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MASTER IN ENVIRONMENTAL MANAGEMENT OF MOUNTAIN AREAS

Caring for livestock farming: an agroecological assessment of farm sustainability using a participatory DEXi-based indicator system

by

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To my daughter Marlene Nancy
Contemporary warrior, may you draw inspiration from it
Mom

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i. List of abbreviations

CISDE – Coopération Internationale pour le Développement et la Solidarité

CREA – Consiglio per la Ricerca in Agricoltura e l'analisi dell'economia agraria

DEXi – Decision Expert for Education

DSS – Decision Support Systems

EFSA – European Food Safety Authority

EIP-AGRI – European Innovation Partnership for Agriculture Productivity and Sustainability

ESSIMAGE – Evaluation and Simulation of Agroecological Systems

FAO – Food and Agriculture Organization

GDO – Grande Distribuzione Organizzata

GDP – Gross Domestic Product

GHG – Greenhouse Gases

GIS – Geographic Information System

GLEAM – Global Livestock Environmental Assessment Model

HLPE – High Level Panel of Experts on Food Security and Nutrition

IDEA – Indicateurs de Durabilité des Exploitations Agricoles

IFPRI – International Food Policy Research Institute

ILRI – International Livestock Research Institute

INVERSION – Agroecological innovations to increase the resilience and sustainability of mountain livestock farms

IOFC – Income Over Feed Cost

IPBES – Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services

iSAGE – Innovation for Sheep And Goat production in Europe

ISTAT – Istituto Nazionale di Statistica

LCA – Life Cycle Analysis

MESMIS - Marco para Evaluación de Sistemas de Manejo de Recursos Naturales Incorporando Indicadores de Sustentabilidad

MOTIFS – Monitoring Tool for Integrated Farm Sustainability

OECD – Organization for Economic Cooperation and Development

OG – Operational Group

OLPI – Organic Livestock Proximity Index

PAT – Provincia Autonoma di Trento

PDO – Protected Designation of Origin

PGT – Public Goods Tool

PLAR – Participatory Learning and Action Research

PUFA – Polyunsaturated Fatty Acids

RISE – Response-Inducing Sustainability Evaluation

SAFA – Sustainability Assessment of Food and Agriculture systems

SDGs – Sustainable Development Goals

TAPE – Tool for Agroecology Performance Evaluation

UK – United Kingdom

UN – United Nations

UN/DESA – United Nations Department of Economic and Social Affairs

UNEP – United Nations Environment Programme

UNESCO – United Nations Educational, Scientific and Cultural Organization

US – United States

USD – United States Dollar

Abbreviations of Units

Abbreviation	Full term
asl	above sea level
BCS	Body Condition Score
BW	Body Weight
$CaCO_3$	Calcium carbonate
CH_4	Methane
CO_2	Carbon dioxide
CO_2-eq	Carbon dioxide equivalent
DM	Dry matter
FCM	Fat Corrected Milk
FU	Forage Unit
g	gram
Ha	Hectare
l	litre
LU	Livestock Unit
kcal	kilocalorie
kg	kilogram
km^2	square kilometer
m	meter
MJ/d	Mega Joule per day
MFU	Milk Forage Unit
N	Nitrogen
N_2O	Nitrous Oxide
p.a.	per annum
q	quintal
UAA	Utilized Agricultural Area
VA	Value Added
WU	Working Unit
yr	year

ii. Abstract

Intensifying animal husbandry is a modern-day response to the growing demand for animal-based products. Consequently, emerging issues related to the livestock farming ability to provide ecosystem services are sparking off the public and scientific debate, stimulating the demand for more sustainable livestock production systems. Sustainability assessment at the farm level is becoming increasingly important as new European policy frameworks are soliciting a profound transformation in agriculture and food systems and have identified agroecology as a systemic approach to sustainability. Despite the presence of a wide variety of farm assessment tools, few have been specifically designed for livestock farming systems and are suitable for assisting the agroecological transition. Furthermore, transdisciplinary and participatory research on published and unpublished agroecological assessment frameworks and tools is needed. The present research aims at contributing to fill the knowledge gap by analyzing and testing DEXi-INVERSION, a participatory Decision Support System recently developed in the Autonomous Province of Trento. The tool allows a holistic sustainability assessment of livestock farming systems to support an agroecological transition at the farm level. The tool analysis has been conducted using a framework to enhance the transparency of decision-making processes, and it has been evaluated according to a set of key aspects for agroecological assessment tools. In order to test its functionalities, twelve farms located in the province of Trento and in the Veneto region have been assessed. Three practical applications are illustrated through farm case studies, namely the use of the tool for (i) evaluating the impacts of different management practices on sustainability; (ii) supporting decision-making processes at the farm level, (iii) monitoring the farm evolution in time. A fourth functionality is tested by (iv) comparing farms' sustainability performances. Furthermore, the research presents the participatory process carried out to apply the tool to livestock farms in the Veneto Region. DEXi-INVERSION can be effectively considered an agroecological assessment tool, however its applicability is limited to livestock farming systems. Despite no general statements can be given, the results suggest that the tool can be successfully applied for all purposes for which it has been designed and offer an original perspective to support the transition towards sustainability. Nevertheless, a common reference framework for the agroecological assessment of food systems is needed.

Al fine di rispondere alla crescente domanda di prodotti animali, si è assistito ad una progressiva intensivizzazione del settore zootecnico. Ciò sta alimentando il dibattito pubblico e scientifico relativamente alla sostenibilità dell'allevamento. La valutazione di sostenibilità delle aziende agricole sta accrescendo d'importanza in quanto può supportare la transizione verso sistemi alimentari più sostenibili, recentemente promossa a livello europeo. In tale contesto, l'agroecologia è stata identificata come approccio sistemico alla sostenibilità. Nonostante la presenza di molteplici strumenti per valutare la sostenibilità in ambito agricolo, pochi sono stati specificatamente elaborati per il settore zootecnico e sono adatti a sostenere la transizione agroecologica. Vi è inoltre l'esigenza di una maggiore ricerca transdisciplinare e partecipativa relativa agli strumenti di valutazione dei sistemi agroecologici. La tesi vuole contribuire a colmare alcune lacune di conoscenza attraverso l'analisi e l'applicazione di DEXi-INVERSION, un sistema partecipativo di supporto alle decisioni recentemente sviluppato nella Provincia Autonoma di Trento. Lo strumento è finalizzato alla valutazione sistemica della sostenibilità di aziende agro-zootecniche per sostenerne la transizione agroecologica. L'analisi dello strumento è stata condotta utilizzando uno schema che favorisce una maggiore trasparenza dei processi decisionali, ed è stato valutato in base ad un set di criteri chiave per gli strumenti di valutazione agroecologica. Al fine di testarne le funzionalità, la valutazione di sostenibilità è stata effettuata su dodici aziende zootecniche situate nella Provincia Autonoma di Trento e nella Regione Veneto. Tre applicazioni pratiche sono illustrate attraverso casi studio aziendali, nello specifico l'uso dello strumento per (i) valutare gli impatti delle pratiche gestionali sulla sostenibilità; (ii) supportare i processi decisionali a livello aziendale; (iii) monitorare l'evoluzione

aziendale nel tempo. Una quarta funzionalità è testata e volta a (iv) comparare il livello di sostenibilità di diverse aziende. Infine, la ricerca presenta il percorso partecipativo attuato al fine di utilizzare lo strumento nelle aziende venete. DEXi-INVERSION apporta elementi di innovazione che possono assistere efficacemente la transizione delle aziende agro-zootecniche verso sistemi più sostenibili, e può essere considerato uno strumento di valutazione agroecologica a tutti gli effetti, sebbene sia applicabile solo alle aziende zootecniche. Nonostante non sia possibile trarre delle conclusioni generali, i risultati suggeriscono che lo strumento possa essere impiegato con successo per tutte le finalità per le quali è stato realizzato, e offrono una prospettiva originale per assistere la transizione sostenibile delle aziende zootecniche. Tuttavia, sarebbe necessario un quadro comune di riferimento per la valutazione in chiave agroecologica dei sistemi alimentari.

1. Introduction

Nowadays livestock farmers are facing several challenges: on one side they are asked on a global level to increase the production of food of animal origin in order to fulfill the demand of a growing, wealthy population. On the other side, they are called for producing sustainably, with a lower environmental impact, especially reducing greenhouse gases emissions, and with a greater attention to animal welfare, while reaching farm profitability. By 2050 the world's population is expected to reach nearly 10 billion people (Cherlet et al. 2018), and the demand for meat and dairy products is envisaged to be respectively 75% and 60% higher compared to 2005/07 (Alexandratos & Bruinsma 2012).
As a response to this growing demand for animal-based products, a progressive intensification of both extensive and intensive livestock systems is gaining ground. Consequently, emerging issues related to the livestock farming ability to provide ecosystem services such as the protection of natural resources, biodiversity preservation, the maintenance of landscapes and cultural values, animal welfare and human health, are sparking off the public and scientific debate, stimulating the demand for more sustainable food systems (Gamborg & Sandøe 2005; Steinfeld et al. 2006; Nguyen 2018).
Within this context, new European policy frameworks, such as the Farm to Fork strategy, are soliciting a profound transformation in agriculture and food chains, and agroecology is gaining importance as a transition pathway towards sustainable food systems (HLPE 2019).

In order to boost their sustainability and contribute to the agroecological transition, livestock production systems need to concurrently satisfy the three dimensions of sustainability (environmental, economic, social) by increasing the efficiency of resource use, enhancing the provision of ecosystem services for the human well-being, reducing the competition food versus feed, increasing the resilience particularly by lowering the pandemic threats and by improving the governance of global and local commons (e.g. climate, water, soil) (FAO 2014). Moreover, livestock rearing embraces all ethical aspects related to human relations to animals (Rawles 2012; D'Silvia 2013).

Moving towards sustainable livestock production systems implies a common frame of understanding of sustainability (Gamborg & Sandoe 2005) and the development of appropriate tools to assess sustainability at the farm level.
Over the past decades we assisted to an "indicator explosion" (Ryley 2009): a variety of farm sustainability assessment tools has been developed and applied to livestock farming systems (e.g. SAFA, RISE, PGT, IDEA, OLPI, MESMIS, MOTIFS), following different approaches and structures, and covering all dimensions of sustainability or only some specific aspects. Certainly, the application of Participatory Learning and Action Research (PLAR) methods has increased in importance to boost stakeholder's participation, of farmers especially. However, few tools have been specifically designed for livestock farming systems, are based on a participatory approach, cover all dimensions of sustainability and simultaneously provide research and sustainability improvements on the ground (Bélanger et al. 2012; Ripoll-Bosch et al. 2012; Laurent et al. 2017; Meul et al. 2008). Furthermore, aside from a few exceptions, the existing tools have been considered unsuitable to support an agroecological transition at the farm level, as they don't or barely consider (i) local conditions, (ii) farmers' involvement, (iii) multifunctionality, (iv) interaction analysis (Trabelsi et al. 2016; Trabelsi et al. 2019; Wiget et al. 2020). More innovative,

transdisciplinary and participatory research on published and unpublished sustainability assessment frameworks and tools is requested (Wiget et al. 2020).
Within this framework, the present degree thesis intends to fill the knowledge gap by analyzing and testing DEXi-INVERSION, a decision support system (DSS) which provides a holistic sustainability assessment of livestock farming systems in order to guide an agroecological transition. The tool has been developed with a participatory approach in the Autonomous Province of Trento, within the European Innovation Partnership 'Agricultural Productivity and Sustainability' (EIP-AGRI) project "Agroecological innovations to increase the resilience and sustainability of mountain livestock farms" (INVERSION) (2017-2021), that I have personally promoted.
Although project activities focused on the implementation of agroecological practices in focus farms, there was the need to monitor progresses in such a way that farmers could feel fully engaged and be able to assess their sustainability performance even after the end of the project. For these reasons, a new set of indicators had to be designed, in order to reflect the peculiarities of the local context, taking into account relevant territorial issues and the heterogeneity of livestock production systems represented by the focus farms. Furthermore, the tool was supposed to support social learning through the diffusion of a culture of sustainability within a context characterized by an imbalance between the prevailing intensive livestock system and the peculiarities of a mountainous agroecosystem.

DEXi-INVERSION has been designed for the socio-economic, environmental and ethical assessment of farm sustainability. Furthermore, the tool allows to evaluate the impacts of different farm management practices on sustainability; to support decision-making processes at the farm level; to monitor progresses towards sustainability; to compare different farms or groups of farms (Pisseri et al. 2020). However, due to the fact that it is newly developed, it has only been tested on the farms which took part to its development, with the aim of assessing farm sustainability.

Within this study, the tool has been applied to livestock farms other than those which participated to its development, apart from 3 farms. Specifically, DEXi-INVERSION has been implemented in 12 farms located in the Autonomous Province of Trento (n=5) and in the Veneto Region (n=7) with the aim of testing the tool for all the purposes for which the tool has been designed.
Specifically, the research presents four practical applications of DEXi-INVERSION, namely the use of the tool for (i) evaluating the impacts of different practices on sustainability; (ii) supporting decision-making processes at the farm level; (iii) monitoring the farm evolution in time; and (iv) comparing farms' sustainability performances. Furthermore, the research presents the participatory process carried out to apply the tool in the Veneto Region.
Given that the sustainability assessment covers a wide spectrum of livestock farms, rooted into different cultural contexts, with diverse production systems, different levels of intensification and multifunctionality, the analysis allows for providing evidences of the versatility of the tool.

The main research questions posed by the present study can be formulated as follows:

- To what extent does DEXi-INVERSION account for the four key features, i.e. local conditions, farmers' involvement, multifunctionality and interaction analysis, which characterize agroecological sustainability assessment frameworks and tools?

- How DEXi-INVERSION can be practically applied to support an agroecological transition?

- Which are the major differences in terms of farm sustainability among and between Trentino and Veneto farms?

- How to facilitate the DEXi-INVERSION applicability and usefulness in contexts different from the one where the tool has been developed?

The introductory part (Chapter 1) presents an overview of the main drivers and outcomes of the global livestock sector, and of sustainability issues related to livestock production systems. Furthermore, this section provides an insight into the vast world of sustainability assessment tools, highlighting the key elements that frameworks and tools should have to support an agroecological transition. The DEXi-INVERSION tool, together with the farms' selection procedure and farm features, are illustrated in Materials and methods (Chapter 2). The results, namely the practical applications of DEXi-INVERSION and the participatory process to encourage the tool acceptance and applicability, are presented in Chapter 3. Finally, results are discussed (Chapter 4) and recommendations are given (Chapter 5).

1.1. The global livestock sector: drivers, outcomes and sustainability issues

The livestock sector represents an important part of global agriculture: it contributes to food security, enhances rural income and livelihoods, provides a variety of ecosystem services depending on the agroecological context, and represents an important risk reduction strategy for vulnerable communities (FAO 2018a; Pandey & Upadhyay 2022).
Livestock systems exploit a vast area of the planet: between 30% and 45% of the land, about 15 billion hectares, is dedicated to livestock including feed production (Cherlet et al. 2018). From an economic perspective, they represent a significant global asset as they generate 40% of the Gross Domestic Product (GDP) of the agricultural sector, which represents 3% of the world's GDP (FAO 2009). Livestock is a source of livelihood for 70% of the 1.4 billion human beings living in conditions of extreme poverty (under 2 USD per day) and mainly located in rural areas (FAO 2009). Hence, livestock systems play a central role in land management and in the fight against poverty through the income generated by the sale of food and non-food animal products (FAO 2009).

Livestock systems have been classified according to different approaches and considering a combination of criteria, such as the availability of land, the degree of dependence on external feed resources, the integration with crop production, the type of product, the agroecological zone, etc. (Mortimore 1991; Seré & Steinfeld 1996; Dixon et al. 2001). For the purposes of the present study, a more recent FAO (2018d) classification has been adopted, as it highlights several sustainability issues such as the dependence on external inputs, GHG emissions, feed vs food competition, resource use efficiency, etc. FAO (2018d) has classified livestock systems into three categories: extensive systems, labor-intensive systems and capital-intensive systems. The classification is based on the combination of the classical production factors land, labor, capital, considering their relative availability and cost. As referring to livestock systems which include landless production, the land factor is replaced by livestock biomass; labor refers to the agricultural population while capital to the amount of GDP available per person (FAO 2018d; Pandey & Upadhyay 2022).
Extensive systems are typically pastoral systems occurring in marginal areas unsuitable for crop production, which efficiently manage natural resources under adverse climatic conditions. They are characterized by low labor and capital inputs, and a low productivity, but they hold a sociocultural importance in pastoralist societies. Despite their inefficiency, they make a minor contribution to GHG emissions and have a great potential in the sequestration of soil organic carbon.
Labor-intensive systems are usually smallholder-based mixed crop-livestock farms which produce staple foods for the family subsistence and sell the surpluses; livestock provides nutritious food and holds sociocultural importance. These systems are considered inefficient if compared to extensive and capital-intensive systems, however they efficiently manage the nutrient cycling giving value to crop residues and provide draft power.
Capital-intensive systems are typically highly productive, highly mechanized and efficient, despite a great dependence from external inputs and the disconnection of feed resources from the physical location of the production units. Negative externalities associated with these systems are the competition between food and feed production, deforestation, disruption of nutrient cycles, antimicrobial resistance, air-soil-water pollution related to the use of chemicals and the high animal density (FAO 2018d).

During the second half of the twentieth century, the world's livestock sector has grown at an unprecedented rate, in order to meet an ever-increasing demand for food of animal origin generated by the combination of population growth, rising per capita incomes in some parts of the world and progressive urbanization (Niamir-Fuller 2016). According to FAO, from the 1960s meat production has more than tripled, reaching nearly 340 million tonnes produced each year. In the same period, world milk production has more than doubled attaining nearly 900 million tonnes (FAOSTAT 2021).
World consumption of milk and dairy products has increased from 75 to 90 kg between 1961 and 2013 (FAOSTAT 2021). In 2005/2007, meat consumption per capita was 80 kg in the developed countries and 27.9 kg in the developing countries, for a world average of 38.7 kg (Alexandratos & Bruinsma 2012). In 2013, the average consumption was around 43 kg of meat per person (FAOSTAT 2021).
Although the rapid growth in animal-product consumption appears to be a circumscribed phenomenon, involving a small number of highly populated and fast-growing emergence countries (i.e. China, India, Indonesia and Brazil), the effects are affecting the global food economy.

The rapid growth of the sector has implied an intensification of livestock systems: it is estimated that 66% of land-based animals (no fisheries) are produced in intensive farms (Niamir-Fuller 2016). The current patterns of livestock production are blamed of causing a negative impact on the environment, human health and animal welfare.

First of all, the sector expansion has represented a driving force of agricultural land use changes, highlighting a dual trend: the increase of animal farming intensity in areas with favorable agroecological conditions and access to markets, and the abandonment of marginal areas due to the harshness of the working environment, a limited economic viability and an insufficient labor availability. Both patterns are the major drivers of biodiversity loss (IPBES 2019), with ongoing processes of deforestation and overgrazing on one side, grassland loss due to shrub and forest encroachment and a reduced provisioning of some ecosystem services on the other side (Niamir-Fuller 2016; Salvador et al. 2016; Bernués 2017). It is estimated that 70% of deforested land in Latin America and Asia has been converted into pasture, and the remaining 30% is cultivated with feed crops, especially soybean: grassland expansion to the detriment of the Amazon forest has sustained the greater rise in the number of cattle, which has increased sevenfold in 40 years (Bernués 2017). Management land practices can therefore promote or deplete soil fertility, carbon storage, biodiversity, water quality and resource use efficiency, and can affect the provision of other ecosystem services.

Furthermore, livestock use of arable lands enters in competition with crop production for a direct human consumption, despite the low conversion rate (around 34%) of human-edible crops fed to animals and delivered to humans as animal products; it is estimated that cereals produced for feeding animals could instead nourish 3.5 billion people (Berners-Lee et al. 2018). In addition, 50% of fertilizers and 70% of herbicides used in agriculture are attributed to the production of crops for feeding animals (Tamminga 2003), with negative externalities such as the eutrophication of water bodies, nitrous oxide emissions and soil contamination.

Another major concern is represented by livestock GHG emissions from livestock and their contribution to global warming. The Global Livestock Environmental Assessment Model

(GLEAM) developed by the FAO outlines that livestock supply chains emitted approximately 8.1 gigatons CO_2-eq in 2010, according to the most commonly metric used, which corresponds to 14.5% of global anthropogenic GHG emissions (Gerber et al. 2013; Grossi et al. 2019). Beef and dairy cattle are the largest contributors, accounting for 5 gigatons CO_2-eq which represent 62% of the sector's emissions (Kiefer et al. 2015). About 50% of the emissions are in the form of methane (CH_4) with ruminants accounting for more than 30% to the global CH_4 emissions (Kiefer et al. 2013). Despite there is no commonly shared methodology in GHG footprint assessment (Lynch 2019), according to Gerber et al. (2013), capital-intensive systems have a lower carbon footprint per product unit than extensive ones: higher emission intensities are associated with low productive systems based on poorly digestible rations, reduced feed conversion efficiency, low growth rates and slaughter weights. However, 45% of livestock GHG emissions are related to feed production and energy consumption, and 9% to land use changes (FAO 2021) and are therefore associated to capital-intensive livestock systems.
Methane emissions are likely higher in extensive systems as they rely on breeding ruminants with a higher fiber ingestion; methane and nitrous oxide emissions increase with overgrazing due to the accumulation of animal excreta in the soil and the anaerobic conditions generated by soil compaction related to animal trampling (Battaglini et al. 2014).
However, extensive systems rely mostly on permanent grasslands which represent one quarter of the world's land and are the major terrestrial carbon sink after forests. It is estimated that improving grazing management in the 5 billion hectares of grassland worldwide could potentially sequester 9.8% of anthropogenic GHG emissions (Bernués, 2017). The estimation of GHG emissions for ruminant husbandry poses major challenges when farming in less favored areas is considered (Kiefer et al. 2015). The degree of farm multifunctionality in terms of diversity of product outputs and ecosystem services provisioning, as well as the management practices implemented, are the main factors reversing the carbon footprint of grassland-based systems (Battaglini et al. 2014; Casasus et al. 2012; Kiefer et al. 2015; Salvador et al. 2016; Bernués 2017).

Livestock impacts on water consumption and water pollution are also relevant in the debate over sustainability: animal feed production absorbs 37% of the water used in crop production (Gerten et al. 2011), and the grey water footprint is of 712 m^3 on average per ton of industrial beef, which is more than double that of extensive beef production (Mekonnen & Hoekstra 2010).

The sector expansion has caused an acceleration in the frequency of infectious diseases originated in animals and transmitted to humans (e.g. avian influenza, coronaviruses, Ebola) with dramatic consequences on public health (Stella et al. 2018; FAO 2021).

Other negative externalities related to the intensification of livestock systems are the excessive use of antimicrobials, the reduced activity and diversity of soil microbial communities related to antibiotic residues, the loss of genetic animal diversity and the lowering of the quality of animal products (Niamir-Fuller 2016).

As pointed out by Dumont et al. (2013), the future of sustainable livestock systems is under debate. Some authors argue that the sector expansion will follow the industrial intensification pathway to be able to sustain a growing population (Steinfeld & Wassenaar 2007), regardless of ethical issues related to the care of natural resources and animal health and welfare (D'Silva 2013). Others suggest that integrated crop-livestock systems could raise productivity and resource use efficiency, with positive impacts on food security and ecosystem services provisioning (Herrero et al. 2010). Nevertheless, a single development perspective cannot be applied due to the wide variety of livestock systems, rooted into different biogeographical conditions and with diverse levels of intensification (Dumont et al. 2013; Bernués 2017). Certainly, the current pandemic, coupled with the worsening of climate change, is posing a major challenge, that is to produce meat and dairy products in a sustainable way, ensuring global food security (Dumont et al. 2013; Faccioni 2018).

1.2. Dimensions and indicators for assessing farm sustainability

Sustainability is the challenge of our time (Sachs 2015) and assessing sustainability is a crucial process for supporting the development of durable farming systems (Lebacq et al. 2013).

Sustainability explores the human-nature interactions and is based on a system of values encompassing several ethical issues. It refers to a system property, that is its dynamic ability to maintain or enhance its essential outcomes over time (Allen & Prosperi 2016).

Despite the widespread application of the sustainability framework, the concept has not a universally agreed definition, and it is usually related to the notion of "sustainable development" (Brutland et al. 1987). In 1988, FAO elaborated its own definition of sustainable development as follows, focusing on the primary sector: "*The management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in the agriculture, forestry, and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technologically appropriate, economically viable and socially acceptable*" (FAO 1988). The Johannesburg Declaration of 2002 reaffirmed the core elements of sustainable development and the interdependency between economic, social development and environmental protection at the local and global scale (UN 2002).

In 2015, the United Nations Member States adopted the 2030 Agenda for Sustainable Development, which represents a plan of action to implement sustainability in different sectors and at different scales, within a defined timeframe (UN/DESA 2016).

More recently, food systems entered at the hearth of debates on sustainability, as emerges from the Farm to Fork Strategy, within the framework of the EU Green Deal. Food systems encompass a wide range of activities and an extended network of actors, with direct and interconnected impacts on food security (food access, food utilization, food availability), environment (e.g. climate change, water availability, biodiversity), socioeconomic goals (e.g. income, employment, public health). At the same time, food systems are affected through feedback loops by agriculture's environmental externalities, outbreaks of epidemics, income inequalities, political instabilities (UN 2015; Allen & Prosperi 2016; Dury et al. 2019; HLPE 2019; Drewnowski et al. 2020).

A sustainable food system is able to provide nutritious and healthy food to satisfy food needs and make it affordable to all without harming the environment; it sustains local production and distribution infrastructures and it takes care of farmers and other workers, consumers and communities (Story et al. 2009). In order to be sustainable, the development of food systems needs to generate positive value along three dimensions simultaneously: economic, social and environmental (Nguyen 2018).

Given that sustainability "*is not a single, easy measurable or ready tangible notion*" (Gamborg & Sandoe 2005), the implementation of the sustainability concept and its adoption as management tool in the different fields represents a great challenge (Garcìa et al. 2018). Therefore, sustainability assessment at the farm level is becoming increasingly important to guide a profound transformation in agriculture and food systems (HLPE 2019).

A sustainability assessment usually covers the environmental, social and economic dimension; however, tradeoffs between the different dimensions can emerge (Wu 2013). Each dimension is divided into major themes, objectives, aspects or components that contribute to a comprehensive description of the dimension itself (Alkan Olsson et al. 2009; Calker 2001). Each component of the sustainability dimensions is further defined by a set of indicators (Lebacq et al. 2013). The complexity of the sustainability framework is therefore made operational through the design of an assessment tool integrating multiple indicators for long-term measurements of sustainability (Calker et al. 2001; Özdemir et al. 2011).

Indicators are significant variables that supply information on a given process and can represent a reference point in decision-making (Gras 1989, Caporali 2015). In system change analysis, indicators are a means of measuring changes connected to an intervention and stimulate improvements (Church et al. 2006; Kreger et al. 2007). Sustainability indicators are conceived as tools to build and structure knowledge and are an expression of social and political norms and priorities (Rametsteiner et al. 2011).
In order to be useful, an indicator must be replicable, relevant to the issue being studied, sensitive, easily accessible and understandable (Girardin et al. 1999). The sensitivity of an indicator implies its capacity to detect little changes in the reality (Vidal & Marquer 2002).
A good indicator must be representative, precise, reliable and solid, in order to allow comparative analyses and to monitor progresses towards sustainability in time and space. Finally, indicators should be elaborated, calculated and adapted at reasonable costs, with a little additional charge as possible when the context changes (Vidal & Marquer 2002). Indicators can be either quantitative or qualitative. Quantitative indicators can provide hard data which are directly measurable, or combined data which requires a specific data collection. Qualitative indicators reflect people's judgments and perceptions and can be based on a self-assessment (Lebacq et al. 2013).

Likewise, a set of indicators should be concise and exhaustive, integrating more sustainability goals within one indicator; minimal, in order to exclude redundancy; representative, to describe the system in a coherent and reliable way; with a good level of complementarity to ensure a comprehensive view of the farming system (Lebacq et al. 2013).

A set of indicators to assess farm sustainability explores the environmental, economic and social aspects of the farming system.
Environmental sustainability at the farm level is conceived as the ability to maintain the natural resources provided by the ecosystem (Van Cauwenbergh et al. 2007), and is generally expressed through different environmental indicators such as water, soil and air quality, biodiversity preservation, input management, land management, GHG emissions (van der Werf & Petit 2002; Lefebvre et al. 2005; Bockstaller et al. 2008; van der Werf et al. 2009; Lebacq et al. 2013).

Economic sustainability is defined as the ability of a farming system to be profitable and to contribute to the wellbeing of the community (van Calker et al. 2001; Van Cauwenbergh et al., 2007). The most used economic indicators are farm income, efficiency, and productivity (Lebacq et al., 2013). However, other indicators are used, such as the degree of independence from external inputs, farm multifunctionality and farm durability over time, the latter related to succession and transmission (Guillaumin et al. 2007). Economic indicators are quantitative indicators, expressed in monetary terms or ratios (Vilain 2008).

Finally, social sustainability indicators either address the farm community, investigating the quality of life of the farmer and his/her family, the level of education and the working conditions, either explore the society's perceptions of agricultural practices, the quality of products and the farm multifunctionality. Social indicators are mainly based on the farmer self-assessment, thus are qualitative (Guillaumin et al. 2007; van Calker et al. 2001).

According to Faccioni (2018), the set of indicators generally do not account for the positive externalities of farming systems, such as the provisioning of ecosystem services. The degree of intensity, the competition with human nutrition, and the level of territorial integration of the farming system, should also be considered to "reward" low-input systems.

Beside the three pillars of sustainability, a fourth aspect should be investigated when assessing livestock farms, namely animal welfare. "*Welfare is a wide term that embraces both the physical and mental well-being of the animal. Any attempt to evaluate welfare, therefore, must take into account the scientific evidence available concerning the feelings of animals that can be derived from their structure and functions and also from their behavior*" (Brambell Report 1965). Rawles (2012) refers to animal welfare as the "*neglected dimension of sustainable development*", perceived as a threat to the business-as-usual model. Animal welfare concerns could be included in the environmental sphere, however environmental preservation deals with ecological collectives (e.g. species, habitats, ecosystems), whereas animal welfare deals with individuals. For these reasons, Rawles (2012) suggests switching the sustainability triangle to a diamond including animal welfare as a fourth dimension (Figure 1).

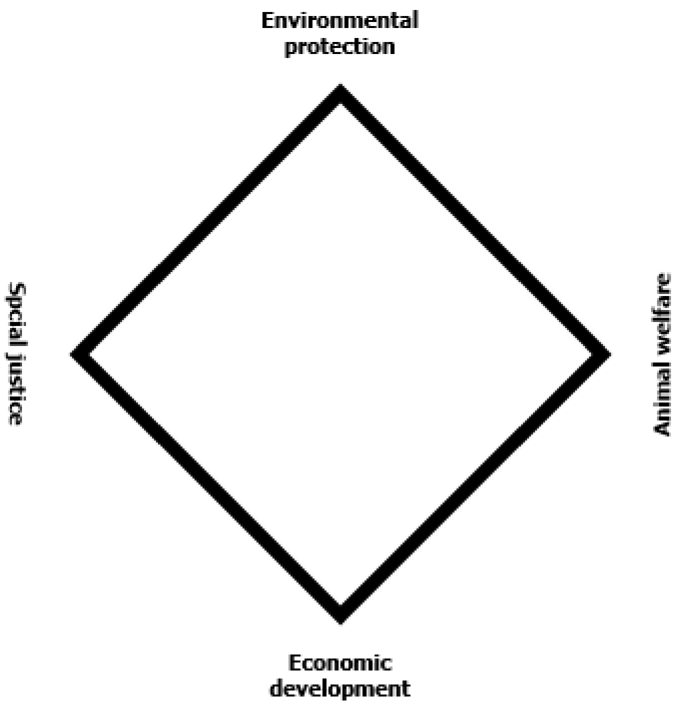

Figure 1. The sustainability diamond (Source: Rawles 2012)

Indicators generally used for assessing animal welfare are the ability to perform natural behaviors (e.g. access to grazing), the quality of the housing system (e.g. cleanliness, light, protection from heat), animal density, health conditions, handling practices (de Olde et al. 2017).

1.3. Methodologies for assessing sustainability of livestock farming systems

Most of sustainability assessment tools address all types of production systems (van Calker et al. 2001). However, some researchers argue that a set of indicators for measuring sustainability should be developed for a specific farming system and strongly linked to its local context, as sustainable agriculture is a time and space specific concept (Zhen & Routray 2003; Meul et al. 2008; Laurent et al. 2017; Munyaneza et al. 2019). As indicators are context, purpose and scale dependent (Freebairn & King 2003), any set should be matched to the characteristics of the specific production system to assess (Munyaneza et al. 2019). In the case the tool is used in different contexts, it should be adapted to the local conditions (de Olde et al. 2018; Zahm et al. 2019).

The sustainability assessment of livestock farming systems either employs generic assessment tools widely implemented in the agricultural sector, with some adaptations to better fit to the system analyzed, or it is grounded on tools newly developed, more linked to the local context (van Calker et al. 2001; Lebacq et al. 2013; Laurent et al. 2017).
The hierarchical structure usually includes the dimensions of sustainability, the themes or major topics within the sustainability pillars, the sub-themes that can be defined by multiple indicators, and the indicators, which represent the smallest assessment unit. However, the structure can vary from one tool to the other. The lack of a common terminology (e.g. a theme can be named topic, spur or component, a sub-theme can be called indicator) makes difficult to properly decode the single assessment units and the different levels of aggregation (de Olde et al. 2017).

Lebacq et al. (2013) identify three approaches in sustainability assessment: *i)* the method-based approach that is based on the selection of existing assessment methods suitable for the issue to evaluate; *ii)* the objective-driven approach, in which an appropriate set of indicators is selected to develop a new assessment tool; *iii)* the data-driven approach, which relies on the selection and calculation of indicators starting from existing data.
If an existing assessment tool is selected and used, inevitably its values and norms will influence the assessment outcomes and the subsequent decision-making process of farmers and policymakers. Transparency and deep understanding of the assessment approach is therefore recommended (Gasparatos & Scolobig 2012; de Olde et al. 2017).
In the case in which a new sustainability assessment tool is developed, its validity is strongly connected to the approach used in the indicator selection, the weighting and the aggregation of indicators (Meadows 1998; Juwana et al. 2012; Lebacq et al. 2013; Gan et al. 2017). The selection of the proper set of indicators represents the main challenge in the objective-driven and data-driven approaches (Lebacq et al. 2013). The set of indicators should address the complexity of the system integrating the environmental, social and economic dimensions, and should represent the system transition towards sustainability (Binder et al. 2010).

Van Calker et al. (2001) have developed a method for assessing sustainability in dairy farming following what Lebacq et al. (2013) would have later classified as an objective-driven approach. The method consists in six sequential steps: firstly, an analysis scheme of sustainability is elaborated through expert consultation. In the second step, a comprehensive list of attributes is produced for each aspect of sustainability, with the use of questionnaires addressed to experts and stakeholders. In the following phase, a sub-set of attributes is selected by experts according to their degree of relevance. Whether an attribute doesn't allow direct or indirect measurements, it must be excluded. A further step provides for the weighting of attributes according to their utility. Finally, the sustainability aspects, or components, are weighted by the different interest groups to build a systemic sustainability index (van Calker et al. 2001).

The weighting of indicators can be determined by following different procedures: *i)* equal weighting, when the same weight is given to the indicators; *ii)* statistic-based weighting where the weights are derived from statistical features of the data; *iii)* public/expert opinion-based weighting, when value judgments are used as a reference (Gan et al. 2017). The weighting of indicators should allow the identification of important farming practices (Bélanger et al. 2012).
The weighting and aggregation of components represents another challenging task in the design of sustainability indices. The weighting reflects the relative importance of the different components in contributing to the overall sustainability of a system.

Finally, sustainability assessments can be driven by either a top-down or a bottom-up approach. In the first case, experts or researchers define the framework and the hierarchical structure of the tool to be applied at the farm level, with little or no participation of stakeholders. On the opposite, the bottom-up approach requires stakeholder participation at all stages of the sustainability assessment, from the definition of the framework to the selection of relevant indicators and the tool validation (Bélanger et al. 2012).
In the last decades, the application of Participatory Learning and Action Research (PLAR) methods to the development of sustainability assessment tools has increased in importance. In particular, farmers are actively involved in the process, that is crucial for the applicability, acceptance, utility of the assessment tool and for the communication of the sustainability performance (de Olde et al. 2017; Wiget et al. 2020). The traditional know-how is merged with the scientific knowledge, contributing to boost agricultural sustainability and resilience (King et al. 2000; van de Fliert & Braun 2002; Fraser et al. 2006; Bélanger et al. 2012; Wiget et al. 2020).
PLAR can be defined as a systemic learning and research approach which aims at facilitating transitions that bring to situational improvements, for example the transfer of theoretical notions of sustainability into practical concepts, tracing a road map for farming systems towards sustainability and contributing to the empowerment of participants (Chambers 1994; Pretty 1995; Friis-Hansen & Sthapit 2000; Reason & Bradbury 2006; Eksvard & Rydberg 2010). Systemic learning refers to a dynamic process of knowledge generation, acquisition, improvement and exchange (Kabourakis 2000). The participating actors are involved at the same time in a process of social learning, problem and instrumental learning, and learning by testing (Glasbergen, 1996; Rametsteiner et al. 2009).

In order to have some standard references, ten assessment tools (Table 1) applied to livestock farming systems are briefly illustrated, highlighting some key features.
The "Sustainability Assessment of Food and Agriculture Systems" (SAFA) (FAO 2013) is an internationally recognized reference framework for assessing the sustainability of food supply chains. Differently from the generic hierarchical structure, the tool introduces the good governance as a fourth sustainability dimension. Its applicability to different farming systems and agroecological contexts (e.g. Gayatri et al. 2016; Cammarata et al. 2021) demonstrates its flexibility. However, the generic framework represents a limit for detecting

context-specific issues (Gasso et al. 2015; Gayatri et al. 2016), and the top-down approach hampers a closer involvement of farmers and policymakers (Gayatri et al. 2016).
The "Response-Inducing Sustainability Evaluation" (RISE) tool offers a holistic assessment at the farm level for simultaneous research, education and improvements of farming practices. It detects farm progresses towards sustainability by evaluating the "State", i.e. the current farm condition, and the "Driving force", that is the estimated pressure the farming system places on a specific indicator (the best score is identified with a State=100 and a Driving force=0) (Urutyan & Thalmann 2011).
The "Public Goods Tool" (PGT) allows the assessment of 11 public goods provided by farms (e.g. soil, biodiversity, animal health and welfare) and it addresses relevant issues such as grazing, fertilizer management and biosecurity which are not present in the other tools (de Olde et al. 2017). According to Marchand et al. (2014), PGT is mainly focused on education rather than on monitoring the farming system.
The French "Indicateurs de Durabilité des Exploitations Agricoles" (IDEA) has been one of the first tools to assess sustainability at the farm level widely adopted in Europe (Bélanger et al. 2012). IDEA has been designed as a self-assessment tool to be used by farmers and by policymakers aiming at supporting the transition towards sustainable and multifunctional farming systems; likewise, it allows comparisons between farms having the same type of production systems and similar soil and climatic features (Zahm et al. 2008; Zahm et al. 2019). The tool introduces some major elements which are unique, especially the concepts of economic transmissibility (de Olde et al. 2017) and the "Ethics and human development" component which investigates animal welfare, the quality of life of farmers and the farm integration in the local context. IDEA lends itself to various adaptations to different contexts and production systems, livestock farming included (De Castro et al. 2009; M'Hamdi et al. 2009; Srour et al. 2009; Boughalmi & Arada 2016; Agossou et al. 2017).

Contrary to the tools already presented, some have been specifically designed for livestock farming systems: the Organic Livestock Proximity Index (OLPI) which aims at supporting the transition to organic farming (Mena et al. 2012; Cruz et al. 2018); the "Monitoring tool for integrated farm sustainability" (MOTIFS) (Meul et al. 2008) designed for Flemish dairy farms; the environmental sustainability assessment method elaborated by Laurent et al. (2017) for dairy farms involved in the Cantal (FR) PDO cheese value chain; the grid for self-assessment for dairy farmers developed by Bélanger et al. (2012). Laurent et al. (2017) have focused the attention on grassland management, applying indicators such as the quantity and quality of grazing, the use of grass in the feed ration, the fodder autonomy.

Apart from OLPI, the other tools have been developed with a participatory approach, which ensures a larger tool adoption and dissemination (Van Meensel et al. 2012). However, some factors such as the lack of stakeholders' involvement at the very beginning of the development process, the lack of communication and divergent expectations between researchers and stakeholders, can act as a barrier (Triste et al. 2014).
Bélanger et al. (2012) describe in detail the six steps for the design of the conceptual framework for sustainability assessment, highlighting the use of participatory techniques such as the Delphy technique and focus groups for the selection of indicators and the definition of reference values. However, some phases such as the selection of the final set of indicators involved only the research team. The overall process was therefore carried out with a series of bottom-up and top-down approaches, whose combination gives better results, according to some authors (Bélanger et al. 2012, King et al. 2000).

An example of a bottom-up assessment tool is the Framework for Assessing the Sustainability of Natural Resource Management Systems (MESMIS for its acronym in Spanish), which allows for the derivation, measurement and monitoring of sustainability indicators within a systemic and participatory assessment process (Ripoll-Bosch et al. 2012). Ripoll-Bosch et al. (2012) have adopted MESMIS to assess livestock farming systems, applying several indicators which are not encountered in other tools, such as animal profitability (net margin per LU), feed efficiency (MJ in products/ MJ in feeds), animal productivity (animal outputs per LU), lambing rate, use of communal grazing areas, distance from slaughterhouse. MESMIS is based on a stepwise approach, which includes (i) the description of the management system, (ii) the identification of critical features that can act as a barrier or enhance sustainability, (iii) the identification of relevant indicators, (iv) the indicator monitoring, (v) the synthesis and integration of results and (vi) the recommendations to improve sustainability. This framework has inspired the development of the Tool for Agroecology Performance Evaluation (TAPE), which has been designed to support the agroecological transition of food systems and is currently in its testing phase in different countries (FAO 2019; Mottet et al. 2020).

Despite the great variety of sustainability assessment tools, some authors (Trabelsi et al. 2016; Trabelsi et al. 2019; Wiget et al. 2020) argue that the traditional methods are not adapted for assessing the performance of agroecological transition farms. Wiget et al. (2020) have evaluated the suitability to agroecological farming systems of 19 assessment frameworks and tools (e.g. IDEA, MESMIS, MOTIFS, PGT, RISE, SAFA), according to 4 key aspects, or essential agroecological principles: (i) adaptability to local conditions, (ii) farmers' involvement, (iii) integration of agricultural multifunctionality, (iv) analysis of interactions.

The first aspect, namely the ability to account for local conditions, refers to "*the adaptation of measurement units and assessment methods to the measures and agroecological practices of local farmers*". The assessment framework has to be linked to the local institutional, social and natural context, that ensures its applicability and understanding to the farmers. For this purpose, frameworks should have a flexible and customizable structure (Wiget et al. 2020). The relevance of this aspect has been pointed out also by other authors with regard to sustainability assessment tools and independently from the agroecological scope (Zhen & Routray 2003; Meul et al. 2008; Laurent et al. 2017; Munyaneza et al. 2019). In order to boost the adaptability to local conditions, frameworks should be based on farmer-based measures, limiting the need of technical support. However, a dual framework structure, with different levels of detail, is recommended. Assessment frameworks should also go beyond the farm level, in order to address the other stakeholders of food systems, who inevitably affect farmers' decisions (Wiget et al. 2020).

The application and comprehension of the sustainability framework at the farm level is strongly related to the second key agroecological principle, that is the farmers' involvement in the development process of assessment frameworks (Wiget et al. 2020). As previously highlighted, PLAR methods have been increasingly adopted to foster stakeholder participation, of farmers especially, that is crucial for many aspects, such as the acceptance of the tool, the incorporation of local knowledge, the use of a comprehensible language. Also in this case, the importance of this aspect emerged from previous studies not related to agroecology (King et al. 2000; van de Fliert & Braun 2002; Fraser et al. 2006; Bélanger et al. 2012).

The third key principle highlighted by Wiget et al. (2020) is multifunctionality, meant as the multiple agroecosystem services provided by an agroecological farming system through the implementation of agroecological practices. Multifunctionality is strongly correlated to the system productivity and resilience. The integration of this concept in assessment frameworks can be achieved by a proper combination of indicators and the use of suitable productivity indicators (Wiget et al. 2020).
Finally, the assessment framework should be based on a holistic approach in order to consider the multiple interactions occurring in agroecological farming systems. This can be attained through the analysis of synergies and trade-offs between indicators (Wiget et al. 2020).

According to Wiget et al. (2020), few frameworks, such as MESMIS, are based on these criteria and are therefore suitable for assessing agroecological farming systems, although some improvements are required (e.g. lack of farm-based measures to collect and evaluate farm data, multifunctionality not fully addressed at the indicator level). Another example of suitable framework is the Evaluation and Simulation of Agroecological Systems (ESSIMAGE), a dynamic tool based on a modeling approach at plot and farm level, and on the interaction of indicators with the Geographic Information System (GIS) software (Trabelsi et al. 2016; Trabelsi et al. 2019). The tool allows for farm assessment before, during and after the agroecological transition, it recognizes the importance of farmers' involvement, it integrates multifunctionality and allows to analyze the interactions between agroecological practices and ecosystem services. However, it results not easily adaptable to local conditions due to a higher complexity of measurement and calculation methods (Wiget et al. 2020).
An additional fundamental aspect considered by Wiget et al. (2020) is the transparency of the tool development process, as previously pointed out by de Olde et al. (2017).
Wiget et al. (2020) also highlight the need for transdisciplinary and participatory research on published and unpublished sustainability assessment frameworks and tools, to facilitate an agroecological transition of food systems. Common guidelines, e.g. based on the FAO 10 agroecology elements (HLPE 2019), should be developed to facilitate the harmonization among the frameworks; moreover further key features characterizing agroecological assessment frameworks should be identified (Wiget et al. 2020).

Table 1. Summary table of the sustainability assessment tools illustrated

Assessment tool	Original aim by tool developers	Sustainability aspects	Hierarchical structure	Examples of tool adoption for livestock systems assessment	Data source	Time for data gathering /Budget	Tool development approach	Suitability for Agro-ecological assessment (Wiget et al. 2020)
SAFA FAO Framework	To provide a tool to assess the supply chain sustainability	Environmental integrity, economic resilience, social well-being, good governance	4 dimensions – 22 themes – 60 sub-themes - 116 indicators. Performance score on a scale from 1 to 5	Beef cattle farms in Indonesia (Gayatri et al. 2016); Organic mountain livestock farms in Sicily (Cammarata et al. 2021); cattle silvopastoral systems in Mexico (Pérez-Lombardini et al. 2021)	Questionnaire with semi-structured questions, direct visits	from few days to few weeks (depending on data availability)	Top-down approach	no
RISE	To provide a holistic sustainability assessment at the farm level and support the dissemination of sustainability practices	Soil use, animal husbandry, nutrient flows, water use, energy and climate, biodiversity, working conditions, quality of life, economic viability, farm management	No dimensions – 10 topics (themes) – 50 sub-themes – 156 indicators. Scoring scale from 0 to 100. "State" and "Driving force" measurements for each sub-theme	Nestlé dairy farms in China (Hani et al. 2003); Armenian dairy farms (Urutyan & Thalmann 2011)	Available data at farm/regional level + farmer interview by trained adviser	3-6 hours (1,5-2 days) / low	Top-down approach	no
PG Tool	To provide a tool to assess the public goods provided by farms	Soil, biodiversity, landscape and heritage, water/ manure management, energy and carbon, food security, agricultural systems diversity, social capital, farm business resilience, animal health and welfare	3 dimensions – 11 spurs (themes) – 57 sub-themes – 185 indicators. Scoring scale from 1 to 5	European sheep and goat farms (Paraskevopoulou et al. 2020)	Available data and farmer knowledge (interview), self-assessment option	2-4 hours / low	Top-down approach	no

Assessment tool	**Original aim by tool developers**	**Sustainability aspects**	**Hierarchical structure**	**Examples of tool adoption for livestock systems assessment**	**Data source**	**Time for data gathering/Budget**	**Tool development approach**	**Suitability for agro-ecological assessment** (Wiget et al. 2020)
IDEA	To provide an operational tool for sustainability self-assessment at farm level	Self-sufficiency, territorial connection, global responsibility resilience, productive and reproductive capacity of goods and services	3 dimensions – 10 components (themes) – 42 aggregated indicators (sub-themes) – 126 indicators. Score system 0-100%	Small ruminants in Libanon (Srour et al. 2009); Dairy farms in Brazil (De Castro et al. 2009); Sheep farming system in Morocco (Boughalmi & Araba 2016)	Self-assessment assisted by an adviser	3-6 hours (depending on data availability)	Top-down approach	no
OLPI	To provide an index to assess the feasibility of the conversion to organic farming	Nutritional management, pasture management, soil fertility and contamination, weed and pest control, disease prevention, breeds and reproduction, animal welfare, food safety, marketing and management	No dimensions – 8 indicators (themes) – 56 variables. Score system 0-100%	Conversion of mountain goat dairy systems to organic production in Spain (Mena et al. 2012); Conversion of agrosylvopastoral dairy cattle systems to organic production in Mexico (Nahed-Toral et al. 2013)	Direct observations of the cattle farms and a questionnaire based on a semi-structured informal interview	-	Top down approach	-
Bélanger et al. tool	Self-assessment tool for farmers to evaluate the agro-environmental sustainability	Soil quality, cropping practices, Fertilization management, Farmland management.	One dimension – 4 components (themes) – 13 indicators (one with 4 sub-indicators). Performance score 1 to 100	Dairy farms in Quebec (Bélanger et al. 2012)	On-farm interviews	-	Series of bottom-up and top-down approaches	-
MOTIFS	User-friendly tool to guide farmers' actions towards sustainability	Use of inputs, biodiversity, productivity and efficiency, profitability, social sustainability, entrepreneurship	3 dimensions – 10 themes (level 1) – 25 sub-themes (level 2) – 45 indicators Scoring scale from 1 to 100	Flemish dairy farms (Meul et al. 2008)	Expert farm evaluation and farm data collection through semi-structures interviews	Several days (more than 2)	Top-down approach with discrete stakeholder participation	no

Assessment tool	Original aim by tool developers	Sustainability aspects	Hierarchical structure	Examples of tool adoption for livestock systems assessment	Data source	Time for data gathering/Budget	Tool development approach	Suitability for agro-ecological assessment (Wiget et al. 2020)
MESMIS	To provide a comprehensive assessment of sustainability	Productivity, stability, reliability, resilience, adaptability, equity and self-reliance	3 dimensions – 7 attributes (themes) - 37 indicators. Reference values set for each indicator	Sheep farming systems in Spain (Ripoll-Bosch et al. 2012)	Semi-structured questionnaire	One session + additional visits to complete data collection	Bottom-up approach	yes
Laurent et al. tool	To provide an environmental assessment at farm level	Management of grassland resources, impact of agricultural practices, management of farm buildings and landscapes, management of local energy and water resources	1 dimension – 4 principles (themes) – 33 indicators. Scoring scale from 0 to 20	PDO cheese value chain in France (Laurent et al. 2017)	Data collection at farm level	Less than 3 hours	Top-down approach with high level of stakeholder participation	-
ESSIMAGE	Assess the agroecological transition process at three scales: agro-environmental, social, economic	Environment, society, economy, crop protection, health	3 dimensions – 5 issues – 24 indicators	Livestock farming systems and crop-livestock farming systems (Travelsi et al. 2019)	Field surveys, spatial analysis	Time and knowledge intensive, partially computer-based	Top-down approach, farmers' involvement considered important	yes

2. Materials and methods

2.1. Materials

In order to answer to the research questions above, the assessment tool DEXi-INVERSION has been applied to 12 livestock farms located in the Autonomous Province of Trento (n=5 farms) and in the Veneto region (n=7 farms) (Table 2).
The research has offered the opportunity to test the tool on livestock farms other than those who participated to its development, and for all the purposes for which the tool has been created. As a matter of fact, DEXi-INVERSION was only tested on the farms which took part to its design, to assess their sustainability. However, the tool can also be used for evaluating the impacts of different practices on sustainability; supporting decision-making processes at the farm level, monitoring the farm evolution in time; comparing different farms or groups of farms (Pisseri et al. 2020).
Within this study, sustainability assessments have been the reference basis for providing four other practical examples of application of the tool. However, since the case studies on the various uses cover only one or a small number of farms, results are only intended to give suggestions, but no general statements can be derived.
Firstly, DEXi-INVERSION has been applied to Farm 1 to test the tool for evaluating the impacts of different practices on sustainability. According to the farm sustainability performance emerged from the assessment, technical advices have been formulated for an agroecological improvement of farm management practices for which the farm was less sustainable.
Secondly, the tool has been applied to Farm 2 with the aim of supporting decision-making processes at the farm level. The sustainability assessment was functional to detect strengths and weaknesses of the farm management system, in relation to a potential agroecological transition. The case study has been presented in April 2021 within the training course "Agroecological practices in ruminant production systems" held by Veneto Agricoltura (RDP 2014-2020); the project work was focused on a farm practice which is not considered an issue (e.g. pasture management, feeding ration, parasitic control, housing system) highlighting limits and opportunities for improvements within an agroecological approach.
In both case studies (Farm 1 and Farm 2), technical advices have been proposed on the basis of the professional experience of the author, with the support of literature sources.
Thirdly, three farms that took part to the tool development, namely Farm 3, Farm 4 and Farm 5, have been re-assessed after a period of one year to monitor the farm evolution in time. The research presents only the case study of Farm 3, in which changes have been more significant.
The fourth practical application of DEXi-INVERSION allows for the comparison of farms' sustainability performances. The global sustainability of the 5 dairy farms in the Autonomous Province of Trento is compared; secondly, sustainability performances of Trentino and Veneto farms are analyzed for the environmental and ethical dimensions, highlighting similarities and differences. The socio-economic dimension has been excluded from the comparative analysis as the economic component was assessed only for one Veneto farm. For this latter aim, statistical data analyses have been conducted using the software DEXi, Microsoft Excel and R.
As a final step, the research offers an overview of the participatory process conducted with farmers of the Veneto region who joined the project "Sustainable grazing" launched by

Veneto Agricoltura and focused on the implementation of agroecological practices. The process aimed at boosting the acceptance and applicability of the tool and was conducted by the technical consultant commissioned by the institution and the author.

Study areas

The Autonomous Province of Trento covers an area of 6,200 km^2 and it is a prevalently mountainous area with 69.8% of its territory above 1,000 m asl and 19.9% above 2,000 m als. Dairy farming is the dominant form of agriculture, with meadows and pastures covering more than 80% of the Utilized Agricultural Area (UAA). Livestock farming represents the 16.7% of the agricultural gross saleable production, similarly to viticulture (17.2%), while fruit farming stand at 33% (ISPAT 2017).
Meadows are mainly located in the valley floors, while pastures for summer grazing are mostly situated above 1,500 m asl. Dairy farms account for 76% of the province's 1,403 cattle farms (ISTAT 2010): the milk is mainly processed by local cooperative dairies and devoted to the production of PDO cheeses, such as Trentingrana, Spressa delle Giudicarie, Puzzone di Moena (Sturaro et al. 2013). However, small-scale mountain dairy farms process their own milk and perform the direct sale of their products.
During the last decades, mountain farms have progressively been abandoned, due to a decrease in the profitability of agricultural activities, ageing of population, changes in land tenure (fragmentation). Between 1980 and 2010, the number of dairy farms has decreased by approximately 80% (ISTAT 2010; Sturaro et al. 2013), confirming the general trend encountered in the Alps (Streifeneder et al. 2007). At the same time, the number of animals per farm has increased, the vertical transhumance has been gradually replaced by intensive, permanent indoor production systems located in the valley floors that rely on high specialized non-autochthonous breeds and high use of extra-farm concentrates (Bovolenta et al. 2008; Battaglini et al. 2014). This has led to a progressive afforestation of high mountain pastures: nowadays only 41% of the cattle belonging to Trentino farms is sent to summer pastures and the management practices tend to be excessively extensive with negative effects related to undergrazing (PAT 2017). The advancing disappearance of grasslands has been coupled with the expansion of vineyards and fruit trees intensively cultivated, with negative effects on landscape heterogeneity and biodiversity (Assandri et al. 2016).

The Veneto region covers an area of 18,345 km^2 which is mostly plain (57%), with 29% of mountainous territories. Livestock farming accounts for 37% of the agricultural gross saleable production (CREA 2020), with over 20,000 farms engaged in livestock, mostly concentrated in the provinces of Treviso, Padua and Vicenza (De Pin 2016).
The dairy sector consists of 3,600 farms and almost 85% of the milk is devoted to the production of PDO cheeses such as Asiago, Montasio, Piave, Grana Padano. Particularly relevant are the pig farming sector, with approximately 600,000 animals reared, and the poultry farm, with turkey meat accounting for 55% of the total national production (Veneto Agricoltura 2015).
The region has experienced one of the most intense and fastest process of modernization of the agricultural sector, based on a progressive concentration of the production in the plains and the abandonment of hilly and mountain areas, with consequent grassland loss or sub-optimal management (Giupponi et al. 2006; De Pin 2016). Between 2000 and 2010 we assisted to a reduction of permanent meadows and pastures of almost 19%, a decrease in the number of livestock farms with up to 50 ha and an increase of those with more than

100 ha (24.3%). The contraction has mostly affected the small barns with less than 10 ha (52.8%), while those of bigger dimensions have become more specialized. As an example, beef cattle farms are just over 1,000 and rear the 85% of cattle, that is more than 360,000 animals (Veneto Agricoltura 2015).
Overall, the increase of intensive farming has led to the loss and fragmentation of natural habitats with detrimental effects on biodiversity in the lowland plains a well as in marginal and mountainous areas (Giupponi et al. 2006; Zimmermann et al. 2010).

Selection of farms and interviews with farmers

Twelve livestock farms (Table 2) were selected for the sustainability assessment. Farms located in the Autonomous Province of Trento were selected among those which were involved in the INVERSION project as partners or beneficiaries of outreach activities (n=16). The decision to limit the choice to this restricted group of farms was grounded on the high level of awareness that farmers had with regard to the concept of sustainability and its practical implications in farm management practices. Such consciousness plays a fundamental role in shaping farmers' aptitude for the assessment of farm sustainability. The selection was conducted in March 2021, during the closing phase of the project, and it was based on two main elements: cattle husbandry represented the main farm activity and the farmer expressed interest in co-evaluating its farm sustainability.
In the Veneto region, the selected farms responded to a call for expression of interest launched by Veneto Agricoltura in May 2021. The aim of the call was to set up a pilot network of livestock farms interested in implementing more sustainable farming practices, and particularly oriented towards increasing the use efficiency of pastures. Differently from Trentino farms where the selection process took place without an ongoing initiative, in Veneto the sustainability assessment has been part of the project activities, aimed at evaluating farms sustainability before and after the implementation of agroecological practices over a period of 18 months. The project, named "Sustainable grazing", started formally in September 2021, however a participatory process on sustainability topics was carried out with farmers before its formal start, aiming at fostering the tool acceptance and applicability through the validation and/or modification of the DEXi-INVERSION set of indicators. Indeed, farmers who responded to the call had already a discrete awareness on sustainable farming practices. Five Veneto farms followed the process from the beginning, two other farms joined the project lately; nevertheless, the assessments of all farms have been included in the present work.
In order to assess farm sustainability, semi-structured interviews were carried out with farmers in Trentino between March and May 2021, while farmers of the Veneto region were interviewed between September and December 2021. Given that the sustainability assessment covers a solar year, data collected in Trentino refer to the year 2020, while those collected in Veneto to the year 2021.
Farmers were interviewed individually in their own farm in two sessions of at least two hours each. In the Veneto farms, the first session was preceded by a field visit to get a deep understanding of the farm structure, the land use, the management practices, the human-animal relationship, etc.
DEXi-INVERSION was used as a framework of reference for the semi-structured interviews. In some cases, additional exchanges with farmers (via telephone or email) were necessary to collect complementary information.

Farm characteristics

The selected farms primarily held rustic cattle breeds (e.g. Rendena, Alpine Grey, Simmental, Aberdeen Angus) well adapted to pasture-based systems, less dependent on inputs and less sensitive to environmental constraints, while some farmers rear high productive cattle breeds (e.g. Friesian, Brown Swiss and crossbreeds with Belgian Blu).

The size of the farms is in the range between 4 and 100 ha, without considering summer pastures; only one farm has a greater extension (1000 ha). The average stocking rate is of 1.5 livestock units ha^{-1}, with a minimum rate of 0.6 and a maximum of 2.5 LU ha^{-1}. The higher stocking rates are observed in farms where the milk is conferred to dairy cooperatives: in these farms the feeding ration of dairy cows is mostly composed of silage maize and grass silage. Differently from the Trentino dairy cooperative system, in the Veneto region dairy farmers are allowed to directly process a part of their milk: this implies opportunities for revenue diversification and product valorization through on-farm sales.

Dairy farms with a small herd size are engaged in milk processing and direct marketing of their products: in these farms, cows are mostly fed with grass and hay.

Concerning beef cattle husbandry, only two farms in the Veneto region are exclusively engaged in this livestock activity, although the management systems differ considerably: in one farm fattening calves are reared grass-fed with little concentrate supplementation, while in the other farm they're mostly kept indoor and the feeding ration has a low forage/concentrate ratio. Beef cattle crossbreeds are reared in other four farms where the direct sale of fresh meat is considered an integrative activity of the multifunctional farm.

The selected farms are managed mostly by young farmers who newly start the farming activity or are managing the family farm (farmers of second generation); they are full time involved in the farm activities. Farms are mainly family-run, but additional staff is employed seasonally or all year round, depending on the farm size and the management system.

Table 2. Characteristics of livestock farms selected (n=12) for the DEXi-INVERSION sustainability assessment

Farm	Location	Elevation (m asl)	UAA (ha)	Herd size**	Stocking rate *** (LU/ha)	Cattle breeds	Management system	Farm activities	On-farm human resources
1	Autonomous Province of Trento	620 m – 1783 m (alpine pastures)	14 ha + 70 ha*	10	0.6	Alpine Grey	Year-round outdoor breeding with shelter, vertical transhumance with summer grazing in alpine pastures. Predominance of hay and grass in the feeding ration.	Dairy products (direct sale)	new generation farmer, full time job; family-run farm with additional staff employed
2	Autonomous Province of Trento	660 m	76 ha	90	1.7	Friesian, Brown Swiss	Loose housing system (with straw bedding), spring and autumn grazing in pastures and in forest for dry cows and young cattle, summer grazing in alpine pastures of young cattle. Predominance of silage maize in the feeding ration.	Milk (cooperative system)	2nd generation farmers, full time job; family-run
3	Autonomous Province of Trento	628 m – 1460 m (alpine pastures)	4 ha + 65 ha*	12	1.7	Original Brown and Rendena	Valley-bottom system: tie barn (with litter and paddock) in winter, spring and autumn grazing, summer grazing in high mountain pastures. Predominance of hay and grass in the feeding ration.	Dairy products, beef meat, charcuterie (direct sale), agritourism and didactic activities in the summer farm	new generation farmer, full time job; family-run farm with additional staff employed
4	Autonomous Province of Trento	650 m	6 ha	7	1.5	Brown Swiss	Loose housing system (without mats or straw bedding), summer grazing of few animals. Predominance of hay n the feeding ration.	Dairy products (direct sale)	2nd generation farmers, full time job; family-run
5	Autonomous Province of Trento	669 m	78 ha	166	2.1	Friesian, Simmental	Permanent loose housing system (with rubber mats) for dairy cows, year-round outdoor breeding with shelter for the small herd of beef cattle (n=6). Predominance of silage maize in the feeding ration of dairy cows, hay and grass for beef cattle.	Milk (cooperative system) and small beef production (direct sale)	2nd generation farmer, full time job; family-run; additional staff employed

Farm	Location	Elevation (m asl)	UAA (ha)	Herd size**	Stocking rate *** (LU/ha)	Cattle breeds	Management system	Farm activities	On-farm human resources
6	Veneto region	200 m – 1417 m (alpine pastures)	72 ha + 30 ha*	80 + 70	1.32	Piedmontese	Loose housing system (with straw bedding), spring and autumn grazing of suckler cows, summer grazing in alpine pastures of suckler cows. Predominance of hay in the feeding ration of suckler cows, concentrates for fattening calves.	Meat (direct sale), agritourism in the summer farm	2nd generation farmer, full time farmer; family-run; additional staff employed
7	Veneto region	4 m	52 ha	45 + 40	1.33	Aberdeen Angus	Year-round outdoor breeding with shelter. Predominance of hay and grass in the feeding ration.	Meat (direct sale)	new generation farmer, full time farmer; additional staff employed
8	Veneto region	24 m	12 ha	4 + 3	1.45	Rendena, Belgian Blu	Year-round outdoor breeding with shelter. Predominance of hay and grass in the feeding ration. Certified Organic.	Horticultural products, cereals, eggs, poultry, pork and beef meat (direct sale), didactic and social activities	new generation farmer, full time farmer; additional staff employed
9	Veneto region	8 m	80 ha	110 + 130	2.5	Friesian, Simmental + crossbreeds (Belgian Blu, Limousine)	Loose housing system (with straw bedding), grazing of young cattle and suckler cows. Variations in the feeding ration according to the groups.	Milk (cooperative system), dairy products, pork and beef meat (direct sale), didactic activities	2nd generation farmer, full time farmer; family-run; additional staff employed
10	Veneto region	200 m – 1267 m (alpine pastures)	47 ha + 43 ha*	70	0.7	Rendena	Loose housing system, summer grazing of the herd in alpine pastures. Predominance of hay and grass in the feeding ration.	Dairy products (direct sale), agritourism in the summer farm	2nd generation farmer, full time farmer; family-run; additional staff employed

Farm	Location	Elevation (m asl)	UAA (ha)	Herd size**	Stocking rate *** (LU/ha)	Cattle breeds	Management system	Farm activities	On-farm human resources
11	Veneto region	200 m	100 ha	140	1.4	Friesian, Brown Swiss, Simmental + crossbreeds (Belgian Blu)	Loose housing system with straw bedding, summer grazing of a small group of fattening calves. Forage/concentrate ratio 60:40 for fattening calves. 30 % of silage maize in the feeding ration of dairy cows. Certified Organic.	Milk (cooperative system), beef meat, apples and juices (direct sale)	new and 2nd generation farmers working together; full time farmer, family-run, additional staff employed
12	Veneto region	76 – 260 m	1000 ha	1400	1.4	Limousine, Aberdeen Angus	Loose housing system, summer grazing in pastures around the barn. Predominance of maize silage in the feeding ration of fattening calves.	Wine (direct sale, GDO, export), dairy products with buffalo milk, meat (direct sale)	Managed by employees

Notes: Farms 3,4,5 took part to the development process of DEXi-INVERSION tool. * Surface of alpine summer pastures directly managed by the farm; ** Cows of 2 or more years of age. For beef cattle farms it is specified the number of suckler cows and of fattening calves. In Farm 9 there are 110 adult dairy cows and 130 fattening calves; *** The stocking rate is calculated by dividing the number of livestock units for the farm UAA (summer pastures excluded). The farm UAA is increased of an additional 4,000 m^2 per LU brought to summer pastures.

2.2. Methods

The tool DEXi-INVERSION allows data organization, measurement, monitoring and comparison of sustainability indicators. It has been built using the open-source software DEXi, a computer program for the development of multi-attribute decision models and their application for the evaluation and analysis of decision options. The decision model is developed by defining attributes (qualitative variables), scales (values assigned to the attributes), trees of attributes (the hierarchical structure), utility functions (aggregation methods of attributes). DEXi facilitates comparative analysis of the attribute values and the graphical visualization of the results (Bohanec 2021).
DEXi-INVERSION is composed of three operational parts:

- the user manual: it covers the description of the system, providing instructions for the completion, evaluation and interpretation of the results. It contains a list of information to collect before the assessment, a detailed explanation of indicators and sustainability thresholds, some examples regarding the computation of quantitative indicators to improve the comprehension, an assessment grid;
- the software open-source DEXi with the combined file DEXi_INVERSION.dxi, to elaborate the data and visualize the results (to be used only on Microsoft Windows platforms). DEXi_INVERSION.dxi represents the dataset of indicators and scores to be imported in the DEXi software;
- the file DEXi_INVERSION.xls consists of spreadsheets to facilitate the calculation of quantitative indicators (e.g. feed ration sheet, water pollutants, economic balance sheet, soil health). It includes an evaluation sheet, graphical representations for each sustainability dimension and the sustainability scores in the format to be imported in DEXi. DEXi_INVERSION.xls allows data elaboration and visualization independently from the software DEXi (for example for non-users of Microsoft Windows platforms).

In this section, the tool is illustrated using the framework elaborated by De Olde et al. (2017) (Figure 2), with the aim of enhancing the awareness and transparency of the decision-making process that guided the development of the tool. The framework considers the development of sustainability assessment tools as a learning process which follows an iterative pathway, with choices and reflections shaping the tool design (Thorsøe et al. 2014; Triste et al. 2014).

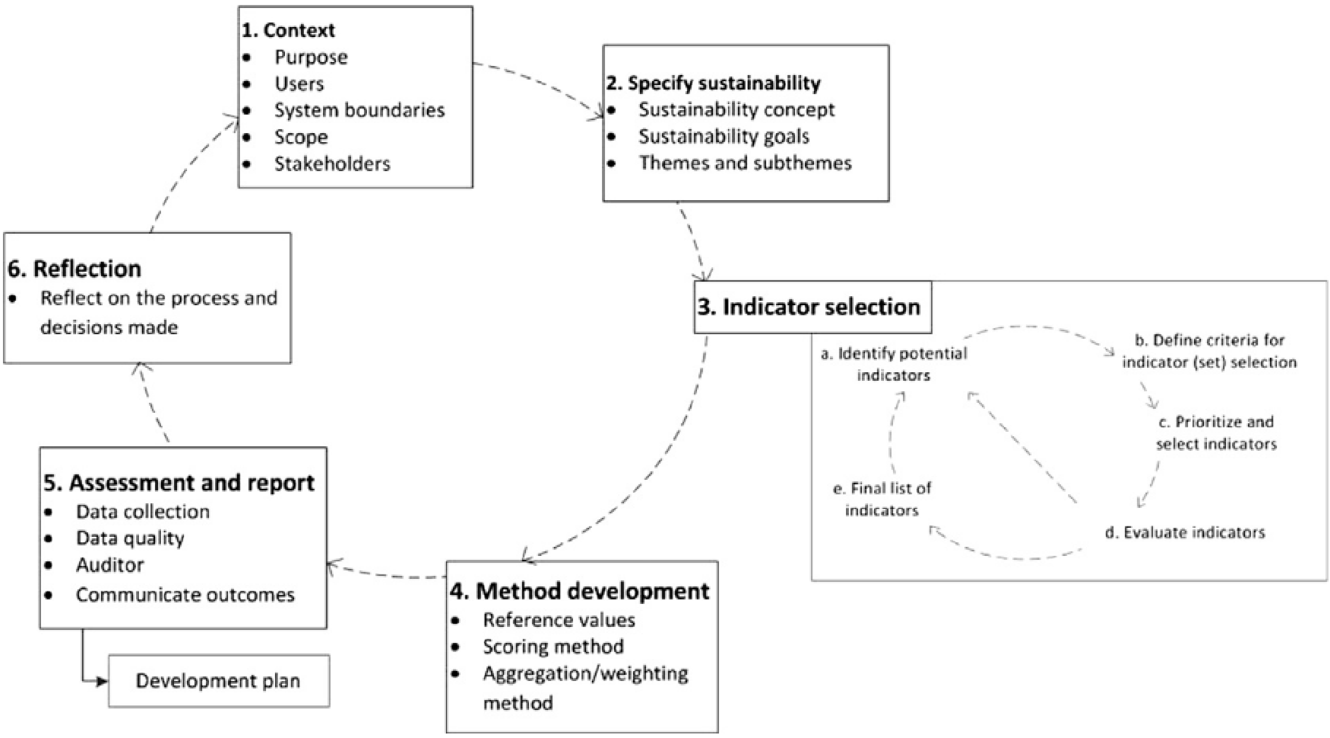

Figure 2. Framework for an in-depth understanding of the decisions taken in the development of sustainability assessment tools. (Source: De Olde et al. 2017)

2.2.1. Context

The first step requires the description of the context in which the tool has been developed, including purposes, users and system boundaries. The spatial (e.g. farm, field, region) and the temporal (e.g. month, year) scope are specified, as well as the production level (e.g. farm, sector), motivating the choices behind the scope definition. Finally, stakeholder participation is investigated, in order to highlight the categories of actors involved and the degree of engagement in the sustainability learning process (de Olde et al. 2017).

DEXi-INVERSION has been developed within the framework of the EIP-AGRI INVERSION project (2017-2021), co-founded by the Autonomous Province of Trento (Project GRANT 444 N.2017IT06RDEI052) in the context of the Rural Development Programme 2014-2020. INVERSION is a bottom-up pilot project that has been promoted by a small group of young farmers who wanted to encourage an agroecological transition in the local livestock farming system, to make it more suitable to the alpine agro-ecosystem.The project aim was to improve the economic viability, the environmental and social sustainability of mountain livestock farms in the Giudicarie Exterior valley (south-west Trentino, northern Italy), by promoting the implementation of agroecological practices in focus farms in order to increase the provisioning of ecosystem services, such as resource use efficiency for mountain livestock farming and crop production, animal welfare, biodiversity at genetic, species and landscape level, soil fertility, mitigation and adaptation to climate change, product quality, landscape and cultural heritage (Barberi et al. 2021).
The valley is rich of areas with great naturalistic, historical and cultural value internationally recognized by the United Nations Educational, Scientific and Cultural Organization (UNESCO), namely the Adamello Brenta Geopark (2008), the Brenta Dolomites World

UNESCO Heritage (2009), the Stilt Houses of Fiavé identified as UNESCO World Heritage Site (2011) and the the Alpi Ledrensi-Judicaria Biosphere Reserve (2015).
Despite the natural and cultural biodiversity richness and efforts made to integrate farming activities with tourism, the traditional agricultural and livestock farming system is almost disappeared leaving the place to intensive systems, with a concentration of livestock beyond the carrying capacity of the area, causing relevant problems of coexistence within the territory and exacerbating the risk of landscape simplification and waste management (PAT 2014). Differently from the provincial trend of cattle reduction, in the Giudicarie valleys livestock farming, mainly represented by dairy farms, has progressively increased the number of animals per farm, simulating the intensive systems of the Po valley (Gubert 2008). As a result of the sector renovation started in the 1970s, high productive breeds, mainly Friesan, are reared in permanent housing systems, with high levels of concentrates in the feed ration and only young animals are sent to high mountain pastures in summer months.
This trend is quite common in the Alps: traditional livestock systems based on the use of pastures and meadows have been affected by a reduction in the number of farms, an increase in the number of animals per farm and the rearing of high specialized and productive breeds (Battaglini et al. 2014). As a consequence, we assisted to a progressive decline in the use of alpine pastures, the abandonment and afforestation of grasslands in slope regions and the concentration of animal husbandry in the valley floor. In the last 70 years, 42% of alpine pastures in the Natural Park Adamello Brenta have been abandoned, and more than 10% of pastures has been recolonized by forest (PAT 2014). Consequently, mountain livestock farming is losing its ability to provide ecosystem services such as conservation of genetic resources, water flow regulation, pollination, climate regulation, landscape maintenance, recreation, ecotourism and cultural heritage (Battaglini et al. 2014).

Within this context, INVERSION project has been the first attempt to encourage a debate on the topic and start a learning process on sustainability applied to the mountain livestock sector. In 2016, five livestock farms (Agriturismo Fattoria Athabaska, Maso Pisoni, Agrilife, Cargos, Misonet) have created the OG “Agroecology for Trentino” to bring agroecological expertise locally and foster the implementation of sustainable farming practices. The OG involved two research institutes (Sant'Anna School of Advanced Studies, Pisa; Institute of BioEconomy, National Research Council, Florence); one vet advisor (Dr Francesca Pisseri) and one local association (Ecomuseum of Judicaria “dalle Dolomiti al Garda”).
EIP-AGRI OGs are multi-actor groups promoting innovative solutions at the local, regional or national level in order to respond to specific territorial challenges; OG stimulate new opportunities for agricultural and livestock farms and facilitate the dissemination of best practices. Farmers acting individually or in associated form are the protagonists of the OG, whose around the partnership and the innovation project is built. The creation of the partnership and the facilitation of the relationships among the partners is being handled by the innovation broker. This role can be played by one of the partners or by an external expert. In the OG, farmers work together with research institutes, universities and advisors who can suggest technical solutions to respond to local constraints. The figure of the technical field advisor can facilitate exchanges between farmers and scientists (Barberi et al. 2021).

The EIP-AGRI OG “Agroecology for Trentino” developed the sustainability assessment tool DEXi-INVERSION: stakeholders have actively participated to the development process from

the first beginning. The creation of the tool can be defined as the result of a series of top-down and bottom-up approaches, which combination can ensure good outcomes (King et al. 2000; Bélanger et al. 2012). The top-down approach finds expression in the hierarchical structure and indicators proposal by a team of researchers and technical advisors part of the OG, with different expertise (agroecology, zootechnics, veterinary science, soil biology, meteorology). The multi-actor and transdisciplinary context in which the tool has been developed, together with the heterogeneity of the farms involved (from small-scale and multifunctional mountain farms to intensive and specialized ones) have provided various and complementary contributions to the system construction, making it flexible to be introduced in different agro-zootechnical realities (Pisseri et al. 2020).
The participatory process followed five main phases: (i) organization of participatory trainings on sustainability topics; (ii) co-selection of indicators within four focus groups; (iii) collective testing of the assessment tool, (iv) restitution of results, (v) farmers' feedback on the participatory process (Pisseri et al. 2020).

The primary purpose of the assessment tool is to provide a holistic sustainability grid for farmers, technicians and researchers to evaluate ruminant and equid livestock systems, either extensive or intensive, located in mountain, hill or plain areas, in order to guide an agroecological transition at the farm level.
As previously highlighted, DEXi-INVERSION can be adopted for different purposes: (i) assess the different dimensions of farm sustainability (socio-economic, environmental, ethical); (ii) evaluate the impacts of different practices on sustainability; (iii) support decision-making processes at the farm level; (iv) monitor the farm evolution in time (for this aim it is recommended a yearly assessment for at least 3 years); (v) compare different farms or groups of farms (Pisseri et al. 2020).
DEXi-INVERSION can be used as a tool of self-assessment or with the support of a technician. In the case of "assisted self-assessment", farmers are guided through the assessment giving freedom to the self-analysis of the farm components. The technical assistance to the farmer is mainly aimed at providing a short explanation of the indicators whether the meaning is less intuitive and giving support in the calculations of quantitative indicators. The assisted assessment allows the farmer to benefit from the implementation of the tool while reducing the time taken by the assessment. This formula can be applied when the sustainability assessment is carried out in a farm for the first time, as it provides a quick, deep and comprehensive understanding and application of the tool, enabling the farmer to autonomously carry out future assessments. DEXi-INVERSION is freely available and can be modified in order to be adapted to different needs and contexts.

2.2.2. Specify sustainability

After the description of the context, the concept of sustainability behind the assessment tool development is explained, outlining specific themes or sub-themes (de Olde et al. 2017).

In the preface of the user manual, Caporali defines DEXi-INVERSION as "*a tool of social learning for the sustainability assessment of farms within their context of action. It responds to the actual needs of dissemination of agroecological knowledge with the aim of restoring the great historical role played by agriculture in the sustainable management of* a *territory. This role has been disowned and undermined by the present industrialized and urbanized society, damaging not only the quality of local ecosystems development and of the entire biosphere, but also the quality of human culture*" (Pisseri et al. 2020).

Agroecology represents a systemic approach to sustainability (Gliessman 2014) and underpins the development of the sustainability assessment tool DEXi-INVERSION. Agroecology is the application of ecological concepts and principles to the design and management of sustainable agroecosystems (Altieri 1995). According to Gliessman (1997), "*The greater is the structural and functional similarity of an agroecosystem to the natural ecosystems in its biogeographic region, the greater is the likelihood that the agroecosystem will be sustainable*". Agroecology is at the same time a science, a set of practices and a social movement. These three dimensions are integrated and co-evolve dynamically, determining the holistic approach of agroecology (Agroecology Europe 2017; Wezel & Silva 2017). As a science, it incorporates elements from agronomy, ecology, sociology and economics (Dalgaard et al. 2003), providing an integrated approach to study the ecology of the entire food system, that means going beyond the resource use efficiency in the field and the short-term evaluation of environmental impacts of agricultural practices (Francis et al. 2003). As a scientific discipline, agroecology is based on a holistic, participatory and action-oriented approach, giving priority to transdisciplinarity that is inclusive of different knowledge systems (Mendez et al. 2013; Agroecology Europe 2017).
As a set of practices, agroecology aims at designing complex and resilient agroecosystems that, by "*assembling crops, animals, trees, soils and other factors in spatially and temporally diversified schemes, favor natural processes and biological interactions that optimize synergies so that diversified farms are able to sponsor their own soil fertility, crop protection and productivity*" (Altieri 2002; HLPE 2019). According to Shiming and Gliessman (2016), "*agroecological practices are those ecologically sound methods which can balance and enhance all ecosystem services provided by agroecosystems and hence benefit to the sustainable development of agriculture*". Wezel & Peeters (2014) define agroecological practices as "*agricultural practices aiming to produce significant amounts of food, which valorize in the best way ecological processes and ecosystem services*".
Even if there is not a defined set of agroecological practices (HLPE 2019), they mainly include the use of local and renewable resources and nutrient cycling; biological nitrogen fixation; improvement of soil structure and health; water conservation; biodiversity conservation and habitat management techniques for crop-associated biodiversity; carbon sequestration; biological pest control and natural regulation of diseases; diversification; mixed cultivation; intercropping; cultivar mixtures; waste management; reuse and recycling as inputs to the production process (HLPE 2019).
Finally, agroecology is a social and political movement that takes care of the relationships between the practical application of agroecology and the society. Within this context, it aims at defending food souvergnity, smallholder food production, family farming and rural communities, healthy and quality food, traditional knowledge, social justice, local identity and culture (Altieri & Toledo 2011; Agroecology Europe 2017; HLPE 2019).

Concerning specifically the agroecological approach and practices applied to livestock farming, Wezel & Peeters (2014) as well as Cayre et al. (2018) highlight that few agroecological publications deal with livestock systems. Dumont et al. (2013) propose five principles for the design of sustainable animal production systems: (i) adopting management practices aiming at improving animal health; (ii) decreasing the inputs needed for production; (iii) decreasing pollution by optimizing the metabolic functioning of farming systems; (iv) enhancing diversity within animal production systems to strengthen their resilience; and (v) preserving biological diversity in agroecosystems by adapting management practices. The link between agroecology and herbivore farming systems with

ruminants is explored by Wezel & Peeters (2014), who propose six groups of principles highlighting the relational aspect of livestock farming with human society : (i) knowledge, culture and socio-economics of farmers, (ii) biodiversity conservation and management, (iii) resource management, (iv) system management, (v) food and health, and (vi) social relations in the society. "*Agroecological herbivore farming systems are driven by farmers and their families who take decisions on the basis of ecological, sociological and economic environments. In this process, they use their own knowledge with the support of technical and scientific information they got from advisers and diverse media. This knowledge is used for managing biodiversity as the key-component and driver of the system. Systems are designed and implemented. In advanced agroecological systems, they are managed in a way that optimize resource use and provide optimum quantity of quality food for consumers. In these systems, social relations seek to develop a new harmony in human societies*" (Wezel & Peeters 2014).
The principles guiding an agroecological livestock farming system are translated into operational practices (Wezel & Peeters 2014) (Figure 3).

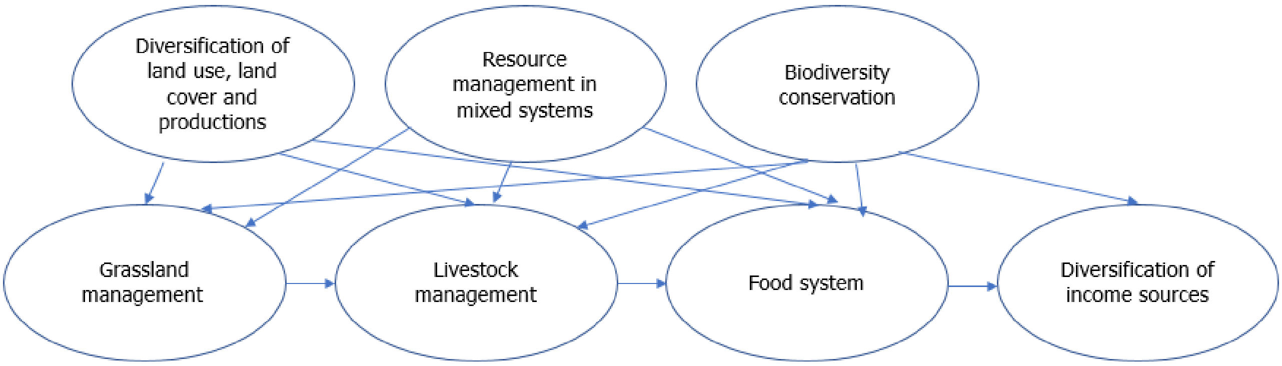

Figure 3. Agroecological practices related to herbivore farming systems, and relations between practices (Source: Wezel & Peeters 2014)

Among the Italian agroecological publications on livestock, De Benedictis et al. (2015) offer a set of core principles drawn up on the basis of the scientific literature on agroecology and the technical field expertise: (i) systemic farm management based on synergic relationships human-animal-environment; (ii) feeding ration based predominantly on self-produced or local forages (e.g. fresh grass, hay) with high nutritional value and an optimal protein content, with a reduction in concentrates and soybean; (iii) implementation of a pasture management plan (including rotational grazing and appropriate agronomic practices); (iv) maintenance of soil cover with permanent grasslands; (v) presence of leguminous species in grasslands; (vi) animal and vegetal species biodiversity; (vii) identification and respect of ethological and physiological animal needs; (viii) no use of ecotoxic pharmacological molecules, use of veterinary drugs only if strictly necessary; (ix) diversification of farm activities, integration of livestock farming with tourism and educational projects (De Benedictis et al. 2015).

The development of the tool followed what Lebacq et al. (2013) have defined the objective-driven approach: an appropriate set of indicators is selected to develop a new assessment tool. The tool is structured in 3 dimensions, 9 components (or themes) and 47 indicators. Differently from the three main pillars of sustainability, in DEXi-INVERSION the social and economic dimensions are merged, and the ethical dimension is introduced.

Ethics refers to a system of values which guides actions of institutions and individuals: it is the ability of institutions and individuals to synthetize the complex framework of values and translate it into virtuous practices (Caporali 2020). The concept of sustainability encompasses several ethical issues, from the responsibility towards future generations, to the impacts of technology on the society, the preservation of the human and natural capital, the fair wage, and the human relations to animals. The ethics of sustainability obliges to face the consequences of a behavior, accepting full responsibility of immediate and long-term externalities (Vidal & Marquer 2002; Kibert et al. 2011).
According to Vidal & Marquer (2002), the ethical dimension of sustainability is the most difficult to transpose into agriculture, however, without ethics in the production function, there cannot be sustainable agriculture. As highlighted by D'Silva (2013) "*When we rear animals in our farms, we have a whole new ethical dimension to add. Animals are sentient beings, that is, they are capable of enjoying their lives and are also capable of suffering. So, if a farmer mistreats their animals, then we would say that is unethical behavior*".
In DEXi-INVERSION, the ethical dimension embraces several aspects concerning animal welfare. In the first steps of the tool structure construction, animal welfare was included into the social dimension, taking as a reference the IDEA tool, where the related indicators are part of the component "Ethic and human development" under the socio-territorial dimension. However, the EIP-AGRI OG agreed to create a dedicated dimension to emphasize the ethical implications of livestock farming on animal welfare and stimulate reflection.
Each dimension is divided into several components. Specifically, the ethical dimension embraces three components, namely animal husbandry systems, livestock management practices, cooperative behaviors. This latter aspect refers to the human-animal interactions and the mutual benefits derived from a cooperative relationship.
The environmental pillar consists of four components: biodiversity, air-water-soil, livestock resources, animal husbandry practices; it investigates the impacts of livestock farming on natural resources, as well as the management of the breeding activity.
Finally, the socio-economic dimension is divided in two components: economic and socio-territorial.

2.2.3. Indicator selection

The third phase consists in defining the sustainability indicators. Firstly, potential indicators should be identified through literature review, databases or expert consultation. Criteria for the selection of an appropriate set of indicators should be defined and prioritize according to emergent trade-offs (e.g. depth of the assessment versus available resources, scientific validity versus easily communicated). Next, indicators should be evaluated with the users to check their feasibility and relevance. Last, the final set of indicators should be defined (De Olde et al. 2017).

The list of potential indicators was collected through the review of scientific literature and the contributions of experts either part of the EIP-AGRI OG, or external ones. Major literature sources exploited were the IDEA tool (Vilain 2008), the Italian guidelines for the evaluation of organic farms sustainability (Abitabile & Arzeni 2013) and the PAW Tool (Pisseri et al. 2019), this latest for animal welfare indicators. The candidate set was composed by 92 indicators which were selected according to the criteria for good indicators (Girardin et al. 1999). The selection process stressed particularly on the identification of multi-dimensional synthetic indicators. Candidate indicators were discussed and selected within the focus groups; during the sessions, farmers proposed some new potential indicators. The process brought to a final set of 47 indicators, 26 for the environmental dimension, 8 for the socio-economic dimension and 13 for the ethical dimension (Pisseri et al. 2020). Thresholds for each indicator are illustrated in Annex 1.

2.2.3.1. Environmental indicators

Component: Air-water-soil

- **Practices for GHG reduction:** Number of farm practices among the following: (i) use of renewable resources (e.g. solar/photovoltaic panels, wind turbines); (ii) reduction of synthetic nitrogenous fertilizers; (iii) reduction of methane emissions from animals through a quality forage feeding ration (Beauchemin et al. 2009); (iv) efficient slurry distribution (e.g. injectors); (v) use of energy efficient equipment; (vi) protection of soil fertility (e.g. minimum tillage, permanent vegetation cover); (vii) multispecies grazing; (viii) rotational grazing; (ix) presence of pluriannual forage crops; (x) balanced LU ha^{-1} ratio.

- **Water conservation measures:** Number of farm practices among the following: (i) mulching or other techniques to limit evapotranspiration; (ii) use of water saving technologies for irrigation; (iii) use of water efficient species/varieties/breeds, autochthonous or selected; (iv) presence of rainwater tanks; (v) re-use of waste water; (vi) minimization of water use in cleaning milking parlour through water pressure regulation and efficient nozzles.

- **Water pollutants:** Number of farm practices among the following: (i) permanent soil cover (e.g. with intermediate and cover crops); (ii) no use of synthetic fertilizers; (iii) use of buffer zones (e.g. use of hedges, presence of at least 5m buffer zone for ditches); (iii) no grazing of animals in degraded areas; (iv) the risk threshold for nitrogen leaching do not exceed 170 kg N ha^{-1} $year^{-1}$.

- **Soil health:** The continued capacity of soil to function as a vital living system (Pankhurst et al. 1997) is assessed following three steps of the Spade test App (https://soilhealth.capsella.eu/) for assessing soil compaction, soil structure, earthworm's abundance. A positive (+1), intermediate (0) or negative score (-1) is attributed to each soil parameter, and the sum of the score of the three parameters represents the value of the indicator. In DEXi-INVERSION, a healthy soil is given by a granular structure (+1), soft soil (+1) and the presence of more than one earthworm and several galleries or excreta (+1). An intermediate level of soil health corresponds to a small polyhedral structure (0), moderate compaction (0) and presence of at least one earthworm and/or una gallery or excreta (0). A soil in critical conditions presents a sub-angular blocky soil structure (-1), a high compaction (-1) and the absence of earthworms, galleries and excreta (-1).

- **Preventive measures for soil erosion:** Number of farm practices among the following: (i) presence of windbreaks; (ii) presence of terraces in slope regions; (iii) presence of channels for collecting running water; (iv) rotational grazing; (v) presence of grass strips of at least 1.5m closed to water bodies; (vi) no slurry distribution in winter; (vii) presence of winter crops; (viii) minimum tillage.

Component: Biodiversity

- **Ecological infrastructures:** It evaluates (i) the surface area covered by ecological infrastructures (https://ipbes.net/glossary/ecological-infrastructure), expressed as percentage on the total farm area; (ii) degree of uniformity in distribution; (iii) presence or absence of active protection and/or conservation measures undertaken by farmers.

- **Animal biodiversity (on pasture):** Number of farm practices among the following: (i) simultaneous presence of different animal species in the same grazing area; (ii) turnover of different species on the same surface; (iii) rotation of different species on surfaces dedicated to agricultural crops.

- **Animal species reared:** Number of species reared.

- **Crop rotation:** Number of years between two successive vegetative cycles of the same crop.

- **Rusticity:** It implies a selection of animals based on their physical conformation and metabolism rather than on productivity. The choice of animals in terms of size and nutritional needs is strongly related to the capacity of the territory to satisfy their requirements and absorb their dejections in a sustainable way. The indicator evaluates if the selection of bulls or replacement females is based on the following parameters: (i) disease resistance; (ii) longevity; (iii) physical conformation; (iv) adaptability to the forage system.

- **Presence of local varieties/breeds:** Number of autochthonous or endangered animal breeds or plant varieties reared/cultivated in the farm.

Component: Animal husbandry practices

- **Amount of grazed land and grazing time:** It evaluates (i) the percentage of Utilized Agricultural Area (UAA) covered by grasslands (grazed and periodically mowed); (ii) the number of months per year of grazing. Attention is also given to the presence/absence of grazing in non-arable areas, which correspond mainly to slope regions in mountain areas.

- **Pasture management:** It measures the presence or absence of a Grazing Management Plan, rotational grazing, ameliorative agronomic practices (e.g. grooming, soil aeration, reseeding), attention to pasture biodiversity.

- **UAA for forage production:** Percentage of UAA for forage production (grass, hay, silage) from pluriannual forage crops.

- **Feeding efficiency of pastures:** Percentage of Forage Units (FU) given by the grass grazed. It measures how much the grass grazed satisfies the nutritional needs of animals, by comparing the FU of the winter feed ration (no grazing) with the FU of the summer feed ration at the time of maximum pasture productivity. The more

nutritional needs are satisfied by grazing, the less supplementary feeding is needed. The narrative explanation of the indicator provides the following example: the daily energy needs of an alpine brown dairy cow of 600 kg, with an average daily production of 18 lt with 4% of fat content, is approximately of 13.3 Milk Forage Unit (MFU). In wintertime, cows are fed with 17 kg of hay and 5 kg of concentrates, while in summertime the supplementary feeding is represented by 5 kg of hay and 1 kg of concentrates. Feeding ration without pasture: 17 kg hay x 0.49 UF= 8.33 UF, 5 kg concentrates x 1 UF= 5 UF. Total UF without pasture=13.33 UF. Feeding ration with pasture: 5 kg hay + 1 kg concentrate = 3.45 UF.
Formula: (a-b)/a*100=x where a=UF in absence of pasture, b=UF in presence of pasture, x=% UF given by grass grazed (see Excel sheet for conversion factors)
Calculation: (13.33-3.45)/13.33*100=74%

- **Protein fodder:** Percentage of protein requirements satisfied by a forage feeding ration. The narrative explanation of the indicator provides the following example: a dairy cow is fed with 22 kg of mountain hay with 10% of protein content and 5 kg of concentrates with 16% of protein content as feeding supplement in wintertime (absence of pasture).
  Formula: (tot. protein intake–proteins from concentrates)/tot. protein intake *100
  Calculation: grams of protein from concentrates: 5000*0.16=800 g; grams of protein from hay: 22,000*0.10=2,200 g. (3,000-800)/3,000*100=73%

- **Health prevention:** Number of farm practices among the following: (i) a health monitoring plan is present; (ii) good level of environmental hygiene; (iii) regular use of diagnostic practices; (iv) attention to animal welfare; (v) regular veterinary attendance.

- **Traditional/alternative medicine:** Ratio of the number of treatments per year to the number of sanitary problems encountered (expressed as a percentage).

- **Antibiotic treatments:** Ratio of the number of treatments per year to the total number of animals (expressed as a percentage).

- **Antiparasitic therapy:** Number of treatments on the entire herd per year.

<u>Component: livestock resources</u>

- **Fertility:** Ratio of the number of newborns to the number of cows in reproductive age (expressed as a percentage).

- **Daily weight gains:** It indicates the daily increase in weight (kg per day) of young animals, and it can be used for beef cattle and for dairy heifers in their growing phase. To compute the daily weight gain, the birth weight is subtracted from the final living weight (at the slaughterhouse for beef cattle or at first insemination for heifers) and divided for the living days of the animal.

- **Efficiency of forage feeding systems:** Daily quantity of concentrates (kg) related to a defined quantity of product obtained (e.g. 5l milk, 0.5kg of daily weight gain). It is suggested to make the calculation referring to the feeding ration of animals in production. The quantity of concentrates increases as the forage quality decreases.

- **Unintentional replacement rate:** Ratio of reformed animal over one year due to fertility or other sanitary problems, to the total number of animals in production (expressed as a percentage). Low unintentional replacement rates indicate good management and animal welfare.

- **Fat and protein yield in dairy husbandry:** Sum of the average milk protein and fat content from mass milk analysis. It is suggested to use average annual values based on at least 4 samples.

- **Omega-6/Omega-3 ratio:** Ratio of Omega-6 to Omega-3 fatty acids. Average values of milk analyses are taken. It is suggested to make at least 2 analyses per season. A lower ratio reflects a forage-based diet and it is inversely related to forage quality.

2.2.3.2. Ethical indicators

Component: animal husbandry system

- **Animal welfare in extensive or semi-extensive breeding systems:** It evaluates (i) the availability of shelters (natural or artificial), the access to water and supplementary feeding; (ii) degree of landscape heterogeneity (diversified environments and microclimatic conditions allows animals to choose the suitable place to fulfill their needs.)

- **Housing systems and housing adequacy:** The quality of housing system is evaluated, as well as the adequacy of facilities and their maintenance. Loose housing systems are positively evaluated when the environment is well ventilated and bright, there is presence of bedding material, surfaces are dry and easy to clean, structural dimensions and design allow an adequate animal mobility and rest, watering and feeding places are in proper proportion to the number of animals (Ventura et al. 2021).

- **Outdoor livestock yards:** The adequacy of outdoor livestock yards is evaluated in terms of adequate dimensions, ease of cleaning, sunlight exposition, slipperiness and presence of watering places.

Component: livestock management practices

- **Feeding ration:** It evaluates (i) the forage/concentrate ratio of the feeding ration, (ii) the degree of feed quality; (iii) the quantity (expressed as a percentage) of silomaize in the feeding ration. Silomaize is accounted for 50% as forage and 50% as concentrate. Grass silages (without grains) are accounted for 100% as forages. The narrative explanation of the indicator provides the following example: a dairy cow with an average milk production of 20 liters is fed with 15 kg of hay (12.7 kg DM), 2 kg of concentrates (1.8 kg DM), 15 kg of silomaize (4.5 kg DM of which 2.25 kg forage and 2.25 kg concentrates).

Formula: (a/a+b)*100=x where a= forages in kg DM, b=concentrates in kg DM, x=%forages in the ration, 100-x=% concentrates in the ration.
Calculation: [(12.7+2.25)/(12.7+1.8+4.5)]*100=78.7
The forage/concentrate ratio is 79/21.

- **Management of the feeding ration:** It evaluates (i) the degree of access to pastures, quality hay and supplements (e.g. minerals); (ii) the adequacy of trough dimensions; (iii) the number of concentrate administrations per day.

- **Body development of young females at first calving:** It is expressed as the percentage of mature body weight. An optimal body development is considered when the heifer reaches two-thirds of the adult cow weight. A sub-optimal development can cause sanitary problems, difficulties in giving birth, poor fertility.

- **Care and management of young animals:** Number of farm practices among the following: (i) large, brightly and easy to clean environments; (ii) presence of dry bedding material in the laying area; (iii) homogeneous groups; (iv) milk temperature is monitored; (v) availability of iced colostrum; (vi) available and clean feed and water; (vii) early grazing; (viii) gradual introduction of concentrates; (ix) free access to fibrous feed; (x) optimal age-body development; (xi) weaning in multiple boxes; (xii) calf weaning at least at 3 months of age.

- **Presence of elderly animals:** Ratio of adult and elderly animals to the total number of animals reared (expressed as a percentage).

- **Partum and post-partum management:** Number of farm practices among the following: (i) expertise in assessing health conditions of the mother and risks related to calving; (ii) attention to hygienic and environmental conditions; (iii) adequate time dedicated to calving and caring of newborns (including attention to colostrum intake); (iv) control of mother health at least every 4 hours during labor; (v) manual intervention if needed; (vi) prompt vet call if the first effort of the breeder is not successful; (vii) control of placenta expulsion; (viii) control of the mother acceptance and care of the newborn.

- **Weaning systems:** The indicator evaluates as low sustainable the early weaning of calves (at birth or in the first week of life), as the abrupt breaking of cow-calf bond exposes the newborn to social and environmental stressors with detrimental effects on animal welfare (Enriquez et al. 2011). On the opposite, natural weaning is positively evaluated; an intermediate sustainability score is attributed when visual and auditory contact is maintained after separation, and the calf is fed with fresh milk or breastfeeding is allowed for at least 30 days after birth and twice a day.

<u>Component: cooperative behaviors</u>

- **Time and attention devoted to observing animal behavior:** It evaluates (i) the presence/absence of observation; (ii) the time devoted to observing animals; (iii) the degree of farmer expertise in identifying signs of distress. The observation of physiological behaviors, such as feeding, drinking, rumination, rest, and of social behaviors, allows the farmer to detect the presence of health problems, environmental or social stressors, and to intervene promptly whether necessary.

- **Human-animal interaction:** Number of farm practices among the following: (i) use of positive rewards; (ii) animals execute the breeder's requests without the need of repetition; (iii) reassuring routines; (iv) the breeder invests time in young animals to make them used to human interaction; (v) the breeder has a reliable and authoritative behavior.

- **Handling of animals:** It evaluates (i) the presence/absence of stress in animal handling among animals and operators; (ii) the degree of farmer expertise; (iii) the adequacy of the tools.

2.2.3.3. Socio-economic indicators

<u>Component: socio-territorial</u>

- **Farm network:** The presence/absence of the following conditions is assessed: (i) the farm is open to the community joining formal and informal farmer networks for purchasing equipment or services; (ii) the farmer directly sells at least 50% of its products; (iii) the farmer welcomes students and interns and develop activities involving people from vulnerable categories; (iv) the farmer takes part in local manifestations to promote local products; (v) more than 50% of forages are purchased locally; (vi) local breeds are reared; (vii) the farmer is part of non-professional associations.

- **Quality of working life:** The presence/absence of the following working conditions is considered: (i) the total weekly hours of workers (farmer included) is of 40-48 hours on average, workers can take days off after hard working periods; (ii) overtime work is on a voluntary basis and remunerated more; (iii) workers have regular pauses of adequate length, lunch break included; (iv) workers can take holidays; (v) safety standards are respected; (vi) workers are satisfied of their job.

- **Intergenerational conflicts:** The presence of family support or conflict situations is investigated in the context of family farms, with young farmers in leadership position.

- **Professional training of farm operators:** It evaluates the number of professional training courses attended by workers (farmer excluded) on a yearly basis.

- **Internal communication and coordination:** The frequency and efficacy of internal communication, the level of organization and the sharing in decision-making processes are evaluated.

Component: economic

- **Profitability:** It measures the total farm productivity expressed as Value Added over the utilized farm surface (€ ha^{-1}). Value Added is the sum of all goods and services produced by the farm less the living expenses. The utilized farm surface includes the Utilized Agricultural Area and the areas exploited for the connected activities. Surfaces seasonally exploited (e.g. high mountain pastures) must be "divided" for 12 months and accounted only for the time period of usage. The indicator wants to reward multifunctional farms, able to increase their productivity beyond the agricultural sphere. From an agroecological perspective, they increase their resilience in diversifying their services.

- **Labour efficiency**: Value Added (€) generated by a Working Unit (WU), where 1 WU refers to 48 weekly working hours. It estimates the farm ability to valorize the labor employed.

- **Vulnerability:** Ratio of the gross production (i.e. the sum of goods and services produced) to the expenses. It highlights the independence of the farm from external sources.

2.2.4. Method development

Reference values, or thresholds, to assess farm sustainability can be based on scientific or target values, on regional averages or can be strongly related to the local context and individual reference frames. The assessment of sustainability at the indicator level is usually expressed using a scoring scale: the indicator scores are added to compute the overall farm sustainability, after having multiplied each of them for the weight attributed to the single indicator. Aggregation of the results can be based on the "Weighted Sum" ranking method, with expert and stakeholder consultations defining the weight for each hierarchical level of the assessment tool, or on the 'Best Worst Case' ranking method, which is based on a minimisation risk approach (Andreoli & Tellarini 2000; de Olde et al. 2017).

In DEXi-INVERSION, quantitative and qualitative threshold values were firstly assigned using scientific literature and expert consultation, and then discussed and modified within the focus group sessions for the adaptation to the local context and users' reference frame Final threshold values are listed in Annex 1. For each indicator, a score was attributed in order to position the farm practices within three sustainability thresholds: high, medium, low. Four different values can be assigned to each indicator according to the answer given by the farmer: "-1" (low sustainability), "0" (intermediate sustainability), "+1" (high sustainability), "*" (data non available). The non-evaluation option is always allowed if the aspect to assess is not relevant to the farm typology, or if available data are not enough to make a correct evaluation. The non-evaluation option doesn't influence the final score, as the weighting of the indicator is automatically re-distributed to the other indicators of the same component. Aggregation of results followed the "Weighted Sum" ranking method. The weights of indicators have been defined by experts starting from the degree of importance assigned by farmers at the end of the collective test of the assessment tool. The weight of components and dimensions was subsequently determined by experts (Table 3).

Table 3. Relative weights of indicators, components and dimensions (in brackets)

		Indicator weight
Environmental dimension (50%)	**Air Water Soil (20%)**	
	1.1.1. Practices for GHG reduction	25%
	1.1.2. Water conservation measures	25%
	1.1.3. Water pollutants	10%
	1.1.4. Soil health	25%
	1.1.5. Preventive measures for soil erosion	15%
	Biodiversity (20%)	
	1.2.1. Ecological infrastructures	15%
	1.2.2. Animal biodiversity	25%
	1.2.3. Animal species reared	10%
	1.2.4. Crop rotation	15%
	1.2.5. Rusticity	20%
	1.2.6. Presence of local varietes/breeds	15%
	Animal husbandry practices (35%)	
	1.3.1. Amount of grazed land and grazing time	15%
	1.3.2. Pasture management	15%
	1.3.3. UAA for forage production	5%
	1.3.4. Feeding efficiency of pastures	5%
	1.3.5. Protein fodder	15%
	1.3.6. Health prevention	15%
	1.3.7. Traditional/alternative medicine	5%
	1.3.8. Antibiotic treatments	20%
	1.3.9. Antiparasitic therapy	5%
	Livestock resources (25%)	
	1.4.1. Fertility	20%
	1.4.2. Daily weight gains	10%
	1.4.3. Efficiency of forage feeding systems	20%
	1.4.4. Unintentional replacement rate	10%
	1.4.5. Fat and protein yield in dairy husbandry	20%
	1.4.6. Omega-6/Omega-3 ratio	20%
Ethical dimension (25%)	**Animal husbandry systems (17%)**	
	2.1.1. Animal welfare in extensive or semi-extensive breeding systems	45%
	2.1.2. Housing systems and housing adequacy	45%
	2.1.3. Outdoor livestock yards	10%
	Livestock management practices (50%)	
	2.2.1. Feeding ration	20%
	2.2.2. Management of the feeding ration	5%
	2.2.3. Body development of young females at first calving	5%
	2.2.4. Care and management of young animals	15%
	2.2.5. Presence of elderly animals	15%
	2.2.6. Partum and post-partum management	15%
	2.2.7. Weaning systems	25%

	Cooperative behaviors (33%)	
	2.3.1. Time and attention devoted to observing animal behavior	25%
	2.3.2. Human-animal interaction	50%
	2.3.3. Handling of animals	25%
Socio-economic dimension (25%)	**Socio-territorial (50%)**	
	3.1.1. Farm network	20%
	3.1.2. Quality of working life	30%
	3.1.3. Intergenerational conflict	10%
	3.1.4. Professional training of farm operators	20%
	3.1.5. Internal communication and coordination	20%
	Economic (50%)	
	3.2.1. Profitability	30%
	3.2.2. Labor efficiency	40%
	3.2.3. Vulnerability	30%

Al illustrated in Table 4, the sustainability score for each component is determined by multiplying the weighted sum of the scores of indicators with the relative weight of the component. In case an indicator is not evaluated, the relative weight is not considered in the computation.

Table 4. Computation of the sustainability score of the component "Animal husbandry practices": an example

Animal husbandry practices 35%	Indicator weight	Sustainability score	Weighted score
1.3.1. Amount of grazed land and grazing time	15%	1	0.15
1.3.2. Pasture management	15%	1	0.15
1.3.3. UAA for forage production	5%	1	0.05
1.3.4. Feeding efficiency of pastures	5%	-1	-0.05
1.3.5. Protein fodder	15%	0	0
1.3.6. Health prevention	15%	1	0.15
1.3.7. Traditional/alternative medicine	5%	#	
1.3.8. Antibiotic treatments	20%	1	0.2
1.3.9. Antiparasitic therapy	5%	0	0
	95%		**0.65**
		0.65 / 95%= 68.4%	

In the same manner, the weighted sum of the scores of the components gives the sustainability score of a dimension, and the global score of the 3 dimensions reflects the overall level of the farm sustainability (Pisseri et al. 2020).

The "sustainability scale" ranges from -100% to +100%: a farm is highly sustainable when the score goes from +33% to +100%, it is mildly sustainable when is rated between -33% and +33%, and it is in the low sustainability when the score ranges from -33% to -100%.

2.2.5. Assessment and report

The final step consists in the sustainability assessment using the set of selected indicators. Within this phase, decisions are taken concerning the data collection, the data quality and the auditor. Once the assessment is concluded, results are reported to the users, fueling the discussion on sustainability (de Olde et al. 2017).

Within the development process of the tool, the sustainability assessment of focus farms took place in a collective session of half a day, following the assisted self-assessment approach. An evaluation grid has been used (Annex 2) to attribute a score to each indicator. Economic data and soil health data were previously collected during individual meetings with researchers. Milk quality and Omega-6/Omega-3 ratio indicators were scored on the basis of milk analyses carried out within the project. The excel sheet was used to compute animal feeding, correcting the percentage of dry matter and protein content according to feed analyses. Therefore, data quality was substantially high as grounded on laboratory analyses, direct farm observations of farmers and experts and farm documentary data. Despite the assisted self-assessment approach should guarantee a high objectiveness in the evaluation process, in some cases farmers' perceptions can prevail creating distortions. This was the case for the qualitative indicators of the component "Cooperative behaviors" aiming at assessing the farmer expertise and engagement in the observation and interaction with the herd. Regarding the restitution of results, individual sessions took place within a technical assistance visit. The graphical representation of farm sustainability was given to farmers in order to have a picture of the present state, stimulate reflections and encourage sustainable choices within the decision-making process.
Graphical representation of the assessment results can be obtained either with the software DEXi (Figure 4) or with the file DEXi-INVERSION-xls (Figure 5).

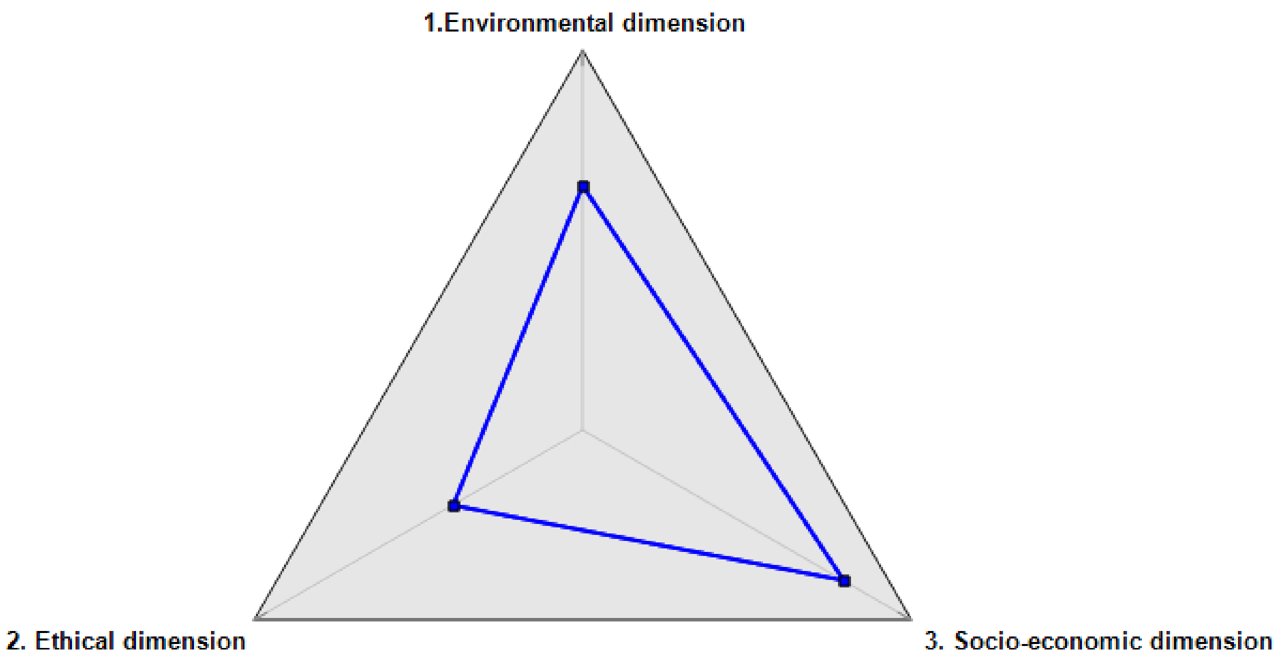

Figure 4. Example of radar chart representing the overall sustainability assessment with DEXi software

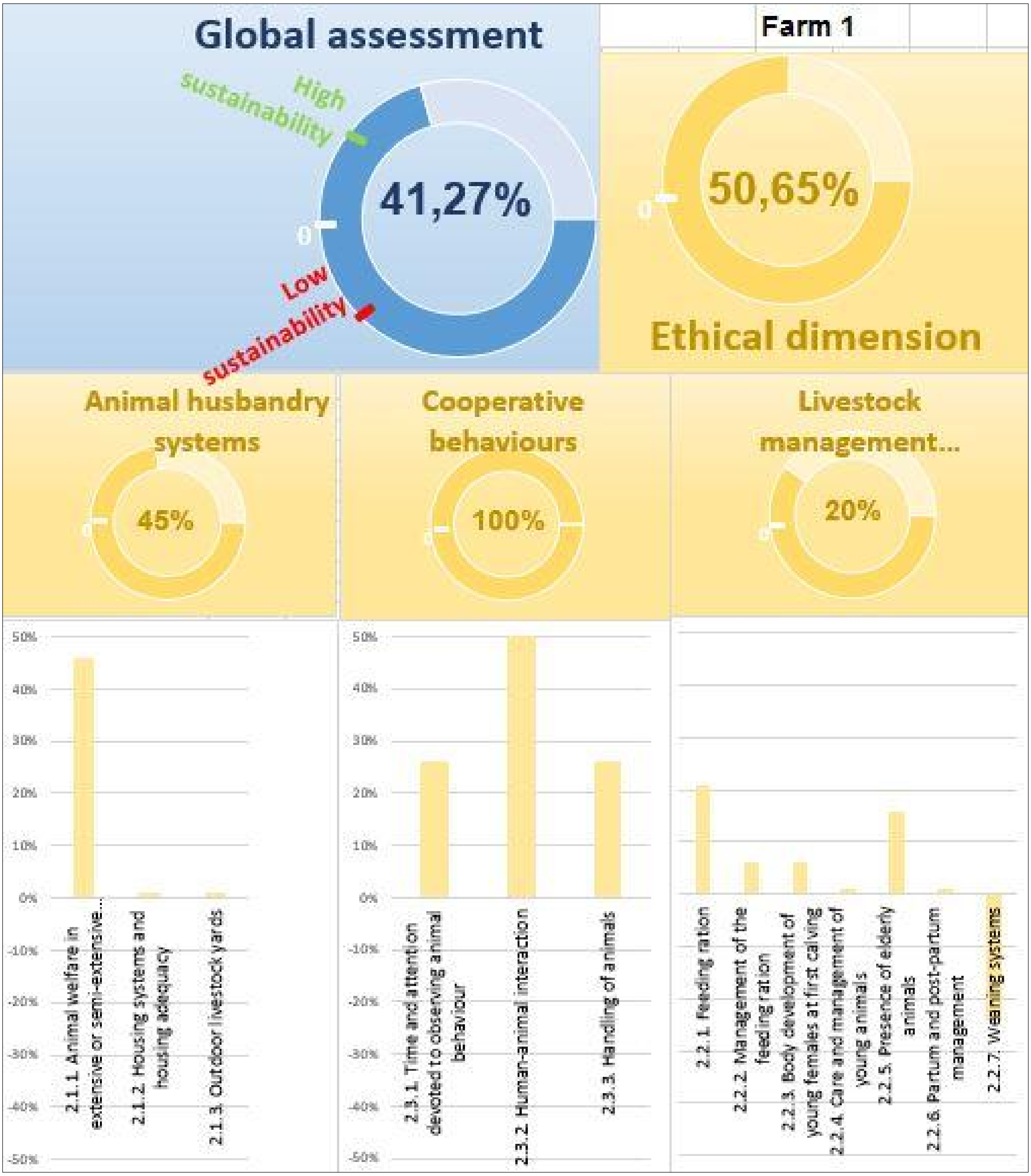

Figure 5. Example of the graphical visualization in DEXi-INVERSION for the overall sustainability assessment and the Ethical dimension, with detailed scores for each component and indicator. The dark session of the ring indicates the share of sustainability, which ranges from -100% to +100%.

Within the present study, data were collected in individual sessions, two per farm of at least two hours each, with an assisted self-assessment approach. Data collected have been organized using DEXi_INVERSION.xls. For each livestock farm an Excel file has been created, with all computations of quantitative indicators and the sustainability scores assigned. The comparison of sustainability performances has been performed and analyzed using the software DEXi and R. Veneto and Trentino farm sustainability performance has been compared only for the environmental and ethical dimension, as the economic indicators were not computed for all Veneto farms, where alternative economic indices have been applied.

2.2.6. Reflections

The final step foreseen in the framework elaborated by de Olde et al. (2017), focuses on reflections concerning the decisions made in the development of the tool, i.e. in the assessment method adopted and in the definition of reference values, and in the ability of the tool implementation in fostering farm sustainability (de Olde et al. 2017).

From a conceptual point of view, the development of the tool has fully adopted agroecology as a systemic approach to sustainability (Gliessman 2014). Agroecological principles have driven the definition of sustainability topics, ethical aspects related to animal welfare and human-animal interactions have been emphasized to stimulate reflection. Certainly, the adoption of the tool goes beyond its main aim as it enhances the dissemination of agroecological practices, and it raises farmers awareness. In this regard, both the tool development and its adoption can be considered as co-learning processes with strong social implications. Deeply rooted into the local context where it has been developed, DEXi-INVERSION has merged farmers' perspectives and experiences with scientific knowledge for the definition of sustainability thresholds, following an iterative participatory process which ended with the collective testing of the tool. The alternation of top-down and bottom-up approaches at different steps of the tool development has ensured an optimal outcome from a methodological point of view, as already noticed by Bélanger et al. 2012.
Certainly, another distinctive aspect of DEXi-INVERSION is that it doesn't propose a unique methodology for data collection, execution of the sustainability assessment and restitution of results: being grounded on a participatory process, the implementation of the tool can vary according to the local context and typology of users involved, confirming its flexible nature.

3. Results

In the following, the results of livestock farms sustainability assessments are presented. The chapter is subdivided into three major sections. In the first part, the sustainability assessment of livestock farms is examined through the presentation of three practical applications of DEXi-INVERSION. Technical advices have been proposed on the basis the professional experience of the author with the support of literature sources. The fourth practical use of the tool, namely the comparison of sustainability performances of Trentino and Veneto farms, is covered in the second section. The third part of the chapter illustrates the participatory process carried out to implement the tool in the Veneto Region.

3.1. Practical applications of DEXi-INVERSION

3.1.1. DEXi-INVERSION for assessing the impacts of different practices on sustainability

Farm 1 is highly sustainable for the three dimensions (+41.3%). However, some critical aspects emerge from the assessment. For the components "Biodiversity", "Livestock management practices" and "Socio-territorial", the farm is positioned in the intermediate level (Figure 6): opportunities for improvement within these spheres are identified. Furthermore, the assessment has highlighted single management aspects which are not negatively influencing the sustainability score of the component (e.g. "Soil health" indicator for the component "Air-water-soil") at the time of the assessment, but could compromise the efficient use of resources for livestock in the future.

- <u>"Biodiversity" component: animal biodiversity (1.2.2), animal species reared (1.2.3), presence of local breeds/varieties (1.2.6)</u>

Sharing spaces between different animal species, for example rummaging chickens in pastures for cattle, can offer several advantages, such as the limitation of ectoparasites or intermediate hosts of parasites and the sustainable increase of farm productivity per hectare. It includes the simultaneous presence of different animal species in the same grazing area, the rotation of different species on the same surface, or the alternance of animal species with agricultural crops. Breeding multiple breeds can sustain livestock genetic diversity and the conservation of autochthonous or endangered breeds. The farm could integrate the dairy farming activity with a small rearing of hens or broilers. The poultry house should be located closed to the barn, in order to free chickens with grazing cows, or right after. Chickens feed on ectoparasites (e.g. flies, gadflies), on fly larvae that develop on cow excreta after few days, or on intermediate hosts of parasites that represent a source of protein (Rosati et al. 2015). Freshwater snails (Lymnaea spp.), which are present when there is water stagnation, are intermediate hosts of Fasciola hepatica, a parasitic trematode which infects grazing ruminants when consuming contaminated fresh forage or water. Fasciolosis causes anemia, unthriftiness, reduced milk production (-10%), lengthening of the parturition interval and fertility reduction. The economic loss due to fasciolosis is estimated to be of 88 euros/cow/day (Bertagnoli et al. 2007). At the same time, the co-presence of cattle with chickens can prevent predation by raptors.

Figure 6. Farm 1 sustainability assessment

The farm could evaluate the introduction of Rendena cows in the herd, which is composed of Grey Alpine cows only. This would favor the conservation of an autochthonous breed; at the same time the dual-purpose attitude could increase farm productivity. Another interesting breed for Farm 1 is the Pinzgauer, an autochthonous dual-purpose breed with limited diffusion, well-adapted to poor mountain pastures, and with an average milk production (5,971 liters per year) slightly higher than Rendena and Grey Alpine breeds.

- <u>"Livestock management practices" component: weaning systems (2.2.7), feeding ration (2.2.1) and related indicators "Housing systems and housing adequacy" (2.1.1), "Protein fodder" (1.3.5) of the component "Animal husbandry practices"</u>

The farmer has chosen spring calving in order to have an immediate forage availability following calving and to wean and market calves prior to winter, without incurring in winter feeding costs for the calves. The calf is separated from the mother at birth, reared in an individual box without visual and olfactive contact with the mother, and fed with maternal milk. The farmer believes that calves reared in multiple boxes tend to suck each other.
Breastfeeding respects the ethological and physiological needs of cows and calves, it strengthens the immune system of the calf, and blood circulation is stimulated when the mother licks the calf during the feeding. Calves show a good growth also after weaning and develop social behaviors. From the side of the breeder, the workload is reduced.
During the first week, the calf sucks 8-9 times per day, and 5-6 in the following weeks. When the calf is separated from the mother, it is usually fed 3-4 times per day, limiting its natural needs. This push the calf to suck from the others. Isolating the calf after birth has a negative impact on the behavioral development, it limits sociability in the first phases, it reduces the chances to move and play. Multiple boxes are preferable when they provide an adequate space for calves (Spengler et al. 2020).
It is recommended to leave the mother with the calf together during the first week, and few hours per day during the following 30 days in a calving area, where the calf can be breastfed. The cow can be regularly milked before or after the breastfeeding. During the first month of life, it is important to ensure a visual and olfactive contact with the mother and keep calves in a multiple box.
At the time of the assessment, the calving area is not present. The barn is traditional but with no ties and cemented floor, leaves are used as bedding material (Indicator 2.1.1 "Housing systems and housing adequacy"). Animals are free to move from the barn to the outdoor yard (where a bale feeder is placed in wintertime) and to marginal pastures and woody areas around the barn. The outdoor yard is in rammed earth, water infiltrates well in the soil without stagnation (Indicator 2.1.3 "Outdoor livestock yards"). Cows give birth in the forest closed to the barn, as they find a protected environment, dry and clean, and separated from the herd. The farmer is expanding the barn in order to offer a shelter for all the cows at once, and adequate feeding places. It is recommended to create a calving area closed to the barn where cows can find a place as comfortable as forest where to give birth, where the visual and olfactive contact mother-calf can be maintained and where it will be easier for the farmer to take care of the newborn.
The body condition score of dairy cows is around 2.5-3. Animals are fed with hay and grass with little supplementary feeding. The commercial concentrate mixture contains flaked grains, flours and bicarbonate. Feeding requirements for dairy cows with respectively 20lt and 30lt of average milk production per day are estimated in order to check whether the actual feeding ration (Tables 5 and 6) satisfies the nutritional needs of lactating cows.

Table 5. Feeding ration of lactating cows with an average milk production of 20 l per day

	% DM	MFU kg^{-1} DM	Crude Protein g kg^{-1} DM	Feed kg tel quel weight	Estimated intake kg DM cow^{-1} day^{-1}	MFU day^{-1}	Crude Protein g day^{-1}
Multi-species hay	87	0.61	100	20	17.4	10.61	1740
Concentrate mixture (flaked maize, wheat flour, soybean, bicarbonate…) Dairy Sprinter 3A NGM Purina	87	1.15	150	4	3.48	4.00	522
					20.88	14.61	2262

Sources: Cappa 1991; Antongiovanni et al. 2020; Pisseri & Barberi 2021. Own data elaboration.

Table 6. Feeding ration of lactating cows with an average milk production of 30 l per day

	% DM	MFU kg^{-1} DM	Crude Protein g kg^{-1} DM	Feed kg tel quel weight	Estimated intake kg DM cow^{-1} day^{-1}	MFU day^{-1}	Crude Protein g day^{-1}
Multi-species hay	87	0.61	100	20	17.4	10.61	1740
Concentrate mixture (flaked maize, wheat flour, soybean, bicarbonate…) Dairy Sprinter 3A NGM Purina	87	1.15	150	6	5.22	6.00	783
					22.62	16.61	2523

Sources: Cappa 1991; Antongiovanni et al. 2020; Pisseri & Barberi 2021. Own data elaboration.

Feeding requirements are calculated using the following equations (Antongiovanni et al. 2020):

NE_l (MJ/d) = 3.4 FCM + 0.043 BW + 5.02

where NE_l = net energy requirements for lactating cows (1MJ=238.85 kcal)
FCM= Fat Corrected Milk (theoretical milk quantity at 4% fat content), kg/d
BW=Body Weight, kg

PDI (g/d) = 49.9 FCM + 0.5 BW + 98

where PDI stands for digestible protein.

The estimated nutritional requirements for lactating cows with an average milk production of 20 l per day are of 13.67 Milk Forage Unit (MFU) and 2264 grams per day of protein.

The estimated nutritional requirements for lactating cows with an average milk production of 30 l per day are of 17 MFU and 2875 of Crude Protein (g day^{-1}).

The winter-feeding ration (without grazing) of dairy cows with an average milk production of 20 l per day is balanced and satisfies maintenance and productive requirements. Protein supply should be increased for cows with an average milk production of 30 l day^{-1}: this could be achieved with a hay richer in proteins, in order not to augment the DM intake (optimal between 20 and 23 kg DM day^{-1}). The hay used by the farmer has an estimated protein content of 10%. Hay with a protein content around 12% could fulfill the protein requirements of the more productive dairy cows (Table 7).

Table 7. Feeding ration with hay at 12% protein content to satisfy protein needs of the more productive lactating cows

	% DM	MFU kg^{-1} DM	Crude Protein g kg^{-1} DM	Feed kg tel quel weight	Estimated intake kg DM cow^{-1} day^{-1}	MFU day^{-1}	Crude Protein g day^{-1}
Multi-species hay	87	0.61	120	20	17.4	10.61	2088
Concentrate mixture (flaked maize, wheat flour, soybean, bicarbonate…) Dairy Sprinter 3A NGM Purina	87	1.15	150	6	5.22	6.00	783
					22.62	16.61	2871

Sources: Cappa 1991; Antongiovanni et al. 2020; Pisseri & Barberi 2021. Own data elaboration.

The farmer should perform lab analyses on self-produced hays, on forages locally purchased or from the Po Valley, in order to efficiently adjust the feeding ration according to the protein content. Furthermore, the concentrate mixture in use is formulated specifically for dairy cows of intensive breeding systems: the presence of bicarbonate is usually given in order to reduce acidosis in cows mainly fed with silage. Maize seeds are flaked, favoring a more rapid release of starch. The farmer could ask for a mixture of cereals (barley, proteic pea, triticale) with raw and crushed grains for a slower release of starch, and without soybean (Table 8).

Table 8. Suggested feeding ration composition with raw cereals for cows producing 20 l per day

	% DM	MFU kg^{-1} DM	Crude Protein g kg^{-1} DM	Feed kg tel quel weight	Estimated intake kg DM cow^{-1} day^{-1}	MFU day^{-1}	Crude Protein g day^{-1}
Multi-species hay	87	0.61	100	20	17.4	10.61	1740
Crushed barley	87	1.15	116	1	0.87	1.000	100,92
Proteic pea	87	1.15	200	2	1.74	2.00	348
triticale	87	1.15	135	1	0.87	1.00	117.45
					20.01	13.61	2188.92

Sources: Cappa 1991; Antongiovanni et al. 2020; Pisseri & Barberi 2021. Own data elaboration.

- <u>"Socio-territorial component": farm network (3.1.1), quality of working life (3.1.2)</u>

The farmer could increase networking with other farms e.g. by joining local projects aiming at supporting mountain livestock farms and participating to local events as an open-door farm or to local markets. Concerning the quality of working life, the farmer has adequate working breaks and holidays, and is satisfied of the job, however the workload remains over the average (40-48 weekly hours). This aspect is common among all breeders, and difficult to improve.

- <u>"Soil heath" indicator (1.1.4)</u>

Meadows closed to the barn are mildly compacted in the top layer, with low presence of earthworms. The famer doesn't distribute manure, there is an abundance of graminaceous species and few leguminous species; in some areas the soil is uncovered. The farmer would like to shift the area from meadows to pastures.
Superficial soil aeration is recommended. Whether the farmer will start grazing, a rational pasture management should be introduced. Grooming at the end of the grazing season allows the distribution of excreta, increasing the soil organic content, favoring the regeneration of perennial grasses and soil microorganism's activity.
In order to have a balanced plant species composition and re-establish the soil vegetal coverage, reseeding operations can be carried out in autumn, when there is less competition with the species already present, and temperature and humidity conditions favor the germination of the seeds. Grass seed at a rate of 20-30 kg seed per hectare is recommended. The use of grass mixture "Trento intensivo", already available in the farm, can be used, leguminous seeds should be added (20%) as they're not present in the commercial mixture. This would favor the functional diversity of the pasture, increasing soil fertility, pasture productivity and the protein content of forages.

- <u>"Antiparasitic therapy" indicator (1.3.9)</u>

The farmer carries out routine mass treatments on young animals after the summer grazing season, but not on adults. Qualitative and quantitative fecal analyses can be carried out in autumn, one month after the descent from high mountain pastures; they can be repeated once the grazing season in the slope region (where the farm is located) is ended, and in spring time at the beginning of the grazing season. Lab analyses can be carried out on different animal groups or on individuals, e.g. showing a slow growth or inappetence. Silvopasture can favor the maintenance of a parasitic population below threshold thanks to tannin ingestion (Pisseri et al. 2013).

3.1.2. DEXi-INVERSION for supporting decision-making processes at the farm level

Overall, Farm 2 is mildly sustainable. An intermediate sustainability is observed for the environmental and socio-economic dimension, while a high sustainability is slightly reached for the ethical dimension (Figure 7).

- <u>Territorial context and farm characteristics</u>

The farm is located at 600 m asl in the valley floor of Giudicarie Exterior valley (south-west Trentino), closed to a relevant peat bog (Natura 2000 site). Different landscapes coexist: a mosaic of different land-uses with semi-natural habitats of high ecological value and a simplified landscape dominated by maize silage monoculture (Figure 8). Peat and clay soils are present, with a good water availability. Mean annual precipitations ranges from 800 to 1100 mm.

Figure 8. Cartography of the territorial context in which Farm 2 is located (Source: Google Maps)

Friesan and Alpine Brown dairy cows are raised on the farm, for a total of 117 LU; 72 are lactating cows. Animals are hosted in a loose housing system without an outdoor yard. Lactating cows are kept permanently in the barn, while dry cows and heifers are moved to high mountain pastures in summer; summer grazing allows to reduce the stocking rate from 2 to 1.7 LU ha^{-1}. In the Autonomous Province of Trento, each LU reared in mountain pastures during the summer season corresponds to 0.4 ha of forage area. Grasslands closed to the barn are grazed in springtime and autumn (Figure 9); forest grazing is also practiced (Figure 10).

Figure 7. Farm 2 sustainability assessment

Figure 9. Grazing cows in pastures closed to the barn

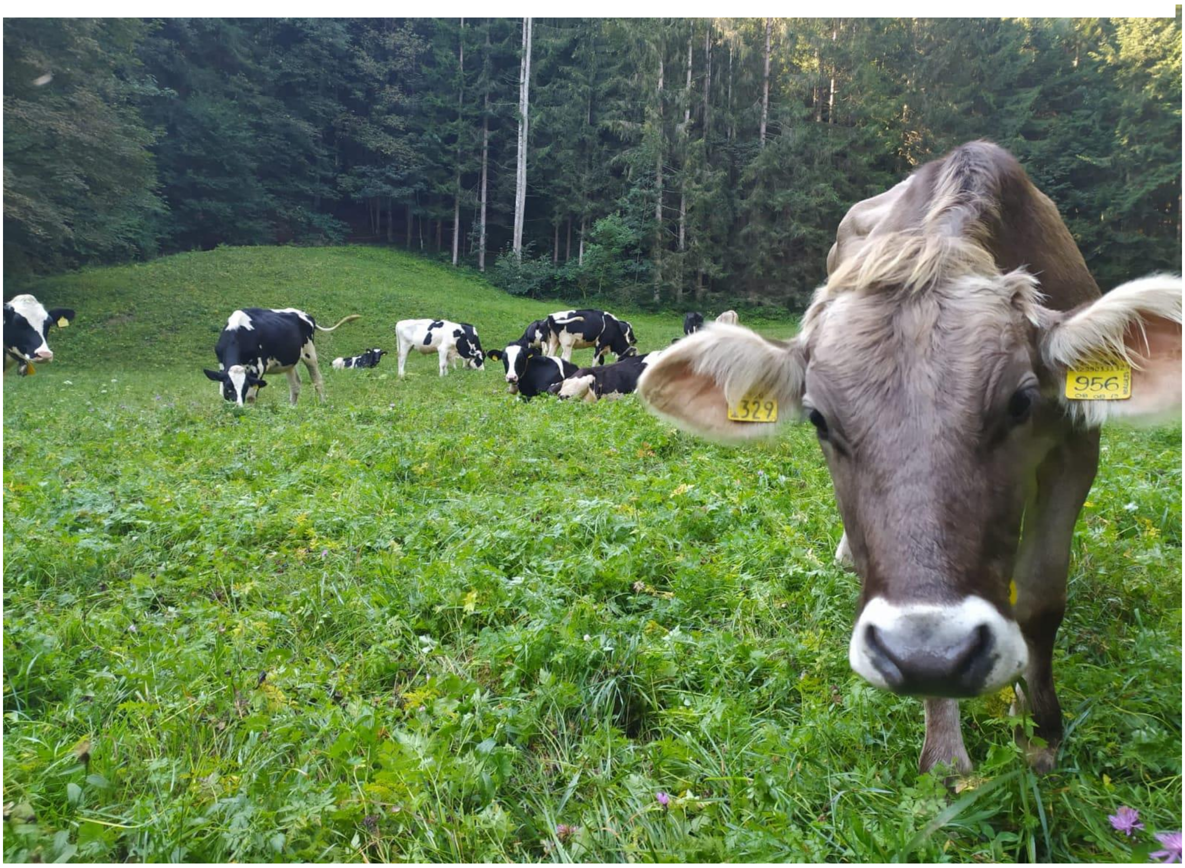

Figure 10. Forest grazing

The total farm extension is of 71 ha, with approximately 10 ha of forest (*Picea abies, Larix decidua, Corylus avellana, Fagus sylvatica*). The UAA is of 58 ha: 42 ha of meadows and pastures, 2 ha of alfalfa, 14 ha of maize for silage (3 ha of which are rotated with winter herbages). Maize fields produce on average 500 q ha^{-1}; meadows present a balanced composition of graminaceous and leguminous species with an average yield of 4 tons DM ha^{-1} $year^{-1}$ (0.84 MFU per kg DM).
The farm is managed by three young brothers (under 40 years old) with a good zootechnical expertise and a good level of internal communication and coordination. Farmers have the willingness to create local networks, actively participate to community life and increase farm sustainability.

- <u>The focus: feeding ration of lactating cows</u>

Lactating cows have an average milk production of 28.4 l cow^{-1} day^{-1} with 4% fat content and 3.6% protein content.
The feeding ration is composed by: 20 kg maize silage, 8.5 kg grass silage (60% DM), 1 kg hay, 2.8 kg maize flour, 2.8 kg flaked corn, 4.8 kg crushed soybean (42% protein), buffer supplementation (0.25kg), $CaCO_3$ 0.2 kg, sodium chloride 0.07 kg, urea88 0.1 kg, mineral supplement 100 gr.
DEXi-INVERSION evaluation of the forage-concentrate ratio and of the protein fodder shows a low level of sustainability (Figure 11).

Indicator 2.2.1 - Feed ration	% forages (dry weight) on the feed ration	% maize silage	% grass silage	
Forage-concentrate ratio in the winter feed ration	36%	26%	19%	
-1	Forage <40%	maize silage > 25%	grass silage < 35%	Low sustainability

Indicator 1.3.5 Protein fodder	% protein from fodder on the feed ration			
Evaluation of protein sources from fodder in the winter feed ration	24%			
-1				Low sustainability

Figure 11. DEXi-INVERSION sustainability assessment of the indicators "Feeding ration" and "Protein fodder"

Regarding the environmental implications of the feeding ration, the farm is self-sufficient in hay, grass silage and silo-maize production. However, maize is mainly cultivated as a monoculture, with no crop rotations. Maize fields are fertilized with slurry and additional nitrogen fertilization. Herbicides are used for weed control. Concentrates are purchased outside the region; relevant environmental implications are related to the use of soybean.

From an economic perspective, feeding concentrates represent 67% of annual expenditures: the estimated cost of the feeding ration is 5.77 Euro cow^{-1} day^{-1}.
Furthermore, the feeding ration influences animal health: acidosis and sub-acidosis, as well as foot problems are diffused among lactating cows.

- <u>Suggestions and implications for a dietary transition towards an "agroecological feeding ration"</u>

The dietary transition foresees a feeding ration for lactating cows with an average production of 25 l cow^{-1} day^{-1} at 4% fat content: the forage/concentrate ratio is increased and the supplementary feeding stuff (soybean included) are substituted with a mixture of crushed cereals.

The transition aims at:

- Restoring the rumen welfare
- Reducing medicine expenditures and unintentional replacement rate
- Increasing animal welfare (although grazing is not introduced)
- Reducing the protein intake while enhancing the synthesis of microbial proteins

A forage-based ration, together with the reduction of soybean, is expected to increase the farm environmental sustainability (permanent soil cover, no chemicals inputs, no or limited transportation). Furthermore, the mixture of crushed cereals is expected to increase cows metabolism (low release of starch); the choice should be oriented on local products to reduce the environmental externalities related to transportation.

To estimate nutritional requirements, the following equations are applied (Antongiovanni et al. 2020):

NE_l (MJ/d) = 3.4 FCM + 0.043 BW + 5.02

where NE_l = net energy requirements for lactating cows (1MJ=238.85 kcal)
FCM= Fat Corrected Milk (theoretical milk quantity at 4% fat content), kg/d
BW=Body Weight, kg

PDI (g/d) = 49.9 FCM + 0.5 BW + 98

where PDI stands for digestible protein.

The estimated nutritional requirements are: 16.57 MFU, 2752 g crude protein (13.7% DM), 20-23 kg DM, which should be met using primarily farm resources (hay, grass silage, maize silage, alfalfa), as presented in Table 9.

Table 9. Suggested feeding ration composition

	% DM	MFU kg^{-1} DM	Crude Protein g kg^{-1} DM	Feed kg tel quel weight	Estimated intake kg DM cow^{-1} day^{-1}	MFU day^{-1}	Crude Protein g day^{-1}
multi-species hay	86	0.67	115	8	6.9	4.6	791.2
ryegrass silage	60	0.77	100	8	4.8	3.7	480
silomaize	35	0.86	86	5	1.8	1.5	150,5
crushed cereals (barley, triticale)	87	1.15	120	2	1.7	2.0	208.8
proteic pea	87	1.15	200	3	2.6	3.0	522
dehydrated alfalfa	91,6	0.7	16	5	4.6	3.2	73.28
soybean	89	1.25	420	1.5	1.3	1.7	560.7
					22.36	18.02	2786.48

Sources: Cappa 1991; Antongiovanni et al. 2020; Pisseri & Barberi 2021. Own data elaboration.

The dietary transition suggests a gradual reduction of silomaize in the order of 2 kg per month along 7 months, for a total of 15 kg. The monitoring of BCS, faeces, urea production, milk fat content, hay quality is recommended.

In order to meet the dietary transition with farm resources, hay production should be increased. Maize fields could be partially converted to permanent meadows, with an estimated saving of 300 Euro ha^{-1} associated to agrochemical inputs (Carlesi et al. 2021); however, one year of transition would be necessary due to weed infestations related to maize monoculture.
In order to increase the feeding ration of 6 kg DM hay for 72 lactating cows, the farm would need 130 t DM $year^{-1}$ (considering a lactation period of 305 days). With an average yield of 6 t DM $year^{-1}$ of hay (Scotton et al. 2012), the farm should increase of 21.6 ha of hay meadows: 6.5 ha of maize fields could be converted to permanent grassland with an estimated hay production of 39 t DM/year, but still 90 t hay should be purchased.

The estimated cost of the suggested feeding ration is 4.60 Euro cow^{-1} day^{-1}: the farmer saves 1.17 Euro cow^{-1} day^{-1} but loses 1.26 Euro cow^{-1} day^{-1} due to the reduced production (less 3l milk per cow at 0.42 cents). Savings related to improved animal health, improved environmental and ethical sustainability are not considered.

- <u>Other suggestions to improve farm sustainability</u>

- Implementation of rotational grazing of lactating cows in pastures closed to the barn during the summer period, if all heifers and dry cows are sent to mountain pastures;
- Creation of an outdoor yard would increase the possibility of movement of the herd during the winter season;
- Postpone the insemination of heifers to reach an optimal weight;
- Coverage of the slurry tank;
- Increase animal biodiversity, at least in mountain pastures;
- Rest periods and crop rotation for arable lands;
- Increase pasture surfaces;
- Sanitary prevention;
- Increase rusticity in the herd.

As a final consideration, the farm should reduce the number of animals in relation to the farm extension, in order to increase animal welfare and hay availability per cow. However, reducing the herd would imply a diversification of farm activities to maintain an economic sustainability.

3.1.3. DEXi-INVERSION as a tool for monitoring the farm evolution in time

Farm 3 has been assessed for two consecutive years: 2020 (in March 2021) and 2019 (in January 2020). The 2019 assessment was conducted within the framework of INVERSION project, while the 2020 evaluation is based on an assisted self-assessment.

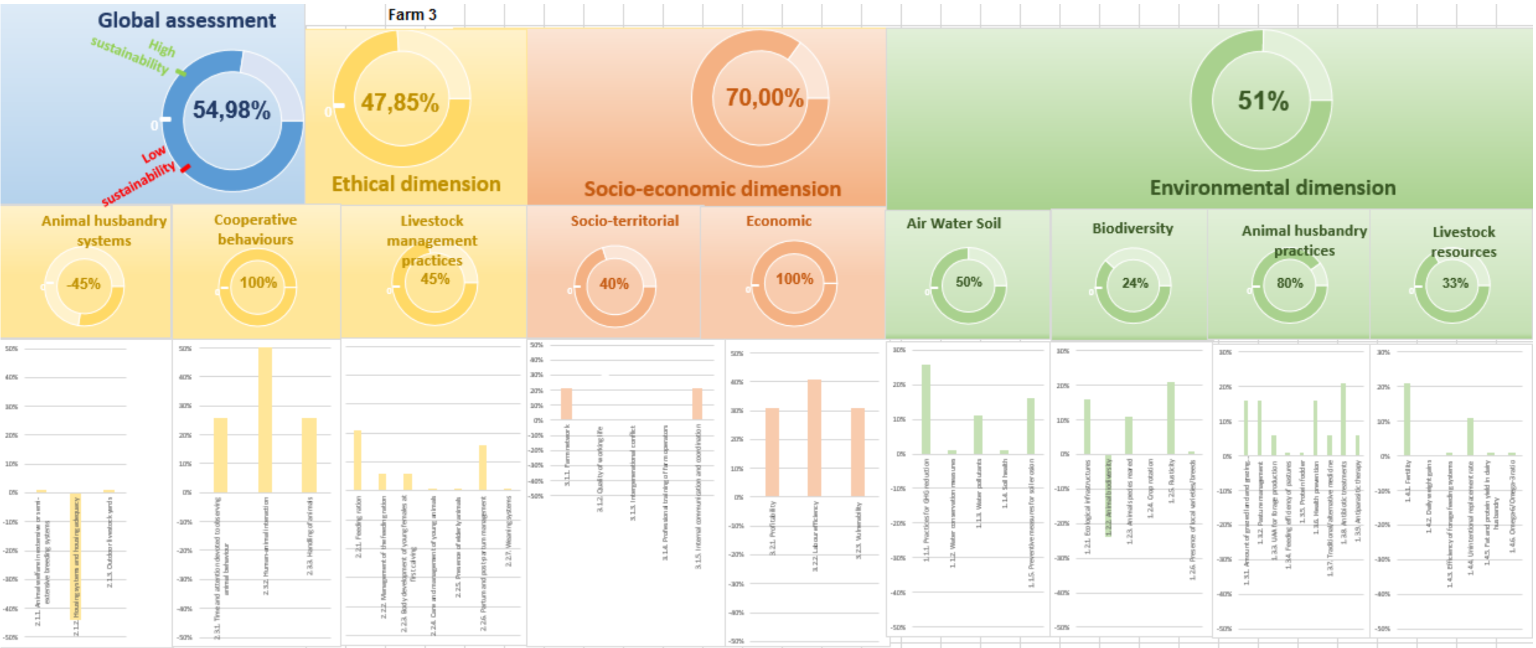

Figure 12. Farm 3: sustainability assessment of the year 2020 (own data elaboration with DEXi-INVERSION.xlsx)

Figure 13. Farm 3: sustainability assessment of the year 2019 (data elaboration with DEXi-INVERSION.xlsx)

Figure 12 and 13 show the graphical representation of the sustainability assessment respectively for the years 2020 and 2019, produced with DEXi-INVERSION Excel spreadsheet. The "Comparison of options" report (Figure 14) elaborated with DEXi software, allows an in-depth analysis at the indicator level, as it highlights major variations occurred between the two years of assessment.

DEXi DEXi_INVERSION_Farm3_2years comparison.dxi 10/10/2021

Comparison of options

Attribute	Farm 3_2020	farm 3_2019
DEXi_INVERSION.beta	20; 30	20
1.Environmental dimension	30; *40*	30
sub_ambiente_1	10; *20*	10
1.1. Component air-water-soil	*50*	
1.1.1. GHG reduction	*+1*	
1.1.2. Water conservation measures	0	
1.1.3. Water pollutants	*+1*	
1.1.4. Soil health	0	
1.1.5. Preventive measures for soil erosion	*+1*	
1.2. Component biodiversity	0; 20; *40*	0; 10; 20
1.2.1. Ecological infrastructures	*+1*	0
1.2.2. Animal biodiversity	-1	
1.2.3. Animal species reared	*+1*	0
1.2.4. Crop rotation	*	
1.2.5. Rusticity	*+1*	
1.2.6. Presence of local varietes/breeds	0	*+1*
sub_ambiente_2	20	
1.3. Component animal husbandry practices	*100*	*90*
pratiche 1	*55*	
1.3.1. Amount of grazed land and grazing time	*+1*	
1.3.2. Pasture management	*+1*	
1.3.3. UAA for forage production	*+1*	0
1.3.4. Feeding efficiency of pastures	0	*+1*
1.3.5. Protein fodder	0	*+1*
pratiche 2	*45*	*30*
1.3.6. Heath prevention	*+1*	
1.3.7. Traditional/alternative medicine	*+1*	
1.3.8. Antibiotics treatments	*+1*	0
1.3.9. Antiparasitic therapy	*+1*	
1.4. Component livestock resources	20; 30; *40*	*40*; *50*; *60*
risorse1	10; *20*; *30*	
1.4.1. Fertility	*+1*	
1.4.2. Daily weight gains	*	
1.4.3. Efficiency of forage feeding systems	0	
risorse2	10	*30*
1.4.4. Unintentional replacement rate	*+1*	
1.4.5. Fat and protein yield in dairy husbandry	0	*+1*
1.4.6. Omega-6/Omega-3 ratio	0	
2. Ethical dimension	-20	
sub_Etica1	*50*	
2.1. Component animal husbandry systems	-40	-60
2.1.1. Animal welfare in extensive or semi-extensive breeding systems	0	
2.1.2. Housing systems and housing adequacy	-1	
2.1.3. Livestock outdoor yard	0	-1
2.3. Component cooperative behaviours	*100*	
2.3.1. Time and attention devoted to observing animal behaviour	*+1*	
2.3.2. Human-animal interaction	*+1*	
2.3.3. Handling of animals	*+1*	
2.2. Component livestock management practices	*40*	*60*
gestione 1	*30*	*20*
2.2.1. Feeding ration	*+1*	
2.2.2. Management of the feeding ration	*+1*	
2.2.3. Body development of young females at first calving	*+1*	0
gestione 2	10	*40*
2.2.4. Care and management of young animals	0	*+1*
2.2.5. Presence of elderly animals	0	*+1*
2.2.6. Partum and post-partum management	*+1*	
2.2.7. Weaning systems	0	
3. Socio-economic dimension	*60*	
3.1. Component socio-territorial	*40*	*50*
3.1.1. Farm network	*+1*	
3.1.2. Quality of working life	0	*+1*
3.1.3. Intergenerational conflict	0	
3.1.4. Professional training of farm operators	0	
3.1.5. Internal communication and coordination	*+1*	0
3.2. Economic component	*100*	*70*
3.2.1. Profitability	*+1*	0
3.2.2. Labour efficiency	*+1*	
3.2.3. Vulnerability	*+1*	

Figure 14. "Comparison of options" report (data elaboration with DEXi software)

Globally, the farm performance confirms its high sustainability, with a slighter reduction in 2020 (-0.93%). A major improvement is registered within the socio-economic dimension (+10%), mainly due to a positive economic performance registered by the indicator "Profitability" (3.2.1). Basically, the farm has increased its Value Added (VA) per unit of utilized area diversifying its activities. The worsening of the perceived quality of working life (3.1.2) has been almost offset by improvements in the internal communication and coordination (3.1.5).
From an ethical perspective, the farm is still weak in terms of housing system: a traditional tie-barn is still present, however a new compost barn for horned animals is at the design phase. In the meanwhile, the farmer has realized an outdoor yard closed to the barn: dairy cows are moved into the yard after the morning milking procedure when weather conditions are favorable, where they can stay until the evening milking. The outdoor yard allows to increase animal welfare during the winter season, and at the same it reduces the time spent by the farmer in the cleaning of the barn.
The farmer has increased the attention towards heifer's bodyweight at first calving, with benefits in terms of subsequent fertility, longevity and productivity. The worsening of indicator scores concerning the care of young animals (2.2.4) and the presence of elderly animals (2.2.5) is mainly due, respectively, to the non-availability of frozen colostrum and to the entrance of new young dairy cows in the herd.
From an environmental point of view, the farm shows a stable trend within the two years of assessment, confirming its high sustainability range. Variations within the Component "Biodiversity" could be due to shortcomings in the first collective assessment procedure, as the farm has not changed animal species nor the practices related to multi-species grazing: Original Brown and Rendena breeds are still the protagonists of the farm, with laying hens sharing the pastures closed to the barn in spring and autumn; pigs descending from summer pastures are reared in a maize field after the harvesting. A slight improvement is registered for the sustainability of the Component "Animal husbandry practices", with a reduced use of antibiotics (1.3.8) and an increase in the UAA for forage production (1.3.3). However, the feeding efficiency of pastures (1.3.4) and the satisfaction of protein requirements by the forage feeding ration (1.3.5) have worsened: micro-climatic conditions have influenced grassland productivity of high mountain pastures (Figure 15), increasing the need to integrate grazing with supplementary feedingstuffs. Weather conditions have also probably also influenced hay protein content, due to the delay of mowing activities after the optimal phase (between inflorescence emergence and anthesis) (Gusmeroli 2004).

Figure 15. Dairy cows in mountain alpine pastures

3.2. DEXi-INVERSION as a tool to compare farms' sustainability performances

In this section, the comparison of farms' sustainability performances is illustrated. Firstly, the global sustainability of the five dairy farms in the Autonomous Province of Trento is compared; secondly, sustainability performances of Trentino and Veneto farms are analyzed for the environmental and ethical dimension, highlighting similarities and differences. The socio-economic dimension has been excluded from the comparative analysis as the economic component was assessed only for one Veneto farm; other economic indicators have been introduced in the Veneto region with the aim of monitoring the agroecological practices implemented (Chapter 5.4.).

3.2.1. Comparison of sustainability performances of Trentino dairy farms

The "Option" sheet of DEXi software summarizes the scores for each sustainability indicator for the five Trentino farms (Figure 16), highlighting with different colors (green, black, red) the high, intermediate or low sustainability.

Option	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
1.1.1. GHG reduction	+1	+1	+1	+1	0
1.1.2. Water conservation measures	0	0	0	0	-1
1.1.3. Water pollutants	+1	0	+1	+1	-1
1.1.4. Soil health	0	*	0	*	+1
1.1.5. Preventive measures for soil erosion, soil cover	+1	+1	+1	+1	+1
1.2.1. Ecological infrastructures	+1	0	+1	*	+1
1.2.2. Animal biodiversity	-1	-1	-1	-1	-1
1.2.3. Animal species reared	-1	-1	+1	-1	-1
1.2.4. Crop rotation	*	-1	*	*	-1
1.2.5. Rusticity	+1	-1	+1	-1	-1
1.2.6. Presence of local varietes/breeds	-1	0	0	-1	-1
1.3.1. Amount of grazed land and grazing time	+1	-1	+1	*	-1
1.3.2. Pasture management	0	*	+1	*	0
1.3.3. UAA for fodder production	+1	*	+1	+1	-1
1.3.4. Feeding efficiency of pastures	+1	+1	0	*	*
1.3.5. Protein fodder	0	*	0	+1	0
1.3.6. Health prevention	0	0	+1	0	0
1.3.7. Traditional/alternative medicine	0	0	+1	-1	0
1.3.8. Antibiotic treatments	+1	-1	+1	-1	-1
1.3.9. Antiparasitic therapy	0	0	+1	+1	+1
1.4.1. Fertility	+1	+1	+1	0	0
1.4.2. Daily weight gain	*	0	*	*	+1
1.4.3. Efficiency of forage feeding system	+1	+1	0	0	0
1.4.4. Unintentional replacement rate	+1	-1	+1	+1	-1
1.4.5. Fat and protein yield in dairy husbandry	0	+1	0	+1	+1
1.4.6. Omega-6/Omega-3 ratio	*	*	0	*	*

Figure 16. Screenshot of the "Option" sheet of DEXi software summarizing the scores of the five Trentino farms for the environmental indicators

The "Evaluation" sheet (Figure 17) includes the scores of indicators, components and dimensions, as computed by the system according to the weighting criteria (see Chapter 5.1.4. Method development). As in the "Option" sheet, colors are used to represent the different sustainability thresholds. In the case one or more indicators haven't been assessed, a range of values is shown for components and dimensions, which considers all possible option values for the indicators not evaluated.

Model | Options | Evaluation | Charts

+1

Option	Farm 1	Farm 2	Farm 3	Farm 4	Farm 5
. DEXi_INVERSION.beta	20;30;40	-40;-30;-20;	20;30	-50;-40;-30;	-30;-20;-10;
.. 1.Environmental dimension	10;20;30;50;	-50;-40;-30;	30;40	-70;-60;-50;	-60;-50;-40
... sub_ambiente_1	0;10	-10;0	10;20	-20;-10;0;10	-10
.... 1.1. Component air, water, soil	50	20;40;60	50	20;50;80	0
..... 1.1.1. GHG reduction	+1	+1	+1	+1	0
..... 1.1.2. Water conservation measures	0	0	0	0	-1
..... 1.1.3. Water pollutants	+1	0	+1	+1	-1
..... 1.1.4. Soil health	0	*	0	*	+1
..... 1.1.5. Preventive measures for soil erosion, soil cover	+1	+1	+1	+1	+1
.... 1.2. Component biodiversity	-30;-20;0	-70	0;20;40	-100;-90;-7(	-70
..... 1.2.1. Ecological infrastructures	+1	0	+1	*	+1
..... 1.2.2. Animal biodiversity	-1	-1	-1	-1	-1
..... 1.2.3. Animal species reared	-1	-1	+1	-1	-1
..... 1.2.4. Crop rotation	*	-1	*	*	-1
..... 1.2.5. Rusticity	+1	-1	+1	-1	-1
..... 1.2.6. Presence of local varietes/breeds	-1	0	0	-1	-1
... sub_ambiente_2	10;20;50	-40;-30;-20;	20	-50;-40;-30;	-50;-40;-30
.... 1.3. Component animal husbandry practices	90	-60;-50;-40;	100	-20;-10;0;10	-20;-10
..... pratiche 1	55	-45;-40;-30;	55	0;10;20;30;4	-20;-10;0
...... 1.3.1. Amount of grazed land and grazing time	+1	-1	+1	*	-1
...... 1.3.2. Pasture management	0	*	+1	*	0
...... 1.3.3. UAA for fodder production	+1	*	+1	+1	-1
...... 1.3.4. Feeding efficiency of pastures	+1	+1	0	*	*
...... 1.3.5. Protein fodder	0	*	0	+1	0
..... pratiche 2	30	-30	45	-30	-20
...... 1.3.6. Health prevention	0	0	+1	0	0
...... 1.3.7. Traditional/alternative medicine	0	0	+1	-1	0
...... 1.3.8. Antibiotic treatments	+1	-1	+1	-1	-1
...... 1.3.9. Antiparasitic therapy	0	0	+1	+1	+1
.... 1.4. Component livestock resources	20;30;40;50;	30;50;70	20;30;40	0;10;20;30;4	0;20;40
..... risorse1	30;40;50	40	10;20;30	-10;0;10	10
...... 1.4.1. Fertility	+1	+1	+1	0	0
...... 1.4.2. Daily weight gain	*	0	*	*	+1
...... 1.4.3. Efficiency of forage feeding system	+1	+1	0	0	0
..... risorse2	-10;10;30	-10;10;30	10	10;30;50	-10;10;30
...... 1.4.4. Unintentional replacement rate	+1	-1	+1	+1	-1

Figure 17. Screenshot of the "Evaluation" sheet of DEXi software with sustainability scores and value ranges for some indicators and components of the environmental dimension

The icon "Selective explanation" produces a report highlighting the weak points (-1 or #) for each farm assessed, as shown in Figure 18.

Weak points

Attribute	Farm 1
1.2.2. Animal biodiversity	-1
1.2.3. Animal species reared	-1
1.2.4. Crop rotation	*
1.2.6. Presence of local varietes/breeds	-1
1.4.2. Daily weight gain	*
1.4.6. Omega-6/Omega-3 ratio	*
2.2.7. Weaning systems	-1
3.1.3. Intergenerational conflict	*
3.1.4. Professional training of farm operators	*
3.2.1. Profitability	-1

Figure 18. "Selective explanation" report of DEXi software highlighting the weak points: for Farm 1

Finally, the graphical representation of sustainability performances is realized with the "Chart" sheet of DEXi software. A radar chart is obtained when at least three parameters per farm are selected (Figure 19). However, a range of values is shown for those dimensions where one or more indicators haven't been assessed, making it harder to clearly understand the results of the assessment.
A smarter graphical representation of the sustainability results can be performed using the Excel spreadsheet DEXi-INVERSION.xlsx as shown previously, however it doesn't allow to produce a unique portrayal for more farms.

The radar charts (Figure 19) as well as the bar chart (Figure 20) and the summary table (Table 10), those latter produced with Microsoft Excel, highlight that Farm 3 has the highest global, environmental and socio-economic sustainability, with respective scores of +55%, +51% and +70%. Farm 1 and Farm 3 are both highly sustainable, with Farm 3 showing the highest score for the ethical dimension (+51%). Farm 2, Farm 4 and Farm 5 are mildly sustainable, and Farm 5 shows the worst global performance (-3%), with the lowest scores for the three dimensions.

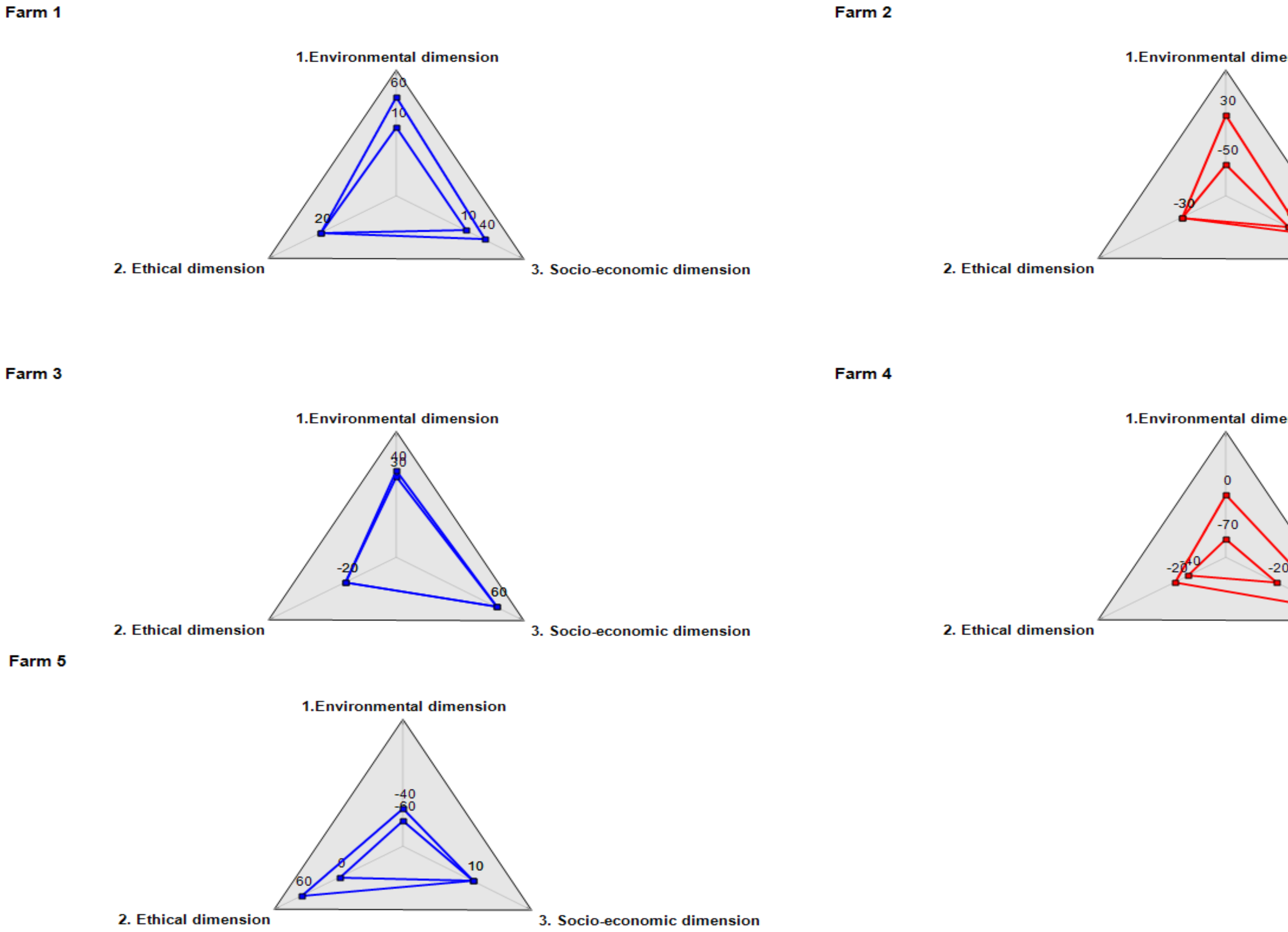

Figure 19. Radar charts representing the sustainability performances of the five farms using the DEXi software

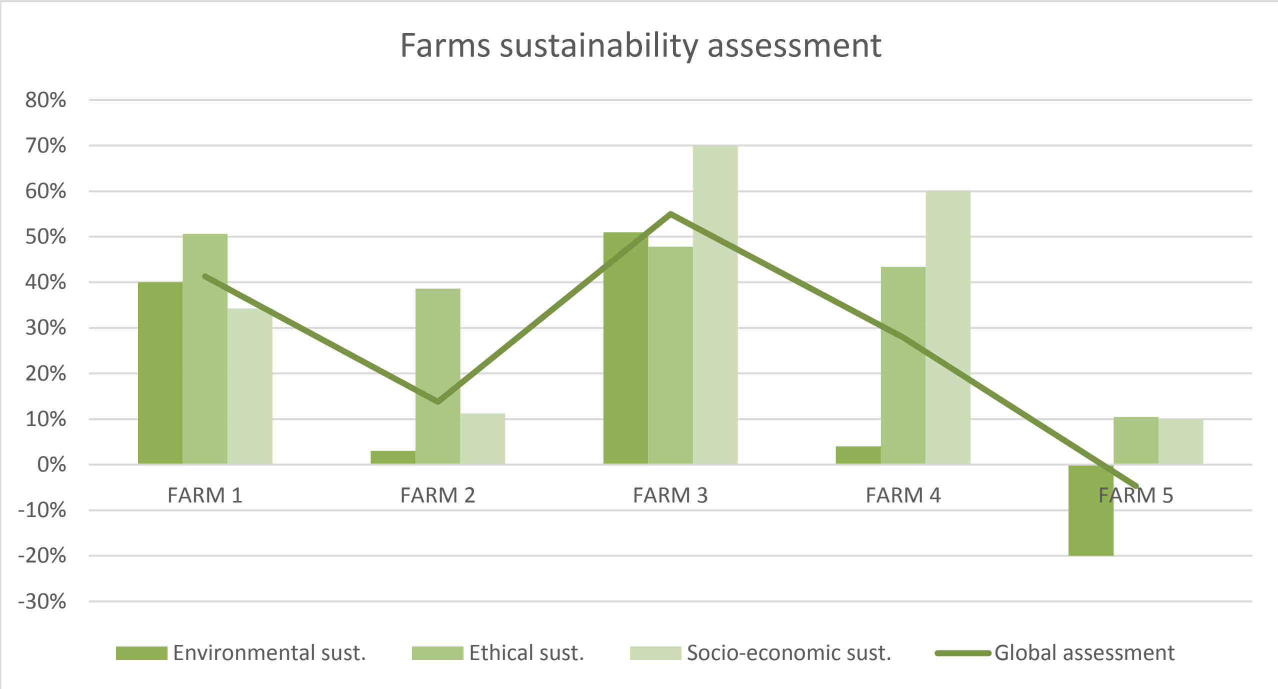

Figure 20. Combination chart representing Trentino farms sustainability scores (elaboration with Microsoft Excel)

Table 10. Sustainability assessment scores per farm, mean and standard deviation of the sample

	FARM 1	FARM 2	FARM 3	FARM 4	FARM 5	Mean	SD*
Global sustainability	41%	14%	55%	28%	-5%	0,26634	0,232773
Environmental sust.	40%	3%	51%	4%	-20%	0,156	0,291942
Ethical sust.	51%	39%	48%	43%	11%	0,38212	0,161459
Socio-economic sust.	34%	11%	70%	60%	10%	0,37108	0,274652

*SD= Standard Deviation

In order to contextualize the sustainability performances, farms characteristics have been reported (Table 11). It emerges clearly that the highest sustainability is observed in small dairy farms with less than 13 adult cows of local breeds at risk of extinction, which bring animals to high mountain pastures, perform cheese production in alpine summer farms and direct sell their products. Another interesting aspect is that both Trentino farms (1 and 3) are managed by first generation farmers, which probably gives a higher freedom in recovering elements of the tradition without distress coming from intergenerational conflicts, and "marketing" them through the direct sale of products. A lower sustainability seems to be associated with the rearing of less rustic breeds, the abandonment of the traditional summer grazing of lactating cows and the belonging to a second generation of farmers. In many cases, this latter aspect acts as a brake on innovation, limiting young farmers in boosting farm sustainability. However, due to the limited number of farms assessed, these considerations cannot be broadly generalized.

Table 11. Matching of sustainability assessment scores with some farms' features

Global sustainability score	Trentino Farm	Herd size	Cattle breeds	Management system	Farm activities	On-farm human resources
55%	3	12	Original Brown and Rendena	Summer grazing in alpine pastures	direct sale	1st generation farmer
42%	1	10	Alpine Grey	summer grazing in alpine pastures	direct sale	1st generation farmer
25%	4	7	Alpine Brown	Loose housing system, summer grazing of few animals	direct sale	2nd generation farmers
14%	2	90	Friesian, Alpine Brown	Loose housing system, summer grazing of young cattle	cooperative system	2nd generation farmers
-3%	5	166	Friesian, Simmental	Permanent loose housing system, summer grazing of young cattle	cooperative system	2nd generation farmer

3.2.2. Comparative analysis of the environmental and ethical sustainability of Trentino and Veneto farms

DEXi-INVERSION allows to compare farm sustainability even within a sample of diversified livestock production systems, with different degrees of intensification and multifunctionality. The environmental sustainability of Trentino and Veneto farms is represented in Figure 21, while Table 12 summarizes the main descriptive data related to the boxplots.
It clearly emerges that Veneto farms are more sustainable from an environmental perspective: the average score is of +30% (Median=0.3), against the 3% (Median=0.03) achieved by Trentino farms. Nevertheless, there is a higher variability between the environmental performances of farms located in Trentino, while a more homogeneous situation is found in Veneto.
Considering the ethical dimension (Figure 22), the reverse situation is observed: Trentino farms show a better performance (43%), but with only 10 percentage points higher than Veneto farms. A more homogeneous scenario is detected in Trentino despite the presence of an outlier; a higher variability is found in the ethical performances of Veneto farms, which oscillates between a minimum score of 23% and a maximum of 83% (Table 12).

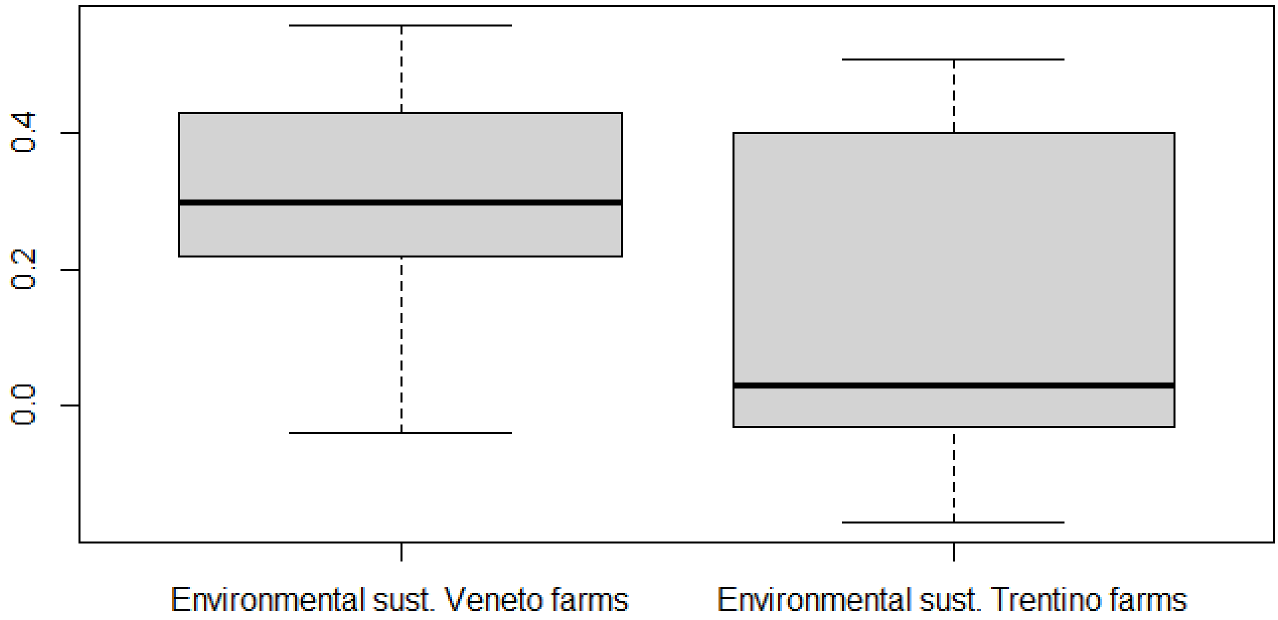

Figure 21. Boxplots of the environmental sustainability performances in Trentino and Veneto farms

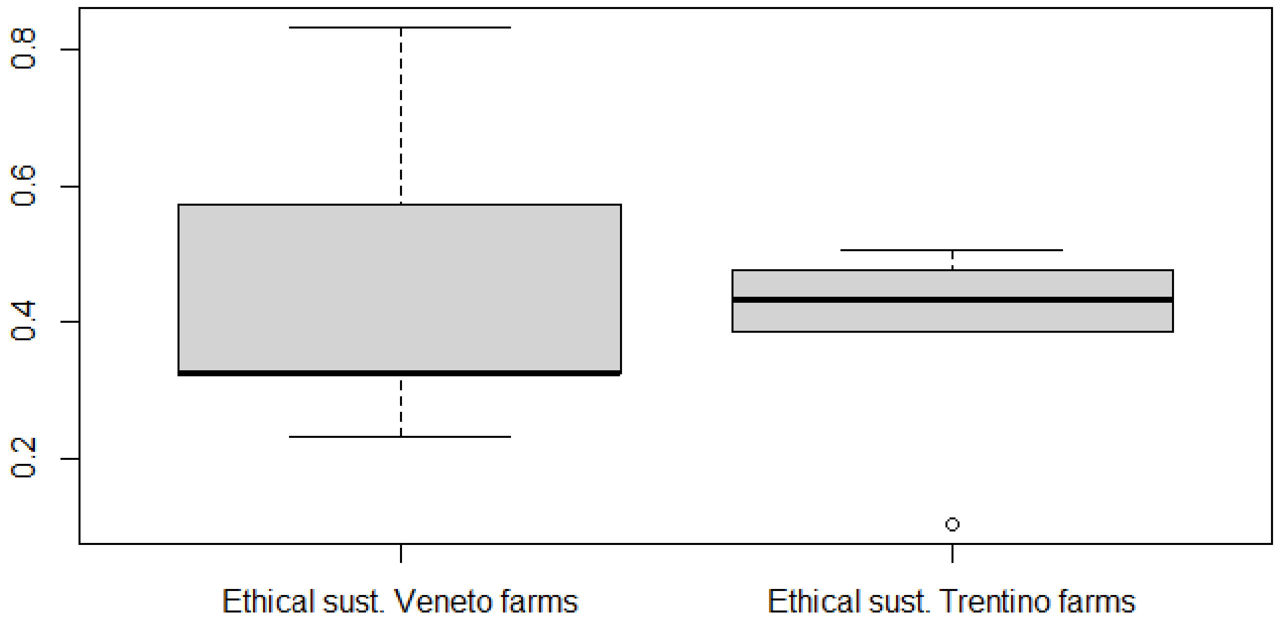

Figure 22. Boxplots of the ethical sustainability performances in Trentino and Veneto farms

Table 12. Descriptive statistical data related to the boxplots on environmental and ethical sustainability

	Environmental sust. boxplots		Ethical sust. boxplots	
	Trentino farms	Veneto farms	Trentino farms	Veneto farms
Min.	-0.170	-0.040	0.105	0.232
1st Qu.	-0.030	0.221	0.386	0.325
Median	0.030	0.300	0.434	0.325
Mean	0.148	0.302	0.382	0.455
3rd Qu.	0.400	0.430	0.478	0.572
Max.	0.510	0.558	0.506	0.832

Going deeply into the environmental dimension, we can observe that both Veneto and Trentino farms are on average highly sustainable for the component "Air water soil" (Figure 23), however performances are largely heterogeneous within Veneto farms, oscillating from -20% to +75%. In Trentino, 3 farms show a similar score, while two are outliers. The lower average value of Veneto farms could be partially attributed to the adoption of different sustainability thresholds for the indicator "GHG emissions": farmers in Veneto applied more restrictive conditions to reach the medium and high level of sustainability.

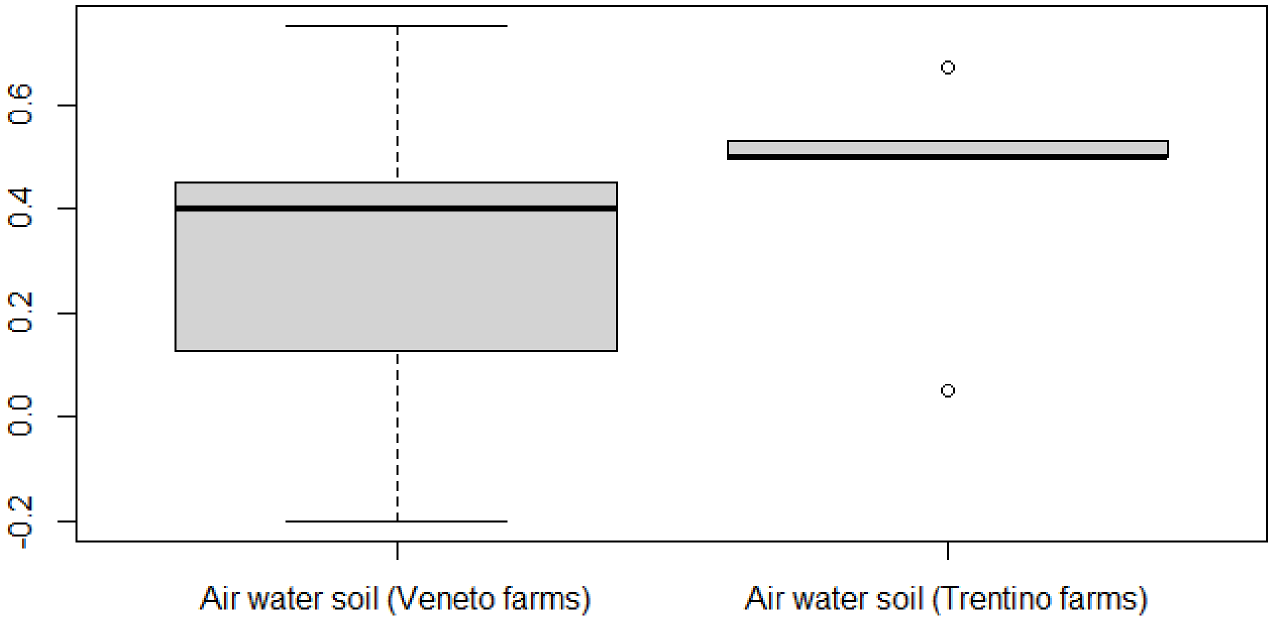

Figure 23. Farms sustainability performances for the component "Air water soil"

A major difference is detected within the component "Biodiversity" (Figure 24), where Veneto farms are mildly sustainable (-5%), while Trentino farms fall in the low sustainability range (-65%). Although a higher heterogeneity can be observed at the landscape level in Trentino farms, which are all located in a mountainous area with a mosaic of different land uses, mostly all farms rear only dairy cows, with no simultaneous presence of different animal species on the same surface and/or alternance of animals with agricultural crops; only 2 farms pay attention to local breeds. The choice of some farmers to rear highly productive breeds is then reflected in a lack of rusticity. Whether maize is cultivated, no crop rotation is performed.

In Veneto, most of the farmers rear more than one animal species, the character of rusticity is considered very relevant and generally more important than breeding and/or cultivating local breeds and/or plant varieties. However, as in Trentino, multispecies grazing systems and the alternance of animals and agricultural crops are not practiced. A 2-year crop rotation is performed, however there is a lack of ecological infrastructures in farms located in the plain.

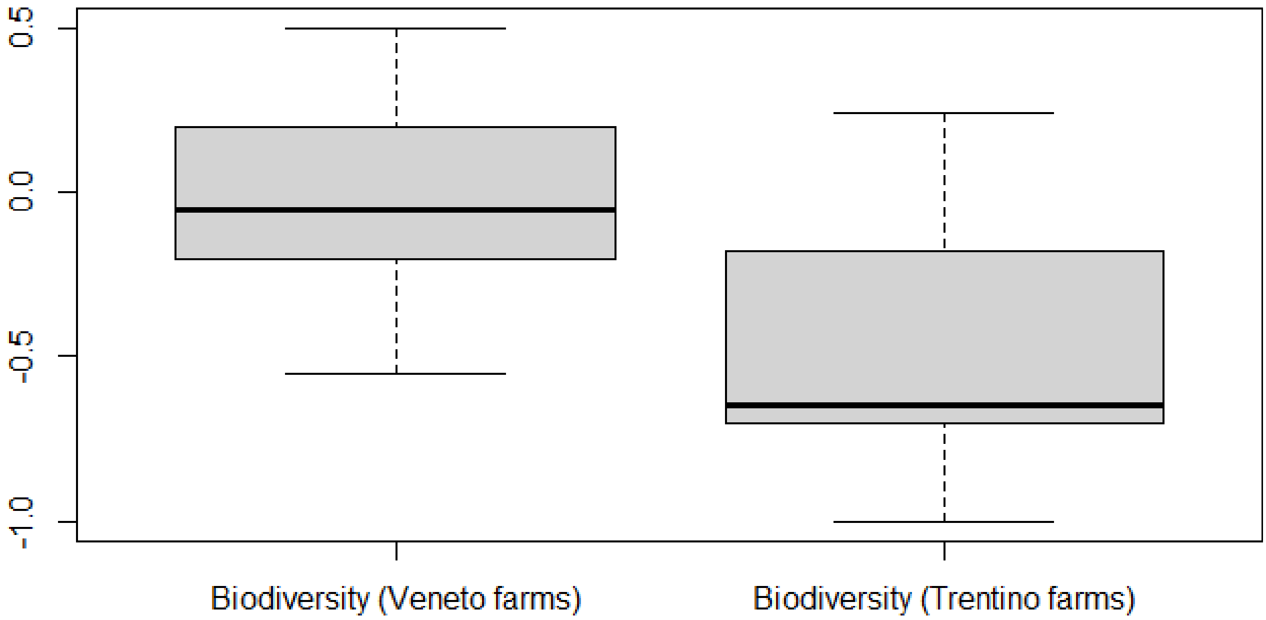

Figure 24. Farms sustainability performances for the component "Biodiversity"

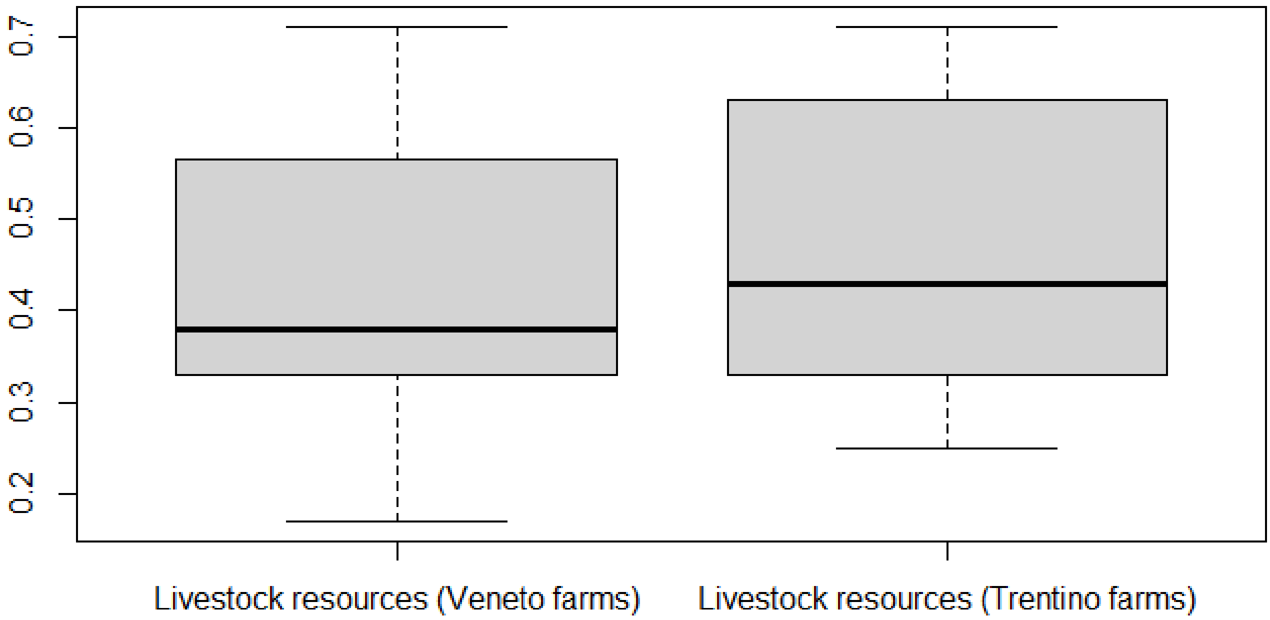

Figure 25. Farms sustainability performances for the component "Livestock resources"

While no significant differences are observed for the component "Livestock resources" (Figure 25), except for a higher variability within Trentino farms performances, a major discrepancy is detected within the component "Animal husbandry practices" (Figure 26).
On average, Veneto farms show a high sustainability performance (median=0.43), while Trentino farms are mildly sustainable (median=0.00), with a higher heterogeneity, as component scores range from -37% to 80%. A greater variability is particularly noticeable in the use and management of pastures and its feeding efficiency: as a matter of fact, grazing is not even practiced in some farms, or at least not for lactating cows. In Veneto, a minimum of one group of animals (e.g. suckler cows, fattening calves, lactating cows) is

reared on pastures for at least 4 months per year. Health prevention practices are more applied in Veneto farms, where the use of antibiotic treatments is generally low regardless the degree of intensification of the livestock production system.

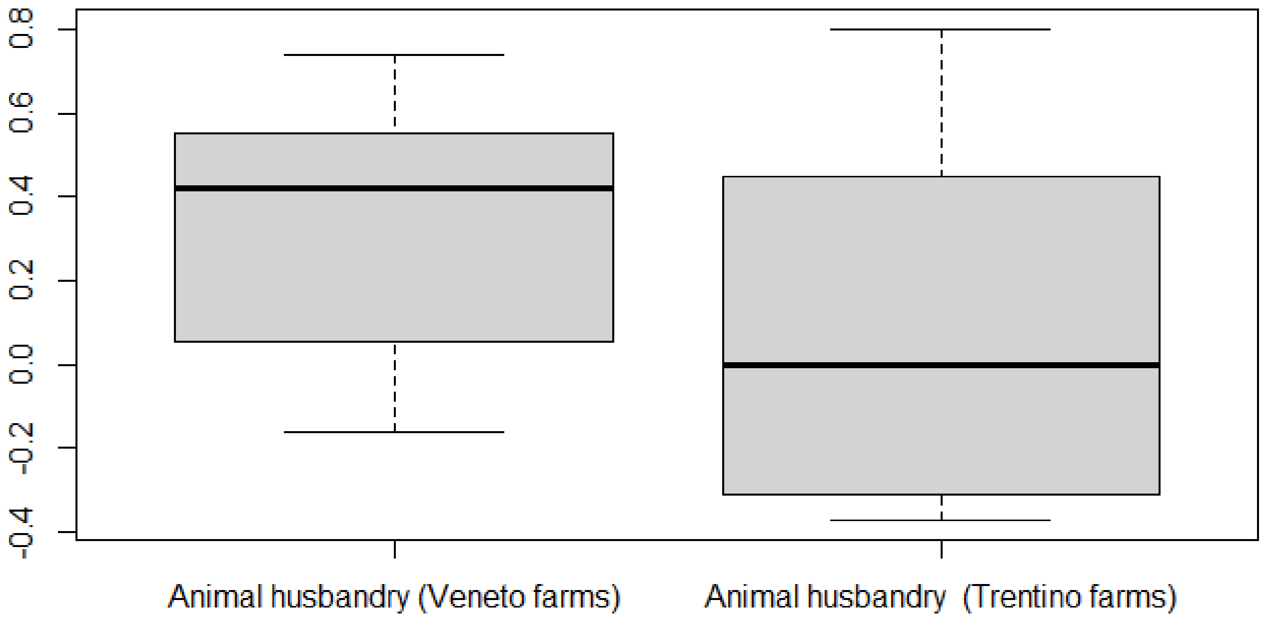

Figure 26. Farms sustainability performances for the component "Animal husbandry practices"

Within the ethical dimension, no differences are observed in the sustainability performance for the component "Livestock management practices" (Figure 27) concerning the feeding ration, the care and management of the different groups of animals (e.g. young animals, heifers) and the weaning system.
Differently, the housing systems as well as the adequacy of rearing conditions in extensive and semi-extensive systems (Component "Animal husbandry systems") appear to be more adequate in Veneto farms (Figure 28).

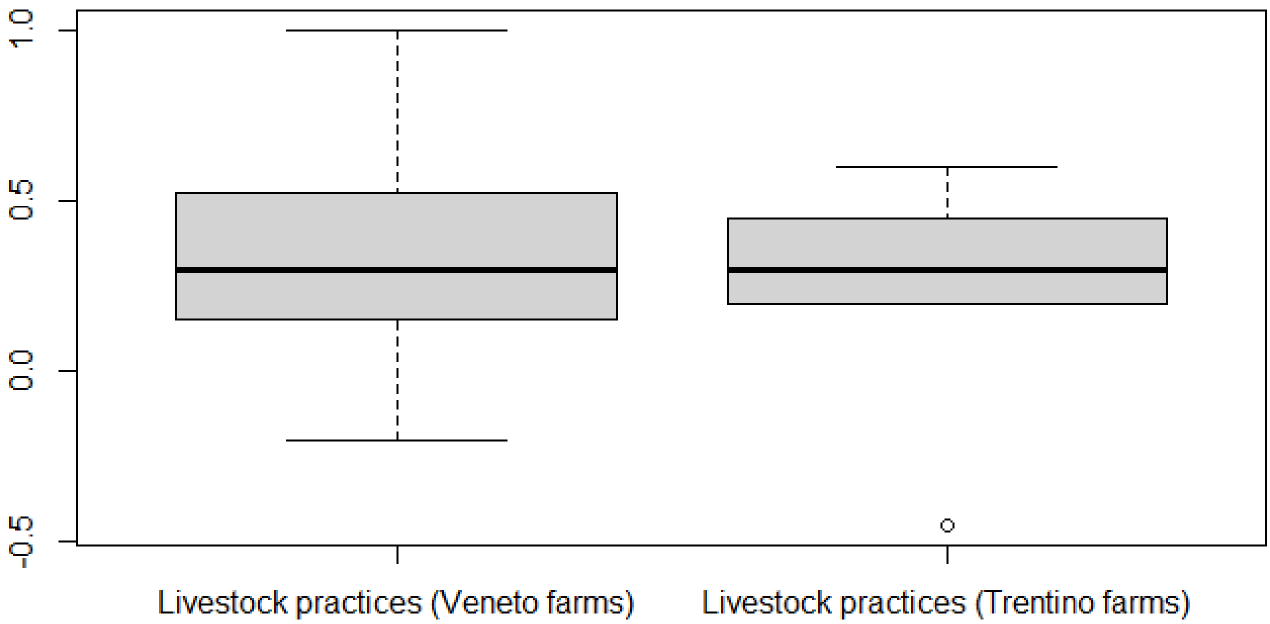

Figure 27. Farms sustainability performances for the component "Livestock management practices"

Finally, Trentino farmers appear to be homogeneously more careful about the interaction with animals, that is synthetically described by the component "Cooperative behaviors" (Figure 29). This could be explained by an increase in awareness of sampled farmers, who directly or indirectly took part to some activities of the INVERSION project before the sustainability assessment. Despite a high sustainability level also registered in Veneto farms, a higher heterogeneity is observed.

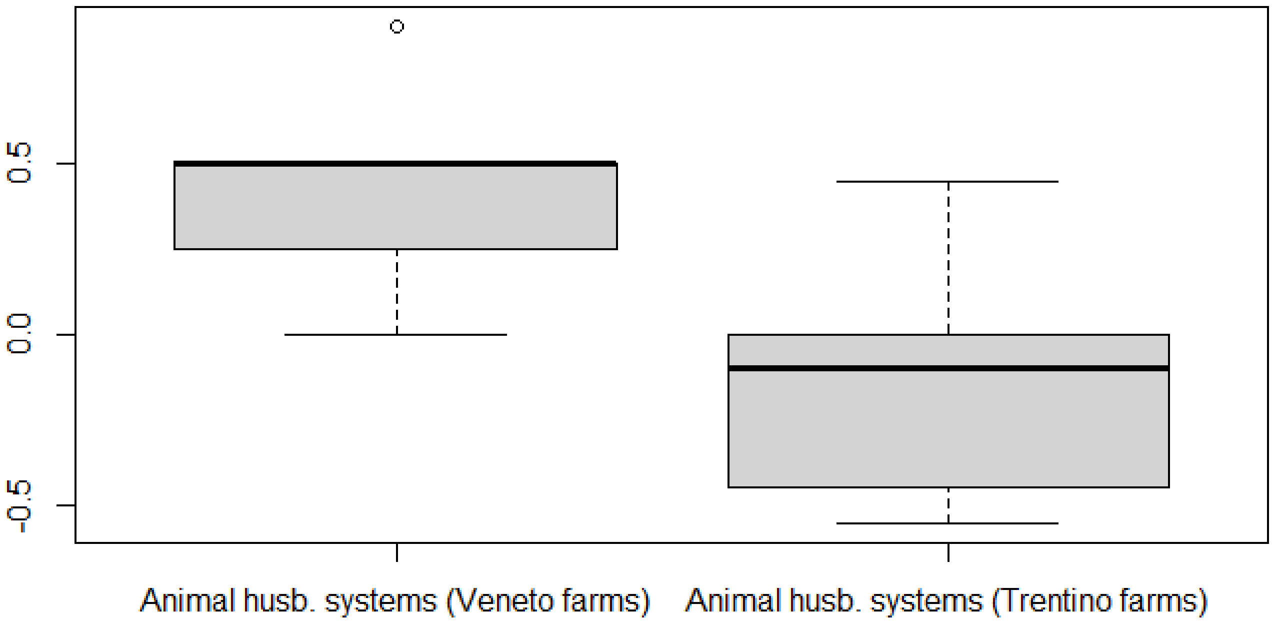

Figure 28. Farms sustainability performances for the component "Animal husbandry systems"

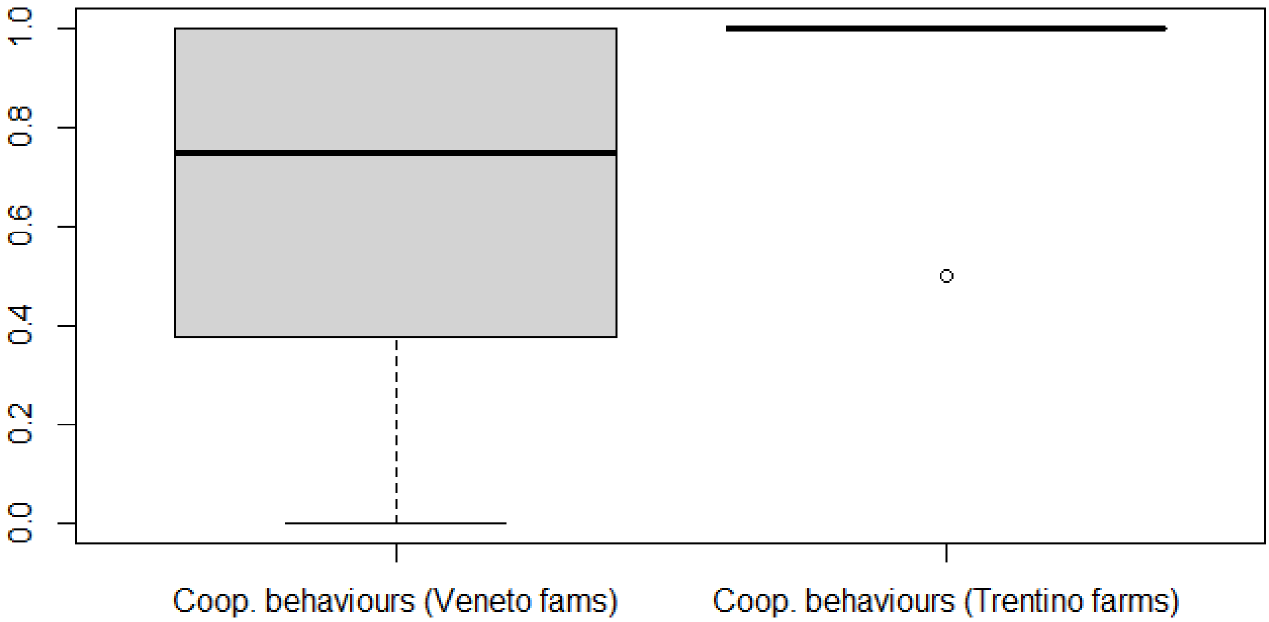

Figure 29. Farms sustainability performances for the component "Cooperative behaviors"

3.3. Participatory process for tool acceptance and applicability

In the Veneto region, the DEXi-INVERSION set of indicators has been discussed with farmers being part of the project launched by Veneto Agricoltura, with the aim of fostering the tool acceptance and applicability.

Four Focus Groups were organized and conducted by the technical consultant commissioned by the institution and the author, three on an online platform due to Covid-19 crisis and one in presence, to discuss on indicators and thresholds of the environmental, ethical and socio-economic dimension. Aim of the sessions was to reach a general consensus before applying the tool for farms sustainability assessment.

The first Focus Group was an introductory meeting focused on sustainability in livestock systems, and it was aimed at introducing the concept of sustainability and its declination into extensive and intensive livestock systems and stimulating reflections and debates. As highlighted by Gamborg & Sandoe 2005, sustainability is not a single, easy measurable and tangible concept, therefore it is necessary to make explicit the interpretation given to the term sustainability, sharing examples of good management practices and adapting the concept to the local context and farms characteristics.

The other Focus Groups centered on different components of DEXi-INVERSION, as follows:

- "Livestock management practices and resources": discussion on 17 indicators of the environmental and ethical dimensions;
- "Air-water-soil, biodiversity and animal welfare": discussion on 22 indicators of the environmental and ethical dimensions;
- "Socio-economic indicators": discussion of 8 indicators.

Before each Focus Group, farmers received in advance the list of indicators to be discussed, with a relative grid to express the degree of utility and feasibility of each indicator, and whether sustainability thresholds should have been discussed and modified. The evaluation grid (Table 13) facilitated the conduct of the discussion, which focused on indicators with at least two farmers' requests of modification of thresholds.

During the sessions, some indicators sparked a lively debate between farmers, namely: Efficiency of the feeding ration, Daily weight gains, GHG reduction, Ecological infrastructures, Crop rotation, Unintentional replacement rate, Quality of working life. The discussion led to the modification of sustainability thresholds for these indicators (Table 14). Overall, 8 over a total of 47 indicators discussed (=17 %) were modified. The adaptation process has mostly concerned the environmental dimension: 6 indicator thresholds were modified and the indicator "Traditional or alternative medicine" was removed.

Differences between original and new thresholds offer an insight into farmers perceptions on sustainability according to their local context. For some aspects, farmers of the Veneto region have been less "sustainable": the quantity of concentrate per 0.5 kg of daily weight gain or per 5 l milk (Efficiency of the forage feeding ration) is increased, meaning that farmers tend to use higher quantities of supplementary feeding to forages to sustain animal productivity. Similarly, thresholds related to the feeding efficiency of pastures have decreased, suggesting that grazing is not considered enough efficient to satisfy the nutritional needs of the herd.

Veneto farmers have expressed an "enhanced" sustainability perception on indicators concerning more the productivity aspects of livestock systems, rather than those focused on efficiency.

Table 13. Example of evaluation grid used in the participatory process in the Veneto region

Component and dimension	**Indicator**	USEFUL	LITTLE USEFUL	NOT USEFUL	NOT FEASIBLE	TO MODIFY	THRESHOLDS DISCUSSION (YES/NO)
1.3. Component animal husbandry practices (ENVIRONMENTAL DIMENSION)	Amount of grazed land and grazing time						
	Pasture management						
	% UAA forage production						
	Feeding efficiency of pastures						
	Protein fodder						
	Health prevention						
	Traditional/alternative medicine						
	Antibiotic treatments						
	Antiparasitic therapy						
1.4. Component livestock resources (ENVIRONMENTAL DIMENSION)	Fertility						
	Daily weight gain						
	Efficiency of forage feeding ration						
	Unintentional replacement rate						
	Fat and protein yield in dairy husbandry						
	Omega-6/Omega-3 ratio						
2.2. Component livestock management practices (ETHICAL DIMENSION)	Feeding ration						
	Management of the feeding ration						

Farmers attributed higher daily weight gains to the medium and low sustainability thresholds of the indicators and considered that a higher sustainability is related to low unintentional replacement rates. This productivity-based vision is also expressed by the modification of the medium thresholds of crop rotations, which reflects most of the Veneto farms assessed, where intense crop rotations are performed. Perfectly aligned with this entrepreneurial vision, farmers expressed their unwillingness to compute EU agriculture funds in the economic balance sheet, as a farm should be considered economically sustainable without public funding. From a social perspective, this vision is translated into a lowering of sustainability thresholds defining the quality of working life.

Table 14. List of indicators modified with Veneto farmers

	Efficiency of the feeding ration		Daily weight gains	
	Original thresholds	New thresholds	Original thresholds	New thresholds
High (+1)	≤ 1 kg	≤ 1,5 kg	> 1,2kg day^{-1}	> 1,1kg day^{-1}
Medium (0)	1-1,5 kg	1,5 -2,5 kg	0,5-1,2kg day^{-1}	0,9 -1,1 kg day^{-1}
Low (-1)	> 1,5 kg	> 2,5 kg	< 0,5kg day^{-1}	< 0,9kg day^{-1}
	GHG reduction		**Crop rotation**	
	Original thresholds	New thresholds	Original thresholds	New thresholds
High (+1)	At least 5 practices	At least 7 practices	4-year crop rotation	4-year crop rotation
Medium (0)	At least 3 practices	At least 5 practices	3-year crop rotation	2-year crop rotation
Low (-1)	Less than 1 practice	Less than 1 practice	no planned rotations	no planned rotations
	Feeding efficiency of pastures		**Unintentional replacement rate**	
	Original thresholds	New thresholds	Original thresholds	New thresholds
High (+1)	>80%	>70%	<15%	<10%
Medium (0)	60-80%	50-70%	15-25%	10-20%
Low (-1)	<60%	<50%	>25%	>20%
	Quality of working life		**~~Traditional/alternative medicine~~**	
	Original thresholds	New thresholds		
High (+1)	6 requirements met	5 requirements met		
Medium (0)	3-5 requirements met	3-4 requirements met		
Low (-1)	less than 3	less than 3		

Even if economic indicators have been fully discussed within the fourth Focus Group, their computation has not been considered a compulsory step in the sustainability assessment of Veneto farms, mainly due to the short duration of project activities. Alternative economic indicators have been introduced, focusing on the calculation of feed costs, in order to monitor the economic efficiency of some agroecological practices that will be introduced in livestock farms, in particular the fattening of beef cattle on pasture and the pasture-based dairy production. However, these indicators have not been integrated and/or used as substitutes in the sustainability assessment tool, but they've been applied in parallel.

In beef cattle farms, feed costs have been calculated per kg of dry matter in the feed ration and related to 1 kg of daily weight gain. In dairy farms, the Income Over Feed Costs (IOFC) has been applied to compute the net income after paying feed costs (Ferreira 2015). The following formula has been used:

IOFC = [Daily average milk production (kg milk) per cow * Milk price (€ kg^{-1})] – total feed costs (€ cow^{-1})

The calculation of indicators related to feed costs will allow for a comparison between the indoor and the pasture-based feed ration of fattening calves and lactating cows. In some dairy farms, the IOFC will be also useful to estimate the economic efficiency of the feed ration before and after the introduction of precision dairy farming systems (e.g. milking robot or automatic feeding systems).

4. Discussion

The development and use of practical, scientifically grounded and comprehensive performance metrics of agriculture and food systems, has been recommended as a basis for assessment, policy implementation and investment decisions within the framework of a transition towards sustainable food systems (HLPE 2019). Although agroecology has been promoted at the European and international level as an innovative approach to foster this transition, few tools are considered suitable for assessing the performance of agroecological transition farms, according to the following evaluation criteria: (i) local conditions, (ii) farmers' involvement, (iii) multifunctionality and (iv) interaction analysis (Wiget et al. 2020). In order to evaluate whether DEXi-INVERSION has been designed considering these four agroecological principles, the present study has provided a deep description of the development process using the scheme elaborated by De Olde et al. (2017), as it enhances the transparency and reliability of assessment frameworks and tools, which is considered an additional fundamental aspect for agroecological assessment frameworks (Wiget et al. 2020).

With regards to the first criterion, i.e. the adaptation to local conditions, the tool has been designed to support mountain livestock farms in their pathway towards sustainability, considering the territorial challenges (e.g. intensification of livestock farming with negative environmental externalities, disappearance of traditional farming practices). The tool has been developed starting from relevant local issues, and it's therefore strongly related to the local social and natural context, as well as to the peculiarities of livestock farms involved in its design. Accounting for local conditions also implies the use of farmer-based measures, limiting the need of technical support (Wiget et al. 2020). As farmers have actively participated to the tool development, assessment indicators and sustainability thresholds have been discussed, modified and finally validated according to farmers' acceptance. Some indicators have been directly proposed by the farmers themselves. Although DEXi-INVERSION can be used for a self-assessment, a technical assistance has always been provided, either to focus farms which took part to its design, either to the farms assessed within the present study. The technical support could be limited to the first assessment, enabling farmers to the tool use in full autonomy for further evaluations. Certainly, specific trainings on some assessment methods (e.g. for soil quality and economic indicators) can be necessary, according to farmers' knowledge.
In order to meet the criterion, a flexible and customizable structure of sustainability assessment frameworks and tools is also recommended (Meul et al. 2008; Munyaneza et al. 2019; Wiget et al., 2020). In particular, Wiget et al. (2020) propose to develop a dual structure based on a multi-scale approach, able to offer different levels of detail and to include the other stakeholders involved in food systems. Certainly, the open-source software DEXi ensures the tool flexibility and adaptability through the modification of the multi-attribute decision model. A dual structure could be developed, providing a simpler assessment level for farmers and a more technical one requiring the support of professionals. However, DEXi-INVERSION has been specifically designed for livestock systems and it is not applicable to other production systems. Furthermore, it has been conceived for the assessment at the farm level, hence the other dimensions of food systems are not included.

Farmers' involvement is the second criterion to evaluate the suitability of assessment frameworks and tools to agroecological transition farms, as it fosters the tool acceptance, understanding and applicability, as well as the incorporation of local knowledge (Fraser et al. 2006; Bélanger et al. 2012; Wiget et al. 2020). PLAR enhances stakeholder involvement and knowledge generation and facilitates transitions towards situational improvements (Chambers 1994; Kabourakis 2000; Eksvard & Rydberg 2010).
DEXi-INVERSION fulfills this principle as it has been developed with a participatory approach by a multi-actor group, namely the EIP-AGRI OG "Agroecology for Trentino", allowing the farmers' participation to the development process from the first beginning. PLAR methods, such as focus groups, have been applied at different stages of the process (e.g. indicator selection and sustainability thresholds definition, weighting of indicators, testing phase). However, the tool cannot be considered purely based on a bottom-up approach, as farmers have not been involved in some steps (e.g. hierarchical structure and indicators proposals, weighting of components and dimensions).
Farmers' involvement has been a central aspect for the tool implementation in the Veneto region, and has been achieved through the adoption of PLAR methods, namely focus groups, for the transfer of theoretical notions of sustainability and the linkage with farming management practices. Furthermore, the set of indicators was reviewed to be understood and accepted by farmers, and minor changes were made to meet farmers' perceptions.

According to the third principle, the concept of multifunctionality should be integrated into agroecological sustainability frameworks and tools by an appropriate combination of indicators and the use of productivity indicators (Wiget et al. 2020). In DEXi-INVERSION, multifunctionality is implicitly defined through the multidimensional sustainability structure of the tool: livestock farming can contribute to multiple environmental, socio-economic and ethical objectives. The economic indicator "Productivity" is explicitly designed to reward multifunctional farms, which are able to increase their productivity beyond the agricultural sphere, enhancing their resilience by diversifying their products and services.

The fourth criterion refers to the analysis of synergies and trade-offs between indicators, which basically reflect the multiple interactions between agroecological practices and ecosystem services (Wiget et al. 2020). This aspect has been addressed within the selection of indicators, which stressed particularly on the identification of multi-dimensional synthetic indicators. This process encouraged the reflection on indicator interaction. As an example, the indicator "Feeding ration" rewards farms using predominantly fresh or dry quality forages. A forage feeding ration promotes an efficient rumen function, reducing the emergence of pathologies and positively influences animal health. Furthermore, when the forage intake occurs through grazing, it has positive implications on animal welfare, and indirectly influences the environmental sustainability, as the presence of permanent meadows and pastures is related to the provisioning of several ecosystem services (e.g. reduction of GHG emissions, carbon sequestration, biodiversity). In addition, the higher quality of forage-based animal products can positively affect the socio-economic sustainability (Pisseri et al. 2020).

Apart from these evaluation criteria, DEXi-INVERSION has adopted agroecology as a systemic approach to sustainability (Gliessman 2014). All the principles of agroecology pointed out by HLPE (2019) and FAO (2018b) have been considered, either within the steps of its development process or in the sustainability topics addressed. Wiget et al. 2020

highlight that the adoption of common guidelines, such as the FAO agroecological principles, could facilitate the harmonization among the frameworks.
Eventually, the less treated aspect concerns healthy diets, as the assessment is more focused on the sustainability of the production system rather than on products. The benefits of grass-based productions on human health are also highlighted by Wezel & Peeters (2014). Nevertheless, the indicator evaluating the Omega-6 to Omega-3 ratio in milk moves in that direction. The same indicator is not applied to meat, despite the presence of literature references giving evidence of a low ratio in grass-fed beef than in grain-fed beef (Stanton et al. 2021). This lack of indicators assessing meat quality has been pointed out also by Veneto farmers.
The tool has not only adopted the general agroecological principles, but also those specifically referring to agroecological livestock farming systems, mainly based on De Benedictis et al. (2015) and expert consultation. The basic elements considered are aligned and cover almost all principles identified by Dumont et al. (2013) for sustainable animal production systems (e.g. management practices to improve animal health, input reduction, biodiversity conservation) and by Wezel & Peeters (2014) for agroecological herbivore farming systems (e.g. economic viability and farmers quality of life, optimization of nutrient cycling, permanent soil cover, self-sufficiency).

An innovative element of DEXi-INVERSION in the framework of agroecological assessment tools is that it includes the ethical dimension, that Rawles (2012) defined "*the neglected dimension of sustainability*". Although other tools encompass indicators regarding animal welfare (e.g. SAFA, RISE, PG Tool, IDEA, MESMIS), the design of an ethical dimension certainly represents a step forward in the development of sustainability assessment tools, as it gives prominence to animal welfare issues among the ethical implications of livestock farming. Surely, the emphasis given to animal welfare is linked to the fact that the tool has been specifically designed for livestock farming systems. Within the indicators assessing animal welfare, a new element is introduced, that is the investigation of the human-animal relationship. Furthermore, the systemic approach of DEXi-INVERSION also allows for an indirect assessment of the impacts of farming practices on animal welfare, as sustainability topics are strongly interconnected with each other.

Another aim of the present study was to provide evidences of the practical applications of DEXi-INVERSION to support an agroecological transition at the farm level.
The case study of Farm 1 presents the use of the tool for evaluating the impacts of different practices on sustainability. The farm assessment highlighted several management aspects which reduce the environmental and social sustainability, concerning e.g. animal biodiversity, weaning systems, housing systems, feeding ration, farm network, soil health. Once the effects of the different practices on sustainability were analyzed, agroecological technical advices were provided to the farmer for improvements.
The case study of Farm 2 gives evidence of the use of DEXi-INVERSION for supporting decision-making processes at the farm level. Specifically, the farm assessment allowed to identify strengths and weaknesses of the farm management system, in relation to a potential "agroecological" dietary transition, i.e. the gradual reduction of silomaize and soybean in favor of dry forages and alternative protein sources. A forage-based ration, together with the reduction of soybean, is expected to increase the farm environmental sustainability (permanent soil cover, no chemicals inputs, no or limited transportation).
Although the tool has been tested for these purposes only on single farms and no general statements can be derived, the results of the assessments provide a deep understanding of

the effects of different practices on sustainability. Consequently, technical suggestions can be given for improvements, when the farm has already adopted an agroecological approach, or for starting an agroecological transition. If in the case of Farm 1, technical advices could realistically be implemented, in Farm 2 the transition is not feasible without a farm restructuring.
The use of the tool for monitoring the farm evolution in time is shown in the case study of Farm 3. The improvement or worsening of farm management practices clearly emerges from the comparison of the assessment results of two consecutive years. However, discrepancies can arise if the assessment at year one is not sufficiently detailed. In the example, the first assessment was carried out within a collective testing, and the description of some management practices was not sufficiently exhaustive to provide an accurate monitoring. In this case, additional information should be collected through farmer interview.

Finally, the tool has been applied to compare farms' sustainability performances. The comparison of the global sustainability of Trentino farms suggests that small dairy farms (< 13 adult cows) managed by farmers of new generation, rearing local breeds at risk of extinction, performing cheese production in alpine summer farms and directly selling their product,s have a higher sustainability. On the other side, dairy farms managed by farmers of second generation, that rear specialized breeds and don't practice the summer grazing, are less sustainable. The comparison of the environmental and ethical sustainability performance of Trentino and Veneto farms shows that Veneto farms are more sustainable for the environmental dimension, especially regarding biodiversity, in terms of animal species reared and the presence of local breeds or plant varieties. Veneto farms also show a higher sustainability for the component "Animal husbandry practices", due to a more diffused grazing of animals, the presence of health prevention practices and a low use of antibiotic treatments. On the other hand, Trentino farms are more sustainable for the ethical dimension, especially regarding the interaction with animals. This is probably a result of an increased farmers' awareness following the implementation of the INVERSION project. As previously highlighted, the analysis doesn't allow a general statement due to the limited number of farms assessed.

From a methodological point of view, two components of the DEXi-INVERSION package, namely the user manual and the file DEXi_INVERSION.xls, have been used for sustainability assessments. Semi-structured interviews were conducted for data collection, using the user manual as a reference framework and the annexed assessment grid; data collected were organized using the file DEXi_INVERSION.xls. The tool presents some limitations for both operational steps. The assessment grid is not sufficiently structured to perform an exhaustive data collection, as it only allows to score sustainability for each indicator. The inadequacy of the tool for data collection is then reflected in a higher effort for data organization.
Another consideration related to the assessment, is that so far, DEXi-INVERSION has been practically applied with technical support. The reason behind is mainly time-related: a self-assessment would have required a greater effort on the part of farmers, who had already to bear the burden of providing farm data. Furthermore, some of the farms assessed didn't receive a training on sustainability topics or participate to sessions on DEXi-INVERSION, which certainly represents a precondition for an effective assessment. The time spent for performing the sustainability assessment is indeed a key aspect to determine whether the tool can be implemented at a reasonable cost. Although the duration of data gathering (two

sessions of at least two hours each) is in line with that of the other tools illustrated, an additional time must be considered for field visits when the farm structure is unknown. Farm data organization and analysis is also a time-consuming operation: a minimum of 4 hours per farm was required to fill the spreadsheets starting from the raw data collected with semi-structured interviews and to elaborate a synthetic report for the restitution of results to farmers (excluding technical advices). Assuming a gross cost of 50 € per working hour (including travel expenses) and a relative short distance to reach the farm (e.g. less than one hour's travelling), we can estimate a total charge of 400 € per farm assessed. By reason of the fact that the assessment is conducted in two sessions to not overload farmers, an extra time (and cost) could be computed according to the distance of the farms to be assessed.

This would be probably a reasonable cost if DEXi-INVERSION was a voluntary sustainability standard providing a third-party certification that farmers could adopt to label as "sustainable" their own farm and/or products. An attempt to "raise" the value of the assessment tool in this direction was made within INVERSION project: the EIP-AGRI OG developed a proposal to adopt the tool for a second-party certification (INVERSION 2021). A label was registered and released in different colors according to the sustainability level achieved and an entry level of sustainability was defined for using the label. However, the proposal has not been practically applied.

Concerning the elaboration of technical advices for farm case studies, this was based on the professional experience of the author and linked to literature sources. In some cases, the task was quite challenging, as not always agroecological livestock practices are technically detailed or provide concrete examples to follow and adapt to the peculiarities of the local context.

Finally, the software DEXi has been used to compare farm performances, either of the same farm in time, either of different farms. Particularly useful are the functions "Selective explanation" report, which highlights the weak points of the farm, and the "Comparison of options" report, which provides an intuitive picture of the major differences between farms. However, the software doesn't allow to perform statistical analyses, so it was necessary to use Microsoft Excel and R to compare farms' performances. Furthermore, the graphical representation of the results tends to be less clear if "non option" values are present; for that aim the graphical visualization produced with the file DEXi_INVERSION.xls is preferable.

5. Conclusions and recommendations

The role livestock farming can play in building sustainable food systems and in contributing to the achievement of SDGs is indisputably essential, despite the great challenges the sector has to face in order to ensure the provisioning of nutritious and healthy animal-source food and enhance an inclusive economic growth, while preserving animal welfare and addressing environmental issues (FAO 2018a). Within this framework, the adoption of DEXi-INVERSION or of similar tools can support the transformation needed in the livestock sector while taking into account the many environmental, social and, I may add, animal welfare externalities that, according to HLPE (2019), have often been neglected in past assessments of agriculture and food systems.

Despite the wide scenario of sustainability assessment tools, DEXi-INVERSION brings elements of innovation that can better assist the development of livestock farming transition pathways towards sustainable, agroecological production systems, as it accounts for local conditions, farmers' involvement, multifunctionality and indicator interaction analysis, which are the key aspects characterizing agroecological assessment frameworks (Wiget et al. 2020). Furthermore, it's based on a transparent development process that enhances its credibility and legitimacy (de Olde et al. 2017), and its development is deeply rooted into agroecological principles and practices. Nevertheless, some ameliorations could be undertaken.

Concerning the DEXi-INVERSION package, a checklist should be prepared to facilitate the interviews with farmers and enable a more accurate information gathering. The checklist could be directly included in the file DEXi_INVERSION.xls to reduce the time required for data organization and processing. In order to reduce eventual costs of the assessment, the second session required for data collection, as well as the restitution of results, could be performed in remote form.

In order to increase its applicability, a dual structure could be developed to enable, on one side, a simple farmer self-assessment, on the other side, a more technical evaluation whose results can be relevant for policy analysis. This would allow a wider implementation of the tool, limiting the technical support for the basic assessment with a consequent cost containment, and enlarging its fields of application, going beyond the farm level. The more "scientific" assessment could include, for example, fodder analyses and fatty acids analyses to evaluate the Omega-6/Omega-3 ratio of milk and meat, which would increase the reliability of the assessment. Even so, a participatory training for farmers on sustainability topics and indicators would still be an essential precondition for an effective assessment.

Certainly, its applicability is limited to livestock farming systems: the use of the tool to assess other production systems or food value chains would require a complete revision of the multi-attribute decision model elaborated with the DEXi software, which is not desirable as it would irreversibly alter the tool and the scope for which it has been conceived. It is instead recommended to link the tool to common agroecological assessment frameworks in order to have a standard reference. Although widely accepted guidelines are still missing, as noticed by Wiget et al. (2020), the Tool for Agroecology Performance Evaluation (TAPE) recently developed by FAO (2019) could act as a potential common framework, facilitating the harmonization among the different tools. Further research could be oriented on testing the applicability of TAPE and on the alignment of DEXi-INVERSION to this standard framework. Moreover, detailed research about agroecological livestock farming indicators and sustainability thresholds is needed to foster the robustness of assessment frameworks and tools dealing with agroecological farms in which animal husbandry is the prevailing activity.

With regard to the tool functionalities, aside from the sustainability assessment, the present study suggests that it can be successfully implemented for evaluating the impacts of different management practices on sustainability, supporting decision-making processes at the farm level, monitoring the farm evolution in time and comparing farm performances. However, the study doesn't provide general statements due to the limited number of farms involved. Therefore, the tool could be tested for these practical applications on a wider sample. Furthermore, research efforts should also be oriented to the development of a comprehensive set of agroecological livestock practices, providing concrete examples of their implementation, that technical advisors can follow and adapt to local contexts. This could indeed facilitate the provision of technical suggestions to support the agroecological transition at the farm level.

To conclude, the present study contributes to the transdisciplinary and participatory research on agroecological sustainability assessment frameworks and tools. Certainly, the value of DEXi-INVERSION goes beyond the sustainability assessment, as it fosters social learning, responding to local needs of dissemination of agroecological knowledge, as stated by Caporali (Pisseri et al. 2020). The cost-benefit ratio of its adoption should be therefore estimated according to the multiple benefits of simultaneous sustainability improvements, applied research and education. However, common reference frameworks are needed for harmonizing the design of agroecological assessment tools, defining a widely accepted set of livestock farming indicators suitable for agroecological livestock farms and a comprehensive collection of management practices and technical tips to effectively support their transition.

6. Annexes

Annex 1

DEXi-INVERSION indicators	Sustainability thresholds		
	High	**Medium**	**Low**
Practices for GHG reduction	At least 5 practices adopted	At least 3 practices adopted	Less than 3 practices adopted, and negative ones applied (e.g. uncovered slurry tanks)
Water conservation measures	At least 5 practices adopted, the farm contributes to water saving at the district level	At least 2 practices adopted, the farm doesn't waste water at the district level	No practices applied, water intensive productions, the farm contributes to water wasting at the district level
Water pollutants	All practices adopted	At least one practice adopted, less polluting chemical products are used, buffer zones are respected	No practices adopted
Soil health	Test score +2, +3	Test score +1 to -1	Test score -2, -3
Preventive measures for soil erosion	At least 5 practices adopted	3 to 5 practices adopted	Less than 3 practices adopted
Ecological infrastructures	> 15% of total farm area uniformly distributed; active conservation measures	5 to 15% of total farm area not uniformly distributed; low conservation action	< 5% of total farm area
Animal biodiversity	More than one practice	At least one practice	No co-presence or alternation
Animal species reared	> 2 species reared	1-2 species reared	Only 1 species reared
Crop rotation	4-year crop rotation	3-year crop rotation	No planning of crop rotations. Cultivations follow market requirements and mid-term farm goals
Rusticity	Genetic selection based on at least on 2 parameters	Genetic selection based on at least 2 parameters and on productivity performances	Genetic selection only based on productivity performances
Presence of local varieties/breeds	> 2 local animal breeds/plant varieties	1-2 local animal breeds/plant varieties	1 local animal breed/plant variety
Amount of grazed land and grazing time	Pastures >60% of UAA, 4 or more months of grazing per year, grazing in non-arable lands for at least 2 months/year	Pastures 30 to 60% of UAA, 2 to 4 months of grazing per year, at least 1 month/year of grazing in non-arable lands	Pastures <30% of UAA, less than 2 months of grazing per year

DEXi-INVERSION indicators	Sustainability thresholds		
	High	**Medium**	**Low**
Pasture management	Pasture Management Plan, rotational grazing, ameliorative agronomic practices, improved biodiversity	Occasional pasture care, little attention towards biodiversity	No practices adopted
UAA for fodder production	> 50% of UAA of grasslands and multiannual forage crops	25 to 50% of UAA	< 25% of UAA
Feeding efficiency of pastures	> 80% FU from grazing	60-80%	< 60%
Protein fodder	> 90%	50-90%	< 50%
Health prevention	All practices adopted	At least 2 practices adopted	One or no practices adopted
Traditional/alternative medicine	Frequent use, for at least 70% of sanitary problems, with the support of an expert vet	Occasional use, for 30% to 70% of sanitary issues	No use or rare use, for less than 30% of sanitary problems
Antibiotic treatments	< 2%	2-10%	>10%
Antiparasitic therapy	0	1 or 2	> 2
Fertility	>80%	60-80%	<60%
Daily weight gains	> 1.2 kg day^{-1}	0.5 - 1.2 kg day^{-1}	< 0.5 kg day^{-1}
Efficiency of forage feeding systems	1 kg or less	1 - 1.5 kg	> 1.5 kg
Unintentional replacement rate	< 15%	15-25%	>25%
Fat and protein yield in dairy husbandry	> 7	6 to 7	< 6
Omega 6/omega 3 ratio	1:1	1:1 - 2:1	> 2.1
Animal welfare in extensive or semi-extensive breeding systems	Extensive or semi-extensive breeding for at least 7 months per year, diversified environments, water and supplementary feeding available, care in animal adaptability	Seasonal extensive or semi-extensive breeding in mountain areas, for at least 6 months per year in hilly regions and lowlands, low environmental heterogeneity, water and supplementary feeding available	Extensive or semi-extensive breeding without shelter and/or shadow, or with difficult access to water and supplementary feeding
Housing systems and housing adequacy	Loose housing system with litter, adequate plants and facilities, good maintenance	Loose housing system with cubicles without litter, inadequacies in plants, no prompt maintenance	Tie barn, loose housing system without litter. Serious plant deficiencies

DEXi-INVERSION indicators	Sustainability thresholds		
	High	**Medium**	**Low**
Outdoor livestock yards	Adequate dimensions, easy to clean, well-exposed to sunlight, non slippy surfaces	Inadequate dimensions and/or not easy to clean and/or without non-slip covering	No paddock in tie barn
Feed ration	Forage-concentrate > 70/30, high feed quality, no silages	40 to 70% of DM from forages, and/or maximum 25% of silomaize, grass silage up to 35%, good feed quality	< 40% of DM from forages in the feed ration, and/or silomaize is > 35%, or poor feed quality
Management of the feed ration	Free and constant access to pastures, quality fodder, free access to supplements, adequate trough dimensions, concentrate feeding frequency twice a day	Limited access to pastures and fodder, one daily concentrate feeding, trough dimensions partially adequate	No access to pastures, limited access to fodder, long daily periods without access to feed, one daily concentrate feeding, inadequate trough dimensions
Body development of young females before giving birth	70%	60-70%	less than 60%
Care and management of young animals	All requirements met	At least 6 requirements met	Less than 6 requirements met
Presence of elderly animals	> 40%	20 to 40%	< 20%
Partum and post-partum management	All requirements met	A t least 4 requirements met	Less than 4 requirements met
Weaning systems	Natural weaning or use of suckler cows	Visual and olfactive contact, natural suckling twice a day for at least 30 days or feeding with fresh milk	Abrupt early weaning (at birth or until 7 days from birth)
Time and attention devoted to observing animal behavior	At least 30 minutes/day in observing the herd, expertise in understanding signs related to social and physiological behaviors	Less than 30 minutes in observing the herd, moderate expertise	No observation
Human-animal interaction	All conditions present	Presence of at least 2 conditions	Presence of less than 2 conditions
Handling of animals	No stress in animals and farm operators, handling operations are rapid and safety, adequate tools	Distress among animals and operators, handling operations carried out in a hurry, no adequate tools	Nervous animals, low expertise of the farm operators

DEXi-INVERSION indicators	Sustainability thresholds		
	High	**Medium**	**Low**
Farm network	At least 5 conditions are present	Between 3 and 5 conditions are present	Less than 5 conditions are present
Quality of working life	All 6 requirements are met	Between 3 and 5 requirements met	Less than 2 requirements met
Intergenerational conflict	Innovation proposals are accepted and sustained	Conflicts between farmers generations are sorted out with internal communication or external support	The family withstands the innovation coming from the younger generation. No attitude towards change
Professional training of farm operators	Regular professional training of farm operators (more than once a year)	Occasional professional training (1 or less per year)	No professional training
Internal communication and coordination	Organizational problems, low quantity/quality of communication, no shared decision-making	Communication is present but not optimal organization, decisions mostly taken by individuals	Well organized farm, good internal communication, shared decision-making
Profitability	> 5000 € /ha	3000 - 5000 € /ha	< 3000 € /ha
Labor efficiency	> 20000 €	15000 - 20000 €	< 15000 €
Vulnerability	> 2	2 - 1.2	< 1.2

Annex 2

Sustainability assessment grid

Farm: **Date:**

Environmental dimension					
Component	**Indicator**		**Sustainability thresholds**		
			High (+1)	**Medium (0)**	**Low (-1)**
1.1. Air Water Soil	1.1.1.	Practices for GHG reduction			
	1.1.2.	Water conservation measures			
	1.1.3.	Water pollutants			
	1.1.4.	Soil health			
	1.1.5.	Preventive measures for soil erosion			
1.2. Biodiversity	1.2.1.	Ecological infrastructures			
	1.2.2.	Animal biodiversity			
	1.2.3.	Animal species reared			
	1.2.4.	Crop rotation			
	1.2.5.	Rusticity			
	1.2.6.	Presence of local varieties/breeds			
1.3.	1.3.1.	Amount of grazed land and grazing time			
	1.3.2.	Pasture management			
	1.3.3.	UAA for forage production			
	1.3.4.	Feeding efficiency of pastures			
	1.3.5.	Protein fodder			
	1.3.6.	Health prevention			
	1.3.7.	Traditional/alternative medicine			
	1.3.8.	Antibiotic treatments			
	1.3.9.	Antiparasitic therapy			
1.4. Livestock resources	1.4.1.	Fertility			
	1.4.2.	Daily weight gain			
	1.4.3.	Efficiency of forage feeding systems			
	1.4.4.	Unintentional replacement rate			
	1.4.5.	Fat and protein yield in dairy husbandry			
	1.4.6.	Omega-6/Omega-3 ratio			

<table>
<tr><th colspan="6">Ethical dimension</th></tr>
<tr><th rowspan="2">Component</th><th rowspan="2" colspan="2">Indicator</th><th colspan="3">Sustainability thresholds</th></tr>
<tr><th>High (+1)</th><th>Medium (0)</th><th>Low (-1)</th></tr>
<tr><td rowspan="3">2.1.
Animal husbandry systems</td><td>2.1.1.</td><td>Animal welfare in extensive or semi-extensive breeding systems</td><td></td><td></td><td></td></tr>
<tr><td>2.1.2.</td><td>Housing systems and housing adequacy</td><td></td><td></td><td></td></tr>
<tr><td>2.1.3.</td><td>Outdoor livestock yards</td><td></td><td></td><td></td></tr>
<tr><td rowspan="7">2.2.
Livestock management practices</td><td>2.1.1.</td><td>Feeding ration</td><td></td><td></td><td></td></tr>
<tr><td>2.2.2.</td><td>Management of the feeding ration</td><td></td><td></td><td></td></tr>
<tr><td>2.2.3.</td><td>Body development of young females at first calving</td><td></td><td></td><td></td></tr>
<tr><td>2.2.4.</td><td>Care and management of young animals</td><td></td><td></td><td></td></tr>
<tr><td>2.2.5.</td><td>Presence of elderly animals</td><td></td><td></td><td></td></tr>
<tr><td>2.2.6.</td><td>Partum and post-partum management</td><td></td><td></td><td></td></tr>
<tr><td>2.2.7.</td><td>Weaning systems</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">2.3.
Cooperative behaviors</td><td>2.3.1.</td><td>Time and attention devoted to observing animal behavior</td><td></td><td></td><td></td></tr>
<tr><td>2.3.2.</td><td>Human-animal interaction</td><td></td><td></td><td></td></tr>
<tr><td>2.3.3.</td><td>Handling of animals</td><td></td><td></td><td></td></tr>
</table>

<table>
<tr><th colspan="6">Socio-economic dimension</th></tr>
<tr><th rowspan="2">Component</th><th rowspan="2" colspan="2">Indicator</th><th colspan="3">Sustainability thresholds</th></tr>
<tr><th>High (+1)</th><th>Medium (0)</th><th>Low (-1)</th></tr>
<tr><td rowspan="5">5.1.
Socio-territorial</td><td>3.1.1.</td><td>Farm network</td><td></td><td></td><td></td></tr>
<tr><td>3.1.2.</td><td>Quality of working life</td><td></td><td></td><td></td></tr>
<tr><td>3.1.3.</td><td>Intergenerational conflict</td><td></td><td></td><td></td></tr>
<tr><td>3.1.4.</td><td>Professional training of farm operators</td><td></td><td></td><td></td></tr>
<tr><td>3.1.5.</td><td>Internal communication and coordination</td><td></td><td></td><td></td></tr>
<tr><td rowspan="3">5.2.
Economic</td><td>3.2.1.</td><td>Profitability</td><td></td><td></td><td></td></tr>
<tr><td>3.2.2.</td><td>Labor efficiency</td><td></td><td></td><td></td></tr>
<tr><td>3.2.3.</td><td>Vulnerability</td><td></td><td></td><td></td></tr>
</table>

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