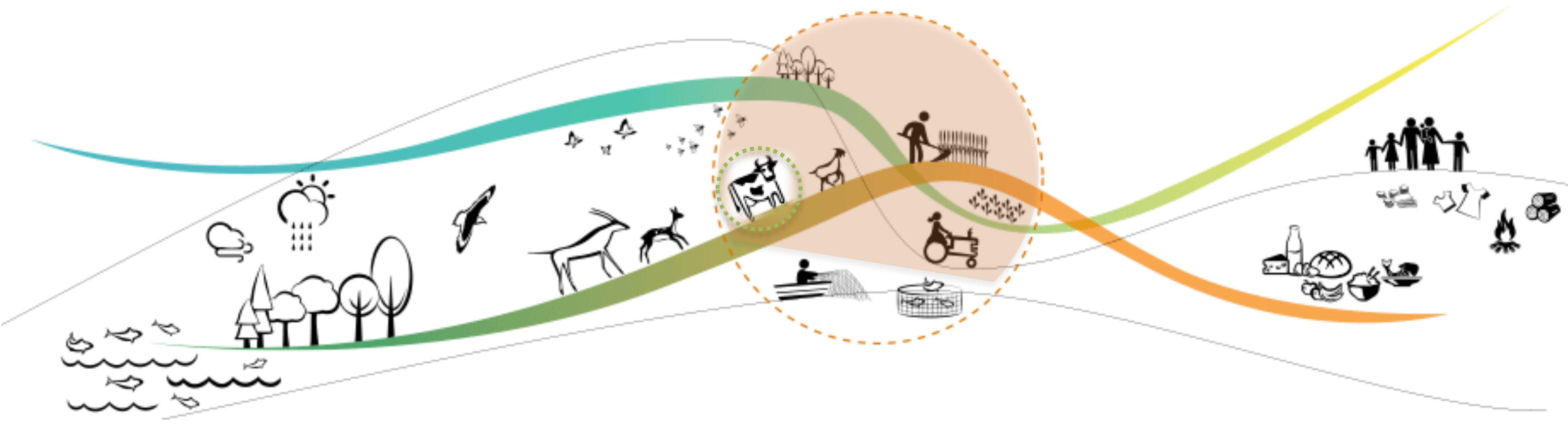
Animal welfare in the context of sustainable dairy farming:

Effects of welfare improvement on environmental impacts of milk production



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Animal welfare in the context of sustainable dairy farming:

Effects of welfare improvement on environmental impacts of milk production

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Thesis

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For Sissa

"The living planet *must* receive a more sympathetic and, above all, a more educated and intelligent approach to husbandry if successive generations are to enjoy a reasonable quality of life."

John Webster
Professor Emeritus at the University of Bristol (UK)
and former member of the Animal Health and Welfare Panel
of the European Food Safety Agency

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List of abbreviations

Technical

AP	Acidification potential
AW	Animal welfare
AWI	Animal welfare improvement
AWIM	Animal welfare improvement measure
CF	Crude fibre
CH_4	Methane
CO_2	Carbon dioxide
CP	Crude protein
ECM	Energy-corrected milk
EE	Ether extracts (crude fat)
EI	Environmental impact
EIM	Environmental impact mitigation
EIMM	Environmental impact mitigation measure
EP	Eutrophication potential
FEP	Freshwater eutrophication potential
FPCM	Fat- and protein-corrected milk
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
LCA	Life cycle assessment
LCC	Life cycle costing
LCSA	Life cycle sustainability assessment
MEP	Marine eutrophication potential
N	Nitrogen
N_2O	Nitrous oxide
NfE	Nitrogen-free extracts
NH_3	Ammonia
NO_3^-	Nitrate
NO_x	Nitrogen oxide
nRER	Non-renewable energy resources
PO_4^{3-}	Phosphate
PS	Production system
RER	Renewable energy resources
SLCA	Social life cycle assessment
SDGs	Sustainable development goals
TAP	Terrestrial acidification

Institutions

AHGHGN	Animal Health and Greenhouse Gas Emissions Intensity Network
EAA	Environment Agency Austria
EEA	European Environment Agency
FAO	Food and Agriculture Organization
FAWC	Farm Animal Welfare Council
IDF	International Dairy Federation
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
OIE	Office International des Epizooties (World Organization for Animal Health)
UN	United Nations
UN FCCC	United Nations Framework Convention on Climate Change
UN HLPE	United Nations High Level Panel of Experts on Food Security and Nutrition

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Summary

Dairy farming is a significant contributor to anthropogenic greenhouse gas and ammonia emissions and resource consumption. In pursuit of more sustainable production to maintain the planet's resource base for future generations, the intensification of dairy farming systems has been promoted. Critics, however, point to a concomitant reduction in animal health and welfare. More recent studies revealed that impaired cow health results in increased emissions from dairy farming. Thus, improving animal welfare is not only an important aspect of social sustainability but is also suggested as an integral component of sustainable agri-food systems.

To contextualize previous research on the environmental impacts of impaired cow welfare, the present thesis aimed at evaluating potential effects of specific welfare intervention measures on the potential contribution of dairy farming to global warming (GWP), terrestrial acidification (TAP), marine and freshwater eutrophication (FEP, MEP) and to the use of renewable and non-renewable energy resources (RER, nRER). Following a comprehensive review on the complex qualitative and quantitative relationship between dairy cow welfare improvement and environmental impact mitigation (paper 1), the environmental effects of a) rubber mat implementation in alleys to abate lameness and of b) the introduction of basket fans for additional ventilation to prevent heat stress were estimated using life cycle assessment methodology (paper 2+3). To this end, the cradle-to-farm-gate environmental impacts of model farm systems derived from national statistics were evaluated before and after the implementation of the welfare intervention measures (baseline scenario vs. intervention scenario). Monte Carlo Simulations were applied to test the robustness of differences between the impact estimates statistically.

Regarding the categories TAP and RER, the beneficial effect of improved welfare through implementation of the intervention measures rubber mats and basket fans prevailed over the environmental burden associated with their production and operation. In contrast, according to sensitivity analyses, material and energy use significantly affected FEP and nRER estimates. Therefore, the emission mitigating effect of improved welfare did not always outweigh the intervention measures' environmental burden in terms of FEP and nRER, depending on the baseline milk production intensity. For GWP and MEP, no significant effect of measure implementation was found.

Nonetheless, it is concluded that improving dairy cow welfare by implementing rubber mats for lameness reduction and basket fans for heat stress abatement can be recommended from an environmental point of view in production systems with a medium milk yield level (6,000-8,000kg) and temperate climatic conditions. To confirm a general benefit of welfare intervention measures for sustainable milk production, further research is needed to evaluate other intervention measures. Assessment accuracy would benefit from a primary data-based evaluation, notably regarding the measures' effectiveness to improve cow welfare and productivity. Considering a wider range of impact categories and expressing impacts also in terms of the utilized agricultural area and of economic and social aspects could help to better understand the significance of animal welfare improvement in the multidimensional context of sustainability.

Zusammenfassung

Die Milchviehhaltung trägt maßgeblich zu den anthropogenen Treibhausgas- und Ammoniakemissionen sowie zum Ressourcenverbrauch bei. Um eine nachhaltigere Produktion zu erreichen und die Ressourcenbasis des Planeten für zukünftige Generationen zu erhalten, wurde die Intensivierung von Milchviehhaltungssysteme weiter vorangetrieben. Kritiker weisen jedoch auf eine damit einhergehende Verringerung der Tiergesundheit und des Tierwohls hin. Neuere Studien haben gezeigt, dass eine beeinträchtigte Kuhgesundheit zu erhöhten Emissionen aus der Milchviehhaltung führt. Die Verbesserung des Tierwohls ist daher nicht nur ein wichtiger Aspekt der sozialen Nachhaltigkeit, sondern wird als integraler Bestandteil nachhaltiger Agrar- und Lebensmittelsysteme angesehen.

Um frühere Forschungsergebnisse zu den mit einem beeinträchtigten Gesundheitszustand von Kühen im Zusammenhang stehenden Umweltauswirkungen zu kontextualisieren, zielte die vorliegende Arbeit darauf ab, mögliche Auswirkungen spezifischer Maßnahmen zur Verbesserung des Tierwohls auf den potentiellen Beitrag der Milchviehhaltung zu den Umweltwirkungskategorien globale Erwärmung (GWP), terrestrische Versauerung (TAP), Meeres- und Süßwasser-Eutrophierung (FEP, MEP) und Nutzung erneuerbarer und nicht-erneuerbarer Energiequellen (RER, nRER) zu bewerten. Nach einer umfassenden Überprüfung und Rezension des komplexen qualitativen und quantitativen Zusammenhangs zwischen der Verbesserung des Wohlbefindens von Milchkühen und der Verminderung der Umweltauswirkungen (Artikel 1) wurden die Umweltauswirkungen von a) der Implementierung von Gummimatten im Laufbereich zur Verringerung von Lahmheit und b) der Einführung von Korbventilatoren für zusätzliche Belüftung zur Vermeidung von Hitzestress mithilfe der Ökobilanzmethode geschätzt (Papier 2 + 3). Zu diesem Zweck wurden die Umweltauswirkungen von Modellbetriebssystemen, die aus nationalen Statistiken abgeleitet worden waren, vor und nach der Implementierung der Maßnahmen zur Verbesserung des Tierwohls (Basisszenario vs. Interventionsszenario) bewertet. Monte-Carlo-Simulationen wurden angewendet, um die Robustheit der Unterschiede zwischen den Schätzwerten der Umweltwirkung statistisch zu testen.

In Bezug auf die Wirkungskategorien TAP und RER überwog der positive Effekt des durch die Umsetzung der Interventionsmaßnahmen Gummimatten und Korbventilatoren

verbesserten Tierwohls gegenüber der mit ihrer Herstellung und ihrem Betrieb verbundenen Umweltbelastung. Im Gegensatz dazu beeinflussten der Material- und Energieverbrauch laut Sensitivitätsanalysen die FEP- und nRER-Schätzungen erheblich. In Bezug auf FEP und nRER überwog daher die emissionsmindernde Wirkung des verbesserten Tierwohls nicht immer die Umweltbelastung der Interventionsmaßnahmen, abhängig von der Ausgangsintensität der Milchproduktion. Für GWP und MEP wurde kein signifikanter Effekt der Maßnahmenumsetzung festgestellt.

Dennoch wird geschlussfolgert, dass die Verbesserung des Wohlbefindens von Milchkühen durch die Implementierung von Gummimatten zur Verringerung von Lahmheit und von Korbventilatoren zur Verringerung von Hitzestress in Produktionssystemen mit mittlerer Milchleistung (6.000-8.000 kg) und unter gemäßigten klimatischen Bedingungen aus Umweltsicht empfehlenswert ist. Um einen allgemeinen Nutzen von Maßnahmen zur Verbesserung des Tierwohls für eine nachhaltige Milchproduktion zu bestätigen, sind jedoch weitere Untersuchungen erforderlich, die weitere Interventionsmaßnahmen bewerten. Die Bewertungsgenauigkeit würde von einer Primärdaten-basierten Wirkungsabschätzung profitieren, insbesondere in Hinblick auf die Auswirkungen bestimmter das Tierwohl verbessernder Maßnahmen auf die Produktivität der Kühe. Die Berücksichtigung eines breiteren Spektrums an Umweltwirkungskategorien und der Bezug der Umweltwirkungen auf die genutzte landwirtschaftliche Fläche sowie auf wirtschaftliche und soziale Aspekte könnten dazu beitragen, die Bedeutung der Verbesserung des Tierwohls im mehrdimensionalen Kontext der Nachhaltigkeit besser zu verstehen.

1 Background and general introduction

In the light of global population growth, the limits of the planet's ecological resource capacity are becoming unequivocally apparent (Gerber et al., 2013b). At the same time, drastic changes in climate and biosphere integrity due to human activities jeopardize the stability of the earth's ecosystem and, thus, the basis of agricultural production (Rockström et al., 2009). To guarantee food security for future generations, scientists of multiple disciplines have urged for an immediate transformation towards sustainable agricultural production (UN HLPE, 2016). However, despite joint efforts in pursuing a prospering planet and in controlling the exponential increase in anthropogenic emissions (e.g., UN, 2015; UN FCCC, 2015), recent forecasts revealed that we are still far from achieving global climate goals and ensuring resource-efficient production patterns (IPCC, 2018; UN, 2019).

Given its considerable impact on air, water and soil quality and on the consumption of natural resources, the dairy farming sector faces the challenge of minimizing its impact on climate change while sustainably optimizing production within the finite boundaries of the planet to contribute to food security (Hristov et al., 2013; Steinfeld et al., 2006). At the same time, the resulting unbowed trend for intensification raised a growing societal awareness and claim for animal-friendly production conditions (Cardoso et al., 2016; Tucker et al., 2013). This thesis focuses on potential synergies and trade-offs of sustainable and welfare-friendly farming practices, emphasising the environmental aspect of sustainable dairying.

1.1 Sustainability in dairy production

In agricultural production, sustainability is commonly associated with a long-standing practice, that does not deplete available natural resources but maintains the system's reproduction capacity over time (Pretty, 2008; Thompson, 2007). Sustainable dairying can thus be characterized as an environmentally sound, profitable and morally just farming practice that strives for a minimized environmental impact, economic viability and consumer acceptance (Capper, 2013). In accordance with the notion of strong sustainability, the well-being of individuals (humans and animals) in an agricultural system is considered inherent to the system's sustainable development. It indicates its capability to reproduce and thus to maintain its functional integrity (Thompson, 2007, 2006).

1.1.1 The concept of sustainability

Definitions of sustainability frequently refer to the so-called Brundtland Report on sustainable development, which was proposed by the UN World Commission in 1987. Accordingly, sustainable development satisfies a present demand without jeopardizing the satisfaction of needs of successive generations. The maintenance of the functional integrity of the environment is thereby considered an essential premise (UN, 1987). For decades, scientific research followed the triple-bottom-line approach, which differentiates three aspects of sustainability, widely known as the three pillars. They delineate sustainable performance and development as the concurrent and balanced pursuit of environmental, economic and social aims (Capper, 2013). The more recent UN agenda for sustainable development exceeds this three-dimensional disposition and argues sustainability in terms of a prospering planet and society, claiming an integrated pursuit of ecological resilience, economic feasibility and moral responsibility (UN, 2015). To explore the impact of human activity on the planet's functional integrity, the concept of the planetary boundaries was developed (Rockström et al., 2009). Based on nine identified biophysical target processes, it determines the margins of anthropogenic perturbation beyond which a substantial destabilization of the earth system is imminent (Rockström et al., 2009; Steffen et al., 2015).

1.1.2 Environmental impacts of dairy farming and their assessment

A 2015 status assessment of the boundary concept revealed, that at least four of the nine planetary thresholds have already been exceeded (Steffen et al., 2015), including those concerning biogeochemical flows (nitrogen, phosphorus) and climate change. As a significant contributor to anthropogenic emissions of carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), ammonia (NH_3), nitrogen oxides (NO_x), nitrate (NO_3^-), and phosphate (PO_4^{3-}), the dairy farming holds a significant share in this development. The sector is thus urged to reduce its environmental impacts, notably in terms of its key contributions, i.e., **global warming, acidification, eutrophication, and land and resource use** (Campbell et al., 2017; Steinfeld et al., 2006).

Agricultural operations, in general, are the single largest contributor to **NH_3** emissions (94% in Europe, EEA (2019)), which primarily arise from livestock production and cattle in particular (Sanchis et al., 2019; Schrade et al., 2012). NH_3 emissions from dairy farming mainly occur during manure storage and its deposition on land as a result of the hydrolysis of urea (Hagenkamp-Korth et al., 2015). Increasing nitrogen concentrations in the soil entail the acidification of the latter, while nutrient leaching to water bodies (nitrogen and phosphorus compounds) effectuates their eutrophication, which contributes to the global transgression of biochemical flows (Rockström et al., 2009).
Moreover, dairy cattle are responsible for 4.3% of total anthropogenic greenhouse gas (**GHG) emissions**, an effect that is mainly triggered by CH_4 emissions from enteric fermentation (77%). CH_4 and N_2O emissions from manure management contribute to 20% of total GHG emissions from dairying, while CO_2 emissions associated with on-farm energy consumption are negligible (3%) (Gerber et al., 2013b). According to the Intergovernmental Panel on Climate Change (IPCC), CO_2 emissions from cows can be assumed to be zero, since the photosynthesized CO_2 stored in plants equals the amount of CO_2 brought back to the atmosphere via respiration (IPCC, 2013). The accumulation of increasing amounts of greenhouse-active gases in the atmosphere leads to a global warming effect (Rockström et al., 2009).
With the increasing intensification of dairy farming systems, their dependence on off-farm concentrates rises markedly (Berton et al., 2020), entailing increased area-based impacts from **land-use-change** and **energy demand** (Hörtenhuber et al., 2011).

In animal production, **life cycle assessment** (LCA) is one of the most widely used methods to estimate such potential environmental impacts of production and to evaluate the use of finite resources. It facilitates the expression of a system's environmental impacts per functional unit by accounting for all inputs (resources, energy, infrastructure, land use) and outputs (product and co-products, emissions) that characterize a production process (Klöpffer and Grahl, 2009). Thus, LCA helps in identifying emission hotspots and production trade-offs and can be used for scenario modelling and to compare the environmental impacts of different production systems (Beauchemin and McGeough, 2013).

The environmental analysis of a product's life cycle is usually based on an internationally standardized assessment tool that operates within the ISO standards 14040-14049 (ISO, 2006, 2001). Species-specific guidance to assess the overall environmental performance of ruminants is provided by the Food and Agriculture Organization (LEAP, 2016), while the sector-specific guidelines of the International Dairy Federation (IDF, 2015) focus on the assessment of GHG emissions only. Despite efforts of standardization, LCAs of milk production still lack **harmonization** in their methodological approach, and results are often difficult to compare, depending on the choice of functional unit, system boundary, co-product handling, and impact assessment methods as well as the range of considered impacts (Baldini et al., 2017; McClelland et al., 2018). A review of 44 milk LCAs conducted between 2009 and 2017 revealed that most assessments refer to milk as the unit of process output and use economic allocation to account for emissions associated with the co-product meat. The four most frequently assessed environmental impacts of cow milk production are its global warming potential (GWP), eutrophication potential (EP), acidification potential (AP), and the use of land as well as renewable and non-renewable energy resources (RER, nRER) (Baldini et al., 2017).

1.1.3 The role of animal welfare in contemporary sustainability frameworks

In addition to the growing societal apprehensiveness for the environmental soundness of food production, farming practices are under increasing scrutiny regarding their effect on animal welfare (Hötzel, 2014). Both aspects determine the consumers' acceptance of animal products (Thornton, 2010; Tucker et al., 2013). With the acknowledgement of current welfare standards (see chapter 1.2.1) in the UN recommendations on sustainable agricultural development, the welfare of farmed animals was formally anchored in the contemporary understanding of sustainable food production (UN HLPE, 2016). The report highlights the importance of welfare as an essential element of sustainable farming and thus as a key contributor to food security (Buller et al., 2018; Keeling et al., 2019). Several integral sustainability assessment frameworks which have been proposed during the last decade, already include the evaluation of welfare-friendly husbandry conditions as part of the benchmarking process on the sustainability of farming patterns (e.g., IDEA, PG, RISE, SAFA, SAI; de Olde et al., 2016) and of human activity in general (SDGs; Keeling et al., 2019a).

The 17 sustainable development goals (SDGs), adopted by the UN member states in 2015, are the most recent and most integral framework expressing the joint effort to confront and tackle the pressing ecological, economic, and political challenges (UN, 2015). Although the welfare of farmed animals is not directly mentioned in the SDGs, a panel of experts from environmental, agricultural, and veterinary sciences identified in 66 out of the total set of 169 sub-targets an association with animal welfare (Keeling et al., 2019). Rather than finding conflict, their analysis attests a mutually enabling effect between animal welfare and sustainability improvement and highlights the importance of animal health and welfare regarding the animals' productivity and product quality (Keeling et al., 2019).

Among other indicator-based guidelines for assessing farm sustainability, the FAO framework for Sustainability Assessment of Food and Agriculture Systems (SAFA) lists animal welfare as an integral component of environmental sustainability, along with the atmosphere, water, land, biodiversity, and energy. Following the concept of Five Freedoms (see chapter 1.2.1), it stresses the physical and psychological well-being of production animals as essential to ensure environmental integrity and specifically highlights the importance of stress reduction and good housing conditions (FAO, 2014).

1.2 The welfare of dairy cows and its implications for sustainability

A dairy cow's health and welfare state directly affect its production efficiency, which in turn determines the animal's emission potential (Gerber et al., 2013a; Gill et al., 2010). Healthy animals have a better ratio of product output to maintenance costs. Consequently, fewer animals are needed to produce a certain amount of a product, and the environmental impact per unit of this product decreases (Bell et al., 2012). Moreover, the welfare of animals co-determines their milk production potential, reproductive performance, longevity, and feed conversion efficiency. Since these factors are key drivers of the overall environmental performance of dairy farming operations, improving the animals' welfare state is generally considered an effective and recommendable emission mitigation strategy for milk production (Hristov et al., 2013; Llonch et al., 2016). Impact reduction potentials between 0.7% - 9.4% and of up to 25% have been reported, depending on the impact category, the type of welfare impairment (disease), and the magnitude of the achieved productivity improvement (ADAS, 2015; Chen et al., 2016; Mostert et al., 2019, 2018a, 2018b; Özkan Gülzari et al., 2018). However, most animal welfare improvement measures can be expected to come at an environmental cost, notably if changes in the infrastructure are involved. To benchmark the overall effect of welfare improvement on the environmental sustainability of dairy production, both the benefits of good welfare on production efficiency and the environmental costs associated with the production and operation of the welfare intervention measure have to be taken into account.

1.2.1 Animal welfare concepts

Animal welfare is usually considered a multidimensional concept (see Table 1). It is frequently described as the physical and mental integrity of the individual and its ability to engage in highly motivated natural behaviour (Fraser, 2008). These dimensions are also reflected in the often-cited 'Five Freedoms' concept of the UK Farm Animal Welfare Council, proposed in 1979 (FAWC, 1993). It characterizes the principle components of well-being as the freedom from 1) thirst and hunger, 2) discomfort, 3) pain and injury, 4) fear and distress, as well as the freedom to 5) express innate normal behaviour. According to the World Organization for Animal Health (OIE) guidelines, adopted in 2005, this requires appropriate shelter, nutrition, handling, and veterinary care to facilitate comfortable living free of pain and diseases, as well as a humane slaughter practice (OIE, 2019). An elaboration with a focus on dairy cow welfare is provided in chapter 7.11 of the corresponding ISO standard 34700 on animal welfare management (ISO, 2016).

A more recent interpretation of the Five Freedoms can be found in the Welfare Quality® framework, a widely used welfare assessment tool. It follows a four-principle paradigm, addressing good feeding, housing and health as we appropriate behaviour, which are represented by 12 tangible welfare criteria (see Table 1, Welfare Quality®, 2009). The latest adaptation of the freedom concept so far (Five Domains) goes beyond the simple avoidance of restrictive and unfavourable husbandry conditions and emphasizes the importance of recognizing the animals' sentience (Mellor and Beausoleil, 2015). Similarly, the 'Quality of Life' scale (FAWC, 2009) inspires to focus on how to provide animals with a life worth living, rather than just establishing conditions essential for survival (Webster, 2016). Both concepts substantiate the animal welfare ideals described in the Five Freedoms with an ethical approach in an attempt to capture the acceptable level of welfare (McCulloch, 2013).

This thesis focuses on intervention measures regarding good housing (freedom from thermal discomfort) and good health (freedom from disease) and thus addresses two major welfare issues in current dairy farming.

Table 1: Categories of welfare, following the concepts Five Freedoms, Welfare Quality®, Five Domains and Quality of Life, and the OIE Principles, adapted from Webster (2013)*.

Five Freedoms	**Welfare Quality®**		**Five Domains**		**Quality of Life** (scale)	**10 General Principle**
(FAWC, 1993)	(Welfare Quality®, 2009)		(Mellor, 2016)		(FAWC, 2009)	(OIE, 2019)
Freedom from hunger and thirst	Good feeding	Absence of prolonged hunger Absence of prolonged thirst	Nutrition	Mental State (positive and negative experiences)	A good life	1 Genetic selection 2/3 Physical Environment
Freedom from thermal and physical discomfort	Good housing	Thermal comfort Comfort around resting Ease of movement	Environment		A life worth living	(comfortable, pro health) 4 Social grouping 5 Air Quality
Freedom from pain, injury and disease	Good health	Absence of pain induced by management procedures Absence of injuries Absence of disease	Health		Point of balance	6 Sufficient feed/water supply 7 Disease control and prevention
Freedom from fear and distress	Appropriate behaviour	Positive emotional state Good human-animal relationship	Behaviour		A life worth avoiding	8 Avoid painful procedures
Freedom to exhibit normal behaviour		Expression of other behaviours Expression of social behaviours			A life not worth living	9 Humane handling 10 Educated stockmen

* The original figure by Webster (2013) was extended by columns 3 to 5. The type of separating line (dashed, solid, double) indicates a differing extent to which the added concepts differ from the Five Freedoms approach of Webster: The Five Domains concept (column 3) operates within similar margins, but includes the overall aspect of the animals' mental state (thus separated by a dashed line). The 'Quality of Life' concept (column 4) describes a superordinate notion of welfare (thus separated by a continuous line). The 10 OIE Principles can be understood as respective operating instructions to the aforementioned concepts and are thus displayed in a double-line separated column at the end.

1.2.2 Current challenges in dairy cow welfare and associated environmental impacts

Production diseases such as lameness and heat stress are among the most pressing welfare challenges in modern-day dairy farming (UN HLPE, 2016). Both conditions can be accompanied by significant losses in production efficiency (yield, fertility) and longevity of affected individuals (Huxley, 2013; Polsky and von Keyserlingk, 2017), thus impinging on their emission potential (Bell et al., 2011; van Knegsel et al., 2014). This is mostly due to the increasing number of heifers required for replacement to produce the same amount of product output and a comparatively higher share of maintenance cost from total production costs (Bell et al., 2012).

Recent studies on the effects of lameness on environmental impacts of milk production revealed a potential increase of up to 7.6% and 9.4% for GWP, and EP and AP, respectively, depending on the prevalence and severity of the disease (Chen et al., 2016). Taking into account also the type of lesion, an average increase of GHG emissions of 1.5% per unit of product was calculated, ranging from 0.4% in the case of digital dermatitis to 4.3% per case of white line disease (Mostert et al., 2018b). Previous studies also suggested potential implications of heat stress for the animals' emissions level due to its effect on production efficiency (Hristov et al., 2013; Place and Mitloehner, 2014). However, a quantitative assessment of trade-offs between heat stress-induced productivity decline and environmental impacts of milk production is still lacking.

1.2.3 Mitigating lameness and heat stress, and potential environmental implications

Intervention measures to prevent and reduce lameness differ depending on the type of lesion that causes the mobility impairment (Bruijnis et al., 2012). Commonly suggested measures include adequate stall design and reduced stocking density to optimize resting behaviour (Cook and Nordlund, 2009; Tucker et al., 2021), increased cleaning frequency to promote good hygiene (Barker et al., 2012) and among other things therapeutic trimming (Ouweltjes et al., 2009), access to pasture (Olmos et al., 2009) and soft flooring to reduce the pressure load and to improve its distribution on the claw (Oehme et al., 2018). Rubber mats are recommended to reduce trauma-induced disorders such as lameness due to sole ulcers (Chapinal et al., 2013). Since the production of rubber mats is associated with a considerable energy demand for the extrusion of the rubber granulate, their implementation in dairy barn alleys can be expected to affect the environmental impact potential of milk production. In contrast, the material demand is negligible since the production of rubber mats in Europe relies on rubber granulate from recycled car tyres.

Common heat stress mitigation technologies in dairy farming include cooling devices, such as fans, misters, showers, and evaporative cooling pads (Ji et al., 2020; Polsky and von Keyserlingk, 2017). Basket fans increase convective heat transfer and enhance evaporation through faster air movement (Wang et al., 2018). Both material and energy demand for the production and operation of fans are relevant in terms of environmental impact.

1.3 A wicked problem

By 2050, the global demand for milk products is projected to have increased by 63% compared to the reference period 2005/2007 (Alexandratos and Bruinsma, 2012). This development will further propel intensification in terms of productivity per animal and per hectare and intensify the competition between food and feed production over the planet's finite resource base (e.g., land, water, energy) (Berton et al., 2020). Yet, the intensification of dairy production seems to conflict with a farming practice that considers the well-being of the animals as its highest priority (Buller et al., 2018; Tucker et al., 2013). Although productivity increase can reduce emissions and the global environmental performance of milk production (Jan et al., 2019), at least per unit of product (Salou et al., 2017) and if trade-offs for meat production are not accounted for (Zehetmeier et al., 2011), the continued selection for genetic improvement of milk yield in the past decades has led to an increase in production diseases and reproductive problems while longevity declined (Oltenacu and Broom, 2010). Impaired health and welfare negatively affect both the individual's environmental impact potential and farm profits (Bell et al., 2015; Chen et al., 2016; Mostert, 2018), and production intensity is negatively correlated with local farm environmental performance (Jan et al., 2019). Thus, farmers face the challenging task of sustainably intensifying production with regard to the environmental impact level (i.e., global vs. local) and ultimately also regarding social and economic impacts, while maintaining good animal welfare.

This is exemplary for the paradox of sustainability and the ambiguity of its pursuit. Sustainability has thus been framed as a wicked problem. Wicked problems cannot be solved (Peterson, 2013) but only be managed, owing to the complex and constantly evolving nature of their multidimensional conceptualization (Thompson, 2007). By zooming in on environmental implications of specific welfare intervention measures, the current thesis addresses concerns on both sides (environmental impact mitigation, animal welfare improvement). It contributes to a more comprehensive understanding of the sustainability challenges in dairy farming and of options for their management. This may allow aligning current production policy in dairy farming with consumers' expectations for environmentally and welfare-friendly production practices.

2 Research gaps

While the linkage of animal welfare with the general sustainability debate has already been established (UN HLPE, 2016), research on the quantitative relationship between cow welfare and environmental impacts of milk production is still fragmentary. At the onset of this research project, the knowledge on respective interdependencies was limited to a largely qualitative description of potential synergies and trade-offs between the two topics (e.g., Place and Mitloehner, 2014; Tucker et al., 2013). Starting with implications of environmental impact mitigation measures for animal welfare (de Boer et al., 2011; Gill et al., 2010; Hristov et al., 2013; Shields and Orme-Evans, 2015), the reciprocal contemplation of environmental aspects in the context of animal welfare has emerged more recently (Llonch et al., 2016; Mostert, 2018; Tucker et al., 2013; Williams et al., 2013). In 2014, scientists from relevant research disciplines stated a **lack of data regarding the potential effects of welfare improvement** on livestock emission levels (AHGHGN, 2014). Whether the pursuit of good animal welfare in dairy farming would compromise or benefit emission mitigation could not be comprehensively answered.

Since then, major progress has been made in determining the quantitative effects of common **health problems** in dairy farming, such as lameness, mastitis and ketosis, on the environmental impact of milk production systems (ADAS, 2015; Chatterton et al., 2014; Chen et al., 2016; Mostert et al., 2019, 2018b, 2018a; Özkan Gülzari et al., 2018; Skuce et al., 2016). The results substantiated the general notion of animal welfare being beneficial in terms of environmental impact mitigation (Hristov et al., 2013; Novak and Fiorelli, 2010; Stott et al., 2010). Most of those studies quantified the potential impact of bovine diseases on **global warming** only, based on scenario modelling of different disease prevalence levels (see Chen et al., 2016; Mostert, 2018; Özkan Gülzari et al., 2018). Impacts of health impairment on other environmental hotspots of dairy farming, notably **acidification, eutrophication or energy use**, are still largely unknown. Moreover, other aspects of an animal's well-being beyond its physical integrity, such as heat stress or thermal comfort, have not been considered so far and neither have potential environmental implications associated with the introduction of specific **health and welfare improvement measures**.

3 Thesis aims and research questions

The overall aim of this thesis was therefore to provide insight into the complex relationship between dairy cow welfare improvement and the potential impacts of milk production on global warming, acidification, eutrophication and energy use. More specifically, the following **objectives** were pursued:

1. to provide an overview on the current scientific knowledge regarding the complex relationship between animal welfare and the environmental impact of dairy farming, including a quantitative assessment of potential synergies and trade-offs (paper 1),
2. to quantify the net environmental impacts associated with the implementation of rubber flooring to reduce lameness, by trading off environmental costs of measure implementation against environmental benefits of concomitant productivity increase due to improved claw health (paper 2),
3. to quantify the net environmental impacts associated with the implementation of basket fans to mitigate heat stress, by trading off environmental costs of measure implementation against environmental benefits of concomitant productivity increase due to improved thermal comfort (paper 3).

The pursuit of the first objective was guided by the **first research question:** 1a) Does the implementation of specific environmental impact mitigation measures (EIMM) have implications for animal welfare (AW) and if so, has the effect been quantified? 1b) Does the implementation of specific animal welfare improvement measures (AWIM) affect the environmental impacts (EI) of dairy production and if so, has the effect been quantified? Regarding letters a) and b), the existence of a mutual interaction and of a qualitative evaluation of the latter regarding letter a) was hypothesized.

Regarding the second and third objective, the **second research question** was whether or not environmental benefits of improved welfare persist despite potential environmental costs associated with the welfare intervention measure. It was hypothesized that the environmental costs of implementing rubber mats and basket fans do not outweigh the emission-mitigating effect of lameness reduction and heat stress mitigation in the modelled production systems.

4 Research approach and thesis outline

To address the first objective a comprehensive literature review was conducted (chapter 5.1). The review contrasts the environmental impact of milk production with animal welfare concerns and aims at balancing the synergies and trade-offs in view of sustainable dairying. After establishing the interdependencies between animal welfare and the environmental impact potential of milk production, both the effect of environmental impact mitigation on animal welfare and the effect of animal welfare improvement on the environmental impact of production are described and quantified, as far as data availability allowed.

The second and third objective were achieved by modelling farms that represent typical production conditions in different areas of Austria. Using LCA, their environmental impact potential was assessed in terms of global warming, acidification, eutrophication and energy use, before and after the implementation of specific welfare measures, notably rubber mats (chapter 5.2) and basket fans (chapter 5.3). Each measure's effect on cow productivity was determined, reflecting the effectiveness of rubber mats in reducing claw lesions and lameness and the potential of convective cooling via basket fans in mitigating heat stress during the summer period.

The concluding discussion in chapter 6 presents the results of the thesis in a broader context of sustainable farming, featuring both methodological challenges and limitations of the modelling approach and general implications for future assessments.

5 Journal contributions

5.1 Paper 1: Interdependencies between animal welfare improvement and emission mitigation in dairy farming

In pursuit of sustainability in dairy farming: A review of interdependent effects of animal welfare improvement and environmental impact mitigation

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Review

In pursuit of sustainability in dairy farming: A review of interdependent effects of animal welfare improvement and environmental impact mitigation

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ABSTRACT

The welfare of dairy cows and their emission potential are two distinct and yet intertwined aspects determining the sustainability of dairy farming. Along with numerous measures to mitigate the sector's environmental impact, good health and welfare are suggested to keep emission levels low. More recently, scientists in both fields have pointed to potential trade-offs for animal welfare arising from the implementation of environmental impact mitigation measures. Research has since focused on the qualitative evaluation of these welfare implications, but little is known about the actual magnitude of the effects on welfare of emission mitigating measures. Moreover, potential environmental impacts associated with welfare improvement measures have hardly been investigated so far, although estimates of respective increases in emission levels associated with various cattle diseases suggest the importance of welfare improvement in pursuit of integral sustainability improvement in dairy farming. For a comprehensive enhancement of the sector's sustainability, a careful balancing of interdependent effects is thus suggested.

This review aims at providing the first inclusive overview on measures of both greenhouse-gas and ammonia emission mitigation and welfare improvement relevant in terms of respective interdependencies. Derived from the literature in both fields, attempts are also made to quantitatively evaluate the interdependent effects. Our findings confirm, that mitigation measures such as breeding for increased genetic yield potential, the use of rumen modifiers and the increase of concentrate ratio in the diet are potentially harmful for the animals' health and welfare, while an increased amount of fat in the diet and the adaptation of the protein ratio to the yield level offer welfare neutral mitigation potential. By contrasting frequently suggested welfare improvement measures with determinants of emission formation, we identified the increase of space allowance and cleanliness, as well as temperature management and access to pasture as welfare measures with potential environmental impact. As for the evaluation of interdependencies, we found that to some extent a quantification of trade-offs is possible for welfare relevant health disorders, such as lameness and mastitis, for which both the effect of welfare improvement measures on their prevalence and an impact range in terms of emissions have already been described in literature. Although further research is needed for a comprehensive balancing of trade-offs, we conclude, that a careful distinction between the effect of an improvement measure and the effect of its impact as suggested in this review may serve as a basis for further research and improve decision-making in dairy farming in terms of sustainability.

1. Introduction

In pursuit of sustainability, the dairy farming sector faces the challenge of producing at minimum environmental impact (**EI**) and reasonable costs, while ensuring good welfare (Place and Mitloehner, 2014). The global climate agreement (UNFCCC, 2015) as well as consumers' acceptance of dairy production (Tucker et al., 2013) are major driving forces in this context. Three of the main determinants of the sector's EI considered in this review are the greenhouse-active gases methane (**CH_4**) and nitrous oxide (**N_2O**) as well as ammonia (**NH_3**), adding to the pollution of air, water and soil (Novak and Fiorelli, 2010). As its contribution to overall anthropogenic emissions is considerable, dairy farming is attributed a significant share in achieving global sustainability goals (Llonch et al., 2016; Place and Mitloehner, 2014). Enhancing production efficiency is no longer promoted for economic reasons only, but also as a potent means of minimizing its EI. However, with the intensification of dairy farming, public scrutiny of the ethics and humaneness of production has increased (Barkema et al., 2015).

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Especially in developed countries, where production levels are already very high, environmental impact mitigation measures (**EIMM**) which aim at further productivity enhancement have been pointed out as potentially detrimental for the welfare of dairy cows, as they might increase the risk for production diseases such as mastitis and lameness (de Boer et al., 2011; Llonch et al., 2016; Oltenacu and Broom, 2010). While good health and welfare are broadly acknowledged as essential regarding productivity (Fall et al., 2008), health impairment has repeatedly been shown to increase the sector's EI (ADAS, 2015; Skuce et al., 2016).

Therefore, both animal welfare and environmental scientists have called for the simultaneous pursuit of animal welfare improvement (**AWI**) and environmental impact mitigation (**EIM**) when striving for more sustainable dairy farming (de Boer et al., 2011; Llonch et al., 2016; Place and Mitloehner, 2014; Tucker et al., 2013). While numerous improvement measures have been described in each field independently, only a few synoptic studies addressed potential interdependencies by pointing out synergetic and antagonistic effects (e.g. de Boer et al., 2011; Llonch et al., 2016; Place and Mitloehner, 2014). For the benefit of an integral sustainability improvement, that takes different aspects of sustainability into account, especially antagonistic interdependencies need to be identified and quantified, to determine potential trade-offs. So far, the scarce knowledge about such interdependent effects primarily relates to welfare impacts resulting from EIMM, while potential environmental impacts of animal welfare improvement measures (**AWIM**) have hardly been investigated yet.

In order to comprehensively address such interdependent effects, we distinguish a primary and a secondary level of effect associated with improvement measures. In terms of EIM, the primary effect level means the implications for AW arising from a certain EIMM (e.g. breeding for increased yield), while the secondary effect level describes the implications of reduced EI on AW. Research in this field is mainly focused on the primary effect level and the qualitative description of welfare implications arising from their implementation (see de Boer et al., 2011; Llonch et al., 2016). Regarding AWI, however, the almost undivided research focus is on the secondary effect level, which addresses the impact of improved health and welfare on emissions, while little is known about potential effects of the implementation of an AWIM (e.g. increasing space allowance) on the EI. Several studies quantitatively assessed the ranges of emission reduction associated with curing specific diseases (ADAS, 2015; Chatterton et al., 2014; Chen et al., 2016; Hospido and Sonesson, 2005; Mostert et al., 2016; Özkan et al., 2015; Skuce et al., 2016), but it is largely unexplored whether AWIM, such as increasing space allowance or providing access to pasture, do per se affect the EI of dairy farming.

This review provides the first integral perspective on sustainability improvement in view of both EIM and AWI in dairy farming, including the attempt to quantify respective interdependencies. To this end, we scrutinized the relevant contributions from both research areas regarding explicit and implicit synergies and especially trade-offs at the interface of emission mitigation and welfare improvement. In the first part, we review selected measures to mitigate CH_4, N_2O and NH_3 emissions, for which welfare implications have been described. We quantify their potential impact in terms of both EIM and AW (see Table 1). Similarly, in the second part, we describe selected measures frequently discussed in terms of improving overall dairy cow welfare. In the absence of specific studies, we condensed the findings of both research areas to a substantiated first quantitative evaluation of their EI, as far as data were available (see Table 2). To quantitatively interlink animal welfare and emission mitigation, we chose two of the major welfare problems in dairy farming, i.e. **lameness** and **mastitis** and describe the primary effects of EIMM on changes in lameness and mastitis prevalence. Both health disorders are highly prevalent in dairy industry worldwide (Potterton et al., 2012; Tremetsberger and Winckler, 2015; van Gastelen et al., 2011) and were repeatedly identified as risk factors for increased emission from dairy cows (Chatterton et al., 2014; Chen et al., 2016; Özkan et al., 2015). On the basis of known ranges of EI for lameness and mastitis are known, we contrast changes in EI with the EIM potential of the measure. Similarly, we evaluate the secondary effect of AWIM targeting lameness and mastitis prevalence and contrast it with the emission level associated with these diseases, to determine potential trade-offs between AWI and EIM (see Table 3). Finally, we briefly discuss future implications arising from this integrated perspective. By pointing out current gaps requiring further research, we open up a potential scope of action, in due consideration of the limits of our approach.

2. Impact of environmental impact mitigation in dairy farming on animal welfare

2.1. The environmental impact of dairy farming

The contribution of bovine milk production to global anthropogenic greenhouse gas (**GHG**) emissions amounts to 4.3% (Gerber et al., 2013b). According to an analysis based on data from the International Farm Comparison Network (IFCN), emissions per unit of product range between 0.8 and 3.07 kg carbon dioxide-equivalents (**CO_2-eq**) per kg of energy corrected milk (**ECM**) (Hagemann et al., 2011), reflecting regional differences in emission intensity of a factor of 7 (Gerber et al., 2011). Key determinants of the sector's contribution potential to global warming (**GWP**) are CH_4 and N_2O (Novak and Fiorelli, 2010). Thereof, CH_4 emissions from enteric fermentation represent 71% of the sector's total direct GHG emissions, followed by N_2O emissions from manure accounting for further 25% (Gerber et al., 2013a). Aside from greenhouse-active gases, emissions of NH_3 from bacterial decomposition of nitrogen (**N**) in the manure add to the overall EI potential of the dairy farming sector, by contributing to processes of acidification and eutrophication (Novak and Fiorelli, 2010). According to the European Environment Agency (EEA), 94% of total anthropogenic NH_3 emissions arise from the agricultural sector (EEA, 2016), of which approximately 50% are attributed to cattle activities (Ferm, 1998).

Several factors determine the actual amount of direct emissions originating from the animal or its manure. Regarding the individual animal, its emission potential is associated with its genetic merit for dry matter intake (**DMI**) and (to a minor extent) for residual feed intake (**RFI**) and feed conversion efficiency (**FCE**), as well as its genetic potential for yield and CH_4 emission (Hristov et al., 2013). While a selection for increased DMI and yield (Knapp et al., 2014), and a high FCE (Hegarty et al., 2007; Skuce et al., 2016; Waghorn and Hegarty, 2011) result in declining emissions per unit of product, the factors RFI (Hegarty et al., 2007) and genetic CH_4 emission potential (Lassen and Løvendahl, 2016) have to be reduced to benefit the mitigation of emission intensity on the animal level. As for emissions from manure, notably N_2O and NH_3, the level of emission is significantly influenced by feeding practices and feed quality (Novak and Fiorelli, 2010). From the point of excretion, manure handling and management, as well as cleanliness (Ndegwa et al., 2008) and temperature (Ngwabie et al., 2011), are key factors in determining the actual level of emitted greenhouse gases and ammonia. In general, frequent cleaning, the minimization of the emitting surface, avoiding volatilisation by regulating air temperature, and the separation of faeces and urine can significantly reduce N_2O and NH_3 emissions in dairy farming (Ndegwa et al., 2008).

2.2. Measures of environmental impact mitigation and how they affect animal welfare

To meet dairy farming's share in achieving global climate goals, the implementation of potent EIM strategies is crucial (Bryngelsson et al., 2016). Numerous measures have been suggested to mitigate direct emissions (e.g. Hristov et al., 2013; Knapp et al., 2014; Ndegwa et al., 2008). They affect breeding, feeding, husbandry and animal

Table 1
Mitigating potential of selected environmental impact mitigation measures (EIMM) regarding CH_4, N_2O and NH_3 emissions in dairy farming, and their implications for animal welfare.

Environmental impact mitigation measure	Emission mitigation potential			Animal welfare implications		A
	CH_4	N_2O	NH_3	Synergies	Trade-offs	
Improving production traits via genetic selection (2.2.1.) ***O:*** *Balanced selection indices, where functional traits are weighed relative to production traits*[1,2]	> 30%[3]	> 30%[3]			- Increased risk for metabolic problems, fertility decline and production diseases, such as lameness and mastitis[2,] andfor involuntary culling[4] ***Q:*** *Estimated mastitis and lameness probability in cows producing 12,000 kg (44.2%, 32.2% resp.) and 6,000 kg (17.9%, 16.2% resp.) milk*[5]	−(~)
Increasing concentrate ratio (2.2.2.) [a] ***O:*** *Provide a minimum of NDF/ peNDF in the cows' diet*[6] ***O:*** *Substitute concentrate with increased fat or protein levels in the diet*[7]	≤15%[8] ≤30%[14 *]			- Can help settle energy imbalances during transition[20] and thus improve fertility and longevity[26]	- Increasing risk for destabilisation of overall rumen health[3] (bloat, inflammation[24], acidosis[25]), foot health problems[9] and increased lameness prevalence[10],metabolic/fertility disorders due to weight gain at calving[20] ***Q:*** *0.077 and 0.021 observations of lameness per week in cows fed 11 and 7 kg of concentrate daily, respectively*[11]	−(+)
Rumen modifiers and urease inhibitors (2.2.3.) [b]				- Rumen modifiers can help lower energy losses and thus reduce metabolic stress[15]		~
Chloroform	≤50%[3 **]					
Nitrate [c]	16%[13] > 30%[14]				- Risk of nitrite toxicity[8, 13]	
Sulphate [c]	≤57%[8 **]				- Risk of toxic sulphide accumulation[13]	
Urease inhibitors		10–30%[14 ***]	> 30%[14]	- Indirect effect of urease inhibitors: decreased risk for lameness prevalence in solid-floor compared to slatted-floor systems[16]		
Fat supplementation (2.2.4.) [a, d] ***O:*** *Consider recommended limitations in total dietary DM*[14]	10–25%[17] 15%[8] 10–30%[14 ****]			- Considered safe to the animal[3] - In transition cows, 3–4% fat of dietary DM is considered beneficial for liver metabolism and health[7,18]	- Exceeded fat limit: increased risk for impaired rumen microbe balance[19], ketosis, fatty liver[20], lameness and mastitis due to weight gain[27] - Reduced diet digestibility and productivity[3, 14]	+(−)
Reducing dietary protein (2.2.5.) ***O:*** *Adjust to animal requirements*		10–30%[3, 14]	> 30%[3]	- Decreased risk for fertility decline[18], hoof disorders[21] and lameness incidence[11, 22] compared to high protein diets	- No welfare trade-offs reported as long as animal requirements are met, and the diet is balanced.	+

[a]Feeding measures to abate CH_4 emissions - their mitigation potential is largely not additive (maximum mitigation of 15%)[8].
[b]Selection of proposed supplements.
[c]Compounds need to be administered in stoichiometric proportions[8].
[d]Lipids from oil seed sources can increase the N content of the feed, thus a combination with high protein diets is not recommended[14].
[*]Concentrate inclusion levels between 35 and 40% of DMI can result in an enteric CH4 mitigation effect of up to 30% compared to a 'standard practice'[3, 14].
[**]CH_4 reduction potential is transient (given no negative impacts on milk production), due to adaptation of ruminal microbes[8].
[***]Reduction potential for indirect N_2O [3].
[****]CH_4 mitigation potential is persistent, according to the majority of studies on the persistency of the fat effect on CH_4 emission reduction[23].
A: Preliminary qualitative assessment of sustainability improvement potential of EIMM (+ potentially positive, ~ potentially neutral, − potentially negative).
O: Optimisation (EIMM adaptation in favour of welfare).
Q: Quantification (approximate quantitative effect of EIMM on AW).
[1]Bell et al. (2015), [2]Oltenacu and Broom (2010), [3]Hristov et al. (2013), [4]Rozzi et al. (2007), [5]Fleischer et al. (2001), [6]Plaizier et al. (2009), [7]Penner et al. (2009), [8]Knapp et al. (2014), [9]de Vries et al. (2015), [10]Barnes et al. (2011), [11]Manson and Leaver (1988), [12]ADAS (2015), [13]van Zijderveld et al. (2011), [14]Gerber et al. (2013a), [15]Llonch et al. (2016), [16]Rouha-Mülleder et al. (2009), [17]Beauchemin et al. (2008), [18]Roche et al. (2013), [19]Loeffler and Gäbel (2009), [20]Tamminga et al. (2007), [21]Buch et al. (2011), [22]Dijkstra et al. (2011), [23]Grainger and Beauchemin, (2011), [24]Plaizier et al. (2009), [25]Nasrollahi et al. (2017), [26]van Knegsel et al. (2014), [27]Solano et al. (2015).

Table 2
Welfare improvement potential of selected animal welfare improvement measures (AWIM) and their implications for the environmental impact (EI) of dairy farming, especially regarding CH_4, N_2O and NH_3 emissions.

Animal welfare improvement measure	Welfare improvement potential	Environmental impact implications		A
		Synergies [d]	Trade-offs	
Increasing space allowance and reducing stocking density (3.2.1.) [a] ***O:*** *Different N reducingoptions depending on flooring and manure management system (slurry-based systems[1], straw-based system[2]) – see 3.2.1.*	- Reduced risk for social stress, competitive behaviour[3,4,5], aggressive interactions[6], displacing events[7,8], injuries[6,9], and lameness due to reduced lying/ prolonged standing time[10,11,12] ***Q:*** *see 3.2.1.*	- Decreased stress benefits CH_4 reduction[13] – no stress induced reduction in FCE[14] - Decreased risk for CO_2 emissions – C sequestration potential of grassland decreases with increasing stocking rates[15 *] - Decreased risk for N_2O losses and N leaching from pasture due to reduced trampling[15 *]	- Increased risk for NH_3 emission from increased emitting surface area[2 *] - Effect on CH_4 emissions differs with grazing system[15 *] - Environmental impacts from changed land use demand[15 *]	−(~)
Increasing cleaning frequency (3.2.2.) ***O:*** *3-5 scraping events daily[7]* ***O:*** *No scraping during main feeding time[16]*	Reduced risk for claw[17] and udder health impairment[7] ***Q:*** *see 3.2.2.*	- Limited NH_3 mitigating effect due to reduced time of manure exposure and reduced contaminated area[2] - Increased scraping frequency + flushing of floors can reduce NH_3 emission by up to 65%[2].	- Increased CO_2 emissions from use of electric energy for the operation of scrapes[19] - Pre-chain emissions from changing resource demand (water, energy)[19]	+
Heat mitigation (3.2.3.) ***O:*** *Use of heat exchangers[20]*	- Reduced risk for heat stress (and associated fertility decline)[21] and metabolic stress[22], for agonistic behaviour[23] and foot health problems[9] **Q:** *see 3.2.3.*	- Benefits GHG and NH_3 mitigation from manure storage[19, 24] - No heat stress-induced reduction in productivity (DMI[25], FCE[13], fertility[21], health[26]) and subsequent increase in CH_4 and N_2O emission intensity[26]	- Increased NH_3 emissions from concrete flooring ($r = 0.66$) with increased ventilation rates for cooling purposes[19] - Increased CO_2 emissions from use of electric energy for the operation of both ventilators or sprinkling devices[19] - Pre-chain emissions from changed resource demand (energy, water)[19]	+(−)
Pasture access (3.2.4.) [b, c] ● during dry period ● 4-week grazing period ● seasonal ● (pasture-based) ***O:*** *Overnight access to pasture; use of stand-off pads*	- Decreased risk for mastitis[27], lameness[7,18], lesions[7], and social stress[3,4] and agonistic interactions[6,28] due to better withdrawal possibilities[28 **] - Comes closest to natural living conditions of cattle[29 ***] **Q:** *see 3.2.4.*	- Reduced CH_4, and N_2O emissions from manure storage[34] and reduced pre-chain emissions (especially CO_2) from feed production (including concentrate[32]) and transport compared to intensive confinement systems[34,35] - Increased C sequestration potential of grassland compared to arable land[33], potentially beneficial forsoil fertilityand water quality[15]	- Bad management can lead to increased GHGand NH_3 emissions and N leaching as a result to e.g. inadequate fodder quality[24], wet conditions and overstocking[15] - Negative effect on environmental impact category land use[34,35]	+(−)

[a]Mitigation is induced by herd management and without reducing animal numbers on the farm[15].
[b]Applicability dependent on the climatic conditions of the region[24].
[c]Good management implicit, in terms of adequately chosen stocking density, weather conditions, grazing system[15] and in accordance with the animals' nutritional demand[24].
[d]For emission mitigating potentials of improved animal welfare and productivity, see Table 3.
[*]Effects on emission levels at a constant herd size (no reduction of animal numbers)[15].
[**]Reduction potentials differ with time spent on pasture (full-time, seasonal, during dry period, 4-week grazing period; for quantification, see 3.2.4.) and space allowance[6].
[***]Access to pasture has been shown to be equally important to cows as access to fresh feed[30]. The choice for pasture or indoor housing is mainly determined by weather conditions and the time of the day[31].
A: Preliminary qualitative assessment of sustainability improvement potential of AWIM (+ potentially positive, ~ potentially neutral, − potentially negative).
O: Optimisation (AWIM adaptation in favour of emission mitigation).
Q: Quantification (for approximate quantitative effects of AWI on EI, see Table 3).
[1]Fjeldaas et al. (2011), [2]Ndegwa et al. (2008), [3]Knierim et al. (2015), [4]Proudfoot and Habing (2015), [5]Wang et al. (2016), [6]Schütz et al. (2015), [7]de Vries et al. (2015), [8]Lobeck-Luchterhand et al. (2015), [9]Irrgang et al. (2015), [10]King et al. (2016), [11]Fregonesi et al. (2007), [12]Dippel et al. (2011), [13]Llonch et al. (2015), [14]Skuce et al. (2016), [15]Novak and Fiorelli (2010), [16]Barker et al. (2010), [17]Somers et al. (2005), [18]Chapinal et al. (2013), [19]Ngwabie et al. (2011), [20]Leinonen et al. (2014), [21]Schüller et al. (2014), [22]Oltenacu and Broom (2010), [23]Schütz et al. (2010), [24]Hristov et al. (2013), [25]Karimi et al. (2015), [26]Place and Mitloehner (2014), [27]Washburn et al. (2002), [28]Charlton and Rutter (2017), [29]von Keyserlingk et al. (2009), [30]von Keyserlingk et al. (2017), [31]Falk et al. (2012), [32]Schulte and Donnellan (2012), [33]de Boer et al. (2011), [34]O'Brien et al. (2012), [35]Arsenault et al. (2009).

Table 3
Potential mitigating effect of improved animal welfare and productivity on GHG and NH_3 emissions from dairy farming.

Welfare and productivity aspects	Emission mitigation potential	Reference
Improved fertility[1]	10–16% of CH_4/ cow (21–24% of CH_4/ herd) 8% of NH_3/ cow (17% of CH_4/ herd)	Garnsworthy (2004)
Improved longevity[2]	6.9kg CO_2-eq/ cow[*] 0.044 kg CO_2-eq/ kg milk solids[*]	Bell et al. (2015)
Improved health	up to 25% of GHG/ unit of product[**]	Chatterton et al. (2014)
Lameness	30 kg CO_2-eq/ t ECM on herd level[***]	Chen et al. (2016)
Subclinical ketosis	18.4 kg CO_2-eq/ t FPCM per case	Mostert et al. (2016)
Mastitis	55.5 kg CO_2-eq/ t FPCM per case	Mostert et al. (2017)
Increased DMI	2–6% of CH_4/ kg ECM (per kg DMI increase)	Knapp et al. (2014)
Reduced animal mortality (culling rate)	≤10% of CH_4 and N_2O/ unit of product[****]	Hristov et al. (2013)

[1]Ideal fertility rate, with oestrus detection rates of 70% and conceptions rates at first service of 65% – achievable with appropriate management, nutrition and genetics.
[2]Increasing survival by 1% per lactation.
[*]Mitigating effect might be reduced due to emissions from an increased number of off-spring used for beef production (de Boer et al., 2011).
[**]Magnitude of mitigation effect depends on the disease, expressed per 1,000 litres of fat and energy corrected milk (**FPCM**).
[***]Values based on a modelled lameness prevalence reduction from 28% to 15% and an associated increase in milk yield of 1.8 kg per cow and day.
[****]Values uncertain, due to limited research.

management (Hristov et al., 2013). Two modes of mitigation may be distinguished. Abatement is induced either (1) directly via a reduction of gas formation from the animal or the manure and/ or (2) indirectly by increasing animal productivity in terms of production traits, health, longevity, fertility and production efficiency (Bell et al., 2012; Knapp et al., 2014). In livestock farming, the indirect mitigation mode is often referred to as the most effective abatement strategy (Hristov et al., 2013; Waghorn and Hegarty, 2011) with a reduction potential exceeding 30% for both CH_4 and N_2O, compared to standard practice in developed countries (Hristov et al., 2013). Generally, an increase in production output leads to an increase in total emissions per animal (Audsley and Wilkinson, 2014; Gerber et al., 2011). However, if productivity enhancement is achieved in terms of improved production efficiency, less energy is lost in form of GHG excretion and emission intensity per unit of product decreases (Bell et al., 2012; Gerber et al., 2011). The mitigating effect of indirect mitigation measures is thus constituted by a more efficient use of available resources (Llonch et al., 2015). For example, selecting for reduced RFI improves the FCE and thus the ratio of milk yield to ingested feed. More efficient cows produce more milk with the same amount of feed (Bell et al., 2012). Fewer cows are needed to produce the same amount of product, which results in a decreased number of heifers required for replacement. The so-called overhead emissions of milk production are thereby reduced, since emissions from rearing are allocated to an increased amount of milk, diluting the environmental burden of the individual (Audsley and Wilkinson, 2014; Bell et al., 2012) and emissions per unit of product decrease. EIMM operating on the direct mode of emission abatement reduce methanogenesis (Knapp et al., 2014) and the microbial transformation and hydrolysis of N in the manure (Ndegwa et al., 2008). Fewer gases are produced, thereby lowering overall gas emission. Depending on the measures used, the mitigation potential for CH_4, N_2O and NH_3 is generally expected to exceed 30% (Hristov et al., 2013). However, due to the adaptability of rumen microbes to changing conditions (Knapp et al., 2014), statistics vary greatly (Ndegwa et al., 2008), ranging from a lack of effect (Knapp et al., 2014) to a reduction of 91% for CH_4 in ruminants (Mitsumori et al., 2012).

For some EIMM, potentially negative effects on animal health and welfare have been described (de Boer et al., 2011; Llonch et al., 2016; Place and Mitloehner, 2014; Shields and Orme-Evans, 2015; Tucker et al., 2013). According to a governmentally commissioned report in the UK in 2009, an estimated 30% of existing EIMM in livestock farming are presumed harmful to the animals' well-being (Llonch et al., 2015). The Intergovernmental Panel on Climate Change (IPCC) has listed animal welfare as an area experiencing both beneficial and adverse impacts from EIM (Smith et al., 2014). For example, EIMM such as "improving feed quality" and "improving animal health" are clearly beneficial for both EIM and welfare (Hristov et al., 2013), while "selecting for improved production traits" and "increasing concentrate ratios" may increase the risk for production diseases (de Boer et al., 2011). This may not only reduce animal productivity and increase management effort but will eventually lead to a reduction of productive lifespan and thus jeopardize their mitigation potential substantially (Oltenacu and Broom, 2010). Such opposed effects are still largely unaccounted for (Leinonen et al., 2014), and an EIMM with detrimental effects on welfare loses mitigation power to a certain degree (Place and Mitloehner, 2014). Whether negative health implications of EIMM could outweigh their mitigation potential, has hardly been investigated so far. Balancing of opposed effects requires a quantitative assessment, but the few relevant synoptic studies provide only a qualitative evaluation of the welfare impacts associated with EIMM (Llonch et al., 2016; Place and Mitloehner, 2014; Shields and Orme-Evans, 2015). In the following, we therefore contrast the specific mitigation potential of welfare-relevant EIMM with a preliminary quantitative assessment of their welfare implications, especially in terms of lameness and mastitis prevalence, based on animal welfare literature (see Table 1). In case of welfare trade-offs, we highlight potential modifications of the EIMM, if available, and describe their implications for EIM and AW.

2.2.1. Improving production traits via genetic selection

For many years, selecting for increased milk production has been a common measure in dairy farming to achieve improvements in productivity (Pritchard et al., 2013). Improving production traits (such as milk yield, fertility and production efficiency) results in a significant indirect reduction of GHG emissions per unit of product (Bell et al., 2012; Gerber et al., 2011). The mitigation potential of increased productivity exceeds 30% for both CH_4 and N_2O emissions (Hristov et al., 2013), depending on the current production level (Gerber et al., 2011), the choice of system boundaries, the ratio of milk and beef production (Zehetmeier et al., 2011), the handling and value of co-products (Flysjö et al., 2011; Zehetmeier et al., 2011) and on how productivity increase is achieved in the system (Audsley and Wilkinson, 2014).

With advancements in genetic potential for primary production traits, the risk for metabolic and reproduction problems has increased as has the probability for production diseases such as mastitis and lameness (Oltenacu and Broom, 2010), further pushing the rates of involuntary culling (Rozzi et al., 2007). These negative correlations result in an overall welfare decline (Oltenacu and Broom, 2010; Pritchard et al., 2013), thus compromising the measure's mitigation potential (see Table 3). As reviewed by Ingvartsen et al. (2003), genetic correlations with lactation milk yield range from of 0.15 to 0.68 and from 0.24 to 0.48 for mastitis and lameness, respectively. Pritchard et al. (2013) found genetic correlations of yield with mastitis and lameness amounting to 0.32 and 0.38, respectively. Fleischer et al. (2001) estimated a 1% increase in mastitis and claw disease appearance probability with every 228 kg and 375 kg increase in milk yield, respectively, for the milk yield range 6,000 to 12,000 kg. Moreover, considering longevity as an independent constitutive characteristic of welfare (Bruijnis et al., 2013), negative correlations between productive lifespan and mastitis (−0.59), lameness (−0.53) or 305-day milk yield (−0.34) further underline the negative impact of increasing yield performance on welfare (Pritchard et al., 2013).

Without selection pressure on functional traits, selecting for increased milk yield would increase emissions per unit of product (Llonch et al., 2016; Lovett et al., 2006; O'Brien et al., 2010; Waghorn and Hegarty, 2011), mainly due to the decline in fertility and increased emissions from non-productive animals (Lovett et al., 2006; O'Brien et al., 2010). Balanced selection indices (e.g. economic breeding index (Schulte and Donnellan, 2010) allow for a simultaneous optimization of welfare and milk yield (Pritchard et al., 2013; Trevisi et al., 2006), by careful weighing of functional traits such as fertility, health and longevity relative to production traits (Bell et al., 2015; Oltenacu and Broom, 2010). Selection against diseases like mastitis and lameness, using direct and/ or indirect breeding measures (Barkema et al., 2015) has positive effects on longevity and fertility, although health traits are generally characterised by low heritability (mastitis: 0.04, lameness: 0.02) compared to production traits (0.29-0.34). The concurrent gain in yield (Pritchard et al., 2013) and disease resistance is therefore slow, but persistent (Barkema et al., 2015) and cumulative (Bell et al., 2015; Pritchard et al., 2013). Generally, improvements in functional traits are considered economically, ecologically and socially beneficial, due to their effects on costs, GHG emissions, and welfare improvement (Pritchard et al., 2013). According to Bell et al. (2015) a one unit change in production traits (e.g. 1 kg milk) and functional traits (e.g. 1% mastitis incidence), with increased survival and reduced milk volume, live weight, residual feed intake, calving interval, mastitis and lameness incidences can bring a 0.9% reduction in GHG emissions per unit of product as well as increased profitability (detailed, see Table 3).

2.2.2. Increasing the concentrate ratio in the diet

Increased concentrate feeding is a frequently suggested feeding measure, resulting in direct and indirect abatement success regarding enteric CH_4 emissions. The maximum reduction potential is estimated to amount to 15%, with decreases of 2% for each 1% increase in dietary non-fibre carbohydrates (NFC) (Knapp et al., 2014). The magnitude of the measure's mitigation potential depends also on the genetic yield potential of the cow (Lovett et al., 2006) and on the environmental impacts associated with the concentrate supply chain, including indirect emissions from concentrate production, processing and transportation or land use change (Lovett et al., 2006; O'Brien et al., 2012).

However, with increasing proportions of highly digestible carbohydrates in the cows' diet, rumen pH decreases (Knapp et al., 2014), notably at dietary NFC ratios exceeding 40% (Gerber et al., 2013a). While for a rumen pH of < 5.5 (sub-acute ruminal acidosis) a CH_4 emission reduction of up to 20% per unit of ECM is described, the EIM potential of reduced rumen pH and increased concentrate levels is compromised by the decline in welfare, DMI (up to 7%) and yield (up to 15%) (Knapp et al., 2014). Acidosis can also result in significantly reduced NDF digestibility, further aggravating rumen destabilisation and increasing the risk for digital dermatitis (Somers et al., 2005). Barnes et al. (2011) describe a trend for increased lameness prevalence on farms with high-yielding dairy cows fed high levels of concentrate to satisfy their increased energy demand. The estimates for lameness-induced increases in metabolic energy requirements (+0.25%), culling rate (+2%) and calving interval (+5%) as well as the reduction in milk yield (−4%) and productive lifespan (−13%) of diseased individuals compared to healthy animals by ADAS (2015) allow for a rough quantitative assessment of the expected welfare impairment (see Table 1).

To avoid digestive disorders such as bloat, inflammation of the rumen (Plaizier et al., 2009), acidosis (Nasrollahi et al., 2017) and foot disorders (de Vries et al., 2015), a minimum of 25% of NDF or physically effective NDF (peNDF) of > 16.5% in the cows' diet are recommended (Plaizier et al., 2009). Balancing the concentrate ratio in the diet in accordance with the animals' energy and rumen health requirements can be challenging in high-yielding dairy cows, especially during transition where increased amounts of starch are fed in the attempt to avoid energy imbalances (Tamminga et al., 2007) and improve fertility and longevity (van Knegsel et al., 2014). Substituting concentrate with increased fat or protein contents in the diet may help reduce CH_4 emissions and health problems related to excess NDF levels, especially during transition (Penner et al., 2009). However, the supplementation of protein works only within certain limits (see 2.2.5), without risking an increase in N emissions.

2.2.3. Feed additives (rumen modifiers) and manure additives (urease inhibitors)

The use of rumen modifiers and manure additives is discussed as a potent mitigation measure to directly reduce enteric CH_4 and N emissions, respectively. Feed additives are aimed at modifying methanogenesis in the rumen to improve the animals' energy efficiency. The CH_4 mitigation potential of feed additives is generally considered very high, amounting to up to 50% for the methanogenesis inhibitor chloroform, which is, however, a transient effect (Hristov et al., 2013). Nitrate decreases enteric CH_4 production by 16% (van Zijderveld et al., 2011) and sulphate by up to 57% (Knapp et al., 2014). There is, however, mention of associated negative implications for the safety of the treated animals and the environment (Hristov et al., 2013; Llonch et al., 2016). Regarding the feed additives fumarate, nitrate and sulphate, the risks for animal and human health result from improper administration (Shields and Orme-Evans, 2015). The transformation processes of nitrate and sulphate in the rumen can result in accumulation of nitrite and hydrogen sulphide, which are toxic to the animal (Knapp et al., 2014; Llonch et al., 2016). Despite promising results of recent research on nitrate and sulphate, Knapp et al. (2014) consider their successful supplementation as rather unrealistic, as it relies on the compliance of stoichiometric proportions and recommendations for appropriate in vivo doses are greatly lacking. Although the use of chemical agents to lower energy losses could reduce metabolic stress and improve the welfare, especially during transition (Llonch et al., 2016), feeding and breeding measures are currently recommended over the large-scale implementation of feed additives to improve productivity and health (Hristov et al., 2013; Knapp et al., 2014). Further research is needed to provide insight into the side-effects of rumen modifiers on animal welfare (Hristov et al., 2013).

Adding urease inhibitors to the manure is a very promising mitigation measure concerning NH_3 emissions from the excreta, with a reduction potential exceeding 30% (Hristov et al., 2013). They reduce the hydrolysis of urea into ammonium N. Compared to standard practice, a 10–30% reduction potential has been estimated for indirect N_2O emissions from NH_3 losses, which can, however, elicit an increase in direct N_2O emissions and CH_4 (Gerber et al., 2013a). The successful use of urease inhibitors requires the separation of faeces and urine, limiting the application to solid floor systems with separation of solids (Hristov et al., 2013). This may have indirect animal welfare implications, as the measure is no option for husbandry systems with slatted flooring and liquid manure handling, especially when combined with deep bedding in the lying area. Regarding foot health, husbandry systems with solid floors were associated with lower lameness prevalence than those with slatted floors in the walking area (28% vs. 41%, Rouha-Mülleder et al., 2009), supposedly due to the increased slipperiness of the slatted floor. Although increasing the amount of straw for bedding can generally help reduce NH_3 emissions from housing and storage, by immobilising ammoniacal N, emissions of N_2O and CH_4 from deep litter may be significant, especially under anaerobic conditions (Novak and Fiorelli, 2010). In terms of an overall emission mitigation, the application of urease inhibitors can be recommended for solid floor systems with urine drainage.

2.2.4. Fat supplementation

Increasing dietary lipids can persistently reduce methanogenesis in ruminants without decreasing yield (Grainger and Beauchemin, 2011). Estimates for CH_4 reduction efficiency range between 3.8% (Martin et al., 2010) and 5.6% (Beauchemin et al., 2008) with every 1% additional fat supplement in the diet. Beauchemin et al. (2008) describe a general reduction potential of 10–25 % in balanced diets, with differences in magnitude depending on the diet composition and its fat content (%), the lipid source and its fatty acid pattern. Expressed as a function of milk output, Martin et al. (2008) suggest a possible reduction of 54 g CH_4 per kg milk when supplementing diets of lactating cows with 5.7% of linseed oil.

The abatement potential of lipid supplementation is however limited. When exceeding the recommended limit of 6–7% fat in total dietary DM, losses in DMI and fibre digestibility can lead to reduced productivity (Martin et al., 2008), potentially counteracting or offsetting the CH_4 mitigating effect (Hristov et al., 2013). Moreover, negative health implications can be expected. The natural production of the rumen microbes is impaired (Loeffler and Gäbel, 2009) and the amount of unwanted non-esterified fatty acids can increase, potentially elevating the risk for fatty liver, weight gain, and ketosis (for associated risk of emission increase see Table 3) (Tamminga et al., 2007). Body condition scores > 3.25 have been associated with increased risk for mastitis and lameness incidence, although the highest lameness prevalence was noted for very thin cows with a score < 2 (46%) (Solano et al., 2015). Regarding transition cows, a lipid supplementation between 3–4% of diet DM is discussed as beneficial in terms of liver metabolism and health (Roche et al., 2013). This leaves only a small window for lipid supplementation as an effective means of overall emission mitigation without welfare risks.

2.2.5. Reducing dietary crude protein (CP) intake

The major feeding measure to abate N emissions from manure (Dijkstra et al., 2011) is the reduction of dietary protein. Its significant reduction potential (Audsley and Wilkinson, 2014) is due to decreased urinary N excretion (Ndegwa et al., 2008). Within limits, these decreases run linearly. According to Hristov et al. (2013), the measure's direct mitigation potential for N_2O ranges between 10–30%, and even exceeds 30% regarding NH_3 emissions, depending on the baseline level.

As long as the ruminally degradable protein is balanced in accordance to the animals' requirements, thus safeguarding unimpaired microbial protein synthesis (Gerber et al., 2013a; Hristov et al., 2013), reducing dietary crude protein intake is considered safe for the animal (Sinclair et al., 2014). While rations high in protein can have negative effects on feed intake (Hristov et al., 2013), milk yield, fertility (Roche et al., 2013), hoof disorders (Buch et al., 2011) and lameness incidence (Dijkstra et al., 2011; Manson and Leaver, 1988), with subsequent risk for emission increases (see Table 3), low dietary protein levels (140–150 g CP/ kg DM) are associated with decreased N emissions without jeopardizing the animals' health, yield level and reproduction success (Sinclair et al., 2014). Manson and Leaver (1988) even found a significantly lower occurrence of clinical lameness in hoof-trimmed cows fed a diet containing 161 g CP per kg DM, compared to not-trimmed cows fed 198 g CP. With decreasing availability of dietary CP, the cow's ability to recycle blood urea to the rumen increases (Kristensen et al., 2010). Thereby, N losses from urine can be reduced, while still guaranteeing an adequate N supply for the rumen microbes. Rumen degradable CP is usually replaced by an increased amount of starchy carbohydrates or ruminally non-degradable protein. A replacement with carbohydrates high in fibre should be avoided, as it would result in an increased CH_4 emission level (Dijkstra et al., 2011). To avoid destabilisation of the rumen pH (Hristov et al., 2013), the supplementary starch proportion needs to be balanced with the composition of the diet and its concentrate ratio. A potential win-win situation is apparent. However, caution is needed in regard to pasturing and protein replacement, as there are hardly any options for optimization. In pasture-based systems, which generally benefit the welfare of dairy cows, the low protein requirements of cows in late lactation and transition can be exceeded easily, leading to health and fertility problems (Roche et al., 2013) and increased N_2O emission levels. High levels of CP in spring grass are suspected of increasing the risk for solar lesions, although the evidence is inconclusive (Sinclair et al., 2014). Feeding supplements with low protein content may help to adjust the diet to the animals' requirements and thus reduce N excretion from urine and faeces (Luo et al., 2010).

3. Impact of animal welfare improvement on the environmental impact of dairy farming

3.1. The animal welfare status in dairy farming

The welfare of animals is usually defined as a function of their affective state, their ability to perform species-specific behaviours and their physical integrity (Fraser et al., 1997). As soon as one of these welfare aspects is compromised, the overall welfare level decreases (von Keyserlingk et al., 2009), which is often followed by a decrease in reproductive performance, life expectancy (Fall et al., 2008) and potentially milk yield (von Keyserlingk et al., 2009). Since animal health is considered the most relevant welfare aspect according to the European Food Safety Authority (EFSA) (Algers et al., 2009), we focus on lameness and mastitis incidence as important welfare indicators. Both conditions are amongst the four major health-related welfare problems in dairy farming, alongside with infertility and metabolic disorders (Ivemeyer et al., 2012) and assumed to be painful (Fogsgaard et al., 2012; Laven et al., 2008), thus negatively affecting the animal's affective state.

3.2. Measures of animal welfare improvement and how they affect the environmental impact

Animal welfare improvement measures can affect the overall EI of dairy farming and the emission potential of the individual (Llonch et al., 2015). In contrast to the perspective on EIM, in animal welfare sciences the almost undivided focus is on the secondary effect level of improvement measures, highlighting the environmental impact reducing effects of good health and welfare (see Table 3) (Llonch et al., 2016; Özkan et al., 2015). However, whether measures to improve an unfavourable welfare situation have per se an effect on the emission level, has less frequently been subject of investigation. So far, a study on endemic cattle diseases in the UK (ADAS, 2015) and a study on broiler welfare (Leinonen et al., 2014) provide the only scarce information regarding primary effects of AWIM. According to these model calculations, the environmental impact of a combination of health improvement measures is lower than the emission mitigating effect of regained health (ADAS, 2015; Leinonen et al., 2014).

Due to the beneficial effects for EIM, the secondary effects of AWIM in terms of improved health and welfare are described as co-determinant for the sector's overall sustainability (FAO, 2014; Tucker et al., 2013). Studies modelling the impact of common diseases in dairy cows on the EI of production (e.g. general: Chatterton et al., 2014; ketosis:

Mostert et al., 2016; lameness: Chen et al., 2016; mastitis: Hospido and Sonesson, 2005; Mostert et al., 2017; Özkan et al., 2015) as well as two governmentally commissioned studies on endemic cattle diseases in the UK (ADAS, 2015; Skuce et al., 2016) confirm that impaired dairy cow health can have a considerable negative impact on the emission level of the animals. Depending on the health disorder, the magnitude of GHG emission increase reaches 25% per t of milk in diseased cows compared to healthy counterparts (ADAS, 2015; Skuce et al., 2016). For mastitis, lameness and infertility, the estimated increases in GHG emissions per unit of milk and per case amount to 7%, 8% and 16%, respectively (ADAS, 2015).

In addition to health improvement, the reduction of stress serves as another strategy to improve overall animal welfare while mitigating the EI of dairy farming. By definition, stress is a condition of imbalanced homeostasis in response to internal events or external stressors, often followed by an increase in cortisol levels. It does not only result from violations of the animal's physical integrity (Backus et al., 2014), but can also be induced by other stressors such as heat (Allen et al., 2015), social factors such as deprivation of social contact, or lack of space (Proudfoot and Habing, 2015). Stress may increase the cows' metabolic rate and energy consumption (Herd and Arthur, 2009), eventually resulting in increased CH_4 and N_2O emission levels (Hristov et al., 2013). Moreover, stress affects determinants of the animals' emission potential such as feed conversion ratio and residual feed intake. According to Llonch et al. (2015), an estimated 37% of the variation in FCE can be explained by stress, with reduced FCE resulting in an increased GHG emission potential (Skuce et al., 2016). Heightened cortisol levels are associated with increased RFI, resulting in increased CH_4 emissions (Llonch et al., 2015). Stress can also affect the animal's health status. According to Proudfoot and Habing (2015), social stressors such as reduced space allowance due to overstocking or social instability may influence the incidence of diseases. For example, small collecting yards can result in agonistic behaviour near the milking parlour, which has been shown to increase the lameness risk (Barker et al., 2010).

The level of increase in GHG emissions resulting from a disease or from stress co-determines the EIM potential of curing the ailment. In general, the CH_4 and N_2O mitigation potential of health improvement in dairy cows is considered rather low compared to other options of EIM, amounting to less than 10% (Hristov et al., 2013) (see Table 3). Variations in emission levels between healthy and diseased cows are largely explained by indirect EI reduction via increased production efficiency of healthy animals, while the effect of direct emission reduction is of minor importance (1–2%) (ADAS, 2015). Increases in productivity are achieved mainly by improved fertility and longevity, rather than increased yield. In fact, the yield level of dairy cows is primarily determined by genetic and nutritional factors (von Keyserlingk et al., 2009), while the health status of the cow has a comparatively small effect on variations in milk yield (Coignard et al., 2014; von Keyserlingk et al., 2013). Still, as a cost for activating the immune system and eliciting an immune response, infected, injured or stressed animals require an increased amount of metabolic energy of up to 1%, depending on the disease (ADAS, 2015). However, illness and stress can result in reduced feed intake and reduced feed efficiency (Chen et al., 2016; Skuce et al., 2016), which puts the yield and emission level in further jeopardy (Knapp et al., 2014; von Keyserlingk et al., 2009).

Based on the knowledge about the positive effects of improved health and welfare for EIM, below we contrast the AWI potential of selected AWIM with the measures' effect on the EI potential of dairy cows (see Table 2). Quantitative estimates are provided where possible to facilitate an evaluation of their effectiveness in terms of overall sustainability improvement. In case of trade-offs, we highlight potential modification options to reduce the negative effects. As for the choice of AWIM, we focused on measures frequently suggested as beneficial to welfare in general (e.g. Fraser et al., 2013; von Keyserlingk et al., 2009) and for which environmental implications can be derived from the knowledge about emission formation. As health aspects are so far best described in regard to EI implications, changes in the welfare status are mainly expressed in terms of health changes.

3.2.1. Increasing space allowance and reducing stocking density

While the number of farms decreased over the past decades, herd sizes increased (Barkema et al., 2015; von Keyserlingk et al., 2009), often accompanied by restricted space allowances and thus increased stocking densities. These trends are considered as potentially negative for animal welfare (de Boer et al., 2011), although the relevant findings are somewhat controversial. Normal behaviour, for example, is described as a function of space allowance (Kilgour, 2012). Insufficient space for withdrawal may induce social stress and potentially injurious competitive behaviour (Knierim et al., 2015; Proudfoot and Habing, 2015). Herd size has been reported to be negatively associated with displacement frequency, supposedly due to the relative increase in space allowance per animal in larger herds (de Vries et al., 2015). Lobeck-Luchterhand et al. (2015) found reduced displacement incidence at the feed bunk at 80% stocking density compared to 100%. Although overstocking does not necessarily lead to impaired behaviour or health and productivity decline (Wang et al., 2016), more recent findings suggest, that an increase in stocking density by 10.0 percentage points above average results in an increase of severe lameness prevalence by 0.5 percentage points as well as a decline in milk yield (King et al., 2016). There is also a certain controversy regarding the relationship between space allowance and lying behaviour. While in several studies no significant association was found between stall stocking density and lying time (Charlton et al., 2014; King et al., 2016), King et al. (2017) point out a trend for reduced lying time with overstocking (> 100%). This trend is supported by the results of Fregonesi et al. (2007), who found a significant reduction in lying time to 11.2 h per day (-13%) at 150% overstocking. They also reported an increased competition for stalls in association with overstocking as well as significantly increased standing time (+17%), which has been described as a risk determinant for lameness (Dippel et al., 2011). For dairy cows, an average lying time of 12 h is recommended (Charlton et al., 2014). According to Schütz et al. (2015) cows temporarily restricted to a 3 m^2 stand-off space spent only 7.5 h lying, while at 6 m^2 lying times were similar to those detected on pasture. Aggressive interactions declined significantly (up to 35%) when increasing space allowance from 3 to 4.5 m^2 per cow in the stand-off area (Schütz et al., 2015). Similarly, Irrgang et al. (2015) showed that in horned cows space allowance in the waiting area of the milking parlour significantly affected agonistic and agitation behaviour and heart rate. Offering an area greater than 1.7 m^2 proved beneficial in terms of welfare, potentially reducing the risk for injuries and stress, especially for lower ranking cows (Irrgang et al., 2015). These findings are supported by Wang et al. (2016), who report a reduction in competitive behaviour during regrouping of cows at reduced stocking densities. Thus, despite some controversy, increasing space allowance and the avoidance of overstocking can be considered beneficial regarding the expression of normal behaviour and positive animal welfare in general.

Regarding its environmental effects, the measure potentially benefits CH_4 reduction, while it might negatively affect N emissions: Increasing space allowance is directly opposed to the EIMM of reducing the emitting surface area that offers a substantial NH_3 mitigation potential (Ndegwa et al., 2008). Avoiding stress and welfare impairment due to overstocking, however, favours CH_4 abatement (Llonch et al., 2015). On pasture, increasing stocking density can lead to an increased risk for N losses to the soil, while the effects on CH_4 emissions depend on grazing management (Novak and Fiorelli, 2010). Assuming that the demand in animal products and the yield level of the animals remain constant, a reduction in stocking density will come at the expense of an increasing demand for space, affecting other aspects of sustainability in dairy farming not further discussed in this review, notably land use change.

To reduce an increase in NH_3 emissions due to increased space, manure management measures come into play. In this article, we focused on measures with implication for the animal. NH_3 emissions can be reduced substantially via the separation of faeces and urine, which is why the following adjustment measures can prove beneficial in terms of EIM. Different floor designs and manure management systems offer various mitigation potentials. Although deep litter and solid manure handling systems generally excel slurry-based systems in terms of N_2O and potentially also CH_4 emissions from housing and storage, the associated floor design per se does not affect emission formation processes (Novak and Fiorelli, 2010). However, since in slatted systems with no bedding material nitrification processes and thus N_2O formation are low due to the largely anaerobic conditions in the slurry, slatted flooring is frequently perceived as the more favourable floor design in terms of EIM compared to solid flooring, despite potential welfare losses (de Boer et al., 2011). Regarding emissions during storage, straw-based systems might, however, offer advantages, as straw can improve the aeration of the manure and increase its C/N ratio, thus limiting the GHG and NH_3 emission potential (Novak and Fiorelli, 2010). Moreover, based on the level of urine separation, different floorings have been associated with varying NH_3 emission levels. For example, the NH_3 reduction potential of concrete flooring, either plane with manure scrapers and grooves or v-shaped with gutters, varies between 35% and 65%. An inclination of solid floors decreases the NH_3 emission potential by 21% to 50% compared to slatted or level solid floor (Ndegwa et al., 2008). According to a review by Ndegwa et al. (2008), inclined solid floors with proper urine drainage have actually been shown to have lower NH_3 emissions compared to slatted systems. They are therefore recommended as favourable in terms of both AW and NH_3 reduction (Pereira et al., 2011), especially when taking into account potential risks for foot health associated with slatted flooring as outlined by Rouha-Mülleder et al. (2009). The floor finish does not significantly affect NH_3 emission levels (Ndegwa et al., 2008). Therefore, the use of rubber topping of slatted or concrete floors for the purpose of improving walking and footing comfort (Flower et al., 2007) as well as claw health (Fjeldaas et al., 2011) can be suggested as beneficial for AW and the mitigation of direct emissions from manure. For lameness prevention, the implementation of rubber floor topping (ADAS, 2015) and mattresses in the lying area as well as reducing stocking density have been identified as cost-efficient measures with high welfare benefit (Bruijnis et al., 2012), compared to measures requiring capital investment for new building design. Still, while changes in stocking density are not directly associated with primary EI, changes in demand for land and the energy demand and cost for producing the rubber overlay need to be taken into account in a comprehensive evaluation of the total emission potential of this measure. ADAS (2015) estimated the overall EI of lameness intervention measures (including the use of rubber mats) at less than 2% per unit milk. Due to the rather small secondary effect of improving lameness on the EI potential of the animals, amounting to 1–2% per animal treated, the emission mitigating effect of curing lameness is lower than expected (ADAS, 2015). Although no comparable assessment has been done yet regarding space allowance per se, these results indicate, that the overall EI of the AWIM is not negligible, which underlines the importance of further research to quantitatively evaluate the measure with regard to both effect levels.

3.2.2. Increasing cleaning frequency

Cleanliness in dairy cows is a key determinant of hygienic milk production, animal health, and overall animal welfare. In addition to being a function of the housing and bedding type (Hauge et al., 2012), the level of cleanliness is determined by the cleaning routine. The frequent use of automatic manure scraping devices for manure removal from the alleys can help to keep the floors dry and clean and thereby reduce the negative effects of unhygienic environment on claw health (Somers et al., 2005). A 1-unit increase in scraping frequency reduced the odds for severe lameness (OR = 0.72, CI = 0.53–0.97, $p = 0.03$) (Chapinal et al., 2013), while a reduction in scraping frequency has been reported to result in an increased risk for both impaired udder and foot health (DeVries et al., 2012). Conflicting findings are reported by Barker et al. (2010), who found a negative association between scraping frequency and foot health. They ascribe these results to an increasing risk for collisions with the approaching scraper, an effect more pronounced during the main feeding period (Barker et al., 2010). As a guiding value, a scraping frequency of 3–5 scraping events daily can be recommended, for which the odds for antagonistic displacements have been found to decrease significantly (OR = 0.54, 95% CI = 0.37–0.78, $p = 0.00$) compared to less than 3 scrapings per day (de Vries et al., 2015), suggesting a reduction in social stress.

Aside from the positive effects of improved floor cleanliness on animal welfare, frequent scraping is generally beneficial in terms of NH_3 emission reduction, as it limits the time of manure exposure (Ndegwa et al., 2008; Ngwabie et al., 2011) and reduces the contaminated surface area (Ndegwa et al., 2008). The time intervals from manure excretion to its removal is recommended to be below 6 h (Pereira et al., 2011). The mitigating potential of scraping is however limited. Increasing the number of scraping events from 12 times to 96 times per day reduced NH_3 emissions by only 5%, which might not outweigh the extra scraping efforts. However, when combining scraping with flushing of floors with water every 2–3 hours, the overall NH_3 reduction potential amounts to 65% in sloped floor systems (Ndegwa et al., 2008). Since other emission influencing factors such as the distribution of urine and faeces (see 3.2.1.), air temperature and ventilation rates (see 3.2.3.) can vary greatly between different systems and cattle housing in general, the extrapolation of presented emission values and mitigation potentials to large-scale dairy production generally needs to be handled with caution (Pereira et al., 2011). Although data for a more detailed quantification is not available to date, the frequent cleaning can generally be considered positive in terms of both AWI and EIM. For a comprehensive assessment of the measure's impact along the whole supply chain of a system, additional resource use (e.g. energy, water) needs to be considered.

3.2.3. Heat mitigation

The environmental temperature affects the behaviour of dairy cows (Karimi et al., 2015; Ngwabie et al., 2011). Activity decreases with increasing temperature (Ngwabie et al., 2011) and cows spend more time standing (Allen et al., 2015; Karimi et al., 2015). Prolonged standing has being reported hazardous to claw health and a risk factor for lameness (Dippel et al., 2011). Moreover, feeding behaviour changes, which may cause up to 37% loss in feed efficiency (Llonch et al., 2015). DMI decreases considerably, as do ruminating and chewing, which results in declining milk yield and health (Karimi et al., 2015), such as an increasing risk for subclinical forms of acidosis (Abdela, 2016). At a constant yield level, decreasing DMI can further result in negative energy balance and metabolic stress (Oltenacu and Broom, 2010). Thermal comfort in dairy cows is commonly determined using the temperature-humidity index (**THI**) (Charlton and Rutter, 2017), with a value of 71 marking the critical upper threshold for beginning heat stress. At THI values above 73 reductions in conception rate by up to 39% and severe economic losses have been reported (Schüller et al., 2014). In a controlled environment with an average THI of 69.7, cows not receiving cooling through sprinklers and fans experienced heat stress and showed a reduction in DMI and yield of 1.8 kg and 4.1 kg per day, respectively (Karimi et al., 2015). Thus, heat stress abatement can positively affect fertility and improve activity and milk yield. Schütz et al. (2010) also reported a reduction in agonistic behaviour in cows on pasture when provided with more shade.

Due to the positive effects on welfare and performance, the environmental impact of non-heat stressed animals is likely to be lower, compared to heat-stressed cows (Place and Mitloehner, 2014). Considering the findings of Karimi et al. (2015), a reduction in DMI of 1.8 kg per cow and day would equal an increase in CH_4 emission potential of up to 12%, according to the review of Knapp et al. (2014). In contrast, with thermal comfort, DMI and activity return to normal and a comparatively decreased CH_4 production relative to intake (Ngwabie et al., 2011). The risk for increasing CH_4 and N_2O emissions per unit of product associated with the reduction of fertility as a result to heat stress (Garnsworthy, 2004) further substantiates the advantages of thermal management for EIM (see Table 3). An effective reduction in air temperature is also beneficial regarding GHG and NH_3 mitigation (Hristov et al., 2013; Ngwabie et al., 2011). CH_4, CO_2 and NH_3 emissions from the manure decrease significantly with a temperature reduction from 35 °C to 5 °C, irrespective of floor type. However, since increased ventilation rates for cooling purposes directly boost ammonia volatilization, NH_3 emissions from concrete flooring may rise considerably. Moreover, the use of both ventilators or sprinkling devices for cooling requires electric energy and water, translating to increased CO_2 emissions, increased costs as well as chain emissions from production and transport of devices (Ngwabie et al., 2011). For a detailed quantification of the primary effects of heat abatement measures on total emission in dairy farming, further research is needed. Findings in poultry farming, however, suggest that the use of heat exchangers could keep additional energy requirements comparatively low (Leinonen et al., 2014). Thus, heat management could generally benefit total emission mitigation, depending on the region and the efforts required for cooling.

3.2.4. Pasture access

Access to pasture combined with indoor feeding as well as pasture-based production systems are often mentioned as beneficial for animal health and welfare. While depending on regional climatic conditions fully pasture-based systems may not be realizable everywhere (Hristov et al., 2013), on many dairy farms the benefits of temporary access to pasture can be used (von Keyserlingk et al., 2009). According to Algers et al. (2009), the risk for mastitis infection is lowest on pasture, while in indoor-housed cows Washburn et al. (2002) found clinical mastitis to occur 1.8 times more often and mastitis related culling rates were 8 times higher compared to cows in pasture systems. Access to pasture has also repeatedly been identified as beneficial in terms of claw lesions and lameness prevalence (see Table 2) (Chapinal et al., 2013; Hernandez-Mendo et al., 2007; Rutherford et al., 2009). This effect is supposedly due to adequate surface conditions (Hernandez-Mendo et al., 2007). Compared to zero-grazing systems, cows with seasonal access to pasture showed a decreased prevalence of lesions and swellings on the whole body (OR = 0.41, CI = 0.27–0.61, at p = 0.00) as well as lower lameness prevalence (OR = 0.68, CI = 0.51–0.90, p = 0.01) (de Vries et al., 2015). The mere introduction of a 4-week grazing period already improved the gait score of lame individuals, compared to control cows in free-stall housing (Hernandez-Mendo et al., 2007) and in farms providing access to pasture during the dry period, the prevalence of clinical lameness was significantly lower than in entirely zero-grazed herds (OR = 0.52, CI = 0.32–0.85, p = 0.01) (Chapinal et al., 2013). Aside from health benefits, pasture is often perceived as a welfare-friendly housing environment, as it comes closest in displaying the natural living conditions of cattle (von Keyserlingk et al., 2009). Providing overnight access to pasture correlates with the preference pattern (Falk et al., 2012; von Keyserlingk et al., 2017), while with increasing THI and rainfall cows prefer to stay indoors (Falk et al., 2012). As pasture is considered to provide more space relative to indoor-housing, the opportunities for exercise and behavioural expression are amplified, aiding the welfare aspects of natural living and affective states. The low levels of agonistic interactions on pasture are believed to be due to better possibilities for withdrawal and maintaining the inter-individual distances (Charlton and Rutter, 2017).

In temperate regions, emission levels in well managed pasture-based systems are generally low (Chobtang et al., 2017), while providing seasonal access to pasture and grass-based diet can help to reduce the overall EI of housed dairy cows, when combined with a significant reduction of concentrate use (Arsenault et al., 2009; O'Brien et al., 2012). According to a study on the marginal abatement costs for mitigation measures in Irish agriculture, every one day increase in the grazing season resulted in a 0.17% reduction in GHG emissions per unit of milk. During the time spent on pasture, CH_4, and N_2O emissions from manure storage are reduced, as are CO_2 emissions, since less energy is spent on feed production (O'Brien et al., 2012) and animal management in the barn. Efficiently managed, pasture is an economic option for sustainability improvement in dairy farming (Schulte and Donnellan, 2012), as it functions also as a sink for soil carbon sequestration due to the lower tillage-induced disturbance (de Boer et al., 2011). Good management involves the choice of adequate stocking density and weather conditions, the grazing system (Novak and Fiorelli, 2010) and the number of cuttings (MacLeod et al., 2015), with the objective of avoiding soil erosion and degradation (de Boer et al., 2011) and optimizing the nutritional supply of the animals (Gerber et al., 2013a).

The risk for CH_4 emissions and N losses from pasture can be reduced by improving the fodder quality and matching the CP and fibre levels of the grass with the animals' requirement (Gerber et al., 2013a; Hristov et al., 2013). This can be a challenging task in pasture-based systems, however supplementing low-protein feed has been described as an option to reduce N excretion (Luo et al., 2010). To additionally minimize the risk for elevated N_2O emission levels and N leaching, the use of run-off pads and restricted grazing are recommended as management options in winter and during wet conditions (Luo et al., 2010). This reduces excreta input to soil and groundwater as well as soil compaction through treading damage and thus benefits pasture growth in spring. In pasture-based systems, a reduction of grazing time from 24 h to 6 h per day in winter can reduce N_2O-N emission per ha by 39%, while total N losses may be reduced by up to 60% compared to year-round grazing via stand-off pads or grazing restriction (Luo et al., 2010). Generally, the N surplus on pasture increases with increasing stocking density (Novak and Fiorelli, 2010), especially during autumn prior to freezing, when the freeze-thaw cycles of the soil promote N loss (Hristov et al., 2013).

4. Concluding discussion

The implementation of emission mitigating measures and the restoration and maintenance of good animal welfare have been suggested as effective approaches to make modern dairy farming more sustainable. Numerous measures have been proposed for both AW improvement and EI mitigation. In response to the repeated call for an integrated and quantitative assessment of the complex interdependencies resulting from the manipulation of either the AW state or the EI level (see de Boer et al., 2011; Llonch et al., 2015), we contrasted the mitigation potential of selected EIMM with quantitative results from the animal welfare literature for a preliminary evaluation of their impact on welfare. Similarly, we attempted to interpret the quantitative welfare improvement potential of AWIM against the backdrop of the underlying modes of EIM and factors influencing the emission potential, to determine potential environmental trade-offs.

Regarding the impacts of **EIMM** on AW in particular, endeavours for mere genetic yield enhancement without due consideration of their implications for correlated fitness traits, the use of increasing dietary concentrate ratios and of feed additives with potential health impact are potentially harmful to welfare. This is especially true for most developed countries since production levels are already very high. Measures operating on the indirect mitigation principle can contribute to the risk of production diseases and thereby counteract EIM due to declining health. However, when simultaneously taking welfare relevant aspects such as functional traits into account, their mitigation potential might be safeguarded. Selection for reduced RFI and CH_4 emissions can serve as an overall positive measure to improve sustainability, as long as the DMI is balanced with the animal's yield potential to avoid an increase in emissions as a result of increased metabolic stress and subsequent health decline. Compensating reduced DMI with excess concentrate ratios in the diet is not a viable option, however, fat supplementation can help to cover the animals' energy requirement. In general, fat supplementation and protein reduction do not pose direct threats to animal welfare, as long as physiological requirements associated with their genetic potential are met. Precision feeding and selection for simultaneous increase of yield and fitness can be considered as comprehensive measures of sustainability improvement.

As for **AWIM** in particular, hardly any data on EI implications is available so far. However, as outlined above for selected measures, no major shortcomings in terms of EIM may be expected as long as adequate housing design and manure management measures are implemented. Although increasing space allowance can lead to increased NH_3 emissions, frequent cleaning as well as adequate temperature management and housing characteristics, like v-shaped concrete flooring with gutters for urine separation, can counteract this trend, in accordance with conditions beneficial for animal welfare. The extra effort for increased cleaning frequency and cooling do not seem to outweigh the positive effects of these measures on AW and EIM, although further research is needed to substantiate this assumption. Providing access to pasture is considered positive in terms of both AWI and EIM. Again, an adequate management in due consideration of weather condition and growth stages of vegetation can limit the potential risk for increased N emissions from pasture due to leaching. Especially overnight access to pasture during dry weather corresponds with the cows' preference pattern and benefits their overall welfare without negative implications for yield and emission potential.

The quantitative evaluation of impacts as attempted in this review provides only an approximate and preliminary insight into the range of effects that can be expected. Regarding the welfare impacts of EIMM on the one hand, a semi-quantitative evaluation was possible for increasing milk yield and concentrate ratio, while no quantitative evaluation of the effect of rumen modifiers on animal welfare could be derived from the existing literature. When reducing the protein content or increasing the fat content of the diet, critical thresholds mark the beginning of potential welfare trade-offs, yet without further specification of their quantitative magnitude. Regarding AWIM on the other hand, implications for EI have been found, but a quantitative evaluation of effects was largely not possible. In the case of an increase in space allowance, this is due to the qualitative nature of the measure. Despite being a welfare determining aspect, increasing space allowance is expressed relative to an existing unfavourable situation rather than tied to absolute values, for which emission potentials could be calculated. In the case of heat abatement, which may be described as beneficial in terms of EIM since emissions from manure are a function of temperature, further assessments of the impact of different THI levels on emission formation could help to specify the EI potential of this measure.

Considering the **EI** of EIMM and AWIM **in a broader sense**, notably regarding changes in indirect emissions (e.g. from production and transport of goods) and resource use (e.g. land, water and energy), allows for a more integral evaluation of the effectiveness of particular measures on the global level and includes aspects such as land use change, deforestation, acidification, eutrophication, and biological integrity. For example, the EIM potential of feeding concentrates is burdened with additional CO_2 and N_2O emissions from production and delivery of additional concentrate feed (Gerber et al., 2011; Lovett et al., 2006). Emissions following land use change (conversion of forest and native grassland into arable land), either abroad or at the national level, may require several years "pay-back time" before annual emission reduction due to concentrate supplementation comes into effect (de Boer et al., 2011). Regarding the increasing reliance on grazed grass in the cows' diet via pasture access, manure storing time decreases as do contributions to indirect emissions from external inputs, including concentrate feeds, fertilizers, electricity, and transport fuels. When expressed per unit of product, pasture-based systems have thus been found to perform better regarding the environmental aspects global warming, acidification and eutrophication potential, compared to intensive confinement systems. When expressed per unit of total farm area, all environmental impacts but global warming were lower in the pasture-based system. Moreover, temporary or continuous pasturing can have a negative effect on the environmental impact category land use (Arsenault et al., 2009; O'Brien et al., 2012) and potential impacts of intensive pasture use on farm biodiversity still require evaluation (Arsenault et al., 2009). However, converting arable land to grassland can help to store additional carbon in the soil, which in turn might benefit soil fertility and water quality (de Boer et al., 2011; Novak and Fiorelli, 2010).

Managing all factors determining an animal's emission potential is complex and challenging, especially when combining EIMM with AWIM. To balance synergetic and antagonistic effects of measures of EIM and AWI, including direct and indirect emissions and in regard to various aspects of environmental impact of dairy farming, the use of integral methodologies such as life-cycle-assessment **(LCA)** is recommended (de Boer et al., 2011; Llonch et al., 2015). Customised measures of EIM and AWI can be identified that fit specific production conditions with a given starting point regarding the status of EI and AW. Moreover, when combining multiple measures, LCA can help to identify additive mitigating effects and consider risks for emission increases form trade-offs between different measures (Luo et al., 2010; Novak and Fiorelli, 2010), thus avoiding emission shifting between systems along the supply chain (de Boer et al., 2011).

In conclusion, we advocate considering AWI and EIM as two equally important and interdependent aspects of sustainability in dairy farming. Further research is needed to elaborate the welfare implications of EIMM and especially the EI of AWIM, notably in regard to quantification. We endorse the use of integral quantitative methodologies such as LCA as a tool to balance the synergetic and antagonistic interdependencies of EIM and AWI on the animal and on the farm level, to identify customised integral EIMM and AWIM. Future assessments should further consider potential impacts of the implementation of AWIM and EIMM along the total dairy supply chain and in regard to other aspects of the dairy farm's environmental impact, such as acidification, eutrophication, and land use. Ultimately, an inclusion of economic and social aspects of sustainability in future assessments would complement the evaluation of specific measures in regard to their practical relevance and thus facilitate decision making with regard to more sustainable dairy farming.

Declaration of interest

None.

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5.2 Paper 2: The effect of rubber flooring to improve cow welfare on environmental impacts of milk production – a case study for Austria

Welfare intervention and environmental impacts of milk production - cradle-to-farm-gate effects of implementing rubber mats in Austrian dairy farms

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Welfare intervention and environmental impacts of milk production – cradle-to-farm-gate effects of implementing rubber mats in Austrian dairy farms

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ABSTRACT

While the environmental impacts of common health disorders in dairy cattle such as lameness have recently been assessed, the effects of specific welfare intervention measures on emissions from dairying are unknown. This study aimed at estimating the impact of lameness intervention through implementation of rubber mats in alleyways on the contribution potential of milk production to global warming (GWP), terrestrial acidification (TAP), freshwater and marine eutrophication (FEP, MEP), as well as to the use of non-renewable and renewable energy resources (nRER, RER). Using life-cycle assessment, the environmental impacts of two model farms in different production areas of Austria (highlands, lowlands) were estimated before and after the implementation of rubber mats. Productivity shortfalls due to lameness in the baseline scenario (S_{basic}) were assumed to be reduced by 50% through improved flooring in the intervention scenario (S_{mats}). For S_{basic} of the highland system, GWP, TAP, FEP, MEP, nRER and RER were estimated at 1.2 kg CO_2-, 22.9 g SO_2-, 0.1 g P-, 3.7 g N-, 2.2 and 18.4 MJ-equivalents per kg milk, respectively. In S_{mats}, significant changes in impact levels were only found for TAP (−1.4%), nRER (+2.5%) and RER (−0.8%) ($\rho \leq 0.001$). For the lowland system, results were of similar, but slightly lower magnitude. In both systems, TAP, MEP and RER estimates proved insensitive to changes in mat durability, due to a negligible impact of emissions associated with the production of mats ($\leq$0.05%). Varying the assumed lameness reduction potential of mats had a proportionate effect on all categories. Considering the effectiveness of soft flooring in reducing physical trauma, the benefits of rubber mats for emission mitigation can be expected to be more pronounced in the case of sole ulcers rather than digital dermatitis. In conclusion, although a significant mitigating effect was shown for TAP and RER only, the findings indicate the potential of health and welfare improvement measures to mitigate emissions from dairy farming or to at least outweigh the environmental costs of their implementation. However, a comprehensive, primary data-based assessment of other intervention measures is needed to substantiate a general benefit of welfare intervention measures for sustainable dairy farming.

1. Introduction

Dairy farming has a considerable impact on environmental resources and services such as air, soil, water and biodiversity and contributes significantly to their degradation, pollution and loss (Hristov et al., 2013; Novak and Fiorelli, 2010). Among other environmental impacts, the average contribution potential of European specialized dairy farms to global warming (**GWP**), terrestrial acidification (**TAP**), freshwater and marine eutrophication (**FEP, MEP**) has recently been estimated to be 1.2 kg CO_2-, 26.1 g SO_2-, 1.1 g P- and 8.1 g N-equivalents (e) per kg of fat- and protein-corrected milk (**FPCM**), respectively (Mu et al., 2017). Average non-renewable energy resource demands (**nRER**) amount to 3.3 MJ-e/kg of energy-corrected milk (**ECM**) (Guerci et al., 2013). Impacts can vary

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greatly depending on region, system type and methodological choices (Baldini et al., 2017). For example, GWP in European farms ranges between 0.8 and 1.8 kg CO_2-e/kg FPCM (Mu et al., 2017), thus confirming earlier reviews (Fantin et al., 2012; Hietala et al., 2015). For Austrian production systems, a narrower range of 0.9–1.17 kg CO_2-e/kg ECM has been described (Hörtenhuber et al., 2010).

Among other measures to mitigate the environmental impact of dairy production, such as the implementation of manure digestion to mitigate GHG emissions (Battini et al., 2014) or the frequent cleaning of surfaces to reduce ammonia emissions (Ndegwa et al., 2008), good animal health and welfare have been suggested to lower impacts (Hristov et al., 2013; Llonch et al., 2016). Recent studies confirmed an increase in emissions due to common cattle diseases, such as lameness, ketosis and mastitis (Chen et al., 2016; Mostert et al., 2018a; Özkan Gülzari et al., 2018). Lameness is among the most relevant health and welfare issues in dairy farming. It is a painful condition of multifactorial aetiology with detrimental economic implications due to productivity losses, fertility decline and an increased culling risk (Bicalho et al., 2009; Huxley, 2013). Reduced productivity leads to increasing environmental impacts per unit of product since individual relative maintenance costs increase and the production of a constant milk amount requires more animals (Knapp et al., 2014). Per case of foot lesion, GWP increased on average by 1.5% per unit of product, with variations depending on lameness cause and associated changes in milk yield, calving interval and culling risk (Mostert et al., 2018b), while an increase in lameness prevalence of 55% resulted in an increase of GHG emissions by up to 7.8%, depending on the severity of the disease. For TAP and FEP, respective estimates amounted to up to 9.4% (Chen et al., 2016).

The knowledge about potential impacts of welfare improvement measures on the environmental performance is very limited (Herzog et al., 2018). While a single report described a less than 2% increase in GHG emissions per unit of product for a combination of lameness intervention measures (ADAS, 2015), the impact of single measures has not been calculated yet (Herzog et al., 2018). Implementation of soft flooring is a frequently suggested intervention measure to improve locomotion and reduce the risk for trauma (Chapinal et al., 2013; Haufe et al., 2009), lesions and lameness (Ouweltjes et al., 2009). The effect is due to higher compressibility and friction on rubber mats compared to concrete (Rushen and de Passillé, 2006). Improved grip can further benefit oestrus and comfort behaviour and cow activity in general (Platz et al., 2008). With improved locomotion, eating time and feed intake increase (Bach et al., 2007) and lameness-induced yield depressions decrease, depending on the type and severity of the foot lesion (Ouweltjes et al., 2009).

In contrast to a change in cleaning (Barker et al., 2012) and claw trimming routines (Ouweltjes et al., 2009), the implementation of rubber mats is associated with environmental costs for additional barn equipment (material, energy). This raises the question of potential trade-offs between the required resource input and the emission mitigating effect of increased productivity due to lameness reduction. Therefore, the objective of the present study was to estimate the effects of introducing rubber mats in alleyways on the environmental impact of milk production in terms of GWP, TAP, FEP, MEP, nRER and RER.

2. Material and Methods

Based on life-cycle assessment (**LCA**), the environmental impact potential of cows in two modelled dairy production systems (**PSs**) was compared before and after the implementation of rubber mats, using Monte-Carlo simulations. While cows in the baseline scenario $\mathbf{S_{basic}}$ were assumed to be lame, for the intervention scenario $\mathbf{S_{mats}}$ a 50% reduction of lameness-induced shortfalls in milk yield, fertility and longevity was considered as well as respective material and energy requirements for the production of the mats and their disposal.

2.1. Dairy production systems (S_{basic})

The two modelled PSs represent typical production conditions in the highland and lowland regions of Austria and differ mainly in production intensity and feeding regime (Table 1). The highland production system (**PS H**) is defined as a low input system in the alpine region of the country, where climatic conditions are ideal for pasture. The lowland production system (**PS L**) is representative of more favourable production conditions in the north-eastern part of the country. Production intensity is higher compared to PS H. All modelling assumptions are based on data retrieved from national statistics and complemented by expert opinion.

Differences between PSs in forage yields and forage quality are mainly due to differences in altitude, which also determines the grass- and cropland ratio, time of harvest and cutting frequency in each system (Table 2). Nutrient and energy contents were derived from feed composition tables and adjusted for harvesting losses (DLG, 1997). Average gross yields obtained per ha of grassland were 7.5 t and 8.2 t of dry matter (**DM**) in PS H and PS L, respectively, with an average forage energy density of 5.92 and 5.97 MJ NEL/kg DM. Based on the stocking density in each PS, forage yields per animal were calculated. Shortfalls regarding the fulfilment of energy demand per animal determined the amount of purchase feed. In both systems, total forage demand is covered from on-farm production. In terms of concentrates, PS H completely relies on off-farm purchase, while PS L is partially self-sufficient.

Feed composition (Table 2) reflects national cultivation practices (IACS, 2015) and was defined relative to the grass-to cropland ratio per PS and to region-specific gross yield levels. Ration ingredients of dairy cows included forage (grass, hay, grass silage, maize silage, clover-grass silage) and concentrate (wheat, barley, triticale, rape seed and sunflower seed meal, dried distiller's grain). The overall percentage of forage per kg of diet DM was higher in PS H (90%) than in PS L (78%), corresponding to shifts in the proportion of concentrates and silage. PS H was designed as a system with a 23% share of pasture in the forage diet, while the zero-grazed cows in PS L were offered green fodder indoors. Diets were balanced with regard to the performance-related nutritional requirements of the cows, as calculated following nutritional recommendations (GfE, 2001). Daily energy requirement per dairy cow was 108.3 MJ NEL in PS H and 116.6 MJ NEL in PS L (Table 1).

2.2. Calculation of emissions

Based on daily DM intake, the animals' nutrient intake was calculated (Table 3). It served as a basis for the calculation of CH_4, N_2O, NH_3 and NO_x emissions from the animals and their manure. Emission calculation included prorated emissions from rearing and dry period and followed established international guidelines (IPCC, 2006a, 2006b) and national calculation schemes (EAA, 2014). Emissions associated with feed production (resources, cultivation, harvesting, processing) and energy requirements (fossil fuel, electricity) were resumed from the inventory database (see section 2.3), while emissions resulting from production and use of pesticides and fertilizer were derived from approximations described in Quantis et al. (2012). $\mathbf{CH_4}$ emissions from **enteric fermentation** were calculated following the equation of Kirchgessner et al. (1995) and amounted to 191 kg and 182 kg CH_4/cow.year for S_{basic} in PS H and PS L, respectively, prorated emissions from rearing and dry period included (Table 4).

Table 1
Key characteristics of PS H and PS L regarding land use, animals and housing system.

Characteristics	PS H	PS L	Reference
Production area	highland	lowland	STAT, (2014)
Grassland to cropland ratio (%)	80:20	50:50	IACS, (2015)
Stocking density (cows/ha)	1.2	1.5	IACS, (2015)
Annual milk yield per cow (kg ECM)	7,000	8,000	ZuchtData, (2017)
Body weight per cow (kg)	700	750	ZuchtData, (2017)
Productive lifespan (years)	3.81	3.81	ZuchtData, (2017)
Calving interval (days)	391	391	ZuchtData, (2017)
Energy demand (MJ NEL/day)	108.3	116.6	GfE, (2001)
Housing system	free-stall	free-stall	Amon et al., (2007a)
Outdoor run	yes	no	Amon et al., (2007a)
Manure management system	slurry	slurry	Amon et al., (2007a)
Pasture access (days/year)	180	-	Steinwidder and Starz, (2015)

Table 2
Feed production characteristics and diet composition in PS H and PS L, according to on- and off-farm supply of forage and concentrates.

Characteristics	PS H	PS L
Number of cuts of permanent grassland/clover leys[a]	3	4
Gross yields of permanent grassland/clover[a] (t DM/ha)	7.5/10	8.2/11
Mean energy density of forage[b] (MJ $_{NEL}$/kg DM)	5.92	5.97
Mean energy density of concentrate[c] (MJ $_{NEL}$/kg DM)	8.23	7.84
Concentrate ratio in diet[d] (% of DM)	11	22
in % of forage DM produced on-farm		
Grass silage	42	34
Hay	15	8
Green fodder	0	8
Pasture	23	0
Clover-grass silage	20	10
Maize silage	0	20
Wheat grain	0	7
Barley grain	0	13
in % of concentrate DM produced off-farm		
Wheat grain	22	23
Barley grain	45	46
Triticale grain	29	0
Rape seed meal[e]	2	16
Sunflower seed meal[e]	1	6
Dried distiller's grain[f]	1	9

[a] Buchgraber and Gindl, 2009,
[b] Resch et al., 2010,
[c] DLG, 1997,
[d] GfE, 2001.
[e] solvent extracted,
[f] with solubles.

Table 3
Average nutrient intake and proportion of daily dry matter intake per dairy cow in PS H and PS L.

Type	Unit	PS H	PS L
Crude fibre	kg CF/day (%)	4.00 (23)	3.70 (21)
Nitrogen-free extracts	kg NfE/day (%)	8.61 (49)	9.58 (53)
Crude protein	kg CP/day (%)	2.72 (16)	2.75 (15)
Ether extracts	kg EE/day (%)	0.43 (2)	0.50 (3)
Ash	kg/day (%)	1.76 (10)	1.53 (8)
Total dry matter intake	kg/day	17.52	18.07

Annual manure emissions per cow were estimated based on the amount of excreta in each PS, which depended on the animals' yield level (Pommer et al., 2014), and on the location of excretion (PS H: 72% barn, 12% outdoor run, 16% pasture; PS L: 100% barn). Calculations of manure CH_4 and direct and indirect N_2O emissions followed IPCC tier 2 methods for country-specific excretion rates (Table 4). Regarding the estimation of **manure CH_4**, the parameter volatile solids was estimated depending on gross energy intake and digestibility of organic matter in the diet, following eq. 10.24 (IPCC, 2006a). Methane conversion factors (MCF) for emissions from pasture and outside run were taken from IPCC, 2006a. For slurry emissions, a national MCF was available, accounting for temperature-dependent variation in emissions per area (Amon et al., 2007b). Differences in the proportion of manure excreted on pasture and in the outdoor run (PS H) were taken into account using weighted emission factors (EF) (Supplementary Table 1).

Regarding the estimation of **direct N_2O from manure storage,** country-specific nitrogen excretion rates (N_{ex}) were calculated based on the uptake of dietary CP minus N transferred into products (milk, calves) (Gruber and Pötsch, 2006). For emissions from slurry and pasture default EFs were applied (IPCC, 2006b), while yard emissions where accounted for based on a national EF (EAA, 2014). Regarding the estimation of **indirect N_2O** emissions, an IPCC recommended default EF was used (IPCC, 2006b). Values for NH_3 and NO_x volatilization from housing, pasture, storage and field application were derived as a fraction of N_{ex}, using national EFs for liquid manure management (EAA, 2014). N and P losses from storage and outdoor run were considered to be zero, as national environmental regulations stipulate run-off free management of manure excreted in the yard, while storage tanks are required to be impermeable and covered in order to avoid emissions (EAA, 2018). N and P emissions from pasture and feed production are considered in the respective datasets of the inventory database (see section 2.3) and were therefore not specifically outlined in Table 4.

2.3. Life-cycle assessment

The assessment of environmental impacts followed the normative guidelines ISO 14040 and 14044 for LCA (ISO, 2006a, 2006b) and was based on the functional unit of 1 kg ECM (Sjaunja et al., 1991). The cradle-to-farm gate perspective defined the system boundary (Fig. 1) and attributional modelling was chosen to facilitate the comparison of results with the literature. The co-product meat from surplus calves and cull cows was considered using biophysical allocation. Allocation factors were calculated as a function of the cows' energy requirement to produce milk and meat (Table 4), reflecting yield level and live weight of the cull cow and offspring relative to productive lifespan (IDF (International Dairy Federation), 2010). Since manure was completely recycled for feed production, allocation was not required (LEAP, 2016). All calculations were conducted with the open source software openLCA v1.7.2 (GreenDelta, 2018) in combination with the cut-off system model of the inventory database ecoinvent v3.2 (Wernet et al., 2016).

For the inventory modelling, inputs and outputs of the process "milk production, from cow | cow milk" in ecoinvent (Wernet et al.,

Table 4
Emissions from enteric fermentation and manure management (rearing and dry period included) as well as applied allocation factors (AFs) for S_{basic} and S_{mats} of PS H and HS L. Values for PS H include prorated emissions from pasture and outdoor run.

Emissions/AFs	Unit	Scenario	PS H	PS L	Reference
$CH_{4\ enteric}$	kg/cow.year	S_{basic}	190.59	181.85	Kirchgessner et al., (1995)
		S_{mats}	189.34	180.57	
$CH_{4\ manure}$	kg/cow.year	S_{basic}	21.74	31.12	IPCC, (2006a) (eq. 10.22)
		S_{mats}	21.58	30.92	
N_{ex}	kg/cow.year	S_{basic}	155.61	146.72	Gruber and Pötsch, (2006)
		S_{mats}	154.33	145.91	
$N_2O_{\ direct}$	kg/cow.year	S_{basic}	1.79	1.15	IPCC, (2006a) (eq. 10.25)
		S_{mats}	1.78	1.15	
$N_2O_{\ indirect}$	kg/cow.year	S_{basic}	1.11	0.93	IPCC, (2006a) (eq. 10.27)
		S_{mats}	1.10	0.92	
NH_3	kg/cow.year	S_{basic}	64.98	53.87	EAA, (2014)
		S_{mats}	64.44	53.57	
NO_x	kg/cow.year	S_{basic}	5.48	5.05	EAA, (2014)
		S_{mats}	5.44	5.03	
AF_{milk}		S_{basic}	0.82	0.83	IDF, (2010)
		S_{mats}	0.84	0.85	
AF_{meat}		S_{basic}	0.18	0.17	IDF, (2010)
		S_{mats}	0.16	0.15	

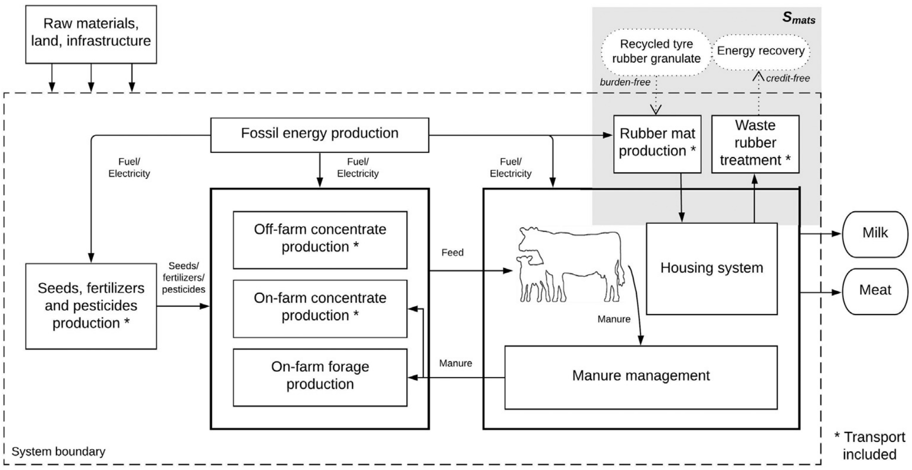

Fig. 1. System boundary and key flows of the milk production system, adapted from Meul et al. (2014).

2016) were adapted based on production assumptions described in sections 2.1 to 2.3. Production of seeds, pesticides, fertilizers and feedstuffs (on-farm, off-farm) was considered as well as the construction and operation of buildings and machinery (e.g. shed, bedding, milking equipment), including respective energy demands (electricity, heat). Transport was taken into account only in regard to purchased concentrates and feedstuff from own production, which was processed off-farm. Livestock and manure management were included in terms of emissions of CH_4, N_2O, NH_3 and NO_x from enteric fermentation, housing, storage and field application. Consumables such as detergents and wrapping foil for silage bales were considered via the database, while udder disinfectants and veterinary drugs were omitted due to lack of data and since no significant effect on results was expected. Characteristics of upstream supply chain activities not detailed above (e.g. amount of pesticides used in crop production, tap water from housing operation) were taken from ecoinvent (Wernet et al., 2016) as well as data on land use changes, soil carbon sequestration and N and P emissions from feed production.

The impact assessment of GWP, TAP, FEP and MEP was performed based on the ReCiPe midpoint (H) method (Goedkoop et al., 2009), where nutrient flows contributing to FEP and MEP are converted to P-e and N-e, respectively. GWP and TAP results are expressed per unit of CO_2-e and SO_2-e, respectively, and are calculated for a 100-year horizon. The method was adapted following Kral et al. (2016) by using recent IPCC characterisation factors for the calculation of GWP: 34 and 36 per kg of biogenic and fossil CH_4, respectively, and 298 per kg of N_2O from manure (climate-carbon cycle feedbacks included) (IPCC, 2013). The calculation of nRER (from nuclear and fossil sources) and renewable energy resources (**RER**) followed the cumulative energy demand method (CED, Frischknecht et al., 2007).

2.4. Welfare intervention modelling (S_{mats})

Inventory data were recalculated to reflect the modelling assumptions for mat production (including transport and disposal) and welfare improvement (Table 5). The modelling of the rubber mats production was based on manufacturer specifications (Co. Kraiburg elastics) and included raw material and energy demand as well as factory buildings. The manufacturing process involved the extrusion, moulding, vulcanization and cutting of the rubber, which

Table 5
Intervention characteristics for S_{mats} of PS H and PS L to estimate the impacts associated with the implementation of rubber mats. For PS L, input for sensitivity analyses regarding varying durability (5, 10, 15 years) and lameness-reduction potential (25, 50, 75%) of rubber mats is included. Values in bold represent the standard welfare intervention scenario S_{mats}.

Intervention characteristics	Unit	PS H	PS L			Reference
			Durability of rubber mats			
		10y	5y	10y	15y	
Rubber[a]	kg/cow.year	**15.1**	43.1	**21.6**	14.4	Co. Kraiburg elastics
Additional energy (mat production)	kWh/cow.year	**22.64**	64.7	**32.3**	21.6	Co. Kraiburg elastics
		Lameness reduction potential of rubber mats				
		50%	25%	**50%**	75%	
Milk yield	kg ECM/cow.year	**7,191**	8,095	**8,191**	8,288	calculated based on Huxley (2013) [b]
Productive lifespan	years	**4.27**	4.04	**4.27**	4.50	adapted from Randall et al., (2016)
Calving interval	days	**387**	389	**387**	385	adapted from Hultgren et al., (2004)

[a] Values calculated based on product characteristics of the mat model KURA P for solid concrete flooring in the walking area (https://kraiburg-elastik.com/en/dairy-cattle/walking-milking-area/paved-concrete-floor-with-scraper/kura-p/accessed 30.03.2020).
[b] Changes in milk yield calculated from Huxley (2013) and adapted according to concomitant changes in productive lifespan (Randall et al., 2016) and calving interval (Hultgren et al., 2004).

requires thermal and electric energy (1.5 MJ/kg rubber). Rubber granulate from recycled car tyres served as raw material and was handled as burden-free input in compliance with the cut-off system model of ecoinvent (Wernet et al., 2016). Required amounts of rubber and energy input were estimated based on dimensions and durability ascribed to the mats (10 years) relative to the barn (50 years). In PS H, the assumed annual rubber demand of 15.1 kg per cow was lower compared to PS L (21.6 kg) due to differences in floor surface (slatted vs. solid). The disposal of mats was considered via an incineration process for waste rubber suggested in ecoinvent, with treatment burdens allocated completely to the milk production process, according to the cut-off approach.

Modelling of S_{mats} was based on the assumption that rubber mats in alleyways would reduce lameness-induced productivity shortfalls contained in the baseline system S_{basic} by 50%. Respective changes in productivity were assumed to be equal in both PSs and were defined based on literature findings for European dairy production: an average milk yield loss of 203 kg per lactation in lame cows was derived from 5 studies described in Huxley (2013). The cows' productive lifespan was assumed to increase by 167 days (+12%) (Randall et al., 2016), while the calving interval was considered to decrease by 4 days (−1%) (Hultgren et al., 2004). Based on these values, the annual increase in cumulative milk yield was assumed to be 191 kg ECM (i.e. +2.7%, PS H and +2.4%, PS L) per cow in S_{mats}. The concomitant increase in daily feed demand per cow was 0.272 g DM for both systems. The increase in energy demand for cooling of surplus milk was 0.8% and 1% in PS H and PS L, respectively.

Two sensitivity analyses were performed for PS L to evaluate the effect of changes in durability (±5 years) and lameness reduction potential of rubber mats (±25 percentage points, **pp**). Respective changes in material and energy demand and in productivity are presented in Table 5.

2.5. Uncertainty information and statistical analysis

Uncertainty information for input data was adopted from ecoinvent (Wernet et al., 2016). For emission outputs, country-specific ranges of variation were assumed based on percentages suggested by the Austrian National Inventory and IPCC (EAA, 2018; IPCC, 2006c). To generate probability distributions for the deterministic impact estimates obtained from LCA, Monte-Carlo simulations were conducted with 1,000 iterations. Outliers were eliminated based on median and median absolute deviation (MAD) (Leys et al., 2013), using a MAD of 6 to account for the smaller interval considered by MAD compared to standard deviation (MAD≙0.6745*SD). Differences in distribution means of S_{basic} and S_{mats} were then tested for robustness to uncertainties using a two-sample *t*-Test ($\alpha = 0.05$). All calculations were performed with SAS Enterprise Guide 7.1 and SAS Studio 3.3 (SAS, 2014).

3. Results

3.1. Baseline scenario (S_{basic})

Except for FEP, MEP and nRER, environmental impacts of milk production were higher in PS H compared to PS L (Table 6). Contribution analysis yielded similar results for both systems (Supplementary Table 2). **GWP** was mainly determined by emissions from enteric fermentation (60%; all values refer to PS L), manure management (16%) and feed production (17%), while the construction and operation of the housing system accounted for only 6%. For **TAP**, manure management emissions were the key contributor (74%) and contributions of the housing system were minor (1%), while **FEP** was mainly driven by emissions associated with the construction (27%) and operation (26%) of the housing system and by feed production (46%). For both **MEP** and **RER**, the contribution of feed production was very high with 80% and 97%, respectively, as compared to impacts from the housing system (<2% and <4%). In contrast, **nRER** was significantly affected by contributions from housing (35%), with 21% resulting from its construction and 12% from operation, while emissions from feed production accounted for 65%.

Variability due to uncertainty in the inventory data was highest for FEP in both systems, followed by nRER, GWP, TAP, MEP, and lowest for RER (Table 6). In contrast to GWP, TAP and MEP, the probability distributions of FEP, nRER and RER did not follow a normal distribution but were right-skewed in both PSs (Fig. 2).

3.2. Welfare intervention scenario (S_{mats})

In both systems, the implementation of rubber mats in the alleys resulted in an increase of GWP, FEP and nRER and a decline of TAP, MEP and RER. However, impact changes were only significant for TAP and RER (both PSs) and nRER (PS H) (Table 6). Compared to S_{basic}, contribution analyses revealed only marginal trade-offs (±1pp) between contributions from housing operations, feed production and the animals, with highest costs of mat production and

Table 6
Potential impact of the scenarios S_{basic} and S_{mats} regarding global warming (GWP), terrestrial acidification (TAP), freshwater and marine eutrophication potentials (FEP, MEP), non-renewable and renewable energy resources (nRER, RER) for PS H and PS L, based on Monte-Carlo simulations (MCS): mean (expressed per kg of ECM), coefficient of variation (CV), 90% confidence interval (CI) with 5th and 95th percentile, relative difference between means of S_{basic} and S_{mats} (MD) and p-value for MD.

Production system	Impact category	Unit	Scenario	MCS	Mean	CV	CI (90%)		MD	
				n		(%)	5th %ile	95th %ile	(%)	*P*
PS H	GWP	kg CO_2-e/kg ECM	S_{basic}	999	1.187	7.6	1.043	1.336	0.2	0.546
			S_{mats}	1,000	1.190	7.8	1.043	1.340		
	TAP	g SO_2-e/kg ECM	S_{basic}	1,000	22.88	6.6	20.33	25.40	**−1.4**	**<0.001**
			S_{mats}	1,000	22.55	6.7	20.12	24.97		
	FEP	g P-e/kg ECM	S_{basic}	981	0.118	45.3	0.060	0.222	0.9	0.817
			S_{mats}	990	0.119	44.3	0.058	0.225		
	MEP	g N-e/kg ECM	S_{basic}	1,000	3.645	6.6	3.274	4.059	−0.1	0.632
			S_{mats}	1,000	3.640	6.9	3.247	4.050		
	nRER	MJ-e/kg ECM	S_{basic}	992	2.236	15.8	1.818	2.967	**2.5**	**0.001**
			S_{mats}	997	2.292	17.3	1.832	3.087		
	RER	MJ-e/kg ECM	S_{basic}	1,000	18.41	2.7	17.68	19.30	**−0.8**	**<0.001**
			S_{mats}	999	18.26	2.8	17.55	19.16		
PS L	GWP	kg CO_2-e/kg ECM	S_{basic}	1,000	1.089	6.8	0.971	1.216	0.5	0.121
			S_{mats}	999	1.095	7.0	0.974	1.220		
	TAP	g SO_2-e/kg ECM	S_{basic}	1,000	19.18	6.5	17.22	21.25	**−1.0**	**0.001**
			S_{mats}	999	19.00	6.4	17.00	21.02		
	FEP	g P-e/kg ECM	S_{basic}	984	0.118	44.5	0.060	0.230	0.9	0.534
			S_{mats}	985	0.119	46,8	0.059	0.237		
	MEP	g N-e/kg ECM	S_{basic}	1,000	4.224	5.2	3.873	4.602	−0.1	0.637
			S_{mats}	999	4.218	5.3	3.861	4.591		
	nRER	MJ-e/kg ECM	S_{basic}	998	2.371	13.5	1.997	3.004	0.8	0.169
			S_{mats}	991	2.390	13.2	2.011	3.032		
	RER	MJ-e/kg ECM	S_{basic}	994	16.78	2.2	16.27	17.49	**−0.6**	**<0.001**
			S_{mats}	992	16.67	2.3	16.08	17.34		

disposal for nRER and highest benefits of improved productivity for GWP (Supplementary Table 2). Compared to S_{basic}, the relative additional environmental costs for mat implementation in PS L per se, i.e. irrespective of changes in welfare, were 2.30, 1.63, 1.13, 0.05, 0.05, and 0.02% for nRER, FEP, GWP, TAP, MEP, and RER, respectively (Supplementary Table 3). Due to the lower rubber demand for slatted floors, these costs were proportionally lower in PS H than in PS L (solid flooring).

Results of sensitivity analyses for changes in mat durability (±5 years) and effectiveness in reducing lameness (±25 pp) are presented in Table 7. Changing mat durability had the highest impact on nRER and negligible impact on TAP, MEP and RER. Changing lameness reduction potential and thus productivity had a close to linear effect in all impact categories and was least pronounced for MEP.

4. Discussion

This is the first study to investigate potential effects of introducing rubber mats in dairy barn alleys on the environmental performance of milk production, while considering welfare benefits. Mat implementation led to a significant increase of nRER (+2.5%), while TAP and RER decreased by 1.4% and 0.8%, respectively. No significant changes were found for GWP, FEP, and MEP (Table 6). TAP and RER estimates were most sensitive to differences in lameness reduction potential, while mat durability particularly affected nRER estimates (Table 7).

Earlier studies on similar dairy production systems across Europe (e.g. Battini et al., 2016; Guerci et al., 2013; Hörtenhuber et al., 2010; Mu et al., 2017) and lameness-induced impact changes (e.g. ADAS, 2015; Chen et al., 2016; Mostert et al., 2018b) allow for an appraisal of the present findings. Despite some differences in baseline assumptions (e.g. milk yield, ration composition), scenario modelling (degree of productivity changes) and LCA methodology (e.g. functional unit, allocation), our findings are largely consistent with those studies. Due to the lack of data regarding the use of RER in milk production and the effect of diseases on MEP, nRER and RER, the following sections primarily focus on GWP, TAP and FEP. Regarding uncertainties (Table 6), similar coefficients of variation were reported by Chen and Corson (2014) for GWP, TAP and FEP of conventional farms, while Mu et al. (2017) found much higher variations for FEP (82%), MEP (49%) and energy use (29%), potentially due to the large variation in nutrient surplus among the farms considered in their study.

The slight trend of impact changes in $\mathbf{S_{mats}}$ associated with the implementation of rubber mats and subsequent lameness reduction (Table 6) reflects the comparatively high additional environmental costs of mat production and disposal regarding GWP, FEP and nRER (1.1, 1.6 and 2.3%, respectively). In contrast, minor impacts of mat production on TAP, MEP and RER (≤0.1%) were more than outweighed by the emission reducing effect of the assumed productivity increase. The generally more pronounced positive effect of the intervention measure in PS H can be explained by the lower annual rubber demand for slatted flooring compared to solid floors in PS L, while the effect on welfare was assumed to be equal in both systems (Table 5). Overall, the described environmental costs for lameness intervention in the present study are in accordance with ADAS (2015), which reported a cumulative increase of GWP by <2% for multiple intervention measures. Given the additional costs for mat implementation, the slight net changes of GWP, TAP and FEP due to lameness reduction in S_{mats} (e.g. PS H: 0.2%, −1.4% and 0.9%, respectively) are lower compared to previously reported effects of lameness on environmental impacts of milk production. For GWP, Mostert et al. (2018b) estimated an average increase of 1.5% for dairy cows with foot lesions. When lameness rate increased by 55%, Chen et al. (2016) reported GWP increases between 2.1% and 7.8%, depending on severity, while TAP and FEP increased by 2.5% to up to 9.4%. Lower absolute baseline values in previous studies (0.92 kg CO_2-e/kg FPCM in Mostert et al., 2018b) and more pronounced reductions in milk yield assumed for lame cows (up to −10% in Chen

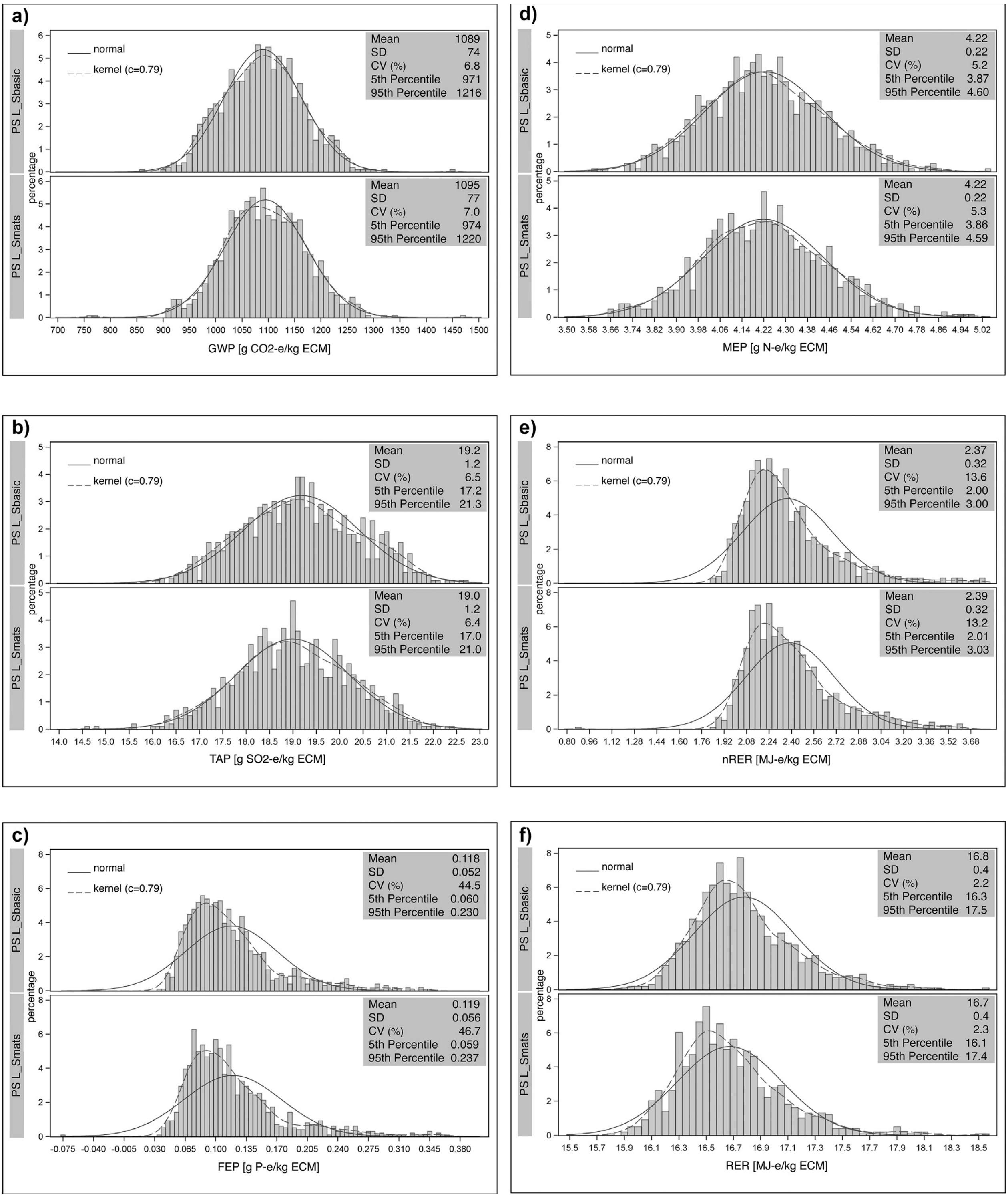

Fig. 2. Probability distributions of *a)* GWP (g CO_2-e), *b)* TAP (g SO_2-e), *c)* FEP (g P-e), *d)* MEP (g N-e), *e)* nRER (MJ-e) and *f)* RER (MJ-e) per kg ECM for S_{basic} and S_{mats} of PS L, based on uncertainty in inventory data.

Table 7
Sensitivity analyses for the standard welfare scenario S_{mats} (10 years durability of rubber mats, 50% lameness reduction) of **PS L**: results show the effect (%) of changes in durability (±5 years, **y**) and lameness reduction potential (±25 percentage points, **pp**) on selected environmental impacts per kg of energy-corrected milk (ECM) compared to S_{mats}.

	S_{mats} (10y, 50%) [point estimate, unit]		Sensitivity analysis (in % of S_{mats})			
			Durability		Lameness reduction	
			-5y	+5y	−25pp	+25pp
GWP	1.066	kg CO_2-e/kg ECM	0.88	−0.29	0.45	−0.45
TAP	18.77	g SO_2-e/kg ECM	0.05	0.00	0.43	−0.43
FEP	0.081	g P-e/kg ECM	1.13	−0.38	0.58	−0.57
MEP	4.095	g N-e/kg ECM	0.12	−0.12	0.12	−0.12
nRER	2.239	MJ-e/kg ECM	1.23	−0.41	0.41	−0.42
RER	16.56	MJ-e/kg ECM	0.02	−0.01	0.45	−0.44

et al., 2016; up to −7.6% in Mostert et al., 2018b; PS H: -2.7%, PS L: -2.4%) resulted in these higher relative increases in impact compared to the scenario outcomes in the present study. Although one scenario used by Chen et al. (2016) is similar to the S_{mats} assumptions for PS H, the reported impact estimates are still higher due to a lower proportion of emissions allocated to meat (12%; PS H: 16%, PS L: 15%). Regarding the estimates for FEP and TAP, no valid comparison can be made with previous studies, mostly due to the use of different impact assessment methods (Payen and Ledgard, 2017). While Chen et al. (2016) used a single indicator combining terrestrial and aquatic eutrophication, the present study assessed aquatic eutrophication only, but separately for inland and marine waters. Moreover, TAP estimates in Chen et al. (2016) were considerably lower due to a higher proportion of pasture in the ration.

Due to limited evidence for the lameness reduction potential of rubber flooring (Bruijnis et al., 2012), productivity shortfalls in S_{basic} were assumed to decrease by 50% in the standard S_{mats} scenario. Our results therefore provide general estimates for the effect of rubber mats on emissions from dairy production, irrespective of lesion type. The **effectiveness of rubber floors** in reducing lameness may, however, depend on the lesion-specific cause of locomotion impairment, which also determines the level of losses in milk yield (Amory et al., 2008). Due to their compressibility, rubber mats reduce pressure overloading (Oehme et al., 2018) and have been shown to effectively reduce trauma-induced lesions (Bruijnis et al., 2012; Ouweltjes et al., 2009). Per case of sole ulcer (SU) and white line disease (WLD), Mostert et al. (2018b) estimated an increase of GWP by 3.6% and 4.3%, respectively. Associated productivity changes amounted to 574 kg and 369 kg for SU and WLD, respectively (Amory et al., 2008), while in the present study a productivity increase of only 191 kg was assumed. Thus, in regard to lameness caused by SU and WLD, the positive effect of implementing rubber mats on environmental impacts of milk production might have been underestimated. Rubber mats are less effective in reducing infectious disorders of the lower leg (Ahrens et al., 2011; Bruijnis et al., 2012) and disorders such as DD have no significant effect on milk yield (Amory et al., 2008), thus resulting in minor changes in GHG emissions only (0.4% per case of DD, Mostert et al., 2018b). Hence, if digital dermatitis (DD) is the main cause of lameness, the welfare benefits of mat implementation are less likely to outweigh emissions associated with rubber mat production, especially in the case of GWP, FEP and nRER, where mat impacts are comparatively high (≥1.1%).

To account for **variability in input parameters** for the intervention scenario S_{mats} (Table 5), sensitivity analyses regarding the effectiveness of rubber mats in reducing lameness (±25pp) and regarding mat durability (±5 years) revealed differences in sensitivity between the selected impact categories (Table 7). Productivity changes mostly affected TAP and RER estimates, which allows for a first appraisal of potential impact changes in regard to e.g. effects of parity, production level and season on lesion incidence rates, which indirectly affect productivity (Bruijnis et al., 2012). Alterations in mat wear limit mainly impacted on nRER, while changes in both effectiveness and durability of mats least affected MEP. Moreover, in the case of reduced mat durability, the use of renewable energy sources during mat production and the choice of end-of-life treatment of rubber mats could considerably affect the outcomes. For instance, the reuse of mats might reduce nRER use, as it saves fossil resources, thus substituting virgin polypropylene production. This can help to reduce TAP, in contrast to the acidifying processes associated with incineration (Marconi et al., 2018).

Overall, limited availability of data may increase uncertainty around the modelled effects of implementing rubber mats. For example, effects of lameness on productive lifespan have been described in one study only (Randall et al., 2016). **Future assessments** would therefore benefit from **primary data** on the effects of soft flooring on cow productivity, especially regarding the estimation of impact categories such as TAP, MEP and RER, which were hardly affected by environmental costs of mat implementation. Moreover, by including parity and body condition score in the modelling, the increasing risk of lameness with higher lactation numbers (Bicalho et al., 2009; Randall et al., 2016) and decreasing body condition (Bicalho et al., 2009) could be taken into account. This would also allow to account for the decreasing effect of lameness on GHG emissions in higher parity cows (Mostert et al. (2018b). Furthermore, lameness has a considerable economic impact (Cha et al., 2010; Charfeddine and Pérez-Cabal, 2017), irrespective of lesion type. We therefore suggest including a comprehensive **economic evaluation** of associated costs in future assessments. While the average costs for rubber mat implementation have been estimated at €28 per cow and year (Bruijnis et al., 2012), cost savings due to foot health improvement in S_{mats} amount to €32, considering at least milk yield losses ($0.17/kg) and prolonged calving interval ($0.99/d) (Bruijnis et al., 2010). This rough estimate points to a potentially positive effect of rubber mat implementation for both emission mitigation and farm profits. A more detailed economic evaluation could substantiate this effect and thus be an incentive for farmers to implement rubber mats, besides welfare benefits (Mostert et al., 2018b).

5. Conclusion

Lameness intervention through the implementation of rubber mats in dairy barn alleys does not affect the majority of the selected impact criteria, but a positive trend in regard to emission mitigation was estimated for TAP and RER. The latter effect can especially be expected for systems with high prevalence of trauma-induced lameness, where the benefits of soft flooring for lameness reduction are high. Future assessments would, however, benefit from empirical data about the effectiveness of rubber mats in reducing lameness prevalence and from long-term studies about the effects of lameness on cow productive lifespan in order to reduce epistemic uncertainty. From an environmental point of view, potential benefits of mat implementation are particularly relevant if renewable energy sources are used for mat production. In conclusion, the findings point to the potential of health and welfare improvement measures to at least outweigh the environmental costs of mat implementation and provide a more differentiated view regarding the environmental impacts of welfare intervention in dairy farming. However, to confirm a generally positive contribution of welfare intervention measures to sustainable milk production, a comprehensive assessment of other intervention measures is needed.

CRediT authorship contribution statement

Anna Herzog: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Funding acquisition. **Stefan Hörtenhuber:** Conceptualization, Methodology, Validation, Writing - review & editing. **Christoph Winckler:** Conceptualization, Methodology, Writing - review & editing. **Iris Kral:** Resources, Software. **Werner Zollitsch:** Conceptualization, Methodology, Resources, 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

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Supplementary Table 1

Emission factors for CH_4 and N_2O emissions, NH_3-N and NO_x-N volatilisation from manure in the barn (liquid manure management), yard, on pasture and during storage and application.

Emissions	Unit	Emission factor$_{MMS, location}$		Reference
$CH_{4\ manure}$	kg CH_4/cow.year	0.09	$MCF_{liquid*}$	EEA, 2014 (tab. 178)
		0.01	$MCF_{pasture/yard}$	IPCC, 2006a (tab. 10.17)
N_2O_{direct}	kg N_2O-N/kg N_{ex}	0.005	EF_{liquid}	IPCC, 2006a (tab. 10.21)
		0.02	$EF_{pasture}$	IPCC, 2006b (tab. 11.1)
		0.013	EF_{yard*}	EEA, 2014 (tab. 190)
$N_2O_{indirect}$	kg N_2O-N/kg N_{ex}	0.01	$EF_{atmospheric}$	IPCC, 2006b (tab. 11.3)
$NH_{3\ housing}$	kg NH_3-N/kg N_{ex}	0.118	$EF_{liquid*}$	EEA, 2014 (tab. 202)
$NH_{3\ storage}$	kg NH_3-N/kg TAN	0.15	$EF_{liquid*}$	EEA, 2014 (tab. 203)
$NH_{3\ application}$	kg NH_3-N/kg TAN	0.5	$EF_{liquid*}$	EEA, 2014 (tab. 207)
$NO_{x\ storage}$	kg NO_x-N/kg TAN	0.007	$EF_{liquid*}$	EEA, 2014
$NO_{x\ application}$	kg NO_x-N/kg TAN	0.01	$EF_{liquid*}$	EEA, 2014

* national calculations

MMS = manure management system

MCF = methane conversion factor

N_{ex} = nitrogen excretion

TAN = total ammoniacal nitrogen (50% from N_{ex} for liquid manure management; EEA, 2014 - tab. 204)

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Supplementary Table 2

Contribution analysis for the scenarios S_{basic} and S_{mats} of PS H and PS L. Contributions in percent of point estimates for each impact category.

		GWP		TAP		FEP		MEP		nRER		RER	
		S_{basic}	S_{mats}	S_{basic}	S_{mats}	S_{basic}	S_{mats}	S_{basic}	S_{mats}	S_{basic}	S_{mats}	S_{basic}	S_{mats}
PS H	feed production	12.9	12.9	19.2	19.2	40.2	40.0	72.1	72.3	59.1	58.2	96.6	96.6
	operation housing system	5.8	6.5	1.2	1.3	59.9	60.0	2.4	2.5	40.9	41.8	3.4	3.4
	construction	3.2	4.0	0.9	1.0	30.0	30.9	1.8	1.9	24.3	25.8	2.3	2.3
	mat production		*0.09*		*0.02*		*0.87*		*0.03*		*0.96*		*0.02*
	mat disposal		*0.55*		*0.00*		*0.02*		*0.01*		*0.07*		*0.00*
	animal	81.3[a]	80.6[b]	79.6	79.5	0	0	25.5	25.3	0	0	0	0
PS L	feed production	17.4	17.6	24.6	24.5	45.7	46.3	80.4	80.3	65.2	64.8	96.6	96.7
	operation housing system	5.7	6.6	1.3	1.4	54.3	53.7	1.9	1.9	34.8	35.2	3.4	3.3
	construction	3.1	4.1	1.0	1.1	27.2	27.8	1.4	1.5	20.7	21.9	2.5	2.2
	mat production		*0.12*		*0.03*		*1.10*		*0.03*		*1.14*		*0.02*
	mat disposal		*0.76*		*0.01*		*0.03*		*0.01*		*0.09*		*0.00*
	animal	76.9[c]	75.9[d]	74.1	74.1	0	0	17.8	17.7	0	0	0	0

[a] enteric fermentation: 65.7%, manure management: 15.6%
[b] enteric fermentation: 65.2%, manure management: 15.5%
[c] enteric fermentation: 60.0%, manure management: 16.0%
[d] enteric fermentation: 60.5%, manure management: 16.4%

Supplementary Table 3

Per se contributions of environmental costs of mat production and disposal, and of environmental benefits of welfare improvement to impacts in S_{basic}. Values based on point estimates of PS L.

	Environmental costs of mat production and disposal, relative to S_{basic}	Environmental benefits of lameness reduction, relative to S_{basic}	S_{mats}: Trade-offs between costs and benefits of intervention
GWP	+1.13	-0.79	+0.34
TAP	+0.05	-0.74	-0.69
FEP	+1.63	-1.56	+0.07
MEP	+0.05	+0.37	+0.42
nRER	+2.30	-0.74	+1.57
RER	+0.02	-0.58	-0.56

5.3 Paper 3: The effect of additional ventilation to improve cow welfare on environmental impacts of milk production – a case study for Austria

Environmental impacts of implementing basket fans for heat abatement in dairy farms

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Environmental impacts of implementing basket fans for heat abatement in dairy farms

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B S T R C T

Health and welfare impairments in dairy cows have been described to increase environmental impacts of milk production due to their negative effect on cow productivity. One of the welfare problems is heat stress, which is gaining importance even in temperate regions. While improving animal welfare may reduce emissions, the mitigation potential depends on the environmental costs associated with specific intervention measures. Taking abatement of heat stress as an example, the aim of the present study was to estimate the effect of implementing mechanical ventilation devices on the contribution potential of milk production to global warming (**GWP**), terrestrial acidification (**TAP**) and freshwater eutrophication (**FEP**). Environmental impacts of two modelled production systems located in alpine and lowland production areas of Austria were estimated before and after the implementation of basket fans, using life cycle assessment. Region-specific climate data were retrieved to determine the number of days with heat stress and to evaluate heat stress-induced productivity shortfalls in the baseline scenario (**S_{basic}**). In the intervention scenario with increased ventilation (**S_{vent}**), this decline was assumed to be eliminated due to the convective cooling effect of fans. For S_{basic}, mean GWP, TAP and FEP impacts were estimated at 1.2 ± 0.09 kg CO_2-, 21.1 ± 1.44 g SO_2- and 0.1 ± 0.04 g P-equivalents per kg milk, respectively. Independent from the production system, in $S_{vent,}$ implementation of fans did not result in significant environmental impact changes, except for FEP of the alpine system (+5.9%). The latter reflects the comparatively high environmental costs of additional cooling regarding FEP (+2.3%) in contrast to GWP (+0.4%) and TAP (+0.1%). In conclusion, the estimated overall effects of mechanical ventilation on GWP, TAP and FEP of milk production were minor and the model calculations point to the potential of heat stress abatement to at least outweigh the environmental costs associated with fan production and operation. To confirm this trend, further assessments are needed, which should be based on primary data regarding the effectiveness of fan cooling to improve cow productivity, and on emission calculation schemes that are sensitive to environmental factors such as wind speed and temperature.

Implications

Better animal welfare reduces emissions per unit of product if improvement measures cause less environmental impact than the savings achieved through increased productivity. We simulated environmental impacts of implementing basket fans to abate heat stress in two modelled dairy farming systems, using life cycle assessment. Fan implementation is associated with additional environmental costs, but these costs are outweighed by the assumed effect of improved welfare on milk yield. This emission mitigating effect of welfare improvement could be more pronounced in countries with similar production systems but higher average temperature, where heat stress abatement also benefits fertility and longevity.

Introduction

The dairy farming sector is an important source of greenhouse gas and nitrogenous emissions (Gerber et al., 2013). Impact estimates can vary subject to the applied analytical method as well as the system type, region and season. Based on life cycle assessment methodology (**LCA**), the average specialized dairy product system in Europe contributes an estimated 1.2 kg CO_2-, 26.1 g SO_2- and 1.1 g P-equivalents (e) per kg of fat- and protein-corrected milk to the potential of global warming (**GWP**), terres-

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trial acidification (**TAP**) and freshwater eutrophication (**FEP**), respectively (Mu et al., 2017). In Austrian dairy farms, GWP has been reported to range between 0.9 kg and 1.2 kg CO_2-e/kg of energy-corrected milk (**ECM**) (Hörtenhuber et al., 2010).

A key driver of a cow's emission potential is its production efficiency in terms of milk yield, fertility and longevity, which is a function of the animal's health and well-being (Place and Mitloehner, 2014). Productivity decline due to impaired welfare leads to an increase in environmental impacts per unit of product, since more animals are needed to produce a certain amount of milk and individual maintenance costs increase (Knapp et al., 2014). The magnitude of impact changes varies per type of health disorder (ADAS, 2015) and was shown to be 2.3% and 3.7% for cows affected by subclinical ketosis and subclinical mastitis, respectively (Mostert et al., 2018a; Özkan Gülzari et al., 2018).

Apart from health disorders, cow productivity is also affected by heat stress, which is frequently determined as a function of temperature and humidity. Respective impacts on the cow's emission potential have not been assessed so far. Due to the rise in global average temperature and the increasing number of heat days, even in temperate climate regions, heat stress-induced productivity decline is currently evolving as one of the major challenges in dairy farming (Gernand et al., 2019; Polsky and von Keyserlingk, 2017). In an effort to cope with the strain of increasing core temperature, cows show signs of physiological and metabolic acclimation, starting with increased water intake, respiration rate and standing time while feed intake decreases (Bernabucci et al., 2010; Cook et al., 2007). First effects on the herd's oestrus activity, cow activity in general (lying/standing time) and milk yield potential have been reported to start at a temperature-humidity index (**THI**) of 57, 67 and 68, respectively (Gernand et al., 2019; Heinicke et al., 2018; Zimbelman et al., 2009), while increasing rates of claw disorders have been associated with reductions in lying time due to mild heat stress (THI 68) (Nordlund et al., 2019). At THI > 73, conception rate declines (Schüller et al., 2014), and at a daily peak THI > 80 eventually the mortality risk increases (Bernabucci et al., 2010). Since maintenance costs for thermoregulatory behaviour increase and productivity declines (Gernand et al., 2019), heat stress leads to an overall increase in animal emissions per unit of product.

The abatement of heat stress has therefore been hypothesized to benefit both animal welfare and emission mitigation (Place and Mitloehner, 2014), but a quantitative assessment of the mitigating effect is still lacking. Among various cooling options, fan cooling is a frequently used measure to reduce or eliminate heat stress in dairy cows. Although the cooling effect of fans is more pronounced when combined with wetting (sprinklers, misters), fans alone are still an effective and easily applicable option, especially in less-humid regions (Ji et al., 2020; Smith et al., 2007). They promote convective heat dissipation from the cow's body to the ambient air (Wang et al., 2018), whereas sprinkling devices have been criticized to become unsustainable in near future due to their large water consumption (Polsky and von Keyserlingk, 2017; Smith et al., 2007).

While product-related emissions decline with increasing productivity (Knapp et al., 2014), material and energy demand for the production and operation of the fans is associated with environmental costs. This raises the question of potential trade-offs between the emission-increasing effect of resource input for additional mechanical ventilation and the emission-reducing effect of improved productivity due to heat stress abatement. A quantitative evaluation of impacts associated with the implementation of basket fans is still lacking. While a first appraisal of potential environmental costs associated with welfare intervention measures in general suggests a less than 2% increase in greenhouse gas emissions (ADAS, 2015), the introduction of rubber mats in dairy barn alleys was found to increase GWP, TAP and FEP by 1.13%, 0.05% and 1.63%, respectively (Herzog et al., 2020). These environmental costs were, however, offset in the case of GWP and FEP, due to the concomitant improvement in claw health and productivity, while TAP even decreased slightly but significantly by 1%.

The objective of the present study was to assess the potential effects of additional ventilation and heat stress abatement on the environmental performance of dairy cows. Effects on GWP, TAP and FEP were estimated before and after the implementation of basket fans. Based on two modelled dairy systems including tie-stall and cubicle housing, simulated environmental costs of fan implementation were weighed against environmental benefits of welfare improvement. The assessment focused on basket fans, due to their frequent use in commercial dairy farms in Austria to complement natural or cross-ventilation. Welfare benefits of heat stress abatement were assumed based on average temperature in two model regions.

Preliminary results of this study have been presented at the UFAW International Symposium 2019 (Herzog et al., 2019).

Material and methods

Two dairy production systems (**PSs**) were modelled and each system's contribution to GWP, TAP and FEP was estimated, using LCA methodology. The baseline scenario (**S_{basic}**) of each PS reflected a typical housing system with natural or cross-ventilation only. For the intervention scenario (**S_{vent}**), we assumed additional mechanical ventilation via basket fans to simulate an extra cooling effect, while also considering material and energy demand for the production and operation of the fans. Cows in S_{basic} were considered to suffer from mild heat stress during the summer months, while respective shortfalls in milk yield were assumed to be absent due to the operation of fans in S_{vent}. Differences in environmental impact estimates between S_{basic} and S_{vent} were tested for their robustness to uncertainties in the modelling parameters, using Monte-Carlo simulations.

Characteristics of the baseline scenario

Following Herzog et al. (2020), two dairy PSs were defined based on data derived from Austrian national statistics (STAT, 2014; IACS, 2015; ZuchtData, 2017). Modelling assumptions simulated typical production conditions in two topographically different parts of the country (Table 1). **PS 1** was assumed to be located in the highlands, where tie-stall housing with pasture access during summer is still common. Cows were pastured at night-time and benefited from fan operation during the day. Cows in **PS 2** were defined to be cubicle-housed with zero grazing, which is representative for dairy farms in the lowlands of Austria (adapted from PS L in Herzog et al. (2020)). With decreasing altitude, the ratio of arable land per farm increased as did feed and milk production intensity.

Forage yields amounted to 7.7 and 8.2 t of DM per ha in PS 1 and PS 2, respectively, and reflect the differences in feed production characteristics between the two modelled systems (Table 1). Feed quality in terms of nutrient and energy contents was assumed accordingly, based on values retrieved from feed tables (German Agricultural Society, DLG, 1997; Buchgraber and Gindl, 2009). Energy density levels of the forage averaged 5.9 MJ **NEL** (net energy lactation)/kg DM. Taking into account stocking density in each PS, forage yields per animal were derived, following the example of Herzog et al. (2020). While both systems were self-sufficient in terms of forage supply, concentrates were bought-in to fulfil the animals' energy requirement. The region-specific portion of arable land in relation to grassland determined each

Table 1
Key characteristics of modelled cow milk production systems PS 1 and PS 2.

Characteristics	PS 1	PS 2	Reference
Production region	Alpine	Lowland	STAT (2014)
Grassland to arable land ratio (%)	100:0	50:50	IACS (2015)
Stocking density (cows/ha)	1.3	1.5	IACS (2015)
Annual milk yield per cow (kg ECM)	6 000	8 000	ZuchtData (2017)
BW of cows (kg)	650	750	ZuchtData (2017)
Productive lifespan (years)	3.81	3.81	ZuchtData (2017)
Calving interval (days)	391	391	ZuchtData (2017)
Energy requirement (MJ NEL/cow/day)	95.35	116.59	GfE (2001)
Housing	Tied	Loose	Pöllinger et al. (2018)
Outdoor run	No	No	Pöllinger et al. (2018)
Manure management system	Solid	Slurry	Pöllinger et al. (2018)
Pasture access (days/year)	100	–	Steinwidder and Starz (2015)
Gross yields of permanent grassland/clover leys (tDM/ha)	7.7	8.2/11	Buchgraber and Gindl, 2009
Average number of cuts of permanent grassland/clover leys	2	4	Buchgraber and Gindl, 2009
Average energy density, forage (MJ NEL/kg DM)	5.82	5.97	Calculated, based on Resch et al., 2010
Average energy density, concentrate (MJ NEL/kg DM)	8.28	7.84	Calculated, based on DLG (1997)
Concentrate ratio in the diet (% of DM)	10	22	Calculated, based on GfE (2001)

Abbreviations: ECM = energy-corrected milk, NEL = net energy lactation.

system's degree of self-sufficiency in terms of concentrate production (Table 1). While PS 1 was fully dependent on bought-in concentrates, PS 2 was partially self-sufficient and produced 51% of the concentrate feed demand on its arable land (Supplementary Table S1).

Diets were defined with regard to the performance-related nutritional requirements, following feeding recommendations (Society for Nutritional Physiology, GfE, 2001). Daily energy requirements per cow ranged from 95 MJ NEL in PS 1 to 117 MJ NEL in the more intensive PS 2 (Table 1). Correspondingly, the share of forage in the diet was higher in PS (90%) in contrast to PS 2 (78%). Ration ingredients (Supplementary Table S1) were resumed from Herzog et al. (2020) and included grass, hay and different types of silage as forage components, and grains, seed meals and dried distiller's grain as concentrate components.

Calculation of emissions

Emissions associated with feed production (resources, cultivation, harvesting, processing) and energy requirements were resumed from the applied LCA inventory database, while emissions resulting from production and use of pesticides and fertilizer were considered using approximations described by Quantis et al. (2012). For the calculation of CH_4, N_2O, NH_3 and NO_x emissions from the animals and their manure excreted on pasture, in the barn or in the outdoor run, international guidelines (Intergovernmental Panel on Climate Change, IPCC, 2006a and 2006b) and national calculation schemes (Environment Agency Austria, EAA, 2014) were used as briefly described below. A detailed description can be found in Herzog et al. (2020).

Calculations were based on nutrient intake of cows (Supplementary Table S2) and included prorated emissions from rearing and dry period. CH_4 emissions from enteric fermentation were calculated based on DM intake (**DMI**) and nutrient contents in the ration, following the equation of Kirchgessner et al. (1995), and amounted to 177 kg and 182 kg CH_4/cow/year in PS 1 and PS 2, respectively (Supplementary Table S3). Manure emissions reflect the amount of excreta dependent on the animals' yield level (Pommer et al., 2014). NH_3 and NO_x were derived based on national calculation schemes (Supplementary Table S3) and region-specific emission factors (Supplementary Table S4) (EAA, 2014). The calculation of manure CH_4 and N_2O emissions followed IPCC tier 2 methodology for country-specific excretion rates (Supplementary Table S3) and was mostly based on default emission factors for cool climate regions (IPCC, 2006b and 2006a; Supplementary Table S4). In PS 2, estimated CH_4 emissions from manure were higher compared to PS 1, with values amounting to 31.12 kg and to 6.08 kg CH_4/cow/year, respectively. In contrast, direct and indirect N_2O emissions were lower in PS 2 (i.e. 1.15 and 0.93 kg/cow/year, respectively) compared to PS 1 (i.e. 4.25 and 1.11 kg/cow/year, respectively), see Supplementary Table S3.

Life cycle assessment

The cradle-to-farm-gate assessment of environmental impacts followed the normative guideline ISO 14040 for LCA (International Organization for Standardization, ISO, 2006) and is described in detail in Herzog et al. (2020). Impact categories were expressed for the **functional unit** of 1 kg ECM (Sjaunja et al., 1991). The **co-product** meat from cull cows and surplus calves were considered using biophysical allocation, where allocation factors (Supplementary Table S3) reflect the relation between milk yield level and live weight production per year (International Dairy Federation, IDF, 2010). All calculations were conducted with the open-source software openLCA v1.7.2 (GreenDelta, 2018) in combination with the cut-off system model of the inventory database ecoinvent v3.2 for attributional modelling (Wernet et al., 2016).

Inputs and outputs of the process "milk production, from cow | cow milk" in the ecoinvent database were adapted to reflect the production assumptions for each PS. The inventory modelling included emissions from livestock and manure management, fertilizer and pesticide application (CO_2, CH_4, N_2O, NH_3, NO_x, NO_3^- and PO_4^{3-} from enteric fermentation, housing, storage and field application), emissions from feed production (on-farm, off-farm), seed, fertilizer and pesticide production as well as emissions from the construction and operation of buildings and machinery (shed, bedding, milking equipment), including respective energy demands (electricity, fossil fuel) (see Fig. 1). For purchased concentrates, transport routes were assumed that reflect distances to typical producing regions within Europe (Supplementary Table S1). Upstream supply chain characteristics not detailed above as well as information regarding land use change were resumed from ecoinvent (e.g. NO_3, SO_2 and P emission from feed production, CO_2 losses from fuel combustion, pesticides used in crop production, consumables) (Wernet et al., 2016). Soil carbon sequestration was not accounted for due to very high uncertainty of existing prediction models (IDF,

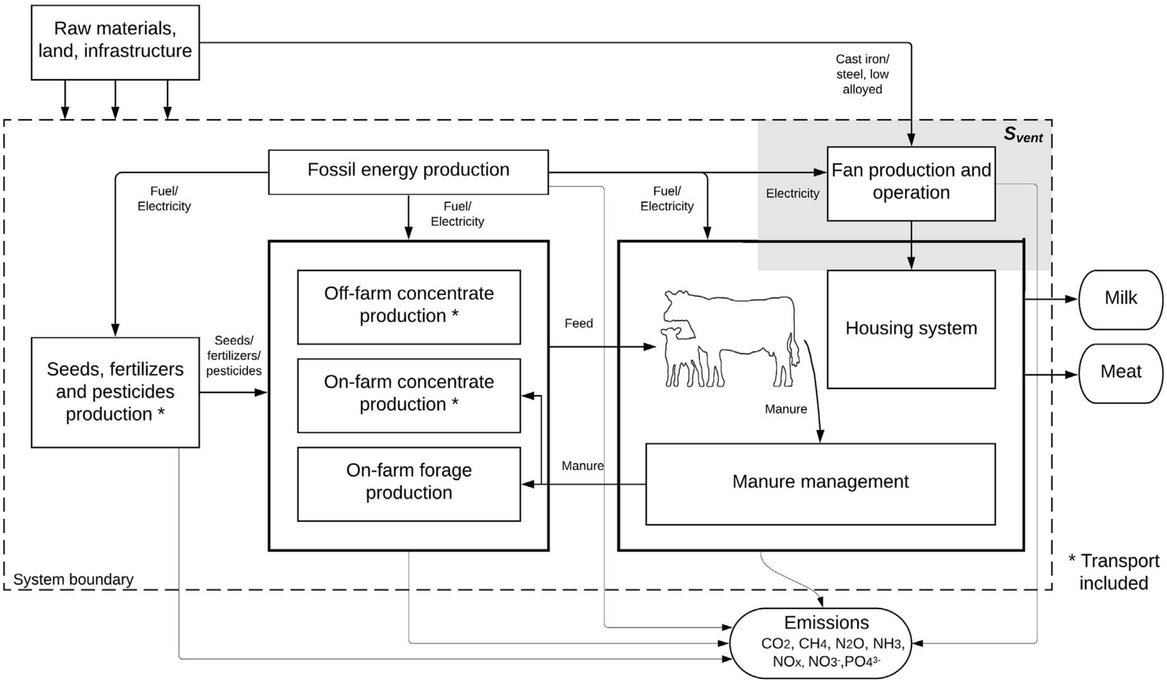

Fig. 1. Key flows and system boundary of the cow milk production system, including the intervention scenario with additional ventilation (S_{vent}), adapted from Herzog et al. (2020)[1] and Meul et al. (2014)[2]. [1]This article was published in Journal of Cleaner Production, vol. 277, Herzog, A., Hörtenhuber, S., Winckler, C., Kral, I. and Zollitsch, W., Welfare intervention and environmental impacts of milk production – cradle-to-farm-gate effects of implementing rubber mats in Austrian dairy farms, no. 123953, Elsevier (2020). [2]This article was published in Agricultural Systems, vol. 131, Meul, M., Van Middelaar, C.E., de Boer, I.J.M, Van Passel, S., Fremaut, D. and Haesaert G., Potential of life cycle assessment to support environmental decision making at commercial dairy farms, pp. 105–115, Elsevier (2014).

Table 2
Assumed annual cooling demand (number of days × fan runtime) and additional DM intake (DMI) in the ventilation scenario S_{vent} of cow milk production systems PS 1 and PS 2, based on heat load in each model region during the summer months: temperature-humidity index (THI) and temperature.

Item		May	June	July	Aug	Sep	Cooling demand (h/year)[b]	Additional DMI (kg/year)[c]
PS 1[a]								
	THI[1]	64.1	65.9	69.2	70.8	65.2		
	Temperature (°C)	19.0	20.2	22.8	24.2	19.8		
	Fan runtime (h/day)[2]	–	6	12	18	6	**1 260**	
	Additional DMI (g/day)[3]	–	19	261	392	–		**20.2**
PS 2								
	THI[1]	66.0	71.1	71.4	72.4	61.9		
	Temperature (°C)	20.7	25.0	24.7	25.2	17.1		
	Fan runtime (h/day)[2]	6	24	24	24	–	**2 340**	
	Additional DMI (g/day)[3]	76	541	509	563	–		**50.7**

[1] Temperature-humidity index (THI), calculated based on region-specific monthly average values for temperature and humidity, following NRC (1971): THI = $(1.8 \times T_{db} + 32) - (0.55 - 0.0055 \times RH) \times (1.8 \times T_{db} - 26)$. T_{db} – dry bulb temperature, RH – relative humidity.
[2] Fans were activated at a monthly average THI 65. Fan runtime was phased stepwise based on heat stress thresholds described in the literature (Allen et al., 2015; Bernabucci et al., 2010; Heinicke et al., 2018; Zimbelman et al., 2009): THI 65 – 6 h, THI 68 – 12 h, THI 71 – 24 h. For THI 70–71, a transition value of 18 h/d was chosen. This classification was presumed in consideration of recommendations for fan cooling in dairy barns described in Pommer et al. (2014).
[3] Calculated based on the formula DMI × (1 – ((°C – 20) × 0.005922)), recommended by NRC (2001).
[a] Cows in PS 1 were pastured at night-time, allowing to factor in the benefits of fan operation during the day.
[b] Annual cooling demand = $_{months}$ (daily fan runtime × 30).
[c] Annual additional DMI = $_{months}$ (daily additional DMI × 30).

2010), while veterinary drugs and udder disinfectants were omitted due to lack of data and since no significant effect on the considered impact categories was expected.

GWP, TAP and FEP were estimated using the impact assessment method ReCiPe midpoint (H) (Huijbregts et al., 2016). GWP and TAP results are calculated for a 100-year horizon and for GWP estimation, recent characterization factors were applied, i.e. 34 and 36 per kg of biogenic and fossil CH_4, respectively, and 298 per kg of N_2O from manure (IPCC, 2013).

Additional ventilation scenario to improve welfare

In contrast to natural or cross-ventilation of the barns in the baseline scenario S_{basic} (no fans), we simulated heat stress abatement in the intervention scenario S_{vent} by modelling the implementation and use of basket fans (Table 2). To determine the cooling demand in each PS, we assessed the heat stress occurrence in each model region by calculating the THI based on region-specific meteorological data for 2017 and 2018. Respective

Table 3
Modelling characteristics of the welfare intervention scenario with additional ventilation S_{vent} for production systems PS 1 and PS 2 to estimate the impacts associated with the implementation of basket fans, including main material components for fan construction, operation characteristics and respective changes in cow productivity. Input for sensitivity analyses of fan runtime variation (±30%) in PS 2 is included (values displayed in parentheses).

Intervention characteristics	Unit	PS 1	PS 2	Reference
Basket fans[a]	items/barn	3	5	Assumed based on fan reach[a] relative to barn type[b]
Cast iron	g/cow/year	122	204	Calculated based on fan characteristics[a] and number of fans per barn
Steel, low alloyed (hot rolled)	g/cow/year	184	306	Calculated based on fan characteristics[a] and number of fans per barn
Fan operation				
Runtime (±30%)	h/year	1 260	2 340 (1 638/ 3 042)	Assumed based on THI in each system (Table 2)
Ventilation intensity	m^3/cow/h	870	870	Pommer et al. (2014)
Power-to-mass ratio	Wh/1 000 m^3	16.43	16.43	Fan specification, calculated based on input power and air circulation[a]
Energy demand[c] (±30%)	kWh/cow/ year	19.61	35.05 (25.02/ 45.09)	Calculated based on runtime, ventilation intensity and fan specifications (power-to-mass ratio)
Animal response to heat stress mitigation				
Milk yield	kg ECM/cow/ year	6 038 (+0.63%)	8 101 (+1.26%)	Calculated based on NRC (2001)
Energy demand (milking and cooling of additional milk)	kWh/cow/ year	1.08	2.68	Calculated based on Pommer et al. (2014)

Abbreviations: ECM = energy-corrected milk, THI = temperature-humidity index.
[a] Characteristics of basket fan model S 22 (item number 990 531): diameter (84 cm), weight (18 kg), input power (350 W), air circulation (21 300 m^3/h), reach (10 m), wear limit (8 years). Manufacturers' data retrieved from https://www.agrar-fachversand.com/Elkat/Landwirtschaft_Katalog2018/? 100 (last accessed 2020-04-30).
[b] Dimensions of housing system types "tied" and "cubicle" as inventoried in ecoinvent, designed for 22 livestock units of dairy cattle (Nemecek and Kägi, 2007).
[c] Energy demand for fan operation and fan controller = ((((Ventilation intensity × run time)/1 000) × power-to-mass ratio)/1 000) + energy demand fan controller (1.6 kWh/cow/year, Pommer et al. (2014)).

fan runtimes were defined in regard to THI-related heat stress response thresholds described in the literature (Bernabucci et al., 2010; Gernand et al., 2019; Zimbelman et al., 2009) and followed recommendations on air velocity for additional cooling of dairy barns as provided in Pommer et al. (2014). It was assumed that the additional mechanical ventilation via fans would safeguard thermoneutral conditions and eliminate heat stress-induced productivity shortfalls presumed for S_{basic}. Based on cooling demand and productivity increase, the baseline inventory data of each PS were recalculated to reflect respective changes in modelling assumptions as detailed in Tables 2 and 3. Main adaptations affected the input variables housing, feed intake and emissions from the animals and their manure.

For both PSs, basket fans of equal size and weight, specifications and wear limit were modelled (Table 3), while the number of fans varied between systems due to differences in barn characteristics assumed for tie-stall and cubicle housing in ecoinvent (Nemecek and Kägi, 2007). For the tie-stall system (PS 1), the additional annual material demand amounted to 306 g per cow, while 510 g was assumed for PS 2 where animals are kept in a cubicle barn. Main material groups were cast iron for the fan engine and low alloyed steel (hot rolled) for the basket. Values were calculated as a function of fan wear limit (8 years) and service life of the barn (50 years). Ventilation intensity (airflow ratio) was defined as recommended by Pommer et al. (2014). Energy demand for fan operation in each system was calculated based on the heat load-adjusted fan runtime, airflow ratio and the fans' power-to-mass ratio, and included an extra charge for fan control, and milking and cooling of additional milk. The annual demand per cow increased with heat load and was 21 kWh and 35 kWh in PS 1 and PS 2, respectively (Table 3). At end-of-life, fans were assumed to be recycled, given the high recycling rates in Austria (Unger et al., 2017) and the legal requirements for keeping components of electronic equipment within the economic cycle as long as possible as envisioned by the European Commission (EC, 2018). In the cut-off modelling approach applied for this study, the recycling activities are not attributed to the milk production process (Wernet et al., 2016). End-of-life treatment of fans was thus considered as burden-free.

Based on the monthly average heat load maximum of THI < 73 (Table 2), the effect of heat stress on cow welfare was assumed to be mild. While sweating, respiration rate and water intake start to increase at THI 65 (Bernabucci et al., 2010), mild heat stress and reduced DMI have been reported at THI 68–71 (Bernabucci et al., 2010; Zimbelman et al., 2009). Following recommendations by the National Research Council, NRC (2001), heat stress-induced changes in DMI were estimated, starting at a temperature above 20 °C. For PS 1, the annual increase in DMI was 20 kg/cow, entailing an increase in annual milk yield of 38 kg ECM, whereas respective changes calculated for PS 2 amounted to 51 kg DMI and 101 kg ECM/cow. Heat stress-induced changes in conception rate and mortality have been reported for THI > 73 (Schüller et al., 2014) and THI > 80 (Bernabucci et al., 2010), respectively, and where therefore not considered in the present study.

Sensitivity analysis was performed for PS 2 to evaluate the effect of changes in fan runtime (±30%). The difference in fan runtime corresponds to a one-month increase or decrease of heat stress at THI 71.

Uncertainty information and statistical analysis

Information on input data uncertainty was resumed from the applied inventory database (Wernet et al., 2016), while country-specific ranges of emission factor variation were applied to calculate output uncertainty (EAA, 2014). For each deterministic environmental impact estimate obtained with LCA, a probability distribution was generated using Monte-Carlo simulations with 1 000 iterations. Results were used to analyse differences in the means of S_{basic} and S_{vent} outcomes, by means of a two-sample *t*-test (0.05). All calculations were performed with the Statistical Analysis Systems SAS Enterprise Guide 7.1 and SAS Studio 3.3 (SAS, 2014).

Results

Baseline scenario

The environmental impact estimates of S_{basic} decreased from the alpine system PS 1 to the lowland system PS 2, across impact categories (Table 4). GWP amounted to 1.32 kg and 1.09 kg CO_2-e/kg ECM in PS 1 and PS 2, respectively. While emissions from enteric fermentation (60%) and from feed production (17%)

Table 4
Contribution of the baseline and the ventilation scenario S_{basic} and S_{vent} of cow milk production systems PS 1 and PS 2 to the environmental impact potential global warming (GWP), terrestrial acidification (TAP) and freshwater eutrophication (FEP), expressed per unit of energy-corrected milk (ECM): mean, CV, confidence interval (CI, with 5th and 95th percentile) and the relative difference in means between S_{basic} and S_{vent} (MD, with *P*-value). Values were derived based on Monte-Carlo simulations.

Production system	Impact category	Unit	Scenario	Mean	CV	CI (90%)		MD	
					%	5th %ile	95th %ile	%	*p*
PS 1	GWP	kg CO_2-e/kg ECM	S_{basic}	1.321	9.5	1.118	1.525		
			S_{vent}	1.314	9.3	1.105	1.515	−0.5	0.231
	TAP	g SO_2-e/kg ECM	S_{basic}	22.96	7.1	20.21	25.68		
			S_{vent}	23.01	7.3	20.35	25.72	0.2	0.477
	FEP	g P-e/kg ECM	S_{basic}	0.135	43.9	0.067	0.249		
			S_{vent}	0.143	45.2	0.072	0.284	**5.9**	0.004
PS 2	GWP	kg CO_2-e/kg ECM	S_{basic}	1.089	6.8	0.971	1.216		
			S_{vent}	1.089	7.2	0.967	1.209	−0.1	0.831
	TAP	g SO_2-e/kg ECM	S_{basic}	19.18	6.5	17.22	21.25		
			S_{vent}	19.08	6.4	17.10	21.10	−0.5	0.065
	FEP	g P-e/kg ECM	S_{basic}	0.118	44.5	0.060	0.230		
			S_{vent}	0.118	43.0	0.060	0.221	0.0	0.890

contributed most to the total estimate (Supplementary Table S5), the impact of emissions from construction and operation of the housing system was minor (<6%). TAP was estimated at 22.96 g and 19.18 g SO_2-e/kg ECM in PS 1 and PS 2, respectively. Key contributors to TAP estimates were manure emissions (74%) and emissions from feed production (25%), while impacts of housing were negligible (1%). A FEP of 0.135 g P-e/kg ECM was estimated for PS 1, while it amounted to 0.118 g P-e/kg ECM in PS 2. Contrary to GWP and TAP, contributions from housing construction (27%) and operation (26%) had a major impact on FEP estimates across PSs (54%). Variability in results due to uncertainties in the inventory data was highest for FEP (CV 45%) in both PSs and of comparable level for GWP (10%) and TAP (7%). Probability distributions of GWP and TAP followed a normal distribution, while for FEP, it was right skewed in all systems (Supplementary Fig. 1).

Intervention scenario with additional ventilation

Compared to S_{basic}, the implementation of basket fans to eliminate heat stress in the intervention scenario S_{vent} did not significantly affect impact outcomes, except for FEP in PS 1, which increased by 6% (Table 4). The additional environmental costs for fan production and operation per se were highest for PS 2 and amounted to 2.3, 0.4 and 0.1% of FEP, GWP and TAP, respectively (data not visible in Table 4, calculated separately). These costs were, however, offset in all systems when taking into account the increase in productivity due to heat stress abatement, except for FEP of PS 1. Differences in contribution analyses between S_{vent} and S_{basic} were negligible (<1%) (Supplementary Table S5). Contributions of fan production and operation in terms of FEP amounted to +0.1% and +0.7%, respectively, while in regard to GWP and TAP, the total impact of mechanical ventilation was +0.3% and +0.1%, respectively. Estimated variability was also similar to ranges calculated for S_{basic}, with highest impact ranges for FEP (0.06 and 0.22 g P-e/kg ECM). Sensitivity analysis for varying fan runtime in PS 2 (±30%) revealed a slight effect on FEP (±0.5%), while TAP remained constant and GWP was hardly affected (Table 5).

Discussion

This is the first study estimating effects of implementing fans in dairy barns to reduce heat stress on the net environmental impact of milk production. Trading off the environmental costs of production and operation of basket fans against the emission mitigating effect of maintaining productivity through heat stress abatement in S_{vent} revealed no significant impact changes compared to S_{basic}, except for FEP in PS 1 (+5.9%). Regarding GWP and TAP, avoided productivity losses outweighed environmental costs of mechanical ventilation in both PSs. Modulating fan runtime (±30%) affected FEP, but not TAP (Table 5).

The order of magnitude of GWP, TAP and FEP in S_{basic} (e.g. PS 2: 1.1 kg CO_2-, 19.2 g SO_2- and 0.1 g P-e/kg ECM, respectively) was largely consistent with previous LCA results for similar dairy production systems across Europe (e.g. Battini et al., 2016; Berton et al., 2020; Hörtenhuber et al., 2010; Mu et al., 2017). Minor deviations from previous estimates were mostly due to differences in methodological approach. Moreover, the slightly lower GWPs reported by Hörtenhuber et al. (2010) for Austrian PSs in similar regions are due to the use of a lower characterization factor for biogenic methane (25). Regarding uncertainties, similar coefficients of variation were reported by Chen and Corson (2014). The impacts estimated for S_{basic} in the present study were therefore considered suitable to assess relative changes in impact potential in S_{vent} due to the intervention measure (i.e. additional ventilation via basket fans).

In S_{vent} of both PSs, the emission-reducing effect of heat stress abatement compensated for the assumed environmental costs of mechanical ventilation for almost all impact categories investigated. Only FEP in PS 1 increased significantly (Table 4). A more pronounced effect regarding eutrophication was expected given

Table 5
Sensitivity analysis for the standard ventilation scenario S_{vent} (runtime: 2 340 h/year) of cow milk production system PS 2: results show the effect (%) of changes in fan runtime (±30%) on selected environmental impacts per kg of energy-corrected milk (ECM) compared to S_{vent}, based on point estimates.

Item	S_{vent} (2 340 h/year) [point estimate, unit]		Sensitivity analysis for fan runtime: $-30\%_{(1\ 620h/year)}$ [in % of S_{vent}]	$+30\%_{(3\ 060h/year)}$
GWP	1.061	kg CO_2-e/kg ECM	−0.04	+0.04
TAP	18.81	g SO_2-e/kg ECM	−0.00	+0.00
FEP	0.081	g P-e/kg ECM	−0.49	+0.48

Abbreviations: GWP = global warming potential, TAP = terrestrial acidification potential, FEP = freshwater eutrophication potential.

the comparatively high additional contribution of emissions from fan operation to FEP (0.7% net increase) in contrast to GWP (0.1%) and TAP (0.0%). This also confirms the sensitivity of the impact category FEP to material and energy demand reported by Herzog et al. (2020), in contrast to TAP. Besides, the higher impact of fan implementation on FEP in PS 1 compared to PS 2 can be attributed to the differences in baseline characteristics between the two systems (i.e. housing type, location and production intensity) and the resulting ratio between the material demand and the assumed emission mitigation potential associated with additional ventilation. Due to the larger space allowance per animal, the cubicle barn in PS 2 required a higher number of fans to provide cooling both in the resting area and in the feeding area, compared to the tie-stall system in PS 1 (Table 3). As monthly average temperature increased with decreasing altitude, the heat stress level was also higher in PS 2 (Table 2) and entailed a more pronounced milk yield increase in S_{vent} (Table 3). Relative to the increased productivity level, the material demand in PS 2 was lower than in PS 1, which yielded a better ratio between welfare benefits and environmental costs of the measure.

Heat stress and its abatement in the present study had a markedly lower **effect on emissions** compared to previous studies on the environmental impacts of diseases, which reported changes in GWP of up to 3.1% per unit of product (Özkan Gülzari et al., 2018). This can not only be explained by the additional environmental costs associated with fan implementation (e.g. PS 2: +0.4% GWP, +0.1% TAP, +2.3% FEP). It also reflects the less pronounced productivity changes assumed for mild heat stress (PS 1: 0.6%, PS 2: 1.3%) compared to the effects of diseases (up to 12.5% in Özkan Gülzari et al. (2018)). Moreover, the studies on disease-related environmental impacts accounted for changes in reproductive performance and culling rate (e.g. ADAS, 2015; Mostert et al., 2018a; 2018b). Although first effects of heat stress on oestrus activity have been reported to start at THI > 57 (Gernand et al., 2019), effects on conception rate were only found at THI > 73 (Schüller et al., 2014), while an increased mortality risk has been described for THI > 79.6 (Bernabucci et al., 2010). As the maximum THI in the present study never exceeded the latter two thresholds, no changes in fertility and culling risk were assumed. For farming conditions with THIs above these thresholds, however, the emission mitigating effect of heat stress abatement can be expected to be higher than the one estimated in the present study, due to the benefits of improved fertility and reduced culling risk on product-related emissions (Mostert et al., 2018a; 2018b). Especially in regions with similar production systems but higher average temperature (e.g. in Italy, France, Northern Spain), fan implementation could thus result in a significant decline of environmental impacts, especially in the case of TAP and GWP, which are hardly affected by emissions from fan production and operation, as shown in contribution analysis (Supplementary Table S5). Although the effectiveness of fan cooling in reducing heat stress reaches its limits at temperatures >28 °C (Ji et al., 2020; Smith et al., 2007), additional wetting could further maximize the mitigating effect, at least in terms of GWP. Although NH_3 emissions from housing would increase (Ngwabie et al., 2011), evaporative cooling allows for a markedly higher heat stress relief in arid regions and respective milk yield increase (Ji et al., 2020).

Due to the lack of empirical data, the **effects on productivity of heat stress abatement through increased ventilation and thus improved welfare** in S_{vent} were estimated from the literature. Fans comparable in size and airflow rate to those modelled in the present study have been described to produce airflow velocities of 0.5–3.5 m/s (Calegari et al., 2014). As for each unit increase in wind speed, a 1.9 unit decrease of THI can be assumed (Mader et al., 2006), fan operation was considered to result in a decrease of THI to values below 68 in both PS, thus rendering the assumed elimination of heat stress in S_{vent} realistic (Smith et al., 2007). Similarly, the estimated changes in productivity are supported by milk yield increases of 0.4 –0.8 kg/cow/day due to fan cooling (Frazzi et al., 2000; Ji et al., 2020). However, the convective heat transfer rate and thus the fans' cooling effect are also affected by the fan-induced change in air turbulence, which is a function not only of airflow velocity, but also of airflow direction (Saha et al., 2013), the position of the cow (Wang et al., 2018) and its distance from the fan (Calegari et al., 2014), barn geometry (Hempel et al., 2016) and the timing of fan activation (by day, overnight, full-time (Spiers et al., 2018)). For instance, compared to lying cows, heat dissipation from standing cows is higher (Wang et al., 2018). To account for potential variation in the fans' cooling effect and in the cows' cooling demand, modulating fan runtime (±30%) revealed a slight sensitivity of FEP (±0.5%), while TAP and GWP were not affected (Table 5). Thus, an over- or underestimation of the assumed effectiveness of fan cooling in the present study and of differences in the individual cooling demand of cows would mostly affect FEP estimates, reflecting the high emission contributions from material and energy demand compared to the overall emission-reducing effect of improved productivity, in contrast to TAP and GWP.

Environmental factors such as airflow velocity, temperature and humidity can significantly affect the formation of CH_4 and NH_3 in dairy barns (Hempel et al., 2016; Sanchis et al., 2019), but current emission calculation schemes account for these factors only to a limited extent (EAA, 2014; IPCC, 2006a). Mechanical ventilation increases the airflow velocity in the barn (Wang et al., 2018), thus promoting NH_3 volatilization from soiled surfaces (Zhang et al., 2008, Sanchis et al., 2019). However, since the sensitivity of NH_3 to changes in airflow speed is not accounted for in the Tier 2 NH_3 calculation models (EAA, 2014; IPCC, 2006a), the additional environmental costs of fan implementation in S_{vent} might have been underestimated. According to Sanchis et al. (2019), an increase in ventilation rate by 100 m^3/h entails an increase in volatilization by 0.007 g NH_3/cow and day. Considering the assumed ventilation rates in S_{vent} for both PSs, the NH_3 emission rates presented in Supplementary Table S4 could thus increase by an additional 0.2% (PS 1) and 0.3% (PS 2). Moreover, the cow cooling effect of the fans can indirectly affect enteric CH_4 emissions, as it influences cow activity, a parameter which is not reflected in CH_4 calculation models (IPCC, 2006a). As the cows' metabolic rate is positively related to enteric CH_4 formation (Hempel et al., 2016), a temperature-related decrease in cow activity reduces overall CH_4 emissions (Ngwabie et al., 2011). Compared to feeding or ruminating cows, overall CH_4 emissions from resting cows are reduced by half (Chagunda et al., 2013). In the moderate climate zone, heat stress-induced changes in cow activity have been reported to start at THI 67 (Heinicke et al., 2018). The impact on GWP of the additional ventilation scenario S_{vent} might therefore have been slightly underestimated. The increase in airflow velocity might further affect the impact, since average wind speeds of 1.5 m/s had a significant effect on manure CH_4 emissions under outdoor conditions (Chagunda et al., 2013). Including, as suggested by the IPCC (2006a) for Tier 3, both the effect of airflow velocity and of temperature on enteric and manure CH_4 emissions would help to reduce estimation error in regard to GWP and improve the robustness of the result.

To reduce the uncertainty related to the assessment of environmental impacts of fan implementation, **future assessments** should be based on **primary data**, at least regarding the effectiveness of mechanical heat stress abatement through increased ventilation to improve cow welfare and productivity. Measuring animal performance (e.g. milk yield, feed intake and feed conversion efficiency) would facilitate to account for the effect of animal factors such as breed, parity, coat colour (Al-Kanaan, 2016), hair coat depth (Berman, 2005) and genetic yield potential (Zimbelman et al., 2009), and for the duration of exposure to hot and humid environment (Bernabucci et al., 2010; Spiers et al., 2018) on the cows' susceptibility to heat stress, which co-determines the cooling demand and thus fan runtime. Based on long-term studies, potential effects of cooling interventions on reducing standing time and respective benefits for claw health and feed intake could also be considered (Nordlund et al., 2019; Tucker et al., 2021; Weigele et al., 2018) as well as potential effects on diseases, productivity shortfalls and fertility (Gernand et al., 2019). The latter would further emphasize the emission mitigation potential of fan implementation, since an increase in productive lifespan generally reduces environmental impacts per unit of product (Knapp et al., 2014). Moreover, continuous on-farm measurements of environmental parameters and animal responses would allow to factor in delayed effects of heat stress on cows, which is particularly relevant for the estimation of enteric CH_4 emissions (Hempel et al., 2016). The data could also be used to calculate a more comprehensive thermal comfort index that includes wind speed and solar radiation and indicators of animal response in the heat stress assessment (e.g. Berman, 2005; Wang et al., 2018). Besides, emissions from fan disposal (**end-of-life treatment**) should be included in the modelling, at least for countries with lower recycling rates than Austria. In this regard, the use of alternative materials (e.g. thermosets instead of alloyed steel) for fan production and green energy mixes could be explored regarding their potential to reduce environmental costs of fan implementation, which could particularly benefit FEP mitigation, due to the high contribution of fan production to the final result (Supplementary Table S5). Finally, for an overall appraisal of the measure's potential to improve sustainability of milk production, future assessments should include an **economic evaluation** to account for costs associated with fan acquisition and operation, and heat stress-induced productivity decline (Ji et al., 2020; Place and Mitloehner, 2014; Polsky and von Keyserlingk, 2017). Such results could facilitate decision making and be an incentive for farmers to implement fans, besides welfare benefits.

Conclusion

Our findings suggest that fan-induced heat stress abatement at least outweighs most of the environmental costs associated with additional ventilation. In terms of GWP and TAP, the implementation of basket fans does not significantly affect the environmental impacts of milk production under the conditions of the modelled dairy systems, i.e. a maximum THI of 72.4 and the prevention of heat stress-induced decrease in milk yield of 1.3% per cow and year. Regarding FEP, environmental costs of fan production can exceed the overall emission-reducing effect of improved productivity, especially if heat load, respective fan run times and welfare benefits are low. However, in view of climate change and expected temperature increases also in temperate regions, benefits of additional cooling measures can be expected to increase. Future assessments would benefit from primary empirical data on the effectiveness of fans in reducing heat stress and subsequent effects on cow productivity, and from emission calculation schemes that are sensitive to changes in environmental factors such as airflow velocity and ambient temperature, as well as animal activity.

Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.animal.2021.100274.

Ethics approval

Not applicable.

Data and model availability statement

Neither data nor the model were deposited in an official repository. The life cycle inventory database ecoinvent v3.2 is available via the website of the provider ecoinvent (https://www.ecoinvent.org/home.html). The open-source life cycle assessment software openLCA v1.7.2 is available via the website of the provider GreenDelta (https://www.greendelta.com).

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Declaration of interest

None.

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Supplementary Table S1

Characteristics of dairy cow feeding regimes in production systems PS 1 and PS 2, calculated based on the ratio of permanent grassland to arable land in each PS and respective gross yield levels.

Feeding regime	PS 1	PS 2
in % of feed DM produced on-farm		
Grass silage	66	34
Hay	23	8
Green fodder	0	8
Pasture	11	0
Grass-clover silage	0	10
Maize silage (whole plant)	0	20
Wheat grain	0	7
Barley grain	0	13
in % of concentrate DM produced off-farm [a]		
Wheat grain	34	23
Barley grain	66	46
Triticale grain	0	0
Rape seed meal *	0	16
Sunflower seed meal *	0	6
Dried distiller's grain **	0	9

[a] Off-farm concentrate feed originated from arable areas in Austria (assumed medium transport distance: 300 km) and other typical European countries of importation (Germany, Italy, Czech Republic) (assumed medium transport distance: 650 km).
* solvent extracted
** with solubles

Supplementary Table S2

Average nutrient intake and dietary proportion (dry matter-basis) per dairy cow in production systems PS 1 and PS 2.

Type	Unit	PS 1	PS 2
Nitrogen-free extracts	kg NfE/day, (%)	7.78 (49)	9.58 (53)
Crude fibre	kg CF/day, (%)	3.66 (23)	3.70 (21)
Crude protein	kg CP/day, (%)	2.30 (15)	2.75 (15)
Ether extracts	kg EE/day, (%)	0.43 (3)	0.50 (3)
Ash	kg/day, (%)	1.58 (10)	1.53 (8)
Total dry matter intake	kg/cow/day	15.75	18.07

Supplementary Table S3

Emissions from enteric fermentation, manure management (dry period and rearing included) as well as applied allocation factors (AFs) for the baseline and the ventilation scenario S_{basic} and S_{vent} of cow milk production systems PS 1 and PS2. Values for PS 1 include prorated emissions from pasture and outdoor run.

Emissions/ AFs	Unit	Scenario	PS 1	PS 2	Reference
$CH_{4\ enteric}$	kg/cow/year	S_{basic}	177.07	181.85	Kirchgessner et al.,
		S_{vent}	177.51	182.84	1995
$CH_{4\ manure}$	kg/cow/year	S_{basic}	6.08	31.12	IPCC, 2006a
		S_{vent}	6.10	31.32	(eq. 10.22 + 10.23)
N_{ex} *	kg/cow/year	S_{basic}	135.23	146.72	Gruber and Pötsch,
		S_{vent}	135.70	147.42	2006
$N_2O_{\ direct}$	kg/cow/year	S_{basic}	4.25	1.15	IPCC, 2006a
		S_{vent}	4.26	1.16	(eq. 10.25)
$N_2O_{\ indirect}$ [a]	kg/cow/year	S_{basic}	1.11	0.93	IPCC, 2006a
		S_{vent}	1.12	0.93	(eq. 10.27)
NH_3	kg/cow/year	S_{basic}	46.28	53.87	EAA, 2014
		S_{vent}	46.44	54.13	
NO_x	kg/cow/year	S_{basic}	24.61	5.05	EAA, 2014
		S_{vent}	24.69	5.08	
AF_{milk}	%	S_{basic}	80.0	83.1	IDF, 2010
		S_{vent}	80.2	83.4	
AF_{meat}	%	S_{basic}	20.0	16.9	IDF, 2010
		S_{vent}	19.3	16.7	

[a] Following national inventory recommendations (EAA, 2018) N losses due to run-off and leaching from manure storage were assumed to be zero, since legal previsions prohibit leaching from storage tanks. N and P losses from manure and fertilizer application were considered via datasets of the inventory database ecoinvent (Wernet et al., 2016).

* N_{ex} = nitrogen excretion

Supplementary Table S4

Emission factors (EF) for CH_4 and N_2O emissions, NH_3-N and NO_x-N volatilisation from dairy cow manure in the barn and yard (y), on pasture (p) and during storage and application.

Emissions	Unit	Emission factor$_{origin}$		Reference
$CH_{4\ manure}$	kg CH_4/cow/year	0.088*	MCF_{liquid}	EAA, 2014 (tab. 178)
		0.02*	MCF_{solid}	IPCC, 2006a (tab.10.17)
		0.01	$MCF_{p/y}$	IPCC, 2006a (tab. 10.17)
$N_2O_{\ direct}$	kg N_2O-N/kg N_{ex}	0.005	EF_{liquid}	IPCC, 2006a (tab. 10.21)
		0.02*	EF_{solid}	EAA, 2014 (tab. 189)
		0.02	EF_p	IPCC, 2006b (tab. 11.1)
		0.013*	EF_y	EAA, 2014 (tab. 190)
$N_2O_{\ indirect}$	kg N_2O-N/kg N_{ex}	0.01	$EF_{atmospheric}$	IPCC, 2006b (tab. 11.3)
$NH_{3\ housing}$	kg NH_3-N/kg N_{ex}	0.118*	EF_{liquid}	EAA, 2014 (tab. 202)
		0.039*	EF_{solid}	EAA, 2014 (tab. 202)
$NH_{3\ storage}$	kg NH_3-N/kg TAN	0.15*	EF_{liquid}	EAA, 2014 (tab. 203)
		0.3*	EF_{solid}	EAA, 2014 (tab. 203)
$NH_{3\ application}$	kg NH_3-N/kg TAN	0.5*	EF_{liquid}	EAA, 2014 (tab. 207)
		0.79*	EF_{solid}	EAA, 2014 (tab. 207)
$NO_{x\ storage}$	kg NO_x/cow/year	0.007*	EF_{liquid}	EAA, 2014
		0.154*	EF_{solid}	
$NO_{x\ application}$	kg NO_x/cow/year	0.01*	$EF_{solid/liquid}$	EAA, 2014

* National calculations. Regarding N emissions: N_{ex} = nitrogen excretion, TAN = total ammoniacal nitrogen (30/50% from N_{ex} for solid/ liquid manure management systems, respectively (EAA, 2014, tab. 204)), relative to ratio of excretion per location: PS 1 (6% pasture, 94% barn), PS 2 (100% barn). Regarding manure CH_4 emissions: MCF = methane conversion factor.

Supplementary Table S5

Contribution analysis for the baseline and the ventilation scenario S_{basic} and S_{vent} of cow milk production systems PS 1 and PS 2. Contribution potentials to global warming (GWP), terrestrial acidification (TAP) and freshwater eutrophication (FEP) are expressed in percent of point estimates for each impact category.

		GWP (%)		TAP (%)		FEP (%)	
		S_{basic}	S_{vent}	S_{basic}	S_{vent}	S_{basic}	S_{vent}
PS 1	feed production	12.5	12.5	23.5	23.5	42.6	42.1
	operation housing system	6.1	6.4	1.3	1.4	57.3	57.9
	construction	3.4	3.6	1.0	1.0	27.6	27.7
	energy demand	2.4	2.5	0.3	0.3	28.3	28.9
	animal	81.3[a]	81.1[b]	75.2	75.1	0	0
PS 2	feed production	17.4	17.4	24.6	24.5	45.7	45.5
	operation housing system	5.7	5.9	1.3	1.4	54.3	54.5
	construction	3.1	3.3	1.0	1.0	27.2	26.9
	energy demand	2.3	2.4	0.3	0.3	25.9	26.4
	animal	76.9[c]	76.7[d]	74.1	74.1	0	0

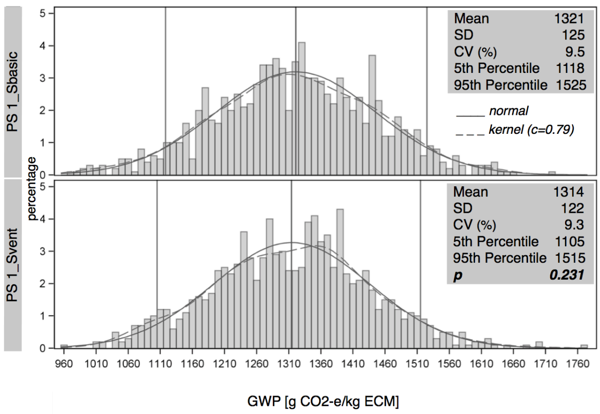
[a] enteric fermentation: 65.7%, manure management: 15.6%

[b] enteric fermentation: 65.2%, manure management: 15.5%

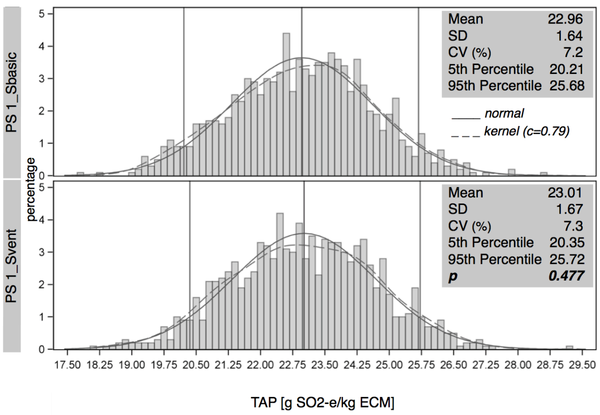
[c] enteric fermentation: 60.0%, manure management: 16.0%

[d] enteric fermentation: 60.5%, manure management: 16.4%

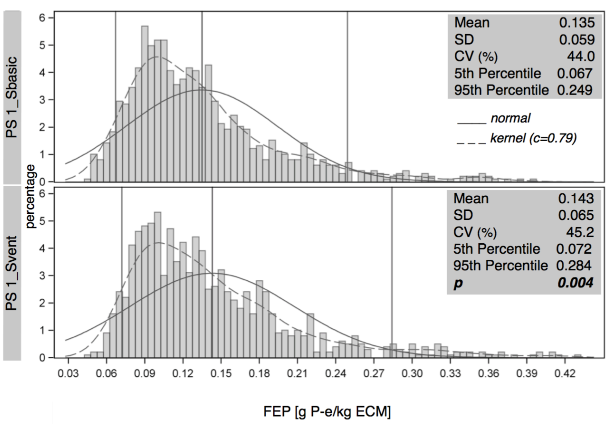
a)



b)



c)



Supplementary Fig. 1. Probability distributions of a) global warming potential (GWP, g CO_2-e), b) terrestrial acidification potential (TAP, g SO_2-e) and c) and freshwater eutrophication potential (FEP, g P-e) per kg energy-corrected milk (ECM) of dairy cows resulting from variation in inventory data for the baseline and the ventilation scenario S_{basic} and S_{vent} of production system PS 1, based on Monte-Carlo simulations. The central vertical line indicates the median, the left and right vertical line mark the predicted 90% confidence interval (from 5th to 95th percentile). The solid and the dashed line represent the probability density function of the normal distribution and the kernel distribution, respectively.

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6 General discussion

The aim of this thesis was to provide a first insight into environmental impacts of welfare intervention measures. Following a literature review on the general relationship between animal welfare improvement and environmental impact mitigation in dairy farming (paper 1), the thesis focuses on the assessment of potential effects of two specific intervention measures (rubber mats, basket fans) on the impacts of milk production on global warming, acidification, eutrophication and energy use (paper 2+3). In the following sections, the key contributions to the existing literature are highlighted, including an appraisal of challenges and limitations associated with the chosen methodological approach. Concluding, the lessons learnt are consolidated in an outlook, and suggestions for future research are provided.

6.1 Research gaps closed

6.1.1 Paper 1 – Literature review

The literature review yielded a comprehensive picture of the state of knowledge regarding potential and evidenced interdependencies between cow welfare and the environmental impacts of dairy farming. It is presented as a conceptual model in Fig. 1. Different connecting lines specify the type (qualitative vs. quantitative) and availability (available, preliminary, not available) of research data that document the relationship.

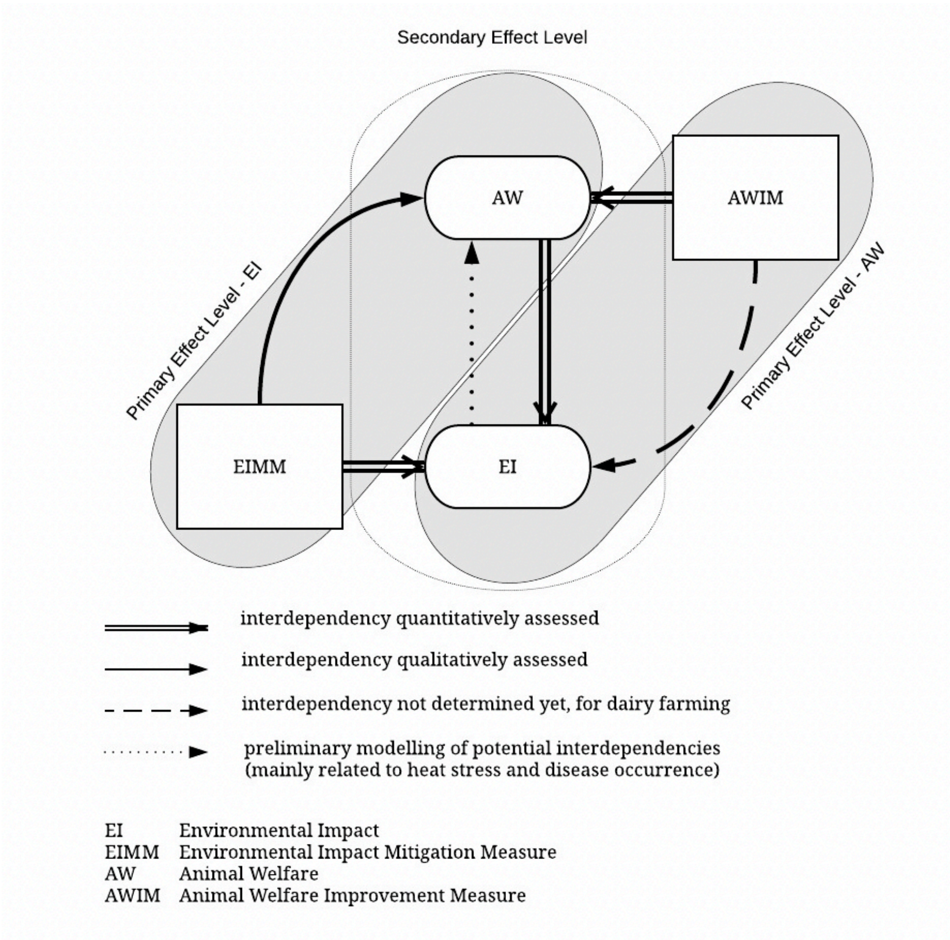

Fig. 1 Conceptual model of the interdependencies of environmental impact mitigation and animal welfare improvement with regard to sustainable dairy farming.

For both subject areas, the environmental impact (EI) of milk production and the welfare of dairy cows (AW), the quantitative effectiveness of respective mitigation (EIMM) and improvement measures (AWIM) is well-documented in peer-reviewed studies (double line). Regarding interdependencies between EI and AW, two levels of effects are discussed in the literature. In the conceptual model, the effects of EIMM on AW and of AWIM on EI are summarized as the primary effect level and interdependencies between EI and AW are delineated as secondary effect level (Fig. 1). From an environmental perspective, research on potential effects of environmental impacts on animal welfare is still in an early stage and based on preliminary modelling (dotted line), whereas the effects of emission mitigation measures on welfare have been evaluated qualitatively (solid line). From the welfare perspective, potential implications of impaired health for the animals' emission potential are currently being investigated quantitatively (double line), however, without accounting for potential environmental costs associated with measures implemented to improve an impaired welfare situation (dashed line). Regarding the secondary effect level, positive effects of animal health and welfare on the animals' environmental impact potential have been described qualitatively and quantitatively (double line). In contrast, potential effects of environmental impacts on cow welfare are delineated in preliminary modelling approaches (dotted line).

First research questions answered

The hypothesis in regard to the first research question was confirmed:

From the first paper contribution, it can be concluded that interdependencies between EI and AW exist on both a primary and a secondary effect level. The extent to which EIMMs affect AW is described qualitatively (1a), while effects of specific AWIMs on EI are largely unknown and have neither been described quantitatively nor qualitatively in peer-reviewed literature (1b).

In 2014, the Animal Health and Greenhouse Gas Emission Intensity Network (AHGHGN), a consortium of scientists of relevant disciplines, raised the question of potential effects of animal welfare improvement for GHG emission mitigation and asked about potential trade-offs between improving health and reducing environmental impact (AHGHGN, 2014). With the two research articles on the effects of the welfare improvement measures rubber mats and basket fans on GWP, TAP and FEP as well as MEP, nRER and RER, this thesis addresses the existing research gap in regard to lameness and heat stress intervention measures and thus contributes to converting the dashed line in the above displayed conceptual figure into a solid one.

6.1.2 Papers 2 and 3 – Original research

Production parameters such as milk yield, fertility and longevity can be used to link the welfare status of an individual with environmental impact assessment (e.g., ADAS, 2015; Chen et al., 2016; Mostert et al., 2018b). Hence, to evaluate potential environmental trade-offs associated with welfare improvement, **intervention measures** with evidenced impact on cow performance were chosen for analysis, based on three criteria: increasing floor softness to reduce lameness, and additional ventilation to abate heat stress were identified as 1) **highly relevant** in view of the prevailing high prevalence of locomotive problems in dairy cows on national and international level (Burgstaller et al., 2016; FVE, 2019) and due to proceeding global climatic changes (APCC, 2014; Steffen et al., 2015; UN, 2019), 2) **easily applicable** in Austrian farming practice, without the need for major changes to the basic structure of the barn, and 3) **feasible**, since the literature provides sufficient data on both, the quantitative effects of lameness and heat stress on cow productivity and the quantitative effectiveness of the two welfare intervention measures. Furthermore, in regard to lameness intervention, the existing research on the environmental impacts of lameness (e.g., Chen et al., 2016; Mostert et al., 2018b) was considered a valuable baseline to evaluate assessment outcomes.

The results of both original research contributions (**paper 2+3**) substantiate the current literature on the benefits of good welfare in regard to emission mitigation (Place and Mitloehner, 2014; Stott et al., 2010; Williams et al., 2013). They allow for a more differentiated view on the potential of disease reduction as a measure of emission mitigation and of sustainability improvement in dairy farming, as previously proclaimed by Mostert et al. (2018a, 2018b, 2019) and Özkan Gülzari et al. (2018). **Environmental costs of measure implementation** can be considerable. They include costs of raw material and energy for the production and the application of the measure. In regard to lameness abatement for example, these costs were marked, although the raw material for mat production is recycled rubber. Nonetheless, in regard to both intervention measures and almost all of the modelled production systems and environmental impact categories, these costs were outweighed by the emission mitigating effect of productivity increase due to the assumed welfare improvement. Environmental costs significantly exceeded benefits only in the case of nRER regarding mat introduction (up to 2.5%) and of FEP in regard to fan implementation (up to 5.9%). The emission mitigating effect of welfare improvement slightly but significantly prevailed in regard to TAP and RER (up to 1.4%

and 0.8%, respectively). As highlighted by contribution analyses for each environmental impact category in both intervention studies, these effects can be explained by the high contribution of impacts from energy demand to both FEP (28%) and nRER (11%), in contrast to GWP, TAP, MEP and RER (<2%). Similarly, contributions of impacts from barn construction were highest for FEP (31%) and nRER (26%), while changes in material and energy demand due to measure implementation hardly affected TAP, MEP and RER, as also confirmed by sensitivity analyses.

While the environmental benefits of cow health have been confirmed in previous studies, the **third paper** is the first to quantitatively estimate such an effect in regard to the welfare aspect thermal comfort. So far, a positive environmental effect of heat stress abatement per unit of product has only been confirmed for poultry and pig production (Kenyon et al., 2013; Leinonen et al., 2014). Place and Mitloehner (2014), however, pointed to a potentially similar effect in cattle, given the benefits for feed intake, feed conversion efficiency and thus productivity (Bernabucci et al., 2010; Gernand et al., 2019). In addition to confirming this functional relationship, the third paper takes into account the complex interdependencies between environmental parameters, such as temperature and airflow speed, and the formation of manure emissions. Despite an increase in CH_4 and NH_3 emissions with increasing temperature and airflow speed, the operation of basket fans can reduce heat stress-induced emission increases and outweigh the environmental costs associated with the production and operation of fans, at least in regard to GWP and TAP. Although FEP increased in one of the modelled systems in the present study, energy-efficient options for controlling microclimatic conditions in the barn (Rong et al., 2014; Vitt et al., 2017) could help to minimize the environmental costs of the intervention measure.

Second research question answered

With few exceptions, the hypothesis in regard to the second research question was confirmed: From the second and third paper contribution, it can be concluded that improving dairy cow welfare can be recommended from an environmental point of view, at least in regard to the implementation of rubber mats for lameness reduction and basket fans for heat stress abatement in production systems with medium milk yield level (6.000-8.000kg) and temperate climatic conditions.

6.2 Methodological approach revisited

The environmental impacts of welfare intervention were estimated based on farm model calculations that combine **three types of data**: 1) national average statistics to describe the product systems (foreground data), 2) data from the inventory database *ecoinvent* (Wernet et al., 2016) to model the supply chain (background data) and the intervention measures and 3) literature data to quantify the effectiveness of each measure in terms of improving cow productivity. Milk LCA studies are frequently based on national average data, especially when the study is aimed at providing a general appraisal of potential environmental effects associated with management options, irrespective of a specific system, and when data collection from real-life experiments would be costly and time-consuming (Baldini et al., 2017; Yan et al., 2011). The inventory database *ecoinvent* (Wernet et al., 2016) is currently the most common information provider for LCAs on milk (Baldini et al., 2017). Associations between impaired welfare (i.e., lameness and heat stress) and productivity are available in the literature and were used to assume changes in productivity and emissions due to welfare improvement in the intervention scenarios.

In the following subsections, methodological challenges and limitations associated with the estimation of environmental impacts of welfare intervention are highlighted, including suggestions on how to integrate welfare in a broader sense than health into the sustainability debate.

6.2.1 Methodological choices and comparability of results

LCA is currently one of the leading methods to estimate the potential environmental impacts of cow milk production. The comparability of results between studies is, however, limited due to methodological choices, which significantly affect assessment outcomes (Baldini et al., 2017). Despite serious efforts of **standardization** (IDF, 2015; ISO, 2006; LEAP, 2016; Wolf et al., 2012), milk LCA studies still lack full harmonization. This has to be kept in mind when comparing the results of this thesis with previous research findings. Nonetheless, valid conclusions could still be drawn since the assessment had been designed as a scenario approach, where each system served as its own baseline for comparison.

According to ISO definitions for LCA, the **functional unit (FU)** of a production process should quantitatively reflect the primary function of the product (ISO, 2006). In dairying, the main function of milk as a staple food can be seen in its nutritional value. It is frequently expressed using the standardization units FPCM (fat- and energy-corrected milk) or ECM (energy-corrected milk) to account for differences in fat and energy content. Sector-specific LCA guidelines recommend FPCM as the FU unit of choice to standardize milk LCAs (IDF, 2015). For the present thesis, however, the ECM method according to Sjaunja et al. (1991) was chosen to ease the comparison of results with previous LCA assessments for Austria (Hörtenhuber et al., 2010) and with first estimations of environmental impacts of lameness (Chen et al., 2016), where the FU is also ECM. While absolute impacts of GWP and, in particular, of AP and EP are significantly higher when expressed per unit of ECM compared to FPCM (Baldini et al., 2017), the choice of FU does not affect relative differences between scenarios.

Emission calculations in the present thesis were based on internationally recognized methodology provided by the IPCC. The Tier 2 approach was chosen to account for region-specific meteorological conditions (cold temperate climate zone), reflected in national emission factors (EAA, 2014). Despite the site-specific calculation of emissions based on production characteristics and climatic conditions in Austria, the results of the two research articles bear meaning of generalisable nature. LCA delivers so-called potential impacts, which are hardly time- or location-dependent due to considering the whole life cycle of a product. It includes a vast amount of upstream chains preceding the actual milk production process on farm as well as commodities of unknown origin. Besides, regarding GWP, it is irrelevant where the respective gases are emitted (Klöpffer and Grahl, 2009). Emission estimates are thus representative for systems with similar production characteristics and feed composition and are comparable with previous calculation results.

Enteric CH_4 emissions in particular were estimated based on the equation suggested by Kirchgessner et al. (1995). In contrast to the more commonly used IPCC method, which is based on gross energy intake only (eq. 10.21 -Tier 2, IPCC, 2006b; Storm et al., 2012), the method of Kirchgessner et al. (1995) calculates enteric CH_4 based on the nutrient composition of the diet (Storm et al., 2012). As rations for the three production systems were modelled based on data from feed tables, detailed information on nutrient contents was available. Thus, the results reflect the country-specific heterogeneity in feed quality due to region and production intensity in the modelled systems. Although estimates of different **CH_4 prediction models** can vary considerably (Storm et al., 2012) and the Kirchgessner equation delivers slightly higher absolute emissions compared to the calculation approach in IPCC (2006) and LEAP (2016), the relative differences between scenarios are not affected.

The selection of the **life cycle impact assessment (LCIA) method** is another key element of standardization. The EU-commissioned International Reference Life Cycle Data System (ILCD) handbook is a general guide to the choice of method to assess a specific impact category (IES, 2011), but the debate on the correct choice of LCIA methods is still ongoing. Only one out of 44 milk LCA studies published between 2009 and 2017 chose ILCD-recommended LCIA methods, while most studies used the method *CML* (Baldini et al., 2017). The *ReCiPe* method (ReCiPe 2008; Goedkoop et al., 2009) applied in the present thesis is a derivative of *CML*. Although it is not yet commonly used in milk LCAs, the ILCD guidelines recommend its use, at least regarding the estimation of FEP. Given the thesis' scope to provide case study evaluations for Austria, the first version of *ReCiPe* was applied. It represents environmental impacts at a national level, whereas its updated version of 2016 is better suited for global-scale assessments (Huijbregts et al., 2017). The choice of LCIA method in the present study also benefited comparability with regard to paper 2, since the same method was used by Chen et al. (2016), one out of two previous studies on environmental impacts of lameness.

6.2.2 Methodological limitations and how to improve future assessments

6.2.2.1 Estimating emission formation

Estimations of emission formation and thus accuracy of future impact assessments would benefit from on-farm data collection. For example, regarding **NH_3** emissions in paper 2, the extent of the soiled area directly affects the emission level (Ndegwa et al., 2008). With increasing duration of use, rubber mats can eventually throw bumps. This could favour slurry accumulation in alleyways despite frequent cleaning runs of manure scrapers and eventually promote NH_3 emissions from housing. Regarding ventilation in paper 3, measuring actual NH_3 emission formation rates at specific fan runtimes could replace the educated assumptions in the present study. A less time-consuming option would be the improvement of emission estimation accuracy of both NH_3 and CH_4 by using meteorological data collected on-farm. The formation of both gases is directly or indirectly affected by temperature (Hempel et al., 2016; Ngwabie et al., 2011), and on-farm measurements of the latter can vary significantly from values retrieved from nearby weather stations as used in the present study (Gernand et al., 2019). In the case of NH_3, it is advisable to consider either the effect of the ventilation rate (wind speed) or the effect of temperature on emission rates to avoid overestimation since the two effects are correlated (Sanchis et al., 2019).

Notably regarding the prediction of heat stress effects on a cow's emission potential, the application of more detailed **CH_4** estimation models (Tier 3) should be entertained (IPCC, 2006). Such models do not only account for net energy requirements, which is the case for Tier 2 models, but they also reflect effects of nutrient intake and temperature. For example, the nutrient-sensitive equation of Kirchgessner et al. (1995) used in the present thesis allows to integrate effects of season, region and feed quality and is thus sensitive also to benefits of e.g., increased levels of fat in the diet for CH_4 mitigation (Grainger and Beauchemin, 2011; Storm et al., 2012). Moreover, refined prediction models that calculate energy requirements based on ambient parameters (e.g., temperature, wind speed) and animal insulation parameters (e.g., hair and fat tissue) help to account for the temperature sensitivity of the animals' metabolism (Bernabucci et al., 2010). Although the benefits of including nutrient intake (CF, NfE, CP, EE) within CH_4 prediction models are controversially discussed (Ellis et al., 2007; Jentsch et al., 2007; Storm et al., 2012), refined CH_4 prediction models can help to avoid the risk of underestimating emissions from medium- and high-producing cows (Cunha et al., 2016). Especially in view of global climatic changes and the high contribution of enteric CH_4 emissions to the overall GWP of milk production (EAA, 2020; Gerber et al., 2013a), detailed CH_4 prediction models would benefit GWP assessment accuracy of milk LCAs in general.

Since the completion of the two research articles, the IPCC has released updated guidelines for emission calculation that better reflect effects of temperature on manure CH_4, N_2O, and NH_3 emission formation and the estimation of the methane conversion factor (IPCC, 2019a, 2019b).

6.2.2.2 Modelling animal welfare improvement

Data availability regarding the effectiveness of welfare intervention measures is a key limiting factor in modelling associated environmental impacts. In the present thesis, quantitative data regarding the effect of rubber mats and fan implementation on milk yield, fertility, and longevity would reduce parameter uncertainty and improve assessment accuracy. Regarding heat stress abatement in particular, **windspeed-sensitive THI** assessment, as suggested by Berman (2005) and Mader et al. (2006), could improve assumptions on the welfare benefits of fan implementation, notably in the absence of direct measurements of physiological parameters. While on-farm data collection is often the most time-consuming part of LCA modelling (Baldini et al., 2017), technical advances in smart agriculture and precision farming offer potential to facilitate measurements (Lovarelli et al., 2020). Other than simply measuring the amount of milk before and after the improving welfare, useful gadgets include anemometers to assess wind speed (Ji et al., 2020) and wearable scanners that reliably transfer real-time core body temperature measurements detected via biosensors (Chung et al., 2020).

In the present study, animal productivity parameters were used to translate the assumed effect of welfare improvement into environmental impact assessment. Consequently, in the case of **impaired welfare conditions with little** or no described **effect on productive performance**, the odds are that the environmental costs of an intervention measure more than outweigh the environmental benefits of improved welfare. For example, per case of digital dermatitis, Mostert et al. (2018b) estimated an average change in GHG emissions of only 0.4%, whereas per case of sole ulcer and white line disease GWP estimates increased by 3.6% and 4.3%, respectively, due to the considerable impact of the latter disorders on milk yield in contrast to digital dermatitis. Nevertheless, digital dermatitis is a serious health disorder of high prevalence and a significant welfare issue.

Therefore, future assessments should also consider the **qualitative effects of welfare improvement** that go beyond mere benefits for productivity (e.g., positive affective states, ability to express natural behaviour, quality of life) and that could substantiate the benefits of welfare for sustainability. Using productivity and, in particular, milk yield as the sole indicator of the animals' well-being is a poor approximation to the actual meaning of the concept of welfare, notably since variation in milk yield is mostly unrelated to welfare (Coignard et al., 2014; von Keyserlingk et al., 2013). Non-monetary values can be considered in LCA by choosing adequate alternative FUs and allocation methods (Baldini et al., 2017) instead of, for example, limiting the FU for food to volume or nutritional aspects (van der Werf et al., 2014).

Besides, high animal welfare standards are increasingly demanded, and consumers are willing to pay more for higher welfare standards in production (Cardoso et al., 2016), which adds 'emotional' value to the product (van der Werf et al., 2014). Thus, the consumers' perception of the naturalness of dairy farming, e.g., the access to pasture or the cow-calf relationship (Hötzel et al., 2017), co-determines the **economic viability** of welfare-friendly milk production (Beaver et al., 2020; van der Werf et al., 2014) and delineates the win-win relationship of **social sustainability** and animal welfare improvement (Tallentire et al., 2018).

While LCA accounts for the environmental aspects only, **life cycle costing (LCC)** and **social life cycle assessment (SLCA)** enable the accommodation of economic and social aspects of welfare intervention in the assessment of production sustainability (e.g., Tallentire et al., 2018; Zehetmeier et al., 2020). LCC would allow accounting for the considerable financial cost some health and welfare impairment conditions such as lameness are associated with, due to decreased productivity, medical intervention, and increased culling risk (Bruijnis et al., 2010; Polsky and von Keyserlingk, 2017), and balancing this cost against the potentially considerable economic effects of specific welfare intervention measures (Bruijnis et al., 2010; Charfeddine and Pérez-Cabal, 2017; Huxley, 2013). SLCA offers the potential to consider animal welfare as a social dimension of sustainable dairying. Tallentire et al. (2018) described a scalable way of incorporating welfare-related indicators into SLCA based on the Five Freedoms concept of welfare assessment. Similarly, parameters of the Five Domains concept of Mellor (2016) could be integrated, thereby linking ethical welfare aspects (e.g., the animals' sentience) to consumers' expectations of animals having a good life, as described in Hötzel et al. (2017). This might improve depicting the qualitative effects of animal welfare intervention within sustainability assessment.

Life cycle sustainability assessment (LCSA, e.g., van Asselt et al., 2015; Zucali et al., 2016) combines LCA, LCC, and SLCA. By embracing the several pillars of sustainable development, LCSA could enable an integral appraisal of animal welfare and welfare intervention in the sense of strong sustainability and thus underpin the role of cow welfare as an essential part of sustainable dairy farming. Yet, method choice must reflect the study's scope (ISO, 2006). With the increasing degree of comprehensiveness of the sustainability assessment, the level of modelling detail decreases. Thus, LCSA would be an adequate choice to compare systems with different levels of animal welfare, thereby pointing up the extensive sustainability benefits of welfare, whereas it is less well suited to depict the subtle effects of specific welfare intervention measures.

6.2.2.3 The scale of LCA modelling matters

Sustainable intensification in terms of combining high animal productivity with low emission rates is often praised as the most effective strategy to sustainably mitigate the environmental impact of animal production (Herrero et al., 2016; Hristov et al., 2013; Notarnicola et al., 2017a; Sala et al., 2017; Soussana, 2014). At the same time, negative effects of intensified production per cow on animal health and welfare jeopardize this goal of sustainability improvement (Llonch et al., 2015; Mostert, 2018; Özkan et al., 2015). Depending on the **choice of FU, allocation method, and modelling style,** LCA offers potential to integrate aspects of welfare (improvement) and emission mitigation and to identify sustainable development options that aid both (Notarnicola et al., 2017a). These choices affect assessment conclusions essentially (Salou et al., 2017).

In the present thesis, environmental impacts of welfare improvement have been expressed **per unit of milk,** and emissions attributable to meat were allocated using biophysical allocation. Assuming a constant annual milk production at farm level, intensification in terms of increasing milk yield per animal is associated with a reduction of product-related impacts (Chobtang et al., 2017), since fewer animals are needed to produce the fixed output and the environmental burden of the rearing phase is allocated to an increased amount of product per animal (Bell et al., 2011; Knapp et al., 2014). However, if beef production is also intended to remain constant, an increase in milk yield does not decrease emissions since more suckler cows are needed to compensate for the reduced number of dairy cows. This effect can be seen if the allocation of environmental burdens between co-products is handled using system expansion (Zehetmeier et al., 2011). Moreover, when effects of welfare improvement are considered **per unit of utilized agricultural area**, production intensification leads to global environmental impact increase (Jan et al., 2019; Salou et al., 2017), notably in terms of global warming, acidification, and eutrophication (Bava et al., 2014; Guerci et al., 2013), even if the local environmental performance of alpine dairy farming systems might benefit (Jan et al., 2019). Hence, while in the present study increased production intensity per cow due to welfare improvement led to a slight but significant decrease of TAP per kg ECM, production intensification would most likely result in an increase of TAP when expressed per ha agricultural area. FEP and GWP would also increase with measure implementation.

Given the competition between food and feed production, the utilized agricultural area is the ultimate limiting factor of production. Thus, future evaluations of the contribution potential of animal welfare improvement to environmentally sustainable milk production should express environmental impacts not only per kg ECM but also in relation to the total occupied land (Godfray et al., 2010) and with regard to effects on the suckler-beef system (Soteriades et al., 2020). The application of the more recently proposed **dual FU** of Ross et al. (2017) might also be helpful to account for the emission-reducing effect of welfare on the limiting factor land. It combines productivity and land use and could thus benefit evaluating potential environmental trade-offs between production intensification and animal welfare (e.g., regarding biodiversity, see McClelland et al. (2018)). Besides, calculating effects for a **greater set of impact categories** would reduce the risk of problem shifting and trade-offs between impact categories (McClelland et al., 2018; Soteriades et al., 2020) and help to promote farming sustainability on the global scale.

The assessment of environmental implications of welfare intervention measures in the present thesis was carried out, presuming a constant national milk output. Accordingly, the **attributional LCA approach** was applied. However, if milk output changes and consumption of dairy products from welfare-improved production increases, **consequential modelling** should be the method of choice to evaluate the effects on pollution and resource flows (Baldini et al., 2017; Thomassen et al., 2008). Compared to attributional modelling, total impacts can be expected to be lower using consequential modelling, as it depicts trade-offs of increased production for closely interlinked sectors such as beef production and dairy processing, including retail (Dalgaard and Muñoz, 2014; Pelletier et al., 2015; Thomassen et al., 2008). Thus, consequential modelling minimizes potential burden shifting from one sector to another (Soteriades et al., 2020; Weidema et al., 2017). It might therefore assist in responsible decision-making between the alternatives of status quo and improved welfare conditions in dairy farming, notably in the event of the nationwide implementation of a welfare intervention measure.

6.3 Where do we go from here?

So far, an integrative environmental assessment of measures to improve cow welfare has been lacking. The results of the two welfare intervention scenarios in the present thesis suggest that except for nRER and FEP in specific production system settings, the emission mitigating effect of the intervention measures in question outweighs or even prevails over the environmental costs associated with their implementation, at least regarding the analysed environmental impact categories. However, whether and to which extent the simultaneous attainment of both welfare improvement and environmental mitigation is generally possible cannot be answered comprehensively. To this end, more research on **other intervention measures** is needed (e.g., effects of increasing cleaning frequency or time spent on pasture, see Herzog et al. (2018)).

6.3.1 What future assessments should provide

Especially regarding health issues of multifactorial aetiology an assessment of impacts associated with the simultaneous implementation of **multiple intervention measures** could be of interest. In this respect, stochastic simulation models can be useful to better simulate the effects of different welfare measures on dynamics of productivity (cf. Mostert et al., 2019, 2018a, 2018b). Besides, long-term studies on the actual **effectiveness** and efficiency **of specific welfare improvement measures** on indirect indicators of welfare and productivity (i.e., longevity and premature culling) would improve the current understanding of the environmental benefits of welfare improvement, notably in the absence of actual farm data. Yet, though time-consuming, the **collection of** respective **primary data** would significantly benefit capturing the real effects of a measure in practice. As previously outlined in the general discussion on the methods, this could improve accuracy of future sustainability assessments as it reduces parameter uncertainty, which is naturally higher when average data is used (Scrucca et al., 2020).

Combining the environmental evaluation of specific welfare intervention measures with an assessment of **marginal abatement costs,** as demonstrated for example in ADAS (2015) and MacLeod et al. (2015), would enable farmers to weigh the advantages and disadvantages of implementing specific intervention measures with regard to their potential effect on both the environment and farm profits. Moreover, including **social aspects of sustainability** such as consumers' expectations for welfare-friendly production conditions could allow integrating the qualitative benefits of welfare improvement for sustainable milk production.

Besides, an **evaluation** based on **consequential modelling** would account for the effects of increased milk output due to improved welfare on other market sectors (notably beef production). Moreover, the additional use of an **area-based FU**, additional impact categories and different emission allocation methods could help identify the consequences of production intensification for global land use and avoid burden shifting between connected sectors. These considerations address the multi-functionality of agricultural systems and thus benefit the evaluation of the overall potential of welfare improvement to promote sustainability in dairy production (Notarnicola et al., 2017b).

6.3.2 Overcoming the wickedness of sustainability – a philosophical note at the end

Along with closing a significant research gap regarding the potential of welfare intervention as a means of emission mitigation, the results of this thesis substantiate the importance of animal welfare in regard to the sustainable development of the dairy sector. The methodological approach adds to the knowledge on how to contextualize animal welfare within sustainability assessment schemes and allows deriving improvement options for future assessments. Nonetheless, taking into account the wickedness of the sustainability concept (i.e., an open-ended problem that cannot be solved but only managed; Peterson (2013)) points to the importance of constantly rethinking the interdependent relationship between animal welfare and different aspects of sustainability, both on global and on local level (cf. Jan et al., 2019), and of integrating new knowledge to better reflect existing synergies and trade-offs.

Regarding this study's scope of evaluating the role of animal welfare improvement in the context of environmentally sustainable milk production, this could include the weighing in of the already occurring changes in climate (e.g., Thivierge et al., 2017) and respective indirect and direct effects on animal welfare (e.g., pasture loss, EC (2018); disease spread, Özkan et al. (2016). Regarding social sustainability aspects, considering effects of positive emotions or improved quality of life could substantiate the suggested integral significance of animal welfare improvement for sustainable food production (Keeling et al., 2019; Place and Mitloehner, 2014; Tallentire et al., 2018; Tucker et al., 2013). Even in the absence of direct quantitative benefits of positive affective states for cow productivity, the affectivity aspect of welfare is a driving force of public acceptability of production and thus a significant component of sustainable animal food production and associated economic and environmental concerns (Notarnicola et al., 2017a; Tucker et al., 2013). Overall, further efforts to contextualize animal welfare within the multidimensional sustainability concept can help identify balanced options for the dairy sector's sustainable development that allow the concomitant improvement of both aspects (i.e., measures of emission mitigation and welfare improvement with mutual benefit).

7 Conclusions

The present thesis provides an overview of the nexus between animal welfare improvement and environmental impact mitigation in dairy farming and assessed potential environmental synergies and trade-offs associated with implementing selected welfare intervention measures. From the findings, the following can be concluded:

- The welfare and the emission potential of cows are distinct and yet intertwined aspects of sustainable dairy farming. While effects of emission mitigation measures on welfare have been described qualitatively, an assessment of potential effects of welfare intervention measures on emissions has been lacking so far.
- Improving cow welfare is beneficial in terms of optimizing the environmental impact of dairy production, as it co-determines the animals' productivity. However, environmental costs associated with specific measures to improve impaired welfare need to be taken into account to determine the overall effect of welfare intervention.
- The benefits of lameness reduction through implementation of rubber mats in alleyways more than outweigh the environmental costs of mat production in regard to TAP and RER, while nRER increased with measure implementation depending on the animals' baseline production intensity.
- The benefits of heat stress abatement through implementation of basket fans for additional ventilation outweigh the environmental costs of fan production and operation, except for FEP depending on the animals' baseline production intensity.
- The eutrophication potential of dairy farming is more sensitive to changes in resource and energy demand associated with the construction and operation of the housing system than global warming and acidification, which are hardly affected.
- Future assessments would benefit from using primary data, notably regarding the effectiveness of specific welfare intervention measures, to reduce parameter uncertainty and to improve the robustness of results.
- Further research is needed to evaluate the environmental effects of welfare intervention measures in general, notably regarding a broader range of impact categories and functional units of assessment, and to specify the benefits of welfare in the multidimensional context of sustainability.

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Dissemination activities apart from journal contributions

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