economic pillars. Besides aiming to produce sufficient food to nourish the ever-growing world population, agriculture also fulfills several other functions for society, such as generating an income for farmers, preserving attractive rural areas, and specific agricultural systems may also contribute to maintaining or even enhancing biodiversity. These multiple functions of agriculture were considered in a novel concept of eco-efficiency assessment of agricultural farms.

The study results revealed a high diversity in eco-efficiency among the respective considered farms as the performance depends on the farm-individual fulfillment of the different considered functions of agriculture. Regarding the different production systems, organic dairy farms were found to score a significantly higher mean eco-efficiency than their conventionally managed counterparts. Unfortunately, such a comparison was not possible for other farm types due to the uneven distribution of the production systems within the farm sample of Paper I. A comparison of different farm types through the meta-frontier specification in DEA showed a slightly higher eco-efficiency of the crop- and wine-producing farms compared to livestock keeping farms (i.e., dairy and beef-producing farms), which can be related to the use of human-edible energy and protein as concentrate on livestock keeping farms. Regarding the improvement of eco-efficiency, specific management options to promote the eco-efficiency of a farm could be pointed out. The identified management options showed a high diversity since eco-efficiency can be improved by either decreasing inputs (i.e., environmental impacts) or increasing outputs (i.e., the performance measures of the considered functions of agriculture). Therefore, the path of improving the eco-efficiency of multifunctional agricultural farms is always farm-individual, may be paved with conflicting goals, and needs to consider the farms' diversity. Purchased inputs were found to be a critical factor in diminishing the eco-efficiency of farms, thus stressing the efficient utilization of on-farm resources and highlighting site-adapted agriculture to foster the eco-efficiency of farms. Regarding dairy farms, especially the purchased concentrate was identified as a central source of environmental impacts that also influences all outputs. Therefore it can be concluded that eco-efficient livestock farming states a major challenge in the future, and especially the considerable impact of the purchased concentrate on livestock keeping farms is tempting one to amend Ludwig Feuerbach's well-known quote from "you are what you eat" into "you are what you feed."

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7. Additional journal contribution

Environmental Assessment of Austrian Organic Dairy Farms With Closed Regional Production Cycles in a Less Favorable Production Area

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Environmental Assessment of Austrian Organic Dairy Farms With Closed Regional Production Cycles in a Less Favorable Production Area

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Extensive dairy production in less favorable production areas has a long tradition in Austria. Nevertheless, dairy production also contributes considerable environmental impacts (EIs), e.g., greenhouse gas emissions, nutrient losses, and land use. Therefore, 20 organic dairy farms located in the Lungau region in Austria were assessed concerning their EIs *via* life cycle assessment (LCA). Cumulative exergy demand (CExD), normalized eutrophication potential (EP), aquatic ecotoxicity potential (AE), and global warming potential (GWP) were considered as impact categories to describe the farms' EIs. The farms were part of a pilot project aiming to produce high-quality dairy products and keep production cycles closed within the project region. Consequently, the purchase of key off-farm resources was only possible within the project region. We adapted existing life cycle inventories to account for those regional resource purchases. Subsequently, the EIs of the 20 farms were related to the functional units (FUs) of 1 kg energy-corrected milk (ECM) and 1 ha agricultural area for milk production and compared to a representative model dairy farm (MDF) that was created based on statistical data and average production values of organic Austrian dairy farms. Compared to the MDF, results show an ∼58% lower EP per ha and 44% per kg ECM of the Lungau farms. Further, the CExD per ha was about 24% lower due to a lower use of resources caused by the lower production intensity of the Lungau farms. Regarding GWP, Lungau farms are favorable considering 1 ha as the FU, whereas the MDF seems advantageous if 1 kg ECM is used as the FU. However, caused by a high variation of purchased roughage and the lower production intensity, the Lungau farms cause higher AE, regardless of the FU. Overall, we identified three principal production parameters determining the environmental performance of milk production in a closed production cycle in a less favorable area, namely, (1) the stocking rate, (2) the fed concentrate, and (3) the purchased roughage. Using those inputs at moderate intensity, the extensively managed Lungau farms can competitively contribute to producing food, thus highlighting the importance of site-adapted agriculture.

Keywords: dairy production, extensive agriculture, regionality, site-adapted agriculture, life cycle assessment

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INTRODUCTION

In recent years, modern agriculture has been facing a seemingly paradoxical challenge. On the one hand, the world population is expected to grow to 9.7 billion people by 2050 (UN, 2017), implying an increased food demand of about 70% compared to 2005–2007 (FAO, 2012). However, on the other hand, agriculture causes substantial environmental impacts (EIs) and contributes significantly to climate change (FAO, 2018).

Agriculture and especially livestock production currently account for about 24 and 14.5% of global anthropogenic greenhouse gas (GHG) emissions, respectively (FAO, 2018). Foley et al. (2011) identified both agricultural expansion [mainly in the tropics where it replaces forests (Gibbs et al., 2010)] and intensification as major contributors to climate change. Intensification has increased dramatically over the last decades and also caused increased energy use, degradation of aquatic ecosystems, and reduced biodiversity (Matson et al., 1997; Diaz and Rosenberg, 2008; Canfield et al., 2010; Foley et al., 2011).

An approach to decrease GHG emissions of agriculture is through the conversion from conventional to organic production (Lamine and Bellon, 2009). However, studies assessing milk production based on life cycle assessment (LCA) have shown that the reduced input use per kg of milk under organic production is offset by lower milk yields and lower feed conversion ratios, resulting in higher CH_4 emissions per kg of milk than that under conventional systems (Tal, 2018; Smith et al., 2019). Conversely, organic systems perform better per unit of agricultural area (Pirlo and Lolli, 2019).

Related to milk production, extensively managed production systems are therefore emphasized to reduce EIs (Haas et al., 2001; Basset-Mens et al., 2009). Such production systems are based on grazing systems, especially on pastures unsuitable for other types of food production, such as arable farming (Foley et al., 2011), and characterized by a decreased use of purchased inputs (e.g., fertilizers, concentrate feed, or energy) and lower stocking rates (Haas et al., 2001; Basset-Mens et al., 2009; Horn et al., 2014).

The resource use and the EIs throughout the life cycles of products or services are generally assessed through LCA (Klöpffer and Grahl, 2009). Thus, LCA helps identify environmental hotspots and allows to derive options to improve the environmental performance of a production system (ISO, 2006a,b). Accordingly, numerous studies have assessed milk production systems through LCA. For a detailed review of recent LCA applications in the dairy sector, see Baldini et al. (2017).

This study aimed to assess the resource use and EIs of milk production of 20 organic dairy farms in a less favorable production area in Austria, which participated in a pilot project that aimed to produce high-quality dairy products and was dedicated to keeping nutrient cycles as closed as possible. Thus, the handling of key inputs is restricted because they have to be purchased from the project region. Therefore, the further goal of the study was to compare the resource use and EIs of the 20 farms to a model dairy farm (MDF) representative for organic milk production in Austria to assess the environmental performance of milk production in a less favorable production area in Austria and its principal determining production parameters.

MATERIALS AND METHODS

Farm Data and Study Region

A set of 20 organically managed farms was evaluated in 2018 for this study. The farms were part of the pilot project "Reine Lungau," which aimed to produce high-quality dairy products and was dedicated to keeping nutrient cycles as closed as possible within the project region. For this purpose, all farm inputs that can be produced in the project region must also be purchased from this area, e.g., feedstuffs, animals, and organic fertilizers. According to Austria's farm classification system (Binder et al., 2015), the farms are denoted as dairy farms. A description of key production parameters of the 20 Lungau farms is given in **Table 1**.

The farms are located in the Lungau region, which complies with the district of Tamsweg and is part of the federal province of Salzburg (**Figure 1**). According to Huber and Arnberger (2021), the region is characterized by forests, alpine pastures, extensive grassland, lakes, and wetlands, and the agricultural sector is dominated by a high proportion of small-scale organic farms. In addition, **Figure 1** indicates that some parts of the study region are also related to arable land, which is mainly used to grow cereals like barley, triticale, or rye for concentrate feed or to cultivate potatoes as cash crop. Generally, unfavorable natural landscape conditions occur in the Lungau region, with low mean annual values of precipitation (774 mm) and temperature (5.2°C) (ZAMG, 2021) and a short vegetation period (180°C−220 days depending on altitude) (Schaumberger and Formayer, 2008).

Model Dairy Farm

In order to have a production system to serve as a representative reference for Austrian organic dairy farms, we compiled output and input data for an MDF. We derived the data from (i) national databases and complemented additional data based on (ii) specific models and (iii) expert judgments. Regarding national databases (i), we selected the total number of organic dairy farms in 2018 and calculated average values to be considered as inventory. Animal categories and numbers, the farm area, the grown crops, and types of grassland uses were derived from the Austrian Integrated Administration and Control System (IACS) (EC, 2021). Output parameters like the yield of milk, crops, and grassland stem from the annual report from the Austrian federal ministry of agriculture, regions, and tourism on the situation of the Austrian agriculture and forestry (BMNT, 2019). (ii) The feed ration was calculated in two steps: first, the amounts of on-farm roughage and concentrate were calculated based on the given grown crops and grassland types. In step two, we adapted the feed ration with purchased (off-farm) concentrate according to the given milk yield. (iii) Expert judgments were used to define the share of pasture intake in the feed ration and estimate the used infrastructure (buildings, equipment, and machinery). Key production parameters of the MDF are also given in **Table 1**.

LCA

Definition of Goal and Scope

This study aims to assess the resource use and EIs related to milk production of 20 extensively managed organic dairy farms from

TABLE 1 | Description of key production parameters of the 20 Lungau farms and the model dairy farm (MDF).

Parameter	Unit	Lungau farms Min	Median ± SD	Max	MDF
Farm area	ha	2.8	20.5 ± 9.6	38.1	22.8
Farm area for milk production	ha MP[a]	2.1	15.2 ± 7.1	28.1	18.2
Share of arable land	%	0	13 ± 25	81	40
Stocking rate	dairy cows ha MP^{-1}	0.5	0.88 ± 0.32	1.90	1.04
Milk production	t ECM[b]	16.3	69.8 ± 41.3	170.5	118.3
	kg ECM dairy cow^{-1}	4,077	5,433 ± 914	6,847	6,228
	kg ECM ha MP^{-1}	2,069	5,240 ± 1,889	9,872	6,488
Fed concentrate	kg DM[c]	0	5,524 ± 4,489	14,974	12,105
Purchased roughage	kg DM	0	0 ± 6,559	22,289	0
Purchased animals	kg LW[d]	0	0 ± 472	1,340	1,260
Fuel consumption	kg ha^{-1}	37	79 ± 27	145	105
Electricity consumption	MJ ha^{-1}	32	2,087 ± 1,867	7,958	2,338
Purchased N fertilizer	kg N	0	0	0	124.3
N fertilization	kg ha^{-1}	46	82 ± 23	137	94

[a]ha MP, ha farm area allocated to milk production.
[b]ECM, energy-corrected milk.
[c]DM, dry matter.
[d]LW, live weight.

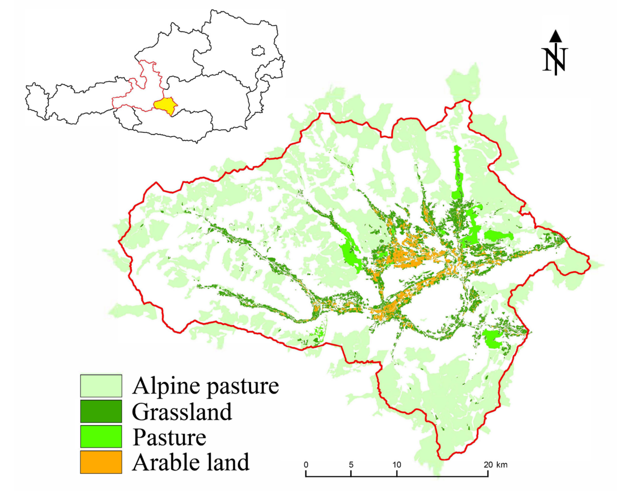

FIGURE 1 | Location of the study region (Lungau) in Austria and agricultural land use based on CORINE land cover data (CLC, 2020).

the Lungau region in Austria. Further, the resource use and EIs of the Lungau farms are compared to the resource use and EIs of a MDF, which is modeled as described in Section MDF and depicts the production system of the average Austrian organic dairy farm.

According to dairy farms being multifunctional systems that, besides producing food, also generate income for farmers and provide environmental services (O'Brien et al., 2012; Grassauer et al., 2021), we consider two functional units in this study: (1) 1 kg of energy-corrected milk (ECM) and (2) 1 ha of agricultural land allocated to milk production (ha MP).

The scope of the study comprises on-farm activities as well as upstream processes related to purchased inputs (off-farm). The considered system boundaries of the Lungau farms are set at the farm gate (i.e., from cradle to farm gate) and are depicted in **Figure 2**. We considered the whole farm area assigned to milk production as the physical limit and one calendar year as the temporal limit of the system under study. According to the regulations of the pilot project, feedstuffs (except mineral feed, cattle salt, and feeding lime), animals, and organic fertilizers must only be sourced from the study region. Other inputs (energy carriers, buildings and equipment, machinery, and seed) can be purchased according to the applicable Austrian organic production regulations (BIO-AUSTRIA, 2021). Due to limited data availability, we could not take the production and application of cleaning and disinfection agents and veterinary drugs into account.

The applied allocation procedure to assign the EIs and resource use to the product group milk production is based on physical and monetary criteria and follows a hierarchical process as described in Pedolin et al. (2021):

I. If possible, the whole impact was assigned to the product group milk production *via* causal relation (i.e., indirect emissions from the milking parlor are fully assigned to milk production). In these cases, no allocation is necessary.
II. If an impact could not be assigned causally, the allocation was based on physical criteria (i.e., livestock units for animal products and farm area for cop products).
III. If physical criteria were not sensible (e.g., when allocating between multiple diverse product groups), monetary criteria were used. If the allocation was necessary, the following distinction was made.
IV. Direct field emissions: one allocation key per field (i.e., one allocation factor for each potential product group).

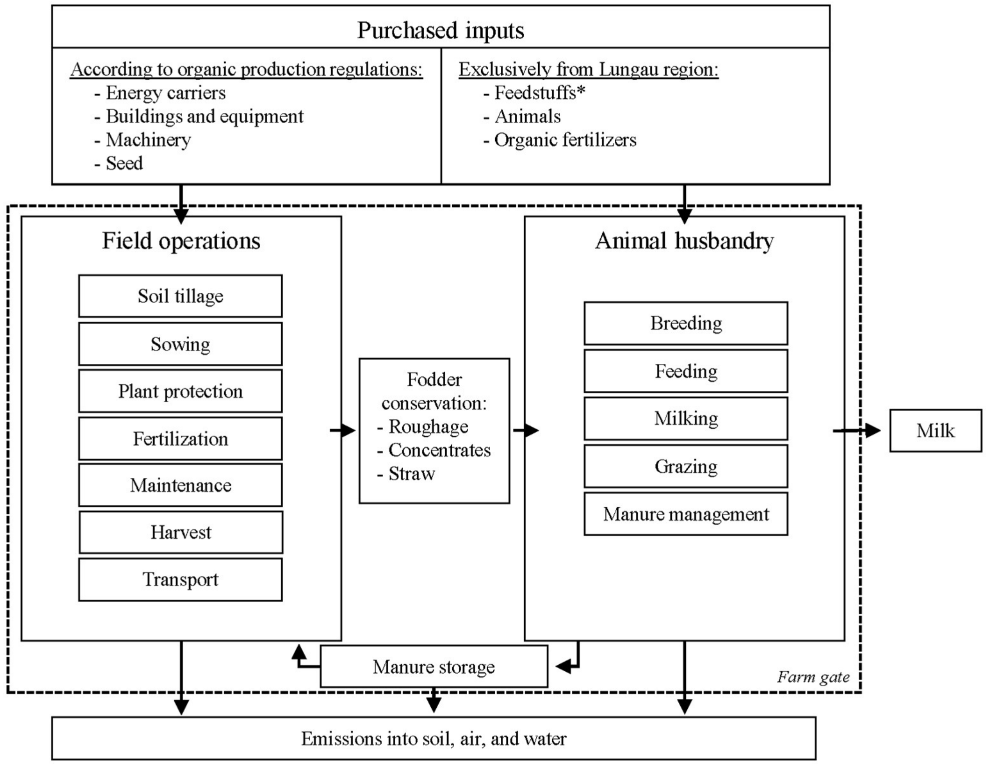

FIGURE 2 | System description of the dairy farms from the Lungau region. *Except for mineral feed, cattle salt, and feeding lime.

V. Indirect emissions from energy carriers, buildings and equipment, machinery, seed, feedstuffs, animals, organic fertilizers, and direct animal emissions: one allocation factor for each potential product group.

Life Cycle Inventory

The life cycle inventory (LCI) stage of an LCA comprises the compilation and quantification of the inputs and outputs of a given product throughout its life cycle (ISO, 2006a). Direct emissions from on-farm activities were assessed through several models that were adapted to Austrian conditions by Herndl et al. (2015): (i) Emissions of phosphorous were estimated based on the work from Prasuhn (2006) and cover PO_4^{3-} deposits into surface waters through soil erosion, drainage, and surface run-off, and into groundwater by leaching. (ii) The leaching of nitrate was assessed based on Richner et al. (2014), which consider the monthly mineralization of nitrogen depending on the soil type, tillage activities and fertilization rates, and the nitrogen uptake from different crops and grassland types. (iii) The accumulation of heavy metals in soil and water was computed based on the methodology from Freiermuth (2006). The model was refined by adding values for heavy metal contents in Austrian soils (Umweltbundesamt, 2004) and Austrian heavy metal deposition rates (Zechmeister et al., 2009). (iv) Emissions related to animal husbandry cover the enteric fermentation of ruminants (CH_4) and emissions from the stable (NH_3), exercise area (NH_3, CH_4), and pasture (NH_3, CH_4, N_2O, NO_x, NO_3^-). (v) Finally, emissions from manure management (NH_3, N_2O, NO_x, CH_4) and manure application (NH_3, N_2O, NO_x, P, NO_3^-) were considered. Both (iv) and (v) were assessed based on Menzi et al. (1997) (NH_3), Nemecek and Kägi (2007) (NO_x), and IPCC Tier 2 models (Dong et al., 2006) (N_2O, CH_4). The assessed direct emissions from on-farm activities (excluding the accumulation of heavy metals in soil and water) of the 20 Lungau farms and the MDF are presented in **Supplementary Table 1**.

Indirect, off-farm emissions from upstream processes related to purchased inputs were estimated through eco-inventories from the SALCA database (Gaillard and Nemecek, 2009) and ecoinvent database version 3.5 (Weidema et al., 2013). However, as shown in **Figure 2**, some purchased inputs (feedstuffs, animals, and organic fertilizer) must stem from the Lungau region according to the regulations of the pilot project. Thus, we adapted existing Swiss eco-inventories for organic agriculture. More specifically, we adapted eco-inventories for the purchase of barley grain, wheat grain, rye grain, grass silage, hay, and calves. The adaptations included a reduction of the transportation effort to account for transportation just inside the study region and reduction in the amount of fertilizer, agricultural machinery, and irrigation based on primary data to reflect the extensive management. A comparison of the EIs of the existing and adapted eco-inventories is given in **Supplementary Table 2**.

Life Cycle Impact Assessment

Building on the LCI, the life cycle impact assessment (LCIA) transforms the direct and indirect emissions and resource use into several EIs (EC, 2010). According to Nemecek et al. (2011), there are three dimensions of EIs which represent different management options: (i) resource management, (ii) nutrient management, and (iii) pollutant management. Based on these dimensions and following the rationale of Grassauer et al. (2021), we selected the following EIs to be considered within this study: (i) cumulative exergy demand (CExD) (Bösch et al., 2007; Alvarenga et al., 2013), (ii) global warming potential 100 years (GWP) (IPCC, 2013), (iii) normalized eutrophication potential (EP) (Hauschild and Potting, 2005), and (iv) aquatic ecotoxicity potential (AE) (Guinée et al., 2001; Kägi et al., 2008; Hayer et al., 2010).

CExD is a comprehensive energy-based indicator for resource demand that aggregates different forms of energy resources into a single indicator (Bösch et al., 2007). GWP is based on the cumulative radiative forcing of various substances over a time horizon of 100 years and gives values relative to those for the reference gas CO_2 (IPCC, 2013). EP comprises eutrophication indicators for aquatic and terrestrial N eutrophication and aquatic P eutrophication (Hauschild and Potting, 2005). Using average European emissions from 2004, these eutrophication indicators are normalized, aggregated, and measured in person year^{-1} (Laurent et al., 2011). Finally, AE assesses the effects of the accumulation of heavy metals in the soil and water.

Due to its integration of several LCIA methods and its specific reflection of the agricultural sector (Gaillard and Nemecek, 2009), SALCA 1.12 was selected as the impact assessment method in this study. The computation of the LCIA was done with SimaPro Developer software version 9.0.0.49 (Pré Consultants, 2019).

Interpretation

For interpretation, the LCA results were broken down into ten different sources: land use, fertilizers, and field emissions; animal husbandry; buildings and equipment; machinery; energy carriers; seed; purchased animals; purchased roughage; purchased concentrate; and other inputs. Further, the LCA results were related to the two functional units as described in Section Definition of Goal and Scope.

RESULTS

The absolute values of the four considered EIs (CExD, GWP, EP, and AE) comprising direct and indirect emissions of the 20 Lungau farms and the MDF are given in **Supplementary Table 3**.

Figure 3 shows the contribution of the ten different sources to the four considered EIs (CExD, GWP, EP, and AE) of the Lungau farms compared to the MDF. The bar of the Lungau farms shows the mean EIs of the 20 farms under study.

Compared to the MDF (6,100 GJ), the Lungau farms have a 38% lower CExD (3,800 GJ). The main contributor to CExD is land use, fertilizers, and field emissions, with a share of 72% in both bars. The purchased animals cause another 12% of CExD on the MDF but contribute only 3% on the Lungau farms.

Regarding GWP, the difference between Lungau farms (105,134 kg CO_2-eq) and the MDF (153,242 kg CO_2-eq) is 31%. Emissions from animal husbandry are the highest contributing source to GWP, with shares of 74% for Lungau farms and 68% on the MDF. Again, emissions from purchased animals contribute another 9% of GWP on the MDF but only 2% on the Lungau farms. Another considerable source of GWP is energy carriers (comprising fuel and electricity consumption), adding 7 and 8% of GWP to the Lungau farms and the MDF, respectively.

The highest difference between Lungau farms and the MDF was found for EP. Whereas, the Lungau farms cause a total of 87 person year^{-1}, the MDF causes 267 person year^{-1}, resulting in a difference of 67%. This difference is mainly caused by lower contributions of critical sources of EP. For example, land use, fertilizers, and field emissions contribute 55% to EP on the MDF and 44% within the Lungau farms. Similarly, eutrophication through animal husbandry causes 29% of EP on the MDF and 26% on the Lungau farms.

Conversely, the lowest difference was found for AE at 19%, with Lungau farms emitting a mean of 216 kg 1,4 DB-eq and the MDF causing 266 kg 1,4 DB-eq. The main sources of AE were buildings and equipment with 24% within Lungau farms and 31% on the MDF, energy carriers with 18% on the Lungau farms, and 23% on the MDF.

In **Figure 4**, the EIs were related to the two considered functional units (i.e., kg ECM on the y-axis and ha MP on the x-axis) and presented as double boxplots with the colored dots showing the median values of the Lungau farms (blue) and the values of the MDF (orange), and the gray area indicating the upper and lower quartiles of the Lungau farms.

Per kg ECM, the Lungau farm's CExD ranges from 31 to 100 MJ with a median of 51 MJ, which is slightly lower than the MDF with 52 MJ. However, when expressed per ha MP, the difference in CExD is higher (24%), with Lungau farms having a demand of 254,426 MJ (with a range of 187,561 to 394,123 MJ) and the MDF demanding 334,663 MJ.

For GWP, we found that the favorable farming system depends on the considered functional unit. Expressed per kg ECM, the MDF seems favorable with 1.3 kg CO_2-eq compared to the Lungau farms with a median of 1.6 and a range of 0.8–2.5 kg CO_2-eq. Conversely, when considering ha MP as the functional unit, the Lungau farms emitted 7,609 kg CO_2-eq (with a range of 5,035–11,533 CO_2-eq), around 9% less than the MDF (8,401 kg CO_2-eq).

Considering EP and regardless of the functional unit, the Lungau farms cause a considerably lower EP. The difference is roughly 44% per kg ECM, with the Lungau farms emitting a median of 0.0013 person year^{-1} (with a range of 0.0006–0.0026 person year^{-1}), whereas the MDF emits 0.0023 person year^{-1}. Per ha MP, the Lungau farms emit 2.9–11.2 person year^{-1} with a median of 6.3 person year^{-1}, which results in a difference of 58% compared to the MDF (15 person year^{-1}).

The favorable farming system regarding AE is the MDF, but the differences show a high margin depending on the considered FU. Per kg ECM, the MDF emits 0.0022 kg 1,4 DB-eq, which is 34% lower than the median value of the Lungau farms (0.0033 kg 1,4 DB-eq). Considering 1 ha MP as the functional unit, the AE (kg 1,4 DB-eq) amounts to 15 for the MDF and a median of 15.6 for the Lungau farms, which equals a difference of only 4%.

A summary of the EIs is given in **Figure 5**, which presents normalized environmental profiles of the Lungau farms (blue)

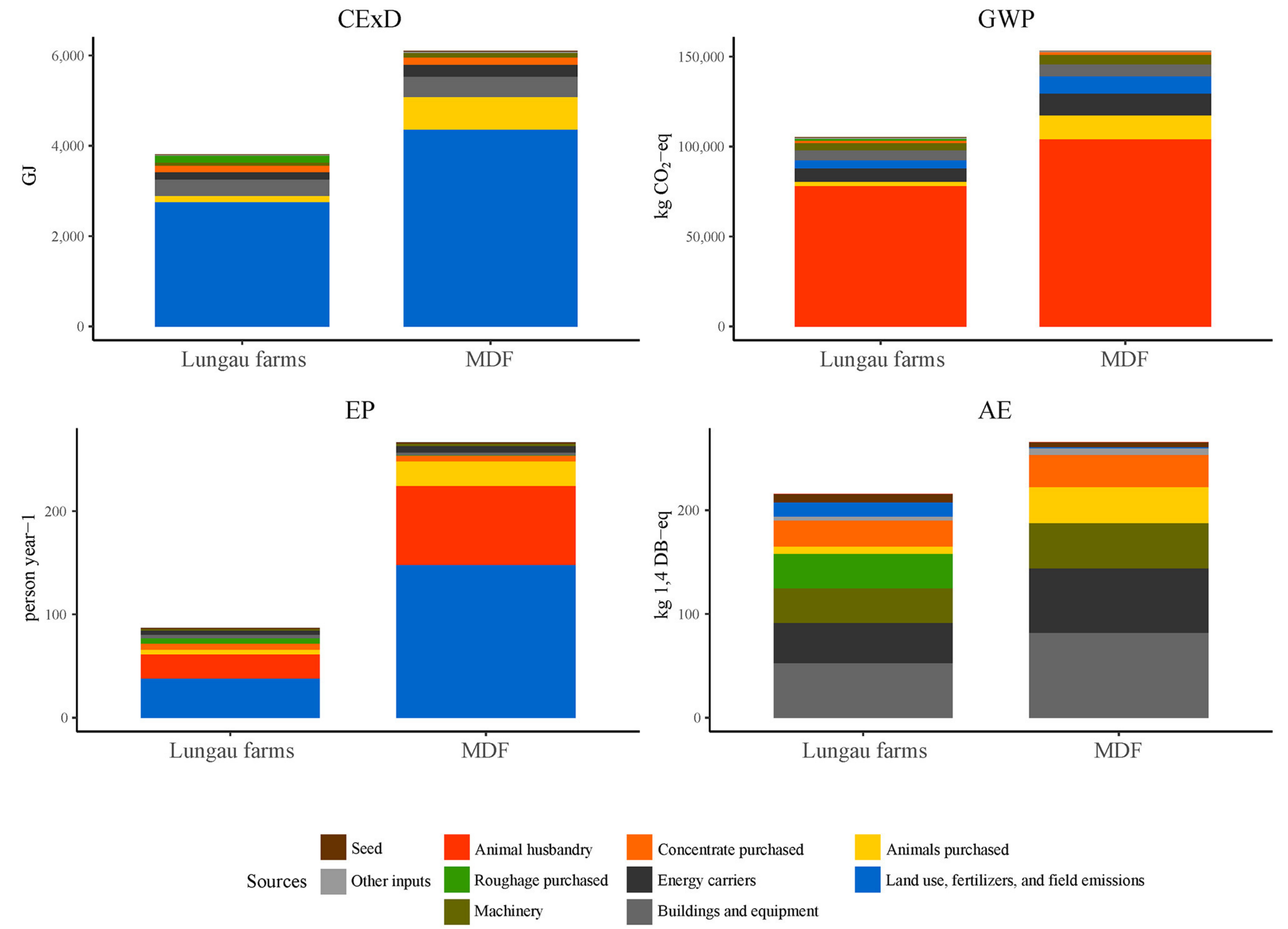

FIGURE 3 | Mean absolute EIs [cumulative exergy demand (CExD), global warming potential 100 years (GWP), normalized eutrophication potential (EP), and aquatic ecotoxicity potential (AE)] of the 20 Lungau farms compared to the model dairy farm (MDF), showing the contribution of the ten different sources.

and the MDF (orange) per (a) kg ECM and (b) ha MP with the respective normalized values. We present the median values for the Lungau farms, and the EIs were normalized to the maximum value to indicate EIs, where further action of the Lungau farms might be needed.

Per kg ECM, the Lungau farms are favorable regarding CExD and EP, whereas the MDF is beneficial concerning GWP and AE. Conversely, considering the functional unit of 1 ha MP, the Lungau farms perform better regarding three out of four EIs (i.e., CExD, GWP, and EP).

DISCUSSION

In **Figure 3**, we compared the mean value of the absolute EIs of the Lungau farms with the MDF broken down into ten different sources and found the values of the Lungau farms to be lower for each of the considered EIs. To set the EIs of the MDF into perspective, we compared them to 12 Austrian organic dairy farms from the study of Grassauer et al. (2021), who assessed the EIs of organic dairy farms distributed to all of Austria under similar system boundaries (**Table 2**). The comparison revealed that the MDF is below the mean but within the range of the EIs.

Looking at the CExD, the most apparent difference between the Lungau farms and the MDF is the source land use, fertilizers, and field emissions, which usually account for a high share of CExD in agricultural production systems (Dewulf et al., 2005; Alvarenga et al., 2013). The difference results from the median Lungau farm cultivating less farm area than the MDF (20.5 and 22.8 ha, respectively; **Table 1**), which indicates the small-structured agriculture common in the inner-alpine region of Austria (BMNT, 2019).

Regarding GWP, the primary source is animal husbandry which accounts for emissions from manure management (N_2O, CH_4) and enteric fermentation in ruminants (CH_4), with the majority originating from the latter (Ogino et al., 2007; Dick et al., 2015; Doltra et al., 2018; Gislon et al., 2020). Therefore, the lower GWP from animal husbandry of the Lungau farms is caused by the lower stocking rates (0.88 and 1.04 dairy cows ha MP^{-1} for Lungau farms and MDF, respectively; **Table 1**), which lead to less enteric fermentation and lower emissions from manure management (Dong et al., 2006).

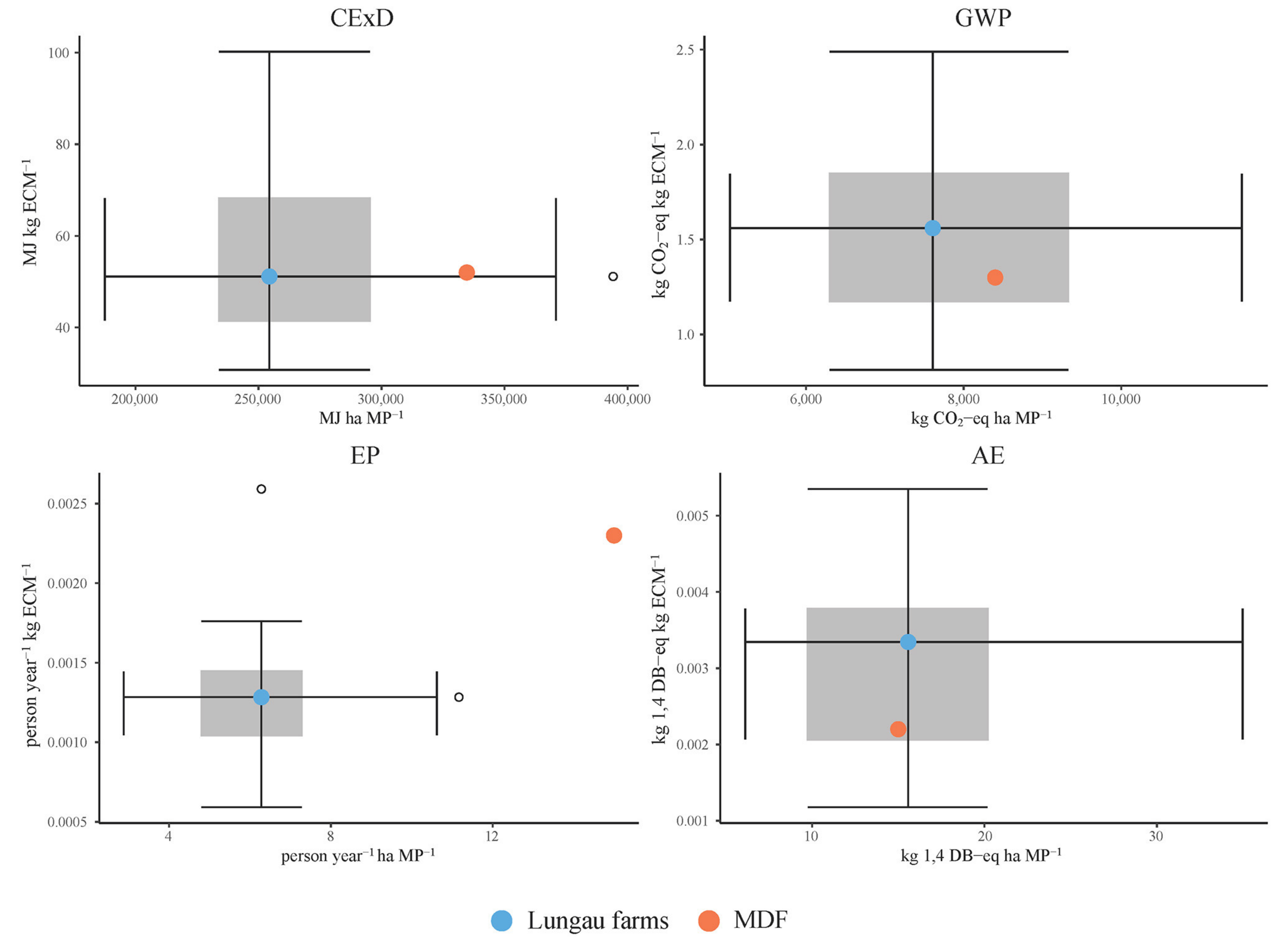

FIGURE 4 | Double boxplots of the EIs per kg ECM (y-axis) and ha MP (x-axis) with the colored dots indicating the median values of the Lungau farms (blue) and the values of the MDF (orange), and the gray area indicating the upper and lower quartiles of the Lungau farms.

The lower stocking rate of the Lungau farms also explains the difference in the source animal husbandry regarding EP by causing less aquatic and terrestrial N eutrophication through ammonia (NH_3) and nitrogen oxides (NO_x) (Menzi et al., 1997; Nemecek and Kägi, 2007), respectively. Further, the lower stocking rate of the Lungau farms leads to a lower N fertilization per farm area (**Table 1**), which, in turn, lowers the emissions from the source land use, fertilizers, and field emissions through reduced N_2O from direct field emissions (Dong et al., 2006) and lower NO_3^- from manure application (Richner et al., 2014). Another reason for the higher EP value from land use, fertilizers, and field emissions of the MDF is the purchase of 124.3 kg N fertilizer and the related indirect fertilizer production emissions (Herndl et al., 2015).

The AE comprises the accumulation of heavy metals in water and soil (Freiermuth, 2006). A relevant difference between the Lungau farms and the MDF is the share of emissions from the source energy carriers. Since the production of energy carriers, especially diesel, is considered a major contributor to heavy metal emissions (Berlin, 2002), the difference can be explained by the lower fuel consumption of the Lungau farms, which is caused by a lower share of arable land (**Table 1**). Another significant difference in AE arises from the import of heavy metals through the purchase of roughage which is practiced by some of the Lungau farms but does not happen at the MDF (**Table 1**).

Due to the crucial importance of the choice of the LCIA method (Hauschild et al., 2013), we conducted uncertainty analyses of the calculated EIs in order to improve the transparency and robustness of the obtained results (Guo and Murphy, 2012). Considering the statistical distribution of all upstream processes, we conducted a Monte Carlo simulation with 1,000 iterations for all 20 Lungau farms and the MDF. The results of the uncertainty analyses are shown in **Supplementary Figure 1** and indicate the highest uncertainties for the AE. This can be explained by a certain degree of uncertainty regarding heavy metal emissions (Pizzol et al., 2011a,b). Due to a high degree of confidence in LCA results related to resource-related EIs and climate change (Niero et al., 2014), the remaining impact categories (CExD, EP, and GWP) show considerably lower uncertainty.

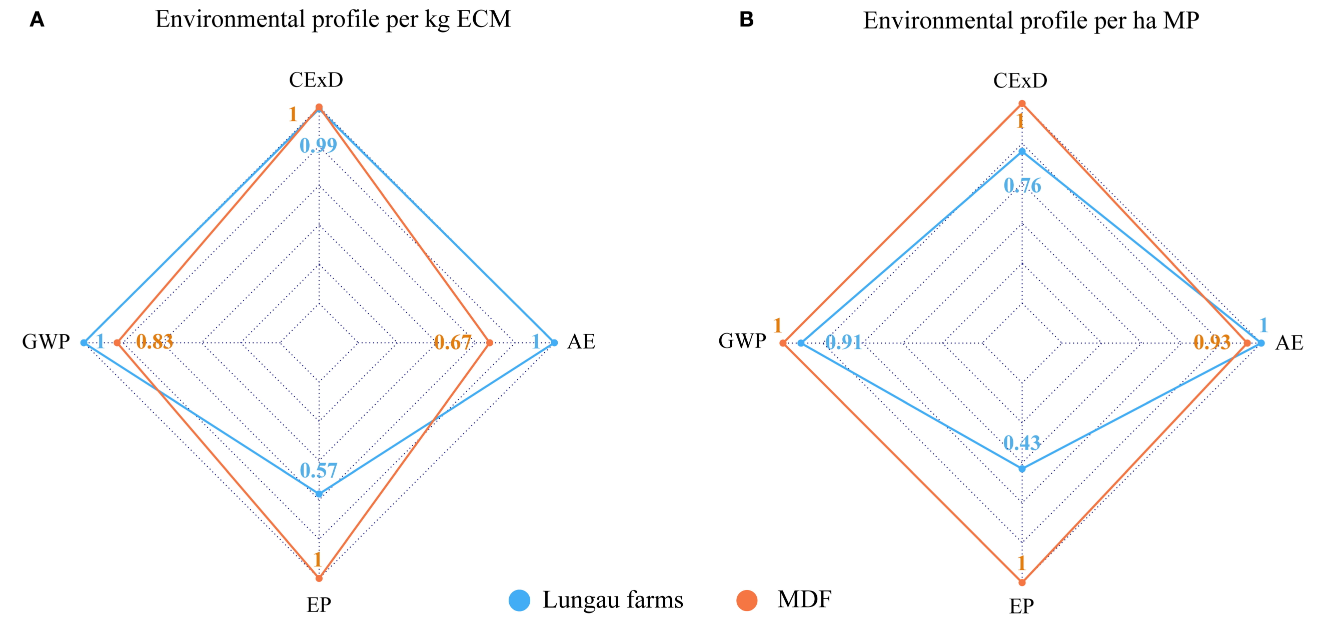

FIGURE 5 | Normalized environmental profiles of the Lungau farms (blue) and the MDF (orange) per **(A)** kg ECM and **(B)** ha MP.

TABLE 2 | Comparison of the absolute EIs of the MDF with EIs of 12 Austrian organic dairy farms from Grassauer et al. (2021).

Environmental impact	Unit	MDF	Grassauer et al. (2021)	
			Mean	Min–max
CExD	GJ	6,100	10,057	3,409–14,919
GWP	kg CO_2-eq	153,242	272,833	88,000–509,000
EP	person year^{-1}	267	330	81–536
AE	kg 1,4 DB-eq	266	581	163–1,144

CExD, cumulative exergy demand; GWP, global warming potential 100 years; EP, normalized eutrophication potential; AE, aquatic ecotoxicity potential.

As depicted in **Figure 4**, the CExD per kg ECM of the Lungau farms ranges from 31 to 100 MJ, with a median of 51 MJ. Since the CExD is highly related to land use (Dewulf et al., 2005; Alvarenga et al., 2013), this variation can be explained by the milk production yield per ha MP. We conducted a correlation analysis between the two parameters and found that the CExD per kg ECM correlates highly significant with the milk production yield per ha MP (Pearson's $r = -0.80$; $p = 2.76e{-}05$). Per 1 ha MP, the CExD of the Lungau farms amounts to a median of 254,426 MJ and the MDF reaches 334,663 MJ. Due to limited evidence in the literature, we compared these values with the work from Huysveld et al. (2015), who assessed the resource use of an intensively managed (10,542 kg fat- and protein-corrected milk (FPCM) per cow) Belgian model dairy farm and reported a CExD of 28.3 MJ kg FPCM^{-1}. According to our recalculation, this results in a CExD of 545,266 MJ ha MP^{-1}. This value is significantly higher than the values obtained in this study (254,426 and 334,663 MJ ha MP^{-1} for Lungau farms and MDF, respectively) and can be related to the management intensity as producing more milk in the same area leads to a higher exergy demand per area.

The median value of GWP per kg ECM of the Lungau farms (1.6 kg CO_2-eq) is 19 % higher compared to the MDF (1.3 kg CO_2-eq). These values are comparable with the results of Hersener et al. (2011), who analyzed the GWP of Swiss organic dairy farms over 3 years under similar system boundaries and reported a median of 1.4 kg CO_2-eq per kg milk (with a range of 1.2–2 kg CO_2-eq). However, the range of GWP per kg ECM in this study is significantly higher (0.8–2.5 kg CO_2-eq) and especially the lower bound seems hard to attain. Nonetheless, Cederberg and Flysjö (2004) reported a mean value of 0.94 kg CO_2-eq kg ECM^{-1} within six Swedish organic dairy farms. Moreover, it should be noted that these low values only occur on Lungau farms with a large share of intensive continuous grazing, which is known to reduce GWP on ruminant keeping farms (Alemu et al., 2017). The range of GWP per ha MP of the Lungau farms (5,035–11,533 kg CO_2-eq) corresponds to the findings of Bystricky et al. (2015), who reported a range of 5,000–12,000 kg CO^2-eq ha^{-1} of 12 Austrian organic dairy farms under similar system boundaries.

Due to limited evidence in the literature, the values and ranges of EP both per kg ECM and per ha MP were compared to the findings of Grassauer et al. (2021), who reported median values of 0.0025 (within a range of 0.0017–0.0035) and 10.3 (within a range of 7.6–11.4) person year^{-1} per kg ECM and ha MP, respectively. The significantly lower EP values of the Lungau farms can mainly be related to lower stocking and N-fertilization rates as manure application and nitrate leaching are the main contributors to EP (O'Brien et al., 2012).

The values of AE per kg ECM (0.0033 and 0.0022 kg 1,4 DB-eq for the Lungau farms and the MDF, respectively) are substantially higher compared to the findings of Arsenault et al. (2009), who assessed Canadian dairy farms of two farming systems (confinement and pasture-based) and reported values of 0.0014 and 0.0013 kg 1,4 DB-eq, respectively. Although the Canadian farms operated conventional, Arsenault et al. (2009) did not consider the use of pesticides, which could have led to values 50 times higher (Knudsen et al., 2019). It should further be noted that Arsenault et al. (2009) assessed intensively managed dairy farms with milk yield averages well over 9,000 kg cow^{-1} leading to lower AE per kg milk. Although the difference in AE per ha MP between the Lungau farms and the MDF seems negligible, there is a considerable variation of values ranging from 6.1 to 35 kg 1,4 DB-eq, which can be attributed to the high variance of purchased roughage (0–22.3 t DM; see **Table 1**).

The adaption of six eco-inventories (i.e., barley grain, wheat grain, rye grain, grass silage, hay, and calves) as presented in **Supplementary Table 2** shows differences up to 13% depending on the considered EI. On the one hand, these differences are caused by the amended transport distances, which only have minor importance on eco-inventories of organic feedstuffs and are subject to high uncertainty (Nemecek and Kägi, 2007). On the other hand, the reduced application of fertilizers leads to lower resource use (CExD) and a reduced accumulation of heavy metals (AE). However, when upscaled to the farm level, the differences in the EIs were even lower.

Summarizing the EIs related to the two considered FUs, as shown in **Figure 5**, and besides the unfavorable natural landscape conditions in the study region, we identify three principal production parameters describing the closed regional production:

1. The stocking rate influences (i) the milk yield per ha MP and, therefore, the CExD, (ii) indirectly the N fertilization, which further affects the EP, and (iii) the GWP per ha MP.
2. The fed concentrate is highly correlated with the milk yield per cow, thus influencing all EIs considering one kg ECM as the functional unit.
3. The purchased roughage leads to an import of heavy metals, therefore affecting the AE.

The Lungau farms operate at a lower level regarding two of the three mentioned production parameters (the high range of purchased roughage is due to different site conditions and limitations of pasture and concentrate). This moderate use of inputs is consistent with the overall unfavorable natural landscape conditions in the Lungau region, and the comparison with the average Austrian organic dairy farm (operating on a more intensive level regarding inputs) showed that such extensive production systems can competitively contribute to producing food and providing environmental services by performing site-adapted agriculture.

CONCLUSIONS

This study assessed the resource use and EIs of 20 Austrian organic dairy farms located in the Lungau region and compared them with an average Austrian organic model dairy farm to determine the main factors influencing the environmental performance of milk production in a closed regional production system. Considering 1 kg ECM as the functional unit (FU), results of farm LCAs indicated that the Lungau farms are favorable regarding CExD and EP, whereas the MDF emitted lower values of GWP and AE. However, we also related the EIs to one ha MP as the second considered FU, which led to the Lungau farms being favorable in three out of four categories (CExD, GWP, and EP). Therefore, we conclude that the choice of FU is crucial when comparing different production systems, thus highlighting the integration of multiple FUs and taking the multifunctionality of agriculture into account. Further, we identified three principal management parameters determining the environmental performance of milk production in a closed production cycle in a less favorable area, namely, (1) the stocking rate, (2) the fed concentrate, and (3) the purchased roughage. Using these inputs at moderate intensity, the extensively managed Lungau farms can competitively contribute to producing food and providing environmental services from an environmental point of view. Therefore, the unfavorable natural landscape conditions in the Lungau region and the extensive management with moderate use of inputs highlight the importance of site-adapted agriculture.

DATA AVAILABILITY STATEMENT

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: doi: 10.5281/zenodo.5709472.

AUTHOR CONTRIBUTIONS

FG: conceptualization, data curation, methodology, visualization, and writing—original draft. MH: conceptualization, methodology, and writing—review and editing. LI: software, methodology, and writing—review and editing. GG: writing—review and editing and supervision. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2022.817671/full#supplementary-material

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Lists of figures and tables

The following two subsections only comprise figures and tables that are not part of Paper I, Paper II, and the additional journal contribution.

Figures

Tables

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Selected publications

Grassauer, F., Herndl, M., Nemecek, T., Guggenberger, T., Fritz, C., Steinwidder, A., Zollitsch, W., 2021. Eco-efficiency of farms considering multiple functions of agriculture: Concept and results from Austrian farms. Journal of Cleaner Production 297, 126662.

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Reviewer for scientific journals

Journal of Cleaner Production	*since 2021*
International Journal of Environmental Science and Technology	*since 2021*
The International Journal of Life Cycle Assessment	*since 2022*